UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Aplicaciones de los Sensores de los Smartphones a la Didáctica de la Física Experimental

TESIS DOCTORAL

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Resumen

Tradicionalmente, el objetivo de las prácticas de laboratorio de las asignaturas de Física es doble: por una parte, que los estudiantes refuercen los conocimientos adquiridos en las clases de teoría; por otra, que se habitúen a las técnicas experimentales. Sin embargo, los alumnos consideran que en ocasiones las prácticas son rutinarias y poco interesantes. Para paliar este problema, se ha hecho uso de diversos recursos basados en las Tecnologías de la Información y las Comunicaciones.

El objetivo fundamental de esta Tesis es proponer diversos experimentos de Física en los que se utilizan como herramientas de medida los sensores de que disponen los *smartphones* de los propios estudiantes, aprovechando las aplicaciones gratuitas existentes para el control de estos sensores y para la toma y transmisión de los datos obtenidos. Con este fin se ha realizado un conjunto de trabajos, recogidos en esta Tesis en formato de compendio de publicaciones, en los que se proponen nuevas experiencias de laboratorio de Física con *smartphones*. En ellas se saca partido del sensor de aceleración para el estudio de las oscilaciones libres y amortiguadas de un *smartphone*, de los modos de vibración de dos acoplados, y del batido mecánico; del sensor de luz ambiente para el análisis de la eficiencia de diversos tipos de fuente, y de la dependencia de la iluminancia con la distancia; y, finalmente, del micrófono para la caracterización del fenómeno del batido acústico.

Las experiencias diseñadas están enfocadas a estudiantes universitarios y de educación secundaria. Las encuestas realizadas muestran la mayor calificación otorgada a este tipo de experiencias con respecto a sus alternativas tradicionales.

Resum

Tradicionalment, l'objectiu de les pràctiques de laboratori de les assignatures de Física és doble: d'una banda, que els estudiants reforcen els coneixements adquirits en les classes de teoria; per una altra, que s'habituen a les tècniques experimentals. No obstant això, els alumnes consideren que en ocasions les pràctiques són rutinàries i poc interessants. Per a pal·liar aquest problema, s'ha fet ús de diversos recursos basats en les Tecnologies de la Informació i les Comunicacions.

L'objectiu fonamental d'aquesta Tesi és proposar diversos experiments de Física en els quals s'utilitzen com a eines de mesura els sensors de què disposen els *smartphones* dels propis estudiants, aprofitant les aplicacions gratuïtes existents per al control d'aquests sensors i per a la presa i la transmissió de les dades obtingudes. Amb aquesta finalitat s'ha realitzat un conjunt de treballs, recollits en aquesta Tesi en format de compendi de publicacions, en els quals es proposen noves experiències de laboratori de Física amb *smartphones*. En aquestes es trau partit del sensor d'acceleració per a l'estudi de les oscil·lacions lliures i esmorteïdes d'un *smartphone*, dels modes de vibració de dos acoblats, i del batut mecànic; del sensor de llum ambiente per a l'anàlisi de l'eficiència de diversos tipus de font, i de la dependència de la il·luminancia amb la distància; i, finalment, del micròfon per a la caracterització del fenomen del batut acústic.

Les experiències dissenyades estan enfocades a estudiants universitaris i d'educació secundària. Les enquestes realitzades mostren la major qualificació atorgada a aquest tipus d'experiències pel que fa a les seues alternatives tradicionals.

Abstract

Traditionally, Physics laboratory practices have two objectives. On the one hand, students reinforce the concepts that they have acquired in theory lessons. On the other hand, they get used to the experimental techniques. However, students sometimes consider that the practices are routine and of little interest. Several resources, based on Information and Communication Technologies, have been used to deal with this problem.

The smartphones of the students themselves incorporate various sensors. Free available applications are able to control the sensors, acquire data and transmit them. The smartphones become measuring tools. The main objective of this Thesis is to propose new experiments for Physics laboratories that take advantage of this way of using smartphones. A collection of works is presented as a set of publications. The acceleration sensor enables us to study: the free and damped oscillations of the smartphone; the normal modes of a coupled two-dimensional vibrating system of smartphones; and the mechanical beat. The ambient light sensor is used to analyze the efficiency of several types of optical sources; the dependence of the illuminance on the distance to the source is also studied. Finally, the microphone enables us to characterize the acoustic beat phenomenon.

The new experiments are focused on university and high school students. Our surveys show the higher rating given to this type of experiences with respect to their traditional alternatives.

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Agradecimientos

Cuando llega el momento de echar la vista atrás y recordar a todas las personas que han contribuido a llevar un trabajo a buen término, lo más habitual es comenzar recalcando que son tantas que resulta imposible mencionarlas a todas. Sin embargo, aunque parezca un cliché, tengo que decir que en mi caso es absolutamente cierto. Vaya por tanto mi más sincero agradecimiento a todas ellas, aunque en especial y en su representación, a las que mencionaré en las siguientes líneas.

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Capítulo 1

Introducción

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El objetivo fundamental de este proyecto de Tesis es extender el uso de los sensores de los teléfonos móviles (*smartphones*) en el área de la Física y la Tecnología, tanto en la educación secundaria como universitaria. Se trata así de generar una nueva perspectiva en el campo de las Ciencias de la Educación, introduciendo elementos de desarrollo tecnológico y social como son estos dispositivos móviles de última generación en el trabajo experimental de laboratorio. En esta memoria de Tesis se recoge en formato de compendio de publicaciones una serie de experiencias innovadoras en las que se aprovecha el cada vez mayor número de sensores que estos dispositivos incorporan, y la creciente disponibilidad de *Apps* gratuitas que permiten controlar dichos sensores.

Antecedentes y objetivos de la investigación

En la sociedad digital actual, el uso de nuevas tecnologías se ha universalizado con la incorporación de los llamados "*dispositivos inteligentes*" (tabletas y *smartphones*). Por ello, hoy más que nunca, es necesario adquirir una educación en Tecnologías de Información y Comunicaciones (TIC), que nos permita no caer en la brecha o fractura digital y poner las nuevas tecnologías al servicio de los ciudadanos, contribuyendo así al desarrollo de una sociedad moderna y equilibrada (Pérez Tornero, 2005). Esta educación en TIC es especialmente importante en secundaria y en la universidad, ya que en ambos escenarios su incorporación resulta más efectiva que en educación infantil y primaria (Pérez Tornero, 2013). No obstante, en estos primeros niveles educativos también se han dado pasos importantes gracias a las pizarras electrónicas (Lim, 2013).

Es por tanto necesario y urgente plantear iniciativas que incrementen el uso y la eficiencia de las TIC en el entorno educativo, que permitan educar en medios y hacer la educación más atractiva para el estudiante, y que además sirvan para formar en valores como la creatividad, el trabajo en grupo, el esfuerzo y la responsabilidad. Dentro de este contexto, la presente Tesis tiene como objetivo fundamental plantear diversas experiencias innovadoras que permitan introducir las TIC en las enseñanzas secundaria y universitaria. En particular, se pretende que los alumnos utilicen sus propios teléfonos inteligentes en el aula para la realización de experimentos de Física.

Tradicionalmente, en el laboratorio se realizan prácticas de laboratorio en las cuales los alumnos ponen a prueba, desde el punto de vista experimental, las leyes de la Física que han estudiado previamente en las clases de teoría. El objetivo de las prácticas de laboratorio es doble: por un lado reforzar los conocimientos teóricos adquiridos en las clases de teoría; por otro, habituarse a las técnicas experimentales propias de laboratorio (manejo de aparatos de medida, toma de datos experimentales, análisis de los mismos, cálculo de incertidumbres, etc). De esta forma, las prácticas de laboratorio permiten realizar experimentos que complementan la teoría, forman a los estudiantes en el método científico, y les hacen interiorizar los conceptos fundamentales (Séré, 2002).

En el laboratorio de Física se utiliza multitud de aparatos de medida. Algunos son muy sencillos (cronómetro, regla,…), y otros más complejos (multímetro, osciloscopio, ordenador,…). Resulta muy importante para la correcta formación del alumno, que adquiera habilidades en la utilización de dichos aparatos de medida, así como en el análisis matemático de los datos obtenidos. Sin embargo, nuestra experiencia docente nos ha permitido comprobar que, en numerosas ocasiones, los alumnos encuentran rutinarias y poco enriquecedoras las prácticas de las asignaturas relacionadas con la Física, lo que conlleva que no se muestren interesados en las mismas y traten de realizar las mínimas medidas exigidas por el profesor lo antes posible para poder terminar la práctica a la mayor brevedad, de manera mecánica, y sin reflexión crítica sobre el trabajo realizado.

Para paliar este tipo de problema, se han utilizado diversos recursos basados en las TIC para realizar innovadores experimentos de Física. En concreto, para la adquisición de medidas se han utilizado como herramientas diversos dispositivos electrónicos con sensores, como son las cámaras digitales (Monsoriu, 2005; Vidaurre, 2008; Monsoriu, 2011; Monsoriu 2015), las *webcams* (Shamim, 2010), los ratones ópticos de ordenador (Romulo, 1997; Ng, 2005), los mandos de Nintendo Wii (Tomarken, 2012), los sensores Xbox Kinect (Ballester, 2013), y otros controladores de videojuegos (Vannoni, 2007). El controlador de Nintendo Wii permite registrar los movimientos simultáneos de varios objetos mediante conexión Bluetooth y explota el uso de tres acelerómetros para seguir los movimientos tridimensionales, y el sensor Kinect de la Xbox posibilita el rastreo de datos en 3D sobre una base de tiempos. Ambos controladores pueden utilizarse en muchos experimentos de Física (Skeffington, 2012). Sin embargo, estos dispositivos requieren un software específico que no está ampliamente disponible en los laboratorios de Física.

