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High resolution sound card stopwatch extends school experimentation

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Abstract: The development of demonstration experiments plays a key role in modern and efficient teaching of physics, chemistry, biology and several other disciplines. Today's computers and electronic devices allow the use of simple software-based instrumentation to achieve flexible and surprisingly transparent experimentation, however, the professional solutions are rather expensive while the "home-made" instruments are often inaccurate and the software can be inconvenient and didactically questionable. There are several attempts to solve these problems and make experiments accessible for almost every teacher and student. In this paper a very simple, ultra low cost, easy-to-make sound card based high-resolution stopwatch will be shown that supports a wide variety of mechanical experiments. Here we present two kinds of experiments, with which we can demonstrate well the usefulness of our device: measurement of the moment of inertia, and study of free-falling balls. We also show how these kinds of measurement methods develops different competences of the students.

Key words: physics education, high-school experiments, computer-aided measurements, measuring with a soundcard

Introduction

Student experiments and measurements are important and efficient tools to increase interest in physics classes. Because of the low number of the classes, the more complex experiments are usually pushed into the background. Software defined instrumentation – where the experiments are real, but the bulk of data processing is realised in software – could help to solve the problem. Students can also see that they can use computers not only for playing games, but also as tools with which they can quickly produce charts to analyse and thus improve their skills.

We show two examples where the use of the device offers new perspectives in secondary-school experiments.

Our simple but high-resolution sound card stopwatch [1] allows us to carry out highly accurate time measurements easily in the classroom at a very low cost. Phototransistors and phototransistors can be directly connected to the microphone input of the sound card without any additional components since the required bias is provided [2,3]. The dedicated software is open-source and available as a single executable [4].

An experimental study of rotational motion

Using conventional instruments we can demonstrate Newton's second law for rotation. A simple example is shown in Figure 1. A light disc is mounted on the rigid rotational axis of a rigid rod (which ends in two small bodies). A light string is wrapped around the edge of the disc, and a ballast is suspended at its free end. After we let go of the hanging body, it falls with a uniformly changing velocity, while the rod rotates with a constant acceleration.

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Figure 1. *A conventional instrument for demonstrating Newton's second law for rotation*

The moment of inertia (I) can be determined from the mass of the hanging body (m), the radius of the disc (R), the displacement of the body (h) and time of motion (t).

Newton's second law for rotation is

$$\tau = I \cdot \alpha, \tag{1}$$

where τ denotes torque and α is the angular acceleration. The latter we can obtain from

$$\alpha = \frac{a}{R} = \frac{2 \cdot h}{R \cdot t^2} \ . \tag{2}$$

Newton's second law for the hanging body is

$$mg - F = ma, \tag{3}$$

where F is the tension force in the thread acting on the body moving with acceleration a.

Using F to describe the rotational law is

$$\tau = F \cdot R = m \cdot (g - a) \cdot R \ , \tag{4}$$

from which, substituting α, we can calculate I:

$$I = \frac{\tau}{\alpha} = \frac{m \cdot (g-a) \cdot R \cdot R \cdot t^2}{2 \cdot h} = \frac{m \cdot g \cdot R^2 \cdot t^2}{2 \cdot h} - \frac{m \cdot R^2 \cdot t^2 \cdot \alpha \cdot R}{2 \cdot h} = \frac{m \cdot g \cdot R^2 \cdot t^2}{2 \cdot h} - \frac{m \cdot R^2 \cdot t^2}{2 \cdot h} \cdot \frac{2 \cdot h \cdot R}{R \cdot t^2}$$
(5)

$$I = \frac{m \cdot g \cdot R^2 \cdot t^2}{2 \cdot h} - m \cdot R^2 = \frac{m \cdot g \cdot R}{\alpha} - m \cdot R^2 \tag{6}$$

Sound card stopwatch techniques open up new perspectives in studying rotational motion, especially in determining the moment of inertia of particles. An accurate stopwatch is an invaluable tool here because this experimental setup does not allow controlling time more accurately in other ways (e.g. by increasing the height).

