STUDENT LEARNING EXPERIENCES FROM DRAG EXPERIMENTS USING HIGH-SPEED VIDEO ANALYSIS

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ABSTRACT
The concept of drag is rarely taught in most undergraduate physics laboratories, because to do so requires the use of fairly sophisticated equipment. In this study, we developed a laboratory unit to study both quadratic and linear drag using high-speed video analysis. The laboratory unit had four objectives, including: (1) to improve the conceptual understanding of drag, (2) to develop technical skills in high-speed video analysis, (3) to develop science inquiry skills, and (4) to motivate student learning. This laboratory unit was part of advanced laboratory work for third year physics students, of whom four students were selected to carry out this laboratory unit. In total, 30 conceptual questions on drag were administered to students before and after the laboratory unit, and students were interviewed in order to explore their learning experiences. After the laboratory unit was completed, students reported that their conceptual understanding on both quadratic and linear drag had increased and that they had gained a positive and productive learning experience.

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INTRODUCTION
The laboratory is an essential part of the science class because it creates a situation in which students can acknowledge and respond, understand problems, and observe and collect data regarding scientific methods, allowing them to make conclusions on the studied topic. If laboratory courses are developed, evaluated and refined based on feedback received regarding their impact on students’ level of knowledge, relevant skills and attitudes, they can provide a valuable opportunity similar to research experience (Galvez & Singh, 2005).

In first year physics classes, students learn theories in lectures and conduct experiments in laboratories to understand relationships between theories and real phenomena; however, there is a lack of suitable laboratories for advanced or intermediate classes, especially in terms of mechanics. Most advanced mechanics courses for physics usually only cover theory; few or no laboratory experiments or in-class demonstrations take place (Bernhard, 2010). Findings from previous studies indicate that upper-level physics students also face difficulties similar to our first year students (Rimoldini & Singh, 2005) in terms of mechanics topics.

Drag is one topic in mechanics that is not covered much in most undergraduate physics curricula; however, understanding drag is essential in order to apply mechanics to the real world situation. The drag on an object is generally dependent on its velocity, and there are two models for drag - a linear model and a quadratic model (Owen & William, 2005). Demonstrating linear and quadratic drag in the laboratory is difficult due to the extreme range of speeds required for these two models. Experiments involving drag have been published, but most focus only on the drag caused by air friction (Takahashi & Thomson, 1999; Heck & Uylings, 2009), or use outdated equipment that needs to be modernized (Owen & William, 2005).

Recently, high-speed video technology has been used to study various mechanical scenarios (Heck & Uylings, 2009), as the price of high-speed camera equipment has become affordable at the consumer level, plus because video analysis software has become more effective and more precise when analysing motion data (Brown & Cox, 2009). As a result, many physicists and physics instructors have started to employ high-speed video analysis techniques to demonstrate mechanics phenomena and/or to conduct experiments. Using high-speed video analysis creates an opportunity to develop both science inquiry skills and technical skills (Heck & Uylings, 2009) and is an alternative, low-cost data collection technique for studying drag.

This paper describes an advance laboratory in 'drag unit', and a subsequent laboratory test carried out that had four objectives: (1) to improve the conceptual understanding of drag, (2) to develop technical skills with respect to high-speed video analysis, (3) to develop science inquiry skills, and (4) to motivate student learning. We chose to teach on a topic of drag because students only learned about air drag in a lecture of free falling objects during their first-year physics course.

CONCEPTUAL UNDERSTANDING: DRAG

An object moving through fluid creates a drag which retards motion, a phenomenon that can normally be described using the Navier-Stokes (non-linear partial differential) equation (Lyle & Howard, 1999). The key factor in determining drag is the Reynolds number, a dimensionless number of the ratio of inertial forces to viscous forces. From previous studies it has been found that falling objects of different shapes have different Reynolds number values (Re) depending on the density of the medium (ρ), the velocity of the object in that medium (υ), the dynamics viscosity of the medium (μ), the characteristic length (d), and the kinetic viscosity (ν) (Lyle & Howard, 1999). According to Heck and Uylings (2009), three case outcomes can be distinguished based on the value of the Reynolds number:

- *Case 1: Linear velocity dependence*. If the Reynolds number is very small ($\mathrm{Re} < 1$), then the drag force linearly depends on the velocity of the object. Examples include dust particles floating in air (Lyle & Howard, 1999), or a sphere falling in viscous liquid or a falling sphere viscometer (Mendoza-Arenas, Perico & Fajardo, 2010).
- *Case 2: Quadratic velocity dependence.* If the Reynolds number is large but not too large ($10^3 < \mathrm{Re} < 2 \times 10^5$), then the drag is proportional to the square of the velocity of the object. Examples of this include falling parachutes (Lyle & Howard, 1999) or falling shuttlecocks (Heck & Uylings, 2009).
- *Case 3: Moderate Reynolds number*. If the Reynolds number is not too small and no too large ($1 < \mathrm{Re} < 10^3$), then we have a combination of linear and quadratic drag.