En este contexto, podemos encontrar en la literatura científica un número creciente de propuestas de experimentos de Física en los que se integra el *smartphone* como un nuevo elemento motivador. El teléfono de los propios alumnos se incorpora en las prácticas de laboratorio como un dispositivo de medida y toma de datos mediante los sensores que lleva incorporados. Se trata de una línea de investigación muy reciente e innovadora, ya que los primeros experimentos docentes sencillos con *smartphones* (Kuhn, 2012; Vogt, 2012) y tabletas (Silva, 2012; Streepey, 2013) fueron publicados a nivel de secundaria en la revista *The Physics Teacher* de la *American Association of Physics Teachers* entre 2012 y 2013. A nivel universitario, podemos también encontrar experiencias de laboratorio muy interesantes con *smartphones* (Monteiro, 2014; Arribas, 2015). Las principales ventajas del uso de los *smartphones* y tabletas en la educación secundaria y universitaria son:

- Estos dispositivos están cada vez más extendidos entre estudiantes de secundaria y universidad. Se estima que más del 90% de los estudiantes disponen de *smartphones* de gama media o superior, por lo que están habituados al uso de esta tecnología.
- Estos dispositivos incorporan diversos sensores, cada vez de mejor calidad y por un precio más reducido (Ma, 2013).
- Cada vez hay más aplicaciones (*Apps*) libres para controlar los sensores de estos dispositivos.

Así pues, todos estos factores ponen de manifiesto que los teléfonos móviles y las tabletas son herramientas TIC ideales para ser introducidas en el laboratorio en estos niveles educativos de forma alternativa a los métodos tradicionales. Con estas experiencias se consigue una mayor motivación por parte de los estudiantes. Es más, la realización de prácticas de Física sorprende a los estudiantes al descubrir nuevas formas de uso de sus propios teléfonos inteligentes, más allá de aquéllas con las que están familiarizados. Además, se puede realizar estos experimentos de Física con un coste de material muy reducido, ya que no se requiere la compra de costosos equipos de laboratorio (sonómetros, luxómetros, gausímetros,…). De esta forma, la incorporación del *smartphone* como herramienta de medida supone una excelente oportunidad en la didáctica experimental de la Física y la Tecnología.

En definitiva, el objetivo fundamental de este proyecto de Tesis es proponer diversas aplicaciones de teléfonos móviles inteligentes en el área de la Física experimental, tanto en educación secundaria como universitaria, aprovechando los distintos sensores que estos dispositivos incorporan y la creciente disponibilidad de *Apps* que los controlan. Como objetivos particulares, se plantea el desarrollo de diversas experiencias con el uso del sensor de aceleración, el sensor acústico y el sensor de luz ambiente como instrumentos de medida.

Estructura de la Tesis

En primer lugar cabe destacar que se trata de una Tesis por compendio de publicaciones, por lo que cada una de ellas puede ser leída de forma autónoma, al contener los aspectos necesarios para su comprensión (marco teórico, objetivos, resultados, conclusiones y referencias). Sin embargo, es importante recalcar que todos ellos se enmarcan en el mismo contexto, la propuesta de nuevas experiencias de laboratorio de Física con *smartphones*. Así pues, la Tesis se estructura en 4 capítulos:

1. Introducción.
2. Publicaciones.
    - Using a mobile phone acceleration sensor in physics experiments on free and damped harmonic oscillations.
    - Direct visualization of mechanical beats by means of an oscillating smartphone.
    - Theoretical and experimental study of the normal modes in a coupled two-dimensional system.
    - Determining the efficiency of optical sources using a smartphone’s ambient light sensor.
    - Visualizing acoustical beats with a smartphone.
3. Discusión de los resultados.
4. Conclusiones.

El **Capítulo 1** de introducción general pretende contextualizar el documento completo de la Tesis para permitir al lector el acceso directo a la información de su interés. Como se ha visto, en el primer apartado se exponen los antecedentes de la investigación y los objetivos planteados. En segundo lugar se indica la estructura de la Tesis completa y se explica el marco común en el que se integran los artículos, y cómo responden a los objetivos planteados inicialmente.

El cuerpo principal de la Tesis está compuesto por el **Capítulo 2** que, como se ha mostrado en la enumeración previa, recoge los cinco artículos que conforman el presente compendio.

El **primer artículo** que se presenta en esta Tesis es un trabajo titulado "*Using a mobile phone acceleration sensor in physics experiments on free and damped harmonic oscillations*" (Castro-Palacio, 2013a). En él se expone de forma exhaustiva y cuantitativa la caracterización de movimientos vibratorios armónicos simples y amortiguados mediante el sensor de aceleración de un *smartphone*. Éste fue el primer trabajo publicado en la literatura científica donde se proponía el uso de los sensores integrados en los teléfonos inteligentes en prácticas de laboratorio de Física en el ámbito universitario. Este artículo se ha publicado en *American Journal of Physics*, editado por la *American Association of Physics Teachers*. A día de hoy es una de las mejores revistas internacionales en el campo de la didáctica de la Física. Así, en el *JCR Science Edition* del año 2013, la revista en cuestión tiene acreditado un factor de impacto de 0,804, y su posición relativa en el ámbito científico de "*EDUCATION, SCIENTIFIC DISCIPLINES*" respecto al número total de títulos recogidos en esta misma área científica es 25/36. También está indexada en el campo "*PHYSICS, MULTIDISCIPLINARY*". Adicionalmente, y con el fin de evidenciar la contribución de este trabajo al desarrollo de posteriores estudios, es también oportuno señalar que, de acuerdo con el *Science Citation Index* (*ISI Web of Knowledge*), esta aportación ha recibido hasta el momento 17 citas.

El **segundo artículo** se titula "*Direct visualization of mechanical beats by means of an oscillating smartphone*" (Giménez, 2017a). Recientemente ha sido aceptado para su publicación en *The Physics Teacher* de la *American Association of Physics Teachers*. Esta revista se encuentra incluida en la *Web of Science* e indexada desde 2015 en el campo "*PHYSICS, MULTIDISCIPLINARY*" del *JCR Science Edition* con un factor de impacto de 0,500 ocupando una posición relativa en este campo de 68/79. Hay que destacar que se trata de la mejor revista internacional en el ámbito de la docencia de la Física a nivel preuniversitario. Durante el proceso editorial, el artículo está disponible en el campo *Physics Education* del repositorio on-line arXiv. En este trabajo, mediante un sencillo montaje adaptado a nivel de secundaria se visualiza directamente en la pantalla de un *smartphone* el batido mecánico que experimenta el teléfono suspendido mediante un muelle sometido a su vez a una fuerza externa armónica.

El **tercer artículo** lleva por título "*Theoretical and experimental study of the normal modes in a coupled two-dimensional system*", y ha sido publicado en la sección de educación de la *Revista Mexicana de Física E* (Giménez, 2017b). Esta revista es editada por la *Sociedad Mexicana de Física* y constituye uno de los foros más importante sobre enseñanza de la Física en Latinoamérica. Se encuentra incluida tanto en la *Web of Science* como en *Scopus*. En este trabajo, se analizan los modos normales de vibración de un sistema de dos osciladores bidimensionales. Para ello, dos *smartphones* se conectan físicamente mediante un sistema de resortes sobre una plataforma sin rozamiento. Sus respectivos sensores de aceleración permiten caracterizar, tanto los modos normales de vibración, como cualquier otro tipo de movimiento acoplado como combinación de dichos modos normales. Hay que destacar que este trabajo constituye la primera propuesta en el campo de la didáctica de la Física experimental universitaria donde se utilizan *smartphones* en la caracterización de movimientos bidimensionales.

El **cuarto artículo** que lleva por título "Determining the efficiency of optical sources using the smartphone's ambient light sensor" (Sans, 2017) ha sido publicado recientemente en *European Journal of Physics*. Esta revista es editada por el *Institute of Physics* y en el *JCR Science Edition* del año 2015 tiene acreditado un factor de impacto de 0,608 y su posición relativa en el ámbito científico de "*EDUCATION, SCIENTIFIC DISCIPLINES*" respecto al número total de títulos recogidos en esta misma área científica es 30/40. También está indexada en el campo "*PHYSICS, MULTIDISCIPLINARY*". En esta ocasión, se propone la utilización del *smartphone* como luxómetro gracias al sensor de luz ambiente que incorpora. Mediante este sensor se ha podido caracterizar la eficiencia luminosa de diferentes fuentes (incandescente, halógena y leds).

