PAPER

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Simple mechanical experiment on forced oscillations

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Abstract

This paper is about an experimental problem on forced oscillations, which was given to 14-year-old primary school pupils at the Slovenian national (final) level of the physics competition in April 2019. At the time when the competition took place these pupils were approaching the end of the school year, when they encountered physics as a school subject for the first time. The objectives of the experimental exam at the competition, the circumstances and the limitations are discussed. The final experimental setup, which is simple, inexpensive and purely mechanical is described and structured form of the problem is given and discussed. The results of the competition are briefly presented. As such, the experiment can also be used as content for an IBL lesson.

Keywords: experimental problem, physics competition, forced oscillations

1. Introduction

Oscillations and waves can be found almost everywhere in physics, but also in everyday life. Basic aspects of these important and broad concepts are already introduced in primary school, usually by observing mechanical oscillations. In this paper we consider a somewhat advanced oscillation phenomenon when viewed from the perspective of primary (physics) education, but on the other hand very often found in the outside world; resonance of a mechanical pendulum.

Some ideas about mechanical experimental setups for teaching damped, coupled and forced oscillations can be found in the literature, e.g. [1–5]. In this article an idea for another version of setup is presented, which is simple and inexpensive. It was designed to be used in the national

physics competition for 14-year-old pupils, but it can also be used in school lessons.

In Slovenia children start primary school (PS) at the age of 6. PS is compulsory, schools are public (more than 99% children attend public PS) and lasts 9 years until the pupils reach the age of 15. Physics is integrated into the *science* subjects in the first seven years of Slovenian PS and becomes a separate subject in the last two (8th and 9th) grades of PS. In a long tradition of physics competitions in Slovenia, last year we ran the 39th and 57th national competitions for primary and secondary school pupils respectively¹. The competition runs in several stages; for primary

¹ Each year the call for competition is at www.dmfa.si.

school pupils these are the school, regional and final national competition. The national phase of the physics competition for primary school pupils is special compared to many other existing competitions (physics, but also non-physics and for both target groups, primary and secondary school pupils) in that it also includes an experimental test [6]. There are obvious reasons why the experimental part of the science competition is generally so rare, and we will address some of them in the conclusions. In this article we discuss in detail an example of an experimental problem given to 14-year-old students who entered the final phase of the competition last year.

About 20%–25% of all pupils in the cohort take part in the first (school) stage of the competition, and every 25th participant of the school level manages to enter the third stage, the national competition. That sums to about 140 pupils from each of the last two grades of the Slovenian PS (14 and 15 years) who have already successfully participated in the two previous stages of the competition and who are given a chance to show their experimental skills and talent in solving experimental problems at the national level. While in the first two stages of the competition only theoretical problems are given to students, an experimental task presents an additional challenge for the participants. Since physics is an experimental science, it is important to include experimental tasks in the physics competition. Also, the ability to solve theoretical problems is not necessarily linked to the ability to solve experimental problems—and vice versa; there are some who are more experimentalists, and others whose preferences lie in theory (of course there is also a cross section). At the national level of the competition we pay attention to both groups of students [6].

2. Objectives

The experimental exam of the national competition lasts 80 minutes, with 70 pupils taking part in the same exam at the same time (after the first round, the two groups alternate; those who have taken the theoretical exam in the first part continue with the experimental exam and vice versa). We need 70 identical sets of equipment. The equipment should not be too sophisticated, but rather simple and inexpensive. We have made some parts

by ourselves with the help of our technical staff at the faculty. The measurements themselves should be quite robust (to be done by inexperienced 14- and 15-year-olds) and completed in about 20–25 minutes.

The first goal of the experimental examination is to test the experimental and practical skills of the students. Students have little time to read the instructions and familiarise themselves with the content of the experimental problem and equipment, to perform the measurements, draw some diagrams and answer some questions, the last of which can be quite complex. Students are asked about the patterns that should have been observed/noticed and some general characteristics of the phenomena observed. They are also asked to draw conclusions on the basis of their (performed) observations and to make predictions about the phenomena they could not observe in their experiment.

3. The experiment

The ultimate goal of the forced oscillations experiment, given to 14-year-old students at last year's national competition, was to draw a resonance curve of a simple pendulum.

Taking into account the above mentioned objectives—the use of simple equipment and simple measuring methods—the main problem of the design were the well known problems of the frequency and amplitude stability of the driving force in purely mechanical system [2, 3]. Besides the main problem there were several others: to obtain a resonance curve of appropriate width—neither too narrow nor too wide, with a pronounced and clearly visible maximum—the damping of the pendulum had to be adjusted accordingly. With the right setting, the damping can also help students to carry out experiments more quickly - if an oscillator is driven at a frequency close to its own, beats are generated (which are described by the sum of steady and transient solution to equation of motion for a damped driven oscillator) [1, 7]. These beats must die away before amplitude response measurements can be made and their decay is described by a characteristic relaxation time. If the damping is too weak, the relaxation time becomes too long, which in turn would prevent students from

taking a whole series of measurements—they only have about 20–25 minutes to measure the pendulum’s response to eight different driving frequencies. Too strong damping of the oscillations, on the other hand, would be a diametrically opposed problem - if the energy is dissipated too quickly, there is nothing left to measure too soon... We will comment on how these obstacles were overcome and also describe the experimental setup.

