AAPT PHYSICS EDUCATION
AMERICAN JOURNAL of PHYSICS

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Citation: Am. J. Phys. **81**, 472 (2013); doi: 10.1119/1.4793438
View online: http://dx.doi.org/10.1119/1.4793438
View Table of Contents: http://ajp.aapt.org/resource/1/AJPIAS/v81/i6
Published by the American Association of Physics Teachers

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Using a mobile phone acceleration sensor in physics experiments on free and damped harmonic oscillations

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(Received 9 November 2012; accepted 11 February 2013)

We have used a mobile phone acceleration sensor, and the Accelerometer Monitor application for Android, to collect data in physics experiments on free and damped oscillations. Results for the period, frequency, spring constant, and damping constant agree very well with measurements obtained by other methods. These widely available sensors are likely to find increased use in instructional laboratories.

[http://dx.doi.org/10.1119/1.4793438]

I. INTRODUCTION

Electronic portable or everyday-use devices offer new opportunities for the physics laboratory at all teaching levels. This has been the case for digital cameras,[1] webcams,[2] the optical mouse of computers,[3,4] XBee transducers,[5] wiimote,[6] and other game console controllers.[7] For instance, digital camera techniques have been widely used to visualize physics concepts.[8–11] Analysis of digitally recorded video can also yield measurements of distances, time intervals, and trajectories of objects, facilitating students' comprehension of otherwise abstract concepts. As another example, the wiimote[6,12,13] has a three-axis accelerometer which communicates with the game console via Bluetooth. The use of accelerometers in the physics laboratory has been described by Weltin[14] and Hunt.[15,16]

Although the wiimote provides a low-cost way to track motion in a variety of physics experiments,[17] it is not a common device in physics laboratories. In this paper, we study the possibility of using another accelerometer-equipped device, which almost all students have with them, although they may not realize it. We use a mobile phone acceleration sensor to study free and damped oscillations of a glider on an air track. Mechanical oscillation is an important topic in

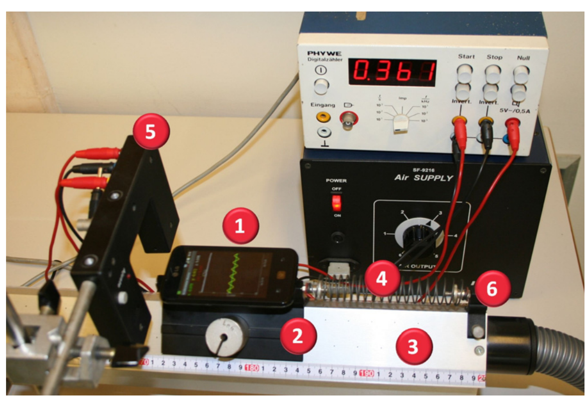

Fig. 1. Photograph of the experimental setup showing (1) smart phone, (2) glider, (3) air track, (4) spring, (5) photometer, and (6) the fixed end.

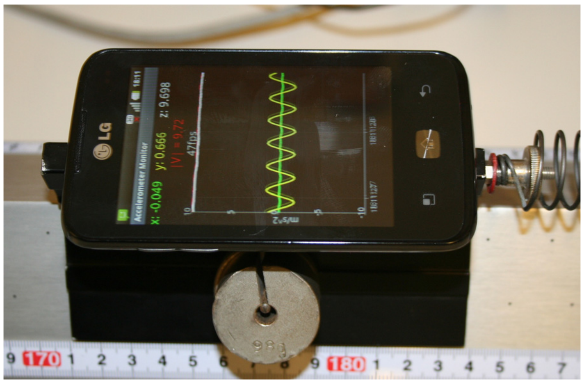

Fig. 2. Close-up of the mobile phone screen showing an acceleration graph for free oscillations.

```
# Accelerometer Values
# filename:  default__10.txt
# Saving start time: Fri Oct 19 19:14:35 GMT+02:00 2012

# sensor resolution: 0.01197m/s^2
#Sensorvendor: The AMI306 Android Open Source Project, name:
AMI306 3-axis Acceleration sensor, type: 1,version : 1, range
19.6

# X value, Y value, Z value, time diff in ms
-0.047 0.229 -0.02 22
-0.051 -0.341 -0.018 22
-0.037 -0.845 0.027 21
-0.016 -1.166 -0.002 22
-0.023 -1.244 -0.019 21
-0.029 -1.049 -0.017 22
-0.026 -0.653 -0.024 22
-0.033 -0.111 -0.039 22
-0.012 0.508 -0.053 21
0.024 0.996 -0.039 22
0.039 1.249 -0.035 22
0.026 1.248 -0.031 21
0.015 0.991 -0.037 22
-0.003 0.556 0.019 21
-0.012 -0.09 0.0 22
-0.019 -0.654 0.0 22
-0.009 -1.083 0.0 21
-0.017 -1.222 0.0 31
-0.015 -1.091 -0.017 21
```