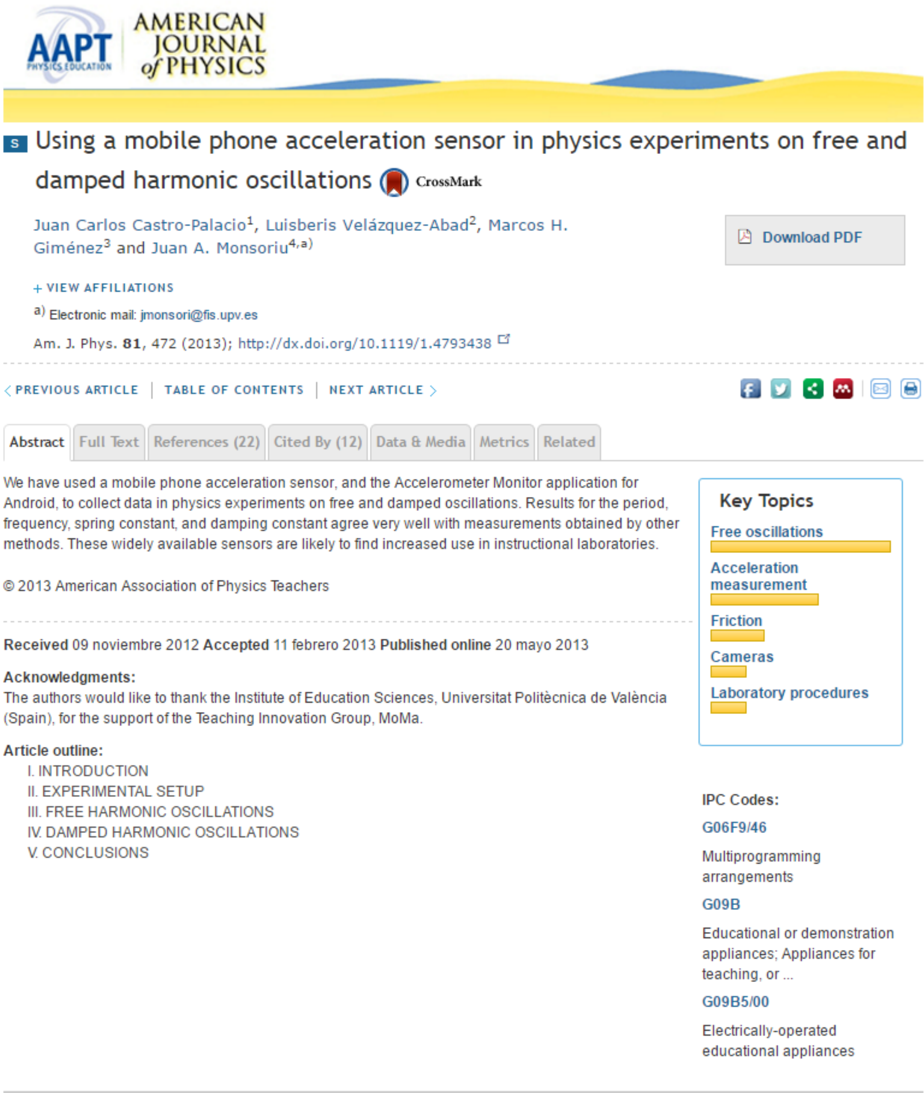
Finalmente, el **quinto artículo** se titula “Visualizing acoustical beats with a smartphone”, y en estos momentos está en revisión por pares en una revista internacional indexada. Durante el proceso editorial, el trabajo remitido está disponible en el repositorio on-line arXiv en el ámbito *Physics Education.* En este trabajo se analiza de nuevo el fenómeno del batido pero aplicado a ondas acústicas. La innovación del trabajo respecto a los anteriores consiste en la utilización del *smartphone* como sonómetro a través de su sensor acústico (micrófono) y mediante una *App* gratuita para tal efecto. De esta forma, se propone el uso de los *smartphones* de los propios alumnos como instrumento de medida en el ámbito de la acústica, reduciendo considerablemente el coste de las experiencias de laboratorio.

A continuación, el **capítulo 3** aporta una breve discusión acerca de los principales resultados mientras que el **capítulo 4** presenta las conclusiones finales de la Tesis así como el cumplimiento de los objetivos planteados. Por último se muestra la **bibliografía general** utilizada a lo largo de toda la Tesis.

Capítulo 2

Publicaciones

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



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

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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.

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Article outline:

Key Topics

- Free oscillations
- Acceleration measurement
- Friction
- Cameras
- Laboratory procedures

IPC Codes:

G06F9/46
Multiprogramming arrangements

G09B
Educational or demonstration appliances; Appliances for teaching, or ...

G09B5/00
Electrically-operated educational appliances

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

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Abstract

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.

1. 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 (Monsoriu, 2005), webcams (Shamim, 2010), the optical mouse of computers (Ochoa, 1997; Ng, 2005), XBee transducers (Ayars, 2010), wiimote (Tomarken, 2012), and other game console controllers (Vannoni, 2007). For instance, digital camera techniques have been widely used to visualize physics concepts (Riera, 2002; Vidaurre, 2002; Greczylo, 2002; Chung, 2004). 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 (Kawam, 2011; Ochoa 2011; Tomarken, 2012) 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 (Weltin, 1966) and Hunt (Hunt, 1985a; Hunt, 1985b).

Although the wiimote provides a low-cost way to track motion in a variety of physics experiments (Skeffington, 2012), 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 most undergraduate physics programs, and many authors have suggested laboratory exercises on this topic (Onorato, 2010; Flores-Hidalgo, 2011). The air track is a useful device for such exercises because the friction force can be easily decreased (Berger, 1988). 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 *Accelerometer Monitor* mobile application. We will then present results for free harmonic oscillations, followed by results for damped oscillations.

2. 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.

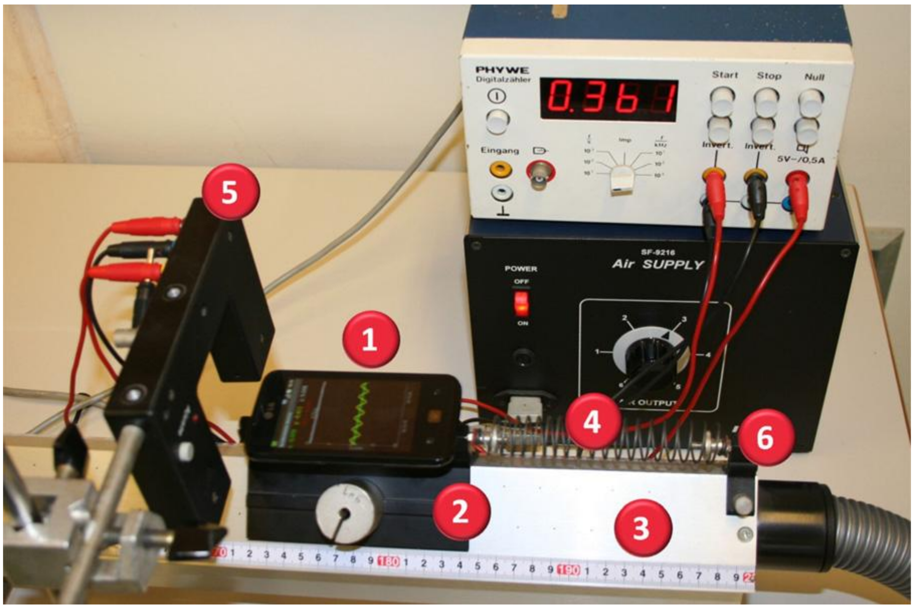

Figure 1. *Photograph of the experimental setup showing (1) smartphone, (2) glider, (3) air track, (4) spring, (5) photometer, and (6) the fixed end.*

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 website*. 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.

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

* https://play.google.com/store/apps

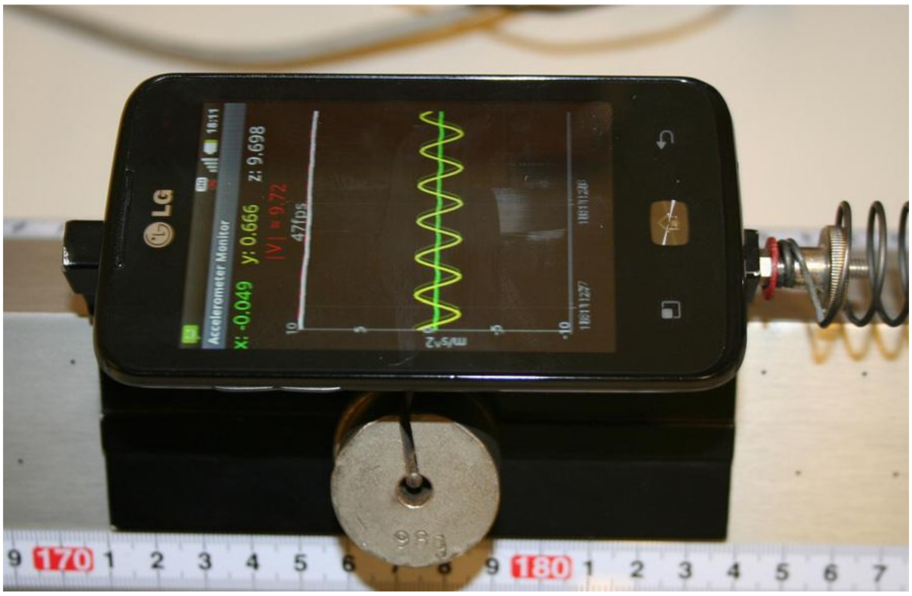

Figure 2. *Close-up of the mobile phone screen showing an acceleration graph for free oscillations.*

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.

3. 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.

```
# 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
```

Figure 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.*

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.