To summarise, the most important goals that an experimental setup must meet are

- cost efficiency,
- sufficient robustness,
- the response of the driven pendulum must be on human scale (measurable with a common stopwatch and a ruler),
- the measurement procedure should be simple,
- the driving frequency should be stable,
- the driving frequency should be variable,
- the driving frequencies should be around 1 Hz, which will be (approximately) the natural frequency of the driven oscillator,
- the driven oscillator should display obvious resonance behaviour.

The solutions of the experimental setup, which include, fulfil and enable the above mentioned goals, are listed below.

- The driven pendulum is a simple mathematical pendulum (a weight on a 20–25 cm long thread) with natural frequency of about 1 Hz.
- Natural oscillations of the driven pendulum are damped and decay in 10–20 oscillations, which was achieved by choosing a suitable weight, see figures 1(a) and (b); the final choice was an extruded polystyrene sphere (EPS) with a diameter of 4 cm and mass 4 g.
- The driven pendulum is forced to oscillate by coupling it to a driving pendulum with variable natural frequency: the driving pendulum was another (heavy) weight on a thread of variable length, as shown in figure 2(a). The length of the thread of the driving pendulum ranged from a few centimetres to 70 cm. Both pendulums were suspended on the same horizontal thread 10 cm apart, as shown in figure 3, and coupled by this thread. (Another simple variation

of this setup—constant driving frequency and variable natural frequency of the driven oscillator—is described in [1].)

- The influence of the driven pendulum back on the driving pendulum is negligible. The masses of the two pendulums differ by three orders of magnitude. The mass of the EPS ball is 4 g and the mass of the driving pendulum is about 340 g. The energy initially introduced into the driving pendulum is dissipated (due to the air resistance force on both pendulums) on a much larger time scale from the time intervals used for the measurements. The driving pendulum was used to continuously supply the driven pendulum with the energy, while the loss of energy has no significant effect on the oscillation of the driving pendulum.

4. Experimental problem

The experimental problem (given in the appendix) is worth 26 points in total. The problem is structured and consists of a sequence of several sub-tasks from (a) to (j) with increasing complexity.

At the beginning, the students have to read the problem, familiarise themselves with the equipment (in introduction) and take the measurements (tasks (a)–(c)). This basic but still non-trivial part of the problem is worth 10 points and a large majority of the students were expected to complete it adequately (remember that these were the students who got to the national level of competition) and they did. The most difficult part of the measurement procedure is to measure the driving and driven oscillation amplitude x_d and x_0 of the driven pendulum in a sequence in a very short time. To get the most accurate results, it is also important to recognise the viewpoint matters and to perform the measurements in a way that minimises the influence of parallax (observing the node and the sphere with only one eye, without moving the head, makes the difference). Figure 4 shows the pupil making the measurements.

Once the data has been collected, it is time to present it. In the next exercises (tasks (d) and (e)), worth 6 points, the students have to calculate frequencies from measured oscillation periods, ratios of driven and driving amplitudes

Figure 1. (a) A set of EPS spheres of different diameters from which a suitable sphere was selected to optimize the experiment, and (b) the selected sphere attached to a 25 cm long thread.

Figure 2. (a) A heavy weight of the driving pendulum attached to a thread with 12 loops, so that the length of the pendulum could easily be varied between a few and 70 cm. (b) A paper clip for quickly attaching the selected loop of the driving pendulum thread. (c) The shortest length of the driving pendulum.

$\frac{x_d}{x_0}$ and draw a diagram showing the ratio $\frac{x_d}{x_0}$ as a function of the driving frequency. The most advanced skill tested here is probably choosing (and denoting) an appropriate scale on both axes to fill most of the space provided with the diagram.

The last part of the problem is the most complex and worth 10 points. The students have to answer five questions (tasks from (f) to (j) in the appendix) where they have to reflect on their observations, deduce, connect, conclude and predict the behaviour of the driven pendulum that has not yet been observed. For example, they have to write the value that the ratio $\frac{x_d}{x_0}$ approaches when the driving frequency is much lower (task (f), or higher, task (g)) than the natural frequency of the driven oscillator ($\rightarrow 1$, $\rightarrow 0$). They can of course try to force low (or high) frequency oscillations with their hands and observe what is happening,

but they have not been told to do so (if it comes to their mind, they can try, it is perfectly fine). In the following task (h) they have to draw a continuation of the resonance diagram they have drawn before when the driving frequency approaches either very small or very high values, as shown with a red dashed line in figure 5.

