Aichi University of Education & Shizuoka University (Japan)

Doctoral Dissertation

Developing ICT-Based Teaching Materials for Physics Education in Cambodia

カンボジアにおける物理教育のためのICTを基礎とした教材開発

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ABSTRACT

The primary objective of the research is to evaluate the current state of science education at senior high schools (referred to as high schools in this report) in Cambodia, specifically in terms of ICT intellectual and physical resources. The aim is also to develop ICT-based teaching and learning materials to enhance the support for Physics education at the high school level. With this purpose, I pose three research questions:

1. Does the current situation of human and infrastructure resources in schools facilitate ICT-based teaching and learning science in Cambodia?
2. What teaching materials can be developed to support ICT-based teaching and learning of Physics in Cambodia?
3. How effective are the developed teaching materials in teaching and learning Physics in Cambodia?

To address the first research question, a survey study with 285 high school principals and science teachers in Cambodia was conducted. The survey sought to answer two more specific questions: 1) How do Cambodian science teachers perceive their knowledge and skills in integrating ICT into teaching, and 2) Does the current state of human and infrastructure resources in schools enable the integration of ICT into science education in Cambodia? The results indicated that high school science teachers in Cambodia have a sufficient understanding of their respective subject matter and teaching strategies. They are also proficient in using ICT for administrative work and communication but cannot utilise ICT to enhance their teaching practices and improve student learning outcomes. The ability of Cambodian high school science teachers to integrate ICT into their teaching practices depends on their knowledge of how to use technology to represent the content and their knowledge of using technology to transform their teaching practices.

Cambodia high schools have acceptable infrastructure, incorporating libraries, science-laboratory rooms, computer labs, internet connection, clean water, toilets and electricity. However, science-laboratory rooms lack materials, especially for ordinary high schools. Similarly, most ordinary high schools have very few or no computers for students to learn and use to support learning. There is a lack of classrooms, leading to having high student-to-classroom ratio and class size, especially in the capital city.

To respond to the second research question, teaching materials focusing on Oscillations and Waves were developed, including three specific topics: 1. Damped Oscillations, 2. The Doppler effect, and 3. Interference. The relevant apparatuses developed were an angle sensor, E-Lab interface, vibrator and simplified ripple tank.

The results are as follows:

1. Damped Oscillations: The study conducted an experiment of damped oscillation in the case of a combination of Coulomb's and Viscous friction effect, employing an angle sensor and video analysis technique for data acquisition. The experiments are simple and handy for controlling variables and parameters in pendulum damping. Either the video analysis technique or angle sensor is appropriate to quantify pendulum motion, allowing precise measurement that leads to highly accurate and reliable results. This study contributes to the use of technology in physics education, specifically in physics experiments.

2. The Doppler effect: The study introduced an ICT-experimental approach for teaching and learning the Doppler effect, using the simplified ripple tank as a tool to visually and quantitatively illustrate the existence of the effect. The Doppler effect could be observed clearly on video. The video analysis technique presented in the study allows for acquiring and analysing data directly from what they observed on video. The results were highly accurate; the experimental measurements agreed with the theoretically predicted values.

3. Interference: The experiment used the developed simplified ripple tank and a smartphone; the interference phenomenon of water waves can be recorded and observed easily. Additionally, by employing video analysis software such as Tracker, experiment videos can be quantified accurately. The results of this study have clear implications for using ICT and water waves for teaching and learning the process of interference phenomenon to deliver a high student understanding of the fundamental phenomenon.

To answer the third research question, a series of teaching practices using the developed teaching materials were conducted in Cambodia with teacher educators, high school Physics teachers, student teachers and high school students. The study used a quasi-experiment with a single-subject pre-test and post-test design. The effectiveness of the teaching material developed for Oscillations and Waves has been proven through comparisons of pre-test and post-test scores, showing large effects and moderate normalised gain scores, along with improvement of Certainty of Response Index and overall positive feedback from participants in the survey, which has shown that it is moderately effective. Additionally, the teaching material is applicable and very useful. In conclusion, the developed teaching materials on Oscillations and Waves are suitable for Physics Education in Cambodia, whether for pre-service training), in-service training), or high school education.

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Aichi University of Education, October 2023

THY Savrin

DEDICATION

In loving memory of my father, Mr SVAY Thy, my enduring hero, and my brother, Mr THY Sithuon, a timeless role model. Despite their departure decades ago, their wisdom remains the guiding force behind my academic accomplishments. Their invaluable advice has been the endless energy propelling me through this demanding doctoral journey. This dissertation is a heartfelt dedication to their enduring spirits, a testament to the memorable impact of their guidance on every step of my academic pursuits. In completing this doctorate, I honour their memory, expressing gratitude for the profound inspiration that continues to resonate within me.

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ABBREVIATION

AI : Artificial Intelligence
CK : Content Knowledge
CRI : Certainty Response Index
CSV : Comma-Separated Value
ESDP : Education Sector Development Project
ICT : Information and Communication Technology
INSET : In-Service Training
LS : Lesson Study
MBS-DAS : Microcontroller-Based Sensor Data Acquisition System
MoEYS : Ministry of Education Youth and Sport
MWCS : Mechanical Waves Conceptual Survey
NGS : New Generation School
NIE : National Institute of Education
OECD : The Organization for Economic Cooperation and Development
OHS : Ordinary High School
OSP : Open Source Physics
PCK : Pedagogical Content Knowledge
PK : Pedagogical Knowledge
PLHS : Prek Leap High School
PRESET : Pre-Service Training
PTEC : Phnom Penh Teacher Education College
SHM : Simple Harmonic Motion
SRS : Secondary Resource School
STEM : Science, Technology, Engineering, and Mathematics
TCK : Technological Content Knowledge
TK : Technological Knowledge
TPACK : Technological Pedagogical Content Knowledge
TPK : Technological Pedagogical Knowledge
USESDP : Upper Secondary Education Sector Development Program

CHAPTER I

FRAME OF THE STUDY

1.1. Motivation for the Study

In 2019, I was a principal of a high school hosted by a French non-government organisation in the southeast Phnom Penh suburb. During a lesson study (LS) discussion on the free fall motion, the experiment required a recording timer based on the Physics experiment guidebook of the National Institute of Education (NIE), which was difficult to find in Cambodia. If ordered from abroad, it would take time and be somewhat expensive over the budget. The discussion was to seek various alternatives. I suggested the LS team consider designing video experiments. At that time, I had no idea about video analysis software. The idea of the video experiment of free fall at that time was to record a video of a falling ball alongside a tape ruler, and near the tape ruler, place a stopwatch (i.e., stopwatch app on a mobile phone) to indicate time. After recording the video, playback the experiment on the computer and record the ball position based on the tape ruler and the time based on the stopwatch in the video. My idea sounded refreshing and appealing. The LS seemed to accept my suggestion. However, they did not make it happen; they did not even try it. One of the reasons was that they might not be confident in teaching experiments with technology. They might think that students would not be able to learn in such a way, or perhaps they found a better alternative for them. Because I was the principal and primarily worked on administrative management and leadership. I let the situation be the way it was; however, this experience sparked the idea of video experiments in my head since then. After researching video experiments for a while, I found many published articles about using video analysis for science experiments and realised information and communication technology (ICT) could be handy for science education, particularly Physics education.

In March 2020, when COVID-19 started to hit Cambodia, the government put strict measures for virus transmission prevention. Following the government measure, the Ministry of Education, Youth, and Sport (MoEYS) announced school closure and put education staff, teachers and students on short vacations earlier to the schedule. When the vacation period was over, the situation was not better. MoEYS continued the school closure measure and encouraged distance learning. While all schools were not ready, they had been struggling to provide distance learning for students. From that point, ICT became a boom for distance education during the school closure. Various ICTs have been adopted for distance education. Online video conferences were employed for synchronous virtual lessons, whereas recorded videos were used for asynchronous format. These two modalities were also adopted in the school where I was working. Once again, as a school principal, I encouraged Physics teachers to use video experiments and introduced Tracker (a video analysis software, more detailed in Chapter III) to them for the Physics lessons. As a result, no one used it or even tried it again. There might be many possible reasons why Physics teachers did not try video-based experiments for their lessons. Since teachers had the full right to choose their teaching material and method suitable for their students, I did not inquire them about that. By the end of October, I resigned from the school and came to Japan soon after for this doctorate program. I did not know what happened afterwards.

Having arrived in Japan and being a research student to prepare for the doctoral entrance exam, I had time to think about the research topic. However, the two stories described above made me ask the question: Why didn't they do it? This question captivated me to think of ICT-based experiments day and night. After reviewing the literature for a while, I realised that ICT for education was one of the most discussed topics among educators around the globe because of the advancement of ICT these days, such as artificial intelligence (AI), big data, and the internet of things, and information utilisation has been playing an essential role in everyday life and almost all aspects of our daily activities. This inspired me to consider ICT-based teaching materials as the topic for this doctorate dissertation, and video-based experiment is a big part of the study. The following section will discuss how important ICT is in science education and why it is necessary to study.

1.2. ICT in Science Education

The impact of ICT on our lives is undeniable, and education is no exception. In today's schools, a range of ICT tools–including computers, tablets, smart TVs, projectors, computer networks, Wi-Fi internet, school databases, printers, word processing, spreadsheets, and presentation software–play a vital role in supporting teaching and learning activities. Science activities, in particular, benefit from ICT tools such as data logging systems, data handling tools, spreadsheets, calculators, graphing tools, and multimedia.

For instance, data logging systems consist of sensors or probes that convert measurable quantities (such as temperature, light intensity, time, position, acceleration, current, and energy) into a voltage that a computer can recognize (Osborne & Hennessy, 2003). An interface connects the sensors to the computer, and a computer program controls the interface and displays data on the screen (Osborne & Hennessy, 2003; Rodriguez, Silva, Rosano, Contreras, & Vitela, 2001).

Data handling tools allow students to perform various functions such as tabulating, restoring, or deriving data from computer logging or practical experiments. These tools also enable them to perform calculations using built-in formulae, sort and search data, and create graphs and charts. Additionally, students can generate new datasets using these tools. Spreadsheets, for instance, are very useful in both static and dynamic modelling of physical phenomena. In static modelling, changing a variable in the model will produce a new output, while dynamic modelling uses an iterative calculation to model a system as a function of time and allows for varying initial parameters (Osborne & Hennessy, 2003).

Multimedia comprises various elements like explanatory video and audio sequences, animated graphics, tutorials, interactive tasks, slide shows, and interactive databases/encyclopaedias (McFarlane & Sakellariou, 2002). Simulations in multimedia include the solar system, the human body, the periodic table, and physical forces (Osborne & Hennessy, 2003). Video, in addition, can be used not only for observing phenomena but also for science experiments (McFarlane & Sakellariou, 2002; Osborne & Hennessy, 2003; Rodriguez et al., 2001). Video-based experiments are based on the analysis of a physical phenomenon observed on a digital video. In science class, "virtual" measurements over the video can be made using video analysis software (Tracker, for example). The video-based experiment allows students to study the theory from a particular observed experiment (Rodriguez et al., 2001).

The use of ICT in science teaching and learning, particularly tools for data handling and graphing, can speed up and streamline working processes, freeing students from spending time on routine and laborious tasks. This enables rapid plotting of diverse variables within a short period, or collection of and comparison between a larger number of results (Osborne & Hennessy, 2003; Rodriguez et al., 2001). Using versatile software tools linked to data logging is particularly helpful, allowing students to explore and present data in different ways with a low investment of time and effort (Osborne & Hennessy, 2003).

Based on the earlier discussion, it is evident that Information and Communication Technology (ICT) plays a vital role in enhancing students' reasoning and inquiry in science education. Among the essential ICT tools for science teaching and learning, a data logging system is the most well-documented tool for hands-on activity and science experimentation (McFarlane & Sakellariou, 2002; Osborne & Hennessy, 2003; Rodriguez et al., 2001). Although video multimedia was also found to be an essential ICT tool in science education (Rodriguez et al., 2001), it was less well-documented in research. Additionally, videos were often used merely to capture an event and play it back on the computer screen instead of logging data with video analysis software to quantify the phenomenon (McFarlane & Sakellariou, 2002).

Moreover, according to McFarlane and Sakellariou (2002) and Osborne and Hennessy (2003), data capture tools are the most significant ICT tools for science education. However, it is still a minor activity in science teaching and learning. Despite its significance, ICT-based science teaching and learning is still not widely used in the current education system worldwide (Osborne & Hennessy, 2003). Therefore, the present study focuses on developing teaching materials using ICT-based data-logging tools incorporating sensor and video analysis.

1.3. Research Questions

The proposed title of this study is “Developing ICT-Based Teaching Material for Physics Education in Cambodia”. The primary objective of the research is to evaluate the current state of science education at senior high schools (referred to as high schools in this report) in Cambodia, specifically in terms of ICT intellectual and physical resources. The aim is also to develop ICT-based teaching and learning materials to enhance the support for Physics education at the high school level. With this purpose, I pose three research questions:

1. Does the current situation of human and infrastructure resources in schools facilitate ICT-based teaching and learning science in Cambodia?
2. What teaching materials can be developed to support ICT-based teaching and learning of Physics in Cambodia?
3. How effective are the developed teaching materials in teaching and learning Physics in Cambodia?

1.4. Research Methodology

The research methods were generally composed of 4 steps:

Step 1: Identifying the situation

Due to the lack of empirical reports on the current state of science education in Cambodia, particularly concerning ICT, survey research was conducted to explore and identify the challenges and opportunities that can be used as guidance for teaching material development and teaching practices.

Step 2: Determining the topics

To prioritize and determine the most appropriate topics, a review of curriculum materials, including syllabus and high school Physics textbooks, as well as the grade 12 national Physics exam papers, was conducted. Additionally, a quick survey was conducted with high school Physics teachers.

Step 3: Developing teaching materials

To identify suitable ICT-based experimental methods, the conditions recognized in Step 1 are taken into consideration. Relevant apparatuses are then developed using available and affordable materials within the context of Cambodia. The experimental method must be both innovative and accurate.

Step 4: Teaching practices

The developed teaching materials were employed to conduct experimental studies with teacher educators, teachers, student teachers, and students to evaluate their effectiveness and applicability with actual teaching and learning. Lesson plans and worksheets were developed for teaching and learning activities, while tests (for pre-tests and post-tests) and surveys were developed to assess the effectiveness and applicability of the teaching materials.

1.5. Structure of the Dissertation

Chapter I presents an overview of the study, including the motivation behind it, the research questions, and a summary of all the chapters.

Chapter II answers the first research question of the dissertation. It reports the current state of high school science education in Cambodia with regard to ICT integration is discussed. This chapter aims to answer the first research question based on a survey of 285 high school principals and science teachers in Cambodia. The survey addresses two specific questions: 1) How do Cambodian science teachers perceive their knowledge and skills in integrating ICT into teaching, and 2) Does the current state of human and infrastructure resources in schools enable the integration of ICT into science education in Cambodia?

Chapter III responds to the second research question of the dissertation. It details the creation of teaching materials focusing on Oscillations and Waves. The chapter covers three specific topics: 1. Damped Oscillations, 2. The Doppler effect, and 3. Interference. The chapter also provides a rationale for selecting the Oscillations and Waves topic. For each topic, the chapter delves into the literature and its gaps, the development of relevant apparatus such as angle sensor, E-Lab interface, simplified ripple tank, experiment procedures and methods, and the results and discussions. The developed apparatuses are an angle sensor, E-Lab interface, vibrator and simplified ripple tank, according to topics.

Chapter IV answers the third research question of the dissertation. It focuses on classroom practices using the developed teaching materials. It was a quasi-experimental study with a single-subject pre-test and post-test design, conducted with teacher educators, teachers, student teachers, and students. The chapter describes the design of the lesson instructions, the development of lesson plans and worksheets, the creation of research instruments (tests and questionnaires), and the results of the experiments.

Chapter V provides the overall results and findings of the whole study and discusses the challenges and opportunities of application of this ICT-based teaching material development. Then, I conclude and, finally, give recommendations for implementation and future development.

CHAPTER II

SCIENCE TEACHERS AND SCHOOL RESOURCES TOWARD INTEGRATION OF ICT IN TEACHING

2.1. Introduction

Cambodia is one of the fastest economic growth countries in the world. Her economy has sustained an average growth rate of 7.7 per cent between 1998 and 2019 (World Bank, 2021). To keep growing at this high pace, Cambodia needs thousands of engineers and technicians (Khieng, Srinivasa, & Chhem, 2015). Cambodia has become a lower-middle-income country since 2015 and aspires to become an upper-middle-income country in 2030 (World Bank, 2021). Science has become a part of the prioritised agendas to promote the economic and social development of the country as specified in the Cambodia Industrial Development Policy 2015-2025 (Royal Government of Cambodia, 2015).

Aligning with the ambition of the Royal Government of Cambodia, MoEYS has made great efforts to reform the education system to promote education in general and science in particular by supporting and implementing the tracking education system at high school since 2010, directing students towards either the science track or the social science track, developing the secondary resource centres (SRCs) in 2011, reforming the national exam from 2014, promoting STEM (Science, Technology, Engineering and Mathematics) education and New Generation School (NGS) policies in 2016, as well as increasing teacher salary. These boil down to the logic that Cambodia needs science and science-related workforces and citizens to serve the labour markets and its economic goal and to be capable of being lifelong learners at a higher level of education or her workplace.

On the other hand, the efforts made by the MoEYS have not made significant improvements yet. Science subjects have gradually been losing their popularity among high school students. The number of student enrolments in the science track dramatically dropped from around 94% in 2014 to about 39% in 2019. On average, about 54% of those who chose the science track passed the National Grade 12 Exam between 2015 and 2019 (Ing, 2019). This trend seems to be reversed to what MoEYS intended to attain despite MoEYS's efforts. Cambodian students have still performed low in science. The National Assessment 2018 showed only 20% of Cambodian 11th-grade students achieved a basic level or higher in Physics (MoEYS, 2019b). Similarly, the results of the Program for International Student Assessment for Development (PISA-D) showed only 5% of the 15-year-old students (equivalent to high school grade 10) attained merely a minimum proficiency level (i.e., level 2 of the 6 PISA proficiency levels) in science. Teaching quality was argued as the main factor accounting for low achievement (MoEYS, 2018).

The quality of teachers defines the quality of education. Teachers and their role are central to discussion among education policymakers (Hanushek & Rivkin, 2006). The quality of teachers can be measured by effective teaching, which is the most outweighing determinant of student learning in the classroom (Sanders & Rivers, 1996). Effective teaching requires good teaching that requires teachers to have strong background knowledge of the subject matter: their content knowledge and pedagogical content knowledge (Kleickmann et al., 2013). While content knowledge represents teachers' understanding of the subject matter, pedagogical content knowledge is the knowledge needed to make the subject matter accessible to students (Shulman, 1986). This knowledge is the key component of teacher competence that supports teachers' instructional practice as well as student learning (Kleickmann et al., 2013).

In addition, the world today is in the Industrial Revolution 4.0 period, where the rapid advancement of ICT affects all aspects of society, and education is not an exception. Knowing the subject matter would not be enough for a teacher. Teachers should know about ICT and be able to utilise it to improve teaching and enhance student learning (Noor-Ul-Amin, 2013). Particularly for science subjects, ICT interventions can be used to enhance the practical investigation (i.e., ICT-based experiment) or as a virtual alternative to real practical work (i.e., simulation) (McFarlane & Sakellariou, 2002; Smetana & Bell, 2012). Therefore, knowledge about ICT should also be considered an essential criterion for being a qualified science teacher in the current era and future.

Regarding ICT for Education, the Education for All National Plan 2003-2015 was an unprecedented official document of Cambodia that mentioned ICT policy in Cambodian education. Since then, significant strategic policies, plans, projects and programs have been documented and implemented concerning ICT in education. One of the specific goals is to enhance the quality of teaching and learning through ICT integration. Although much effort has been made over these last two decades, ICT usage in teaching and learning remains limited (MoEYS, 2019a), as can be seen in the baseline statistics of the Education Strategic Plan (2019-2023) showing only five per cent of upper secondary schools used ICT as a supporting tool in teaching and learning. Fortunately, enormous efforts and investments in distance learning during the COVID-19 outbreak have fostered digital transformation and proliferated ICT in education in Cambodia (Heng, 2021; Thy, Ly, & Ean, 2023).

Technological pedagogical content knowledge was first postulated by Koehler and Mishra (2005), denoted as TPCK, and was changed to Technology, Pedagogy and Content Knowledge by Thompson and Mishra (2007), suggested as a Total PACKage (TPACK) for effective teaching with technology (Voogt, Fisser, Pareja Roblin, Tondeur, & van Braak, 2013). TPACK has emerged as a widely accepted framework for information and communication technology (ICT) integration in teaching (Graham, 2011) and become a much-discussed research topic (Chai, Koh, Tsai, & Tan, 2011). The framework of TPACK has been adopted in various settings (Pamuk, Ergun, Cakir, Yilmaz, & Ayas, 2015). In this regard, there is a lack of empirical evidence about the integration of ICT in teaching and learning in Cambodia, especially through the TPACK lens. While TPACK internationally has been regarded as special knowledge to optimize or integrate ICT in teaching and learning (Chai, Koh, Tsai, et al., 2011; Graham, 2011), through a Google Scholar search with a broad keyword like "TPACK AND Cambodia", merely, a relevant publication was found. It was a study conducted by Chea, Bo, and Minami (2022) to assess Cambodian secondary school teachers' readiness to adopt distance teaching during the school closure due to the COVID-19 outbreak, with which the TPACK self-rating score indicates the readiness level. The study broadly investigated the secondary education level as a whole (i.e., grades 7 to 12) and teaching staff in social and hard science disciplines, aimed to compare secondary resource schools, which received technical and financial support to enhance ICT for teaching and learning through the Upper Secondary Education Sector Development Program (USESDP 2), with ordinary secondary schools. The study showed that Cambodian teachers indicated low confidence in technology in general (i.e., TK score was below media point). Surprisingly, teachers from the schools with better ICT and related resources and who received ICT training showed lower confidence in all technology-related domains of TPACK compared with teachers from ordinary schools. The authors questioned this finding and suggested further study to answer. The study did not include all types of schools in Cambodia. Therefore, the results did not capture all aspects of schools in Cambodia. The authors also suggested further study with different angles and approaches to triangulate the findings.

School facilities were also a concerning topic while addressing teaching and learning quality. Cambodian school infrastructure has been seen as relatively poor and under-resourced, even worse in rural areas (MoEYS,

2018) and has slowly been developed. Nationwide, there are 741 high schools, of which 75% are public schools. Most public schools (i.e., 74%) are in rural areas (MoEYS, 2021). Beginning with the Education Sector Development Project 2 (ESDP2), launched in 2011, eighteen public schools were converted to SRCs consisting of two science labs, two computer labs with internet services, an e-library and a large seminar room. Followed by three other projects for a decade, the number has increased to as many as 67 schools in total, equivalent to about 12%. In addition, the functioning of SRCs has been under-investigated and under-improved due to the insufficient operation budget and low teacher competency in laboratory skills. As part of the educational reform in 2014, New Generation Schools (NGS) were established with better facilities. As for 2023, there are 6 (less than 1%) NGS high schools in Cambodia.

Given the above discussion, there is a dearth of empirical literature regarding the current situation of ICT in education in Cambodia, particularly in the context of high school science education using the TPACK framework. This motivates me to conduct a thorough study to better comprehend the current state of science education in Cambodia. The study aims to identify the challenges associated with teaching and learning science through ICT integration in upper secondary education in Cambodia, focusing on human and infrastructure resources. It also aims to propose suitable solutions for improvement. This chapter presents the results of the study. Therefore, the chapter aims to answer two main questions:

1. How do Cambodian science teachers perceive their knowledge and skills in integrating ICT into teaching their subjects?
2. Does the current situation of human and infrastructure resources in schools facilitate teaching and learning science in Cambodia?

TPACK is the framework for knowledge and skills in integrating ICT into teaching in this study. The first question was decomposed into two sub-questions to be answered, including:

1.1 How do Cambodian science teachers perceive the seven TPACK knowledge domains? Do their perceptions differ among gender, qualification, school type and school location?

1.2 How do Cambodian science teachers' demographics (i.e., age, teaching experience) and the seven TPACK knowledge domains correlate with each other? And which are the predictors of the TPACK knowledge domain?

2.2. Teachers’ Knowledge Based on the TPACK Framework

Based on Shulman (1986), teaching is a complex process that needs to emerge between specialized content knowledge, expertise in the instruction of specialized subjects and general pedagogy called Pedagogical Content Knowledge (PCK). The revolution of technology has reshaped the education systems. Mishra and Koehler (2006) introduced the inclusion of technology into the Shulman (1986) framework to understand the need for teacher knowledge for effective teaching with technology, namely Technological Pedagogical Content Knowledge (TPACK). According to Mishra and Koehler (2006), teachers’ knowledge consists of three main components: content knowledge (CK) (knowledge of the subject matter); pedagogy knowledge (PK) (knowledge of methods and processes of teaching and learning); and technology knowledge (TK) (the understanding of various technologies). The interaction between those components gives four more complex knowledge domains such as pedagogical content knowledge (PCK), technological content knowledge (TCK), technological pedagogical knowledge (TPK) and technological pedagogical content knowledge (TPACK), as shown in Figure 2.1. While PCK deals with the teaching process with specific content (knowledge of teaching methods with respect to subject matter content), TCK refers to the knowledge of utilising technology to develop a representation of certain content (knowledge of subject matter representation with technology). TPK is the knowledge of using technology to change the way of teaching (knowledge of using technology to implement different teaching methods), and TPACK refers to the knowledge of teachers to integrate technology into teaching their content subject (knowledge of using technology to implement teaching methods for different types of subject matter content). Introducing technology in the teaching and learning process was believed to enhance students’ 21st-century skills and affect teaching methodology (Koehler et al., 2011).

However, integrating technology into the classroom is not a simple process. Teachers must be able to utilise technology to represent the specific concept differently and more meaningfully (Mishra & Koehler, 2006). OECD (2020b) reported that many teachers feel uncomfortable using technology in instruction due to accessibility and ICT competency. The TPACK framework has been used for more than a decade to evaluate teachers’ knowledge required for technology integration; this framework shows the relationship between the three bodies of knowledge and the transformation among the overlapping areas. A significant number of empirical studies have been contributing to the development of the theory of TPACK knowledge.

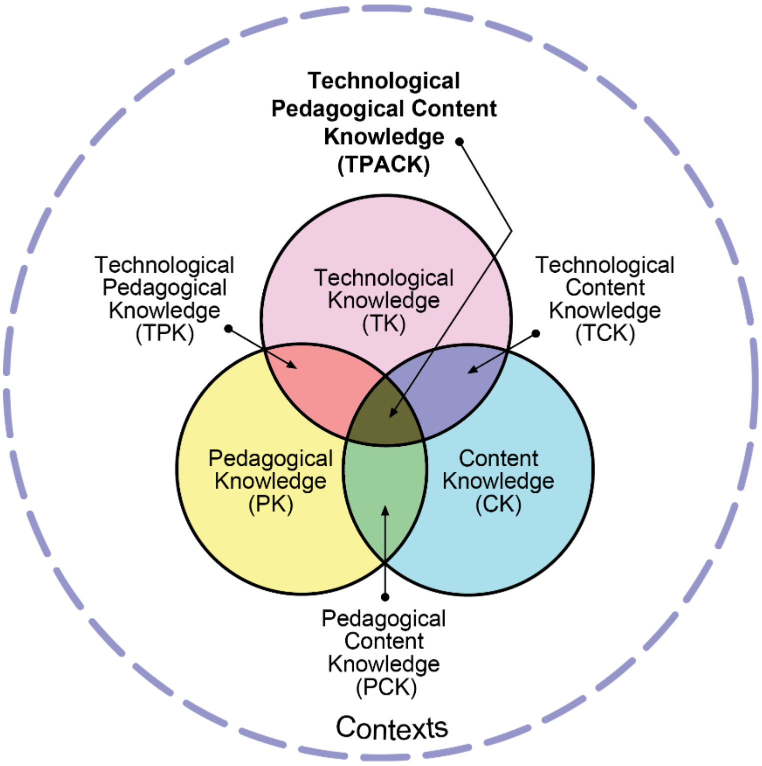

Figure 2. 1: TPACK framework (source of image http://tpack.org)

Nonetheless, to date, how TPACK constructs were developed, especially in relation to complex constructs of PCK, TCK, TPK and TPACK, and these constructs related to each other remains debated (Lin, Tsai, Chai, & Lee, 2013). Context has been pointed out as a keyword to address the disagreement and proposed as the eighth component of TPACK (Brianza, Schmid, Tondeur, & Petko, 2022). Therefore, more empirical studies in different contexts must be conducted to contribute to a more comprehensive and precise TPACK framework.

Studies have explored the extent to which teachers have TPACK perception and the factors that predict TPACK perception. Liu, Zhang, and Wang (2015) surveyed 6650 K12 teachers and reported that teachers rate themselves as high in PK and CK but relatively low in technology-related knowledge domains (i.e., TK, TPK, TCK and TPACK). Similarly, Koh, Chai, and Tsai (2014) studied 354 Singapore teachers and found that teachers were more confident in CK, PK and PCK but not very confident in the technology-related knowledge domains. Likewise, De Freitas (2018) examined 93 junior high school Mathematics teachers in South Africa and reported that the teachers perceived relatively low scores in TK and even more for the other technology-related knowledge domains. Corresponding results were also reported in studies conducted by Chai, Chin, Koh, and Tan (2013), Jang and Tsai (2013), and Archambault and Crippen (2009) that teachers were more optimistic in non-related technology knowledge domains (i.e., CK, PK, and PCK).

The world today is in the Industrial Revolution 4.0 period, where the rapid advancement of ICT affects all aspects of society, and education is not an exception. Knowing the subject matter and general pedagogy would not be enough for a teacher. Teachers should know about ICT and relevant pedagogy and be able to utilise it to improve teaching and enhance student learning (Noor-Ul-Amin, 2013). Therefore, knowledge about ICT should also be considered an essential criterion for being a qualified science teacher in the current era and future. However, the above literature showed that most teachers are highly confident in subject matter and general pedagogy but need more improvement in technology-related knowledge. Since the level of satisfaction in each domain depends on some variables, including age, gender, and teaching experience, these variables will be discussed in the following sections.

Gender is an important factor in almost all aspects of educational study. Studying under the umbrella of the TPACK framework addressed gender gaps among knowledge domains (Chang, Tsai, & Jang, 2014; Chea et al., 2022; Gómez Trigueros & Yáñez de Aldecoa, 2021; Irwanto, Redhana, & Wahono, 2022; Jang & Tsai, 2013; Jordan, 2011; Koh & Chai, 2011; Lin et al., 2013). Lin et al. (2013) reported that female in-service science teachers were higher in PK but lower in TK compared to their male counterparts. They addressed ICT as a masculine preference, and males had relatively rich experience with computers. However, such differences were not statistically evidenced for the pre-service teacher group. They further suggested that career environment might alter female science teachers' notions of ICTs. Jang and Tsai (2013) discovered that male teachers perceived higher than their female partners in TPACK and TK. Scherer, Tondeur, and Siddiq (2017) uncovered that female teachers indicated lower competencies than male teachers with regard to all technology-related domains (i.e., TK, TCK, TPK and TPACK). Nevertheless, there was no biological explanation for the differences rooted in the social context in which males and females were put (Castéra et al., 2020). Therefore, the relationship between gender and perceived TPACK knowledge domains is still vague and needs more research (Jordan, 2011).

Teaching experience (TE), representing the number of years of teaching, seems to have a clearer direction of relationship with TPACK knowledge domains, especially for the four technology-related domains (i.e., TK, TCK, TPK and TPACK). Many studies indicated that TE had negative associations with teachers’ perception of technology (Jang & Tsai, 2013; Koh et al., 2014; Lee & Tsai, 2010). Lee and Tsai (2010), for example, studied teachers' perception of TPACK knowledge domains regarding educational use of the World Wide Web and revealed that older teachers with more years of experience perceive less self-efficacy of Web-related TPACK. Likewise, Koh et al. (2014), in a study about teachers' perceptions of constructivist-oriented TPACK, found similar relationships that teaching experience was negatively correlated with technology-related knowledge domains. On the other hand, age was found to have an inconsistent relationship with teachers' perception of technology. Some studies showed a negative relationship (Castéra et al., 2020; Koh et al., 2014; Lee & Tsai, 2010; Lin et al., 2013), whereas several studies indicated no relationship (Guo, Dobson, & Petrina, 2008; Hsu & Chen, 2018). Even though TE and age are strongly dependent (Castéra et al., 2020), their relationships with technology-related domains of TPACK are somehow different. More empirical examinations are needed.

2.3. Public Schools in Cambodia

2.3.1. Types of school

The Cambodian education system follows the 6+3+3 structure, which is similar to many other education systems around the world. This structure consists of six years of primary education followed by six years of secondary education. However, there are different types of secondary schools in Cambodia. According to MoEYS (2021), there are 1,812 secondary schools. The college system, which is borrowed from the French education system, consists of grades 7, 8, and 9, and there are 1,253 colleges in Cambodia. The lycée system, also borrowed from the French education system, has two types: six years (524) and three years (35). This means that the majority of lycées in Cambodia provide education from grade 7 to 12, while a few only offer education from grade 10 to 12. In secondary education, there are commonly three terms used to refer to different grade levels. Lower secondary school (LSS) or junior high school, which includes colleges and lycées, refers to grades 7 to 9. Upper secondary school (USS), also known as senior high school or simply high school, refers exclusively to grades 10 to 12. Therefore, there are a total of 1,777 LSS and 559 USS schools in Cambodia (MoEYS, 2021). However, these schools fall under three categories: Ordinary schools (OS), Secondary Resource Schools (SRS), and NGS. Each of these school types offers distinct programs.

OHS and SRS are non-autonomous schools that follow the Cambodian national curriculum. MoEYS assign teachers and staff to these schools. However, OHS typically have poorer infrastructure, lacking in science laboratories and computer labs. On the other hand, SRS have better infrastructure, which includes a resource building that has two science laboratories, two computer labs with internet services, an e-library, and a large seminar room. Additionally, SRS receive extra budget and technical support for teacher professional development.

NGSs are semi-autonomous and can generate some income in addition to government subsidies. They can modify the curriculum to suit their context and recruit teachers and staff as needed and wanted. NGSs are richer in infrastructure, especially related to ICT. Every teacher receives a laptop computer, a monthly bonus on top of the state salary and technical support from a local non-government organization (NGO).

In Cambodia, the condition of high schools is generally better than that of junior high schools or primary schools, especially when it comes to ICT. Therefore, the current study focuses only on high schools. The high school teachers have a bachelor's degree and have completed a one-year teacher training program for high education, the so-called Bachelor+1. Some teachers choose to upgrade their qualifications to a master's degree or higher through professional development programs and scholarships. Although all the schools in the study are public, they receive varying levels of support in terms of finances and technical assistance, depending on their type and location. These variables, such as qualifications, school type, and location, could affect the quality of education in high schools.

2.3.2. Some education indicators associated with school

Teachers' knowledge is considered an internal factor contributing to effective teaching, influencing student learning in the classroom (Sanders & Rivers, 1996). However, several external factors also contribute to effective teaching. While teaching and learning require the existence of teacher and student, the teacher-student interaction is the most critical to effective teaching (Koc & Celik, 2015). Two factors that affect teacher-student interaction in the school are class size (the number of students per class) and student-to-teacher ratio (the number of teachers divided by the number of students). When class size is big, students are less likely to interact with teachers and vice versa. There is less teaching on a one-to-one basis. Teachers have less time to focus on students, while students have less time to actively attend teacher activities during class (Mishel, Rothstein, Krueger, Hanushek, & Rice, 2002; Schanzenbach, 2014). This is in a similar vein to the student-to-teacher ratio. Class size and student-to-teacher ratio are generally associated with each other, sometimes considered the same. They both are strongly associated with the number of classrooms and teaching staff available in the schools; however, they are different. Even though the class size is small, the student-to-teacher ratio can still be high, depending on how many classes a teacher is responsible for.

Besides, school facilities such as science laboratories, computer labs and Internet connection, library, clean water and sanitation, and electricity are essential and indirectly and directly contribute to an effective school (Murillo & Román, 2011). Science laboratories allow teachers and students to do various laboratory activities as part of the teaching and learning process. The laboratory has become a distinctive feature of science education (Hofstein, 2017). Science laboratories directly affect students' attitudes and academic performance as per the instructional theory of learning interaction (Pareek, 2019).

The computer is a prominent ICT tool and is becoming increasingly more effective in supporting secondary education (Murillo & Román, 2011). A computer with an internet connection enables students to explore, create, connect, and build digital literacy. The students can access real-time and up-to-date knowledge (e.g. new scientific discoveries) and resources such as science simulation software and videos. In this regard, schools should have computer labs with internet connection for students, especially in developing countries where most students cannot afford a computer. More importantly, the effectiveness is associated with the student-to-computer ratio (the number of computers divided by the number of students), where the lower the ratio, the better (Murillo & Román, 2011).

Libraries have also served crucial roles in teaching and learning. Fundamentally, a library is an organized set of resources, which includes human services as well as the entire spectrum of media (e.g., text, video, hypermedia) (Marchionini & Maurer, 1995). These resources have their role in supporting and improving teaching and learning (Kuhlthau, 2010; Murillo & Román, 2011). Williams, Wavell, and Morrison (2013) studied the impact of the school library on learning. The results revealed that school library is an attribute to improving academic attainment, successful curriculum or learning outcomes and positive attitude towards learning.

Electricity is crucial for everyday school operations, including lighting and powering all electrical and electronic devices to support administration things and the teaching and learning process. Last but not least, water and sanitation are unarguably important indicators for an effective school. Poor availability and access to water and sanitation are major health concerns and constitute a principal barrier to quality education in schools and narrowing the gender gap in education (Jewitt & Ryley, 2014; Sommer, 2010). Agol and Harvey (2018) reported that the lack of toilets and water sources puts girls at a higher risk of dropping out of school than boys. Poor water and sanitation particularly emphasized the challenges of girls in managing their menstrual hygiene (Jewitt & Ryley, 2014).

2.4. Current Situation of Science Education in Cambodia

The state of science teaching and learning in Cambodia reflects both challenges and opportunities for improvement. While empirical evidence is lacking, assessments indicate that many Cambodian science teachers exhibit deficiencies in both subject content knowledge and pedagogical content knowledge (Khlok, 2021; Set, 2016; Tandon & Fukao, 2015). This stands in contrast to neighbouring countries such as Thailand and Vietnam, where teachers tend to possess a more robust understanding of their subjects and effective teaching methods (Tandon & Fukao, 2015).

One prevalent issue in Cambodian science classrooms is the persistence of traditional teaching methods (Khlok, 2021; Mam, 2021), with rote learning being the dominant approach. This pedagogical style, often referred to as "root teaching and learning," is characterized by a linear progression of lessons where teachers move from one topic to another without sufficient emphasis on understanding or critical thinking. This approach diminishes the effectiveness of science education, as students may memorize information without truly comprehending the underlying concepts (Khlok, 2021). Teaching and learning content heavily relies on textbooks, specifically the national textbook, which is the only choice available to Cambodian teachers. There are no other alternatives, especially those written in the Cambodian language (Khlok, 2021). Consequently, teachers consistently employ identical, typically traditional, teaching methods (Mam, 2021). This limited resource landscape underlines the need for diverse educational materials and innovative teaching approaches.

The conventional teaching method in Cambodian science classrooms follows a predictable pattern. Teachers typically initiate the lesson by revisiting the previous topic through a series of questions posed to the students. However, the transition to the new topic, referred to as "today's topic," lacks a meaningful connection to prior knowledge. This disjointed approach may contribute to a fragmented understanding of scientific principles among students.

During the lesson, teachers predominantly rely on explanation and demonstration to convey the content, limiting opportunities for interactive and participatory learning. The practice of having students copy information directly from the board into their notebooks further reinforces a surface-level understanding, as it encourages memorization rather than comprehension.

Furthermore, the use of formulaic problem-solving approaches is commonplace. While teachers may present and solve sample problems, the emphasis is often on memorizing formulas rather than fostering a deeper understanding of the underlying principles. This rote application of formulas may hinder students' ability to apply scientific concepts in real-world scenarios, limiting the practical utility of their education.

The conclusion of the lesson typically involves a recapitulation of what has been covered, accompanied by homework assignments or additional advice. However, the effectiveness of this recapitulation may be limited due to the fragmented nature of the teaching approach.

Numerous schools in Cambodia are operating with inadequate infrastructure, a lack of access to potable water, a scarcity of ICT-related materials, and underutilized electricity access (MoEYS, 2018). Science laboratory rooms, often empty of materials, leaving unused and dirty, hinder effective hands-on learning experiences. Despite the presence of some educational resources, their potential remains largely untapped.

A notable deficiency in Cambodia's science education system is the limited incorporation of hands-on activities and experiments in classrooms (Khlok, 2021; Set, 2016). While occasional demonstrations of natural phenomena may occur, the majority of these activities are teacher-centric, leaving students as passive observers. The opportunity for students to actively engage in practical experiments, design investigations, and develop critical thinking skills is minimal. This lack of hands-on experience impedes students' ability to explore and deepen their understanding of scientific concepts.

The scarcity of experiment design skills among teachers exacerbates this issue. Many science teachers lack the know-how to create meaningful experiments and develop accompanying worksheets (Khlok, 2021). Consequently, experiments in Cambodian science classrooms are often viewed as a means to verify existing theories rather than opportunities for students to explore, question, and develop a profound understanding of scientific principles (Maeda et al., 2006).

The situation of science teaching and learning in Cambodia, as described, reflects a notable gap in Technological Pedagogical Content Knowledge (TPACK) among science teachers. TPACK is a framework that emphasizes the integration of technological, pedagogical, and content knowledge to enhance teaching and learning experiences (Mishra & Koehler, 2006). In the Cambodian context, the deficiency in TPACK is evident across various dimensions.

Firstly, there is a pronounced lack of subject content knowledge and pedagogy among Cambodian science teachers (Tandon & Fukao, 2015). This deficiency extends to both the content they are expected to impart to students and the pedagogical strategies employed to facilitate effective learning (Khlok, 2021; Set, 2016; Tandon & Fukao, 2015). A solid foundation in subject content knowledge is crucial for delivering comprehensive and meaningful science education (Tandon & Fukao, 2015).

Secondly, the limited ICT knowledge and skills of Cambodian science teachers pose a significant challenge. While teachers may possess basic computer skills for administrative purposes, their proficiency in leveraging technology for teaching and learning is notably insufficient. The primary focus on computer skills for administrative tasks rather than utilizing technology as a teaching tool underscores a missed opportunity to enhance the educational experience for students.

Moreover, the limited perspective on using ICT for education, as emphasized, indicates a lack of awareness or exposure to the varied opportunities technology provides in the field of science education. The focus on computer labs in schools primarily for basic ICT training, rather than integrating technology to enhance science education, underlines this constrained viewpoint.

2.5. Methodology

2.5.1. Participants

The selection of participants followed three steps of the sampling process, as the following. Firstly, I purposively selected one province from each of the four regions of Cambodia (Tonle Sap, coastal and sea, central plain, mountain) and the capital city. Due to the budget constraint, only one province that represented the uniqueness of its region was selected. Therefore, I decided to do it purposively. In addition, the capital city was in the central plain; however, its characteristics were far different from other provinces in the same region. Secondly, four high schools from each chosen province, with the criteria of being two urban schools and two rural schools, were purposively and conveniently selected, whereas, for the capital, two downtown and two suburban schools. Thirdly, the selection of teachers followed a convenient sampling method, where all approachable science teachers in each selected school, during administering the survey, were requested to participate in this study. It is worth noting that the procedure was trying to collectively cover the characteristics of the sample as much as possible, aiming to have a representative sample of the Cambodian high school science teacher population. When the sample size required was small, together with the complicated nature of Cambodia's geography, employing a random selection method cannot guarantee that all these characteristics are included proportionally in the current study. The total number of participants in this study was 285, of which 45 were school principals and 240 were science teachers.

2.5.2. Instruments

The study employed a survey research method. I developed two questionnaires used to collect data: the principal questionnaire and the teacher questionnaire.

- The principal questionnaire had 21 questions in total, asking about demographic information, school facilities and statistics of students and teachers.
- The teacher questionnaire had two sections. The first section comprises 10 questions about the participants' demographic information. The second section consists of 29 Likert-type scale items, of which 22 items were adopted from the work of De Freitas (2018) and modified to suit the Cambodian context as well as science education. I developed another 7 items to increase the content validity of the instrument to assess participants' perception of TPACK. The work of De Freitas (2018), using a four-point Likert scale, fundamentally relied on the works of Schmidt et al. (2009) and Chai, Koh, and Tsai (2011) who employed a five-point scale. In this study, rather than using a four-point scale, I employed a five-point scale the same as the original scale (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree). For content validity, the instrument was reviewed and approved by a team of science teacher educators and members of the Commission of Research Development and Innovation of NIE in Cambodia.