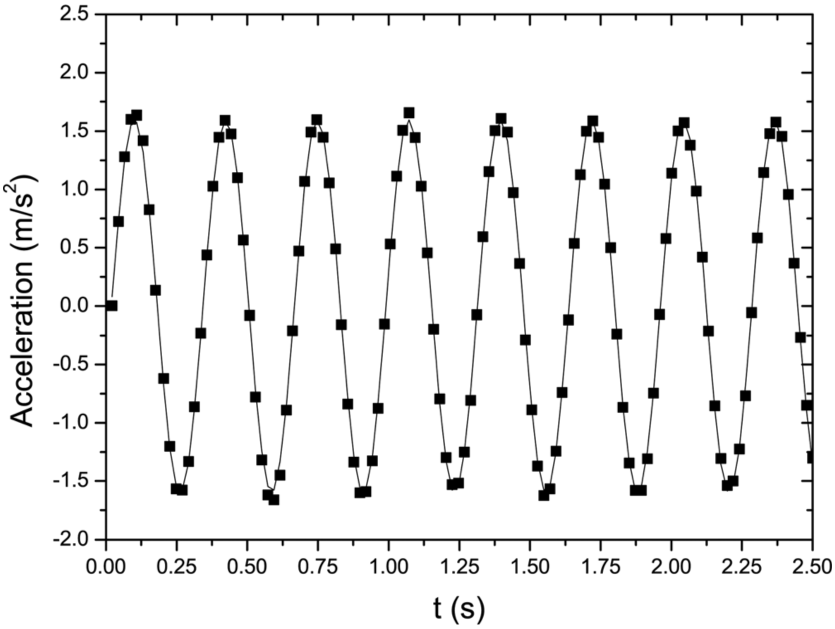

Figure 4. *Example of the experimental acceleration data (squares) and fitted curve (solid line) for mass m_3.*

	$m \pm 0.0001$ (kg)	$A \pm \delta A$ (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	06285	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

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

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%.

	$T_{fit} \pm \delta T_{fit}$ (s)	$T_{photo} \pm 0.001$ (s)	*Difference (%)*
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 II. *Comparison of period 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.*

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 $\omega_0^2 = k_{fit}/m$, 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.

	$m^{-1} \pm \delta m^{-1}$ (kg^{-1})	$\omega_0^2 \pm \delta\omega_0^2$ (rad^2/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 III. *Data for the calculation of the spring constant.*

Figure 5. *Photograph of the smartphone displaying an acceleration graph for the case of damped oscillations*

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

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.*

4. 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,

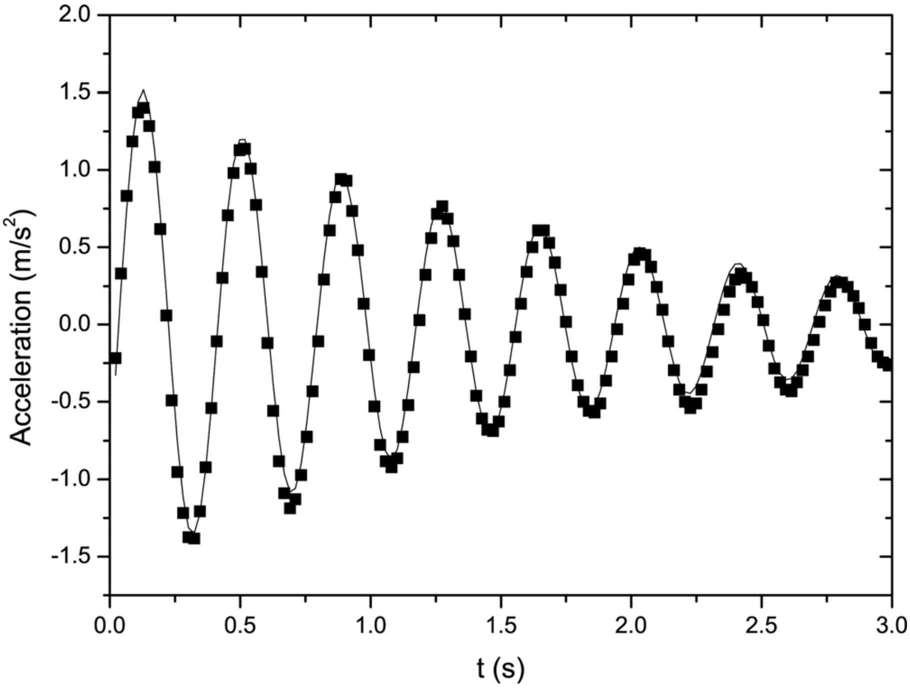

Figure 6. *Experimental acceleration data (squares) and fitted curve (solid line) for damped oscillations.*

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

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.

	$D \pm \delta D$ (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 V. *Parameters and their errors from fitting the acceleration data for damped oscillations.*

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

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

where T_{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.

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

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

5. 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 (Bobillo-Ares, 1995) and various types of pendulum motions.

6. 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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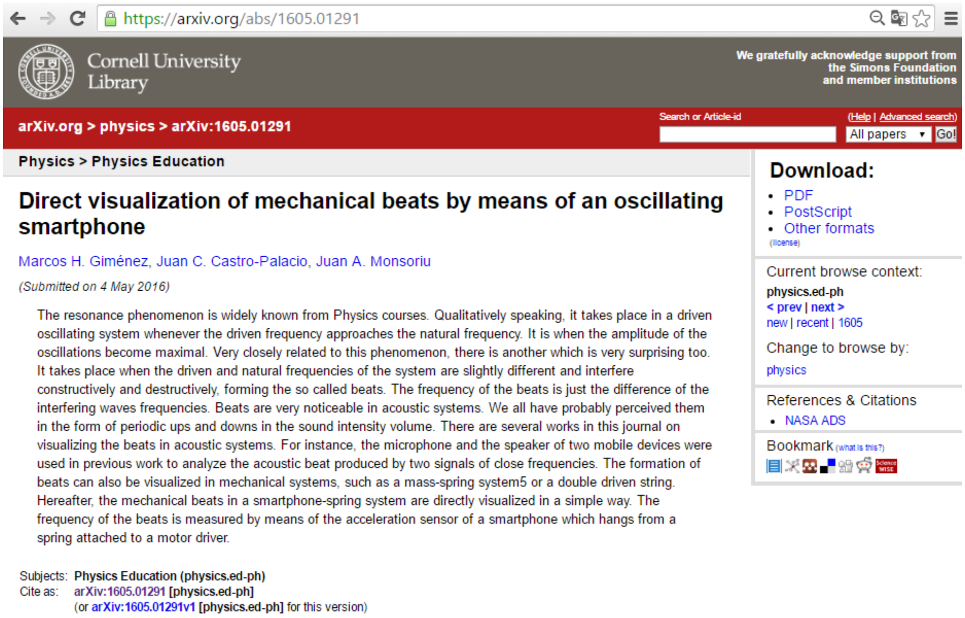
Direct visualization of mechanical beats by means of an oscillating smartphone



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Direct visualization of mechanical beats by means of an oscillating smartphone

Marcos H. Giménez, Juan C. Castro-Palacio, Juan A. Monsoriu

(Submitted on 4 May 2016)

The resonance phenomenon is widely known from Physics courses. Qualitatively speaking, it takes place in a driven oscillating system whenever the driven frequency approaches the natural frequency. It is when the amplitude of the oscillations become maximal. Very closely related to this phenomenon, there is another which is very surprising too. It takes place when the driven and natural frequencies of the system are slightly different and interfere constructively and destructively, forming the so called beats. The frequency of the beats is just the difference of the interfering waves frequencies. Beats are very noticeable in acoustic systems. We all have probably perceived them in the form of periodic ups and downs in the sound intensity volume. There are several works in this journal on visualizing the beats in acoustic systems. For instance, the microphone and the speaker of two mobile devices were used in previous work to analyze the acoustic beat produced by two signals of close frequencies. The formation of beats can also be visualized in mechanical systems, such as a mass-spring system5 or a double driven string. Hereafter, the mechanical beats in a smartphone-spring system are directly visualized in a simple way. The frequency of the beats is measured by means of the acceleration sensor of a smartphone which hangs from a spring attached to a motor driver.

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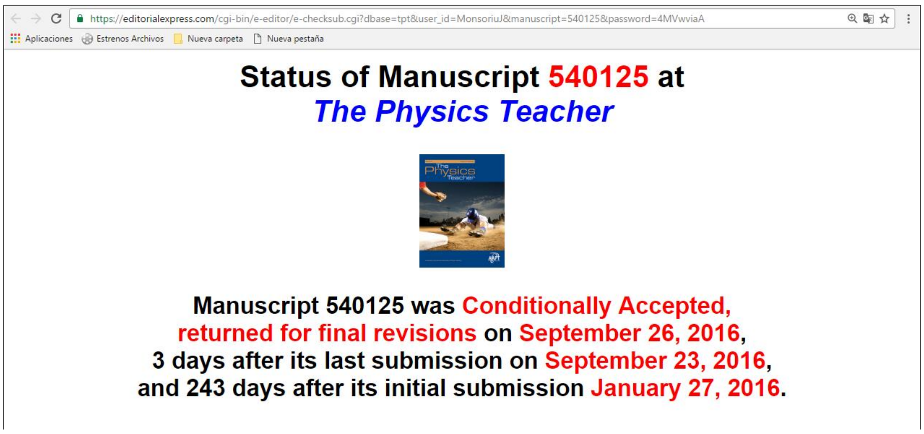

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Direct visualization of mechanical beats by means of an oscillating smartphone

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1. Introduction

The resonance phenomenon is widely known from Physics courses (Resnick, 1999). Qualitatively speaking, it takes place in a driven oscillating system whenever the driven frequency approaches the natural frequency. It is when the amplitude of the oscillations become maximal.

Very closely related to this phenomenon, there is another which is very surprising too. It takes place when the driven and natural frequencies of the system are slightly different and interfere constructively and destructively, forming the so called “beats”. The frequency of the beats is just the difference of the interfering waves frequencies.

