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Smartphones on the air track. Examples and difficulties

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In this paper we describe a classical experiment with an air track in which smartphones are used as experimental devices to obtain physical data. The proposed experiment allows users to easily observe and measure relationships between physical magnitudes, conservation of momentum in collisions and friction effects on movement by utilizing the users' own mobile devices.

I. Introduction

Smartphones and tablets have sensors that can be used to redesign physics experiments by substituting laboratory equipment with those devices [1]. This technique can enrich data availability in an experiment and also reduces its costs. The work in the laboratory under controlled conditions can also help experimenters to learn the use and limitations of smartphones and to apply them in experiments outside the laboratory. In this paper, we show some results obtained in a classical experiment, pointing out basic concepts that can be explored and analyzed by using smartphones, as well as some difficulties of the work.

II. Using the smartphone in an air-track experiment

A simple and usual mechanics experiment consists in studying linear movement on an air track without friction. On it, positions, speeds and accelerations can be measured by using measuring tapes, chronometers or more sophisticated photoelectric cells. Here, we discuss how smartphones can be used to analyze the movement of a body in three different configurations of the experiment: elastic collisions between two carts, accelerated movement of a cart pulled by a falling body via pulley, and movement of a cart when the air pump is switched off and it is stopped by friction.

As experimental devices in our work we used two smartphones, a Samsung Galaxy S3 mini and a Samsung Galaxy S4. These smartphones were placed horizontally on the moving carts with their Y-axis pointed along the direction of the movement and their Z-axis vertically. The carts can hold additional weights so that we could study interactions between bodies with same or different masses. To access the data recorded using the sensors of the smartphones, we used two Android apps: SensorMobile [2] and Physics Toolbox [3], so that the advantages or disadvantages, accuracy and numerical noise, of different apps can also be analyzed.

i. Elastic collisions between carts in a horizontal air track

This is a simple experiment that is done by using two carts, each with a smartphone measuring its acceleration, allowing us to check the momentum conservation in a collision between two bodies. In our experiments, we used different configurations

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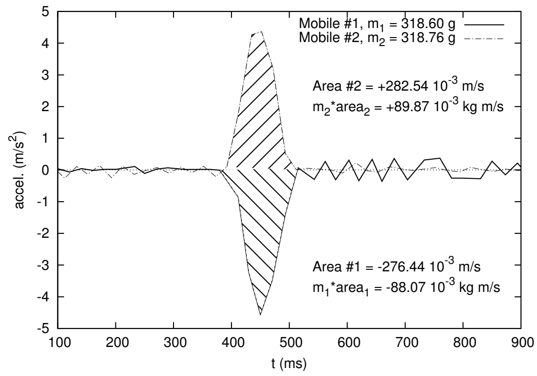

Figure 1: Accelerations of two bodies of equal mass during a collision. A spreadsheet can be useful to calculate the area under the acceleration curves and check momentum conservation readily.

that can be explored: both carts moving on the air track in the same or in opposite directions, or one cart at rest while the other moves towards it. Moreover, by adding different masses to the carts we have analyzed collisions between bodies with the same or with different masses.

Figure 1 shows the results of one of such experiments corresponding to an elastic collision between two bodies (cart plus smartphone) of similar masses. In this case only one of the bodies was moving before the impact. Once the acceleration of each body is measured by the smartphones, the CSV files generated by the apps can be transferred to a computer and analyzed easily using a spreadsheet program. Here the spreadsheet was used to obtain the area under the curve of each acceleration using a simple numerical method like the trapezoidal rule. As can be seen in Fig. 1, when the masses are nearly equal the areas calculated from the smartphone data are also similar (the difference is a little larger than the 2%) considering the experimental noise. And multiplying those areas by the masses of the bodies the conservation of linear momentum is checked, as shown in Fig. 1.

ii. Frictionless movement of a cart pulled by a falling body through pulley

Another dynamics problem studied in the first courses of physics is the movement of a body, on a frictionless horizontal or inclined plane, connected to a cable that passes over a pulley and then is fastened to a falling object. Here, we study such movement by placing a smartphone on the moving cart and measuring its acceleration.