Principal Component Analysis (PCA) with Varimax Rotation was performed to assess the internal structure of TPACK since the instrument incorporated adopted items that were contextualized to the Cambodian context and some newly developed items. The minimum factor loading criteria was set to 0.50. The results showed that all communalities were over 0.50. The Kaiser-Meyer-Olkin measure of sampling adequacy was 0.95, above 0.80, and Bartlett's test of sphericity was significant ($\chi 2(406) = 6640.85$, $p < .001$). With eigenvalues greater than one confirmed by parallel analysis (Hayton, Allen, & Scarpello, 2004), the factor solution derived from this analysis yielded three factors for the scale, which accounted for 70.17 per cent of the variation in the data. The reliability of the instrument was assessed on the overall and seven subscales of TPACK. The internal consistency reliability (Cronbach's alpha) was 0.97 for the overall scale and ranged from 0.80 to 0.92 for the subscales (Table 2.1).

Table 2. 1: Descriptive statistics of the seven TPACK knowledge domains

	Number of Items	Mean (N = 240)	Standard Deviation	Cronbach's Alpha
CK	3	3.61	0.82	0.85
PK	5	3.46	0.79	0.92
TK	5	3.16	0.90	0.90
PCK	3	3.51	0.79	0.80
TCK	4	2.91	0.89	0.86
TPK	4	2.59	0.95	0.89
TPACK	5	2.47	0.84	0.87

2.5.3. Data analysis

The raw data collected from the questionnaire were entered into a Microsoft Excel spreadsheet and cleaned. The data analyses were performed using the Statistical Package for the Social Sciences (SPSS v.25). For the first sub-question of the first question and the second question, the data analysis employed descriptive statistics such as mean, standard deviation and percentage, and inferential statistics such as t-test, One-Way ANOVA, and Chi-Square, where appropriate, to examine the association of some demographic variables, including gender, school type and location. The second sub-question of the first question was answered by examining the relationship between perception of TPACK knowledge domains and age and teaching experience using Pearson’s correlation statistics and then by multiple regression analysis. Stepwise regression models were conducted with the TPACK knowledge domain as the dependent variable and the remaining knowledge domains, age and teaching experience as the independent variables, using the enter method, which variable with a higher Pearson’s correlation coefficient was entered into the model first.

2.6. Results

- Descriptive statistics

A total of 240 teachers participated in this study. Out of these, 44.6% were females, with an average age of 40.4 (SD = 8.15) and an average of 11.8 years (SD = 8.99) of teaching experience. The majority of the teachers held a bachelor's degree (80.0%), while 14.6% held a master's degree or higher. 45 principals participated, of which 26.7% were females. The average age of the principals was 48.62 (SD = 7.30), and their average experience as a principal was 9.52 years (SD = 5.27). Around 58% of the principals held a bachelor's degree, while 40.0% held a master's degree or higher (refer to Table 2.2).

Table 2. 2: Number of participants by qualification

	Teachers: No. (%)	Principals: No. (%)
12+2	11 (4.60)	0 (0)
Bachelor	192 (80.0)	26 (57.8)
Master or higher	35 (14.6)	18 (40.0)
Other	2 (0.80)	1 (2.20)
Total	240 (100)	45 (100)

Research Question 1.1: How do Cambodian high school science teachers perceive the seven TPACK knowledge domains? Do their perceptions differ among gender, qualification, school type and school location?

According to a survey, Cambodian high school science teachers rated their knowledge relatively high for CK (Mean = 3.61), PK (Mean = 3.46), PCK (Mean = 3.51), and TK (Mean = 3.16). However, they rated themselves relatively low for TCK (Mean = 2.91), TPACK (Mean = 2.47), and TPK (Mean = 2.59) compared to the median score of 3.00. These scores suggest that Cambodian high school science teachers have a good understanding of their specialized subject and teaching strategies, as well as basic knowledge and skills in how to use ICT for administrative work and communication. However, they seem to lack the ability to utilize ICT to improve their teaching and enhance student learning. This result suggests that Cambodian high school science teachers may be more comfortable with traditional teaching aspects, i.e., prefer a whiteboard-pencil/pen-paper-based classroom environment to an ICT-based environment.

Table 2. 3: Results of post-hoc tests for multiple comparisons among school types

			Mean Difference	Std. Error	95% Confidence Interval	
					Lower	Upper
TK	NGS	SRS	0.59^{**}	0.19	0.13	1.05
		OHS	0.81^{***}	0.20	0.35	1.27
	SRS	OHS	0.22	0.12	-0.06	0.5
TCK	NGS	SRS	0.71^{**}	0.19	0.26	1.16
		OHS	0.82^{***}	0.19	0.36	1.27
	SRS	OHS	0.11	0.12	-0.17	0.39
TPK	NGS	SRS	0.72^{**}	0.20	0.24	1.2
		OHS	0.78^{**}	0.21	0.29	1.27
	SRS	OHS	0.06	0.13	-0.24	0.36
TPACK	NGS	SRS	0.88^{***}	0.18	0.46	1.29
		OHS	0.90^{***}	0.18	0.48	1.32
	SRS	OHS	0.02	0.11	-0.23	0.28

Note: $^{***}p < .001$, $^{**}p < .01$, $^{*}p < .05$

An independent-sample t-test was used to examine the differences in TPACK knowledge domains among genders. The results showed that there was no significant difference between male and female teachers, indicating that they perceived the same level of knowledge in all TPACK domains. Similarly, a One-Way ANOVA was conducted to analyse the variables of qualification, school type, and school location. The ANOVA test revealed only school type variable was statistically significant differences in TK ($F(2, 237) = 8.645$, $p = .000$), TCK ($F(2, 237) = 9.074$, $p = .000$), TPK ($F(2, 237) = 7.474$, $p = .001$) and TPACK ($F(2, 237) = 13.906$, $p = .000$). Post-hoc tests were conducted using Tukey's HSD for multiple comparisons. Results indicated that science teachers from NGS perceived higher levels of technology-related knowledge domains, including TK, TCK, TPK and TPACK, as compared to SRS and OHS. Table 2.3 provides a detailed report of these findings.

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Research Question 1.2: How do Cambodian high school science teachers' demographics (i.e., age, teaching experience) and the seven TPACK knowledge domains correlate with each other? And which are the predictors of the TPACK knowledge domain?

The results presented in Table 2.4 demonstrate that the seven TPACK knowledge domains have significant positive correlations with each other, ranging from moderate to very strong association. The study found that PCK highly and positively correlates with CK and PK, which suggests that Cambodian high school science teachers believe that their ability to teach their subject is strongly associated with their knowledge of the subject matter and teaching strategies. The study also found that TCK moderately correlated with CK and strongly with TK, and TPK with PK and TK. These results indicate that the teachers believe that their TCK and TPK weigh TK heavier than CK and PK, respectively. In other words, advancing their capacity in using various technologies (TK) may lead to more effectively improved science teachers' ability to utilize technology to teach their subject content (TCK) or diverse teaching approaches (TPK).

The study further found that TPACK has a strong correlation with TK and a very strong correlation with TCK and TPK. These associations may indicate that Cambodian high school science teachers' perception of TPACK (i.e., knowledge for integrating technology into their teaching in any area) strongly relates to advancing their TK.

Regarding age and teaching experience, the study found that although their coefficients are small, denoting a weak association, both are significantly and negatively correlated only with the four technology-related domains of TPACK. This suggests that older or more experienced teachers possess less knowledge of integrating technology into their teaching.

Table 2. 4: Correlations among seven TPACK knowledge domains, age and teaching experience (TE)

	CK	PK	TK	PCK	TCK	TPK	Age	TE	TPACK
CK	1								
PK	0.853^{**}	1							
TK	0.621^{**}	0.627^{**}	1						
PCK	0.902^{**}	0.894^{**}	0.638^{**}	1					
TCK	0.578^{**}	0.606^{**}	0.816^{**}	0.629^{**}	1				
TPK	0.486^{**}	0.547^{**}	0.722^{**}	0.551^{**}	0.797^{**}	1			
Age	0.031	-0.005	-0.313^{**}	0.011	-0.317^{**}	-0.221^{**}	1		
TE	0.029	-0.011	-0.313^{**}	0.015	-0.307^{**}	-0.219^{**}	0.940^{**}	1	
TPACK	0.478^{**}	0.515^{**}	0.684^{**}	0.563^{**}	0.822^{**}	0.814^{**}	-0.276^{**}	-0.263^{**}	1

Note: $^{***}p<0.001$, $^{**}p<0.01$, $^{*}p<0.05$

In the data analysis section, stepwise regression analyses were performed to determine the relationship between TPACK, age, teaching experience, and other TPACK constructs. The results showed that TCK and TPK were the predominant predictors of TPACK, explaining 74% of the total variance in Model 2. The remaining factors, including PCK, explained only 1% of the variance. The beta values analysis revealed that TCK, TPK and PCK had positive predictive power on TPACK. The stepwise regression of the models was statistically significant at $p = 0.000$ with an adjusted R-squared of 0.75 (Table 2.5).

Table 2. 5: Stepwise regression models

Model		B	Std. Error	Beta	Sig.	R^2
1	(Constant)	0.218^{*}	0.107		***	0.67
	TCK	0.774^{***}	0.035	0.821		
2	(Constant)	0.179	0.095		***	0.74
	TCK	0.443^{***}	0.052	0.470		
	TPK	0.386^{***}	0.048	0.439		

Model	B	Std. Error	Beta	Sig.	R^2	Model
3	(Constant)	0.216^{*}	0.103		***	0.74
	TCK	0.478^{***}	0.063	0.507		
	TPK	0.396^{***}	0.049	0.450		
	TK	-0.051	0.054	-0.055		
4	(Constant)	0.116	0.129		***	0.74
	TCK	0.462^{***}	0.064	0.490		
	TPK	0.393^{***}	0.049	0.446		
	TK	-0.070	0.056	-0.076		
	PCK	0.061	0.047	0.057		
5	(Constant)	0.156	0.130		***	0.75
	TCK	0.460^{***}	0.064	0.488		
	TPK	0.399^{***}	0.049	0.453		
	TK	-0.059	0.056	-0.064		
	PCK	0.194^{*}	0.080	0.183		
	PK	-0.161^{*}	0.079	-0.152		
6	(Constant)	0.180	0.130		***	0.75
	TCK	0.458^{***}	0.064	0.486		
	TPK	0.390^{***}	0.049	0.443		
	TK	-0.045	0.056	-0.049		
	PCK	0.284^{**}	0.099	0.266		
	PK	-0.131	0.081	-0.124		
	CK	-0.126	0.081	-0.123		
7	(Constant)	0.402	0.207		***	0.75
	TCK	0.439^{***}	0.065	0.466		
	TPK	0.395^{***}	0.049	0.448		
	TK	-0.063	0.058	-0.068		
	PCK	0.295^{**}	0.099	0.277		
	PK	-0.128	0.081	-0.121		
	CK	-0.115	0.081	-0.113		
	Age	-0.005	0.004	-0.051		
8	(Constant)	0.446	0.295		***	0.75
	TCK	0.439^{***}	0.065	0.466		
	TPK	0.395^{***}	0.049	0.448		
	TK	-0.062	0.058	-0.067		
	PCK	0.294^{**}	0.099	0.276		

	B	Std. Error	Beta	Sig.	R^2	Model
	PK	-0.127	0.081	-0.120		
	CK	-0.115	0.081	-0.113		
	Age	-0.007	0.010	-0.070		
	Teaching Experience	0.002	0.009	0.020		

*Note: ***p<0.001, **p<0.01, *p<0.05*

Research Question 2: Does the current situation of human and infrastructure resources in schools facilitate teaching and learning science in Cambodia?

- **School facilities**

According to data provided by school principals, all schools have libraries and toilets, while 78.9% of schools have science laboratory rooms and computer labs. Internet connection is available in all schools, and about 95% of them have access to electricity and clean water.

Teachers were asked to assess the sufficiency of material resources for teaching and learning, as well as the science laboratory rooms, library, and toilets. Table 2.6 summarizes the results, showing that teachers rated the science laboratory rooms at 4.90, the sufficiency of laboratory materials at 4.85, the library at 7.27, and the toilet at 6.10 out of 10. These scores indicate that the library assessments were relatively high, while the toilet assessments were moderate. On the other hand, the assessments for science laboratory rooms and the sufficiency of laboratory materials were relatively low, and there were significant gaps between schools. NGS received the highest score of 8 points, while SRS was rated at 5.52 points and OHS at 3.38 points.

Furthermore, schools in the Capital were rated above average (6.04) compared to schools in other locations, which fell below average (4.73 and 4.03 for urban and rural, respectively). The overall student-to-room ratio was 44.2, but the numbers varied significantly depending on the school location (Table 2.6). The ratio was highest in schools located in the Capital, reaching up to 77.1. This indicates that schools in the Capital lacked adequate classrooms for use.

The student-to-classroom ratio (the number of rooms divided by the number of students) was 43.4, and there was no significant difference in the number of students per class between regions. However, schools in the Capital had about 50.4 students per class, which indicated that they used a shift system with morning and

Table 2. 6: Assessments of the laboratory, material resource, library and toilet by school types and school locations

	Laboratory Rate Mean (SD)	Material Resources Rate Mean (SD)	Library Rate Mean (SD)	Toilet Rate Mean (SD)
		School Types		
NGS	8.04 (2.01)	8.00 (1.91)	7.14 (1.65)	6.60 (2.33)
SRS	5.52 (2.69)	5.25 (2.84)	7.03 (1.89)	6.00 (2.54)
OHS	3.38 (3.06)	3.58 (2.98)	7.61 (1.82)	6.09 (3.22)
P-value	***< .000***	***< .000***	.102	.596
		School Locations		
Capital	6.04 (3.23)	5.96 (3.46)	6.81 (1.71)	6.46 (2.53)
Urban	4.73 (3.09)	4.66 (2.98)	7.19 (1.88)	6.12 (2.85)
Rural	4.03 (2.90)	4.11 (2.82)	8.33 (1.54)	5.50 (3.04)
P-value	***.007***	***.011***	***.002***	.294

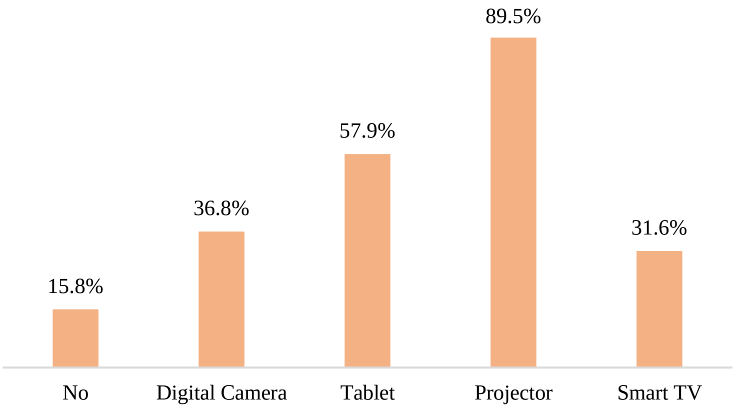


Figure 2. 2: Other electronic devices available in schools

afternoon classes. The number of students per class varied depending on the type of school. NGS had the fewest students per class with a mean of 33.4 (SD = 0.59).

The student-to-computer ratio (the number of computers divided by the number of students) was 55.0, and there was a wide range of numbers across school types. NGS had the lowest ratio 15.1, while OHS had the highest ratio 70.0. Most schools had other electronic devices besides computers, such as projectors, smart TVs, tablets, and digital cameras. About 90% of schools had projectors, and about 60% had tablets for teaching and learning. However, around 16% of schools had no extra electronic devices, as shown in Figure 2.1.

- **Teacher and staff**

Based on the data collected, 53.8% of the teachers own a computer, 12.1% own a tablet, and 96.3% own a smartphone. The chart in Figure 2.2 shows the percentage of teachers who own these devices and have access to the internet categorized by school type. When it comes to computer ownership, approximately

Table 2. 7: Ratios of students to teacher, room, classroom and computer by school types and school locations

	Student-to-Staff Ratio Mean (SD)	Student-to-Teacher Ratio Mean (SD)	Student-to-Room Ratio Mean (SD)	Student-to-Classroom Ratio Mean (SD)	Student-to-Computer Ratio Mean (SD)
			School Types		
NGS	14.0 (1.47)	17.9 (3.42)	34.8 (12.8)	33.5 (0.59)	15.1 (6.32)
SRS	18.2 (7.51)	22.3 (7.17)	42.3 (23.9)	44.4 (7.42)	57.5 (34.8)
OHS	17.8 (3.82)	20.1 (4.09)	47.7 (21.9)	45.2 (11.8)	70.0 (39.0)
P-value	*.098*	*.193*	*.403*	***.036***	***.026***
			School Locations		
Capital	18.6 (4.00)	21.3 (3.88)	77.1 (30.0)	50.4 (22.7)	53.1 (64.7)
Urban	16.1 (5.92)	19.4 (5.86)	35.6 (12.3)	40.6 (5.27)	39.5 (22.3)
Rural	20.1 (3.60)	23.0 (4.09)	44.2 (13.8)	45.8 (5.06)	79.8 (51.0)
P-value	*.063*	*.081*	***.005***	*.323*	*.216*

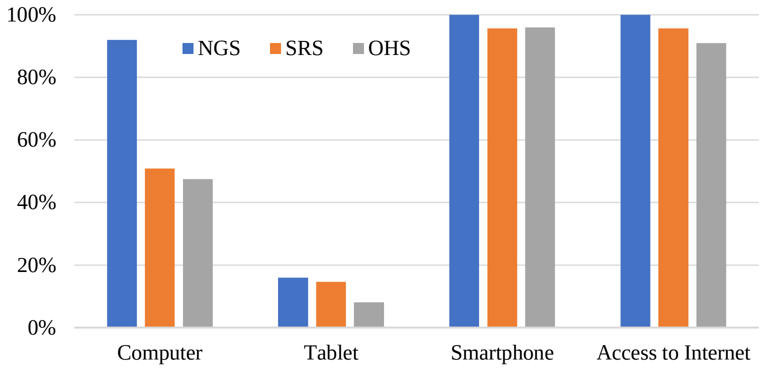


Figure 2. 3: Percentage of teachers owning electronic devices and access to the Internet by school type

90% of NGS teachers own a computer, while only around 50% of SRS and OHS teachers do. Additionally, more than 95% of all teachers had a smartphone and 94.2% had internet access. The student-to-staff ratio (the number of staff divided by the number of students) averaged at 17.4 and the student-to-teacher ratio averaged at 20.5. These Figures were consistent across all school types and locations, as shown in Table 2.7.

2.7. Discussions

Based on the research findings, it seems that high school teachers in Cambodia face difficulties in effectively utilizing ICT to enhance their teaching and improve student learning outcomes. In particular, science teachers in Cambodian high schools may prefer traditional teaching methods, such as using whiteboards, pencils, pens, and paper, over an approach that relies on technology. This finding contradicts the study conducted by Chea et al. (2022), which found that Cambodian high school teachers had relatively low technological knowledge (TK) but were still more likely to use ICT in their teaching. This contradiction may be because Chea et al.'s (2022) study was conducted during the COVID-19 outbreak when many schools in Cambodia were not fully reopened, and ICT was still being used for distance learning.

The present study on gender reveals similar results as Koh and Chai (2011), indicating no significant difference in all knowledge domains. However, Irwanto et al. (2022) found that females scored higher than males only in PK. In contrast, Gómez Trigueros and Yáñez de Aldecoa (2021) observed that males were perceived as superior to females in TCK, TPK, and TPACK, while Jang and Tsai (2013) substantiated this only for TK and TPACK. Chang et al. (2014) studied two groups of teachers who used different ICTs and found a gender difference in one group but not in the other. Lin et al. (2013) discovered that female science teachers exhibited higher self-confidence in PK but lower self-confidence in TK than males. Chea et al. (2022) found that male teachers scored higher than their female counterparts in all knowledge domains. Therefore, existing literature on gender and knowledge domains is inconsistent, especially for TK and technology-related knowledge domains. Further exploration is required to establish a clear position on the role of gender in these domains.

The findings on age are in line with Chea et al.'s (2022) study. Lin et al. (2013) also reported similar correlations between age and technology-related areas, but only among in-service teachers. In contrast, Koh et al. (2014) found that age was negatively correlated with TK, TPK, and TPACK, but not TCK, which was not statistically significant. Regarding teaching experience, Koh et al. (2014) reported negative correlations between teaching experience and all four technology-related areas. Furthermore, Lee and Tsai (2010) explored teacher self-efficacy towards web-based TPACK (TPCK-W) and found that more experienced teachers perceived low self-efficacy concerning TPCK-W. However, those with more experience with the web had higher self-efficacy. These findings suggest that teachers' knowledge can become outdated due to the rapid development of technology. Teachers cannot master all technologies available, but they must focus on the most relevant ones and constantly adapt to them in their teaching. Although older teachers may feel less confident, the study by Lee and Tsai (2010) suggests that they can still be willing to adopt recent technologies for teaching. Otherwise, as teachers grow older, they may lose their confidence and motivation to use technology.

The results of a recent study show that Cambodian science teachers' ability to integrate technology into their teaching practices, known as TPACK, heavily depends on their knowledge of how to use technology to represent content (TCK) and how to use technology to change their teaching methods (TPK). The study found that a sound understanding of different technologies (TK) is closely related to TPACK, but it is indirectly connected and integrated through TCK and TPK. These findings align with Pamuk et al.'s (2015) study, which also found TPK, TCK, and PCK to be positive predictors of TPACK. Additionally, this study supports the findings of Dong, Chai, Sang, Koh, and Tsai (2015), Koh, Chai, and Tsai (2013) and Celik, Sahin, and Akturk (2014)), which suggest that TCK and TPK are the primary predictors of TPACK. However, Schmid, Brianza, and Petko (2020) found that TPK and PCK were the most significant predictors of TPACK, while TCK was not considered a substantial predictor.

The class size in Cambodia is pretty big, on average about twice as many as in European or OECD countries (about 20 students per class) (OECD, 2023). Such a big class size can lead to less teacher effectiveness or quality of teaching and learning (Akerhielm, 1995; Koc & Celik, 2015; Schanzenbach, 2014). Literature could not give a clear-cut conclusion on class size and outcome relationship (Akerhielm, 1995); however, there was an agreement that reducing class size could lead to student-centred teaching, more individualized instruction, fewer disruptions and less student misbehaviour (Hattie, 2005). Reducing class size can help to enhance teaching and learning (Schanzenbach, 2014) but is a very costly decision, and the size effect is rather small, about 0.1-0.2, compared to other educational interventions (Hattie, 2005). According to Smith and Glass

(1980), 10-15 students, at least below 20, per class is regarded as reasonably small. In this sense, it would be challenging for a least-developed country like Cambodia.

The student-to-teacher ratio of Cambodian high schools remains high compared to European and OECD countries. While only 12 and 13 in European and OECD countries, respectively (OECD, 2023), Cambodia is about 1.7 times bigger. This should be another concern for Cambodia. Koc and Celik (2015) argued that the effectiveness of teachers depended on teacher-student interaction and this interaction heavily depended on the number of students per teacher (i.e., student-to-teacher ratio), not directly on class size. In their study 'The Impact of Number of Students per Teacher on Student Achievement', Koc and Celik (2015) found a moderate negative correlation between the student-teacher ratio and achievement.

The pivot of class size and student-to-teacher ratio discussions toward effective teaching or learning outcomes is student-teacher interaction. Class size indicates student-teacher interaction during classes, whereas the student-to-teacher ratio is overall. Learning does not happen only during but also before and after the classes. If the teacher's schedule is not tight, they have time for students and help them learn. In this sense, the solution should be that hiring more teachers is more cost-effective than constructing more school buildings aiming at reducing class size, particularly for developing countries like Cambodia, where the annual budget for education is limited. However, this solution may not apply to the schools in the capital city of Phnom Penh, where the scarcity of classrooms is about double compared to the other areas. Furthermore, the traditional practice of the shift system should be greatly reduced or discontinued because lots of curriculum time is lost annually (Dawson, 2010). MoEYS should consider building extra buildings in existing schools and, if possible, opening new high schools to share the exceeding number of students from existing high schools. Besides, the school principal should consider grouping students who share a similar manner which is beneficial from a class size (Akerhielm, 1995) and assign appropriate teachers to such a class. Teachers should be aware of and apply the concept of excellence in teaching for different class sizes (Hattie, 2005).

Science laboratories have played important roles in science education (Hofstein, 2017). They enhance the science teaching and learning process and affect students' attitudes and academic performance in science (Pareek, 2019). However, Cambodia seems to be moving slowly on this. Overall, Cambodian high school science laboratories are still in poor condition, particularly for OHS, which is the same as what has been reported by Set (2016) and Mam (2021). Cambodia needs more political and financial commitment from MoEYS or the Royal Government of Cambodia to improve this situation.

Educational technologies in the classroom become increasingly necessary, and the computer is the primary tool. Computer technologies can transform traditional into state-of-the-art teaching and learning by accessing information to explore new knowledge and allowing teachers and students to interact with peers and experts and express and communicate beyond classroom walls (Songer, 2007). Word processing, spreadsheet, and presentation software have facilitated text preparation and printing freely as wanted. For science classes, computer simulations present theoretical or simplified models of real-world components, phenomena, or processes, including animations, visualizations and interactive laboratories' (McFarlane & Sakellariou, 2002; Smetana & Bell, 2012). Believing in such advantages, many countries around the globe keep trying to reduce the student-to-computer ratio to 1 (one computer for one student). Japan, for example, through the GIGA (Global and Innovation Gateway for All) School program by March 2024, every pupil will have one terminal (a PC or a tablet) with high-speed and secure Internet for their learning at school (The Japan Times, 2021). In some advanced economy countries such as Luxembourg, the United Kingdom, the United States, New Zealand, Australia etc., the student-to-teacher ratio has already been smaller than one, where the OECD average is about 1.25 (OECD, 2020a). Sadly, in Cambodia, the ratio is extremely high (55), even compared to its neighbouring countries like Thailand (1.25) and Vietnam (4) (OECD, 2020a). More effort and investment are required for Cambodia to reduce the number and to catch up with neighbouring countries in the region. In the meantime, schools may organise schedules for students to access school computers with a clear purpose (i.e. for learning or support learning). It may also be possible that schools offer priority to only students of senior level rather than all students. Therefore, the schools could optimise this shortage of resources. Research evidenced that just one hour per day of using a computer could significantly improve student reading and mathematics performance (Lee, Brescia, & Kissinger, 2009).

2.8. Conclusions and Implications

High school science teachers in Cambodia have an adequate understanding of their respective subject matter and teaching strategies. They are also proficient in using ICT for administrative work and communication but cannot utilise technology to enhance their teaching practices and improve student learning outcomes. Moreover, male and female teachers demonstrated similar levels. Science teachers from NGS were found to have better technology-related knowledge, concerning integrating technology into teaching their content subject, as compared to SRS and OHS.

The ability of Cambodian science teachers to integrate technology into their teaching practices (i.e., TPACK) depends on their knowledge of how to use technology to represent content (TCK) and their knowledge of using technology to transform their teaching practices (TPK). The study found that a solid understanding of different technologies is closely linked to a teacher's ability to integrate technology into their content subject, but this connection is indirectly integrated through their knowledge of how to use technology to represent the content and how to use it to transform their teaching methods.

Cambodia high schools have an acceptable infrastructure, incorporating libraries, science-laboratory rooms, computer labs, internet connection, clean water, toilets and electricity. However, science- laboratory rooms lack materials, especially for OHS. Similarly, most OHSs have very few or no computers for students to learn and use to support learning. There is a lack of classrooms, leading to having high student-to-classroom ratio and class size, especially in the capital city. The number of science teachers is also insufficient, leading to a high student-to-teacher ratio. These are the challenges for Cambodian science teachers to teach effectively.

There are some implications from this study. Teachers' capacity development programs or INSET (In-Service Training) should focus on ICT in general and on distinct ICTs for each subject and the pedagogical aspects possessed by those ICTs to enhance teaching and learning and, especially, take more care of the older or longer years of experienced teachers. Schools should support and motivate science teachers to integrate ICT into their teaching and learning. Ordinary and secondary resource schools should learn how NGS have done with their science teachers concerning ICT. The impact of gender on the perception of integrating ICT into teaching various subjects is not fully understood. However, it is worth considering the hypothesis that male teachers have a higher level of technology-related knowledge than their female counterparts, and investigating this further.

MoEYS should increase the number of high school science teachers recruitment. In Phnom Penh, MoEYS should build extra buildings in existing schools and, if possible, construct a few new high schools to share some students from existing schools which helps reduce class size and student-to-teacher ratio. For OHS, MoEYS should put more effort and investment into incrementing the number of laboratory materials, both types of items and their quantity, and the number of computers.

Cambodian teachers need extra support to enhance their expertise in their major and develop pedagogy mastery. MoEYS should have continuous professional development or INSET programs to strengthen teachers' subject content matter and pedagogy. As for ICT for education, in the short run, MoEYS should have professional development or INSET programs on how to teach effectively using ICT, and in the long run, university courses or PRESET (Pre-Service Training) teacher training programs should consider such a topic in the curriculum.

CHAPTER III

DEVELOPMENT OF ICT-BASED TEACHING MATERIAL ON OSCILLATIONS AND WAVES

3.1. Why Oscillations and Waves?

Oscillations are variations that occur in a medium or system over a while. They are a repeated movement around an equilibrium position. A system is said to oscillate when some of its parameters (such as voltage, intensity, or speed) achieve values that are repeated with recurrence. On the other hand, waves are disturbances that occur in a medium in space, such as density, pressure, or magnetic field. These disturbances may be elastic or deformable, and they involve the transportation of energy without the need for the movement of matter. Understanding the operation of oscillations is crucial in describing wave movements since waves are generated by oscillations. Oscillations and waves are vital since they explain the behaviour of periodic phenomena and the transmission of energy without the need for the presence of a mass or body.

Besides, waves are ubiquitous in the world around us and have played a significant role in our daily lives, particularly over the last two centuries. The applications of waves are responsible for everyday items such as microwave ovens, as well as outer space exploration through instruments such as the Hubble telescope. They bring us music, TV and most of the information we receive. Waves facilitate communication and help us to see things. Waves can transfer energy in various forms, some of which are incredibly useful. Light, sound and almost every musical instrument work through waves. Waves have applications in almost every field of everyday life—almost every aspect of our daily lives, in some way, involves waves.

The study of waves and wavelike phenomena is crucial to almost every branch of Physics, including quantum and particle physics, high-energy physics, plasma physics, electromagnetism, solid-state physics, atmospheric physics, geophysics, and more. This is because waves and wavelike behaviour appear to be intimately intertwined with the universe and all matter and radiation within it, from the subatomic to the intergalactic scale.

The Cambodian curriculum developers have recognized the importance of understanding the phenomena and behaviour of oscillations and waves. I analysed the Cambodian high school Physics syllabus and revealed that there is a significant amount of content dedicated to this topic, accounting for 25% of the entire syllabus. Table 3.1 provides a breakdown of the proportion of high school Physics topics included in Cambodia.

Table 3. 1: Proportion of topics included in the Cambodian Physics syllabus

Topics	Grade 10 No. of hours (%)	Grade 11 No. of hours (%)	Grade 12 No. of hours (%)	Overall No. of hours (%)
1. Mechanics	28 (36.8)	72 (47.4)		100 (43.9%)
2. Thermodynamics	13 (17.1)	17 (11.2)	24 (15.8)	54 (23.7%)
3. Oscillations and waves		27 (17.8)	30 (19.7)	57 (25.0%)
4. Electricity and magnetism	18 (23.7)	36 (23.7)	72 (47.4)	126 (55.3%)
5. Optics	12 (15.8)			12 (5.3%)
6. Energy and life	5 (6.6)			5 (2.2%)
7. Modern Physics			26 (17.1)	26 (11.4%)
Total (No. of hours per annum)	76 (100)	152 (100)	152 (100)	228 (100%)

Table 3. 2: Content existed in the grade 12 national exam

Topic Area	No. of Item	Mark	Mark (%)
1. Electricity and magnetism	36	277	48.17
2. Oscillations and waves	4	20	3.48
3. Thermodynamics	47	278	48.35
Total	87	575	100

However, I observe that at the school level, teachers tend to give more importance to other topics instead of oscillations and waves. In some schools, the teachers do not teach this topic to the students or teach it at the end of the school program. They only teach it if they have time, and if not, they skip it. Some teachers argue that oscillations and waves are not important because they would not exist in the grade 12 national exam. They find it difficult to convince students to study this topic in class since it would not exist in the national exam. I collected the Physics national exam papers of grade 12 from 2014 to 2019 (i.e., 7 exam papers) and analysed them. The results show that out of a total of 87 items, only 4 items were about oscillations and waves. This topic was only worth 20 marks out of 575 marks in the term mark score. It was about 4% of the total content that existed in the national exam for these past 6 years. Table 3.2 shows the results of the Physics national exam papers analysis.

As part of the investigation, I conducted a quick online survey among high school Physics teachers. The survey consisted of three questions: 1) asking teachers to select their top three favourite topics to teach, 2) inquiring about their difficulties in teaching waves, and 3) asking about their difficulties in conducting experiments on waves. A total of 111 high school Physics teachers volunteered to participate in the survey. The results of the first question are presented in Table 3.3, and are consistent with the findings discussed earlier that oscillations and waves are not popular topics for teachers to teach. The topic that teachers love to teach the most is general mechanics, followed by electricity and magnetism.

Many teachers have reported that teaching students about waves, especially when it comes to the second and third questions, can be challenging. They attribute this difficulty mainly to their lack of competence. Some feel that they lack sufficient knowledge to teach the subject effectively, while others struggle to explain the abstract phenomena of waves to students. Few teachers mention their students' background knowledge as a contributing factor to the difficulty. Additionally, when it comes to conducting experiments, many teachers have expressed that they do not know how to conduct experiments on waves, and they blame their lack of competency for this. For those who are capable of doing so, there is also a shortage of materials available in their schools.

Based on this discussion, it is evident that Cambodian students and teachers have been losing interest in as well as devaluing oscillations and waves despite their importance. Additionally, teachers lack the necessary knowledge to effectively teach these topics, and there is a shortage of materials to conduct experiments. These issues are the reason why I chose to study the development of teaching materials for this subject. The purpose of this study is to improve Physics education in

Cambodia and other applicable areas by developing teaching materials that enhance the competency of Physics teachers, particularly in oscillations and waves.

Table 3. 3: Percentages of the three most favourite topics to teach by Physics teachers

Topic	1st	2nd	3rd
1. General mechanic	35.1%	12.6%	14.4%
2. Fluid mechanic	0.0%	7.2%	4.5%
3. Oscillations and waves	3.6%	2.7%	8.1%
4. Electricity and magnetism	30.6%	24.3%	11.7%
5. Optics	5.4%	4.5%	11.7%
6. Thermodynamics	14.4%	12.6%	17.1%

3.2. ICT-Based Teaching Material

In Chapter I, we discussed the significance of ICT in science education. In Chapter II, we revealed the present state of science education in Cambodia. It is noteworthy that approximately 80% of high schools in Cambodia have a computer lab, while 95% of them have access to a power grid. Additionally, more than 50% of science teachers own a computer, which is a valuable resource that can be utilized. Hence, there is an opportunity to develop ICT-based teaching materials. Doing so would have two benefits: firstly, the developed teaching materials can be used, and secondly, the materials can help teachers teach using ICT and enhance their ICT skills simultaneously.

The study developed two types of ICT-based teaching material. The first one is based on microcontroller-based sensor data acquisition and the second one is video-based experiments.

3.2.1. Microcontroller-based sensor data acquisition system (MBS-DAS)

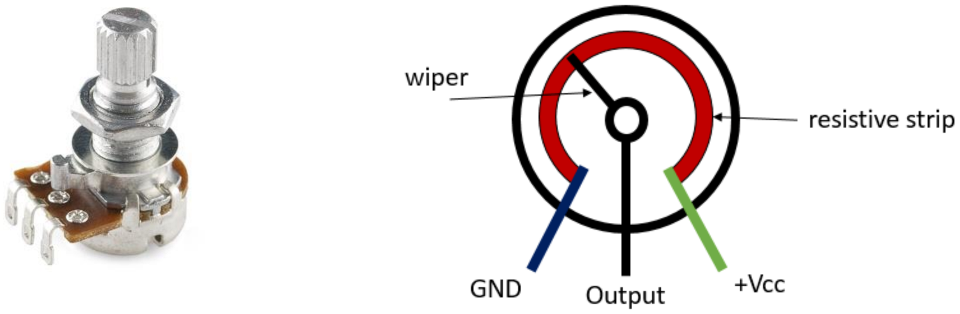
Microcontroller-based sensor data acquisition system (MBS-DAS) comprises two parts: a microcontroller-based sensor, which in this case is an Arduino-based angle sensor, and a data acquisition app called E-Lap. The following sections will provide more details about the two parts.

a. Angle sensor

The study focuses on the oscillations of a pendulum, so measuring the angle position is crucial. I developed an angle sensor for this purpose. The angle sensor is a potentiometer that is programmed using the Arduino IDE. It is used to track the angular position of a pendulum as it swings and sends the measured data to the serial port.

Box 3. 1: Arduino IDE sketch for the angle sensor

```
# define knob 0
float elapse_time = 0.00;
int delay_time = 25;
void setup(){
  Serial.begin(9600);
}
void loop(){
  int knob_value = analogRead(knob);
  elapse_time = float(millis())/1000.0;
  // set equilibrium position (0 degree)
  float angle = (float(knob_value)*300/1023)- 139.880;
  // calibrate measurement
  angle = angle/1.2314;
  Serial.print(elapse_time);
  Serial.print(" , ");
  Serial.println(angle, 4);
  delay(delay_time);
}
```



(a) (b)

Figure 3. 1: (a) Photo of a real potentiometer, (b) the inside of a potentiometer

Figure 3.1 illustrates a potentiometer. The potentiometer has three terminals that are arranged in a row, ground terminal (GND), output terminal, and +Vcc terminal. A potentiometer works by varying the position of a sliding contact across a uniform resistance. In a potentiometer, the entire input voltage is applied across the whole length of the resistor, and the output voltage is the voltage drop between the fixed and sliding contact. The potentiometer has an angular range of 0 to 300 degrees, and it provides a linear change in value. The resistance value is 10k ohms, perfect for Arduino use. The code is designed to map and calibrate voltage values resulting from the change in resistance to angle. The sketch for the angle sensor in Arduino IDE can be found in Box 3.1. As shown in the sketch, only two values, i.e., time and angle will be transmitted to the serial port to be compatible with the E-Lab interface (more detail about the E-Lab interface in the following section).

To use the angle sensor, the output terminal of the potentiometer is connected to the output terminal of an Arduino analogue output pin, such as A0. The potentiometer's +Vcc and GND terminals should be connected to the 5V and GND pins on the Arduino, respectively. To power the Arduino UNO and send data to the serial port at the same time, connect it to the computer via a USB cable. From hereafter, when an angle sensor is mentioned, it refers to a potentiometer connected to Arduino UNO and ready to measure the angle.

b. E-Lab interface

The E-Lab interface is a simple app that I developed using Python code. It is used to conduct science experiments with microcontroller-based sensors. The E-Lab interface can receive experimental data of two variables, separated by a comma or a semicolon (for example: “0.001, 2.339” or “0.234; 3.897”), at once through the serial transition to display a live graph and save experiment data on a computer. Experimental data saved by the E-Lab interface is a CSV (comma-separated value) file that can be opened directly with any spreadsheet software such as Microsoft Excel or Google Sheets to analyse the experiment data.

Box 3.2 indicates the Python code creating the E-Lab interface, and Figure 3.2 illustrates the E-Lab interface. E-Lap interface displays in two languages, i.e., Cambodian and English. It is handy to use. When using, set the baud rate and serial port identical to the microcontroller’s, and then click on the “Start” button to start data collection and live graph dialogue will pop up. Figure 3.3 shows what live graph dialogue looks like. When finished, click the “Stop” button. The E-Lab interface will be closed. A CSV file, experimental data labelled “data.csv”, will be created in the same location where E-Lap is located.

Box 3. 2: Python code of the E-Lab interface

```
from tkinter import *
import serial
from drawnow import *

root = Tk()

root.title("E-Lab")
root.geometry("250x150")

def make_graph():
    plt.xlim(0, 200)
    plt.ylim(-100, 100)
    plt.title("Experiment")
    plt.grid(True)
    plt.xlabel("Time")
    plt.ylabel("Measured Data")
    plt.plot(for_graph, label="Angular Displacement")
    plt.legend(loc="upper left")

def write_data(data_to_write_to_file):
    header = ["Time", "Angular_Displacement"]
    with open('data.csv', 'w', encoding='UTF8', newline='') as f:
        writer = csv.writer(f)
        writer.writerow(header)
        writer.writerows(data_to_write_to_file)

def serial_data_to_number(data):
    new_data = ""
    for digit in data:  # to covert data read from serial port to number
        if digit.isdigit():
            new_data = new_data + digit
        elif digit == "-":
            new_data = new_data + digit
        elif digit == ".":
            new_data = new_data + digit
        elif digit == ",":
            new_data = new_data + digit
        elif digit == ";":
            new_data = new_data + digit
        data = new_data.split(',')
    return data

def select_baud(event):
    number = int(clicked1.get())
    return number

def select_port(event):
    text = clicked2.get()
    return text
```

```
def set_serial():
   port = clicked2.get()
   baudrate = int(clicked1.get())
   data = serial.Serial(port, baudrate)
   return data

def start_program(data):
   data_file = []
   i = 0
   while True:
      while data.inWaiting() == 0:
         pass

      serial_data = str(data.readline())
      data_as_string = serial_data_to_number(serial_data)
      record = []
      try:
         for_graph.append(float(data_as_string[1]))
         record.append(float(data_as_string[0]))
         record.append(float(data_as_string[1]))
         data_file.append(record)
      except Exception:
         print('There is an erro of appedding data.')

      i += 1
      if i >= 200:  # to keep the last 300 data points on plot
         for_graph.pop(0)

      drawnow(make_graph)
      write_data(data_file)

def stop_program():
   sys.exit()

for_graph = []
myLabelKh = Label(root, text="សូមជ្រើសរើស Baudrate និង Port ឱ្យត្រឹមត្រូវ")
myLabelKh.grid(row=0, column=0, columnspan=2, sticky='WE')
myLabelEng = Label(root, text="(Please select the right Baudrate and Port)")
myLabelEng.grid(row=1, column=0, columnspan=2, sticky='WE')

myLabelPort = Label(root, text="Baud")
myLabelPort.grid(row=2, column=0, sticky='WE')
myLabelBaud = Label(root, text="Port")
myLabelBaud.grid(row=2, column=1, sticky='WE')

Baudrates = ["4800", "9600", "19200", "31250", "38400", "57600", "74880",
"115200", "230400", "250000"]
Ports = ["COM1", "COM2", "COM3", "COM4", "COM5", "COM6", "COM7",
"COM8", "COM9", "COM10"]
```

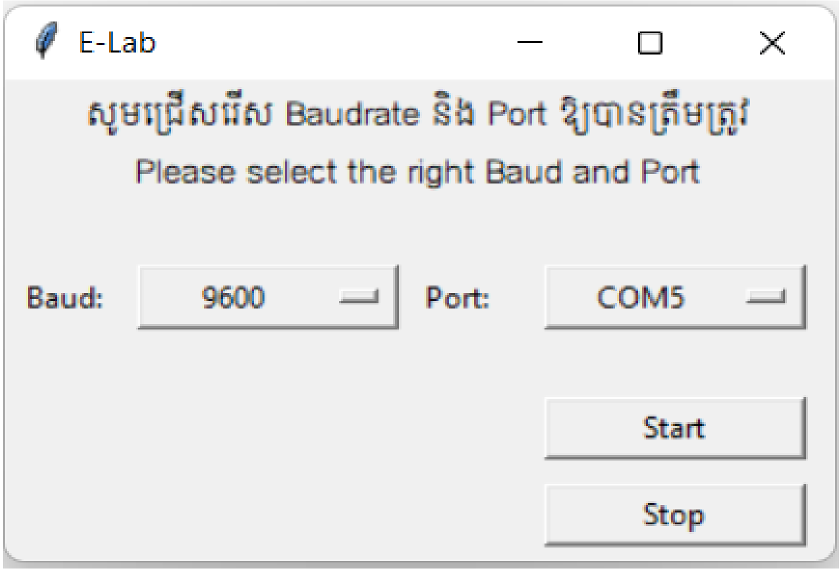
```
clicked1 = StringVar()
clicked1.set(Baudrates[1])
dropBaudrate = OptionMenu(root, clicked1, *Baudrates, command=select_baud)
dropBaudrate.grid(row=3, column=0)
dropBaudrate.config(width=10)

clicked2 = StringVar()
clicked2.set(Ports[4])
dropPort = OptionMenu(root, clicked2, *Ports, command=select_port)
dropPort.grid(row=3, column=1)
dropPort.config(width=10)

myButton = Button(root, text="Start", width=13, command=lambda:
start_program(set_serial()))
myButton.grid(row=4, column=1, padx=10, pady=20)

myButton = Button(root, text="Stop", width=13, command=stop_program)
myButton.grid(row=4, column=0, padx=10, pady=20)

root.mainloop()
```



សូមជ្រើសរើស Baudrate និង Port ឱ្យបានត្រឹមត្រូវ

Please select the right Baud and Port

Baud: 9600

Port: COM5

Figure 3. 2: Screenshot of E-Lab interface

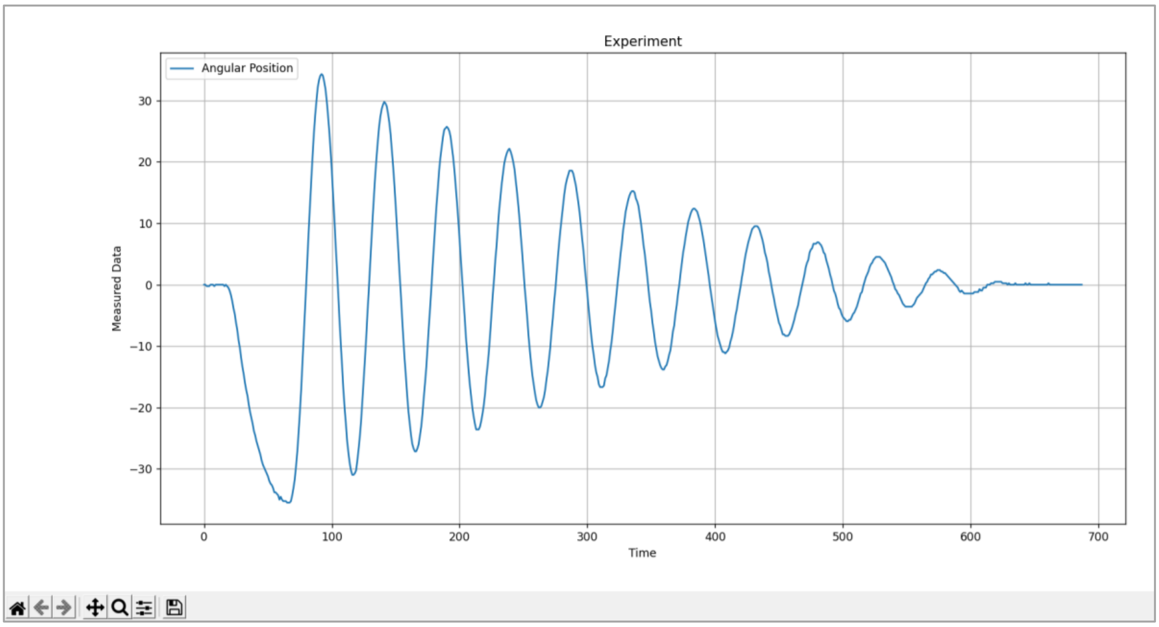


Figure 3. 3: Screenshot of the live graph while acquiring data using E-Lap.