Changing the distance of the body (placed originally to the end of the rod) from the axis of the rod we can get the relationship between distance and moment of inertia. Our results are summarised in Table 1. We also present two graphs: the first one shows the moment of inertia as a function of distance (Fig 2), while on Figure 3 there are the squares of distances on the x axis. It is easy to see that the linearised curve intersects the y axis above zero: this is caused by the moment of inertia of the rod.

Table 1. *Moment of inertia measured as a function of distance of the body from the axis of the rod (Where mass: m=0.006 kg, radius of the dial: r=0.02 m, height: h=0.69 m)*

Time	Angular acceleration	Moment of inertia	Distance	Square of the distance
t [s]	β [1/s^2]	Θ [kg · m^2]	R [m]	R^2 [m^2]
4.1140	4.0769	0.0003		
5.6176	2.1865	0.0005	0.0350	0.0012
7.0427	1.3911	0.0008	0.0550	0.0030
8.6372	0.9249	0.0013	0.0750	0.0056
10.4624	0.6304	0.0019	0.0950	0.0090
12.2868	0.4571	0.0026	0.1150	0.0132
14.2124	0.3416	0.0034	0.1350	0.0182
16.0603	0.2675	0.0044	0.1550	0.0240
17.9504	0.2141	0.0055	0.1750	0.0306

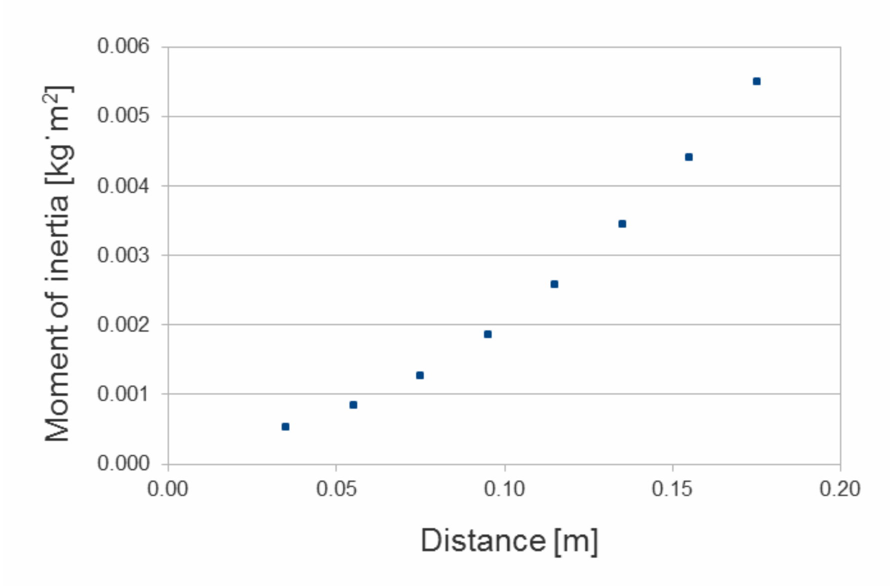

Figure 2. *Moment of inertia measured as a function of the distance of the body from the axis of the rod*