Figure 2 shows some results of two measurements of this type. They correspond to the acceleration suffered by a body (cart plus smartphone) of mass m_c = 318.76 g on a horizontal plane when the falling body has different masses in two different experiments, m_b = 20.02 g and 29.99 g. According to the theory studied in the classroom, assuming that there is no friction, the acceleration of the cart is $a = \frac{m_b}{m_c+m_b} g$ that for our conditions gives accelerations $a_{(m_b=20.02)} = 0.579$ m/s^2 and $a_{(m_b=29.99)} = 0.843$ m/s^2. As can be seen these results agree well with the average acceleration of the cart as measured by the smartphone on it. The users could also add a second smartphone on the falling body and check that the acceleration of the cart and that of the falling body are the same within the experimental accuracy, according to this simple model. From the accelerometer measurements, the dependence of the travelled space with acceleration and time in the uniformly accelerated movement can be checked. If the length of the cable is the same in two measurements with different falling masses, then the ratio of travelling times $\Delta t_2/\Delta t_1$ must be equal to the square root of the ratio of the average accelerations measured by the smartphones $\sqrt{a_2/a_1}$. As can be seen from the measurements in the figure, $\Delta t_2/\Delta t_1 \approx 1.199$, while for the accelerations $\sqrt{a_2/a_1} \approx 1.207$, so that the the theoretical dependence $s = \frac{1}{2}at^2$ is easily proved.

iii. Movement with friction of a cart pulled by a falling body through pulley

In this section, we show some results that can be obtained if the air pump of the track is set off and the cart moves with friction. For this experiment the lower part of the cart should be protected, for example with duct tape, to avoid damaging the air track with scratches, which will also vary the friction coefficient as the experiment is performed. The experiment is the same as in the section ii., except for the existence of friction. The acceleration of the cart is lower than the one without friction, the cart decelerates, and finally stops if the cable is long enough for the falling object to reach the floor

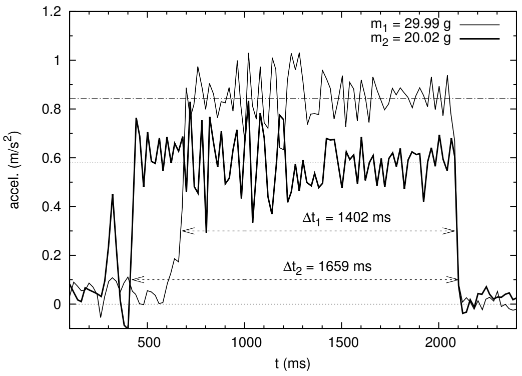

Figure 2: Measurements of the acceleration of a cart on an air track when pulled by different masses in two experiments. The average values of acceleration, in the two experiments, marked with lines in the figure, were $a_1 \approx 0.84$ m/s^2 and $a_2 \approx 0.58$ m/s^2

before the cart gets to the track end.

Figure 3 shows an example of the results with the smartphone accelerometer in such experiment. That figure shows acceleration data of three independent measurements under the same conditions to illustrate the repeatability of the results. Some comments are necessary about the results shown in the figure. As can be seen there, the acceleration is positive when the movement is accelerated, and changes its sign when the falling body reaches the floor and the friction decelerates the movement of the cart. A very remarkable result that immediately calls our attention is the oscillations in the accelerated part of the movement. As can be seen in Fig. 3 (and in Fig. 4), these oscillations appear consistently in all the experiments and then, cannot be considered an experimental artifact. In our opinion, these oscillations appear due to the combined effect of the push on the string of the falling body and the pull due to the friction on the cart attached to the end of the string. These oscillations do not appear when the air pump is working and there is no friction. From our point of view, these oscillations reflect variations in the acceleration of the cart due to changes in the string tension. This is a problem that we consider very interesting to see. When this experiment is done using classical measurement devices the usual approximation that considers inextensible strings and constant tension seems to hold true, but smartphone sensors are sensible to small variations in them, as can be seen here. This observation can help the experimenters to consider the limitations of the physical model and the influence of the string characteristics. Figure 3 shows in an inset the experimental points of the three measurements together with a damped oscillation with period $T \approx 0.105$ s. For the theoretical behaviour we have tested accelerations for pure Coulomb and pure viscous damping but the experimental results seems to be a mixing of both behaviours, what makes more difficult its analysis. The inset in Fig. 3 shows a comparison of the experimental points with a theoretical curve for the acceleration. From this comparison, we have an estimation of the initial elongation of the string to be around $1.2 \cdot 10^{-3}$ m (the length of the string used in this experiment was approximately 1.75 m). In addition, a qualitative analysis of the oscillations was acomplished by using strings with different elasticity. We observed that these oscillations were less noticeable for strings with lower elasticities, and that even for low elastic strings these oscillations were masked by the experimental noise. On the other hand, for more rigid strings, such as metallic strings, the amplitude of the oscillations was smaller due to their lower deformation. Anyway, both the mixing of effects in this result and its experimental difficulties could make an exact analysis harder than in the classical version of the experiment.