3.2.2. Video-based experiment

A video-based experiment involves recording phenomena demonstrations with a digital camera and analysing them with video analysis software. In this study, Tracker was used.

What is Tracker?

Tracker is a free tool for image and video analysis and modelling, designed for physics education. It is built on the Open Source Physics (OSP) Java framework and can open various video formats including videos with extension mp4, avi, wmv, flv, or mov, animated gif images, and numbered sequences of jpg, png or gif images (Brown, Hanson, & Christian, 2020).

Tracker offers a variety of features including object tracking with position, velocity, and acceleration overlays and graphs, special effect filters, multiple reference frames, calibration points and line profiles for analysis of spectra and interference patterns. It is specifically designed for use in introductory college physics labs and lectures. The tracking includes

- Manual and automated object tracking with position, velocity and acceleration overlays and data.
- Centre of mass tracks.
- Interactive graphical vectors and vector sums.
- RGB line profiles at any angle, time-dependent RGB regions.

How to use Tracker can be easily learned through video tutorials within the app or on YouTube. For more details about Tracker, refer to https://physlets.org/tracker/.

3.2.3. Model and data fitting

In Physics, principles, laws, and theories are often expressed using mathematical equations, also known as mathematical models or formulas. When conducting experiments, scientists typically measure two variables of the formula at once while controlling for others. The data obtained is then used to create a model that fits the principle, law, and theory being studied. From this model, scientists can identify or obtain other variables or constants. Linearization is the most common and easiest method employed in Physics experiments for modelling and fitting experiment data. Linearization involves creating a straight line that approximates the variable in the model based on its value and slope, making it an effective method for calculation purposes. For instance, in the free fall equation, $h = 0.5gt^2$, variable h is measured due to a change in time t. By using the linearization method, the experimenter can plot h against t^2, which allows him/her to obtain the value of g by calculating the slope of the fit line. The value of g is equal to the slope divided by 0.5.

Linearization is a simple but powerful method, but it may not be applicable in every situation. For example, for a spring-mass system with a simple harmonic oscillation function $x = Asin(\omega t + \varphi)$. If the displacement x is measured with respect to time t, linearization cannot be applied. In such cases, experimenters need to find alternative methods to fit the data. Fortunately, there are many alternatives to linearization for data fitting. In this study, I introduced MS Excel add-in called Solver, which can be used as an alternative method for data fitting.

Suppose a student conducted an experiment on a spring-mass system and obtained a dataset, as shown in Figure 3.4. How can this data be fitted to a model using MS Excel?

To fit this data, one can use the least-squares method on MS Excel Solver. The least squares method is a statistical technique used to determine the best fit for a set of data points to a model. It functions by minimizing the sum of the deviations (differences) of the points from the plotted curve. In essence, the least squares method provides the underlying logic for the placement of the line of best fit among the data points under examination.

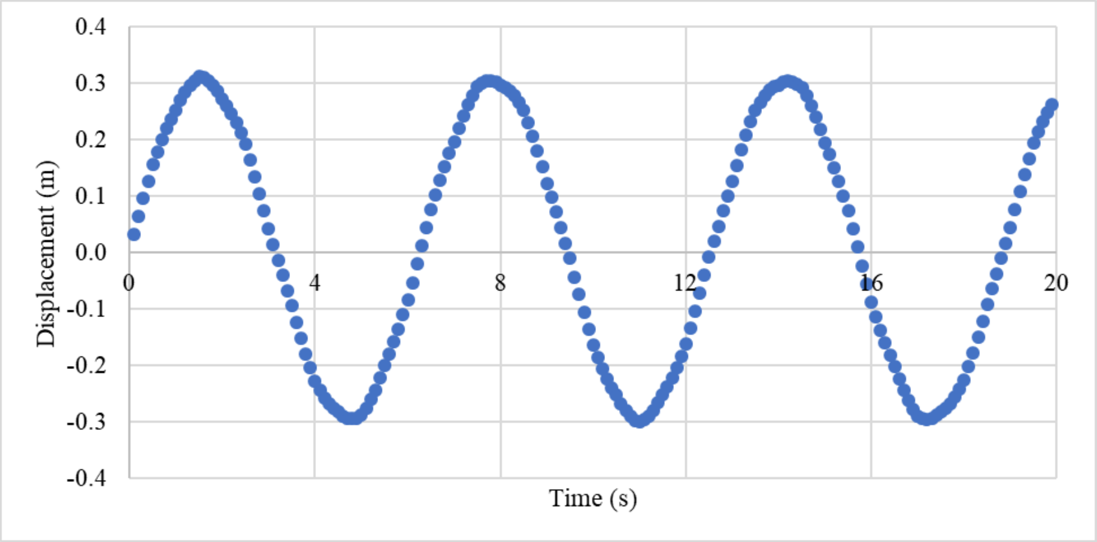
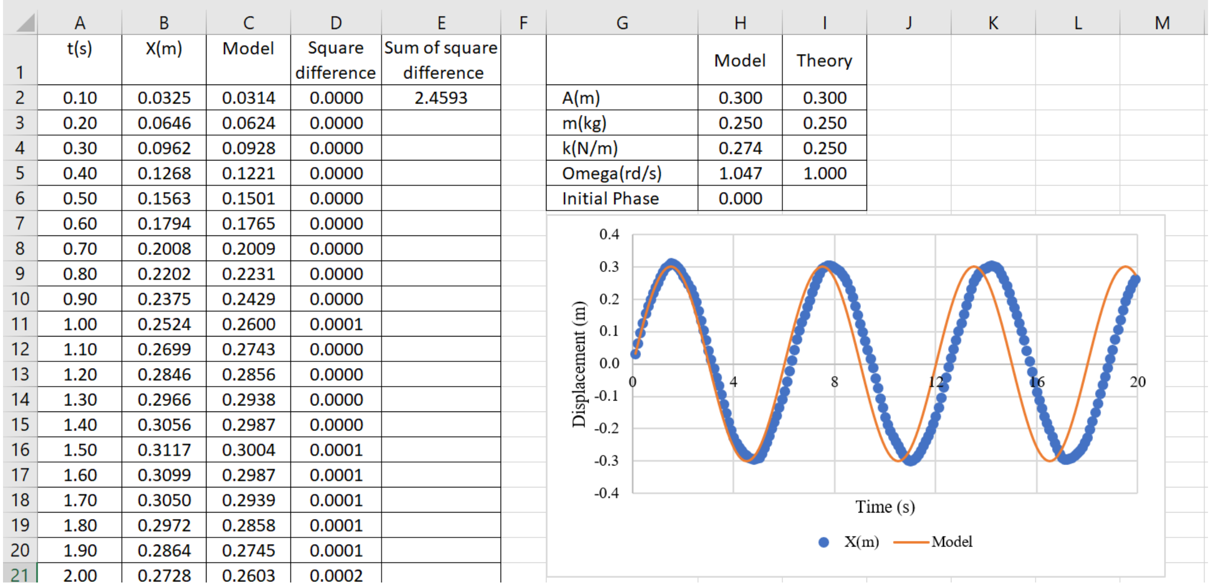


Figure 3. 4: Plot of an example data

Figure 3.5 shows how the data is organized, with the time data in column A, displacement data in column B, and model data in column C. The oscillation function of a string-mass system is given by the model $x = A\sin(\omega t + \varphi)$. We can approximate the values of $A \approx 0.30m$, $T \approx 6.0s$ and $\varphi \approx 0$ from Figure 3.4. Using the value of T, we can find ω: $\omega = 2\pi / T \approx 1.047 rad / s$. Enter these values in column H (as shown in Figure 3.5).

- Creating the model dataset in column C: Starting from cell C2, use the formula "=\$H\$2*SIN(\$H\$5*A2+\$H\$6)", then copy this formula through the end of the dataset to obtain the full model dataset by selecting and dragging or double-clicking on the small square on the bottom right of cell C2.
- Calculating the Square Difference (SD) in column D: Use the formula "=(B2-C2)^2" and copy it through the end of the dataset.
- Calculating the Sum of the Square Difference (SSD) in column E: Use the formula "=SUM (D2:D200)". This simply sums all data in column D. Noting that the number of rows depends on the actual data.
- Plot the experiment and model data on the same chart, with the experiment data in a scatter plot and the model in a line graph. In Figure 3.5, the difference between the data and the model before fitting can be seen.



	A	B	C	D	E
1	t(s)	X(m)	Model	Square difference	Sum of square difference
2	0.10	0.0325	0.0314	0.0000	2.4593
3	0.20	0.0646	0.0624	0.0000	
4	0.30	0.0962	0.0928	0.0000	
5	0.40	0.1268	0.1221	0.0000	
6	0.50	0.1563	0.1501	0.0000	
7	0.60	0.1794	0.1765	0.0000	
8	0.70	0.2008	0.2009	0.0000	
9	0.80	0.2202	0.2231	0.0000	
10	0.90	0.2375	0.2429	0.0000	
11	1.00	0.2524	0.2600	0.0001	
12	1.10	0.2699	0.2743	0.0000	
13	1.20	0.2846	0.2856	0.0000	
14	1.30	0.2966	0.2938	0.0000	
15	1.40	0.3056	0.2987	0.0000	
16	1.50	0.3117	0.3004	0.0001	
17	1.60	0.3099	0.2987	0.0001	
18	1.70	0.3050	0.2939	0.0001	
19	1.80	0.2972	0.2858	0.0001	
20	1.90	0.2864	0.2745	0.0001	
21	2.00	0.2728	0.2603	0.0002	

G	H	I
	Model	Theory
A(m)	0.300	0.300
m(kg)	0.250	0.250
k(N/m)	0.274	0.250
Omega(rd/s)	1.047	1.000
Initial Phase	0.000	

Figure 3. 5: How to organise data for fitting to the model in MS Excel

To use the MS Excel Add-in Solver for the first time, follow these steps:

1. Go to File → Options

2. The Excel Options dialogue box will appear. Select Add-ins on the left-hand menu.

3. From the Manage list box, choose Excel Add-ins and click Go. The Add-ins dialogue box will appear.

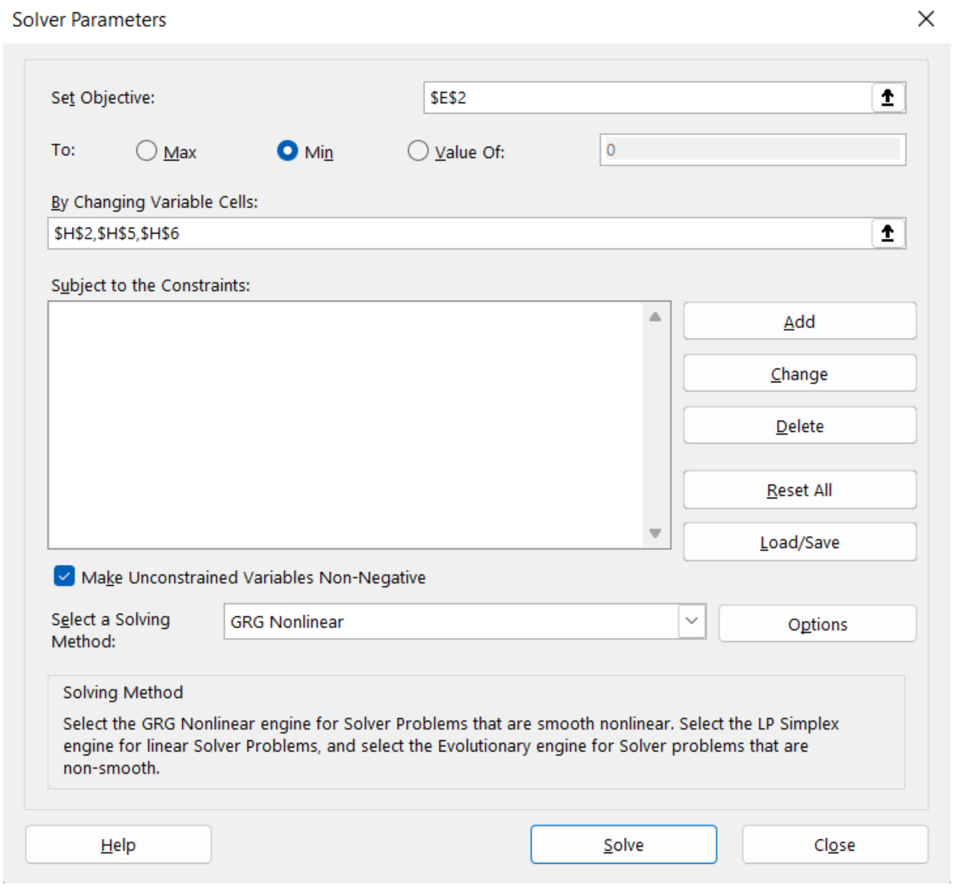
4. Select Solver Add-in and click OK.

To use Solver, you need to go to the Data menu and click on Solver, located at the right end of the menu. This will open the Solver Parameters Dialogue box, which is displayed in Figure 3.6.

In the Set Objective Box, select cell “E2”, which represents the SSD cell. Next, choose "Min" from the radio button options. This indicates that you want to minimize the SSD to obtain the best-fit line, using the least squared method.

In the "By Changing Variable Cells" section, select “H2, H5, H6”. This means that these variables will be changed to obtain the minimum value of SSD.

Finally, click “Solve”. This will open the Solver Results Dialogue box, alert that a solution is found and ask if we want to keep this solution or restore original values. So, select an appropriate option and press OK.



Solver Parameters

Set Objective: E2

To: ○ Max ● Min ○ Value Of: 0

By Changing Variable Cells:

H2,H5,H6

Subject to the Constraints:

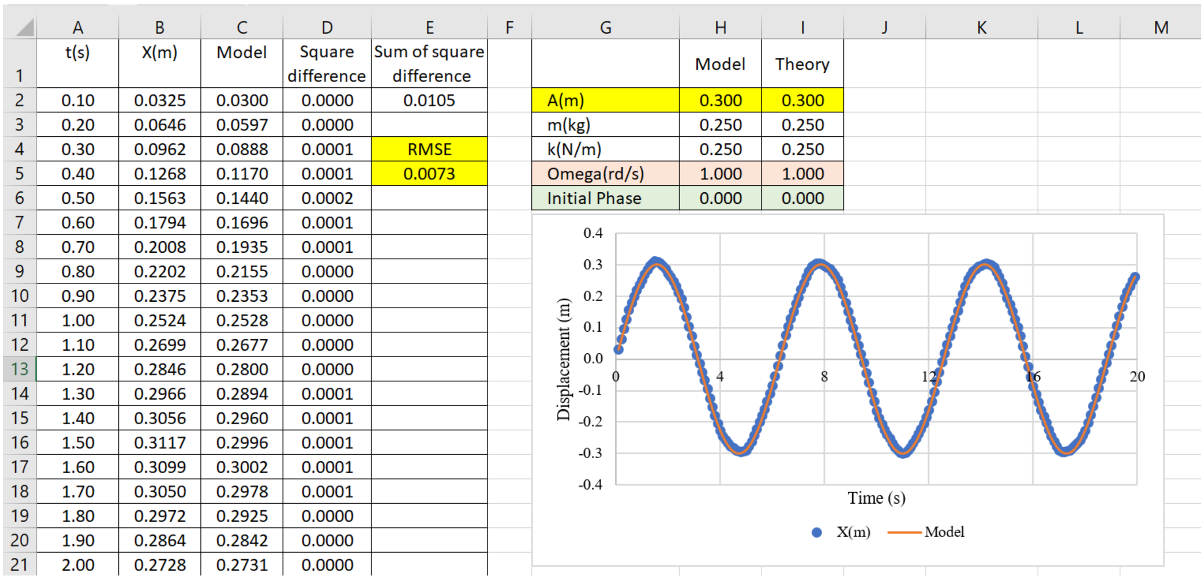
☑ Make Unconstrained Variables Non-Negative

Select a Solving Method: GRG Nonlinear

Solving Method

Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

Figure 3. 6: Illustration of Solver parameters dialogue box



	A	B	C	D	E
1	t(s)	X(m)	Model	Square difference	Sum of square difference
2	0.10	0.0325	0.0300	0.0000	0.0105
3	0.20	0.0646	0.0597	0.0000	
4	0.30	0.0962	0.0888	0.0001	RMSE
5	0.40	0.1268	0.1170	0.0001	0.0073
6	0.50	0.1563	0.1440	0.0002	
7	0.60	0.1794	0.1696	0.0001	
8	0.70	0.2008	0.1935	0.0001	
9	0.80	0.2202	0.2155	0.0000	
10	0.90	0.2375	0.2353	0.0000	
11	1.00	0.2524	0.2528	0.0000	
12	1.10	0.2699	0.2677	0.0000	
13	1.20	0.2846	0.2800	0.0000	
14	1.30	0.2966	0.2894	0.0001	
15	1.40	0.3056	0.2960	0.0001	
16	1.50	0.3117	0.2996	0.0001	
17	1.60	0.3099	0.3002	0.0001	
18	1.70	0.3050	0.2978	0.0001	
19	1.80	0.2972	0.2925	0.0000	
20	1.90	0.2864	0.2842	0.0000	
21	2.00	0.2728	0.2731	0.0000	

	G	H	I
1		Model	Theory
2	A(m)	0.300	0.300
3	m(kg)	0.250	0.250
4	k(N/m)	0.250	0.250
5	Omega(rd/s)	1.000	1.000
6	Initial Phase	0.000	0.000

Figure 3. 7: Data changed after fitting to the model in MS Excel.

Figure 3.7 displays the data after it was fitted to the model. The SSD value decreased to 0.0105, indicating a good fit. The chart clearly shows how well the fitted line (orange line) matches the data. The Root Mean Squared Error (RMSE) can calculated from the SSD value. Simply enter this formula in cell E5: "=SQRT(E2/199)" - where 199 is the total number of data points in this example. In row H, the new values of amplitude A, angular frequency ω, and initial phase φ were calculated from the fitting. These new values can be compared to the theory to see how well the model fits the data.

3.3. Teaching Material on Damped Oscillations

3.3.1. Introduction

Oscillation is the repeating motion of an object in which it continues to return to a given position after a fixed time interval. Elementary oscillation is a simple harmonic motion (SHM), whereas a complicated oscillation combines two or more SHM. The pendulum and the spring-mass system are the two most common SHM oscillators. When an oscillator is oscillating, and its amplitude decreases with time, it is called damped oscillation (Serway & Jewett, 2014).

The literature, regardless of demonstration or simulation, mathematical modelling, or quantification, shows the spring-mass system has been dominant in studies of SHM in general and damping in particular. The spring-mass system motion is linear, handy for acquiring data, and its equation can be directly solved. The pendulum motion, on the other hand, is plane motion. The data acquisition somehow requires a more complicated system and setup (González & Bol, 2006; Squire, 1986; Wang, Schmitt, & Payne, 2002). Besides, the equation is not linear. Its solutions generally require advanced mathematical treatments and methods and vary from one author to another, and this topic has been dominant in the studies concerning the pendulum, e.g., Amrani, Paradis, and Beaudin (2008), Beléndez, Hernández, Márquez, Beléndez, and Neipp (2006), Beléndez, Pascual, Méndez, Beléndez, and Neipp (2007), and Fulcher and Davis (1976).

Involved in teaching physics for decades, I have observed that damped oscillations have been regarded as an unimportant topic, especially at the high school level. Students were taught in a way that damped oscillation was a minor phenomenon and taken as negligible. Usually, the students only view the damping concept as a disadvantage in an oscillatory system. This can lead to missing crucial applications of damping. In contrast, damping always exists in all oscillatory systems and is difficult to avoid but it has to be dealt with. The damping concept is a foundation for many engineering implications to study at a more advanced level, especially in a degree in engineering. Many systems require the advantage of damping to reduce unwanted oscillations and make the systems work better (e.g. suspension system of a car or a bullet train) (Shi & Cai, 2008) and/or safer (e.g. tuned mass damping in a long-span bridge or skyscraper) (Chen & Wu, 2008; Rana & Soong, 1998).

Concerning damping, viscous damping (exponential decay) has been referred to rather than Coulomb damping (linear decay), even though they coincide in most oscillatory systems (González & Bol, 2006; Molina, 2004; Serway & Jewett, 2014) and as a combination effect (Hauko, Andreevski, Paul, Šterk, & Repnik, 2018; Hinrichsen & Larnder, 2018; Ricchiuto & Tozzi, 1982). And when both were addressed, usually in a separate analysis, in many cases, by treating one superior to another (Poonyawatpornkul & Wattanakasiwich, 2013; Zonetti, Camargo, Sartori, De Sousa, & Nunes, 1999). Interestingly, the Coulomb effect leads to a piecewise decay function (Barratt & Strobel, 1981; Hauko, Andreevski, Paul, Šterk, et al., 2018; Lapidus, 1970; Molina, 2004; Onorato, Mascoli, & DeAmbrosis, 2010), but it has been assumed as continuous linear, leading to significant error (Hinrichsen, 2020). From the review, there is a lack of literature which examines these problems in the case of the pendulum. Therefore, the current study investigates the combination of viscous and dry friction damping in compound pendulum oscillation.

The measurements of pendulum motion using standard tools such as a ruler, a protractor or a chronometer are challenging or impossible. On the other hand, using commercial products in many ways is somehow expensive. Therefore I want to employ two modern instruments that are cheap and handy to quantify the experiments in this study, which are video analysis and a microcontroller sensor. Video analysis technique has been gaining more and more popularity in science experiments, which allows an easy setup using improvised materials to acquire data (Thy & Iwayama, 2021) and can be gotten for free, i.e. Tracker (Brown et al., 2020). The microcontroller sensor has also become a favoured tool for science experiments because it can be found anywhere at a low price. In addition, it is flexible and easy to use.

3.3.2. Theory

The study does not focus on solving the differential equations since detailed solutions can be found in previous studies such as Beléndez et al. (2006), Beléndez et al. (2007), and Fulcher and Davis (1976). The study uses a compound pendulum (see Figure 3.8) that consists of more parameters than a spring-mass system or simple pendulum, and the phenomenon is also slightly different and requires different treatment. Thus, in this theory section, they are addressed.

3.3.2.1. Undamped oscillations

Newton's second law:

$$\sum \tau = I\alpha \tag{O.1}$$

where *I* is the moment of inertia of the system, α is angular acceleration, and τ is the torque due to a force F: $\tau = d \times F$.

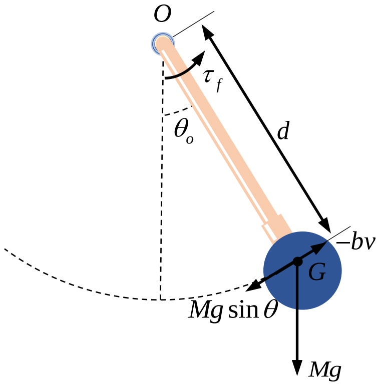


Figure 3. 8: Compound pendulum system and its parameters.
G is the centre of mass, swinging about the pivot O.

Let's begin with the undamped pendulum.

In this case, F is a restoring force: $F = -Mg\sin\theta$. Then,

$$\tau = -Mgd\sin\theta = I\alpha$$

$$I\alpha + Mgd\sin\theta = 0$$

$$\ddot{\theta} + \frac{Mgd}{I}\sin\theta = 0 \text{, or}$$

$$\ddot{\theta} + \omega_o^2 \sin\theta = 0 \tag{O.2}$$

with ω_o is the angular frequency, where $\omega_o^2 = Mgd / I$, M is the mass of the system, *g* is the acceleration due to gravity, *d* is the distance from the centre of mass to pivot, *I* is the moment of inertia of the system, and θ is the amplitude of angular displacement. The oscillations of the pendulum are subject to the initial conditions. In this study, $\theta(0)=\theta_0$ and $\dot{\theta}(0)=0$, where θ_o is the amplitude of the oscillation.

Equation O.2 is a non-linear differential equation. There is no analytical solution. Its solution is expressed as an elliptic integral, which could be solved numerically or using approximations (Amrani et al., 2008). Most of the time, this equation is solved under the condition of a small-angle approximation $\sin\theta \approx \theta$. Then, equation O.2 becomes a linear differential equation (i.e. $\ddot{\theta}+\omega_o^2\theta=0$) that is very easy to solve. The period of the oscillation is given by

$$T_o = 2\pi\sqrt{\frac{I}{Mgd}} \tag{O.3}$$

The period for this case is amplitude-independent. Thus, the angular displacement as a function of time is written

$$\theta(t)=\theta_o\cos\omega_o t \tag{O.4}$$

However, the exact solution of equation O.2 to the period of the oscillation is given by $T_{ex}=T_o(2/\pi)K(k)$, where $k=\sin^2(\theta_o/2)$ and $K(k)$ is the complete elliptic integral of the first kind. The values of elliptic integrals are tabulated for numerous values of k (Hedrick, 1957). Using the power expansion of (Beléndez et al., 2006) and Fulcher and Davis (1976), the exact period may be written

$$T_{ex}=T_o\left(1+\frac{1}{16}\theta_o^2+\frac{11}{3072}\theta_o^4+\frac{173}{737280}\theta_o^6+\ldots\right) \tag{O.5}$$

According to equation O.5, the exact period is amplitude-dependent, where the first three terms have usually been employed (Hinrichsen, 2021), with errors of less than 0.1% for the angle up to 75^o (Gatland, 2007). From the literature, most approximations of different methods obtained the same first term of the exact solution, where their errors were less than 1% for the angles up to 75^o (Beléndez et al., 2006; Gatland, 2007). And for the amplitude up to 135^o, the pendulum is practically and periodically harmonic, i.e. the simple harmonic function provides an excellent approximation to the solution of equation O.2 with the exact period T_{ex} (Beléndez et al., 2006; Gatland, 2007). Therefore, in the current study, I use the first term of the exact value, i.e. $T_{ex}=T_o(1+\theta_o^2/16)$, and the simple harmonic function to govern the study. The equation O.2 can be rewritten to

$$\ddot{\theta}+\omega_{ex}^2\theta=0 \tag{O.6}$$

with $\omega_{ex}=2\pi/T_{ex}$, the exact angular frequency of the oscillation. The angular displacement as a function of time is

$$\theta(t)=\theta_o\cos\omega_{ex}t \tag{O.7}$$

Note that this approximation is also applied to other solutions in the following sections of this paper to be handy and suit an introductory level.

3.3.2.2. Damped oscillations

Damped oscillation can be caused by a viscous resistance and/or Coulomb friction force or torque. The viscous damping oscillation is characterized by an exponential decay, whereas the Coulomb damping possesses a linear decay (Serway & Jewett, 2014). Generally, real systems have both forms of damping, so the oscillation decay is a combination of exponential and linear functions.

- **Viscous damping**

Viscous damping refers to the damped motion by a force or torque opposing motion proportional to the velocity. This can be affected by a fluid or a magnet. In this case, the resistive torque $\tau_d=-bvd=-bd^2\dot{\theta}$ is added into the equation, so that the total torque of the system becomes $\tau=\tau_d+\tau_g=-bd^2\omega-mgd\sin\theta$. Plug the total torque in equation (O.1) and apply the same arrangement in section 1, then

$$\ddot{\theta}+2\gamma\dot{\theta}+\omega_o^2\sin\theta=0 \quad \text{or}$$

$$\ddot{\theta}+2\gamma\dot{\theta}+\omega_{ex}^2\theta=0 \tag{O.8}$$

where $\gamma=bd^2/2I$, and b is the viscous damping coefficient. This study focuses solely on the underdamped case ($\gamma<\omega_{ex}$), where the oscillation decays exponentially. A detailed solution of similar equations can be found in the literature, e.g. Hinrichsen and Larnder (2018) and Molina (2004). The general solution to equation O.8 in this case is

$$\theta(t)=\frac{\omega_{ex}}{\omega}\theta_o e^{-\gamma t}\cos(\omega t-\phi) \tag{O.9}$$

where $\omega^2 = \omega_{ex}^2 - \gamma^2$, and $\tan\phi = \gamma / \omega$. The term $\theta_o e^{-\gamma t}$ illustrates that the amplitude of the oscillation decays exponentially with time.

- **Coulomb damping**

Coulomb damping is known as dry friction or sliding friction damping, caused by a frictional force or torque occurring between adjacent members, which is always opposite in the direction of the motion and independent of amplitude and frequency, leading to linear decay. The friction occurs at the pivot *O*. The fractional torque is denoted by τ_f and assumed constant to simplify the solution. In this case, the total torque of the system becomes $\tau = \tau_g + \tau_f$.

Plug the total torque in equation (1), and after rearrangement, then

$$\ddot{\theta} + \frac{Mgd}{I}\sin\theta + \frac{\tau_f}{I}Sgn(\dot{\theta}) = 0 \qquad \text{or}$$

$$\ddot{\theta} + \omega_o^2 \sin\theta + \eta Sgn(\dot{\theta}) = 0 \qquad \text{or}$$

$$\ddot{\theta} + \omega_{ex}^2 \left(\theta + \Delta Sgn(\dot{\theta})\right) = 0 \tag{O.10}$$

where $\Delta = \frac{\eta}{\omega_{ex}^2}$, $\eta = \frac{\tau_f}{I}$ and $Sgn(\dot{\theta}) = -1,\ 0,\ 1$ for $\dot{\theta} < 0, \ = 0, > 0,$ respectively, aligning with the condition that the friction torque always opposes the motion. A detailed solution of similar equations may be found in various literature, e.g. Hauko, Andreevski, Paul, Šterk, et al. (2018), Molina (2004), and Lapidus (1970). In this case, the general solution to the equation O.10 is

$$\theta_n(t) = \left(\theta_o - (2n+1)\Delta\right)\cos\omega_{ex}t + (-1)^n\Delta \tag{O.11}$$

where *n* is the number of the half periods of oscillation $n = 0, 1, 2, 3, \ldots$. The term $\theta_o - (2n+1)\Delta$ is the envelope which is a periodic step function with a linear decreasing value, and its period is equal to the period of oscillation (Hauko, Andreevski, Paul, Sterk, & Repnik, 2018). Every half period (π / ω_{ex}) the amplitude decreases by 2Δ, decreasing at a constant rate with time. This rate is the change amplitude 2Δ divided by π / ω_{ex} , which is $2\eta / \pi\omega_{ex}$. The last term $(-1)^n\Delta$ indicates that the equilibrium position shifts every half period, leading to the discontinuity of displacement vanishing (Hinrichsen & Larnder, 2018).

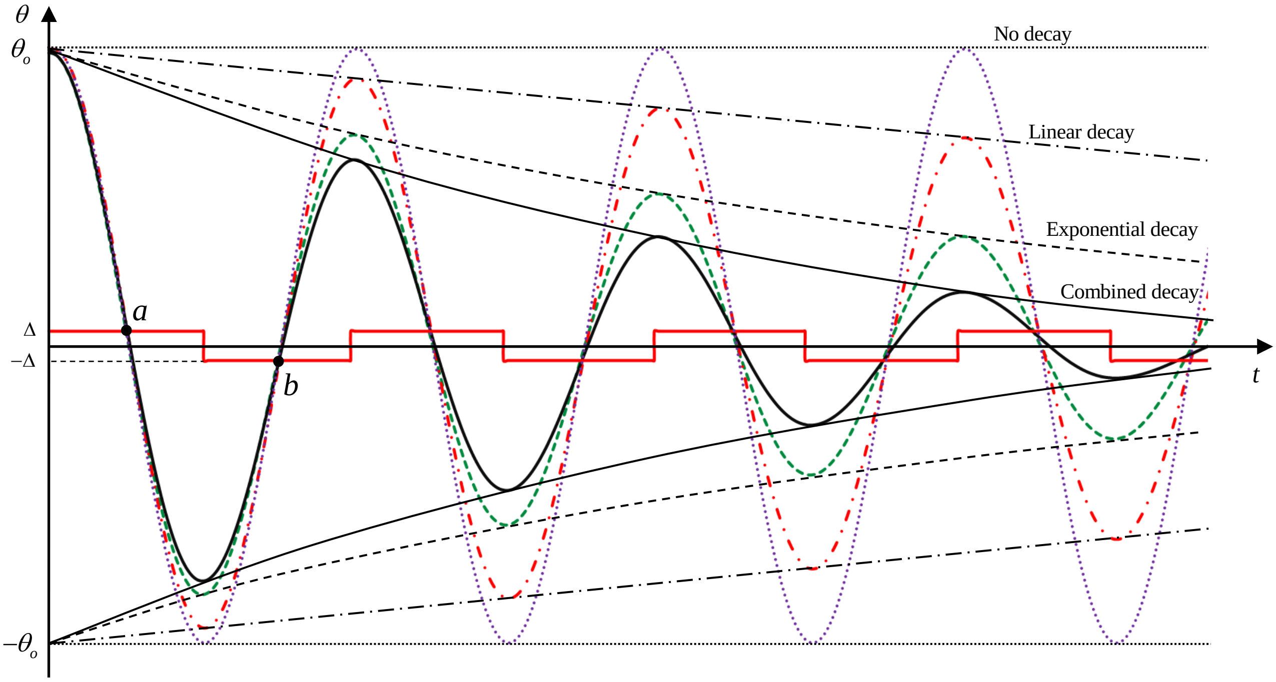


Figure 3. 9: No decay and different types of decay. The dotted-purple is the no decay curve, dotted-dashed red is viscous, dashed green is dry friction, and solid black is a combined case, modelled using equations O.7, O.9, O.11 and O.13, respectively. The envelope lines with the corresponding type of lines and labels represent the amplitude decay curves. Points a and b, intercepts between rectangular curves (solid-red line), are examples of shifted equilibriums for the linear and combined decay due to dry friction in each half oscillation.

- **Combined damping**

In the real situation, a compound pendulum possesses both characteristics of damping, and it is difficult to separate. In this case, mathematically, it is the combination of equations O.8 and O.10. Then we have

$$\ddot{\theta}+2\gamma\dot{\theta}+\omega_{ex}^2\left(\theta+\Delta Sgn(\dot{\theta})\right)=0 \tag{O.12}$$

The detailed solution of a similar equation to equation (12) can be found in (Hinrichsen & Larnder, 2018), then

$$\theta_n(t)=\frac{\omega_{ex}}{\omega}\left(\theta_o-\Delta\frac{2\beta^{-n}-(1+\beta)}{1-\beta}\right)e^{-\gamma t}\times\cos(\omega t-\phi)+(-1)^n\Delta \tag{O.13}$$

where $\beta=e^{-\gamma T/2}$ is the decayed amplitude per half period due to viscous resistance, $\omega_{ex}^2=\omega^2+\gamma^2$ and $\tan\phi=\gamma/\omega$. The amplitude decay is

$$\left|\theta_n\right|=\left(\theta_o-\Delta\frac{2\beta^{-n}-(1+\beta)}{1-\beta}\right)e^{-\gamma t}+\Delta$$

$$\left|\theta_n\right|=\theta_o\beta^n-\Delta\frac{(1+\beta)(1-\beta^n)}{1-\beta} \tag{O.14}$$

Equation O.14 is derived from a generalization of the geometric series of decays of amplitude from the first half oscillation ($n = 0$) (Hinrichsen & Larnder, 2018), representing the displacement at the beginning of the n^{th} half oscillations. For the two successive half oscillations, it can be written (Hinrichsen, 2020)

$$\begin{aligned} |\theta_n| &= (\theta_{n-1} - \Delta)\beta - \Delta \\ &= \theta_{n-1}\beta - \Delta(1+\beta) \\ |\theta_n| &= \theta_{n-1}e^{-\gamma T/2} - \Delta(1+e^{-\gamma T/2}) \end{aligned} \tag{O.15}$$

which shows that for every half oscillation, the amplitude decays due to viscous damping, the first term, plus $(1+e^{-\gamma T/2})/2$ of the frictional decay 2Δ. For pure viscous damping $\Delta = 0$, $|\theta_n| = \theta_o \, \mathrm{e}^{-n\gamma T/2}$, and pure frictional damping $\gamma = 0$, $|\theta_n| = \theta_o - 2n\Delta$.

3.3.3. Apparatuses and experimentation

a. Pendulum

There were several options when it came to making a pendulum, such as using a physical or compound pendulum. A solid rod with a bob (as shown in Figure 3.10a) allows for variation in pendulum mass by changing the bob and length of the pendulum by changing the position of the bob along the rod. On the other hand, a

(a) (b)

Figure 3. 10: Illustrations of pendulum alternatives (a) a solid rod with a bob, (b) a solid bar

solid bar (as shown in Figure 3.10b) allows for changing the bar or adding mass to it. In this report, I used a pendulum comprising an aluminium rod and a metal bob (Figure 3.11).

b. Experimental setup and investigation

Figure 3.11 illustrates the materials used and their setup. The bob was attached at one end of the aluminium rod, while the other end was connected to the angle sensor. The angle sensor was connected to the computer through a USB cable. The E-Lab interface was running on the computer, waiting to read data from the serial port and display a live graph of the experiment. Once the experiment was over, the E-Lab interface was stopped, and the experiment data was saved as a CSV file for data analysis.

A small-strong magnet and an aluminium plate were used to adjust the viscous coefficient[1]. The magnet was attached to a side of the bob (i.e. on the connector that connects the bob and the aluminium rod, Figure 3.11-A, and the aluminium plate was placed opposite it. Moving the plate closer to or further from the magnet could change the viscous coefficient. On the other side of the bob facing the camera, a small black and white spot, like an eye, was stuck to create high contrast for tracking during video analysis.

The bob was pulled out and tied with a piece of yarn to another stand to set out an initial displacement. The smartphone was mounted on a tripod parallel to the swing plane. When the angle sensor was connected; the smartphone camera was ready and started recording, as well as the E-Lab interface, and the yarn was cut to begin oscillation.

The experiments were recorded at 120 fps by an iPhone 12 Pro using the slow-motion function. The recording was held on until the pendulum stopped and stayed still for a moment. Then, the recorded experiment video was sent to a computer for analysis.

Table 3. 4: Specification of the pendulum used

Variables	Value
$M\ \left(\times 10^{-3} kg\right)$	62.3 ± 0.1
$d\ \left(\times 10^{-2} m\right)$	38.3 ± 0.1
$I\ (\times 10^{-3} kgm^2)$	9.40 ± 0.2
$\omega_o (rad/s)$	4.90 ± 0.01
$T_o (s)$	1.26 ± 0.01

---

[1] The viscous damping factor is due to a viscous drag, a force that an object feels as it moves through a fluid or magnetized material moves in a magnetic field. For the control's sake, I uses a magnetic factor rather than fluids.

In the study, I discussed two experiments with the setup and procedure described above. In the second experiment, the viscous effect was increased by placing the aluminium plate slightly closer to the bob but trying to keep both factors, remaining significantly contributing to the damping. I employed an identical angle sensor in both experiments, expecting to see dry friction effects that were the same as the results of the two experiments. However, to ensure the reliability of the results, several analyses were performed and compared the results. Table 3.4 shows the specification of the pendulum.

3.3.4. Data analysis and results

The video analysis was performed by using Tracker (Brown et al., 2020). On Tracker, the video frame rate was set to 120 fps, the same as the recorded frame rate. The calibration was made by opting for the pivot of the pendulum to be the origin of the coordinate system and the stand pole to be the vertical axis. The protractor and point mass tools were employed respectively to measure the initial displacement and track the positions of the bob while swinging. Times and corresponding angular positions were obtained (see Figure 3. 12).

Data analysis was performed in Microsoft Excel 2019. First, the obtained data was imported into Microsoft Excel. Second, equation O.13 was modelled. Last, the Solver, a Microsoft Excel add-in, was used to fit the models to the obtained data accordingly. The angular frequencies, initial amplitude, dry friction damping parameter, and viscous damping coefficient were fitted by least-squares minimization.

Each experiment had two datasets, obtained by angle sensor and video analysis. Figures 3.13a and 3.13b show the two datasets of the first experiment were fitted by equation O.13 models, respectively (RMSE: 0.0104 and 0.0093). Similarly, Figure 3.14 is for the second experiment datasets (RMSE: 0.0065 and 0.0103). Overall, equation O.13 models had excellent fits with the datasets. Table 3.5 summarizes the results of the analyses. It is consistent between the sensor and video analysis data in both experiments, with a percentage difference of less than 4%. Compared to theory, the parameters such as period, angular frequency and moment of inertia obtained by the model fit have a percentage error of less than 5%.