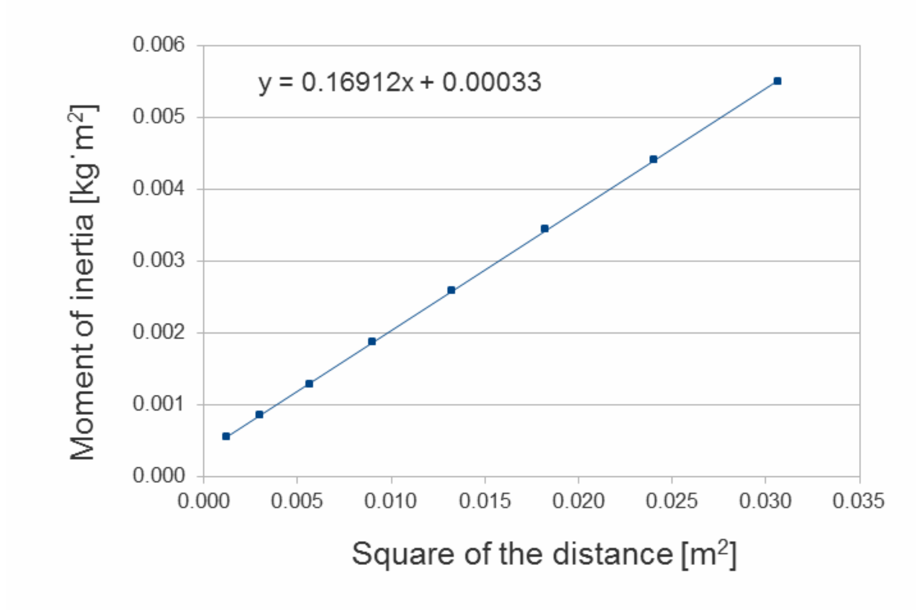

Figure 3. *Moment of inertia as a function of the square of the distance*

Therefore our measurement method is appropriate to determine the moment of inertia very accurately. Additionally, students could learn the importance of linearisation during the evaluation.

Studying the motion of free-falling bodies

Using a sound card and some free software, Ganci [5] produced convincing results in measuring the value of the local gravitational acceleration in the classroom. Hunt and Dingley [6] also exploited the accuracy of sound card measurements to study the bouncing of different balls.

Considering drag force and buoyant force, we can apply the dynamic equation for a free-falling ball:

$$m \cdot a = m \cdot g - F_d - F_b \ , \tag{7}$$

where F_d is the drag force and F_b is the buoyant force. The former can be calculated from the volume of the body and the density of the medium:

$$F_b = \rho_{air} \cdot V_{ball} \cdot g \tag{8}$$

The magnitude of the drag force – depending on the velocity and the size of the body and on the properties of the medium – is proportional to the velocity ($F = 6 \cdot \pi \cdot \eta \cdot r \cdot v$) or to its square

$$\left(F_d = \frac{1}{2} \cdot c \cdot \rho \cdot A \cdot v^2 \right) . \tag{9}$$

In both cases, the acceleration (as well as the fall time) of the body depends on the mass.

Linear drag:

$$a = g - \frac{\rho_{air} \cdot V \cdot g}{m} - \frac{6 \cdot \pi \cdot \eta \cdot r}{m} \cdot v \tag{10}$$

Quadratic drag:

$$a = g - \frac{\rho_{air} \cdot V \cdot g}{m} - \frac{c_{air} \cdot A \cdot \rho_{air}}{2 \cdot m} \cdot v^2 \tag{11}$$

We expect in both cases that the ball with larger mass will have a shorter fall time. Dropping bodies with the same mass but with different volumes, the difference of fall times is measurable only under special circumstances (e.g. with balls dropping from a high tower). However, using a sound-card stopwatch makes it possible also in the classroom. At first we were wondering if the difference of fall times of an iron ball and a ping pong ball is measurable or not. We fastened a pin to the latter, while to ensure the accurate timing of the start, we used an electromagnet disassembled from an old photocopier.

It was a question whether the rotation during the motion influenced the fall times of the balls or not. If a falling ball rotates, a small part of the potential energy turns into into rotational energy, slightly decreasing the velocity of the dropped body. Additionally, in the case of a definitely inhomogeneous ball (like the ping pong ball equipped with a pin), we could not guarantee that it is the velocity of the centre of mass we measure in every moment. For that reason, we observed the balls marked with a brush-pen during the fall and we found that there is no detectable rotation; therefore we could eliminate the problems mentioned before.