Fig. 3. A fragment of the output data file of the Accelerometer Monitor application. The first three columns give the three acceleration components while the fourth column gives the elapsed time between measurements.

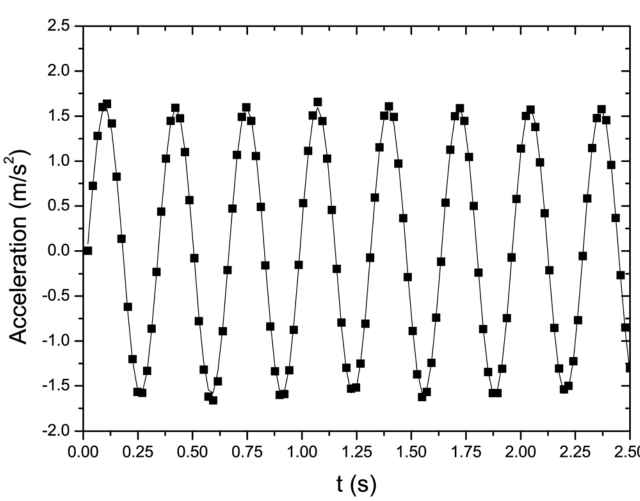

Fig. 4. As an example of the experimental acceleration data (squares) and fitted curve (solid line) for mass 3.

Table I. Parameters and their errors from fitting the acceleration data for free oscillations.

	$m \pm 0.0001$ (kg)	$A \pm \delta A$ ($\mathrm{m/s^2}$)	$\omega_0 \pm \delta\omega_0$ (rad/s)	$\phi_0 \pm \delta\phi_0$ (rad)	R^2
m_1	0.3045	1.082 ± 0.008	24.747 ± 0.010	-0.797 ± 0.015	0.9938
m_2	0.4043	1.204 ± 0.006	21.546 ± 0.005	2.479 ± 0.009	0.9968
m_3	0.5004	1.598 ± 0.006	19.408 ± 0.004	-0.377 ± 0.007	0.9984
m_4	0.6084	1.171 ± 0.007	17.669 ± 0.006	-0.397 ± 0.011	0.9953
m_5	0.6285	0.856 ± 0.007	17.371 ± 0.006	2.553 ± 0.016	0.9875
m_6	0.6961	1.542 ± 0.008	16.526 ± 0.007	2.830 ± 0.011	0.9966

most undergraduate physics programs, and many authors have suggested laboratory exercises on this topic.[18,19] The air track is a useful device for such exercises because the friction force can be easily decreased.[20] Although the use of an air track and glider is traditional, we are not aware of others who have used a mobile phone as an accelerometer in such an experiment.

In this paper, we will first describe the experimental setup and the features of our software, the Acceleration Monitor mobile application. We will then present results for free harmonic oscillations, followed by results for damped oscillations.

II. EXPERIMENTAL SETUP

A photograph of the experimental setup is shown in Fig. 1. The mobile phone is placed on a glider, which rests on the air track and is connected to a fixed end by a spring. While the air is flowing, the glider can oscillate almost freely after receiving a push. The mobile phone used in our experiments was a model LG-E510 running Android version 2.3.4. This phone's mass is 124.0 g and the glider's mass is 180.6 g. The mass of the glider can be changed by adding weights at both sides, thus changing the frequency of oscillation.

To collect data from the mobile sensor, we used the free Android application Accelerometer Monitor, version 1.5.0, which can be downloaded from the Google Play web site.[21] The application reports the three components of the phone's acceleration at regularly spaced time intervals. The effect of gravity can be removed from the data. The precision in the measurement of the acceleration is $\delta a = 0.01197\,\mathrm{m/s^2}$ and the average time step is $\delta t = 0.02\,\mathrm{s}$. Since the oscillations take place along the y axis, the values of the acceleration for the x and z axes remain very close to zero. This application also allows saving the output data to a file, from which the data can be used for further analysis.