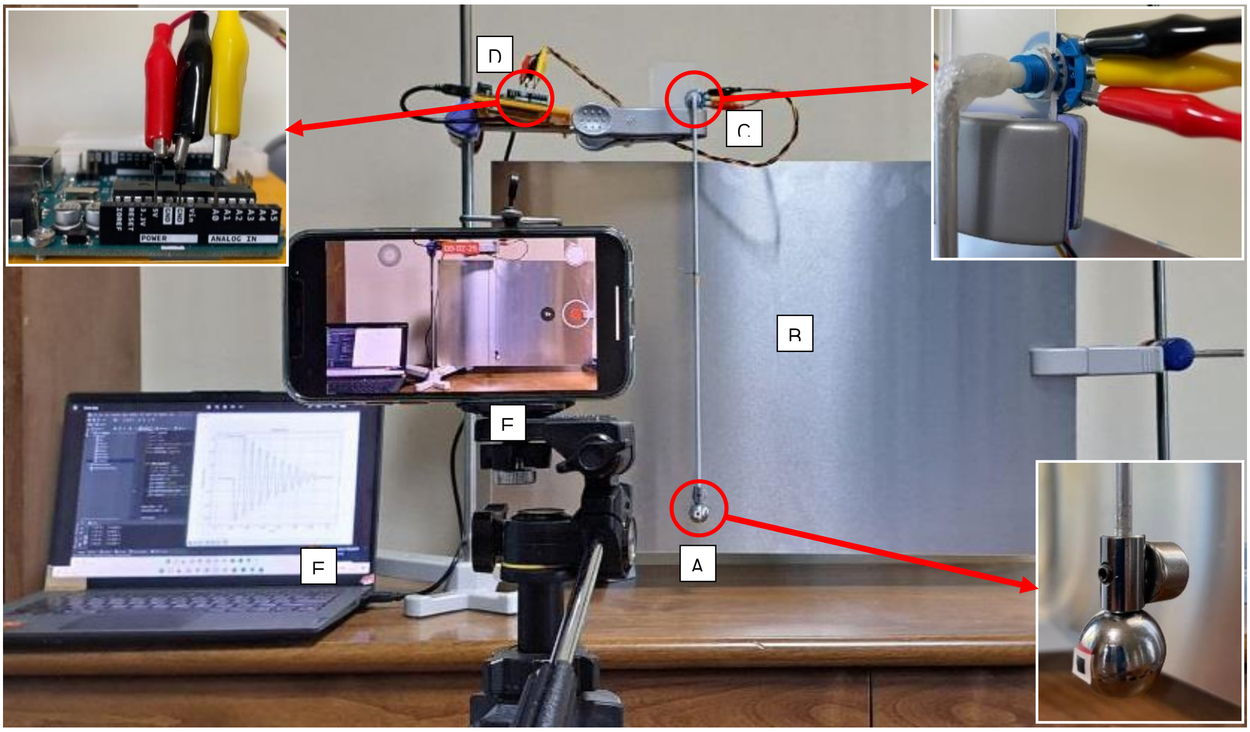
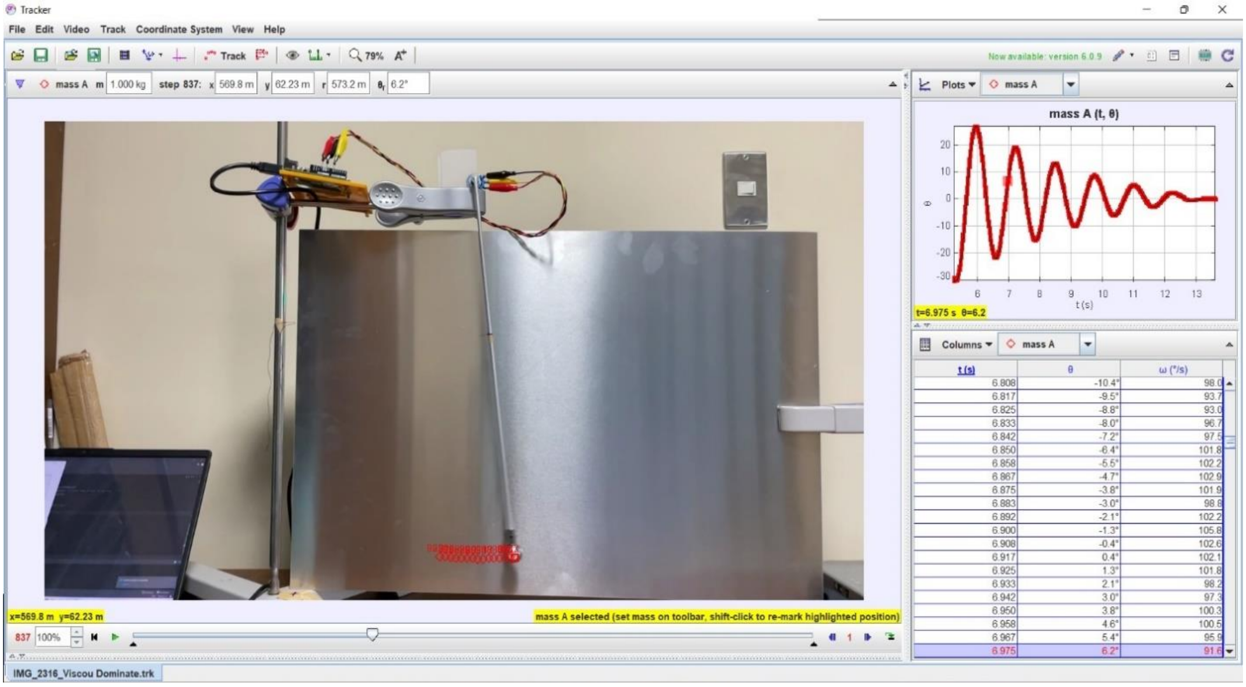


Figure 3. 11: Materials used and their setup. (A) Bob and a strong magnet, (B) aluminium plate, (C) angle sensor (potentiometer) connection, (D) Arduino connection, (E) Computer running python script collecting data from the sensor, and (F) Smartphone recording video.



mass A m 1.000 kg step 837: x 569.8 m y 62.23 m r 573.2 m θ_r 6.2°

t=6.975 s θ=6.2

x=569.8 m y=62.23 m

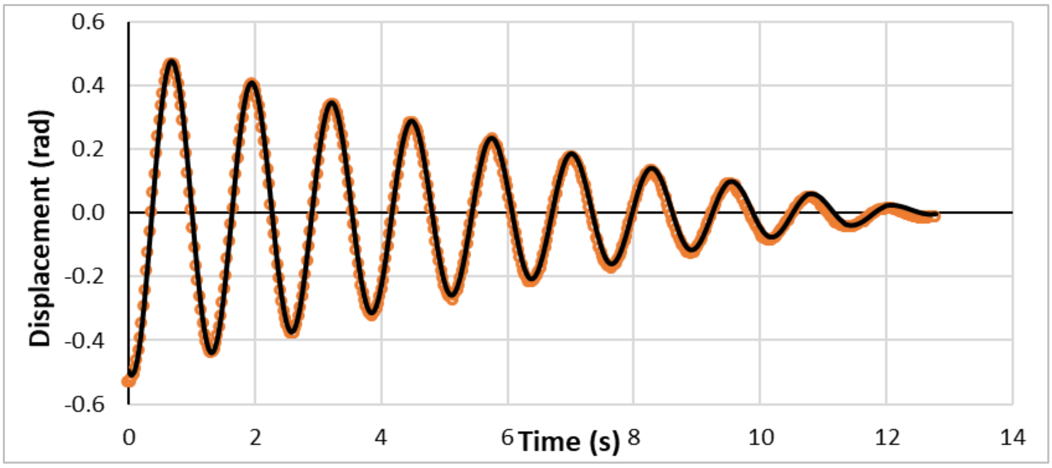
mass A selected (set mass on toolbar, shift-click to re-mark highlighted position)

t (s)	θ	ω (°/s)
6.808	-10.4°	98.0
6.817	-9.5°	93.7
6.825	-8.8°	93.0
6.833	-8.0°	96.7
6.842	-7.2°	97.5
6.850	-6.4°	101.8
6.858	-5.5°	102.2
6.867	-4.7°	102.9
6.875	-3.8°	101.9
6.883	-3.0°	98.8
6.892	-2.1°	102.2
6.900	-1.3°	105.8
6.908	-0.4°	102.6
6.917	0.4°	102.1
6.925	1.3°	101.8
6.933	2.1°	98.2
6.942	3.0°	97.3
6.950	3.8°	100.3
6.958	4.6°	100.5
6.967	5.4°	95.9
6.975	6.2°	91.6

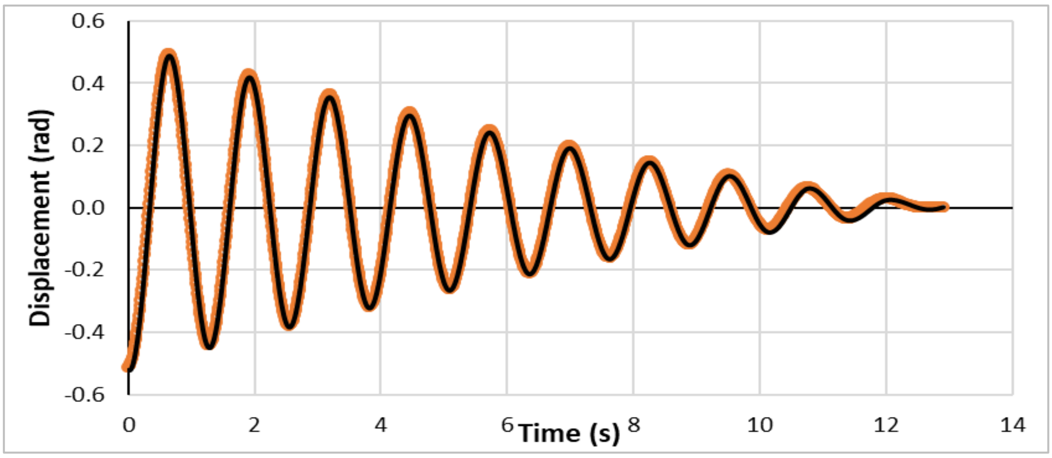
Figure 3. 12: Screenshot of Tracker while tracking bob motion to acquire data.

Table 3. 5: Summary of all values of variables and parameters obtained from the analysis angle sensor and video analysis data fitted to equation O.13. And the percentage errors in parentheses were calculated by comparing with theory predicted values in Table 3.4.

Variables & Parameters	1st Experiment			2nd Experiment		
	Angle sensor (% error)	Video analysis (% error)	Difference (%)	Angle sensor (% error)	Video analysis (% error)	Difference (%)
$\theta_o (\times 10^{-1} rad)$	5.16 ± 0.08 (2.0)	5.30 ± 0.09 (4.74)	2.7	5.33 ± 0.01 (5.3)	5.49 ± 0.01 (8.4)	2.9
$\omega (rad / s)$	4.96 ± 0.04 (1.3)	4.96 ± 0.03 (1.1)	0.2	4.97 ± 0.03 (1.4)	4.97 ± 0.02 (1.5)	0.1
$\omega_{ex} (rad / s)$	4.96 ± 0.04 (1.3)	4.96 ± 0.03 (1.1)	0.2	4.97 ± 0.03 (1.4)	4.97 ± 0.02 (1.5)	0.1
$T(s)$	1.27 ± 0.08 (1.3)	1.27 ± 0.01 (1.1)	0.2	1.27 ± 0.08 (1.3)	1.26 ± 0.06 (1.5)	0.1
$T_{ex}(s)$	1.27 ± 0.08 (1.3)	1.27 ± 0.01 (1.1)	0.2	1.27 ± 0.08 (1.3)	1.26 ± 0.06 (1.5)	0.1
$I (\times 10^{-3} kg / m^2)$	9.80 ± 0.02 (3.9)	9.84 ± 0.02 (4.4)	0.5	9.79 ± 0.04 (3.8)	9.79 ± 0.04 (3.8)	0.0
$\gamma (\times 10^{-3} / s)$	62.8 ± 2	62.9 ± 2	0.1	109 ± 3	107 ± 2	1.2
$b (\times 10^{-3} Ns / m)$	8.39 ± 0.3	8.47 ± 0.3	0.9	14.6 ± 3	14.4 ± 3	1.2
$\Delta (\times 10^{-3})$	8.27 ± 0.1	8.40 ± 0.1	1.6	8.30 ± 0.1	8.60 ± 0.1	3.6
$\tau_f (\times 10^{-3} Nm)$	1.99 ± 0.1	2.03 ± 0.1	2.0	2.00 ± 0.03	2.08 ± 0.02	3.9

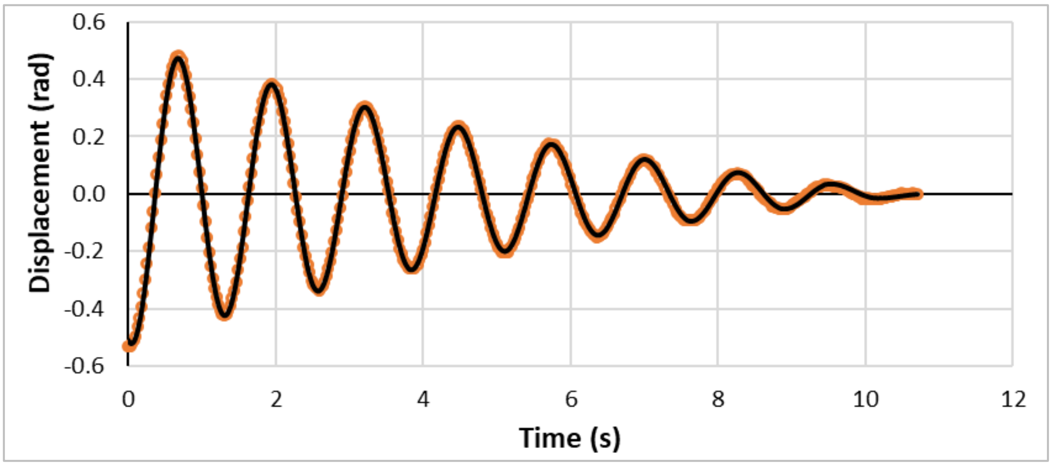


(a)

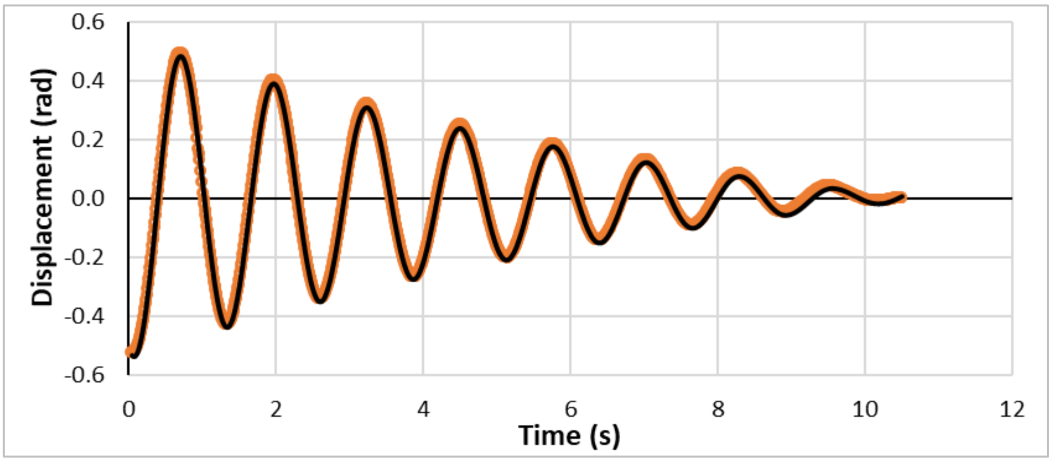


(b)

Figure 3. 13: Experiment 1 data, (a) sensor data and (b) video analysis data. Data (orange circle) and equation O.13 model (solid black line).

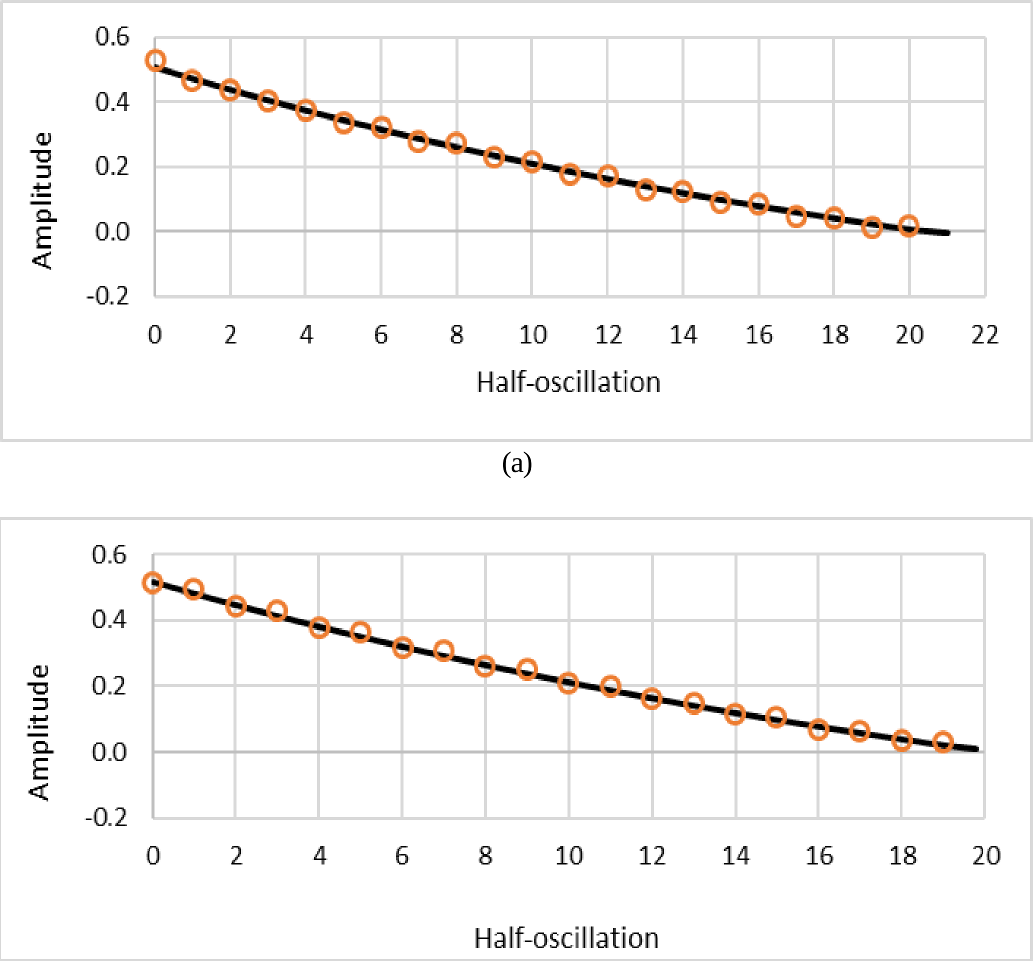


(a)



(b)

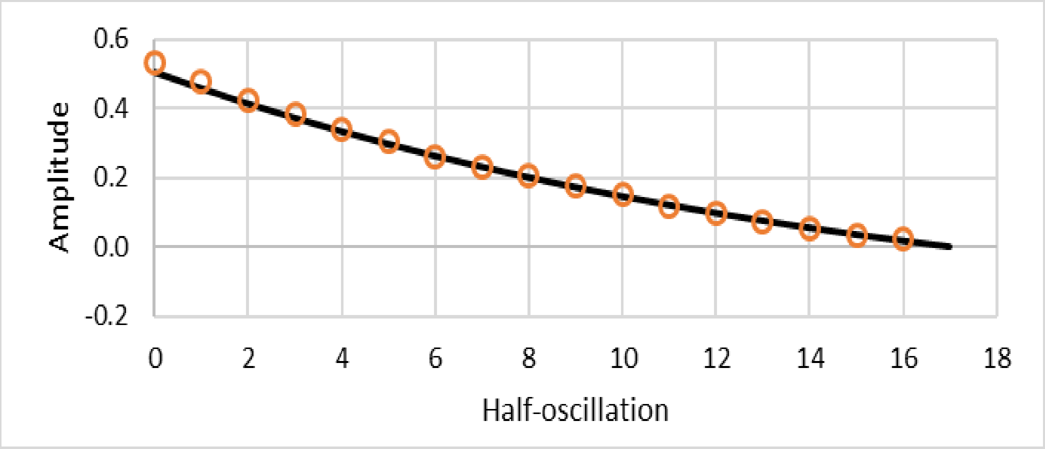
Figure 3. 14: Experiment 2 data, (a) sensor data and (b) video analysis data. Data (orange circle) and equation O.13 model (solid black line).



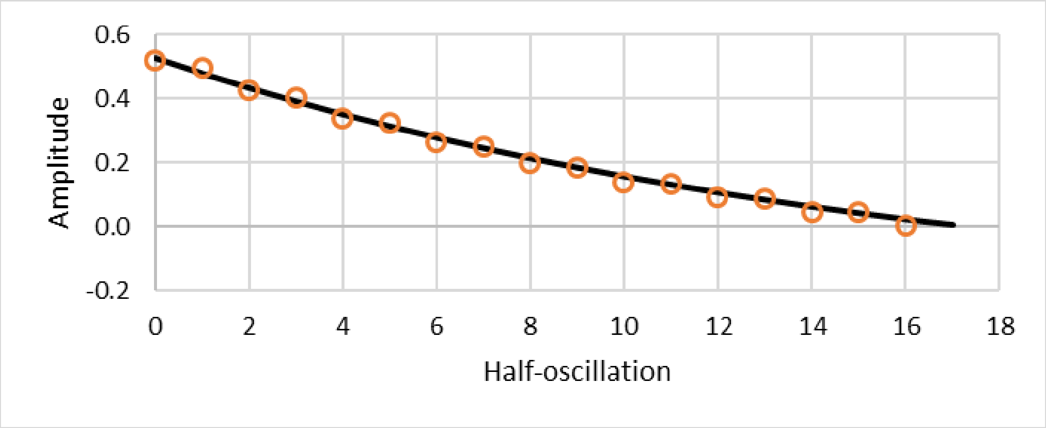
(a)

(b)

Figure 3. 15: Experiment 1 data, (a) sensor data and (b) video analysis data. Data (orange circle) and equation O.15 model (solid black line).

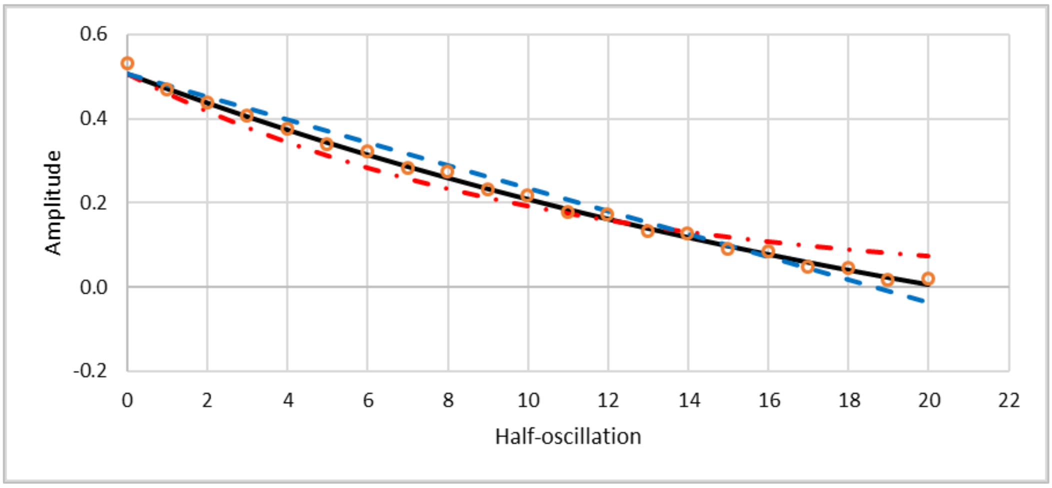


(a)

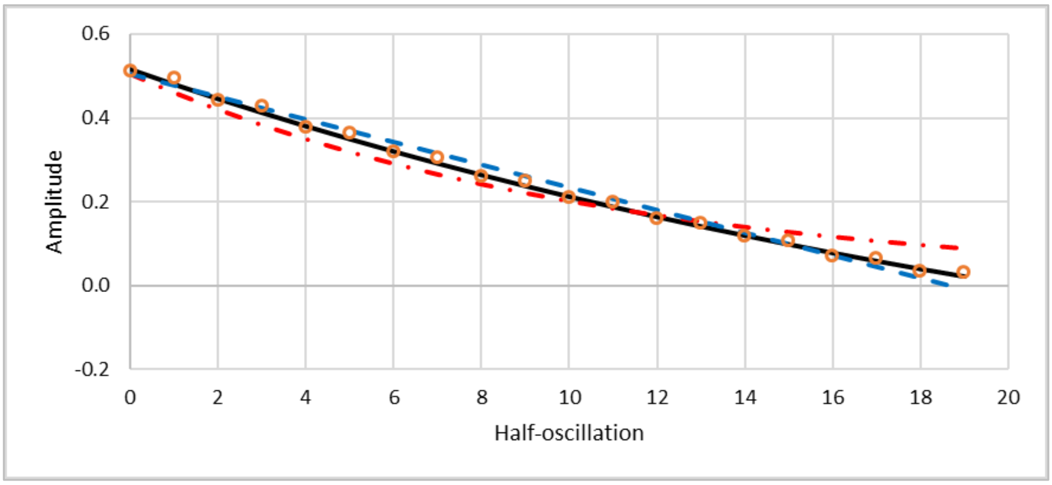


(b)

Figure 3. 16: Experiment 2 data, (a) sensor data and (b) video analysis data. Data (orange circle) and equation O.15 model (solid black line).

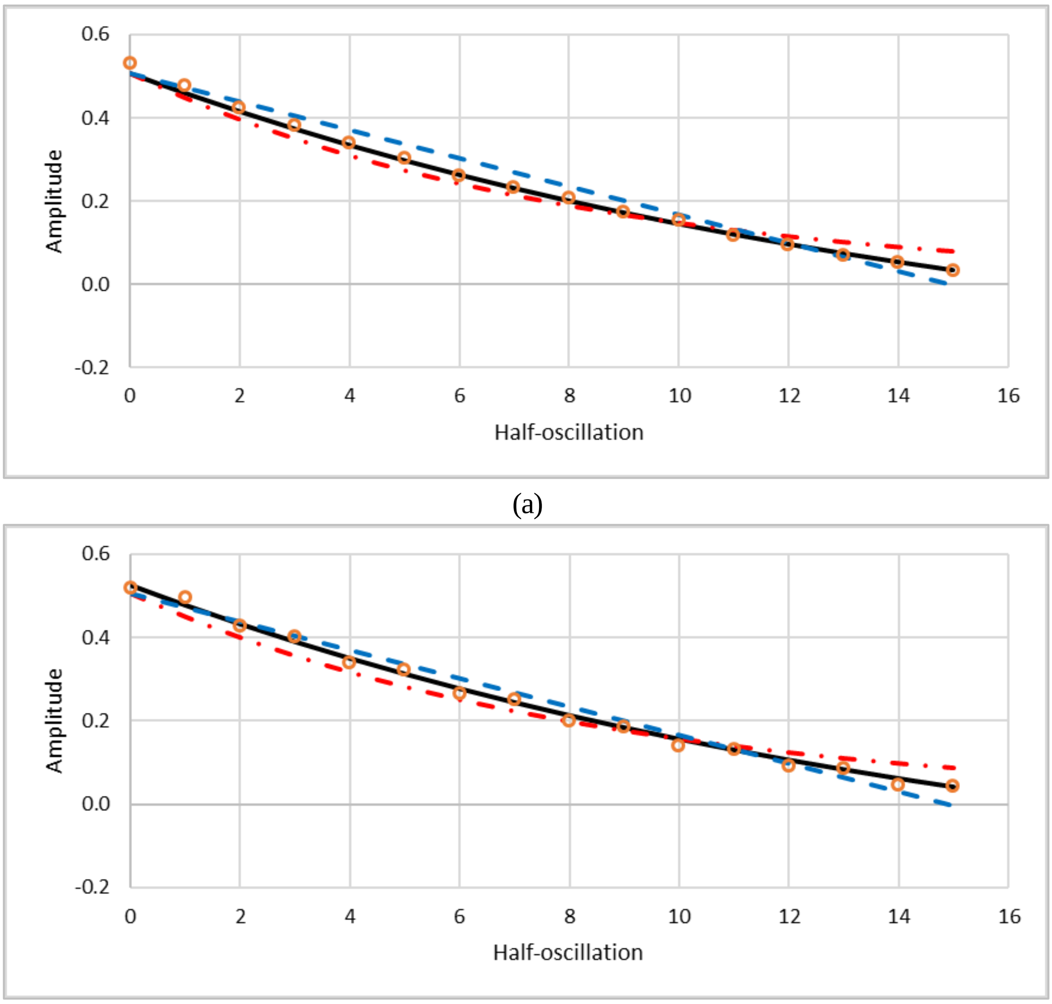


(a)



(b)

Figure 3. 17: Experiment 1 equation O.15 model comparison, (a) sensor data and (b) video analysis data. Data (orange circle), combination (solid black line), dry friction (blue dash line) and viscous (red dash-dot line).



(a)

(b)

Figure 3. 18: Experiment 2 equation O.15 model comparison, (a) sensor data and (b) video analysis data. Data (orange circle), combination (solid black line), dry friction (blue dash line) and viscous (red dash-dot line).

From the model fits, the dry friction damping parameters Δ estimated from the four datasets were also consistent as expected by the experiment design, with the values ranging from 8.27 to 8.60 (the percentage difference between the minimum and maximum values of about 4% or 0.13 standard deviation). This leads to obtaining frictional torque ranging from $(1.99 \pm 0.1) \times 10^{-3} N/s$ to $(2.08 \pm 0.2) \times 10^{-3} N/s$ (the percentage difference between the minimum and maximum values of about 4.5% or 0.035 standard deviation). The viscous damping factor γ, on the other hand, was varied by design; however, in each experiment, the results showed consistency between the sensor and video analysis, with a percentage difference of about 1.0% in both experiments. For the first experiment, the values were $(62.8 \pm 2) \times 10^{-3} / s$ and $(62.9 \pm 2) \times 10^{-3} / s$, leading to viscous coefficients b to be $(8.39 \pm 0.3) \times 10^{-3} Ns/m$ and $(8.47 \pm 0.3) \times 10^{-3} Ns/m$. For the second experiment,

γ was $(109 \pm 3) \times 10^{-3} / s$ and $(107 \pm 2) \times 10^{-3} / s$, leading to viscous coefficients b to be $(14.6 \pm 3) \times 10^{-3} Ns / m$ and $(14.4 \pm 3) \times 10^{-3} Ns / m$.

- **Analysis of amplitude decay**

Equation O.15 indicates the amplitude decay in the half oscillation n^{th} due to viscous and dry friction damping, which is $|\theta_n| = \theta_{n-1} e^{-\gamma T/2} - \Delta(1 + e^{-\gamma T/2})$.

In this analysis, first, $|\theta_n|$ are extracted from the angular displacement and treated as absolute values. Then equation O.15 is modelled and fitted to the extracted data. Figures 3.15a, 3.15b, 3.16a and 3.16b show the good fit of equation O.15 models to the extracted data with RMSE: 0.0074, 0.0088, 0.0069, 0.0111, respectively. From the model fit, dry friction parameters Δ are $(8.20 \pm 0.1) \times 10^{-3}$ and $(8.50 \pm 0.1) \times 10^{-3}$ for the first experiment and $(8.30 \pm 0.1) \times 10^{-3}$ and $(8.50 \pm 0.1) \times 10^{-3}$ for the second experiment, respectively, for sensor and video analysis data. These values are consistent with previous values obtained from fitting equation O.13 models, ranging from $(8.27 \pm 0.1) \times 10^{-3}$ to $(8.60 \pm 0.1) \times 10^{-3}$

Besides, viscous parameters γ are $(61.0 \pm 1) \times 10^{-3} / s$ and $(60.0 \pm 1) \times 10^{-3} / s$ for the first experiment and $(100.0 \pm 3) \times 10^{-3} / s$ and $(98.0 \pm 3) \times 10^{-3} / s$ for the second experiment, respectively, for sensor and video analysis data, compared with the previous results of $(62.8 \pm 2) \times 10^{-3} / s$ and $(62.9 \pm 2) \times 10^{-3} / s$ and $(109 \pm 3) \times 10^{-3} / s$ and $(107 \pm 2) \times 10^{-3} / s$. The percentage difference of the first experiment is about 4%, and 8% for the second experiment.

Equation O.15 is also handy to compare how well the viscous, dry friction and the combination of the two fitted to data. The equation represents the combined effect, but it is not a big deal setting $\gamma = 0$ remaining solely dry friction effect or $\Delta = 0$ remaining only viscous effect. For this analysis, two more models are added to the analysis, which are $|\theta_n| = \theta_o e^{-n\gamma T/2}$; $(\Delta = 0)$ and $|\theta_n| = \theta_o - 2n\Delta$; $(\gamma = 0)$, addressed in the theory section.

Figures 3.17 and 3.18 illustrate equation O.15 modelled due to the three cases fitted to the data. Neither viscous nor dry friction effects have a good fit. In addition, I observed that the values of the γ and Δ obtained from modelling based on a silo effect were about double compared values estimated by the combination effect model. This is evident in the fact the damping was caused by the combination effects. Mathematically, when one parameter was missing, another one remaining was loaded to get the best fit possible.

3.3.5. Conclusions

The experiments were simple and handy for controlling variables and parameters in pendulum damping. Either the video analysis technique or microcontroller angle sensor was appropriate to quantify pendulum motion, allowing precise measurement that leads to highly accurate and reliable results.

Viscous and dry friction damping in the pendulum occurs in a pair, except for the simple pendulum. Although it is small, or one dominant over the other, attempting to model using the silo effect usually gives a significant error, especially when trying to estimate those damping coefficients. Therefore equations O.9 and O.11 should not be used, namely when the two damping factors contribute to the damping, but use combined equation O.13 instead.

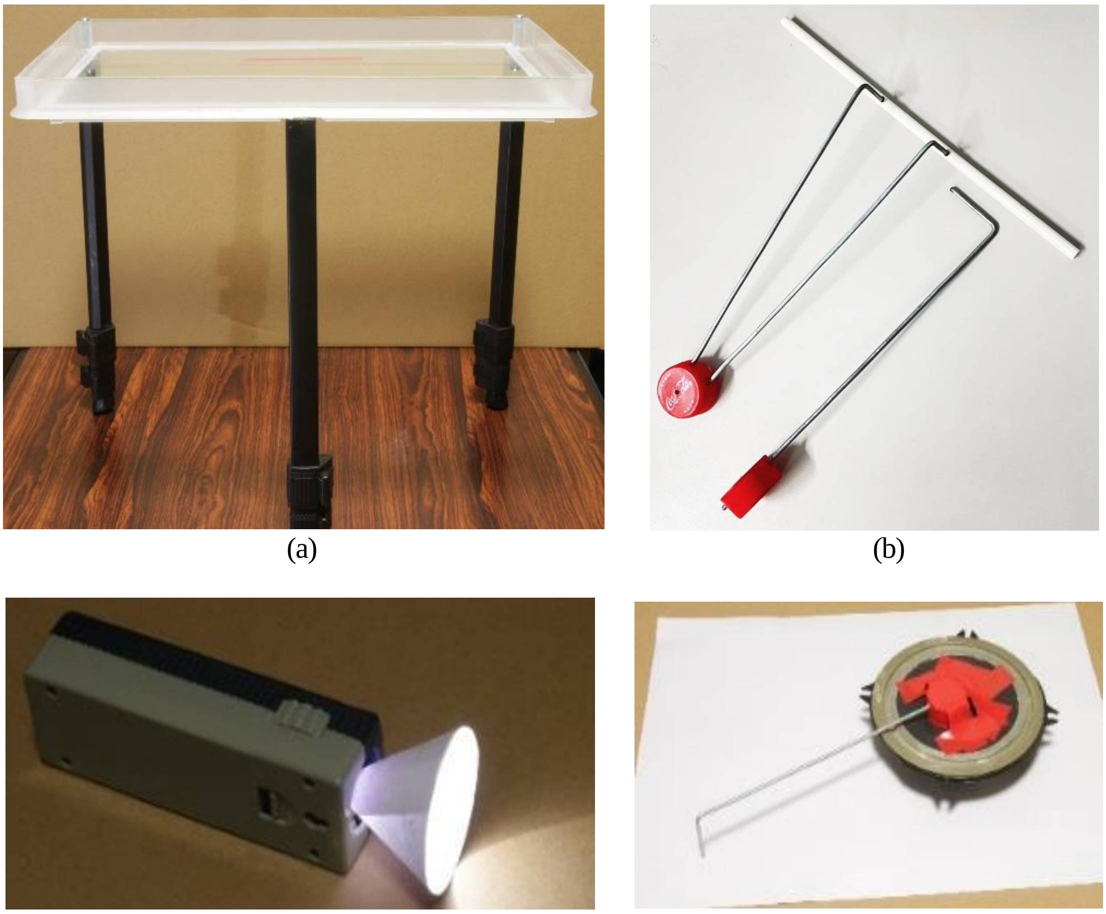
This study contributes to the use of technology in physics education, specifically in physics experiments. It is relevant for either high school physics or university introductory physics as the basis to advance study in the damped oscillation of the pendulum.

3.4. Teaching Material on Waves

3.4.1. Development of simplified ripple tank

A ripple tank is a shallow glass tank of water commonly used in physics to demonstrate the fundamental properties of waves. It is essentially a specialized wave tank that is typically illuminated from above. Some smaller ripple tanks are designed to fit onto the top of an overhead projector and are illuminated from below. When ripples are generated on the surface of the water, they are projected as shadows onto a screen underneath the tank. The basic principles of waves, such as reflection, refraction, interference, and diffraction, can all be demonstrated with a ripple tank.

A standard commercial ripple tank made in Japan can cost anywhere between 59,000 to 188,000 JPY (equivalent to 564 to 1798 USD or 408 to 1300 GBP) and does not include a signal generator. Therefore, I developed a simplified ripple tank that primarily uses household materials and costs only about 1,000 JPY (9.5 USD, 6.8 GBP). This alternative was much cheaper, more feasible and flexible for teachers to use in most countries (see Figure 3. 19).



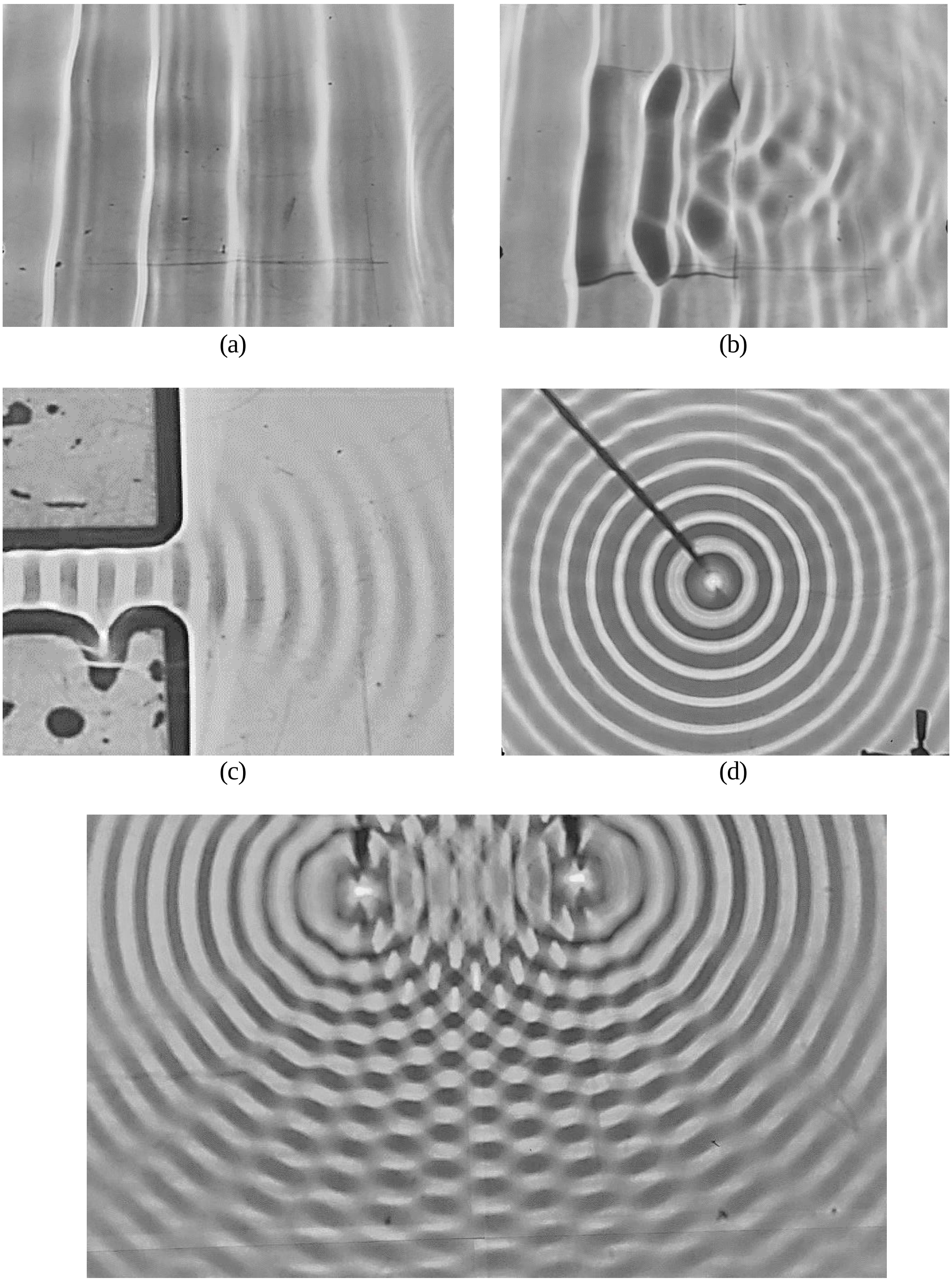
(a) (b)

(c) (d)

Figure 3. 19: Simplified ripple tank. (a) tank, (b) vibrator arms, (c) flashlight, and (d) vibrator and A3 paper screen.

- A plastic shoebox (400JPY, 3.8USD, or 2.8GBP) was used as the ripple tank, and its bottom part was replaced with transparent argillic material. The tank was supported by three legs utilized from a used tripod (500JPY, 4.8USD, or 3.5GBP) (Figure 3. 19a).
- A LED flashlight (100JPY, 0.96USD, or 0.69GBP) was employed as the light source. Its parabolic reflector was placed with a conical white paper attached to its front to get soft and uniform light (Figure 3. 19c).
- A white A3-paper was used as the screen (Figure 3. 19d).

An old speaker could be repurposed as a vibrator by attaching an L-shaped metal wire, called a "vibrator arm," to create waves while the vibrator is in operation Figure 3. 19c). A vibrator with one arm could create circular waves, while one with two arms could create interference waves. When attached to a plastic straw to the two arms, it could produce plane waves (Figure 3. 19b).


(a) (b)

(c) (d)

(e)

Figure 3. 20: Demonstration of wave phenomena using simplified ripple tank, (a) plane waves, (b) refraction, (c) diffraction, (d) circular waves, and (e) interference of two wave sources

To fully operate the ripple tank, several supporting apparatuses such as a signal generator, and a stand were necessary. Furthermore, the purpose of the study was to develop an experiment based on ICT, specifically a video-based experiment. Therefore, a digital camera or smartphone, as well as a document camera, were required to observe and record wave phenomena that were produced by the simplified ripple tank. The setup will be described comprehensively when conducting a specific experiment. Figure 3.20 displays some wave phenomena using the simplified ripple tank developed, (a) plane waves, (b) refraction, (c) diffraction, (d) circular waves, and (e) interference of two wave sources.

3.4.2. Teaching material for the Doppler effect

3.4.2.1. Introduction

The basic concepts of mechanical wave phenomena are the crucial foundation for understanding advanced physics topics (Fazio, Guastella, Sperandeo-Mineo, & Tarantino, 2008; Kryjevskaia, Stetzer, & Heron, 2011; Wittmann, Steinberg, & Redish, 1999). The Doppler effect, a mechanical wave phenomenon, has been significantly applied in everyday life phenomena and advanced fields such as astronomy, spectroscopy, meteorology, and health science (Coman, 2005; Fazio et al., 2008; Wittmann et al., 1999). In everyday life, people can simply experience the Doppler effect while an ambulance is coming and leaving them. In astronomy, for example, Edwin Hubble discovered an important scientific finding due to his comprehension of the Doppler effect. In 1929, he observed that Nebulae emitted severely Doppler shift wavelength known as the “redshift” while it was a normal emission; Edwin Hubble understood that was because Nebulae was moving away and so reached his that the universe was expanding (Sterm, 2016).

How does the Doppler effect occur?

Figure 3.21 depicts how the Doppler effect occurs. S is a wave source, and O_A and O_B are observers. A circle represents the crest of waves. When the source is stationary, the observers observe the same wavelength (see Figure 3.21a). While moving toward an observer, each observer observes a different wavelength (see Figure 3.21b). The effect occurs because of the relative speed between the observers and the source. The relative velocity increases while moving closer to each other, leading to the experience of a decreased wavelength. Reversely the relative velocity decreases while moving further from each other, leading to the experience of an increased wavelength.

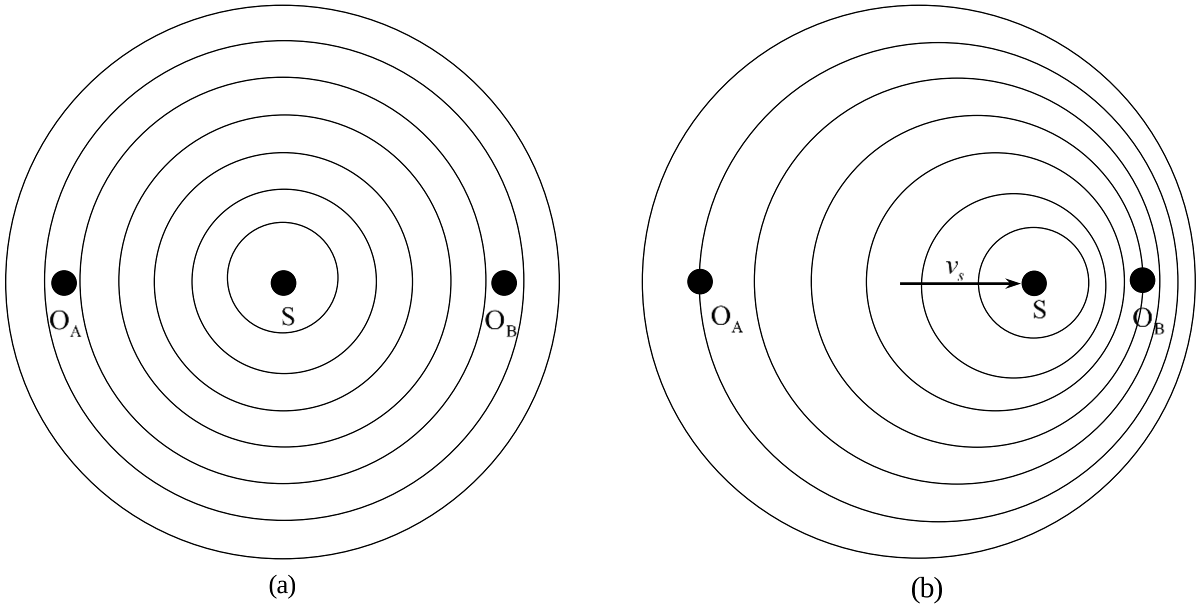


Figure 3. 21: Illustration of the Doppler effect (a) When the system is stationary, there is no effect. (b) the Doppler effect occurs when the source moves relative to the observers.