There is also a question (task (i)) about the special detail of the experiment, which is related to the coupling of two oscillators and their mutual interactions. If they follow the written instructions, and especially wait a little before taking measurements, and if they pay attention to what is going on while waiting to start to measure, they may notice few (fading) beats of the driven oscillator. The phenomenon is clearly visible in the beginning of the oscillations when the driving frequency is almost equal to the natural frequency of the driven oscillator, i.e. when the thread lengths

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Figure 3. An experimental set-up, (a) a side view, (b) a front view and (c) a detail showing a horizontal thread from which both pendulums are suspended. A wooden rod holding the two pendulums is attached to the table. A scale is drawn on the white paper behind the pendulums (d), which serves as an aid for measuring the driving and oscillation amplitude.

of both oscillators are almost equal. Even if they do not notice the beats, they can notice the oscillations are not steady in the beginning, but become such in approximately 10 seconds.

The last question was:

- (j) Write down three observations on the oscillation of a particular pendulum or on the coupling between the oscillations of both pendulums that are not related to the shape of the resonance curve. (3 points)

Figure 4. A pupil making the measurements.

Figure 5. A resonance diagram, drawn from measurement data (red points and black line), and a continuation of the diagram for lower and higher frequencies (red dashed lines), as asked for in the subsequent tasks.

For each appropriate observation the student received 1 point. We have anticipated these possible observations:

- Both pendulums oscillate with the same frequency,
- a swing with the heavy mass obviously influences the swing with the light mass, while the influence in the opposite direction is not (easily) visible,
- if the light pendulum is allowed to swing by itself, the oscillation of the light pendulum

dies off quickly, while the heavy pendulum experiences only negligible damping,

- the oscillation frequency does not depend on the amplitude of the oscillation (at least not very much),
- longer thread means lower natural frequency (longer period of oscillation),
- depending on the driving frequency compared to the natural frequency of the driven oscillator ($\nu < \nu_0$ or $\nu > \nu_0$), both pendulums oscillate (almost) ‘in the same direction’ (in phase) or ‘in opposite directions’ (antiphase),
- near the resonance, the driven oscillator follows the driving oscillator with a time delay of (approximately) $1/4$ of the period.

We are very much in favour of asking these open questions at the end. All tests are evaluated by a team of markers, and if there are doubts about the plausibility of certain answers, there is a lively discussion among the markers (which are mostly students of the main subject Physics or Educational Physics). This is a win-win situation: the discussion among the markers guarantees that the tests are evaluated objectively (the same criteria are used for all of them), but the markers themselves also practise their analytical skills in analysing the texts written by the pupils and also learn from the sometimes very profound observations and descriptions written by these young and bright children.

5. Outcomes

We will only briefly present the results achieved in the competition. There were 135 pupils who took part in the competition at national level. The diagram in figure 6 shows their distribution according to the total number of points (Tp) they received in the experimental problem. We can see that most of them succeeded in carrying out the measurements (max 10 points) and also calculations and at least partially drew a diagram (max 16 points). But there are also 21 of them who have done more; they have solved the problem almost completely and answered even the most advanced questions.

At this point we must stress once again that this was a national competition, and the aim of the competition is to get only a few—not many—the

Figure 6. Distribution of participants according to the total number of points in experimental problem.

best. If the problems are rather difficult, it is easier to achieve this objective, to be able to discriminate among the best of the best. A distribution with a really thin tail in the region with the best results is a distribution that we want for a competition at national level. We have obviously succeeded in presenting problems in competition which are not too difficult—but difficult enough.

6. Conclusions

Even though the complete treatment of the phenomenon observed and measured in the experiment goes far beyond the physics curriculum of primary school, it was suitable for our purpose. It was not about fully understanding and comprehending a theoretical model of forced oscillations, but rather about focusing on what is going on, what can be observed, measured, noticed, discovered and recognised. The important properties of the phenomenon under study, such as the fundamental fact that a pendulum can oscillate at any frequency (and not only at its own natural frequency) and that oscillations decay if the energy is not constantly fed into the system (to a driven pendulum), have been observed and recognised. Many other non-trivial properties have also been observed, such as the resonance behaviour when the driving frequency is similar to the natural frequency of the driven oscillator, the limit behaviour at very low or very high driving frequencies, the phase shift between the oscillations of the driving

and driven pendulum, and also the need for a constant supply of energy.

As mentioned at the beginning, the experimental part of the physics (or other science) competition is rare at national level, especially when the participants compete as individuals. The main reason is simultaneity: all participants have to experiment at the same time; we need enough space for everyone, not to mention the number of identical (and tested) devices. There are some science competitions based on experiments, but in these cases the experiments are done in advance, either at school or at home, before the competition [8, 9].

Experimental problems, such as the one presented in this article, are a challenge for the pupils, but it is also a great challenge and pleasure for us to design the problems. We already have a nice collection of problems and they are freely available (in Slovenian language) on the website².

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² Every year at the end of the national physics competition we publish a Competition Newsletter on the website. In this newsletter we publish the theoretical and experimental problems (as well as the solutions to the problems) given to the pupils at the national level of the competitions. The newsletters can be found at <https://www.dmf.si/Tekmovanja/FiOS/ArhivNalog.aspx>.

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