Table II. Comparison of periods calculated from the fit to accelerometer data (column 2) and obtained with a separate photometer measurement (column 3). The fourth column shows the percentage difference.

	$T_{\mathrm{fit}} \pm \delta T_{\mathrm{fit}}$ (s)	$T_{\mathrm{photo}} \pm 0.001$ (s)	Diff. (%)
m_1	0.2539 ± 0.0001	0.259	1.99
m_2	0.2916 ± 0.0001	0.291	0.21
m_3	0.3237 ± 0.0001	0.323	0.23
m_4	0.3556 ± 0.0001	0.356	0.11
m_5	0.3617 ± 0.0001	0.365	0.91
m_6	0.3802 ± 0.0002	0.380	0.05

Table III. Data for the calculation of the spring constant.

	$m^{-1} \pm \delta m^{-1}$ (kg^{-1})	$\omega_0^2 \pm \delta\omega_0^2$ ($\mathrm{rad}^2/\mathrm{s}^2$)
m_1	3.2841 ± 0.0011	612.4 ± 0.5
m_2	2.4734 ± 0.0006	464.2 ± 0.2
m_3	1.9984 ± 0.0004	376.7 ± 0.1
m_4	1.6437 ± 0.0003	312.2 ± 0.2
m_5	1.5911 ± 0.0003	301.8 ± 0.2
m_6	1.4366 ± 0.0002	273.1 ± 0.2

Table IV. Comparison of results for the measured spring constant: from a fit to the accelerometer results, by hanging a static weight, and the percent difference.

From the fit $k_{\mathrm{fit}} \pm \delta k_{\mathrm{fit}}$ (N/m)	With static weight $k \pm \delta k$ (N/m)	Diff. (%)
187.9 ± 0.6	189 ± 7	0.58

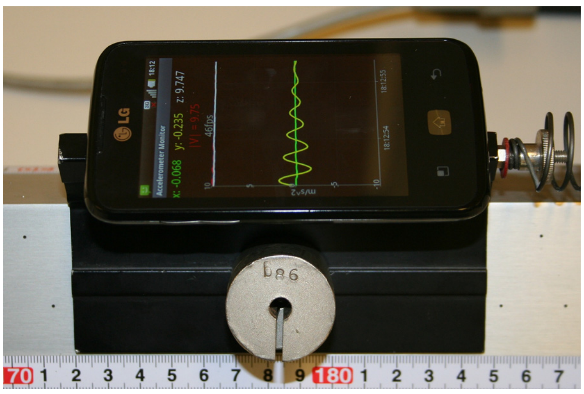

Fig. 5. Photograph of the smart phone displaying an acceleration graph for the case of damped oscillations.

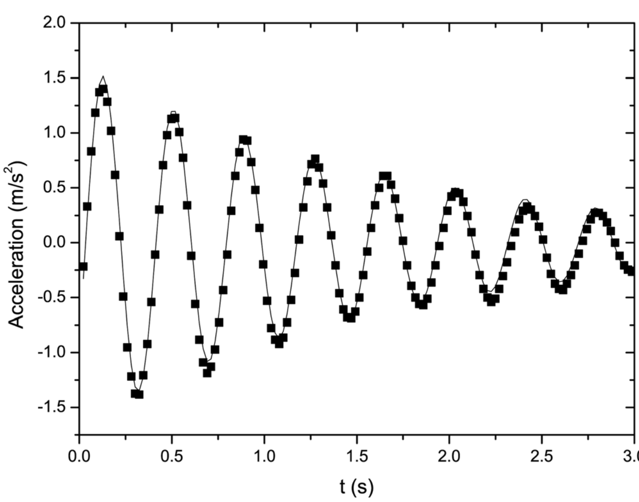

Fig. 6. Experimental acceleration data (squares) and fitted curve (solid line) for damped oscillations.

Once the application has been downloaded to the mobile device, a simple test can be performed to check for correct functioning. If the phone is left quiet on a horizontal surface, the application output curves for the acceleration should indicate values very close to zero for all axes.

For the case of damped oscillations, some dissipation of the amplitude of the oscillations can be obtained by slowing the air flow to the air track.