3.4.2.2. Rationale

In high school physics, the Doppler effect is generally introduced as a sound wave phenomenon. The phenomenon is invisible to the naked eye. It would be difficult for students to understand (Fazio et al., 2008; Wittmann et al., 1999).

The experiment plays a central role in physics education that contributes to a deeper understanding of the physics concept (Koponen & Mäntylä, 2006). Silverman (1995) addressed that the experiment allows students to witness basic phenomena, introduces students to practice apparatus and measurement techniques, and gives students a flavour of science research. Thus, the Doppler effect should be taught and learned experimentally in order to make students understand not only conceptually but also visually and quantitatively. A phenomenon visualisation can orientate a scientific phenomenon that catches the students' interest and curiosity (Bell, Urhahne, Schanze, & Ploetzner, 2010). Additionally, science lessons should help students develop skills, especially science process skills, and practice them appropriately through the scientific method to master those skills or learn new ones (Michael, 2018).

A significant number of empirical studies on how to teach and learn the Doppler effect use conceptual explanation or explanation of mathematical modelling (Dibble, 2000; Fox, 1944; Heaps, 1941; Rojas & Fuster, 2007; Slusarenko & Worner, 1989). And even though some studies use phenomenon visualisation (Chakarvarti, 1981; Fernando, 1975; Klein & Nagel, 1980; Weltin, 1961; Zeleny, 1942), very few studies employ quantification (D'Anna & Corridoni, 2016; Saba & Rosa, 2001; Serra, 1997).

In 1975, Fernando (1975) proposed a procedure to demonstrate the Doppler effect in a ripple tank whereby a 100-ml burette is attached at the top of a pole firmly mounted on a movable carriage with a stopcock adjusted to give a steady flow of discrete droplets to the water in a ripple tank beneath. When the carriage is pushed slowly by hand, the Doppler effect on the water surface can be shown. Following Fernando's (1975) procedure, Klein and Nagel (1980) successfully depicted the Doppler effect phenomenon in a ripple tank. However, not satisfied with the fact that the visualisation was too short, they employed a different method by using a loudspeaker as a wave generator and a circular Lucite disk as a ripple tank. The Doppler effect could be continuously observed while turning the disk at 6-20rpm.

Rather than visualisation, Serra (1997), as mentioned in D'Anna and Corridoni (2016), proposed an experimental procedure to quantify the Doppler effect directly using a photodiode as a receiver to detect light strips travelling across the ripple tank screen to establish the Doppler effect experiment. The procedure, however, was slightly complicated and outdated. Then, D'Anna and Corridoni (2016) adapted the experiment procedure proposed by, Serra (1997) but used modern materials to quantify the Doppler effect in a ripple tank instead. Their investigation was that the source was stationary while the receiver, the light sensor, was moving. They collected data via the light sensor connected to an oscilloscope. Then, shift wavelength, shift frequency, and velocity of the source were measured and calculated.

It is clear from the discussion of the existing literature above that most studies that experiment with the Doppler effect tend to separate visualisation from quantification. The current study presents an experimentation method that both visualises and quantifies the Doppler effect, using digital technology.

Two stages of the experiment process were carried out. Firstly, a simplified ripple tank was set up and used to depict the Doppler effect, with the whole experiment recorded by a digital camera. The procedure was adapted from Fernando (1975) and Klein and Nagel (1980). Secondly, video analyses of the recorded experiment were conducted to quantify the Doppler effect. It should be noted that over the last two decades, many studies have investigated and suggested video analysis-based experiments as a new approach to teaching and learning physics (Brown, 2005; Brown & Cox, 2009; Brown et al., 2020; Bryan, 2010; Laws & Pfister, 1998; Wee, Chew, Goh, Tan, & Lee, 2012; Wee & Leong, 2015). Using either free or commercial software costs much less expensive compared to the sophisticated laboratory. The experimental procedure and findings were easy and impressively accurate. The current study used Tracker (Brown et al., 2020).

3.4.2.3. Experimental apparatuses and setup

The experiment was carried out using the developed simplified ripple tank. Figure 3.22 illustrates the experimental setup. Because the brightness of the LED flashlight was low, the experiments were carried out in low-light conditions; It had an advantage in increasing contrast on video. The tank was filled with 5-7mm depth of water; set the flashlight about 30-40cm above and from the centre of the tank surface; and lay the A3 paper on the floor beneath the tank facing the flashlight. The camera was situated right above the A3 paper on one side of the tank. On the bottom of the tank, 5-10cm tape was employed as a scale when analysing the video. The vibrator was placed on a movable cart right below the light source located on the other side of the tank opposite the camera, and the ripple tank was adjusted to make the vibrator arm touch the water surface.

Figure 3. 22: The Doppler effect's experimental setup

To create ripples, the vibrator was connected to a signal generator. When pushing softly to make the cart move at a constant velocity the Doppler effect occurred.

3.4.2.4. Recording and analysing video

A high-contrast video enhanced visualisation and analysis. Thus, the camera was manually controlled, mainly altering focus and shutter speed. The higher shutter speed boosted a clearer crest and trough image of the ripples. The shutter speed was set to the highest as possible with an exposure range between -2 to -1. The video frame rate, in addition, was set at the same as the signal generator frequency, which is 60fps (frames per second). Furthermore, the videos were recorded in monochrome mode, black and white, to receive less noise background and produce a pleasant look video.

The videos were recorded immediately after starting the experiment. To check the reliability of the experiment results, two videos were recorded and analysed. A video was recorded by a smartphone, Sony Xperia SOV38, and the other one by a DSLR, Canon 70D, hereafter written Xperia and 70D, respectively.

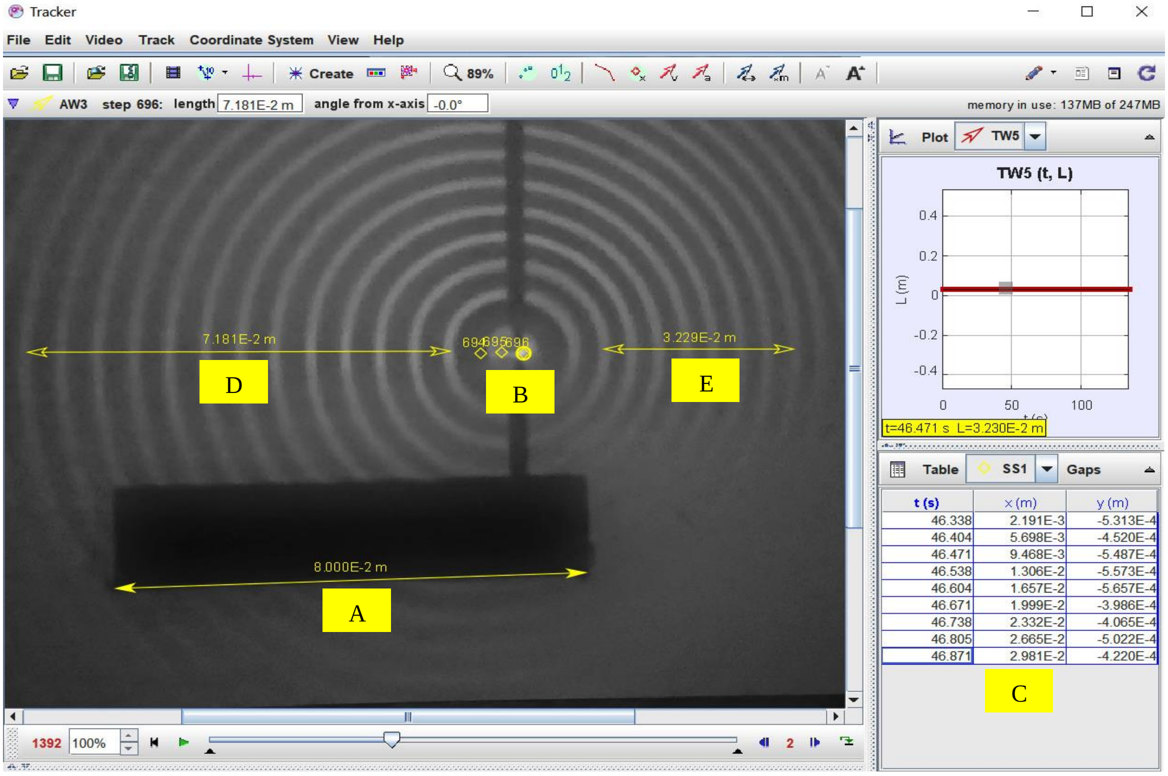
The videos contained three scenes, the no-wave, the stationary-source, and the moving-source. The no-wave (5-10s) was for calibrating the measurement tools such as a meter stick or tape meter on Tracker; the stationary source (10-the 20s) was to measure the initial frequency of the stationary source before the effect, and the moving source (20-30s) was for the measurement of the Doppler shift frequency.

The video analysis consists of four steps. The first step was scaling. Like other measurements, the calibration had to be done properly before measuring. The ripples on the videos ware magnified, and the calibration was made with a sticker shadow (8.0cm in reality) to scale for the whole measurement during the video analysis. To ensure the accuracy of the calibration, it was made in the no-wave scene because, in the other two scenes, the sticker shadow was broken by the water ripples.

The second step was measuring the wavelength of the source while stationary to estimate its initial frequency. This step was done on the stationary-source scene of the video. There ware a few length measurement tools on Tracker, and the tape measure tool was chosen as the measurement tool. A single measure was made by trying to measure as many ripples as possible. The same way was done five times on the separate video frames (see the data in Table 3.6).

The third step was the estimation of the moving velocity of the source. This step was done in the last scene, the moving source. To estimate the velocity, the point mass tool was used to track the source movement on video. From the point mass tracking, the displacement versus time data ware obtained (Table 3.12).

The fourth step was intended to measure the Doppler shift frequency. The procedure was the same as the second step. The measurement was to be done on the frames in the third scene where the source was tracked. In the case the source moves toward the receiver, ripples ahead ware measured (Figure 3.23-E) and moving away from the receiver, the ripples behind ware measured (Figure 3.23-D). The data were recorded in Tables 3.7 and 3.8, respectively.



step 696: length 7.181E-2 m angle from x-axis -0.0°

memory in use: 137MB of 247MB

t=46.471 s L=3.230E-2 m

t (s)	x (m)	y (m)
46.338	2.191E-3	-5.313E-4
46.404	5.698E-3	-4.520E-4
46.471	9.468E-3	-5.487E-4
46.538	1.306E-2	-5.573E-4
46.604	1.657E-2	-5.657E-4
46.671	1.999E-2	-3.986E-4
46.738	2.332E-2	-4.065E-4
46.805	2.665E-2	-5.022E-4
46.871	2.981E-2	-4.220E-4

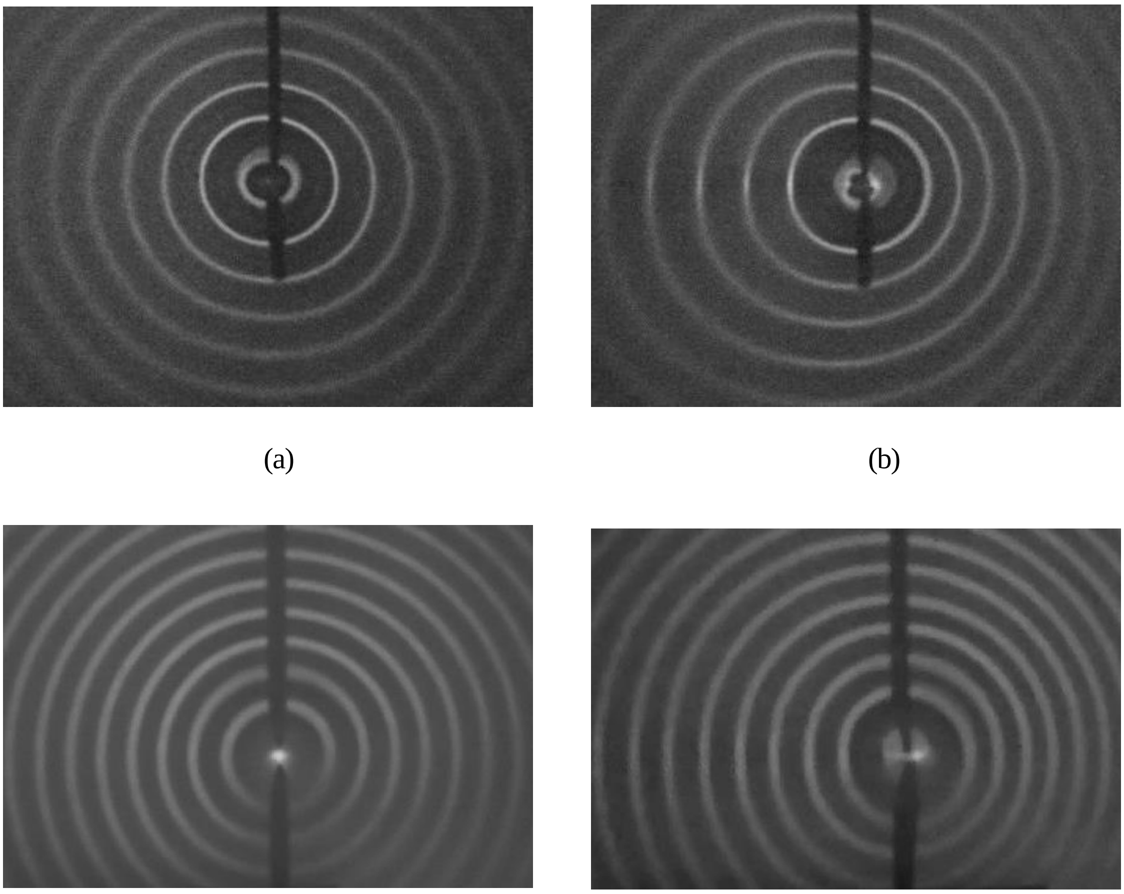
Figure 3. 23: A screenshot of Tracker while collecting experimental data from a video recorded by Xperia. A: scaling measurement to the reality, B: point mass tracking position of the source movement, C: data record table of point mass, D: measuring decompressed wavelengths, E: measuring compressed wavelengths.

Figure 3.23 shows the four steps of the video analysis. Figure 3.23-A illustrates calibrating the distance as long as the black bar in the video to 8.00cm. It has been done since the first scene of the video. The black bar is the shadow of the plastic tape. Figures 3.23-B, 3.23-D and 3.23-E are in the third scene of the video. Figure

3.23-B, the small yellow diamonds show the tracked positions of the source moving along the video frames. Figure 3.23-C, the data of displacement versus time tracked by the point mass tool on Tracker.

3.4.2.5. Results

The visualisation of the Doppler effect phenomenon was shown clearly (see Figure 3.24). Figures 3.24a and 3.24c indicate waves while the sources are stationary, whereas 3.24b and 3.24d indicate the Doppler shift waves while the sources are moving. As described in textbook content, on the right part of Figure 3.24b and 3.24d, the ripples were compressed, which indicated the source was moving toward the receiver. On the left part, the waves were decompressed, which showed that the source was moving away from the receiver.



(a) (b)

(c) (d)

Figure 3. 24: Illustration of the waves in the ripple tank before and after the source moves. (a) and (b) recorded by DSLR, (c) and (d) recorded by smartphone.

Table 3. 6: Experiment data: Measuring initial wavelengths of the source

Xperia			70D		
Number of Waves	Length (±0.01 cm)	Wavelength (±0.002 cm)	Number of Waves	Length (±0.01 cm)	Wavelength (±0.001 cm)
6	3.13	0.521	8	4.09	0.512
6	3.15	0.525	8	4.05	0.506
6	3.17	0.528	8	4.13	0.516
7	3.67	0.523	7	3.71	0.529
5	2.64	0.528	6	3.11	0.519

Table 3. 7: Experiment data: Measuring shift wavelengths toward the receiver

Xperia			70D		
Number of Waves	Length (±0.01 cm)	Wavelength (±0.001 cm)	Number of Waves	Length (±0.01 cm)	Wavelength (±0.001 cm)
8	3.73	0.466	7	3.07	0.439
8	3.73	0.466	6	2.64	0.441
7	3.23^{**}	0.461^{**}	7	3.06	0.437
8	3.71	0.464	6	2.60	0.433
7	3.23	0.461	5639	3.06	0.437

Table 3. 8: Experiment data: Measuring shift wavelength away from the receiver

Xperia			70D		
Number of Waves	Length (±0.01 cm)	Wavelength (±0.001 cm)	Number of Waves	Length (±0.01 cm)	Wavelength (±0.001 cm)
7	4.12	0.600	8	4.39	0.549
7	4.20	0.600	7	3.87	0.553
12	7.18^{*}	0.598^{*}	8	4.51	0.564
7	4.16	0.594	6	3.35	0.558
9	5.38	0.597	8	4.56	0.570

Table 3. 9: Wavelengths obtained from the experiment

	Wavelength (cm)	
	Xperia	70D
Stationary source	$0.525 \pm 0.008^{***}$	0.516 ± 0.003
Doppler shifts toward a receiver	0.464 ± 0.007	0.437 ± 0.004
Doppler shifts away from a receiver	0.598 ± 0.006	0.559 ± 0.003

Table 3. 10: Velocities obtained from the experimental

	Velocity (cm s^{-1})	
	Xperia	70D
Stationary source	$30.9 \pm 0.2^{***}$	31.1 ± 0.01
Doppler shifts toward a receiver	32.6 ± 0.2	33.4 ± 0.01
Doppler shifts away from a receiver	29.3 ± 0.2	30.1 ± 0.01

Table 3. 11: Initial and shift frequencies derived from the experiments.

	Frequency (Hz)	
	Xperia	70D
Stationary source	$58.9 \pm 1.3^{***}$	60.3 ± 0.8
Doppler shifts toward a receiver	70.1 ± 1.7	76.4 ± 1.1
Doppler shifts away from a receiver	49.0 ± 1.0	53.9 ± 0.7

Tables 3.6, 3.7, and 3.8 record the experimental data obtained from the measurement on the second and fourth steps. The wavelengths in the three tables were obtained from the length divided by the number of waves. The mean of the five values in each table was the wavelength of each case. The results are summarized in Table 3.9.

In Figure 3.23-D, for example, a tape measure tool reads $(7.18 \pm 0.01)\text{cm}$[2] (Table 3.8) of 13 crests, equal to 12 waves. So, $(7.18 \pm 0.01)\text{cm}$ divided by 12 equals $(0.598 \pm 0.001)\text{cm}^{*}$, which was a single measurement of

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(* ** ***) The asterisk in the text guide readers to the corresponding quantities used to calculate as examples.

a wavelength. This is an example of a single measure of the decompressed wavelength due to the Doppler effect while the source was moving away.

Figure 3.23-E is an example of the compressed wavelength. A tape measure tool read $(3.23 \pm 0.01)\text{cm}$ ** (Table 3.7) of 8 crests, equal to 7 waves. So, it was $(0.461 \pm 0.001)\text{cm}$ **.

When the wavelengths were identified, the propagation velocities of the three conditions were calculated by employing the Kevin law for water surface waves (Clark, 1959; Serra, 1997). The propagation velocity of a capillarity ripple *v* can be derived by:

$$v = \sqrt{\left(\frac{g}{k} + A\frac{k}{\rho}\right)\tan(k\,h)} \tag{D.1}$$

where $g = 9.81\text{m}\,\text{s}^{-2}$ is the gravitational acceleration, $k = \frac{2\pi}{\lambda}$ is the wave number ($\text{rad}\,\text{m}^{-1}$), *A* is the surface tension ($\text{N}\,\text{m}^{-1}$), ρ is the water density $\text{kg}\,\text{m}^{-3}$, and *h* is the depth of water (m).

The experiment was conducted at room temperature of 20°C; the surface tension of water was $A = (72.8 \pm 0.4)10^{-3}\ \text{N}\,\text{m}^{-1}$ (Vargaftik, Volkov, & Voljak, 1983), the water density of $(998.21 \pm 0.83)\text{kg}\,\text{m}^{-3}$ (Tanaka, Girard, Davis, Peuto, & Bignell, 2001), the depth of water $h = (0.6 \pm 0.1)\text{cm}$, and a wavelength $\lambda = (0.525 \pm 0.008)\text{cm}$ *** from Table 3.9, for example, the propagation velocity *v* was $(30.9 \pm 0.2)\text{cm}\,\text{s}^{-1}$ ***. The same method was applied, the other velocities were obtained and recorded in Table 3.10.

The frequency *f* of the propagation wave:

$$f = \frac{v}{\lambda} \tag{D.2}$$

where *v* is the propagation velocity ($\text{m}\,\text{s}^{-1}$), and λ is the wavelength (m).

Using data in Tables 3.9 and 3.10, for example, the velocity of $(30.9 \pm 0.2)\text{cm}\,\text{s}^{-1}$ *** divided by the corresponding wavelength of $(0.525 \pm 0.008)\text{cm}$ *** in the previous section, giving the frequency of $(58.9 \pm 1.3)\text{Hz}$ ***. All frequencies were determined and recorded in Table 3.11.

To this point, the Doppler shift frequency was obtained from the experiment data. It is essential to confirm the experimental results with the values predicted by the theoretical formula.

When a source is moving toward a stationary receiver, the Doppler shift frequency f_1' is derived by:

$$f_1' = f\frac{v}{v - v_s} \tag{D.3}$$

When a source is moving away from a stationary receiver, the Doppler shift frequency f_2' is derived by:

$$f_2' = f\frac{v}{v + v_s} \tag{D.4}$$

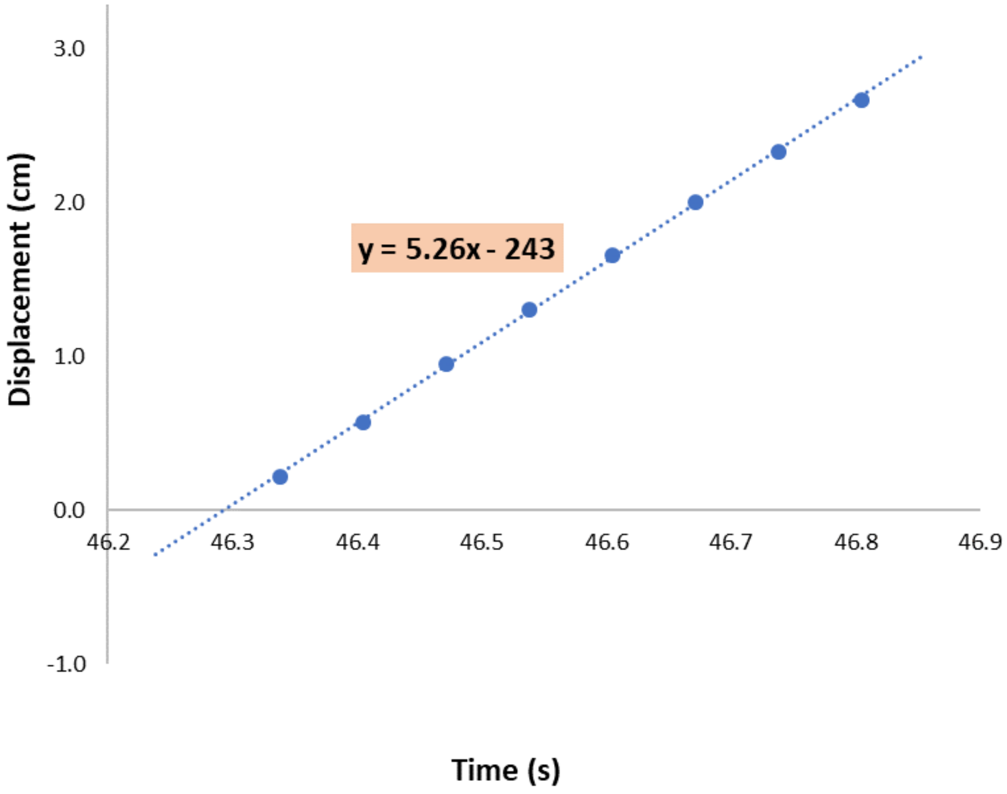
where *f* is the frequency of the source, *v* is the propagation velocity and v_s is the moving velocity of the source.

According to equations D.3 and D.4, to calculate the Doppler shift frequency, wave velocity, source velocity and initial frequency had to be known. In previous sections, wave velocities (Table 3.10) and initial frequencies (Table 3.11) have already been determined, but not yet source velocity. At this point, data in Table 3.12 was used.

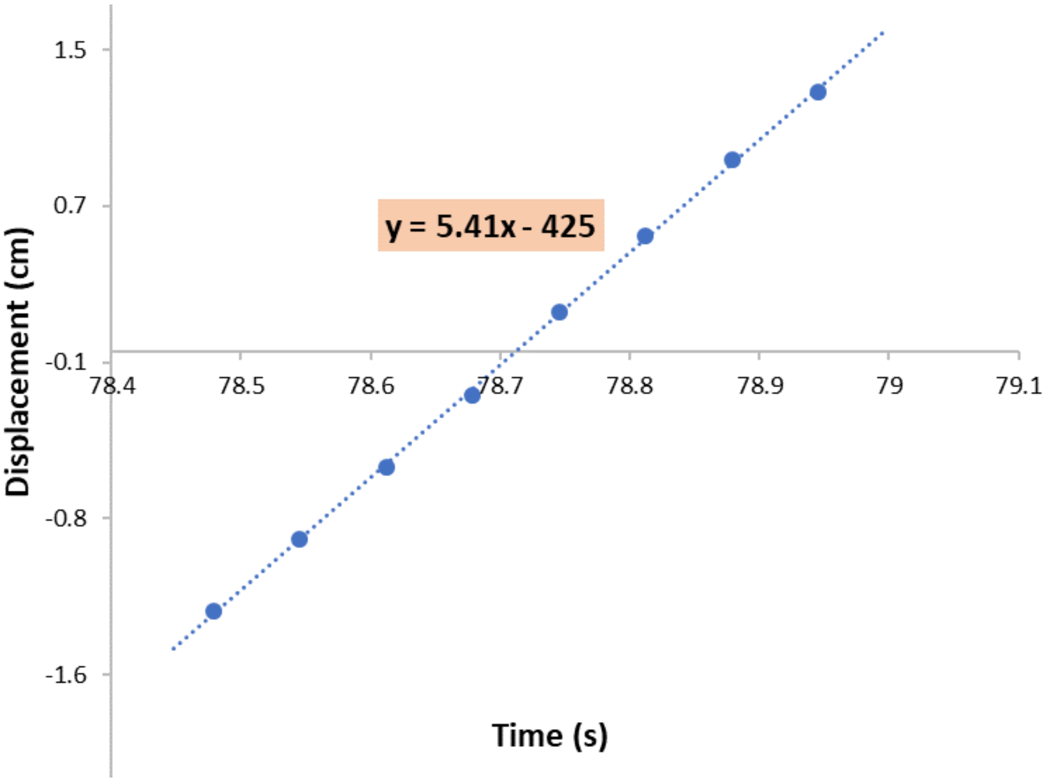
The Doppler effect occurs when a source and a receiver displace relative to each other at a constant velocity. To check that, scatter plots were constructed using data from Table 3.12 as illustrated in Figure 3.25. Figure 3.25 indicates the linear relationships between displacement and time, meaning that the source was moving at a constant velocity. Thus, the slope of the line graph was the velocity. In this case, $(5.26 \pm 0.08)\text{cm}\,\text{s}^{-1}$ and $(5.41 \pm 0.05)\text{cm}\,\text{s}^{-1}$, Xperia and 70D respectively. At this point, the predicted frequency of the Doppler shift was found. As an example, for Xperia data, initial frequency $f = (58.8 \pm 1.3)\text{Hz}$, propagation velocity

Table 3. 12: Displacement versus time

Xperia		**70D**	
Time (±0.02 s)	Displacement (±0.008 cm)	Time (±0.02 s)	Displacement (±0.008 cm)
46.34	0.219	78.48	-1.25
46.40	0.570	78.55	-0.899
46.47	0.947	78.61	-0.552
46.54	1.31	78.68	-0.205
46.60	1.66	78.75	0.193
46.67	2.00	78.81	0.557
46.74	2.33	78.88	0.921
46.80	2.67	78.95	1.25



(a)



(b)

Figure 3. 25: Displacement versus time graph, (a) Xperia and (b) 70D

$v = (30.9 \pm 0.2)\mathrm{cm\,s^{-1}}$, and source velocity $v_s = (5.26 \pm 0.08)\mathrm{cm\,s^{-1}}$; applying equation D.3, the shift frequency toward the receiver is $f_1' = (71.0 \pm 3.4)\mathrm{Hz}$, and applying equation D.4, the shift frequency away from the receiver was $f_2' = (50.3 \pm 2.4)\mathrm{Hz}$. The same rule was applied for 70D data; the results were summarized in Table 3.13.

Table 3. 13: Comparison of frequencies obtained by the experiment and predicted by the theoretical formula

		Frequency (Hz)		Error
		Experiment	Theory	
Xperia	Shift toward	70.2 ± 1.7	71.0 ± 3.4	1.05%
	Shift away	49.0 ± 1.0	50.3 ± 2.4	2.53%
70D	Shift toward	76.4 ± 1.1	73.0 ± 1.6	4.71%
	Shift away	53.9 ± 0.7	51.4 ± 1.1	4.97%

3.4.2.6. Discussions

Visual demonstration orientates a scientific phenomenon that catches the students' interest and curiosity (Bell et al., 2010) and significantly boosts students' understanding of scientific concepts compared to traditional lecture (Maričić, Cvjetićanin, & Anđić, 2019; McKee, Williamson, & Ruebush, 2007). Empirically, previous studies on the Doppler effect supporting teaching and learning prioritise essentially the visual demonstration (Chakarvarti, 1981; Fernando, 1975; Klein & Nagel, 1980; Weltin, 1961; Zeleny, 1942), but those studies mainly focus on proposing procedures, which are sometime complicated and outdated, and whose results were not clearly illustrated. The current study extended the literature by proving the Doppler effect, using a set of simple and inexpensive (but powerful) tools (such as a self-made ripple tank, a digital camera, a smart phone, and others) and a two-stage procedure to both visualize and quantify the effect. The resultant output of the experimentation could show clearly and count accurately the Doppler effect phenomenon.

The current study validated an experiment method to visualise and quantify the Doppler effect. The apparatuses were cheap, easy to find and simple to use. The results of the experimentation were highly accurate and consistent. According to the results summarized in Table 3.13, the Doppler shift frequency obtained by the experimental measurement matched the theoretically predicted values with an error of less than five per cent.

On the other hand, the signal generator frequency was (60.0 ± 0.1)Hz, and the initial source frequencies measured by the experiments were $(58.9 \pm 1.3)\text{Hz}$, using Xperia and $(60.3 \pm 0.8)\text{Hz}$, using 70D. These numbers resembled each other with errors of less than two per cent, 1.86% and 0.47% for Xperia and 70D, respectively compared to the signal generator value.

Overall, results from this study constitute various positive implications on teaching and learning the Doppler effect phenomenon.

First, the data collection and analysis in this study rely on video analyses of the experimentation videos recorded by a smartphone and a DSLR. There was no significant difference in the measurement $t(28) = 1.235,\ p = 0.227$ between the videos recorded by both devices. The result implied that experimenting with the Doppler effect was no longer an expensive undertaking for teachers. It should be noted from this study that a smartphone tends to be more convenient, cheaper, and more user-friendly, and each teacher may own one. A smartphone could easily record a brighter video in low light conditions than a DSLR does; however, a DSLR produced better contract depth between crest and trough, yet it might be somewhat complicated for school teachers to use a DSLR without enough experience, and they might not own one. The video analysis software, Tracker, was also free of charge and easy to install and use on one's own, with its Help option and/or YouTube tutorial videos available.

This paper, however, reported only the results of the videos of 60Hz recorded at 60fps. I tried with the frequency ranging from 30Hz to 60Hz recorded at different video frame rates (i.e. 24-60fps) using both devices. The results fell within the errors of less than 5.0%. Systematic and random errors might account for the error of the results. Generally, the random error was due to spotting pixels on the video file while measuring. The calibration and the skewness of the image on the video frame due to the camera position and angle were causes of the systematic error. Thus, it was recommended that teachers should be more careful with this issue.

What was more, the study used primarily household materials, which was much cheaper than a standard commercial ripple tank. Besides, I used a professional laboratory signal generator intending to compare the frequency obtained from the experiment and the signal generator to see the efficiency of my simplified apparatuses and data collection tool and method. As expected, the results confirmed that they worked together very well. In this sense, the whole experiment package was very cost-effective for teaching and learning physics in general and even more for low-budget schools.

In terms of electricity need, among the apparatuses used for my experiment, only a signal generator was operated by household electrical power; the others used battery power. If the signal generator was replaced with a signal generator app on the smartphone or the vibrator with a DC motor removed from a toy car or an unused CD ROM drive, the whole package becomes battery-powered, needing neither a signal generator nor household electric power. In this regard, it may be appropriate for rural schools in developing countries that may lack the laboratory materials and the household electrical power supply.

In the context of distant learning, especially during the pandemic period, it would be challenging for teachers to teach and students to learn the Doppler effect comprehensively. So, my experimentation reported in this paper would be a preferable choice. Though learning from a distance, students still have the chance to learn experimentally and actively.

3.4.2.7. Conclusions

The study introduced an experimental approach for teaching and learning the Doppler effect, using the simplified ripple tank as a tool to visually and quantitatively illustrate the existence of the effect. The Doppler effect could be observed clearly on video recorded by either a smartphone or a DSLR. Then, a video analysis technique was presented to allow learners to acquire and analyse data directly from what they observed on video. There was no significant difference in the measurement between videos recorded by both devices. The results were highly accurate; the experimental measurements agreed with the theoretically predicted values.

Since previous studies focused on solely visualisation or quantification, this study may serve as a comprehensive method for teaching and learning the Doppler effect using experimentation. The uses of experimentation may not only enhance student understanding in general but also promote the scientific approach to teaching and learning physics. Also, such an experimentation-based method of teaching and learning fits well into the current context of the digital generation of students and technology-influenced education. Science teaching without real experimentation may be boring and ineffective, so by combining them with technology, the science lessons may be more appealing.

For further studies, three aspects are suggested for consideration: (1) using a vibrator system that may use a generator application or a battery-powered one, (2) using video analysis applications that run on a smartphone or a tablet, rather than on a desktop or a laptop, and (3) using a technique to experiment at very lower, 1-30Hz or a higher frequency, 90Hz or above.

3.4.3. Teaching Materials for Interference

3.4.3.1. Introduction

The world we are living in is full of waves. Applications of waves are essential to our lives, especially in these last two centuries. Wave applications account for everyday household items (such as microwave ovens), to outer space investigation (such as the Hubble telescope).

Unlike solid objects, waves transfer energy without transferring mass, and two or more waves can occupy one location in space at the same time and interact with each other. When two identical waves, called coherent waves, in phase interact with one another, this builds one giant wave. This is known as constructive interference, whereas out-of-phase waves cancel each other, known as destructive interference. In both cases, which is the two waves superpose each other, and mathematically, the resultant wave is the sum of them.

There are two main types of waves, mechanical waves and electromagnetic waves. Being waves, both have common properties and characteristics such as wavelength, period, propagation, reflection, refraction, diffraction, interference and so on. Electromagnetic wave has many more significant applications within modern technology. In wave physics, the study of the electromagnetic wave has dominated. Regarding interference, the wave model of light has dominated research. These results can be seen by searching via a search engine such as google scholar.

The interference model of waves is a piece of fundamental knowledge for advanced physics, in the areas of quantum mechanics and solid-state physics (Ambrose, Shaffer, Steinberg, & McDermott, 1999; Coetzee & Imenda, 2012; Sobel, 2002; Vokos, Shaffer, Ambrose, & McDermott, 2000). In 1801, Thomas Young introduced one of the crucial experiments in physics history for studying interference of light (Sobel, 2002), which was later called Young's double-slit experiment. In this case, monochromatic light was directed through two very narrow slits creating an interference pattern of bright and dark stripes, called fringes, on a screen placed at the appropriate distance from the slits. The bright fringes resulted from constructive interference, whereas the dark fringes were from destructive interference.

Regarding interference, early studies repeatedly found that many students at all levels struggled with developing a conceptual understanding (Coetzee & Imenda, 2012; Sobel, 2002; Vokos et al., 2000). In the United States of America, following their course, students were unable to apply double-slit interference of light after the course. This was because they failed to comprehend the importance of path or phase difference (Ambrose et al., 1999). It was argued that there was a lack of emphasis on the concept of path length difference when discussing the equation of angular position of interference patterns ($\Delta = d \sin \theta$) (Sobel, 2002). In the Republic of South Africa, students showed confusion between in-phase and out-of-phase and thought that interference was associated only with constructive interference (Coetzee & Imenda, 2012). Such findings reflected the ineffectiveness of traditional lectures in the university course (Ambrose et al., 1999). In addition, because the behaviour of the wave model of light was invisible, light plus light becoming no light (dark), would be a strange phenomenon for those who did not understand destructive interference.

It is clear from the discussion of the existing literature above that most studies on interference used light waves, and this was reported to be challenging or hard to comprehend because the interactions could not be seen. In this case, the use of a mechanical wave such as water waves can be a model to understand such abstract phenomena as interference because water shows visible interference of wave forms. Surface water waves in a ripple tank are one way to achieve this (Sobel, 2002). Thus, the current study presents a comprehensive method for investigating the interference of water waves. The study aims: (1) to demonstrate the interaction of two coherent waves, which creates interference patterns, using a simplified ripple tank; and (2) to analyse the interference of water waves in the ripple tank. The ripple tank has been convenient for demonstrating almost all common wave properties and behaviours (Chien, 1954; Hajnal, Templer, & Upstill, 1984; Kuwabara, Hasegawa, & Kono, 1986; Logiurato, 2014; Thy & Iwayama, 2021). However, direct quantification of some wave phenomena in the ripple tank has also been shown to be challenging or impossible, regardless of employing additional tools and techniques (Barik, Roy, & Kar, 2005; D'Anna & Corridoni, 2016; Hajnal et al., 1984; Thepnurat et al., 2020; Thy & Iwayama, 2021); which is why very few studies of quantifying interference waves using the ripple tank have been found, and all are simulations (Chandler, 2001; Maurer, 2013; Wagner, 2006). A study that I conducted on the Doppler effect using a simplified ripple tank to experiment and Tracker (Brown et al., 2020) to quantify the video experiment recorded by a smartphone camera revealed that the measurement methods were simple and the results were highly accurate. Therefore, in this study, I adopted similar apparatuses and methodology.

There are two methods for studying a physical phenomenon: (1) the method of experiment and observation and (2) the method of mathematical reasoning (Dirac, 1940). A physical phenomenon can generally be described by mathematical representation, called theory (Dirac, 1940; Irving & Mullineux, 2013; Stone & Goldbart, 2009). An experiment either quantitatively or qualitatively collects data and infers the results to support the theory (Dirac, 1940; Feynman, Leighton, & Sands, 1964; Koponen & Mäntylä, 2006; Weinberg, 1994). In the following sections, the fundamental theory and mathematical model of the interference will be addressed and discussed and this will be followed by experimental implementation.

3.4.3.2. Interference of two coherent waves

a. General equation

Figure 3.26 shows two identical waves S_1 and S_2, superposing each other in space. The solid lines shown represent the crests, and the dashed lines represent the troughs. Constructive interference occurs wherever a solid line meets a solid line, or a dashed line meets a dashed line; this type of interference results in the formation of an antinode (e.g. point *P*). Destructive interference occurs wherever a solid line meets a dashed line; this type of interference results in the formation of a node (e.g. point *Q*). An interference pattern is a standing wave pattern, characterized by the presence of nodes and antinodes that are standing still.

Antinodes fall along lines, called antinodal lines. Nodes also fall along lines, called nodal lines. Those lines are hyperbolae that will be discussed in the following section.

At S_1 and S_2 : $y_1 = y_2 = A\sin\omega t$ and at a point in space, assuming the amplitudes are maintained: $y_1 = A\sin(\omega t - kr_1)$, $y_2 = A\sin(\omega t - kr_2)$ and the resultant-superposed wave $y = y_1 + y_2$.

Apply $\sin A + \sin B = 2\sin[(A+B)/2]\cos[(A-B)/2$, then

$$y = 2A\cos\pi\left(\frac{r_1 - r_2}{\lambda}\right)\sin\left(\omega t - \pi\frac{r_1 + r_2}{\lambda}\right) \tag{I.1}$$

where A is the amplitude, λ is the wavelength, r_1 and r_2 are the wave paths, $\omega = 2\pi / T$ is the angular frequency, $k = 2\pi / \lambda$ is the wave number, t is the time, T is the period and y, y_1 and y_2 are displacements.

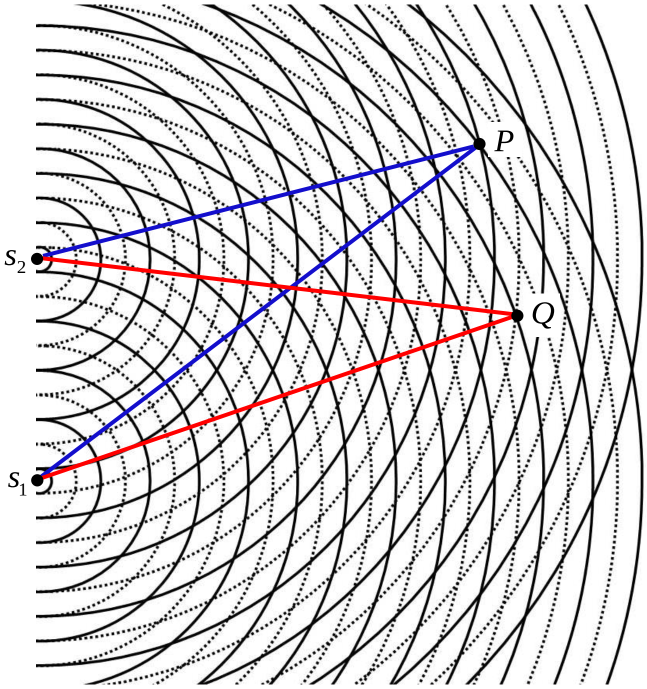


Figure 3. 26: Two coherent waves interfere with one another in space: *P* shows constructive interference and destructive interference is shown at *Q*. The solid lines represent crests, whereas dashed lines represent troughs.

Equation I.1 indicates that regardless of time, the amplitude of the resultant wave is associated with only the cosine term of $\cos\pi[(r_1 - r_2)/\lambda]$, where only the location matters. It has been assumed that the amplitudes are maintained, in order to make the mathematic equation less complicated. In reality, the amplitudes decrease with increasing distance; however, the lines of maximum constructive interference are where the crests from the two waves meet, which corresponds to $\cos\pi[(r_1 - r_2)/\lambda] = 1$, or $r_1 - r_2 = n\lambda$. Maximum constructive interference is shown at point *P*. The lines of destructive interference are where the crests of one wave meet the troughs of another wave, which corresponds to $\cos\pi[(r_1 - r_2)/\lambda] = 0$, or $r_1 - r_2 = (2n+1)\lambda/2$. Destructive interference is shown at point *Q*. In both cases, $n = 0,1,2,3,\ldots$. The two identical waves are called coherent waves, and $r_1 - r_2$ is the path length difference of the two waves.

- **Location of interference patterns**

Use an xy cartesian-coordinate system, where S_1 and S_2 are on the y-axis and the origin midway between S_1 and S_2. Define d as the distance between S_1 and S_2 then the coordinates of the two sources are S_1 $(0, -d/2)$ and S_2 $(0, d/2)$. The path length difference $r_1 - r_2$ in the previous section is represented by Δ, written as

$\Delta = r_1 - r_2$, where $r_1 = [x^2 + (y + d/2)^2]^{1/2}$ and $r_2 = [x^2 + (y - d/2)^2]^{1/2}$. Thus,

$$\Delta = \sqrt{x^2 + \left(y + \frac{d}{2}\right)^2} - \sqrt{x^2 + \left(y - \frac{d}{2}\right)^2} \tag{I.2}$$

Solve equation I.2 by squaring twice to get rid of the radical and obtain

$$y^2 = \frac{\Delta^2}{d^2 - \Delta^2} x^2 + \frac{\Delta^2}{4} \tag{I.3}$$

Equation I.3 defines a hyperbola with an asymptote as

$$y = \pm \frac{\Delta}{\sqrt{d^2 - \Delta^2}} x \tag{I.4}$$

According to equation I.3, the interference patterns are branches of hyperbolae from points between the two sources, known as the foci. At a far distance, the interference patterns, by the nature of hyperbola, tend to their asymptotes as defined by equation I.4, and at a much further distance, where $x >> d$, they overlap. Figure 3.27 shows a hyperbolic interference pattern and its asymptote.