Beats are very noticeable in acoustic systems. We all have probably perceived them in the form of periodic ups and downs in the sound intensity volume. There are several works in this journal on visualizing the beats in acoustic systems (Kuhn, 2014; Ganci, 2015; Keeports, 2015). For instance, the microphone and the speaker of two mobile devices were used in previous work (Kuhn, 2014) to analyze the acoustic beat produced by two signals of close frequencies. The formation of beats can also be visualized in mechanical systems, such as a mass-spring system (Andersson, 2005) or a double driven string (Carmichael, 2004).

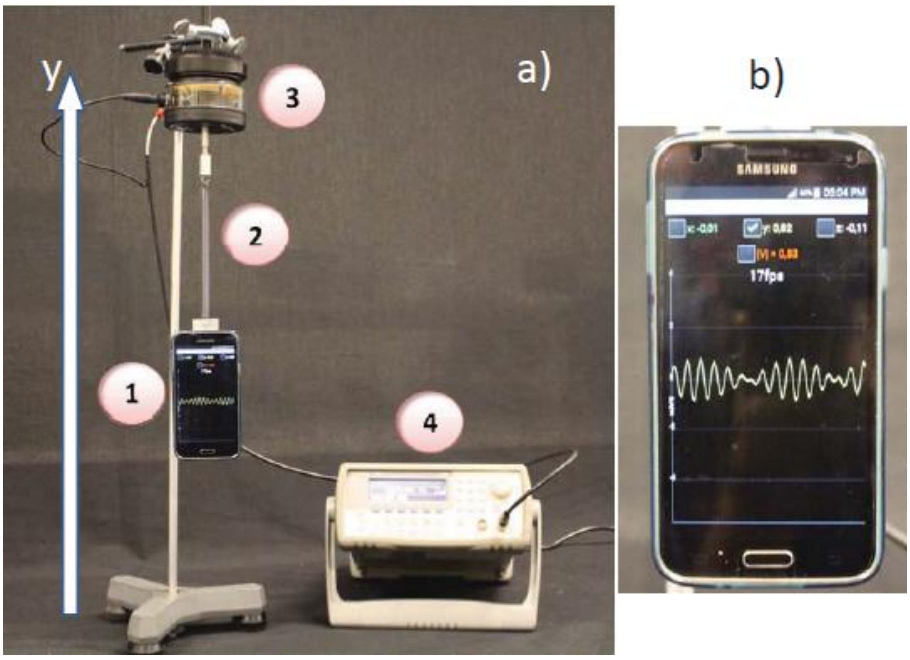

Figure 1. *The experimental setup, consisting of the smartphone (1), the spring (2), motor driver (3), and the AC generator (4), is included in panel a. A smartphone showing beats on the screen is included on the right hand side, in panel b. The y-axis is used as a reference axis.*

Hereafter, the mechanical beats in a smartphone-spring system are directly visualized in a simple way. The frequency of the beats is measured by means of the acceleration sensor of a smartphone which hangs from a spring attached to a motor driver.

2. Equations governing the beats

From the experimental setup in Fig. 1, the Second Newton's Law can be stated as follows:

$$F_0 \sin(\Omega t + \phi) - ky - bv = ma \tag{1}$$

where $F_0 \sin(\Omega t + \phi)$ is the driving force acting on the system, F_0 is its amplitude, Ω its frequency and ϕ the initial phase. The term $-kx$ represents the elastic force exerted by the spring on the smartphone and k, the spring constant. The term $-bv$ is the damping force exerted by the air on the system, where b is the damping coefficient and v the velocity of the oscillating smartphone. On the right hand side of the equation are the mass of the smartphone m, and its acceleration a. The natural frequency of the system is $\omega_0 = \sqrt{k/m}$.

The solution of the above equation for a free oscillating system, that is, without damping ($b = 0$) and driving forces ($F_0 = 0$), can be expressed as,

$$y_1(t) = A \sin(\omega_0 t + \varphi) \tag{2}$$

If the damping force is present, the solution is a little more complicated and results in a damped oscillation,

$$y_1(t) = Ae^{-t/\tau} \sin(\omega t + \varphi) \tag{3}$$

where $\tau = 2m/b$ is the relaxing time of the damped oscillations and,

$$\omega = \sqrt{\omega_0^2 - (1/\tau^2)} \tag{4}$$

Eq. (3) is the solution of the homogeneous equation governing the damped oscillations (Eq. (1)). Moreover, we can define a particular solution of Eq. (1) as (see Gaffney, 2002),

$$y_2(t) = D \sin(\Omega t + \phi') \tag{5}$$

where the amplitude is,

$$D = \frac{F_0}{m\sqrt{(\Omega^2 - \omega_0^2)^2 + (2\Omega/\tau)^2}} \tag{6}$$

Finally, the general solution of Eq. (1) is the sum of both solutions given in Eq. (3) and (5),

$$y(t) = y_1(t) + y_2(t) = Ae^{-t/\tau}\sin(\omega t + \varphi) + D\sin(\Omega t + \phi') \tag{7}$$

A small damping force ($b \approx 0$) would mean a large τ. Then, the experimental term becomes $e^{-t/\tau} \approx 1$. Under this assumption, the above equation reduces to,

$$y(t) = A\sin(\omega_0 t + \varphi) + D\sin(\Omega t + \phi') \tag{8}$$

being $D = F_0 \,/\, [\, m\, |\Omega^2 - \omega_0^2|\,]$. The beats appear in the system of Fig. 1 when the frequencies Ω and ω_0 in Eq. (8) are only slightly different. In our experimental setup, the oscillation data are captured with the accelerometer of the smartphones. In this respect, the expression for the acceleration of the system should be defined from Eq. (8) as,

$$a(t) = \frac{d^2y}{dt^2} = B\sin(\omega_0 t + \varphi) + E\sin(\Omega t + \phi') \tag{9}$$

where $B = -\omega_0^2 A$ and $E = -\Omega^2 D$. Using some trigonometric identities, Eq. (9) can be rewritten as

$$a(t) = C\sin\left(\frac{\Omega + \omega_0}{2}t + \varphi_s\right) \tag{10}$$

with $C = \sqrt{\mathrm{B}^2 + \mathrm{E}^2 + 2BE\cos(|\Omega - \omega_0|\, t + \varphi_c)}$.

The phases ϕ_s and ϕ_c can be derived from the different parameters involved in the system, but this is not relevant for the visualization of the beats in this work. It can be noticed that the frequency in Eq. (10) is the average frequency, $(\Omega + \omega_0)/2$. On the other hand, the amplitude C is modulated by an envelope curve of frequency $|\Omega - \omega_0|$.

3. Description of the experiment and analysis

First of all, the motor driver is turned off and the natural frequency of the system is determined. The nearly free oscillations captured by the acceleration sensor of the smartphone are shown in Fig. 2a. The sensor data are collected with the Android application *Accelerometer Monitor* which can be downloaded from Google Play website*. The value of the natural period, T_0, directly measured from the plot is $T_0 = 0.369$ s, so the natural frequency without the driving force is $f_0 = 1/T_0 = 2.710$ Hz. In the next experiments, the motor driver is turned on. The driving frequency is set to $f = 2.769$ Hz (experiment I) and $f = 2.952$ Hz (experiment II), corresponding to the difference between the driving and the natural frequencies, $|f - f_0| = |\Omega - \omega_0|/(2\pi)$, of 0.059 Hz and 0.242 Hz, respectively. The corresponding data registered for these frequencies with the acceleration sensor are shown in Fig. 2b. The oscillation beats are clearly seen.

From direct measurements on Fig. 2b, the values of the beat frequencies (f_{beat}) can be obtained. Results are included in Table I along with the frequency difference ($|f - f_0|$) calculated from the value set at the AC generator minus the natural frequency obtained from the fit (Fig. 2a) when the motor driver is off. Even when results are not rigorously obtained, a good agreement is observed, that it, the percentage deviations in the last column are lower than 2% for both cases.