Other results can be obtained easily by the users. From the masses of the cart ($m_c = 318.8$ g) and of the falling body ($m_b = 358.05$ g) they can calculate the theoretical acceleration without friction, resulting $a_{teo} = 5.18$ m/s^2, that is clearly higher than the experimental value in the accelerated part of the movement, whose average value is $a_{exp} = 2.386$ m/s^2 (see Fig. 3). Using this experimental value, the students can obtain the friction coefficient between the duct tape protecting the cart and the track with $\mu = (m_b g - (m_c + m_b) a_{exp})/(m_c g)$, resulting $\mu = 0.61$. Once μ is known the friction deceleration $a_{friction} = \mu g = 5.94$ m/s^2 can be calculated, that, as shown in Fig. 3, agrees well with the experimental results within the experimental noise. From the experimental data the impulse-momentum relationship can also be observed. As the cart started and ended its movement with null speed, the areas under the acceleration and deceleration curves in Fig. 4 must have the same value

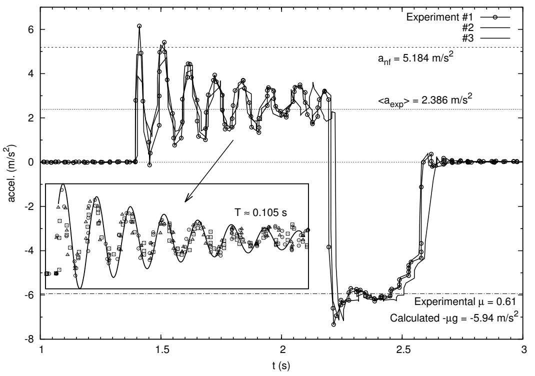

Figure 3: Results of four independent measurements of the acceleration of a cart pulled by a falling body via a pulley when there is friction between the cart and the air track. The values of the theoretical acceleration without friction, a_t, and of the experimental average acceleration, a_e, are marked with straight lines. One of the measurements has been represented with lines and points to show the position of the experimental points.

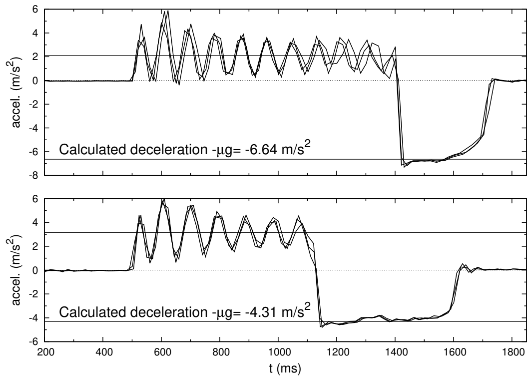

Figure 4: Accelerations recorded by the smartphone in an experiment like that in Fig. 3 but two different friction coefficients: painted Al cart on Al track (above) and duct tape covered cart on Al track (below). The cart and the falling body masses were m_c = 317.3 g and m_b = 359.1 g, respectively. The experimental average accelerations of each case have been marked with horizontal lines, as well as the deccelerations once the falling body reaches the floor.

but opposite signs. By using a spreadsheet program and the numerical trapezoidal rule, those areas can be easily obtained.

Finally, Fig. 4 shows another result that can be discussed. Results for two different conditions of friction are shown in it: an aluminium cart on an aluminium track and a duct tape covered cart on an aluminium track. Due to different friction coefficients, the cart accelerations are different and, consequently, their travelled times. As for Fig. 3, the users can calculate the dynamic friction coefficients and the corresponding decelerations, and compare them with the experimental results. A final result that can be discussed is the influence of different friction coefficients on the stopping times.

III. Conclusions

Smartphone sensors are very useful tools that permit to do measurements in the laboratory and outside it. The use of these devices can also increase the interest in physics and facilitate the understanding of the physical phenomena. We have shown some results of an air track experiment using a smartphone. Some of the concepts reinforced with this experiment are acceleration, collisions, momentum, friction, friction coefficient, impulse-momentum theorem and even elasticity. These experiments can also be useful to learn the importance of sensors accuracy and measuring frequency, as well as the reliability of the used applications.

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