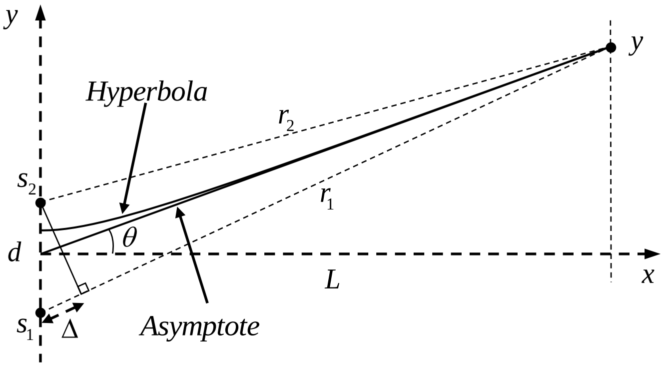


Figure 3. 27: Coordinate system of interference patterns of two coherent waves.

By the definition of hyperbolae, the absolute difference between distances from a point on an interference pattern to the foci is constant. That constant is a path length difference, initially defined as $\Delta = r_1 - r_2$. According to the equation I.4, the slope is $\tan\theta = [\Delta / (d^2 - \Delta^2)^{1/2}]$, and Figure 3.27, $\tan\theta = y/L$, then

$$y \simeq \frac{\Delta L}{\sqrt{d^2 - \Delta^2}} \tag{I.5}$$

For constructive interference, where the path length difference $\Delta = n\lambda$, then

$$y_C \simeq \frac{n\lambda L}{\sqrt{d^2 - (n\lambda)^2}} \tag{I.6}$$

and for destructive interference, where the path length difference $\Delta = (2n+1)\lambda / 2$, then

$$y_D \simeq \frac{(2n+1)\lambda L}{\sqrt{4d^2 - [(2n+1)\lambda]^2}} \tag{I.7}$$

Many textbooks are written in terms of small-angle conditions, where $d >> \lambda$: $\tan\theta \approx \sin\theta \approx y / L$. From Figure 3.27, it can be rearranged to get $\sin\theta = \Delta / d$ or $\Delta = d\sin\theta$, giving $y = \Delta L / d$ in which the constructive interference is

$$y_C \approx \frac{n\lambda L}{d} \tag{I.8}$$

and the destructive interference is

$$y_D \approx \frac{(2n+1)\lambda L}{2d} \tag{I.9}$$

Note that in equations I.5, I.6 and I.7 the asymptotic equal sign $(\simeq)$ is used because these equations are the approximation using the asymptotic behaviour of the hyperbola, and in equations, I.8 and I.9 the approximation sign $(\approx)$ is used because these equations are the approximation at small-angle condition, which is a linear approximation.

3.4.3.3. Experimental setup and measurements

This study used the developed simplified ripple tank. Figure 3.28 illustrates the apparatuses used and their setup. To carry out the experiment, the tank was filled with water to about 5-7mm depth, the flashlight was fixed on the stand at 30cm above and an angle from the centre of the tank surface. The white paper was laid on the floor beneath the tank and facing the flashlight. The smartphone was set on the tripod and situated on one side of the tank. The vibrator was placed on the other side, the ripple tank was adjusted to make the vibrator arm touch the water surface, and a coin was placed in the tank near the vibrator arm.

The video was recorded with three footages, labelled as no wave, single source, and twin sources; and a duration of 10-15s for each footage. The no-wave footage was used to calibrate the measurement tools on Tracker; the single source footage was used for wavelength measurement, and the twin sources' footage was used to identify interference loci. In the single-source experiment, only one arm was attached to the vibrator, and in the twin sources, another arm was added.

The tape measurement tool was employed for the whole measurement process. First, in the no-wave footage, the tape measurement tool was calibrated from the diameter of the coin image to its actual size, which was 2cm. Next, in the single source footage, the wavelength is measured. The waves created by a point source were circular, and the measurements were performed in three directions: the left, the right, and below the point source, as shown in Figure 3.29. A single measurement was made by trying to measure as many waves as possible. The mean of the three lengths was the wavelength. The measurement data are recorded in Table 3.14. Lastly, in the twin sources' footage (which is the interference footage), both constructive and destructive interference patterns were quantified. Those were performed at the same horizon as far as possible from the sources. Measuring the first-order interference pattern, for example, was measuring both its positive order and its negative one. The mean value was the measurement of the first order (see Figure 3.30). The measurement data were recorded in Tables 3.15 and 3.16, respectively.

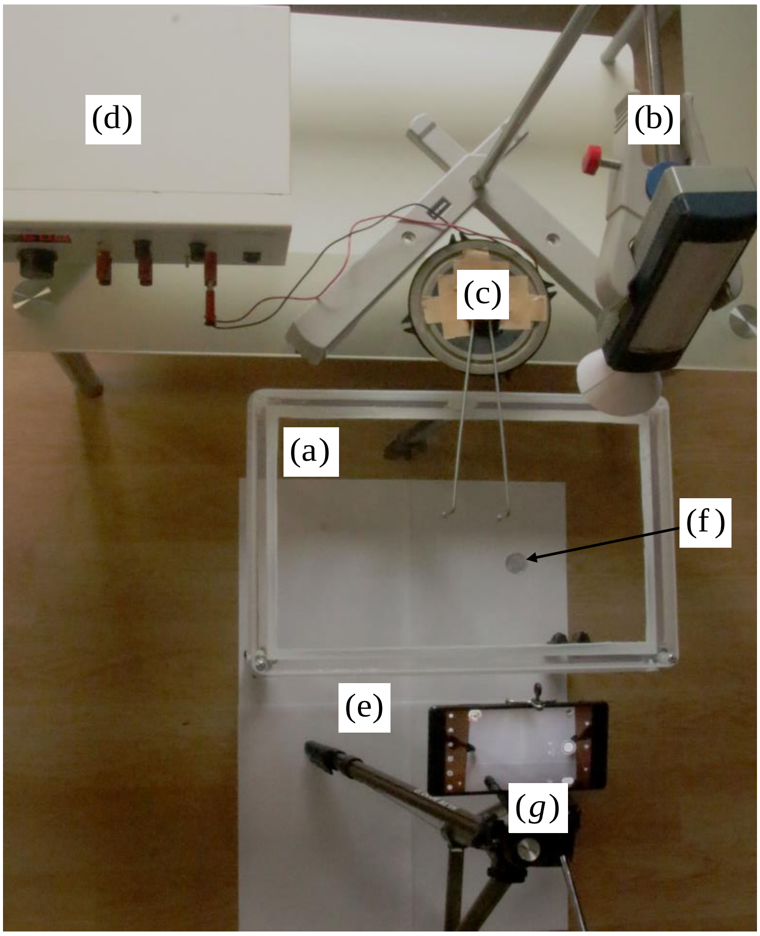
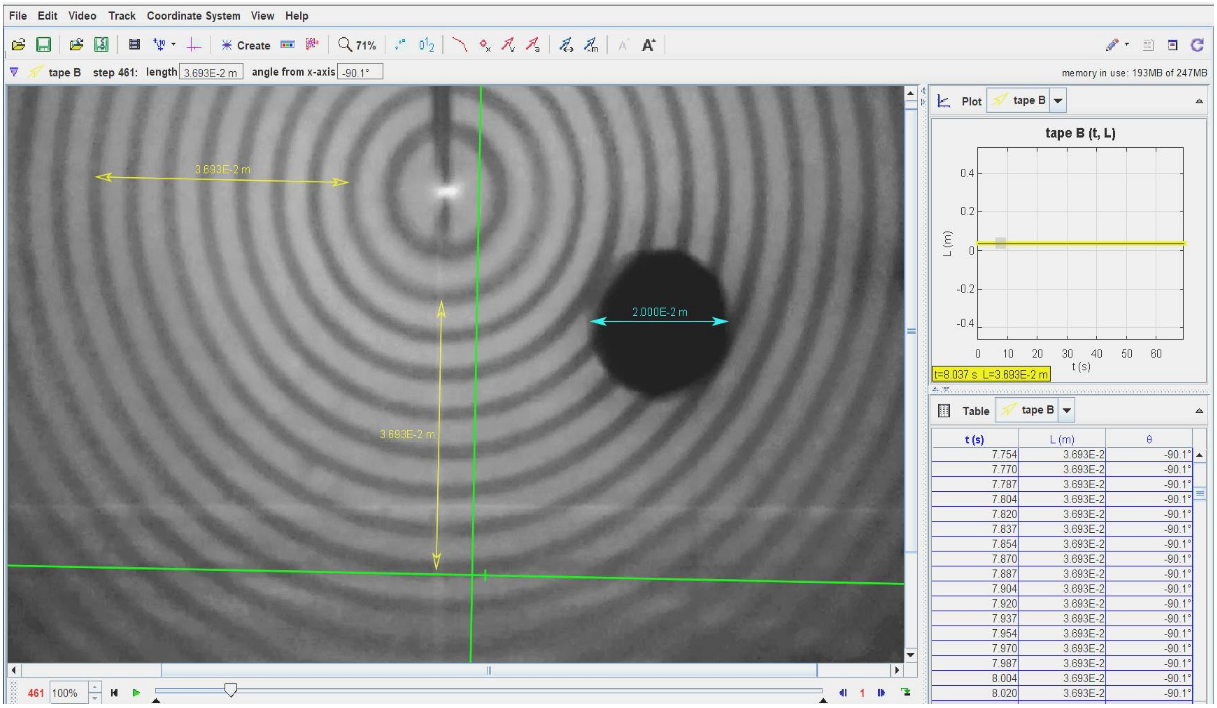


Figure 3. 28: Experimental setup. (a) Tank, (b) LED flashlight and stand, (c) vibrator, (d) signal generator, (e) white paper, (f) coin, and (g) smartphone and tripod.

3.4.3.4. Results

The results showed the phenomenon of two coherent waves interacting with one another to generate interference patterns which could be observed clearly and appealingly by the naked eye (see Figure 3.31a). Nodes and antinodes appeared in hyperbolic nodal and antinodal lines, respectively. As shown in Figure 3.31b, the dashed lines are nodal, and the solid lines are antinodal. It should be notable that just immediately off the sources, the patterns became perfectly straight lines. This will profoundly be discussed later in part 3.4.3.5. Interference is a common phenomenon for all waveforms; however, standing wave occurrences create interference patterns that can only be observed in water waveforms. For the wave model of light, interference patterns may only be seen as alternating bars of brightness and darkness on a screen similar to alternating y_C and y_D , as illustrated in Figure 3,31b, what happened between the sources and the screen cannot be seen.

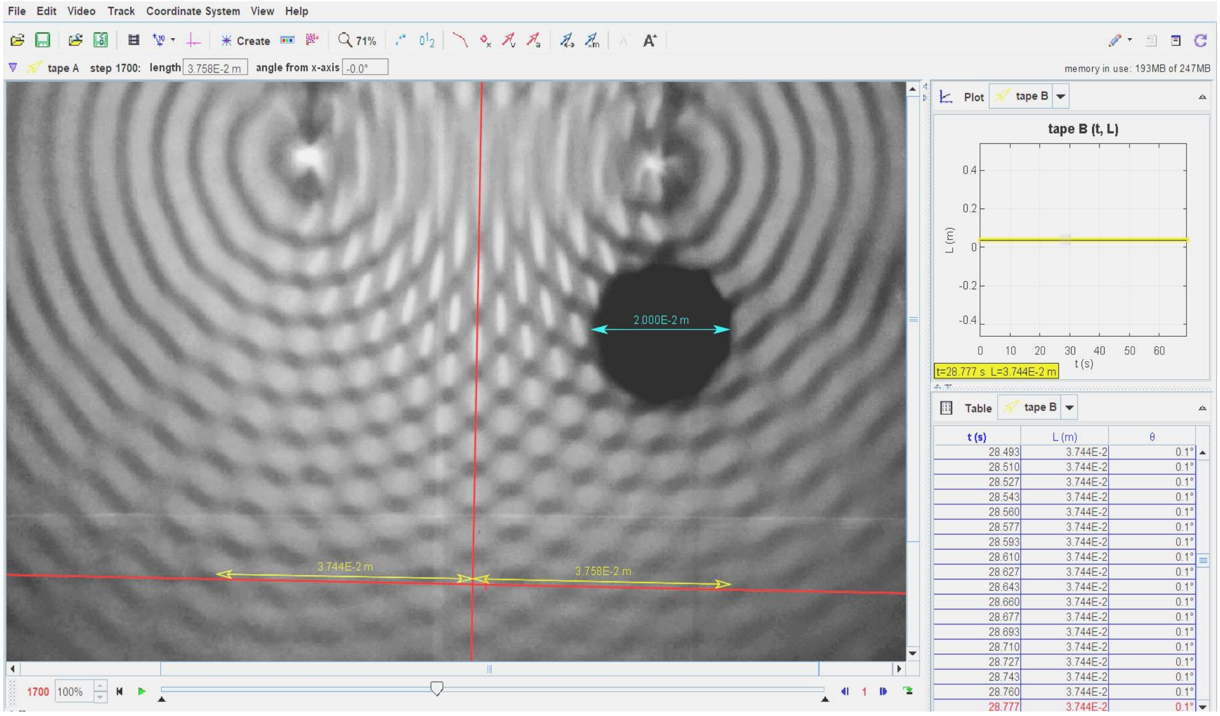


tape B step 461: length 3.693E-2 m angle from x-axis -90.1°

t=8.037 s L=3.693E-2 m

t (s)	L (m)	θ
7.754	3.693E-2	-90.1°
7.770	3.693E-2	-90.1°
7.787	3.693E-2	-90.1°
7.804	3.693E-2	-90.1°
7.820	3.693E-2	-90.1°
7.837	3.693E-2	-90.1°
7.854	3.693E-2	-90.1°
7.870	3.693E-2	-90.1°
7.887	3.693E-2	-90.1°
7.904	3.693E-2	-90.1°
7.920	3.693E-2	-90.1°
7.937	3.693E-2	-90.1°
7.954	3.693E-2	-90.1°
7.970	3.693E-2	-90.1°
7.987	3.693E-2	-90.1°
8.004	3.693E-2	-90.1°
8.020	3.693E-2	-90.1°

Figure 3. 29: Screenshot of the single source footage: Measuring wavelength. The black-round object is the coin used to calibrate the measurement tool. The infinite-cross lines are coordinate axes used to calibrate the video frame angle.



tape A step 1700: length 3.758E-2 m angle from x-axis -0.0°

memory in use: 193MB of 247MB

t=28.777 s L=3.744E-2 m

t (s)	L (m)	θ
28.493	3.744E-2	0.1°
28.510	3.744E-2	0.1°
28.527	3.744E-2	0.1°
28.543	3.744E-2	0.1°
28.560	3.744E-2	0.1°
28.577	3.744E-2	0.1°
28.593	3.744E-2	0.1°
28.610	3.744E-2	0.1°
28.627	3.744E-2	0.1°
28.643	3.744E-2	0.1°
28.660	3.744E-2	0.1°
28.677	3.744E-2	0.1°
28.693	3.744E-2	0.1°
28.710	3.744E-2	0.1°
28.727	3.744E-2	0.1°
28.743	3.744E-2	0.1°
28.760	3.744E-2	0.1°
28.777	3.744E-2	0.1°

Figure 3. 30: Screenshot of the twin sources' footage: Measuring loci of interference patterns. The coordinate axes are used to calibrate the video frame angle, set the origin at zero constructive interference pattern and set the horizon for the measurement.

Table 3. 14: Measurement of wavelength.

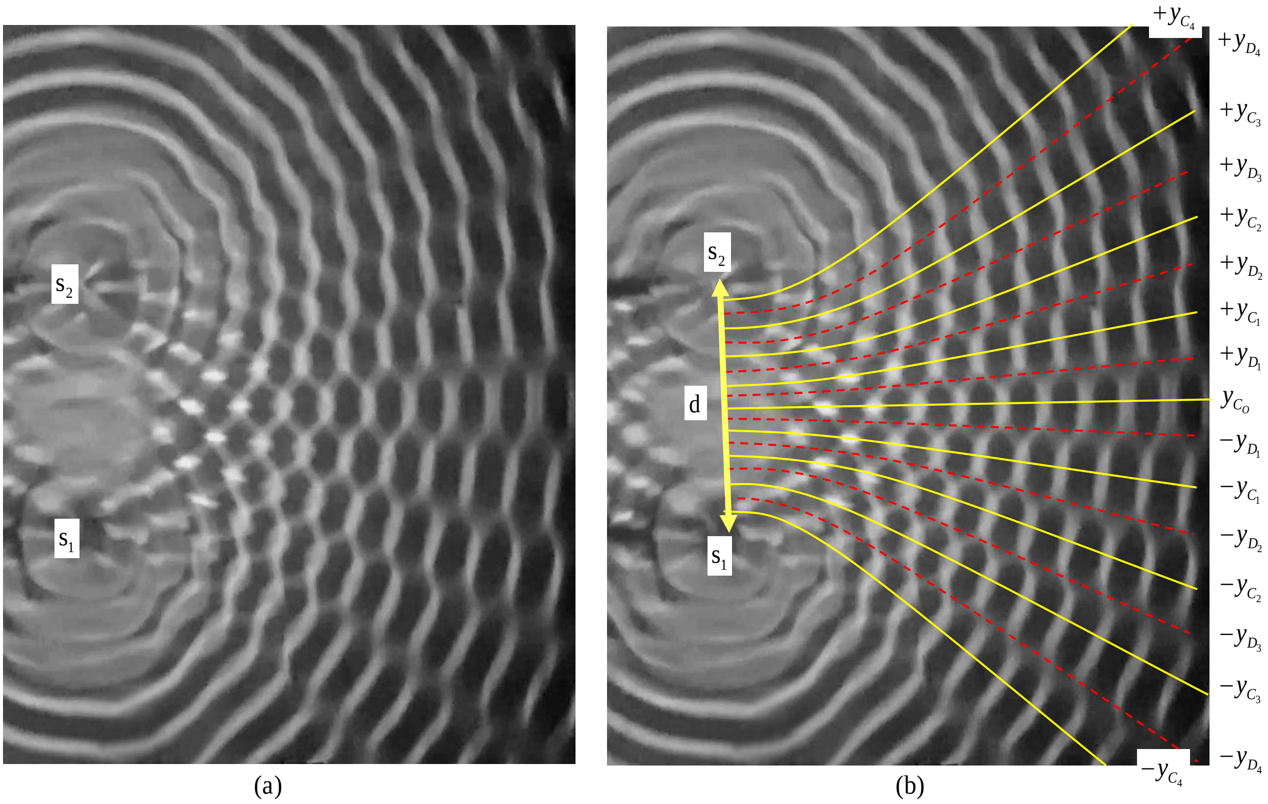
Position	Length ±0.2(mm)	Number of Wave	Wavelength ±0.02(mm)
Right	64.3	12	5.36
Left	36.9	7	5.28
Below	36.9	7	5.28
Average		5.30	

Table 3. 15: Loci of the constructive interference patterns from measurement.

n	order	$+y_C$ ±0.1(mm)	$-y_C$ ±0.1(mm)	Average ±0.1(mm)
0	0	0.00	0.00	0.00
1	1	6.20	6.40	6.30
2	2	12.8	12.8	12.8
3	3	20.2	19.9	20.0
4	4	28.1	28.1	28.1
5	5	37.6	37.4	37.5
6	6	49.8	48.9	49.3
7	7	66.4	65.4	65.9

Table 3. 16: Loci of the destructive interference patterns from measurement.

n	order	$+y_D$ ±0.1(mm)	$-y_D$ ±0.1(mm)	Average ±0.1(mm)
0	1	2.80	3.30	3.00
1	2	9.40	9.80	9.60
2	3	16.3	16.4	16.4
3	4	24.1	24.0	24.0
4	5	32.1	32.5	32.3
5	6	42.9	41.6	42.2
6	7	56.4	55.4	55.9



(a) (b)

Figure 3. 31: (a) Illustration of the interference patterns of two coherent waves, (b) yellow-solid lines are antinodal lines of constructive interference, whereas red-dashed lines are nodal lines of destructive interference.

Table 3. 17: Predicted values of loci of the constructive interference patterns.

n	order	$y_C \approx \frac{n\lambda L}{d}$ (mm)	$y_C \simeq \frac{n\lambda L}{\sqrt{d^2-(n\lambda)^2}}$ (mm)
0	0	0.00	0.00
1	1	6.20 ± 0.2	6.20 ± 0.2
2	2	12.3 ± 0.3	12.6 ± 0.4
3	3	18.5 ± 0.5	19.5 ± 0.6
4	4	24.7 ± 0.6	27.3 ± 0.8
5	5	30.8 ± 0.8	36.4 ± 1.1
6	6	37.0 ± 1.0	48.0 ± 1.4
7	7	43.2 ± 1.1	64.5 ± 1.9

Table 3. 18: Predicted values of loci of the destructive interference patterns.

n	order	$y_D \approx \frac{(2n+1)\lambda L}{2d}$ (mm)	$y_D \simeq \frac{(2n+1)\lambda L}{\sqrt{4d^2-[(2n+1)\lambda]^2}}$ (mm)
1	1	3.10 ± 0.1	3.10 ± 0.1
2	2	9.30 ± 0.2	9.40 ± 0.3
3	3	15.4 ± 0.4	16.0 ± 0.5
4	4	21.6 ± 0.6	23.3 ± 0.7
5	5	27.8 ± 0.7	31.6 ± 0.9
6	6	33.9 ± 0.9	41.8 ± 1.2
7	7	40.1 ± 1.0	55.4 ± 1.6

Thus far, the measurements have been done with the results presented in Tables 1, 2 and 3. Next, for discussion, the predicted values were calculated, using equations I.6 and I.8 for constructive interference and I.7 and I.9 for destructive interference. In this study, where $d = (50.0 \pm 1)\text{mm}$, $L = (58.2 \pm 0.2)\text{mm}$ and the wavelength, $\lambda = (5.30 \pm 0.02)\text{mm}$ and then the predicted values are calculated and presented in Tables 3.17 and

3.18. To ease the investigation, the results were plotted in scatter charts (Figures 3.32 and 3.33). For equations I.6 and I.7, the measured values matched the predicted values throughout the entire range. However, for equations I.8 and I.9, the measured values matched only the first few predicted values. The percentage errors between the measurements and predicted values were calculated and presented in Table 3.19. With the identified wavelength, it is worth checking how accurate the measurement was. Firstly, the measured frequency should be calculated and then compared with the frequency generated by the signal generator.

To determine the frequency, the formula $f = v/\lambda$ was applied, where λ was the wavelength and v was the propagation velocity, which could be calculated using Kevin's law for surface waves (Clark, 1959). Given the above, then

$$v = \sqrt{\left(\frac{g\lambda}{2\pi} + \frac{2\pi A}{\lambda\rho}\right)\tan\frac{2\pi h}{\lambda}} \tag{I.10}$$

where $g = 9.81\,\mathrm{m\,s^{-2}}$ is the gravitational acceleration, λ is the wavelength, A is the surface tension, ρ is the water density and h is the depth of water.

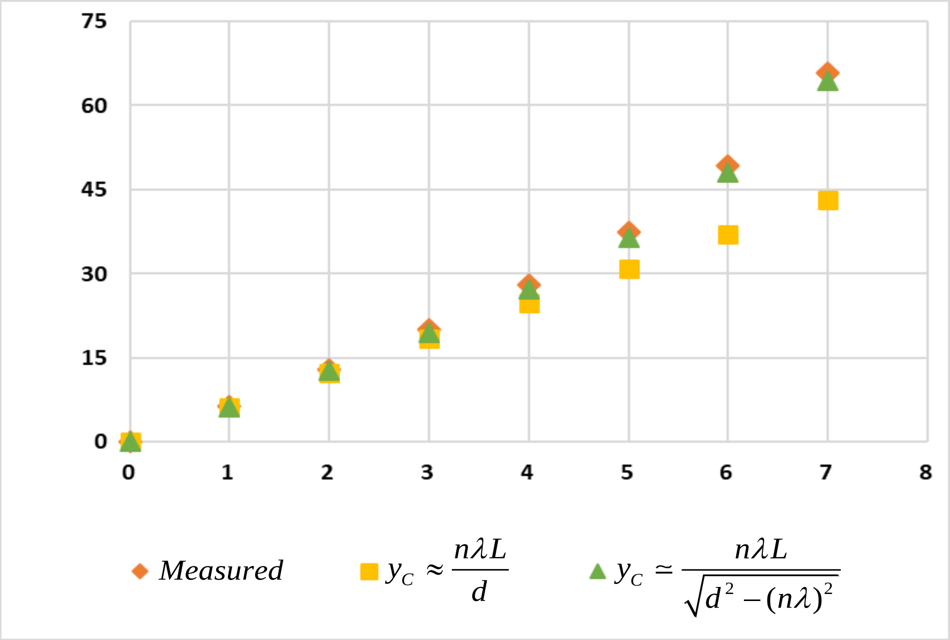


Figure 3. 32: Loci of the constructive interference patterns measured versus predicted values.

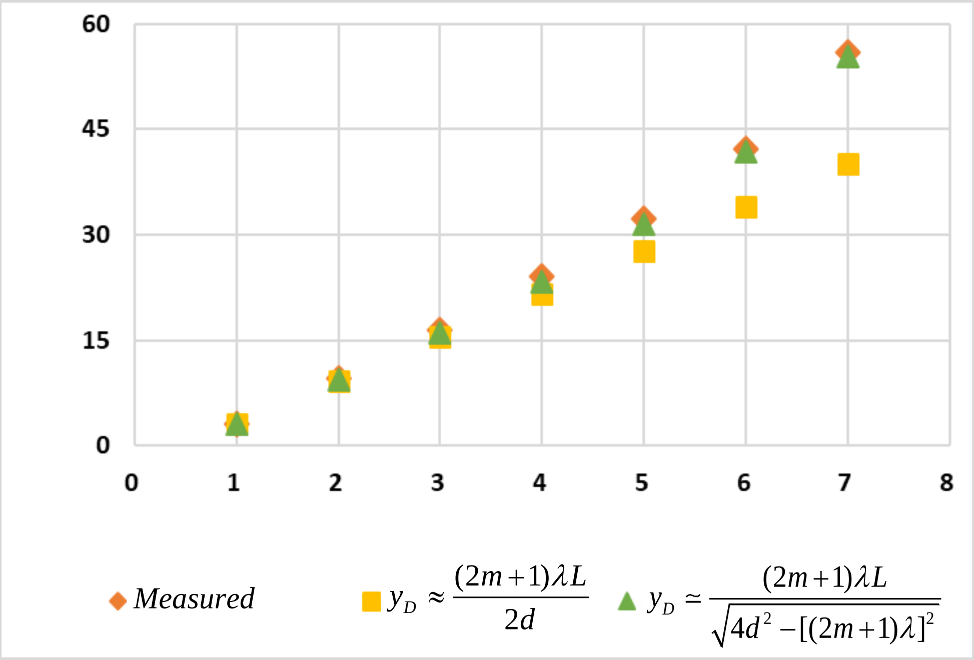


Figure 3. 33: Loci of the destructive interference patterns measured versus predicted values.

Table 3. 19: Percentage errors between the predicted values and the measured values.

Order	Constructive		Destructive	
	Eq. (I.8)	Eq. (I.6)	Eq. (I.9)	Eq. (I.7)
1	1.8%	1.2%	1.3%	1.5%
2	3.9%	1.6%	3.5%	2.2%
3	8.1%	2.5%	6.1%	2.3%
4	13.8%	3.0%	11.3%	3.3%
5	21.6%	3.1%	16.4%	2.3%
6	33.2%	2.8%	24.5%	1.1%
7	52.6%	2.2%	39.4%	0.94%

The experiment was conducted at room temperature of $20^\circ\mathrm{C}$; the surface tension of water $A=(72.8\pm0.4)10^{-3}\ \mathrm{N\,m^{-1}}$ (Vargaftik et al., 1983), the water density $\rho=(998.21\pm0.83)\,\mathrm{kg\,m^{-3}}$ (Tanaka et al., 2001), the depth of water $h=(0.6\pm0.1)\,\mathrm{cm}$, and then the propagation velocity v was $(30.8\pm0.4)\,\mathrm{cm\,s^{-1}}$.

Thus, the measured frequency was $f=(58.0\pm1.0)\mathrm{Hz}$. As the frequency at the generator was

(60.0 ± 0.1)Hz. So, the percentage error was 3.3%. This result reflected the fact that the measurements were highly accurate.

3.4.3.5. Discussions

The ripple tank is advantageous for demonstrating wave properties and behaviours (Chien, 1954; Hajnal et al., 1984; Kuwabara et al., 1986; Logiurato, 2014; Thy & Iwayama, 2021). However, a commercial ripple tank with a stroboscopic illumination system is expensive (Thy & Iwayama, 2021) and in addition, direct quantification is still a challenge. The current study employed a simplified ripple tank to experiment on interference, a smartphone camera to record the experiment, and free video-analysis software to quantify the video. The whole experimentation was simple, and the results were impressive in that the interference patterns were appealingly depicted in the video recording similar to stroboscopic ripple tanks' results (Dyer, 1937).

In section 2.2, the hyperbolic loci of interference patterns would theoretically be in straight lines when $L >> d$, then asymptotic behaviour can be applied to predict the loci of the interference patterns using equation I.6 for the constructive interference and equation I.7 for the destructive interference (Sobel, 2002). In this study, $L = (58.2 \pm 0.2)\text{mm}$, where $d = (50.0 \pm 1)\text{mm}$, meaning that $L = 1.16d$. As seen in Figure 3.31, the patterns, however, became straight almost immediately off the sources. According to Poon (2002), the accuracy of the asymptotic approximation of hyperbolic interference pattern is better than 10% for $L > 1.12d$ and better than 1% for $L > 3.54d$. In this context, the results of the current study with errors of around 3% were remarkable. The condition $L > 3.54d$ would be the limitation of this study. There were two main reasons: (a) the four- or five-times magnification of the image due to the point light source limited the length L, and (b) the screen used in the experiment was already wide enough for the smartphone camera to record clear image from 30 to 40cm distance.

The percentage errors presented in Table 3.19 were calculated by *(Experiment value − Predicted value / Predicted value)* × *100%*. Except for the first order of the destructive interference predicted by equation I.7, which was a negative value, all other values are positive. In addition to fewer errors, it proved that the values predicted by equations I.6 and I.7 derived by the approximation of the asymptotic behaviour were smaller than the predicted values; This acknowledges the fact that the asymptotes were below the curves.

Despite attempting the comparison between the measured and predicted values as presented in the results section, there is another possible way that the investigation can be performed by using the data in Tables 3.15 and 3.16 to discuss the relationship between path length difference and angular position ($\Delta = d\sin\theta$), discovered in section 2.2. This way is also suitable for studying the interference of water waves. First, $d\sin\theta$ should be calculated using data from Table 3.15 for constructive interference and Table 3.16 for destructive interference together with the known L and d . This can, then, be discussed in the following two ways: (1) Using the calculated values to discuss path length difference conditions associated with wavelength. In Tables 3.20 and 3.21, the multiplier is calculated by the path length difference divided by the measured wavelength. One can see that for constructive interference, the path length difference is associated with a full wavelength (multiplier can simply be rounded to integer), whereas in destructive interference, the path length difference is

Table 3. 20: Calculation of wavelength and multiplier in the case of constructive interference

Y_C	$\sin\theta$	Path Difference (mm)	Wavelength ±0.09(mm)	Multiplier
6.30	0.1074	5.37	5.37	1.0
12.8	0.2154	10.8	5.38	2.0
20.0	0.3254	16.3	5.42	3.1
28.1	0.4347	21.7	5.43	4.1
37.5	0.5421	27.1	5.42	5.1
49.3	0.6468	32.3	5.39	6.1
65.9	0.7498	37.5	5.36	7.1

Table 3. 21: Calculation of wavelength and multiplier in the case of destructive interference

Y_D	$\sin\theta$	Path Difference (mm)	Wavelength ±0.09(mm)	Multiplier
3.00	0.0523	2.63	5.23	0.5
9.60	0.1625	8.13	5.42	1.5
16.4	0.2710	13.5	5.42	2.6
24.0	0.3819	19.1	5.46	3.6
32.3	0.4857	24.3	5.40	4.6
42.2	0.5878	29.4	5.34	5.5
55.9	0.6930	34.6	5.33	6.5

associated with a half wavelength (recognised by 0.5 decimal). (2) Use the path length difference conditions to calculate the wavelengths and compare the results with the measured value. The average values of $(5.40 \pm 0.09)\text{mm}$ for the constructive interference and $(5.37 \pm 0.09)\text{mm}$ for the destructive interference compared to the measured value of $(5.30 \pm 0.02)\text{mm}$. The errors are less than 2%. These can be a way for teaching and learning interference to emphasise the path length difference, where a lack of evidence is seen in the literature (Sobel, 2002). Once again, these results confirm the accuracy of the measurements.

To understand physical phenomena, an experimental observation method and mathematical reasoning are usually employed (Dirac, 1940). These two generally work complementally with each other. In class, the student may be introduced to different models to understand or predict a phenomenon. Each model is made by a particular assumption. One model might fit well to the phenomenon; other models might not fit as well, depending on how well the assumption was made. The student can test the models by experimentation. In the current study, I employed two models commonly used for identifying the locations of interference patterns using an asymptotic approximation and a linear approximation. According to the results, the model using asymptotic approximation was better than linear approximation when based on small-angle assumption. The small-angle approximation seemed to work much better in the interference of wave models of light. In practice, d is a fraction of a millimetre, and light wavelength is at the nanoscale. It, thus, corresponds to the condition $d >> \lambda$ of the small-angle.

I observed that in some textbooks and other teaching and learning materials, regardless of high school or undergraduate level, the asymptotic approximation equations I.6 and I.7 rarely exist. According to the results of this study, the use of the linear approximation equations I.8 and I.9 when dealing with the first, second or third order should be possible. The findings caution teaching and learning interference of water waves against using the linear approximation. I recommend widely addressing and discussing asymptotic approximation, not just linear approximation, in teaching and learning activities or materials.

Studies repeatedly found students have misconceptions about the propagation speed of a wave regarding its frequency (i.e. wavelength) (Kennedy & de Bruyn, 2011; Maurines, 1992; Wittmann et al., 1999). It is therefore worth stressing that the propagation speed is related to the wave's wavelength and frequency by $v = \lambda f$, but it is set by the properties of the medium through which it is travelling. In general, the wave propagates at constant speed in a medium. Varying the frequency of the wave will result in no effect on its propagation speed but will affect the wavelength. However, in the case of water, according to equation I.10, modifying frequency (or wavelength) will change the propagation speed of a water wave.

3.4.3.6. Conclusions

The interference phenomenon should be introduced using the water wave model. With a simplified ripple tank and a smartphone, the whole phenomenon can be recorded and observed easily by the naked eye. Additionally, by employing video analysis software such as Tracker, experiment videos can be quantified accurately. The results of this study have clear implications for using water waves for teaching and learning the process of interference phenomenon to deliver a high student understanding of the fundamental phenomenon. For later topics regarding the other waveforms, such as sound waves or wave models of light, teachers can use analogies to aid understanding.

CHAPTER IV

TEACHING PRACTICES OF OSCILLATIONS AND WAVES

4.1. Introduction

This chapter aims to address the third research question, which is to determine the effectiveness of the teaching materials developed for teaching Physics in Cambodia. The following section will present the study design, participants, instruments, instructional aspect model, data analysis, and results in detail.

4.2. Methodology

The study employed a quasi-experiment design known as the one-group pre-test-post-test design (Gay, Mills, & Airasian, 2012), where groups of participants are based on their natural setting and the effect of treatment (i.e., teaching practice in the case of this study) is measured by the difference between pre-test and post-test scores.

4.2.1. Participants

The focus of the study is on the use of ICT for teaching and learning. However, the adaptation of ICT for education in Cambodia is not widespread. Therefore, I selectively chose two schools with acceptable ICT facilities, where teachers and students use computers for teaching and learning, either through personal devices or school-owned equipment. The two selected schools are Phnom Penh Teacher Education College (PTEC) and Prek Leap High School (PLHS). In PTEC, four out of five Physics teacher educators and 72 second-year student teachers volunteered to participate in the study. In PLHS, all nine Physics teachers and 31 grade 11 students volunteered to participate in the study. The study comprised a total of 116 participants, out of which 75 were females. Table 4.1 shows the details of all the participants. It is important to note that both Biology and Chemistry student teachers who were in their foundation year (i.e., second year) participated in this study. They all studied the same science subjects, including Physics, Chemistry, Biology, and Earth Science, the same as Physics student teachers.

Table 4. 1: Summary of the number of participants in the study

		Gender		Total
		Male	Female	
PLHS	Physics teachers	6	3	9
	Grade 11 students	17	14	31
PTEC	Physics teacher educators	4	0	4
	Physics student teachers	8	17	25
	Chemistry student teachers	3	22	25
	Biology student Teachers	3	19	22
	Total	**41**	**75**	**116**

4.2.2. Instruments

Two research instruments were used in this study: tests (pre-test and post-test) and questionnaires. The tests were conducted to assess the participant's understanding of the topics before and after the teaching practices. The purpose of the tests was to determine whether the participants had gained a better understanding of the topics after the teaching practice, and if so, to what extent. The questionnaires were used to gauge the participants' perception of the teaching practices.

a. Tests

I have developed three two-tier structure tests. The format of the test is multiple-choice questions, with each item accompanied by a test taker's confidence level using the Certainty Response Index (CRI). The CRI measures the level of confidence in answering each test item and is presented on a scale compiled by Hasan, Bagayoko, and Kelley (1999), which is presented in Table 4.2. The CRI method is useful for assessing teaching effectiveness and providing the test administrator with more information about the test taker's understanding of the concepts being tested. According to Hasan et al. (1999), getting wrong answers with a low average CRI

Table 4. 2: CRI scale and confidence level

Scale	Description
0	Total guess answer
1	Almost a guess
2	Not sure
3	Sure
4	Almost certain
5	Certain

(<2.5) indicates a lack of knowledge, and does getting correct answers (just a lucky guess). On the other hand, getting correct answers and a high average CRI (>2.5) indicate high concept mastery, whereas getting wrong answers indicates misconceptions.

The three tests cover the concepts of oscillations, the Doppler effect, and interference (refer to Appendix 3 for further details on the tests). Each test was used as a pre-test and post-test. I developed tests on oscillations and interference consisting of 11 items for each (Tables 4.3 and 4.4, respectively). The test on the Doppler effect consists of 12 items, three of which were adopted from the Mechanical Waves Conceptual Survey (MWCS) developed by Tongchai, Sharma, Johnston, Arayathanitkul, and Soankwan (2009), and I developed nine items. To ensure content validity, all tests were reviewed and revised several times by two high school Physics teachers, two Physics educators, and me myself. The tests were piloted and checked for internal consistency (i.e. Cronbach alpha). For the three tests, the Cronbach alpha was between 0.73 and 0.78, indicating an acceptable reliability (Bland & Altman, 1997; Tavakol & Dennick, 2011).

Table 4. 3: Content of items of test on the concept of Oscillations

Item	Label	Content
Item1	Q1.1	Relationship between the period and mass of a pendulum
Item2	Q2.1	Relationship between the period and initial displacement of a pendulum
Item3	Q3.1.1	Relationship between the period and length of a pendulum
Item4	Q3.2.1	Relationship between the period of a pendulum and gravitational acceleration
Item5	Q4.1.1	Relationship between the period and size of the bob of a pendulum
Item6	Q4.2.1.1	Period of a pendulum under Viscous damping oscillations
Item7	Q4.2.2.1	
Item8	Q5.1.1	Relationship between the period and mass of a physical pendulum
Item9	Q5.2.1	Relationship between the period and length of a physical pendulum
Item10	Q6.1.1	Period of a pendulum in Coulomb’s damping oscillations
Item11	Q6.2.1	

Table 4. 4: Content of items of test on the concept of the Doppler effect

Item	Label	Content
Item1	QI.1.1	Frequency of sound waves
Item2	QI.2.1	Velocity of sound waves
Item3	QI.3.1	
Item4	QII.1.1.1	Doppler effect of stationary sound source and observer
Item5	QII.1.2.1	Doppler effect of a moving observer toward a stationary sound source
Item6	QII.1.3.1	Doppler effect of a moving observer away from a stationary sound source
Item7	QII.2.1.1	Doppler effect of moving sound source toward a stationary observer
Item8	QII.2.2.1	Doppler effect of moving sound source and observer toward each other
Item9	QII.2.3.1	Doppler effect of a moving sound source away from a moving observer
Item10	QII.3.1.1	Doppler effect of moving sound source away from a stationary observer
Item11	QII.3.2.1	Doppler effect of moving sound source and observer away from each other
Item12	QII.3.3.1	Doppler effect of a moving sound source away from a moving observer

Table 4. 5: Content of items of test on the concept of Wave Interference

Item	Label	Content
Item1	Q1.1	Relationship between the phase difference and constructive interference
Item2	Q2.1	Relationship between the phase difference and destructive interference
Item3	Q3.1	Relationship between the path length difference and constructive interference
Item4	Q4.1	Relationship between the path length difference and destructive interference
Item5	Q5.1	Loci of constructive interference
Item6	Q6.1	Loci of destructive interference
Item7	Q7.1	Relationship between the path length difference and constructive interference
Item8	Q8.1	Relationship between the path length difference and destructive interference
Item9	Q9.1	Loci of constructive and destructive interference
Item10	Q10.1	Relationship between the path length difference and constructive interference
Item11	Q11.1	Relationship between the path length difference and destructive interference

b. Questionnaires

The questionnaire asked participants to rate their views on teaching and learning related to certain topics, using a 4-point scale ranging from highly negative to highly positive. For instance, in Relevance, 1 = not relevant at all, 2 = not relevant, 3 = relevant, and 4 = very relevant. The questionnaire included seven aspects: 1. Interestingness, 2. Understanding, 3. Importance, 4. Usefulness, 5. Relevance, 6. Difficulty, and 7. ICT skill. I used the 4-point scale to obtain a clear-cut view of the participants' opinions on each of the seven aspects, whether positive or negative (refer to Appendix 3.4 for further details on the tests).

4.2.4. Data analysis

The data collected from the tests and questionnaires were entered into a Microsoft Excel spreadsheet and cleaned. As described in the participants section, there were four different levels of participants: teacher educators, teachers, student teachers, and students. However, for data analysis, the data for teacher educators and teachers were combined into one dataset, while the data for student teachers and students were combined into another dataset, particularly for the topic of Oscillations, in which all types of participants participated in the teaching practice. The Statistical Package for the Social Sciences (SPSS v.25) was used for the data analysis. Descriptive statistics, such as frequency and percentage, were used to summarize the participants' perceptions from the survey and to reflect the applicability and feasibility of the teaching practices. Additionally, inferential statistics, i.e., paired-sample t-test, were used to examine the difference between pre-test and post-test scores. Cohen's d (Cohen, 2013) was used to examine effect size. Cohen's d for a paired-sample t-test can be calculated by dividing the mean difference by the standard deviation of the difference, as shown below.

Cohen's d formula:

$$d = \frac{\text{Mean difference}}{\text{Standard diviation of difference}} \tag{4.1}$$

- $2 \leq d < 0.5$: Small effect
- $0.5 \leq d < 0.8$: Moderate effect
- $d \geq 0.8$: Large effect

The average normalized gain <g> was also used to evaluate students' improvement through learning, as defined by (Hake, 1998). This measure provides more information than a simple difference, as it calculates the fraction of concepts learned that were not already known at the beginning of the course. To put it in another way, it is the ratio of the difference between the average post-score and the average pre-score (or actual gain) to the difference between the full score and the average pre-score (or maximum possible gain).

Normalise gain formula:

$$\text{Normalised gain } (\text{<g>}) = \frac{\text{Post-test score\%} - \text{Pre-test score\%}}{100\% - \text{Pre-test score\%}} \tag{4.2}$$

The gain value indicates how much the learners have improved from their maximum possible increase. There are three categories of gain:

- $\text{<g>} < 0.3$: Low gain
- $3 \le \text{<g>} < 0.7$: Medium gain
- $\text{<g>} \ge 0.7$: High gain

Followed by CRI analysis as well as participant's perception of understanding and interest, the effectiveness of teaching practices could be evaluated.

Last but not least, the applicability and usefulness of the teaching materials were examined based on the analysis of participant's perceptions of the relevant items.

4.3. Teaching Practices

The teaching practices were divided into two formats: workshops and instructions. The workshop format was designed for Physics teacher educators and high school Physics teachers. This format was considered INSET, where I acted as a trainer and the participants as trainees. Participants worked individually in most of the activities, which gave them more opportunities to experience all aspects of the training.

The instruction format was designed for student teachers and high school students, and involved participants working in groups to perform one or two experiments. During the results-sharing section, each group would present their findings and conclusions, providing an opportunity for all participants to learn about experiments they may not have personally conducted. For instance, in the oscillation topic, there were several experiments available; however, each group was only able to perform a subset of these, such as undamped oscillations or damped oscillations with Coulomb's damping, viscous damping, a combination of the two, or the use of a tracker or angle sensor. Through sharing their results and conclusions, groups were able to learn from each other's experiences.