In studying drag, we have to measure a terminal velocity. The concept map for drag is shown in Figure 1, and this map is presented to students when lecturing on drag.

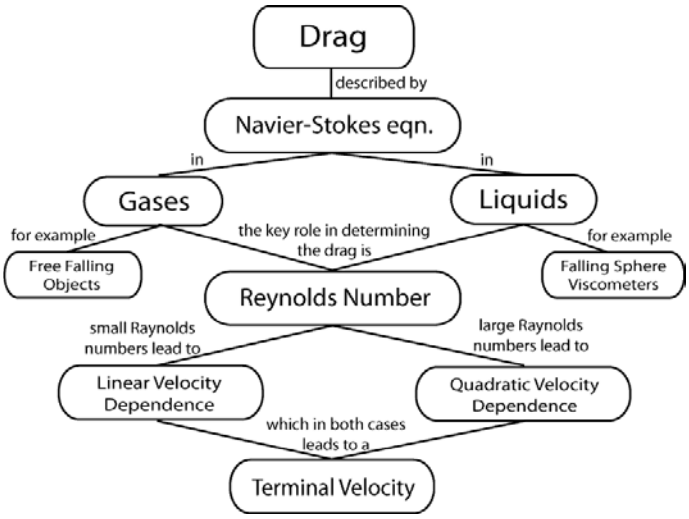

Figure 1: Concept Map for Drag

In order to help students understand drag in fluids, covering both linear and quadratic drag, we developed two experiments: a free falling of various objects, and damped oscillations. These experiments are good examples of physics phenomena dealing with drag and were developed from previous studies (Takahashi & Thomson, 1999; Heck & Uylings, 2009; Shamim, Zia, & Anwar, 2010). The details of both modules will be described in the next section.

TECHNICAL SKILLS: HIGH-SPEED VIDEO ANALYSIS

The use of high speed cameras has increased significantly in recent years because the technology has become affordable at the consumer level, giving teachers and students the opportunity to record and study the physics of motion. By combining high-speed video with video analysis software, a user can manipulate data to calculate velocities, acceleration and other mechanical values (Page, Moreno, Candelas, & Belmar, 2008). The high-speed camera used in these laboratory experiments was the Casio EXILIM Pro EX-F1 digital camera - which can capture video at 300, 600 and 1200 frames per second, and we used free video analysis software called Tracker, which is specifically designed to analyze physics experiments (Brown & Cox, 2009).

Before the students started any experiment, they were taught about the sources of error that appear in 2D coordinate measurements (Page, Moreno, Candelas, & Belmar, 2008) — by setting up the camera and using the video analysis software.

LABORATORY PEDAGOGIES

With appropriate laboratory pedagogies, meaningful learning in the laboratory can occur if students are given sufficient time, plus opportunities for interaction and reflection with a teacher (Hofstein & Lunetta, 2003). In traditional laboratories, students follow specific, detailed directions to arrive at a predetermined outcome, and spend most of their time doing the experiments without investing too much thought. Gaddis and Schoffstall (2007) categorized laboratory pedagogies into four types according to the experimental design (given by the instructor or generated by the students) and learning approaches used (inductive or deductive), plus the type of conclusions reached (predetermined, or reached from the data or not) (Gaddis & Schoffstall, 2007). The four types of laboratory pedagogies are:

- *Expository or traditional laboratory*. Students follow specific detailed directions to arrive at a predetermined outcome. The learning approach here is deductive.
- *Open inquiry.* Students are expected to develop their own hypotheses and design their own procedures; the outcome is not determined. The learning approach here is inductive.
- *Problem-based*. Students design their own experiments to solve the proposed problem and the outcome is mostly undetermined. The learning approach here is deductive.
- *Guided inquiry or discovery-based experiments*. Students are provided with a tested procedure to arrive at a predetermined outcome. The learning approach here is inductive.

In this study, we used both guided and open inquiry methods for our laboratory pedagogies, as shown in Table 1.