* https://play.google.com/store/apps

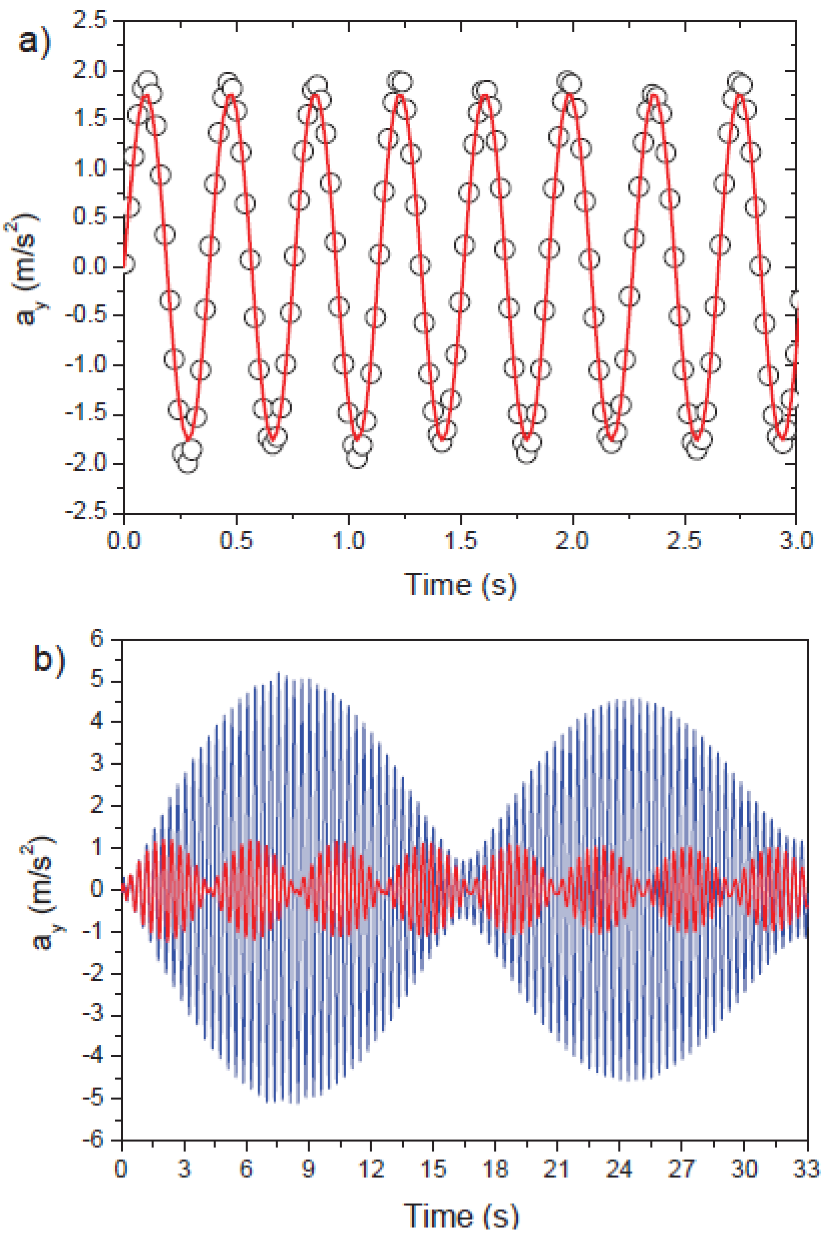

Figure 2. *Free oscillations of the smartphone as recorded by the acceleration sensor (panel a), and driven oscillations for* $|f - f_0| \approx 0.059$ *Hz (blue line) and 0.242 Hz (red line) (panel b).*

	Driving frequency f (Hz)	Theoretical beat frequency $\|f-f_0\|$ (Hz)	Experimental beat frequency f_{beat} (Hz)	D (%)
Exp. I	2.769	0.059	0.060	1.7
Exp. II	2.952	0.242	0.239	1.3

Table I. *Driving frequency (f), frequency difference ($|f-f_0|$) calculated from the value set at the AC generator minus the natural frequency obtained from the fit (Fig. 2a) when the motor driver is off, and frequency of the beats (f_{beat}) measured on Fig. 2b. The percentage deviations (D) are included in the last column.*

4. Acknowledgments

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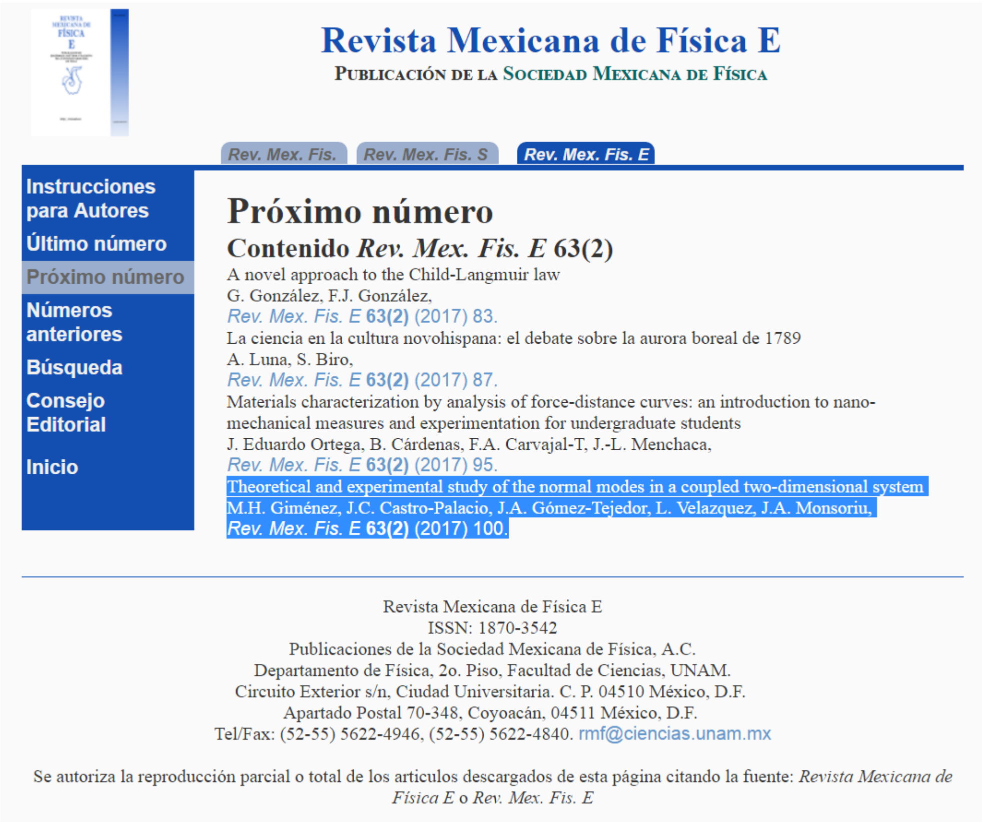
Theoretical and experimental study of the normal modes in a coupled two-dimensional system



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Theoretical and experimental study of the normal modes in a coupled two-dimensional system

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Abstract

In this work, the normal modes of a two-dimensional oscillating system have been studied from a theoretical and experimental point of view. The normal frequencies predicted by the Hessian matrix for a coupled two-dimensional particle system are compared to those obtained for a real system consisting of two oscillating smartphones coupled one to the other by springs. Experiments are performed on an air table in order to largely reduce the friction forces. The oscillation data are captured by the acceleration sensor of the smartphones and exported to file for further analysis. The experimental frequencies compare reasonably well with the theoretical predictions, specifically, within 1.7% of discrepancy.

1. Introduction

The study of the normal modes is a central issue in understanding the properties of solids and molecules, such as solid phonons and vibrations of polyatomic molecules (Jimenez, 1998; Castro-Palacio, 2005; Castro-Palacio, 2007; Lombardi, 2009). Therein, the formalism of the Hessian matrix is a common approach (Ashcroft, 1976; Jimenez, 1998; Castro-Palacio, 2005; Castro-Palacio, 2007). Therefore, this topic is included in the courses of Physics and Chemistry degrees later in the syllabus. In this report, for instance, the collective oscillations of a periodic solid, the phonons, which reveal important information, e.g. about thermal and electrical conductivity, can be derived experimentally from neutron scattering. In the case of polyatomic molecules, normal modes are connected to the vibrational spectrum, which can be measured using a number of spectroscopic techniques. From a teaching point of view, the simplest classical model to characterize the vibrational modes of a polyatomic molecule can be a particle system coupled by pair potentials (Wilson, 1995).

In general physics courses, the topic of coupled systems has been basically analyzed by means of linear 1D models (Resnick, 1999). It is also possible to find a number of works in the literature on the experimental characterization of coupled 1D systems connected to external drivers (Givens, 2003), i.e. by using video-analysis techniques (Monsoriu, 2005), electromechanical systems (Molina-Coronell, 2015) or sensors (Castro-Palacio, 2013b). However, when it comes to everyday life, most oscillations are more than one-dimensional. This is a good reason for including two-dimensional oscillation experiments in physics teaching (Bobillo-Ares, 1995; Pérez-Huerta, 2009).

Simple experiments involving oscillations are largely facilitated by introducing smartphones as oscillating bodies in one (Kuhn, 2012) and two dimensions (Tuset-Sanchis, 2015). The acceleration sensor carried by these devices can be used to collect the oscillation data which can be exported to file for further analysis (Castro-Palacio, 2013a). This is a major advantage since the way of studying two-dimensional oscillations in previous work (Bobillo-Ares, 1995) was somewhat tedious. For example, the trajectory of an oscillating puck on an air table can be followed by the trace and described by it onto paper, which is later digitalized to extract the information of the trajectory (Bobillo-Ares, 1995). The introduction of the smartphone acceleration sensor to measuring this kind of two-dimensional oscillations represented a major progress in our previous work (Tuset-Sanchis, 2015) where mechanical Lissajous figures were obtained in a very simple way.

In this work, we present an exhaustive theoretical and experimental study of the normal modes in a coupled 2D system. The experimental setup consists of two smartphones on an air table connected to each other by springs and to fixed ends. The air table allows us to largely reduce the friction forces. In these experiments the mobile phones themselves are the bodies under study. The coupled oscillations are captured with the acceleration sensors of the smartphones and the data are exported to file for ulterior analysis.

It should be pointed out that the smartphones are just measurement tools here. Its use is not the main contribution of this work. In fact, two-dimensional oscillations could be also analyzed by using other techniques, i.e. video analysis techniques (Riera, 2003; Monsoriu, 2005). However we have preferred to use smartphones since they allow for a fast and direct acquisition of data. Based on the collected data, the normal modes in the 2D system of coupled oscillators can be deeply analyzed, which is the main objective of this work. The theoretical frequencies derived from this analysis based on the Hessian matrix are compared with those obtained from processing the smartphone sensor data. In this way, we provide an example of a physics teaching experiment on 2D coupled oscillations which contributes to further close the existing gap in the General Physics courses. In this simple way, students may be introduced to the vibrational properties of solids and molecules.

The outline of the paper is the following. In Section 2, the setup used to carry out the experiments is described. It consists basically of two smartphones as oscillating bodies and an air table. It follows, in Section 3, the description of the Hessian matrix formalism which is applied to a coupled two-dimensional particle system. The results and discussions on the experiments and the comparison with the theoretical model are included in Section 4. Finally, in Section 5, some conclusions are drawn.