Two separate workshops were held, one at each school campus for Physics teachers and Physics teacher educators. To avoid disturbing the regular teaching schedule of the participants, I scheduled the workshops during the weekly professional development sessions, when the teachers were usually together. The students and student teachers had more flexible schedules and thus each group participated in only one topic using their free schedules. Grade 11 students and Physics student teachers in teaching practice attended the Oscillations workshop, held separately at each school campus. Chemistry student teachers participated in the topic of the Doppler effect, while Biology student teachers took part in the topic of Interference. Due to the time constraint and the conflicting schedules of the participant groups, participants from PLHS participated in teaching practice on the topic of oscillations.

All of the participants were unfamiliar with the new ICT-based teaching materials that I developed. To familiarize them with the necessary ICT for the teaching practices, I spent a couple of sessions (1 session = 1.5 hours) introducing them to Tracker, an angle sensor, the E-Lab interface for data collection, MS Excel for modelling and fitting data, and more. The number of sessions required for this ICT familiarization stage varied depending on the topic each group of participants would participate in, with some requiring 2-4 sessions. For example, those who were not supposed to attend the Oscillations teaching practice took shorter sessions as they did not need to know about angle sensors and the E-lap interface.

Additionally, each teaching practice for a given topic required two sessions to complete, followed by a post-test and survey. During the first meeting with participants, I did a self-introduction, explained the teaching practices, and administered a pre-test. I was able to meet each participant group once per week, except the Physics teacher educators, whom I could meet for two sessions per week. This resulted in a time gap of about 4-5 weeks between the pre-test and the post-test.

4.3.1. Lesson design

The lessons in this study were based on experiments that followed the scientific method. Figure 4.1 shows the steps of the lesson, wherein I simplified the process into six steps for the Cambodian lesson plan.

Firstly, the lessons started by reviewing relevant knowledge or previous content that the learners had already learned. This served as a foundation for them to learn new content in today's lesson. Secondly, the learners were introduced to a problem by observing some phenomena qualitatively and quantitatively, where applicable. They then addressed a key question which they would seek the answers to immediately in the lesson. Thirdly, the learners hypothesized and tried to answer the key question with their knowledge. Fourthly, they conducted experiments to test their hypothesis by collecting data on some variables. Fifthly, the data collected was analysed and interpreted to answer the key question. Finally, the learners discussed the results and made conclusions by answering the key question.

In the lessons, there are two types of worksheets available for learners. Before starting each actual lesson, these two types of worksheets were introduced and explained to learners clearly. The first is a paper-based worksheet that learners can use throughout the entire lesson, while the second is an MS Excel-based worksheet designed for steps 4 and 5 of the lesson. With the MS Excel-based worksheet, learners can perform various calculations, plot graphs, create models, fit data to models, and organize data to help interpret results. Figure 4.2 illustrates what an MS Excel-based worksheet looks like. All the paper-based worksheets can be found in Appendix 2.

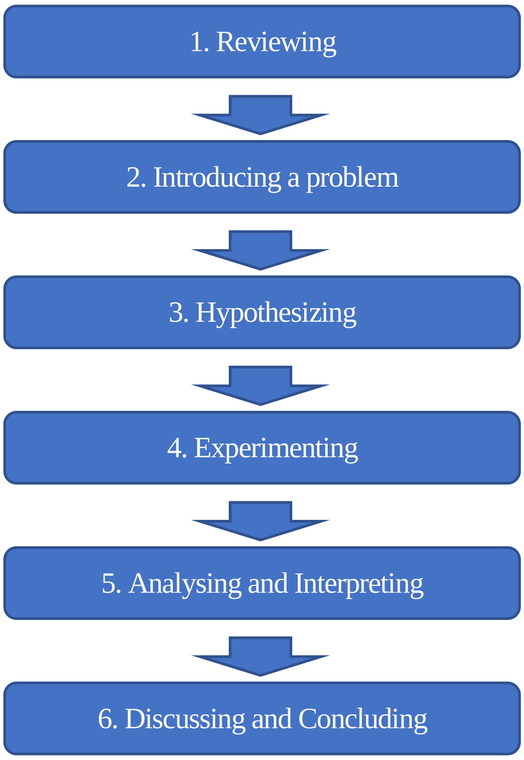
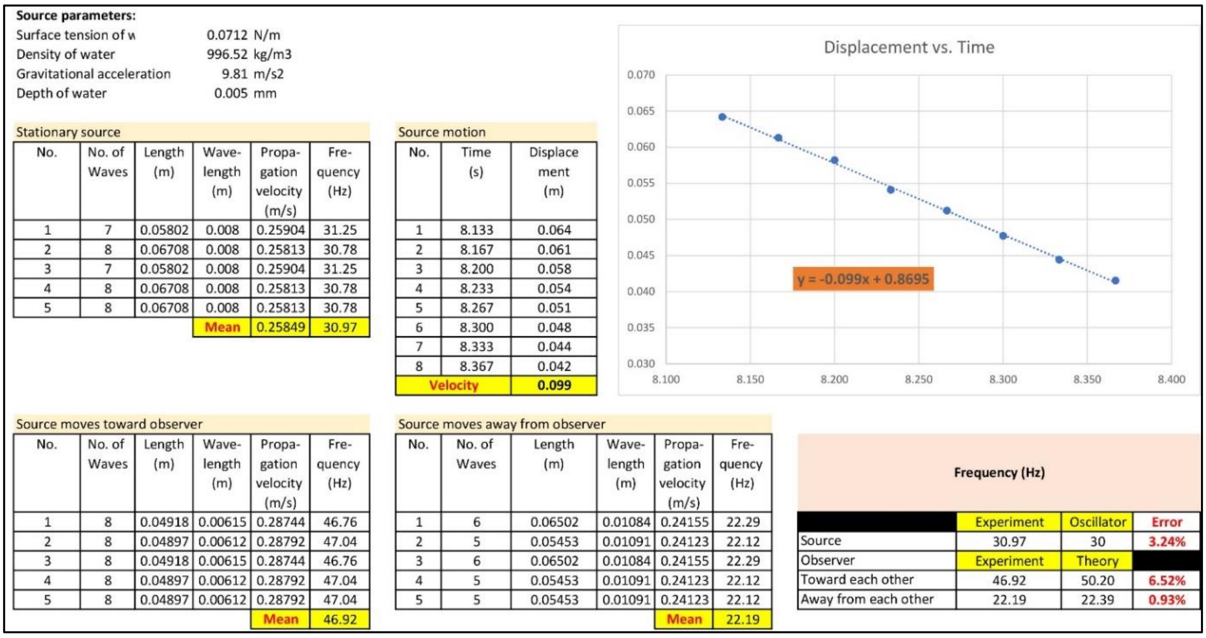


Figure 4. 1: Flow of the lesson for teaching practice



Source parameters:

Surface tension of w	0.0712	N/m
Density of water	996.52	kg/m3
Gravitational acceleration	9.81	m/s2
Depth of water	0.005	mm

Stationary source

No.	No. of Waves	Length (m)	Wave-length (m)	Propa-gation velocity (m/s)	Fre-quency (Hz)
1	7	0.05802	0.008	0.25904	31.25
2	8	0.06708	0.008	0.25813	30.78
3	7	0.05802	0.008	0.25904	31.25
4	8	0.06708	0.008	0.25813	30.78
5	8	0.06708	0.008	0.25813	30.78
			Mean	0.25849	30.97

Source motion

No.	Time (s)	Displace ment (m)
1	8.133	0.064
2	8.167	0.061
3	8.200	0.058
4	8.233	0.054
5	8.267	0.051
6	8.300	0.048
7	8.333	0.044
8	8.367	0.042
Velocity		0.099

Source moves toward observer

No.	No. of Waves	Length (m)	Wave-length (m)	Propa-gation velocity (m/s)	Fre-quency (Hz)
1	8	0.04918	0.00615	0.28744	46.76
2	8	0.04897	0.00612	0.28792	47.04
3	8	0.04918	0.00615	0.28744	46.76
4	8	0.04897	0.00612	0.28792	47.04
5	8	0.04897	0.00612	0.28792	47.04
				Mean	46.92

Source moves away from observer

No.	No. of Waves	Length (m)	Wave-length (m)	Propa-gation velocity (m/s)	Fre-quency (Hz)
1	6	0.06502	0.01084	0.24155	22.29
2	5	0.05453	0.01091	0.24123	22.12
3	6	0.06502	0.01084	0.24155	22.29
4	5	0.05453	0.01091	0.24123	22.12
5	5	0.05453	0.01091	0.24123	22.12
				Mean	22.19

Frequency (Hz)

	Experiment	Oscillator	Error
Source	30.97	30	3.24%
Observer	Experiment	Theory	
Toward each other	46.92	50.20	6.52%
Away from each other	22.19	22.39	0.93%

Figure 4. 2: Screenshot of an MS Excel-based worksheet for the Doppler effect lesson.

The teaching and learning materials, as well as the lesson instructions, were assessed by analysing the participants' improvement in their understanding of concepts after the lesson. In addition, the participants were asked to complete questionnaires to provide feedback on the feasibility and usefulness of the materials. These aspects will be demonstrated in more detail in the following sections.

4.3.2. Teaching practice on oscillations

a. Lesson instruction

The pendulum consists of a string or a light rod with a weight at one end. Its unique characteristics were first examined by Galileo. In 1602, he conducted experiments to determine whether the periods of pendulums were constant. The period is the time it takes for a pendulum to complete a single oscillation and return to its original position. Galileo discovered that each pendulum has a constant period. Even today, this topic is commonly discussed in classical physics mechanics classes when talking about oscillations.

However, based on my experience as a high school Physics teacher and Physics teacher educator for almost 15 years, I have noticed that many students have misconceptions about the period of a pendulum. They often confuse it with the amplitude of oscillations. When discussing the period, they imagine the amplitude of the oscillation. As a result, they mistakenly believe that the period of oscillation decreases over time in damped oscillations. In reality, it is the amplitude that gradually decreases over time, while the period remains constant, as Galileo discovered about four centuries years ago.

In Cambodia, experiments on oscillations are conducted to confirm which parameters affect the period of the oscillations and which ones do not. For example, the length of the pendulum affects the period, while the mass of the pendulum does not. The traditional method used to experiment on oscillations involves assuming that the period of the oscillation is constant, then setting a pendulum to swing for 10 oscillations and recording the time. By dividing the recorded time by 10 oscillations, they obtain the period of oscillation. To check the effect of length, they repeat the same procedure with a change in length. This helps them understand the relationship between the length and the period of a pendulum.

While this traditional method is good, it is not sufficient. For instance, it does not demonstrate how to prove that the period of oscillations does not decrease over time, even though the oscillations are damping. It also does not demonstrate the effects of different damping factors, such as Coulomb’s friction and viscous drag, or how to obtain damping factors of damped oscillation. This has led to the development of new ways to study oscillations as detailed in Chapter III.

During the teaching practices, the participants conducted experiments on the oscillations of simple and physical pendulums. They explored undamped and damped oscillations, including Coulomb's damping, viscous damping, and the combination of both. Data was collected using the Tracker tool and angle sensor with the E-Lab interface, where applicable. This data was then plotted on a graph and analysed using MS Excel to obtain parameters such as period, angular frequency, and damping factors. By tracking the values of period, frequency, and angular frequency of the pendulum throughout the oscillations, they were able to compare the obtained values with the theoretical values. The lesson conclusions were drawn at the end of the lesson. The participants of the teaching practice on this topic are 4 Physics teacher educators, 9 high school Physics teachers, 25 Physics student teachers and 31 high school students.

b. Effectiveness

A paired samples t-test was conducted to determine if there was a difference between the teacher educators' and teachers' understanding of Oscillations before and after the workshop. The results indicated that after the workshop, the teacher educators' and teachers' understanding of Oscillations (*M* = 7.38, *SD* = 2.43) was significantly higher than before the workshop (*M* = 4.46, *SD* = 2.37). The difference between the two tests was statistically significant, *t* (12) = 4.76, *p* = < .001. Cohen's d and normalized gain <g> were calculated. Cohen's d value was 1.33, indicating a large effect, while the normalized gain <g> of 0.45 indicated an average improvement of 0.45 times the maximum possible gain after the teaching practice. On average, teacher educators and teachers answered 41% correctly with a confidence level of 2.08 on the pre-test, showing a lack of conception. On the post-test, on the other hand, they got 67% correct answers with a 3.02 confidence level, exhibiting concept mastery.

Another paired samples t-test was conducted to assess whether there was a difference between student teachers' and students' understanding of Oscillations before and after the workshop. The results indicated that after the teaching practice, the student teachers' and students' conception of Oscillations (*M* = 5.11, *SD* = 2.72) was significantly higher than before the workshop (*M* = 2.00, *SD* = 1.25). The difference between the two tests was statistically significant, *t* (55) = 8.72, *p* = < .001. Cohen's d and normalized gain <g> were calculated. Cohen's d value was 1.16, indicating a large effect, while the normalized gain <g> of 0.35 indicated an average improvement of 0.35 times the maximum possible gain after the teaching practice. On average, student teachers and students answered 18% correctly with a confidence level of 1.88 on the pre-test, displaying a lack of conception. On the post-test, they got 46% correct answers with a 3.19 confidence level, indicating mastering the concept.

According to the survey data analysis, all participants found the lesson instruction interesting, with around 50% finding it very interesting. Besides, 77% of teacher educators and teachers, as well as 89% of student teachers and students, believed that they understood the content of the teaching practice. An additional 15% of teacher educators and teachers and 9% of student teachers and students acknowledged that they understood the content very well. Overall, these results suggest that the teaching practices concerning Oscillations were highly effective.

c. Applicability and usefulness

The survey showed that 92% of teacher trainers and teachers found the teaching material and lesson instruction relevant to their work. Of these, 58% considered it to be very relevant. Around half of the participants found the lesson easy. An impressive 77% acknowledged that they could use ICT in the lesson. All of the teacher educators and teachers agreed that this ICT-based teaching material and lesson instruction is important and useful. More than half of them emphasized its utmost importance and usefulness.

Similarly, the survey revealed that 93% of student teachers and students found the teaching material and lesson instruction relevant to their major. Of these, 27% considered it to be very relevant. Only 25% found the lesson easy. However, 61% of student teachers and students acknowledged that they could use ICT in the lesson, which is a good number. All of the student teachers and students admitted that this ICT-based teaching material and lesson instruction are important and useful. Half of them stressed its very importance and usefulness.

4.3.3. Teaching practice on the Doppler effect

a. Lesson instruction

In the Cambodian high school physics textbooks, the Doppler effect is described as the sound of an ambulance siren moving down the road. However, the last two versions of the Cambodian National Physics textbook do not include a single illustration of the Doppler effect. In class, physics teachers typically describe the same scenario and ask students to imagine the phenomenon. They then discuss the mathematical representation and analysis underlying the phenomenon and solve related problems.

The role of experiments in physics education is crucial for a deeper understanding of physics concepts (Koponen & Mäntylä, 2006). According to Silverman (1995), experiments enable students to witness basic phenomena, practice using apparatus and measurement techniques, and get a glimpse into scientific research. Therefore, it is important to teach and learn the Doppler effect experimentally, so that students can grasp the concept not only in theory but also visually and quantitatively. Visualizing a phenomenon can pique the students' interest and curiosity (Bell et al., 2010). In high school physics class, the Doppler effect is usually introduced as a sound wave phenomenon. However, since the phenomenon is not visible to the naked eye, students may have difficulty understanding it (Fazio et al., 2008; Wittmann et al., 1999).

For the Doppler effect topic, the participants observed the phenomenon through a recorded video and used Tracker to analyse it. They obtained variables such as initial frequency and shifted frequencies. Based on these results, they discussed the underlying mathematics of the phenomenon and other cases, such as the observer moving or both the source and observer moving. The participants of the teaching practice on this topic are 4 Physics teacher educators and 25 Chemistry student teachers.

b. Effectiveness

A paired samples t-test was performed to assess the difference in the Physics teacher educators' understanding of the Doppler effect before and after a workshop. The results showed that the Physics teacher educators' understanding of the Doppler effect after the workshop (*M* = 9.50, *SD* = 1.92) was significantly higher than before (*M* = 3.50, *SD* = 3.78), *t* (3) = 4.65, *p* < .05. Cohen's d and normalized gain <g> were calculated. Cohen’s d value was 2.32, indicating a large effect, while the normalized gain <g> of 0.50 indicated an average improvement of 0.50 times the maximum possible gain after the teaching practice. On average, teacher educators answered 23% correctly with a confidence level of 2.27 on the pre-test, showing a lack of conception. On the post-test, on the other hand, they got 62% correct answers with a 3.58 confidence level, exhibiting concept mastery.

Likewise, a paired samples t-test was conducted to determine if there was a difference in the student teachers' understanding of the Doppler effect before and after teaching practice. The results showed that the student teachers' understanding of the Doppler effect after teaching practice (*M* = 5.84, *SD* = 3.22) was significantly higher than before (*M* = 1.76, *SD* = 1.30), *t* (24) = 5.52, *p* < .001. Cohen's d and normalized gain <g> were calculated. Cohen’s d value was 1.10, indicating a large effect, while the normalized gain <g> of 0.31 indicated an average improvement of 0.31 times the maximum possible gain after the teaching practice. On average, student teachers answered 12% correctly with a confidence level of 1.74 on the pre-test, displaying a lack of conception. On the post-test, they got 39% correct answers with a 2.72 confidence level, indicating improvement in the concept.

According to the survey data analysis, all teacher educators found the lesson instruction very interesting and understood the content of the lesson. Student teachers of 83% found it interesting, and another 17% found it very interesting. Additionally, 75% of student teachers believed that they understood the content of the teaching practice. These results, all together, suggest that the teaching practices concerning the Doppler effect were highly effective.

c. Applicability and usefulness

According to the survey, all teacher educators found the material and instruction to be relevant to their work, with 50% of them considering it to be very relevant. However, only 25% of them found the lesson easy. Surprisingly, 75% of them acknowledged that they could use ICT in the lesson. All the teacher educators agreed that this ICT-based teaching material and lesson instruction is important and useful, with more than 75% of them emphasizing its utmost usefulness.

Similarly, the survey revealed that all student teachers found the teaching material and lesson instruction relevant to their major, with 25% of them considering it to be very relevant. However, almost all of them found the lesson not very easy. Nevertheless, about half of the student teachers confirmed that they could use ICT in the lesson. All the student teachers admitted that this ICT-based teaching material and lesson instruction is important and useful.

4.3.4. Teaching practice on interference

a. Lesson instruction

Several studies (Coetzee & Imenda, 2012; Sobel, 2002; Vokos et al., 2000) have shown that many students across all levels struggle with developing a conceptual understanding. For instance, they fail to grasp the importance of path length or phase differences (Ambrose et al., 1999). There is also a lack of emphasis on the concept of path length difference when discussing the equation of the angular position of interference patterns ($\Delta = d \sin \theta$) (Sobel, 2002).

When teaching interference in Cambodia, in Physics class, the interference of two wave sources is usually discussed in the form of mathematical representation and experiments are seldom conducted. If experiments are conducted, it is usually the double-slit experiment of light (using a laser beam) in which the phenomenon is invisible, and the focus of the experiment is on the locus of bright and dark fringes, rather than the path length difference, which is the most crucial condition for interference occurrences.

On the other hand, Cambodian Physics textbooks and other teaching and learning materials do not address the asymptotic approximation. Instead, they rely on linear approximation, which results in significant errors when the fringe order increases (from the 4th and higher), particularly for water waves. I highlighted it in the study in Chapter III. The lesson should emphasise the relationship between path length difference and angular position since it is the underlying criterion for interference occurrences. Therefore, the main objective of this teaching practice lesson is to examine path length differences by analysing interference patterns. In teaching practice of the interference topic, the participants observed and analysed the interference pattern using Tracker. They sought a relationship between path length difference and wavelength. Furthermore, from the analysis, the participants could identify parameters, including wavelength, propagation velocity, and frequency of the wave, used to compare with theory or known value to evaluate the accuracy of the experiment. The participants of the teaching practice on this topic are 4 Physics teacher educators and 22 Biology student teachers.

b. Effectiveness

A paired samples t-test was performed to evaluate whether there was a difference in the Physics teacher educators' understanding of Interference before and after the workshop. The results showed that the Physics teacher educators' understanding of Interference significantly increased after the workshop ($M = 9.50$, $SD = 1.92$) compared to before ($M = 4.50$, $SD = 0.58$), $t\,(3) = 5.48$, $p < .05$. Cohen's d and normalized gain <g> were calculated. Cohen’s d value was 2.73, indicating a large effect, while the normalized gain <g> of 0.77 indicated an average improvement of 0.77 times the maximum possible gain after the teaching practice. On average, teacher educators answered 41% correctly with a confidence level of 1.61 on the pre-test, showing a lack of conception. On the post-test, on the other hand, they got 86% correct answers with a 3.50 confidence level, exhibiting concept mastery.

Similarly, a paired samples t-test was conducted to determine whether there was a difference in the Biology student teachers' understanding of Interference before and after the teaching workshop. The results showed that the Biology student teachers' understanding of Interference increased significantly after the workshop ($M = 5.45$, $SD = 2.72$) compared to before ($M = 2.09$, $SD = 1.07$), $t\,(21) = 5.12$, $p < .001$. Cohen's d and normalized gain <g> were calculated. Cohen’s d value was 1.09, indicating a large effect, while the normalized gain <g> of 0.38 indicated an average improvement of 0.38 times the maximum possible gain after the teaching practice. On average, student teachers answered 19% correctly with a confidence level of 1.90 on the pre-test, displaying a lack of conception. On the post-test, they got 50% correct answers with a 3.08 confidence level, indicating mastering the concept.

The survey analysis revealed that all participants found the lesson instruction interesting, with 75% of teacher educators and 23% of them finding it very interesting. Additionally, all teacher educators and teachers, as well as 60% of student teachers and students, believed that they understood the content of the teaching practice. Overall, these results suggest that the teaching practices related to Interference were highly effective.

c. Applicability and usefulness

The survey found that all teacher educators considered the material and instruction introduced to be relevant to their work, with 50% of them finding it very relevant. Half of them found the lesson easy, and 75% confirmed that they could use ICT in the lesson. Moreover, all teacher educators agreed that this ICT-based teaching material and lesson instruction is important and useful.

Similarly, 78% of student teachers found the teaching material and lesson instruction relevant to their major. However, 73% of them found the lesson somewhat challenging, and only 41% of them felt confident in using ICT in the lesson. Nonetheless, 95% of student teachers acknowledged that this ICT-based teaching material and lesson instruction is important and useful.

4.4. Conclusions

The effectiveness of the teaching material developed for Oscillations and Waves has been proven through comparisons of pre-test and post-test scores, showing large effects and moderate normalised gain scores, along with improvement of CRI and overall positive feedback from participants in the survey, which has shown that it is moderately effective. Additionally, the teaching material is applicable and very useful.

The participants found the lessons to be challenging, but they agreed that they could use the related ICT in their teaching practice. The use of ICT-based lessons was a new experience for them, and both the instructional method and the technology used were unfamiliar, especially when it came to science experiments. However, the two-period training provided for the use of such ICT was insufficient, particularly for student teachers and students, to become proficient in using the technology. Even common science experiments posed a challenge for Cambodian teachers and students, based on My experiences. I strongly believe that if the participants use these ICTs for a while, they will get used to them and become a handy tool to experiment with many more, not only for the topics I developed.

It is worth noting that pre-test scores for all topics and the CRI of teacher educators and teachers revealed a lack of knowledge about Oscillations and Waves, which was echoed by the results of the quick survey discussed in Chapter IIMy introduction. The teaching practice covered a lot of content regarding Oscillation and Waves, despite appearing as only three lessons. The overall results demonstrated an improvement in the knowledge of Oscillations and Waves among teacher educators, teachers, student teachers, and students.

In conclusion, the developed teaching material on Oscillations and Waves is suitable for Physics Education in Cambodia, whether for INSET, PRESET, or high school education.

CHAPTER V

DISCUSSIONS, CONCLUSIONS, AND RECOMMENDATIONS

In this Chapter, I overview the overall results and findings of the whole study and discuss the challenges and opportunities of application of this ICT-based teaching material development. Then, I conclude and, finally, give recommendations for implementation and future development.

5.1. Discussions

The results of the survey presented in Chapter II suggest that Cambodian science teachers possess the necessary subject matter knowledge and pedagogical skills to teach their subjects effectively. According to Shulman (1986), teaching is a complex process that involves the integration of subject content knowledge and general pedagogy. These two elements are crucial for teachers to design effective teaching and learning models and are widely recognized as teacher knowledge (Berry, Depaepe, & Van Driel, 2016). The quality of teaching depends on teachers' subject content knowledge and pedagogical skills to facilitate effective teaching and promote a fruitful learning experience for students (McNamara, 1991).

ICT plays a significant role in science education. In the current age of the 21st century, ICT is involved in all aspects of life (Noor-Ul-Amin, 2013). In education, ICT has gained popularity for making the teaching and learning process more successful and fascinating (Bhattacharjee & Deb, 2016; McFarlane & Sakellariou, 2002). Regarding ICT integration into teaching, Cambodian science teachers have demonstrated sufficient knowledge of basic ICT for administration work, social communication, and professional development. However, it seems that Cambodian science teachers face difficulties in the effective utilisation of ICT to enhance their teaching and improve student learning outcomes.

This is critical for ICT for education (Noor-Ul-Amin, 2013). While in the information age, teachers need to be able to effectively utilise their ICT knowledge and skills in teaching in a way that can improve student learning. By analysing some ICT-related items of the survey, the data shows that 59.6% of the teachers affirmed that they knew how to use social media, and 54.2% knew how to use online conferencing tools. About half of the teachers believed that they could update their knowledge and skills in their field from various sources on the Internet. However, only one-third of the teachers displayed knowledge about different ICT technologies used to teach the content in their subject. Less than one-fourth felt confident in using online learning platforms to give lessons to their students. Regarding the effective use of computers, only 21.3% of teachers believed they could do it. For knowledge in advanced ICT, 21.3% of teachers confirmed knowing how to create and publish web pages, and only 3.3% demonstrated an understanding of computer programming and how to code.

According to Bingimlas (2009), this may involve three main barriers to effective ICT integration: lack of confidence, lack of competence, and lack of access to resources. All these barriers reflect the current situation of Cambodian science education. Concerning resources, although Cambodian high schools have acceptable infrastructure, incorporating libraries, science-laboratory rooms, computer labs, internet connection, clean water, toilets and electricity, science-laboratory rooms lack materials, and computer labs lack computer students to learn and use to support learning, especially for OHS.

The regression analysis presented in Chapter II revealed that the ability of Cambodian science teachers to integrate ICT into their teaching practices (TPACK) depends on two factors: their knowledge of how to use technology about the subject content knowledge (TCK) and their knowledge of using technology to transform their teaching practices (TPK). This means that teachers should be proficient in using various ICTs related to their subject and understand the pedagogical aspects of those ICTs in order to enhance student learning and succeed in teaching their subject using ICT.

The current study developed ICT-based teaching materials on several topics under Oscillations and Waves. Regarding Oscillations, I developed an angle sensor from a potentiometer and E-Lab interface. These apparatuses are handy for damped oscillations. Combining them with video-based experiments recorded with a smartphone can be used for teaching and learning a wide range of topics in Oscillations, covering undamped, viscous damping, Coulomb's damping and a combination of viscous and Coulomb's damping. For Waves, I developed a simplified ripple tank from household materials and a vibrator from an old speaker. These apparatuses can be used with a smartphone to make videos of various wave phenomena such as type of waves, reflection, refraction, diffraction, interference, the Doppler effect, etc. The videos can be quantified, which, in this study, the research quantified the Doppler effect and interference phenomena.

Despite the developed materials, the smartphone and computer also played critical roles in these ICT-based teaching materials. While almost all teachers own a smartphone, and the usage is not complicated. The smartphone is not a concern. The computer, on the other hand, is critical. E-lab requires a computer to run on and log data from the sensor, while video-based experiment requires Tracker, which requires a computer to run on, to analyse. Last, the data was analysed in MS Excel, which also requires a computer to run. This may concern OHS, which lacks computer labs and computers to support learning, although about half of the teachers own a computer. This issue needs more commitment from the government through MoEYS to speed up building a computer lab and equipping computers at every OHS. As for the immediate solution, MoEYS should provide several computers to OHS. In terms of enhancing science teaching and learning, this is far less expensive compared with investing in a standard science laboratory.

Overall, the developed material worked quite well in terms of accuracy and helped improve the knowledge and understanding of the learners on topics. In Chapter III, the results of the experiments had percentage errors of less than 5%. Teaching practices in Chapter IV showed moderate improvement in all participants with high satisfaction. The vast majority of the participants found the teaching materials and instructions interesting, relevant and worthwhile. These materials would be beneficial resources for Physics education, particularly in Cambodia, where many schools have poor science laboratories and a shortage of materials.

These results, however, must carefully imply that such ICT-based teaching material might replace conventional teaching material. They have distinct roles to play in science education differently. It depends on the situation or the context of a particular education system, schools, and level of education. Moreover, we should never suggest that such ICT-based teaching and learning necessarily transforms science education. Although the findings in this study indicated the developed ICT-based teaching materials and method of instruction on Oscillations and Waves took superior advantages over the conventional one, this model might not apply to other topics. We need to acknowledge the critical role the science teacher played in creating conditions for ICT exploitation in teaching and learning, not only the ICT itself (Osborne & Hennessy, 2003). The findings, however, proved that the developed teaching materials and instructions could help improve the TCK and TPK of Physics teachers, which are critical factors for effective ICT integration in teaching Physics.

The use of developed teaching materials and instruction can be very helpful for Physics teachers unless they adapt them to their teaching and learning. However, several constraints can hinder their motivation to do so. According to Osborne and Hennessy (2003), teachers often face limitations such as a lack of time to gain confidence and experience with technology, limited access to resources, curriculum overload with content, assessment methods that don't require the use of technology and a lack of subject-specific guidance on how to use ICT to support learning.

The current study also identified some of these constraints. The participant received very short time training on the use of ICT relevant to teaching practices. In the survey concerning teaching practices, many participants raised about difficulties with their learning, and I could see that it linked to the use of ICT for experimenting. While conducting teaching practices, I observed that the participants had been trying hard on the computer to complete learning activities during the teaching practice. Although the vast majority actively engaged in all activities and completed all assigned tasks with good results and showed excitement with the results they got at the end of the lesson, there would be a question for teacher educators, teachers, and student teachers whether they will adopt these ICT-based teaching materials for teaching in the future or not, where they need mastery of these ICT to train students and use in the lesson. Besides, science education in Cambodia has also been facing content-loaded and content-based examinations, which might contribute to their demotivation to implement such ICT-based teaching material.

5.2. Conclusions

Cambodian high school science teachers possess adequate knowledge of subject contents, teaching strategies for their respective subjects, and ICT for administrative purposes as well as to support their work related to the subject matter. However, Cambodian high school science teachers require additional knowledge of specialized ICT for education to enhance their teaching and improve students' learning in their respective subjects. The capability of Cambodian science teachers to incorporate ICT into their teaching practices (TPACK) depends on technological content knowledge and technological pedagogical knowledge.

As for school facilities, Cambodian high schools possess appropriate facilities such as libraries, science laboratory rooms, computer labs, internet connection, clean water, toilets, and electricity. However, ordinary high schools lack laboratory materials and computers for students to use to support their learning. Moreover, the inadequate number of classrooms and science teachers leads to large class sizes and high student-to-teacher ratios, which makes it challenging to teach science subjects, especially science experimentation.

The study developed teaching material on Oscillations and Waves, incorporating Damped Oscillations, the Doppler effect and Interference. The experiment methods of using Arduino-based sensors and Tracker video analysis gave high accuracy of the results. Using these developed teaching materials with the scientific method instruction model could provide good ICT-based learning experiments for learners and improve learners' conception of the topics and ICT skills for Physical education.

The developed teaching material used materials and tools commonly used in daily life. The materials are inexpensive compared to standard laboratory materials and can be used for multiple purposes. They are suitable for schools with poor facilities and limited budgets, like most schools in Cambodia, especially for integrating ICT into science education.

Overall, the developed teaching material and instruction are ICT-based and suitable for Physics Education in Cambodia at all levels, both general and higher education.

5.3. Recommendations

The study developed ICT-based teaching materials suitable for Physics education in Cambodia. However, successful implementation requires consideration of relevant factors.

The physics teacher, who is the most critical body, must master the content (i.e., Oscillations, including undamped and damped, the Doppler effect, including stationary and moving source and observer, and Interference) and the relevant ICT skills, especially how to use Tracker to analysis video and how to use MS Excel for data modelling. These knowledge and skills are crucial power underlying confidence and motivation for the teacher to teach, using the ICT-based teaching material in their class. It is not very difficult, but it is new. Teachers may take some time to learn and master them. Regarding video-based experiments, teachers should know how to set up and record video experiments; otherwise, the measurement may not be accurate. The angle sensor and the E-Lab interface are not complicated. Just knowing how to connect to a computer, the teacher can use it. It is handy.

Schools, especially ordinary schools, should afford some computers and Arduino for these ICT ways of teaching and learning and encourage teachers and students to use it. This would not be a big budget for school, but it is different for the teacher or student as an individual.

Policymakers and MoEYS should allocate funds for some essential tools like computers, not necessarily a computer lab, and Arduino boards in regular schools. This will provide students with ICT-based teaching materials and improve their learning experience.

To improve the teaching of Physics with the integration of ICT, INSET and PRESET programs should prioritize ICT for Physics. The training content should include well-developed teaching materials and instructional methods that promote the use of ICT. The content and material created in this study can be used as a resource.

It is important to note that this study is based on a cross-sectional analysis, which may limit the findings in terms of time. Therefore, conducting more replication and longitudinal studies can provide better results and more information about this topic.

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APPENDIX 1

APPENDIX 1.1: Survey questionnaire for high school science principals

Survey Questionnaire
(School Principal)

Code: …………………………
School Name/Code: ………………………

1. City/Province: ………………………………….
2. School location: ☐ a. Urban ☐ b. Rural
3. Type of school
   ☐ a. Resource school ☐ b. Network resource school ☐ c. Common public school
   ☐ d. Private School ☐ e. New Generation School
4. Gender: ☐ a. Male ☐ b. Female
5. Age: ……………………
6. Years of experience as a school principal: ………………….
7. Total number of students: ………………… Female: …………………
8. Total number of staff: …………..… Female: ………………
9. Total number of teaching staff: …………..… Female: ……………………
10. Number of rooms: …………………………
11. Number of classrooms: …………………………
12. Is there a science laboratory in your school? ☐ a. Yes ☐ b. No (skip logic)
13. Are there science laboratory materials for teaching and learning? ☐ a. Yes ☐ b. No (skip logic)
14. Is there a running water system in the school? ☐ a. Yes ☐ b. No
15. Are there usable toilets in the school? ☐ a. Yes ☐ b. No
16. What kind of electricity does your school access? (You may choose more than one)
    ☐ a. Not access to electricity
    ☐ b. Government Electricity/Private Company
    ☐ c. Solar electricity
    ☐ d. Electric generator
    ☐ e. Battery
    ☐ f. Other: ……………………………
17. Is there a computer lab in the school? ☐ a. Yes ☐ b. No
18. Total number of computers: ………………………………
19. Is there Internet for usage in school? ☐ a. Yes ☐ b. No
20. Other ICT facilities for teaching and learning (you may choose more than one):
    ☐ a. Tablets ☐ b. Digital camera ☐ c. Projector ☐ d. Smart TV ☐ c. Smart/Interactive board
    ☐ e. Others: ……………………………………
21. Is there a functioning library in the school? ☐ a. Yes ☐ b. No

APPENDIX 1.2: Survey questionnaire for high school science teachers

Survey Questionnaire
(Science Teacher)

Code: …………………………
School Name/Code: ………………………
Teacher Name/Code: ………………………

I. General Information

1. City/Province: ………………………………….
2. School location: ☐ a. Urban ☐ b. Rural
3. Gender: ☐ a. Male ☐ b. Female
4. Age in years: ……………………………
5. Type of school
   ☐ a. New Generation School ☐ b. Resource school ☐ c. Network resource school
   ☐ d. Ordinary high school
6. Major: ……………………………
7. Teaching subject: 1. ………………………………… 2. ……………………………………
8. Qualification:
   ☐ a. Bachelor ☐ b. Master ☐ c. Doctor ☐ d. Other …………………………
9. Professional certificate:
   ☐ a. General education ☐ b. Bachelor+1 ☐ c. 12+2 ☐ d. Other: …………………
10. Teaching experience in years: …………………………

II. Teacher's Technological Pedagogical Content Knowledge (TPACK)
Respond to each of the statements below by making a selection which best represents your response
1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree
Mark only one choice per statement

	Statements	1	2	3	4	5
CK-1	I am confident that I have sufficient knowledge about my subject.					
CK-2	I consider myself an expert in my subject.					
CK-3	I can develop a deeper understanding of the content of my subject.					
PK-1	I can guide my students to adopt appropriate learning strategies.					
PK-2	I can help my students to monitor/manage their learning.					
PK-3	I can help my students to reflect on their learning.					
PK-4	I can plan group learning activities for my students.					
PK-5	I teach my students to use discussion effectively during joining group work.					
TK-1	I have the technological skills to use computers effectively.					
TK-2	It is easy for me to learn ICT technology.					
TK-3	I know how to use social media (e.g. Facebook, YouTube, Telegram).					
TK-4	I know how to use conferencing tools (e.g. Zoom, and Google Meet).					
TK-5	I am confident in using online learning platforms (e.g. Google Classroom, SeeSaw, Moodle) to give lessons to my students.					
PCK-1	I can select teaching approaches that are effective in developing scientific thinking.					

PCK-2	I use a variety of teaching strategies to help my students better understand the content of my subject.					
PCK-3	I am confident that I have sufficient knowledge and skills in teaching science experiments in my subject.					
TCK-1	I know about different ICT technologies that I can use to teach the content in my subject.					
TCK-2	I can use technologies for alternative representation of content in my subject.					
TCK-3	I can utilize appropriate computer software or smart device apps to do science experiments on my subject.					
TCK-4	I can update my knowledge and skills in my subject from various sources on the Internet.					
TPK-1	I show my students how to use ICT to plan their learning.					
TPK-2	I require my students to use ICT to construct different representations of my subject content.					
TPK-3	I require that my students collaborate by using ICT to solve problems in my subject.					
TPK4	I can use ICT to alternate my teaching approaches.					
TPACK-1	I know particular ICTs to teach particular matching content in my subject (e.g. Crocodile Physics, Chem Draw, …).					
TPACK-2	I can use ICT in my classroom that enhances my daily teaching (e.g. word processing, spreadsheets, presentation software).					
TPACK-3	I can make video content to help my students learn my subject productively.					
TPACK-4	I am sufficiently knowledgeable to provide leadership at my school in how to combine the affordances of ICT with the specific pedagogical approaches required for science (my subject) teaching.					
TPACK-5	I can develop various science teaching materials corresponding to the content and context of my classroom.					

APPENDIX 2

APPENDIX 2.1: Worksheet of teaching practices on Oscillations

Worksheet

[part1]

Topic: Oscillations
- Objective: Investigate oscillations of the simple and physical pendulum
- Material and tools: Bob, string, stands, aluminium bar, Arduino-based angle sensor, Videos of undamped and damped oscillation of simple and physical pendulums Tracker (video analysis software), E-Lab interface and computer.

Discuss theory

- Period formula:..
....
....
....
- Relationship between period, frequency and angular frequency of a pendulum/oscillation ....
....
....
....
....

Oscillation functions

$\theta(t) = \theta_o \cos(\omega t - \phi)$ ....
....
θ_o : ....
ω: ....
t : ....
ϕ : ....

Activity 1: Observe undamped oscillations and quantity of some parameters of the oscillations using Tracker
Period:...
Frequency:..
Angular frequency: ....
Amplitude: ....
Phases: ....
....
....

Activity 2: What will happen when oscillation continues as it goes?
State your hypothesis:
....
....
....
Share your hypothesis with the class and discuss it. If there are some changes after discussion, write the changes down below
....
....
....
....

Discuss theories:

Oscillation function of damped oscillation:

- Coulomb's friction effect: $\theta_n(t) = \left(\theta_o - (2n+1)\Delta\right)\cos\omega_o t + (-1)^n \Delta$, which

$\Delta = \dfrac{\eta}{\omega_o^2}$ ……………………………………………………………………………………

$\eta = \dfrac{\tau_f}{I}$:……………………………………………………………………………………

$Sgn(\dot{\theta}) = -1,\ 0,\ 1$ for $\dot{\theta} < 0, \quad = 0, > 0,$ ……………………………………………………………

- Viscous friction effect: $\theta(t) = \dfrac{\omega_o}{\omega}\theta_o e^{-\gamma t}\cos(\omega t - \phi)$, which

$\theta_o e^{-\gamma t}$:……………………………………………………………………………………

……………………………………………………………………………………………………

$\omega^2 = \omega_o^2 - \gamma^2$:……………………………………………………………………………

……………………………………………………………………………………………………

$\gamma = b/2\ell$:……………………………………………………………………………………

……………………………………………………………………………………………………

$\tan\phi = \gamma/\omega$:……………………………………………………………………………

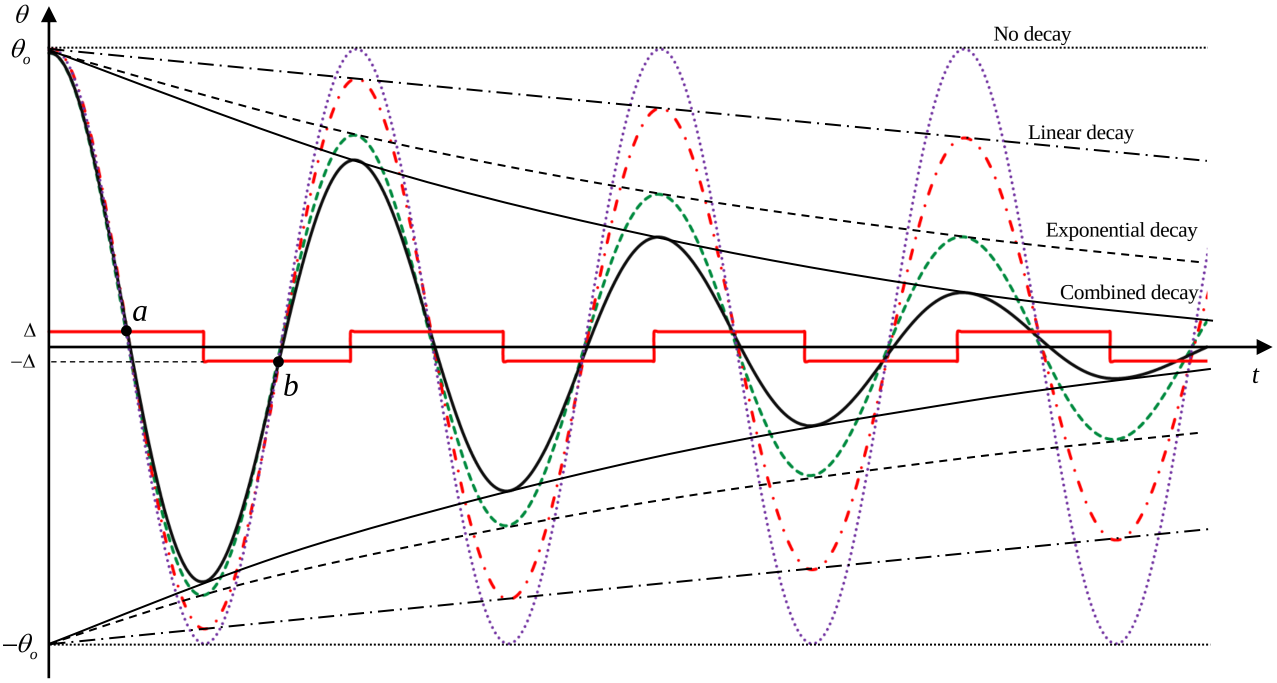
……………………………………………………………………………………………………

- Combined of both effects: $\theta_n(t) = \dfrac{\omega_o}{\omega}\left(\theta_o - \Delta\dfrac{2\beta^{-n} - (1+\beta)}{1-\beta}\right)e^{-\gamma t} \times \cos(\omega t - \phi) + (-1)^n \Delta$ ……………………

$\beta = e^{-\gamma T/2}$: ……………………………………………………………………………

……………………………………………………………………………………………………

……………………………………………………………………………………………………



Worksheet
[part2]

With your group member with the assigned topic, work on a computer and Excel worksheet to acquire the data with the assigned materials and measure some parameters below:

Period: ....
Frequency:..
Angular frequency: ....
Amplitude: ....
Initial phase:...

From the acquired data, create a model and fit your data with the model. Find the remaining parameters (all applicable listed below), compare the values with theoretically calculated values, and calculate the percentage errors.

θ_o : ....
ω: ....
ω_o : ....
T : ....
T_o : ....
I : ....
γ : ....
b : ....
Δ : ....
τ_f : ....

- What did you observe concerning the period, frequency, and amplitude of oscillations when it undergoes damping?..
....
....
- What can you say about your result based on the percentage errors calculated?
....
....
....

Share your results with the class in a short presentation and discuss it. What you want to share, note it below:
....
....
....
....
....
....