III. FREE HARMONIC OSCILLATIONS

Figure 2 shows the screen of the Accelerometer Monitor application during free harmonic motion, with negligible friction. The acceleration is accurately modeled by a sinusoidal function of time, so we fit the data to the formula,

$$a(t) = A \sin(\omega_0 t + \phi_0), \tag{1}$$

where A is the acceleration amplitude, ω_0 is the angular frequency, and ϕ_0 is the phase constant.

In order to start the oscillations in the system, the glider with the mobile was pulled to the right and then released. We collected data for six different glider masses, obtained by adding weights to both sides of the glider. Figure 3 shows a portion of the text output from the Accelerometer Monitor application, with header data and then a long data list, with columns for each of the three acceleration components and the time interval between measurements. We used a least-squares fit to determine the three parameters A, ω_0, and ϕ_0, from these data.

The scatter of the data points and the fitted curve are shown in Fig. 4. Table I shows the parameters and their errors from fitting to Eq. (1). The quality of the fit can be seen in the values of the regression coefficient R^2, always close to 1.

Table II compares the period of oscillation, calculated from the fitted frequency, to a separate measurement of the period obtained directly from a photometer. In most cases, the discrepancies are less than 1%.

Once the values of the mass (m) and the frequency of the free oscillations (ω_0) have been obtained, the spring constant k_{fit} can be calculated. To do so, we have carried out a least-squares linear regression to fit the equation $\omega_0^2 = k_{\mathrm{fit}}/m$, using the values shown in Table III. We also made a separate measurement of the spring constant by hanging a 500 g mass from the spring and measuring the static shift in the position. A comparison of the two results for k is shown in Table IV.

IV. DAMPED HARMONIC OSCILLATIONS

By reducing the air flow in the air track, we can introduce significant friction and study damped oscillations. Figure 5 shows the screen of the mobile phone after a series of damped oscillations. Assuming linear damping for simplicity, we can fit the acceleration data to the formula,

$$a(t) = De^{-\gamma t} \sin(\omega t + \phi), \tag{2}$$

Table V. Parameters and their errors from fitting the acceleration data for damped oscillations.

	$D \pm \delta D$ ($\mathrm{m/s^2}$)	$\gamma \pm \delta\gamma$ (s^{-1})	$\omega \pm \delta\omega$ (rad/s)	$\phi \pm \delta\phi$ (rad)	R^2
m_6	1.64 ± 0.02	0.58 ± 0.02	16.52 ± 0.01	-0.56 ± 0.01	0.9816

Table VI. Comparison of the relaxation time obtained from the measured damping constant, $\tau_{\rm fit} = 1/\gamma$, with the relaxation time τ_d obtained from Eq. (3).

$\tau_{\rm fit} \pm \delta\tau_{\rm fit}$ (s^{-1})	$\tau_d \pm \delta\tau_d$ (s^{-1})	Diff. (%)
1.71 ± 0.02	1.70 ± 0.04	0.59

where D is the initial acceleration amplitude, γ is the linear damping constant, and ϕ is a phase constant. Figure 6 shows a fit of the data to this formula, while Table V shows the parameters obtained from the fit.

The relaxation time, τ, is the inverse of the damping constant: $\tau = 1/\gamma$. It can also be derived from the formula,

$$\tau = \frac{T_d T_{\rm fit}}{2\pi} \frac{1}{(T_d^2 - T_{\rm fit}^2)^{1/2}}, \tag{3}$$

where $T_{\rm fit}$ is the period of the free oscillations (see Table II) and $T_d = 2\pi/\omega$ is the period of the damped oscillations. In Table VI, we compare the values of the relaxation time obtained from each of these formulas.

V. CONCLUSIONS

We have studied free and damped oscillations in a very simple way using a mobile phone acceleration sensor and the free Accelerometer Monitor application for the Android operating system. Results for the period, frequency, and spring constant are in good agreement with more traditional measurements of these quantities. We have also studied damped oscillations and obtained consistent results for the effective linear damping constant. The success of these measurements demonstrates the feasibility of using a mobile phone acceleration sensor in the general physics laboratory. For example, the mobile phone accelerometer could also be used to study two-dimensional motions on an air table[22] and various types of pendulum motions.

ACKNOWLEDGMENTS

The authors would like to thank the Institute of Education Sciences, Universitat Politècnica de València (Spain), for the support of the Teaching Innovation Group, MoMa.

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