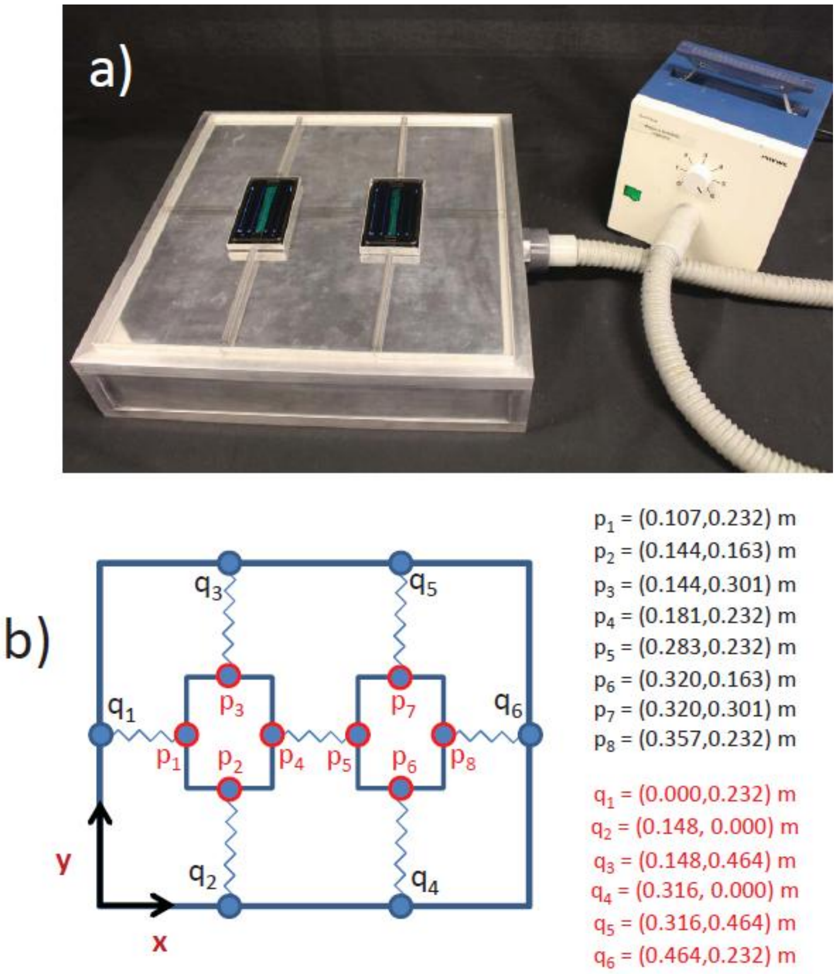

Figure 1. *Photograph of the experimental setup: a) global view of the squared air table, the air supplier, the springs, and the smartphones; b) geometric parameters of the system at rest.*

2. Experimental setup

A photograph of the experimental setup used for obtaining the vibrational normal modes in a coupled 2D system is shown in Fig. 1a. It consists of the air table, the air supplier, the springs, and two smartphones Samsung Galaxy S2 GT-I9100 bearing an Android version 4.03. The mass of the smartphones (plus the carrying tray) is $m = (174.4 \pm 0.1)$ g for both smartphones. As indicated in the figure, the lay out of the spring is a two-plus-signs geometry. The air table is a square of side (0.464±0.001) m. The force constant of the springs is $k = (20.6 \pm 0.1)$ N/m and their natural length is $d = (0.058 \pm 0.001)$ m. The remaining geometric parameters of the system are shown in Fig. 1b.

3. Hessian matrix formalism

First of all, the normal frequencies for the coupled system of Fig. 1 are calculated by a methodology based on the Hessian matrix formalism (Ashcroft, 1976). This formalism was successfully used in previous work, for instance, to calculate the phonons of rare gas solids (Jimenez, 1998; Castro-Palacio, 2005; Castro-Palacio, 2007). In this respect, the total potential energy of the system can be calculated taking into account the geometric variables defined in Fig. 1b and the displacement vectors,

$$\begin{aligned} \Delta\vec{r_1} &= \vec{r_1} - \vec{r_1}_0 = \left(x_1 - x_{1_0}\,, y_1 - y_{1_0}\right) \\ \Delta\vec{r_2} &= \vec{r_2} - \vec{r_2}_0 = \left(x_2 - x_{2_0}\,, y_2 - y_{2_0}\right) \end{aligned} \qquad (1)$$

Where $\vec{r_1}_0 = \left(x_{1_0}\,, y_{1_0}\right)$ and $\vec{r_2}_0 = \left(x_{2_0}\,, y_{2_0}\right)$ are the vector positions of the smartphones at the equilibrium positions and $\vec{r_1} = (x_1, y_1)$ and $\vec{r_2} = (x_2, y_2)$ are the corresponding vector positions when the smartphones are in motion.

It should be noted that the springs stretch approximately three times their natural length. In this respect, we have made an independent experiment to check the linearity of the springs. In these conditions and considering the harmonic approximation, the total potential is given by,

$$U = \frac{k}{2}\sum_{i=1}^{7}(d_i - d_0)^2 \qquad (2)$$

where the elongation of each spring, d_i, can be determined from the points represented in Fig. 1b and from the displacements in Eq. (1),

$$\begin{aligned} d_1 &= |\overrightarrow{q_1p_1} + \Delta\overrightarrow{r_1}| & d_5 &= |\overrightarrow{q_5p_7} + \Delta\overrightarrow{r_2}| \\ d_2 &= |\overrightarrow{q_2p_2} + \Delta\overrightarrow{r_1}| & d_6 &= |\overrightarrow{q_6p_8} + \Delta\overrightarrow{r_2}| \\ d_3 &= |\overrightarrow{q_3p_3} + \Delta\overrightarrow{r_1}| & d_7 &= |\overrightarrow{p_4p_5} + \Delta\overrightarrow{r_2} - \Delta\overrightarrow{r_1}| \\ d_4 &= |\overrightarrow{q_4p_6} + \Delta\overrightarrow{r_2}| \end{aligned} \tag{3}$$

Here, d_0 is the natural length of the springs. Thus, at rest ($\Delta\overrightarrow{r_1} = \Delta\overrightarrow{r_2} = (0,0)$), the seven springs are still elongated and the energy of the system represented by Eq. (2) is minimal but not zero.

From Fig. 2, it appears that there are seven degrees of freedom in general, three for the center of mass of each smartphone and one for the rotation about the center of mass of the system. However, we have not considered rotations in our two-dimensional model consisting of two coupled particles. Under these conditions, and taking into account that oscillations take place on the $\{x,y\}$ plane, we have a system with four degrees of freedom, namely, translations along *x*- and *y*- axes for each smartphone. The dynamical matrix (Hessian matrix) (Ashcroft, 1976) is then expressed as,

$$D_{i_\alpha j_\beta} = \frac{1}{m} \left(\frac{\partial^2 U}{\partial u_{i_\alpha} \partial u_{j_\beta}} \right) \Bigg|_{u_{i_\alpha}=0; u_{j_\beta}=0} \tag{4}$$

where U is the total potential energy and u_{i_α} (u_{j_β}) is the displacement of the *i*-th (*j*-th) particle ($i,j = 1,2$) along the α (β) axis ($\alpha,\beta = x,y$). As a result, a two-dimensional matrix is obtained.

The evaluation of this matrix at the equilibrium positions and further diagonalization yields the four vibrational eigenfrequencies squared. These normal frequencies will be denoted as ω_x^S, ω_y^S, ω_x^A, and ω_y^A, corresponding to the symmetric and antisymmetric modes and for the *x*- and *y*- axes, respectively.

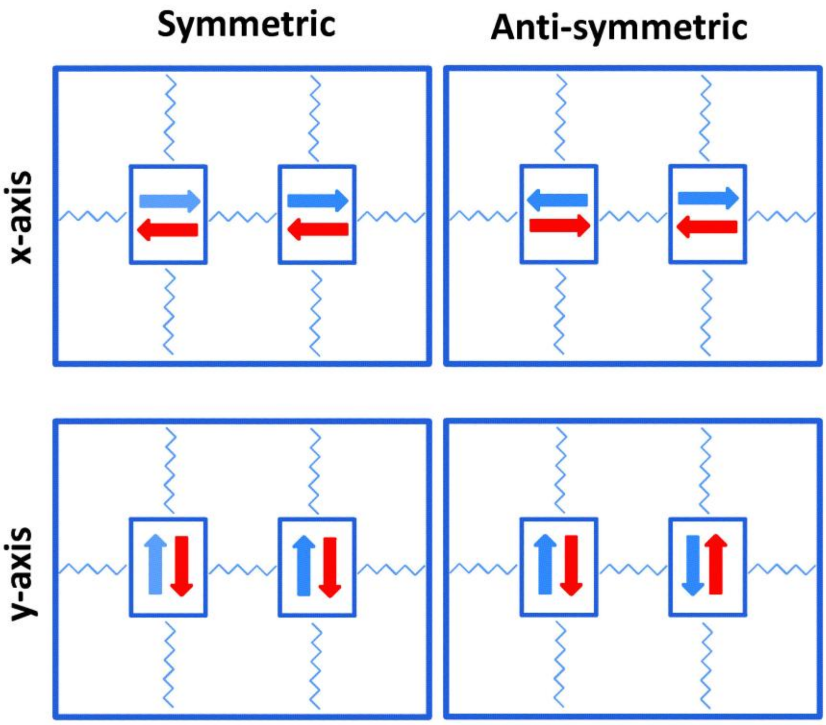

Figure 2. *Schematic representation of the normal modes. Arrows of the same color in each panel indicate the direction of a simultaneous movement of the smartphones.*

By using the potential energy expression, $U = U(x_1,y_1,x_2,y_2)$ given by Eq. (2), the above Hessian matrix, evaluated at the equilibrium positions is,

$$D = \begin{pmatrix} 388.493 & 0.000 & -118.119 & 0.000 \\ 0.000 & 341.233 & 0.000 & -50.953 \\ -118.119 & 0.000 & 388.493 & 0.000 \\ 0.000 & -50.953 & 0.000 & 341.233 \end{pmatrix} (rad/s^2) \quad (5)$$

The eigenvalue problem that has been solved can be stated as follows,

$$(D - \lambda I)v = 0 \quad (6)$$

where D is the Hessian matrix, I the unitary matrix, v a non-zero vector (called "eigenvector") and $\lambda=\omega^2$, the corresponding eigenvalue. The eigenvalues result from the diagonalization of the matrix, $D-\lambda I$.