Table 1: Activities carried out, time spent and laboratory pedagogy used in each laboratory class

Class	Activities	Time (hrs)	Laboratory Pedagogy
1	Pre-test	0.5	
	Lecture	1.5	
	Video analysis exercises	0.5	
2	Module 1	3	Guided inquiry
3	Module 2	2.5	Guided inquiry
	Discuss a mini project	0.5	
4	Mini project	3	Open inquiry
5	Mini project	3	Open inquiry
6	Presentation	0.5	
	Post-test	0.5	

METHOD

This laboratory used was part of an advanced laboratory for third year physics undergraduates at Chiang Mai University in Thailand. Students could choose to do four laboratories for a whole semester, and each laboratory took four weeks. Table 1 displays the activities carried out within this laboratory over the four weeks. In total four third year students selected this laboratory.

MODULE 1: FREE FALLING OBJECTS

This module aimed to familiarize students with high-speed video analysis and investigate the motion of objects under quadratic air drag, being based on previous studies on the air resistance of falling balls, balloons (Gluck, 2003; Messer & Pantaleone, 2010), shuttlecocks (Heck & Uylings, 2009) and cup-cake cups (Brown & Cox, 2009). The students were provided with a procedure to investigate air drag affecting free falling objects. They used Tracker to compare both quadratic model and linear model with the real data, as shown in Figure 2. This laboratory module used guided inquiry approach.

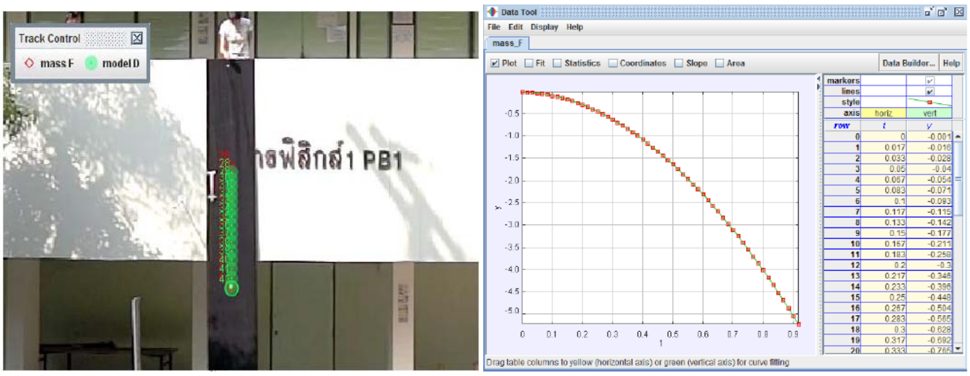

Figure 2: Screen shots of student work on Module 1

MODULE 2: DAMPED OSCILLATION

This module aimed to investigate the motion of an object under the influence of linear liquid drag. The experiment was based on previous studies on the damped motion of spherical objects in viscous liquids, such as water (Mendoza-Arenas, Perico & Fajardo, 2010), honey and glycerin (Shamim, Zia, & Anwar, 2010). The students attached a small solid sphere with spring, let it oscillate in liquid, recorded high-speed video and analyzed its motion using Tracker, as shown in Figure 3. Information can be extracted from the position-time graphs. In the under-damped case, we used these oscillations to determine the viscosity of the fluid.

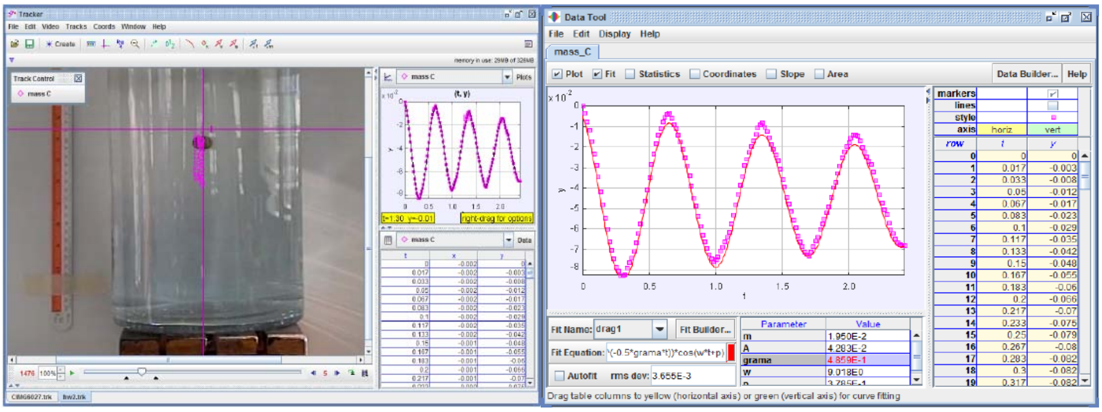

Figure 3: Screen shots of student work on Module 2

MINI PROJECT

The mini project was based on open inquiry, so students proposed their own hypotheses and designed their own procedures with guidance from an instructor. They also had an opportunity to operate the high-speed camera with minimum help from the instructor. Most of the students' mini projects were extended from either module 1 or module 2. For example, one student developed a hypothesis that a size of container might have an effect on an error in determining the viscosity. Thus she repeated an experiment with different sizes of container.