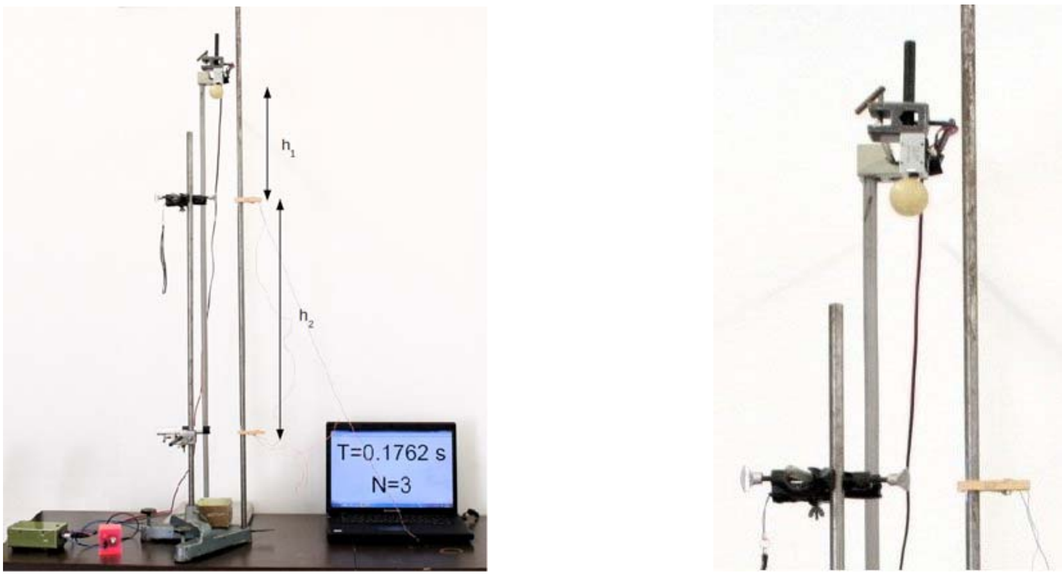

Figure 4. *Experimental arrangement by studying free-falling ball*s

In the first arrangement, the height of fall between the place of start and the first gate (h1) was 30.4 centimetres, while the distance of the two gates (h2) was 58.5 cm (fall times were measured in the latter section).

Table 2 shows the results: the fall times of the iron ball are clearly shorter, and the errors of the measurements are very small.

Table 2. *The first set of fall times*

Index of measurements	Falling ball	Radius of the ball [m]	Mass of the ball [kg]	Time [s]	Average [s]	Standard deviation [s]
1	iron ball	0.0190	0.2250	0.1763	0.1763	0.0001
2	iron ball	0.0190	0.2250	0.1763		
3	iron ball	0.0190	0.2250	0.1762		
1	ping pong ball	0.0190	0.0030	0.1845	0.1847	0.0006
2	ping pong	0.0190	0.0030	0.1842		

	ball					
3	ping pong ball	0.0190	0.0030	0.1853		

In the second arrangement, the first photogate was fixed directly at the level of the bottom of the balls. In that case, the displacement of the balls was 71.7 cm. This arrangement makes it easier for students to analyse the problem, because we can use the equations mentioned above with starting velocities equal to zero (which helps much to calculate the drag force and the buoyant force). We could also measure the differences of velocities in that case (see Table 3).

Table 3. *The second set of fall times (the first photogate was fixed directly at the level of the bottom of the balls)*

Index of measurement	Ball type	Radius of the ball [m]	Mass of the ball [kg]	Time [s]	Average [s]	Standard deviation [s]
1	iron ball	0.0190	0.2250	0.3039	0.3040	0.0001
2	iron ball	0.0190	0.2250	0.3040		
3	iron ball	0.0190	0.2250	0.3039		
4	iron ball	0.0190	0.2250	0.3040		
1	ping pong ball	0.0190	0.0030	0.3128	0.3135	0.0015
2	ping pong ball	0.0190	0.0030	0.3165		
3	ping pong ball	0.0190	0.0030	0.3137		
4	ping pong ball	0.0190	0.0030	0.3128		
5	ping pong ball	0.0190	0.0030	0.3125		
6	ping pong ball	0.0190	0.0030	0.3129		

As we can see, the difference between the average fall times of the two kind of balls are much larger than the standard deviations of the measurements.

Conclusion

We have shown two experiments that take advantage of the accuracy of our devices to determine special physical parameters hard to measure with conventional techniques. Using our method, also applicable as an IBL programme, it is possible to teach these laws of Nature via student activity.

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