The overall conclusion from what you learned about oscillations:
....
....
....
....
....
....
....

APPENDIX 2.2: Worksheet of teaching practices on the Doppler effect

Worksheet

Topic: Doppler effect
- Objective: Investigate the Doppler effect phenomenon
- Material and tools: Video of Doppler effect of water waves in a ripple tank and Tracker (video analysis software) and computer.

Review

- **R**elationship between period and frequency of waves ....
....
- Relationship between propagation velocity and wavelength ....
....
- Propagation velocity of water waves: $v=\sqrt{\left(\frac{g\lambda}{2\pi}+\frac{2\pi A}{\lambda\rho}\right)\tan\frac{2\pi h}{\lambda}}$ ....

....
....
....
....
....

Activity 1: Observe a video of circular waves and quantify some parameters using Tracker

- Wavelength ....
- Propagation velocity ....
- Period and frequency of waves ....
- Compare the values with theory or known values ....

....
....
....
....

Activity 2: What will happen when waves are set to displace with a constant velocity?
State your hypothesis:
Wavelength:..
Frequency:..
....
....
....

Watch the video and note what you observe.
Wavelength:..
Frequency..
....
....
....
Discuss with your hypothesis..
....
....
....
....

- Work on your computer and Excel worksheet, and measure the wavelength in front of and behind the source and make comparisons by calculating percentage error.

What is propagation velocity? ....
....
What is the frequency of the wave source? ....
....
....
....
Compare with the given value and calculate the percentage between the two values
....
....
....

Discussion

What is the mathematical representation of this phenomenon?
- When the source is stay still: ....
....
....
....
- When the source starts to displace: ....
....
....
....
....
....
....
- How about when an observer displaces? ....
....
....
....
....
....
....
....
....
- How about when the two cases occur at the same time? ....
....
....
....
....
....
....
....

APPENDIX 2.3: Worksheet of teaching practices on Interference

Worksheet

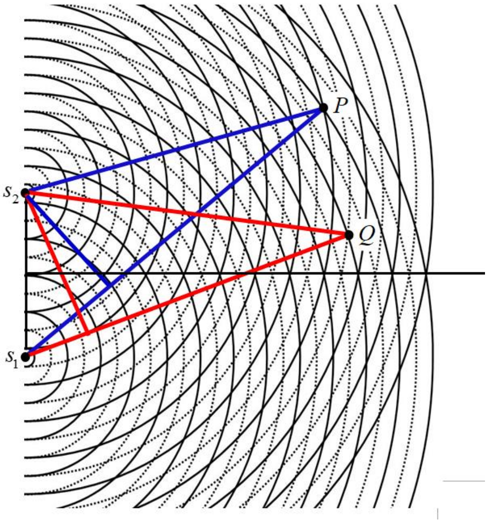
Topic: Interference
- Objective: Investigate interference pattern
- Material and tools: Video of interference of water waves in a ripple tank and Tracker (video analysis software) and computer.

Review
- **R**elationship between period and frequency of waves ....
- Relationship between propagation velocity and wavelength ....
- Superposition principle and interference (observing video and discussion) ....
....
....
- Propagation velocity of water waves: $v=\sqrt{\left(\frac{g\lambda}{2\pi}+\frac{2\pi A}{\lambda\rho}\right)\tan\frac{2\pi h}{\lambda}}$ ....
....
....

Activity 1: Observe a video of circular waves and quantify some parameters using Tracker

- Wavelength ....
- Propagation velocity ....
- Period and frequency of waves ....
- Compare the values with theory or known values ....
....
....
....

Activity 2: What will happen when two coherence waves meet and interact with each other?
- State your hypothesis:
....
....
....
Observe a video interaction of two coherence waves and discuss the theory underlined
- Coherence waves ....
....
....
- At point P: Constructive interference ....
Path length difference Δ : $d\sin\theta = n\lambda$ ....
....
....
....
- At point Q: Destructive interference
Path length difference Δ : $d\sin\theta = (2n+1)\lambda/2$ ....
....
....



- Observe a video interference of waves and quantify some parameters using Tracker. Work on your computer and Excel worksheet, and measure a few positions (at least 3) of constructive interference and destructive interference and associated path length difference. Note values you find and make comparisons by calculating percentage error.

	Constructive interference		Destructive interference	
Order	Δ	Wavelength	Δ	Wavelength
	Average		Average	
	Error (%)		Error (%)	

What is propagation velocity? ....
....

What is the frequency of the wave source? ....
....
....
....

Compare with the given value and calculate the percentage between the two values
....
....
....

Discussion and conclusion:

- How large are the errors you got? Discuss them.
....
....
....
....
....
....

- What can you conclude from your measure with such errors?
....
....
....
....
....

- From the results of the interference pattern analysis, what you would say about the relationship between path length difference and interference occurrences?
....
....
....
....
....
....
....

APPENDIX 3

APPENDIX 3.1: Pre- and post-test on the concept of Oscillations

Name: ....
Gender .... Class ....
School...

Test on the Concept of Oscillations
(20 minutes)

Consider the cases below and tick in the box (☑) in front of the only one correct answer and your confidence to answer each question.

Confidence level:
0 = Total guess   1 = Almost guess   2 = Not sure
3 = Sure   4 = Almost certain   5 = Certain

Case 1: Given two pendulums as shown in Fig.1. Pendulums have the same length and size, but the mass of pendulum 2 is double the mass of pendulum 1.

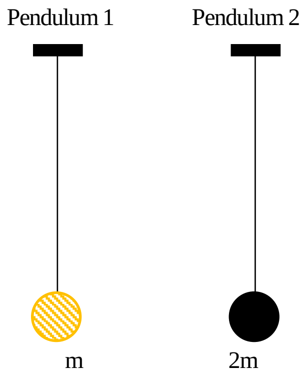


Fig.1

Q1.1. Periods of both pendulums T_o and T_o' respectively, which

- ☐ a. $T_o' = T_o$ because the period of a pendulum does not depend on its mass.
- ☐ b. $T_o' = 2T_o$ because the period of a pendulum is proportional to its mass.
- ☐ c. $T_o' = \frac{1}{2}T_o$) because the period of a pendulum is reversely proportional to its mass.
- ☐ d. $T_o' < T_o$ because pendulum 2 has a bigger mass, experiences more gravity force and swings more speedily.
- ☐ e. $T_o' > T_o$ because pendulum 2 has a bigger mass and experiences more weight, it is difficult to swing.

Q1.2. Confidence level:

☐ 0 = Total guess   ☐ 1 = Almost guess
☐ 2 = Not sure   ☐ 3 = Sure
☐ 4 = Almost certain   ☐ 5 = Certain

Case 2: Given two identical pendulums. Each pendulum is pulled from its equilibrium position. Pendulum 1 is at angle θ while pendulum 2 is at angle β . θ and β are small angles, and $\beta = 2\theta$ (Fig.2). Both pendulums are released to swing freely.

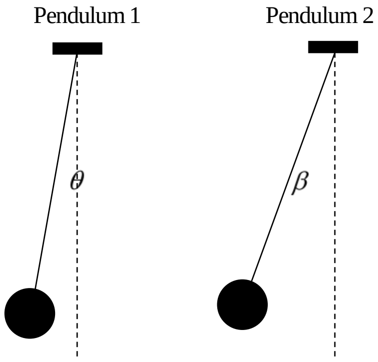


Fig.2

Q2.1. Periods of both pendulums T and T' respectively, which

- ☐ a. $T' \approx T$ and constant.
- ☐ b. $T' \approx 2T$ and constant.
- ☐ c. $T' \approx T$ and gradually decrease.
- ☐ d. $T' \approx 2T$ and gradually decrease.

☐ e. $T' < T$ because starting at a larger angle, pendulum 2 swings faster and spends less time completing each oscillation.

Q2.2. Confidence level:

☐ 0 = Total guess
☐ 1 = Almost guess
☐ 2 = Not sure
☐ 3 = Sure
☐ 4 = Almost certain
☐ 5 = Certain

Case 3: 3.1. Given two pendulums as shown in Fig.3. Pendulums have the same mass and size, but the length of pendulum 2 is double the length of pendulum 1.

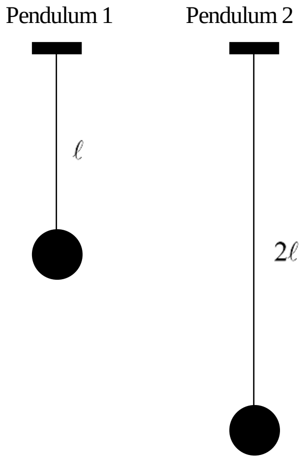


Fig.3

Q3.1.1. Periods of both pendulums T_o and T_o' respectively, which

☐ a. $T_o' = T_o$ because the period of a pendulum does not depend on its length.

☐ b. $T_o' = 2T_o$ because the period of a pendulum is proportional to its length.

☐ c. $T_o' = \frac{1}{2}T_o$ because the period of a pendulum is reversely proportional to its length.

☐ d. $T_o' = \sqrt{2}T_o$ because the period of a pendulum is proportional to the square root of its length.

☐ e. $T_o' = \frac{1}{\sqrt{2}}T_o$ because the period of a pendulum is reversely proportional to the square root of its length.

Q3.1.2. Confidence level:

☐ 0 = Total guess
☐ 1 = Almost guess
☐ 2 = Not sure
☐ 3 = Sure
☐ 4 = Almost certain
☐ 5 = Certain

3.2. Suppose pendulum 1 is brought to the moon, at which the gravitational acceleration is 6 times weaker than at the earth ($g_m = \frac{1}{6}g_o$).

Q3.2.1. The period of pendulum 1 on the moon is T_{mo} , which

☐ a. $T_{mo} = T_o$ because the period of a pendulum does not depend on gravitational acceleration.

☐ b. $T_{mo} = 6T_o$ because the period of a pendulum is proportional to gravitational acceleration.

☐ c. $T_{mo} = \sqrt{6}T_o$ because the period of a pendulum is proportional to the square root of gravitational acceleration.

☐ d. $T_o' < T_o$ at the moon, the pendulum experiences less gravitational force, and it swings at a smaller angle.

☐ e. $T_o' < T_o$ at the moon, there is no atmosphere, and the pendulum swings faster.

Q3.2.2. Confidence level:

☐ 0 = Total guess
☐ 1 = Almost guess
☐ 2 = Not sure
☐ 3 = Sure
☐ 4 = Almost certain
☐ 5 = Certain

Case 4: 4.1. Given two pendulums. Pendulums have the same length and mass, but the diameter of pendulum 2 is double the diameter of pendulum 1, as shown in Fig.4.

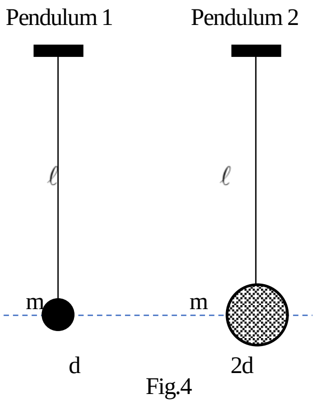


Fig.4

Q4.1.1. Periods of both pendulums T_o and T_o' respectively, which

☐ a. $T_o' \approx T_o$ because the period of a pendulum does not depend on the size of the bob.

☐ b. $T_o' = 2T_o$ because the period of a pendulum is proportional to the size of the bob.

☐ c. $T_o' = \frac{1}{2}T_o$ because the period of a pendulum is reversely proportional to the size of the bob.

☐ d. $T_o' < T_o$ because pendulum 2 has a larger cross-sectional area, experiences a stronger air drag and swings at a smaller angle.

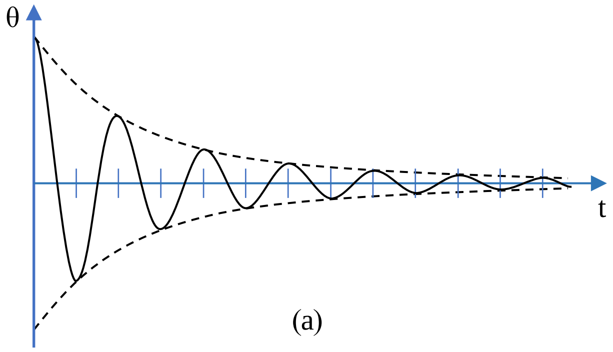
☐ e. $T_o' > T_o$) $T_o' < T_o$ because pendulum 2 has a larger cross-sectional area, experiences stronger air drag and swings slower.

Q4.1.2. Confidence level:

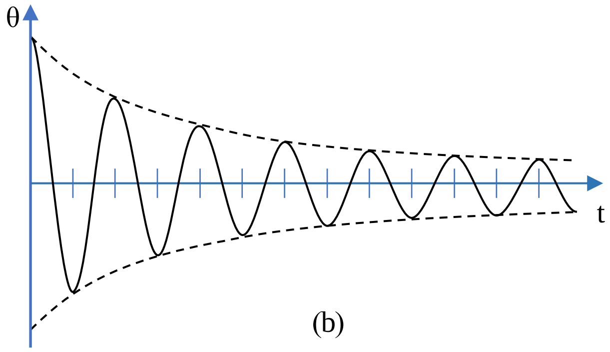
☐ 0 = Total guess ☐ 1 = Almost guess ☐ 2 = Not sure
☐ 3 = Sure ☐ 4 = Almost certain ☐ 5 = Certain

4.2. Each pendulum is pulled from its equilibrium position at the same angle and released to swing in the air. The graphs below indicate the characteristics of their oscillations. Choose the graph that best represents each pendulum.

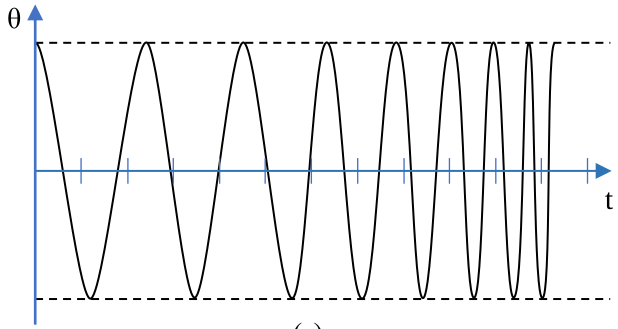
Q4.2.1.1. Pendulum 1: ☐ a. (a) ☐ b. (b) ☐ c. (c) ☐ d. (c) ☐ e. (e) ☐ f. (f) ☐ g. (g)	**Q4.2.1.2.** Confidence level: ☐ 0 = Total guess ☐ 1 = Almost guess ☐ 2 = Not sure ☐ 3 = Sure ☐ 4 = Almost certain ☐ 5 = Certain
Q4.2.2.1. Pendulum 2: ☐ a. (a) ☐ b. (b) ☐ c. (c) ☐ d. (c) ☐ e. (e) ☐ f. (f) ☐ g. (g)	**Q4.2.2.2.** Confidence level: ☐ 0 = Total guess ☐ 1 = Almost guess ☐ 2 = Not sure ☐ 3 = Sure ☐ 4 = Almost certain ☐ 5 = Certain



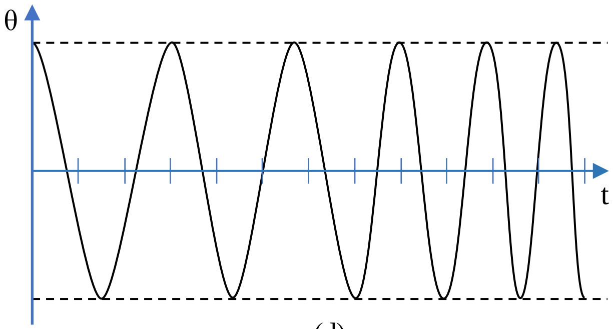
(a)



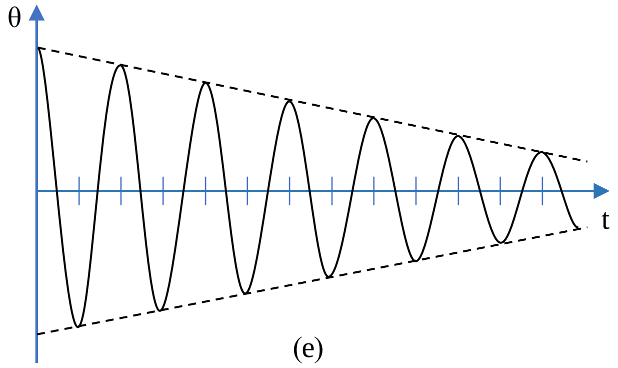
(b)



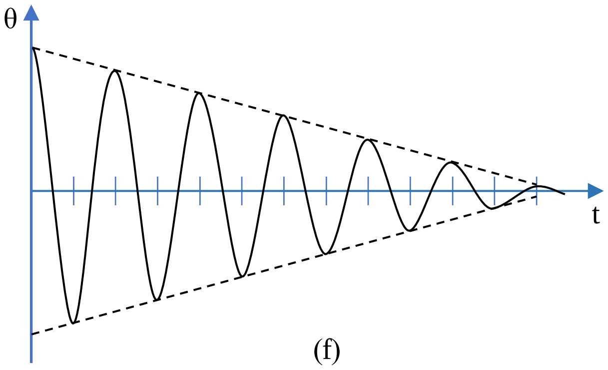
(c)



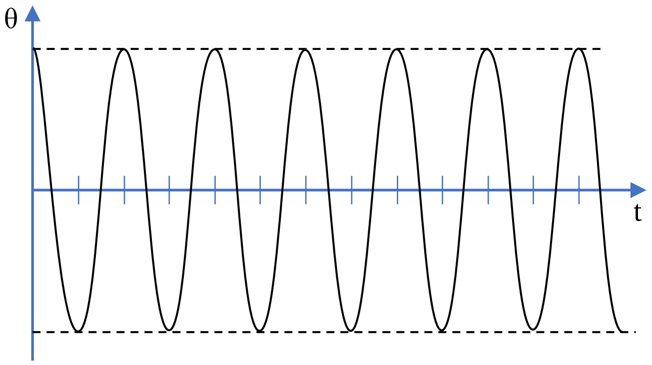
(d)



(e)



(f)



(g)

Case 5: A thin uniform bar with a small hole at one end is suspended at a fixed pivot, becoming a physical pendulum, as shown in Fig. 5. The period of the pendulum is T_o.

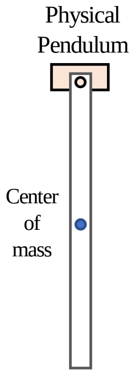


Fig.5

5.1. One more bar with identical properties is attached to the pendulum, doubling its mass but not affecting its length or centre of mass.

Q5.1.1. The period of the pendulum is T_o', which

☐ a. $T_o' = T_o$ because the period of this pendulum does not depend on its mass.

☐ b. $T_o' = 2T_o$ because the period of this pendulum is proportional to its mass.

☐ c. $T_o' < T_o$ because a bigger mass causes a stronger friction force at the pivot and it swings at a smaller angle.

☐ d. $T_o' > T_o$ because a bigger mass experiences a stronger gravitational force and it swings faster.

☐ e. $T_o' > T_o$ because a bigger mass makes the pendulum difficult to swing (swing slower) than before.

Q5.1.2. Confidence level:

☐ 0 = Total guess
☐ 1 = Almost guess
☐ 2 = Not sure
☐ 3 = Sure
☐ 4 = Almost certain
☐ 5 = Certain

5.2. Suppose the length of the pendulum increases to twice its previous length.

Q5.2.1. The period of the pendulum is T_o'', which

☐ a. $T_o'' = T_o$ because the period of this pendulum does not depend on its length.

☐ b. $T_o'' = 2T_o$ because the period of this pendulum is proportional to its length.

☐ c. $T_o'' > T_o$ because its length increases.

☐ d. $T_o'' < T_o$ because a bigger mass causes a stronger friction force at the pivot and it swings at a smaller angle.

☐ e. $T_o'' < T_o$ because a bigger mass experiences a stronger gravitational force and it swings faster.

Q5.2.2. Confidence level:

☐ 0 = Total guess
☐ 1 = Almost guess
☐ 2 = Not sure
☐ 3 = Sure
☐ 4 = Almost certain
☐ 5 = Certain

Case 6: Two identical thin uniform bars drilled with a small hole at their one end are suspended at two different fixed pivots, becoming two physical pendulums, as shown in Fig. 6. Both pendulums are pulled from their equilibrium position at the same angle and released to swing (air friction is negligible). The graphs below indicate the characteristics of their oscillations. Choose the graph that best represents each pendulum.

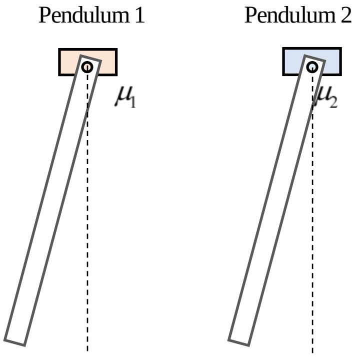
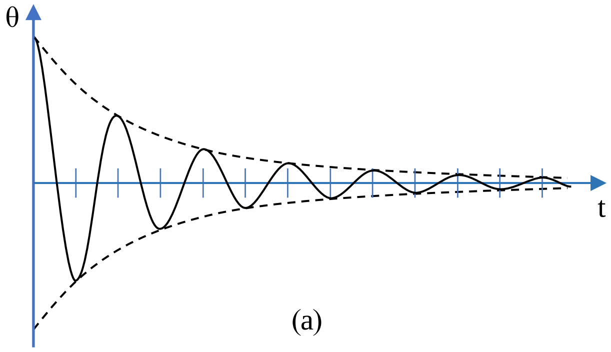
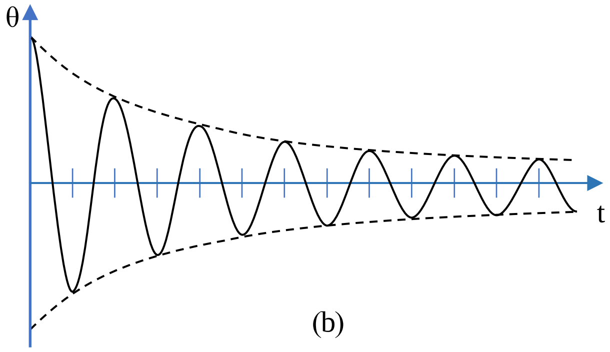


Fig.6

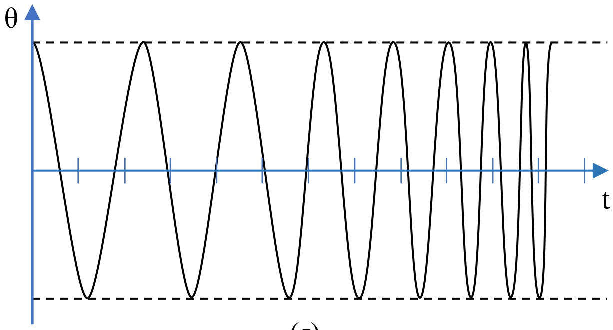
Q6.1.1. Pendulum 1: ☐ a. (a) ☐ b. (b) ☐ c. (c) ☐ d. (c) ☐ e. (e) ☐ f. (f) ☐ g. (g)	**Q6.1.2.** Confidence level: ☐ 0 = Total guess ☐ 1 = Almost guess ☐ 2 = Not sure ☐ 3 = Sure ☐ 4 = Almost certain ☐ 5 = Certain
Q6.2.1. Pendulum 2: ☐ a. (a) ☐ b. (b) ☐ c. (c) ☐ d. (c) ☐ e. (e) ☐ f. (f) ☐ g. (g)	**Q6.2.2.** Confidence level: ☐ 0 = Total guess ☐ 1 = Almost guess ☐ 2 = Not sure ☐ 3 = Sure ☐ 4 = Almost certain ☐ 5 = Certain



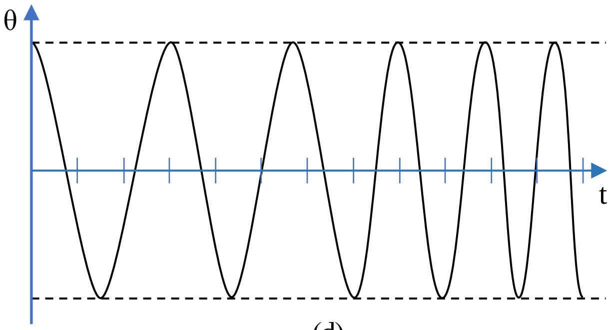
(a)



(b)



(c)



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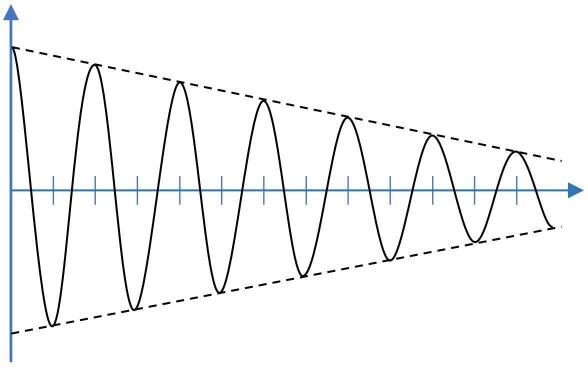
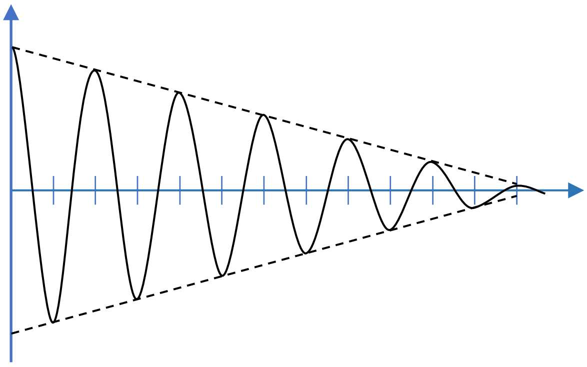
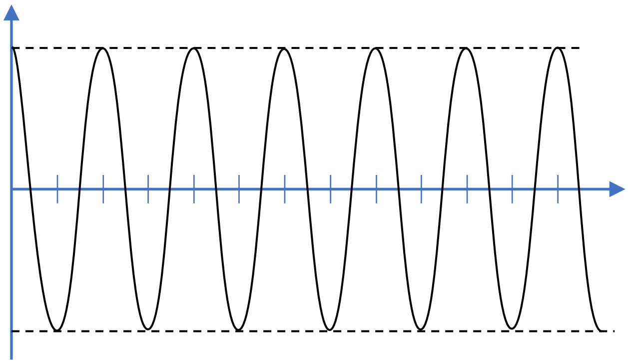






APPENDIX 3.2: Pre- and post-test on the concept of the Doppler effect

Name: ....
Gender .... Class ....
School..

Test on the Concept of the Doppler Effect
(20 minutes)

Consider the cases below and tick in the box (☑) in front of the only one correct answer and your confidence to answer each question.

Confidence level:

0 = Total guess	1 = Almost guess	2 = Not sure
3 = Sure	4 = Almost certain	5 = Certain

I. General Concept

QI1.1. Two students are singing at the same volume. Student **X** sings at a high pitch, and Student **Y** sings at a lower pitch. Which of the following is true?

☐ a. The two frequencies are the same, but the amplitudes are different.
☐ b. The two amplitudes are the same, but the frequencies are different.
☐ c. The two frequencies are the same, and the amplitudes are also the same.
☐ d. The two frequencies are different, and the amplitudes are also different.
☐ e. The two frequencies are different, and the amplitude cannot be compared.

QI1.2. Confidence level:

☐ 0 = Total guess	☐ 1 = Almost guess	☐ 2 = Not sure
☐ 3 = Sure	☐ 4 = Almost certain	☐ 5 = Certain

Consider the following description and answer questions 2 and 3.
Students **X** and **Y** are standing 50 meters apart and yell “Yo!” at each other at exactly the same time.

QI2.1. They yell at each other at the same volume, but **Y** yells with a higher pitch than **X** does. Who will hear the other’s sound first?

☐ a. They will hear each other at exactly the same time because the speed of sound waves depends on the properties of the air.
☐ b. **X** will hear the sound first because the speed of sound waves depends on frequency according to $v = \lambda f$.
☐ c. They will hear each other at exactly the same time because the speed of sound waves depends on amplitude.
☐ d. **X** will hear the sound first because sound with a higher frequency is more penetrating.
☐ e. **Y** will hear the sound first because the speed of sound waves depends on frequency according to $v = \lambda f$.

QI2.2. Confidence level:

☐ 0 = Total guess	☐ 1 = Almost guess	☐ 2 = Not sure
☐ 3 = Sure	☐ 4 = Almost certain	☐ 5 = Certain

QI3.1. Student **Y** yells louder than **X**, but they yell at each other with the same pitch. Who will hear each other’s sound first?

☐ a. **X** will hear the sound first because the speed of the waves depends on the amplitude of the sound.
☐ b. **Y** will hear the sound first because the speed of sound waves depends on inversely on the amplitude of the sound.

☐ c. They will hear each other at exactly the same time because the speed of the waves depends on the frequency according to $v = \lambda f$.

☐ d. They will hear each other at exactly the same time because the speed of the waves depends on the properties of the air.

☐ e. **X** will hear the sound first because the wave with the larger amplitude travels further.

QI3.2. Confidence level:

☐ 0 = Total guess
☐ 3 = Sure
☐ 1 = Almost guess
☐ 4 = Almost certain
☐ 2 = Not sure
☐ 5 = Certain

II. Doppler Effect

Case 1: An ambulance stops on a straight road to pick up a victim. The ambulance beeps its siren at a certain frequency f_s . Meanwhile, a boy stands silently on the sidewalk and observes the ambulance. On the same road, a girl rides her bicycle in the direction of the ambulance with a fixed speed vector. Additionally, a man is running down the street in the opposite direction of the girl, with the same velocity vector as hers, but at a slower speed. Please refer to Fig. 1 for a visual representation.

Fig. 1

QII1.1. The boy hears siren at frequency f_o , which	Confidence level
☐ a. Constantly equal to the source frequency (f_s) ☐ b. Constantly higher than the frequency of the source $(> f_s)$ ☐ c. Constantly lower than the frequency of the source $(< f_s)$ ☐ d. Equal to the source frequency and gradually decreases ☐ e. Low than the source frequency and gradually increases	☐ 0 = Total guess ☐ 1 = Almost guess ☐ 2 = Not sure ☐ 3 = Sure ☐ 4 = Almost certain ☐ 5 = Certain
QII1.2. The girl hears siren at frequency f_o' , which	Confidence level
☐ a. Constantly equal to the source frequency (f_s) ☐ b. Constantly higher than the frequency of the source $(> f_s)$ ☐ c. Higher than the source frequency and gradually decreases ☐ d. Equal to the source frequency and gradually increases ☐ e. Low than the source frequency and gradually increases	☐ 0 = Total guess ☐ 1 = Almost guess ☐ 2 = Not sure ☐ 3 = Sure ☐ 4 = Almost certain ☐ 5 = Certain
QII1.3. The man hears siren at frequency f_o'' , which	Confidence level
☐ a. Low than the source frequency and gradually decreases ☐ b. Equal to the source frequency and gradually decreases ☐ c. Higher than the source frequency and gradually decreases ☐ d. Constantly lower than the frequency of the source $(< f_s)$ ☐ e. Constantly equal to the source frequency (f_s)	☐ 0 = Total guess ☐ 1 = Almost guess ☐ 2 = Not sure ☐ 3 = Sure ☐ 4 = Almost certain ☐ 5 = Certain

Case 2: After receiving the victim, the ambulance is driven at a constant velocity vector towards the boy and passes the man as shown in Fig. 2.

Fig. 2

QII2.1. The boy hears siren at frequency f_o, which	Confidence level
☐ a. Constantly equal to the source frequency (f_s) ☐ b. Constantly lower than the frequency of the source ($< f_s$) ☐ c. Constantly higher than the frequency of the source ($> f_s$) ☐ d. Low than the source frequency and gradually increases ☐ e. Equal to the source frequency and gradually increases	☐ 0 = Total guess ☐ 1 = Almost guess ☐ 2 = Not sure ☐ 3 = Sure ☐ 4 = Almost certain ☐ 5 = Certain
QII2.2. The girl hears siren at frequency f_o' , which	Confidence level
☐ a. Low than the source frequency and gradually increases ☐ b. Higher than the source frequency and gradually increases ☐ c. Increasingly unpredictable ☐ d. Constantly higher than the frequency of the source ($> f_s$) ☐ e. Constantly equal to the source frequency (f_s)	☐ 0 = Total guess ☐ 1 = Almost guess ☐ 2 = Not sure ☐ 3 = Sure ☐ 4 = Almost certain ☐ 5 = Certain
QII2.3. The man hears siren at frequency f_o'' , which	Confidence level
☐ a. Constantly lower than the frequency of the source ($< f_s$) ☐ b. Constantly equal to the source frequency (f_s) ☐ c. Decreasingly unpredictable ☐ c. Equal to the source frequency and gradually decreases ☐ d. Higher than the source frequency and gradually decreases	☐ 0 = Total guess ☐ 1 = Almost guess ☐ 2 = Not sure ☐ 3 = Sure ☐ 4 = Almost certain ☐ 5 = Certain

Case 3: The ambulance continued to drive past the boy as shown in Fig. 3.

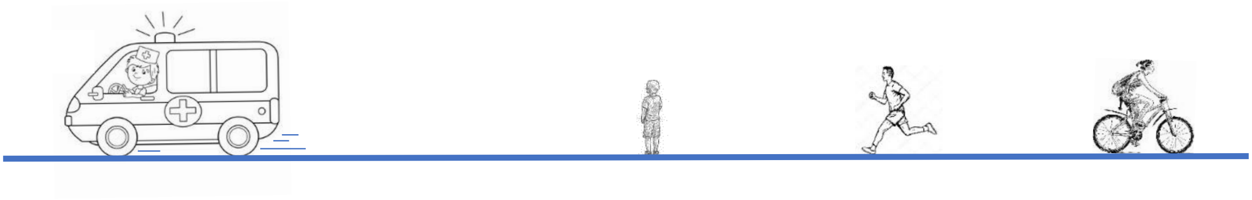


Fig. 3

QII3.1. The boy hears siren at frequency f_o , which	Confidence level
☐ a. Constantly equal to the source frequency (f_s) ☐ b. Constantly lower than the frequency of the source (< f_s) ☐ c. Equal to the source frequency and gradually decreases ☐ d. Low than the source frequency and gradually increases ☐ e. Higher than the source frequency and gradually decreases	☐ 0 = Total guess ☐ 1 = Almost guess ☐ 2 = Not sure ☐ 3 = Sure ☐ 4 = Almost certain ☐ 5 = Certain
QII3.2. The girl hears siren at frequency f_o' , which	Confidence level
☐ a. Low than the source frequency and gradually increases ☐ b. Equal to the source frequency and gradually decreases ☐ c. Decreasingly unpredictable ☐ d. Constantly lower than the frequency of the source (< f_s) ☐ e. Constantly equal to the source frequency (f_s)	☐ 0 = Total guess ☐ 1 = Almost guess ☐ 2 = Not sure ☐ 3 = Sure ☐ 4 = Almost certain ☐ 5 = Certain
QII3.3. The man hears siren at frequency f_o'', which	Confidence level
☐ a. Decreasingly unpredictable ☐ b Equal to the source frequency and gradually decreases ☐ c. Low than the source frequency and gradually increases ☐ d. Constantly lower than the frequency of the source (< f_s) ☐ e. Constantly equal to the source frequency (f_s)	☐ 0 = Total guess ☐ 1 = Almost guess ☐ 2 = Not sure ☐ 3 = Sure ☐ 4 = Almost certain ☐ 5 = Certain

APPENDIX 3.3: Pre- and post-test on the concept of Interference

Name: ....
Gender .... Class ....
School...

Test on the Concept of Wave Interference
(20 minutes)

Consider the cases below and tick in the box (☑) in front of the only one correct and your confidence to answer each question.

Confidence level:
0 = Total guess   1 = Almost guess   2 = Not sure
3 = Sure   4 = Almost certain   5 = Certain

1.1. Phase difference for constructive interference $\Delta\varphi$ $(n = 0,1,2,3,...)$:

☐ a. $\Delta\varphi = n\frac{\pi}{2}$ ☐ b. $\Delta\varphi = (2n+1)\frac{\pi}{2}$ ☐ c. $\Delta\varphi = (2n+1)\pi$
☐ d. $\Delta\varphi = n\pi$ ☐ e. $\Delta\varphi = n(2\pi)$

1.2. Confidence level:
☐ 0 = Total guess   ☐ 1 = Almost guess   ☐ 2 = Not sure
☐ 3 = Sure   ☐ 4 = Almost certain   ☐ 5 = Certain

2.1. Phase difference for destructive interference $\Delta\varphi$ $(n = 0,1,2,3,...)$:

☐ a. $\Delta\varphi = n\frac{\pi}{2}$ ☐ b. $\Delta\varphi = (2n+1)\frac{\pi}{2}$ ☐ c. $\Delta\varphi = (2n+1)\pi$
☐ d. $\Delta\varphi = n\pi$ ☐ e. $\Delta\varphi = n(2\pi)$

2.2. Confidence level:
☐ 0 = Total guess   ☐ 1 = Almost guess   ☐ 2 = Not sure
☐ 3 = Sure   ☐ 4 = Almost certain   ☐ 5 = Certain

3.1. Path length difference for destructive interference Δ $(n = 0,1,2,3,...)$:

☐ a. $\Delta = \frac{\lambda}{2}$ ☐ c. $\Delta = n\frac{\lambda}{2}$ ☐ c. $\Delta = (2n+1)\frac{\lambda}{2}$
☐ d. $\Delta = n\lambda$ ☐ e. $\Delta = (2n+1)\lambda$

3.2. Confidence level:
☐ 0 = Total guess   ☐ 1 = Almost guess   ☐ 2 = Not sure
☐ 3 = Sure   ☐ 4 = Almost certain   ☐ 5 = Certain

4.1. Path length difference for destructive interference Δ $(n = 0,1,2,3,...)$:

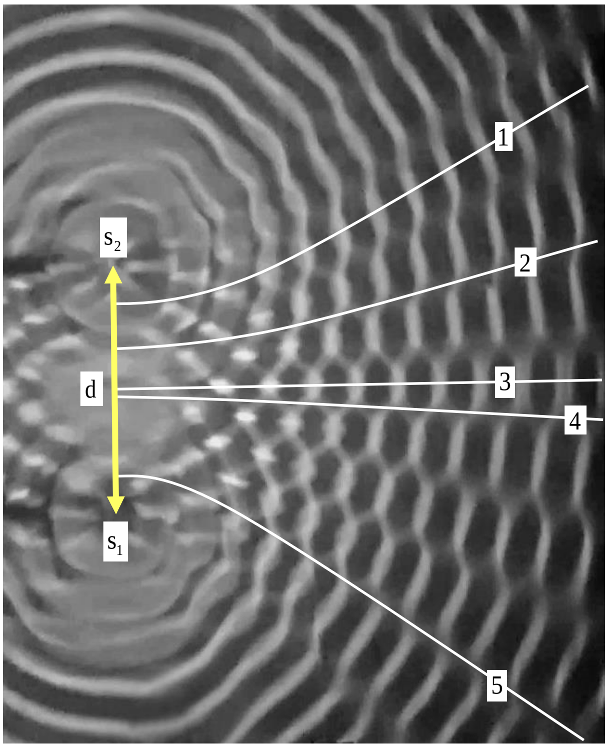
☐ a. $\Delta = \lambda$ ☐ b. $\Delta = n\lambda$ ☐ c. $\Delta = n\frac{\lambda}{2}$
☐ d. $\Delta = (2n+1)\lambda$ ☐ e. $\Delta = (2n+1)\frac{\lambda}{2}$

4.2. Confidence level:

☐ 0 = Total guess
☐ 1 = Almost guess
☐ 2 = Not sure
☐ 3 = Sure
☐ 4 = Almost certain
☐ 5 = Certain

Consider the following description and answer questions 5 and 6.

In the figure on the right S_1 and S_2 are two coherence waves sources. Points 1, 2, 3, 4 and 5 are points of waves superpose and interfere with each other.



5.1. Which points does constructive interference occur?

☐ a. 3
☐ b. 1 and 3
☐ c. 1, 2 and 3
☐ d. 2, 4 and 5
☐ e. 1, 2, 4 and 5

5.2. Confidence level:

☐ 0 = Total guess
☐ 1 = Almost guess
☐ 2 = Not sure
☐ 3 = Sure
☐ 4 = Almost certain
☐ 5 = Certain

6.1. Which points does constructive interference occur?

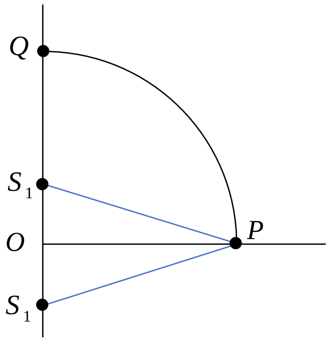
☐ a. 3
☐ b. 1 and 3
☐ c. 2, 4 and 5
☐ d. 3, 4 and 5
☐ e. 1, 2, 4 and 5

6.2. Confidence level:

☐ 0 = Total guess
☐ 1 = Almost guess
☐ 2 = Not sure
☐ 3 = Sure
☐ 4 = Almost certain
☐ 5 = Certain

Consider the following description and answer questions 7 to 11.

In the figure on the right S_1 and S_2 are two coherence waves sources with wavelength λ apart from each other by $d = 2\lambda$. P lies on the perpendicular bisector of distance *D*, at a distance greater than *D* from the sources, as seen in the figure. Q is on the line passing S_1 and S_2, which $OP = OQ$.



7.1. What is the path length difference of point P ?

☐ a. 0 (zero)
☐ b. 0.5λ
☐ c. λ
☐ d. 1.5λ
☐ e. 2λ

7.2. Confidence level:

☐ 0 = Total guess
☐ 1 = Almost guess
☐ 2 = Not sure
☐ 3 = Sure
☐ 4 = Almost certain
☐ 5 = Certain

8.1. What is the path length difference of point Q?

☐ a. 0 (zero) ☐ b. 0.5λ ☐ c. λ
☐ d. 1.5λ ☐ e. 2λ

8.2. Confidence level:

☐ 0 = Total guess ☐ 1 = Almost guess ☐ 2 = Not sure
☐ 3 = Sure ☐ 4 = Almost certain ☐ 5 = Certain

9.1. Which statement below is right about P and Q?

☐ a. P and Q are points of constructive interference occurrences.
☐ b. P and Q are points of destructive interference occurrences.
☐ c. P is point of destructive interference occurrence, while Q is point of destructive interference occurrence
☐ d. P is point of constructive interference occurrence, while Q is point of destructive interference occurrence
☐ e. P and Q are points of constructive and destructive interference occurrences.

9.2. Confidence level:

☐ 0 = Total guess ☐ 1 = Almost guess ☐ 2 = Not sure
☐ 3 = Sure ☐ 4 = Almost certain ☐ 5 = Certain

10.1. On PQ (including P and Q), how many constructive interferences occur?

☐ a. 1 ☐ b. 2 ☐ c. 3
☐ d. 4 ☐ e. 5

10.2. Confidence level:

☐ 0 = Total guess ☐ 1 = Almost guess ☐ 2 = Not sure
☐ 3 = Sure ☐ 4 = Almost certain ☐ 5 = Certain

11.1. On PQ (including P and Q), how many destructive interferences occur?

☐ a. 1 ☐ b. 2 ☐ c. 3
☐ d. 4 ☐ e. 5

11.2. Confidence level:

☐ 0 = Total guess ☐ 1 = Almost guess ☐ 2 = Not sure
☐ 3 = Sure ☐ 4 = Almost certain ☐ 5 = Certain

APPENDIX 3.4: Survey questionnaire of participant perception on teaching practices

Please take a moment to complete a survey regarding this topic's teaching and learning experience. Please answer each question based on your personal experience and perception of the lesson.

1. How interesting did you find the lesson?
    - ☐ 4. Very interesting
    - ☐ 3. Interesting
    - ☐ 2. Not interesting
    - ☐ 1. Not interesting at all

2. How well do you understand the lesson?
    - ☐ 4. Very clear
    - ☐ 3. Clear
    - ☐ 2. Not clear
    - ☐ 1. Don't understand

3. How important do you think the lesson is?
    - ☐ 4. Very important
    - ☐ 3. Important
    - ☐ 2. Not important
    - ☐ 1. Not important at all

4. How useful did you find the lesson?
    - ☐ 4. Very useful
    - ☐ 3. Useful
    - ☐ 2. Not useful
    - ☐ 1. Not useful at all

5. How relevant did you find the lesson?
    - ☐ 4. Very relevant
    - ☐ 3. Relevant
    - ☐ 2. Not relevant
    - ☐ 1. Not relevant at all

6. How difficult did you find the lesson?
    - ☐ 4. Very difficult
    - ☐ 3. Difficult
    - ☐ 2. Easy
    - ☐ 1. Very easy

7. How skilful do you feel in using ICT (specifically Tracker, Sensor, and MS Excel) during the lesson?
    - ☐ 4. Skillful
    - ☐ 3. Can use
    - ☐ 2. Not skillful
    - ☐ 1. Cannot use

Thank you for your participation.