INSTRUMENT

To measure students' conceptual understanding, we developed 20 questions: thirteen multiple-choice questions and seven open questions. The concepts of quadratic air drag were tested using the thirteen multiple-choice questions and the concepts of linear liquid drag were tested using the seven open questions. Examples of the multiple-choice and open questions are shown in Figures 4 and 5, respectively. The 20 questions were given to students as both pre and post-test.

5. The air drag acting on a falling object is directly proportional to ____________

a) a square of its velocity when the object has a high value of velocity.
b) the object velocity when the object has a low value of velocity.
c) a square root of the object velocity, according to $v = \sqrt{v_0^2 + 2gs}$
d) Both a) and b)

Figure 4: Example of a multiple-choice question on quadratic air drag

12. Consider a spherical mass attached to a spring oscillates in liquid, as shown in the below figure. Draw a free body diagram of all forces acting on the mass that is moving downward.

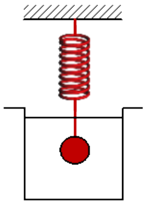

Figure 5: Example of an open question on linear liquid drag

RESULTS AND DISCUSSION

STUDENTS' CONCEPTUAL UNDERSTANDING

The students' scores from the conceptual questions - both pre- and post-instruction, are displayed in Figure 6. Students performed better in response to both quadratic and linear drag questions after instruction.

STUDENTS' LEARNING EXPERIENCES

After the students had carried out the post-test, the researchers interviewed them to explore their learning experiences. All the students stated that they were satisfied with what they had learned in this laboratory, and mentioned that designing their own experiments had increased their level of interest and motivated them to learn and analyze the data. They also said that learning about drag had helped them make the connection between physics principles and real world phenomena. They said they had been excited about using a high-speed camera and high-speed video analysis, mentioning other experiments that could be undertaken using this technique. They said they preferred the small group work, as it had allowed them to learn from the others students - learning to solve problems as a group.

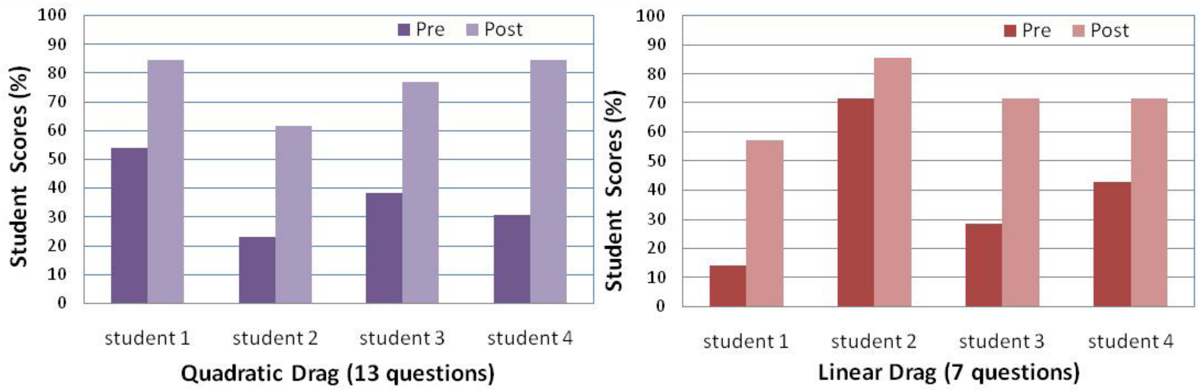

Figure 6: Student scores (%) pre- and post-instruction on quadratic drag and linear drag

CONCLUSIONS

In this study, we developed two experiments on linear and quadratic drag using high-speed video techniques. In designing the whole unit for this laboratory, we used the guided inquiry method to teach both experimental modules, and used an open inquiry approach for the mini project. By the end of the laboratory experiment, the students' level of understanding on drag had improved, plus they had developed skills, both in the use of high-speed video analysis and in scientific inquiry. The students said they were satisfied with their learning experience from this laboratory and reported having had a positive and productive learning experience.

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