The resulting normal modes (the square root of the eigenvalues) are, ω_x^S=16.443 rad/s, ω_y^S=17.038 rad/s, ω_x^A=22.508 rad/s, and ω_y^A=19.804 rad/s. It should be noted that these values are only valid for small displacements about the equilibrium positions. It can also be noted that the eigenfrequencies obtained for the x-axis are significantly different from the ones from the 1D model, that is: $(\omega_x^A)^2 = 3(\omega_x^S)^2$. This is due to the effect of the vertical springs (p_2q_2, p_3q_3, p_6q_4 and p_7q_5) on the horizontal oscillations (for us, "horizontal" is when the oscillation is along the x-axis and "vertical" along the y-axis). In addition, and as expected, the eigenfrequencies along the y-axis also differ from the ones obtained for the x-axis. For instance, the symmetric mode along the y-axis is affected by the horizontal springs, namely, p_1q_1 and p_8q_6 (p_4p_5 does not stretch in this case), while the symmetric mode along the x-axis is affected by the four aforementioned springs. However, in the case of the antisymmetric mode along the y-axis, the horizontal spring p_4p_5 is affected.

It is also possible to perform a more exhaustive study of the normal modes of oscillation by using Newton's Second Law. For example, as for the horizontal symmetric mode, the total potential given by Eq. (2) can be particularized as, $\Delta\vec{r_1} = \Delta\vec{r_2} = (\Delta x, 0)$ where $\Delta x = x\text{-}x_0$ is a synchronized displacement of both bodies along the x-axis direction. In this situation, the potential energy only depends on the global displacement Δx. Taking into account that all involved forces are conservative, the net force acting on the system is, $\vec{F} = -\vec{\nabla}U$. For the particular case under consideration $F(x) = -dU/dx$. On the other hand, Newton's Second Law can be expressed as $F(x) = m_{Total}\, d^2x/dt^2$, where $m_{Total} = 2m$ is the total mass of the system. Therefore, the resulting nonlinear second-order differential equation governing the system is,

$$-\frac{dU}{dx} = 2m\frac{d^2x}{dt^2} \tag{7}$$

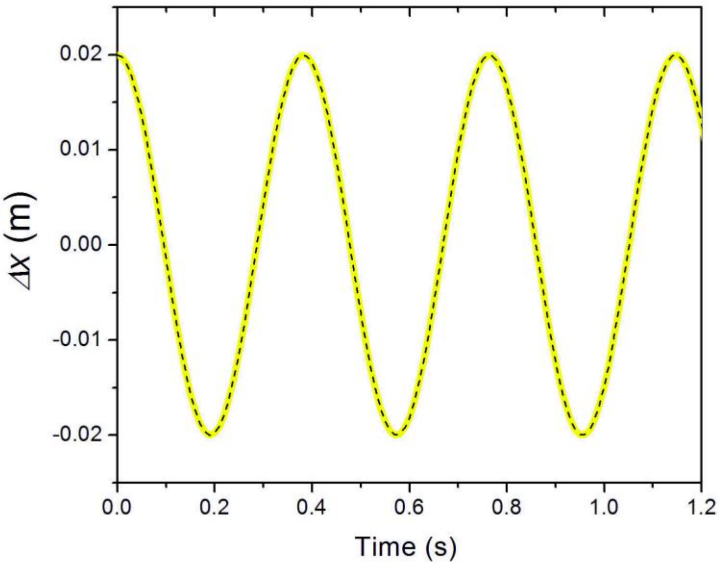

Figure 3. *Simultaneous displacement of the bodies along the x-axis versus time. The curves of the numerical (exact) (yellow solid line) and harmonic (black dashed line) trajectories overlap visually.*

It should be pointed out that in Eq. (7), which governs the symmetric horizontal mode, elastic forces of both horizontal and vertical springs are present. The vertical springs stretch even when the particles move along the *x*-axis only. Contrary to a simple 1D model of coupled oscillations, there is no analytical solution of Newton's Second Law for the 2D case and so a numerical solution is required.

By using the function NDSolve of the software Mathematica*, Eq. (7) can be solved numerically using Δx_0 and $dx/dt = 0$ as initial conditions. NDSolve uses a LSODA approach, switching between a non-stiff Adams method and a stiff Gear backward differentiation formula method. For an initial displacement $\Delta x_0 = 0.02$ m, the numerical solution of Eq. (7) provides the trajectory displayed in Fig. 3 (solid line). Additionally, the harmonic oscillation $\Delta x(t) = A\cos(\omega_x^S t)$ with $A = \Delta x_0$ is shown in the same figure (dashed line), It can therefore be seen that curves overlap visually.

* Wolfram Research, Inc., Mathematica version 8.0, http://www.wolfram.com/mathematica

From Fig. 3, the exact period of oscillations can be determined, $T = 0.3818$ s, and from it the exact (from solving Eq. (7)) value of the frequency, $\omega = 16.457$ rad/s. The discrepancy between this value and the harmonic result ($\omega_x^S = 16.443$ rad/s) is only 0.09%. The small discrepancy between both results is due to the influence of the vertical springs. The horizontal projections of the forces exerted by these springs are linear only for small displacements. This study can be repeated for the antisymmetric mode by imposing $\Delta\vec{r_1} = -\Delta\vec{r_2}$ in the potential *U*.

A similar analysis for the symmetric and antisymmetric normal modes along the *y*-axis, and using 0.02 m as initial displacement, yields discrepancies between the harmonic and the exact frequencies within 1% in all cases. The smaller the initial displacement the smaller the discrepancy. For instance, discrepancies within 0.3% are obtained if 1 cm is used as initial displacement. The smaller the displacements the better the harmonic approximation approaches the physical experiment. Thereby, the Hessian matrix formalism constitutes a very good approximation for obtaining the normal frequencies of a coupled 2D system in basic Physics courses.

4. Results and discussions

In order to check the normal frequencies predicted from the Hessian matrix, experiments using the experimental setup of Fig. 1 are carried out. The oscillation data are captured by the acceleration sensor of the smartphones. From previous experiments, we already know that the acceleration sensor in our smartphone’s models is located at the center of the smartphone, which is coincident with the center of mass of the system (Castro-Palacio, 2014). However, the position of the acceleration sensor may not be at the geometrical center for other models (Mau, 2016).

For the interaction with the mobile sensor, the free Android application *Accelerometer Toy*, version 1.0.10, is used. This application takes 316 kB of SD card memory and can be downloaded from the Google play website[*]. The values of the acceleration components on *x*-, *y*- and *z*- axes are registered at each time step. The precision in the measurement of the

[*] https://play.google.com/store/apps

acceleration is $\delta a = 0.03\,\text{m/s}^2$ and of time is $\delta t = 0.01\,\text{s}$. This application also allows to save the output data to file from which further analysis can be performed. Once the application is downloaded to the mobile device, a small test can be done to ensure the device is working correctly. If the mobile is left undisturbed on a horizontal surface, the application output curves for the acceleration should indicate values very close to zero for all axes. This application was successfully used in other experiments to study uniform and uniformly accelerated circular motions (Castro-Palacio, 2014).

Five experiments are performed using the setup of Fig. 1. In the first four experiments, the system is set to oscillate by hand with approximately normal frequencies (symmetric and antisymmetric) along *x*- and *y*- axes, respectively. For the case of the symmetric mode, mobile phones are displaced about 1 cm towards the positive *x*-axis and towards the positive *y*-axis, respectively. For the antisymmetric mode, one of the mobile phones is displaced to the left and the other to the right for the *x*-axis, and downward and upward for the *y*-axis, respectively.

The data registered by the acceleration sensor of each smartphone for the symmetric and antisymmetric oscillations (see Fig. 4) can be fitted to a harmonic function, $a(t) = A\sin(\omega t+\varphi)$ where A is the amplitude, ω the angular frequency and φ the phase. The fitting was carried out by using the non-linear fitting algorithm Levenberg-Marquardt (Levenberg, 1944; Marquardt, 1963). The results for the frequencies are registered in Table I.

	Smartphone 1	Smartphone 2
ω_x^S (rad/s)	16.158±0.016	16.207±0.016
ω_y^S (rad/s)	16.854±0.013	16.732±0.010
ω_x^A (rad/s)	22.158±0.012	22.115±0.012
ω_y^A (rad/s)	19.988±0.017	19.860±0.020

Table I. *Frequencies and uncertainties from the fit of the acceleration data to $a(t) = A\sin(\omega t+\varphi)$ along x- and y- axes for the smartphones 1 and 2.*

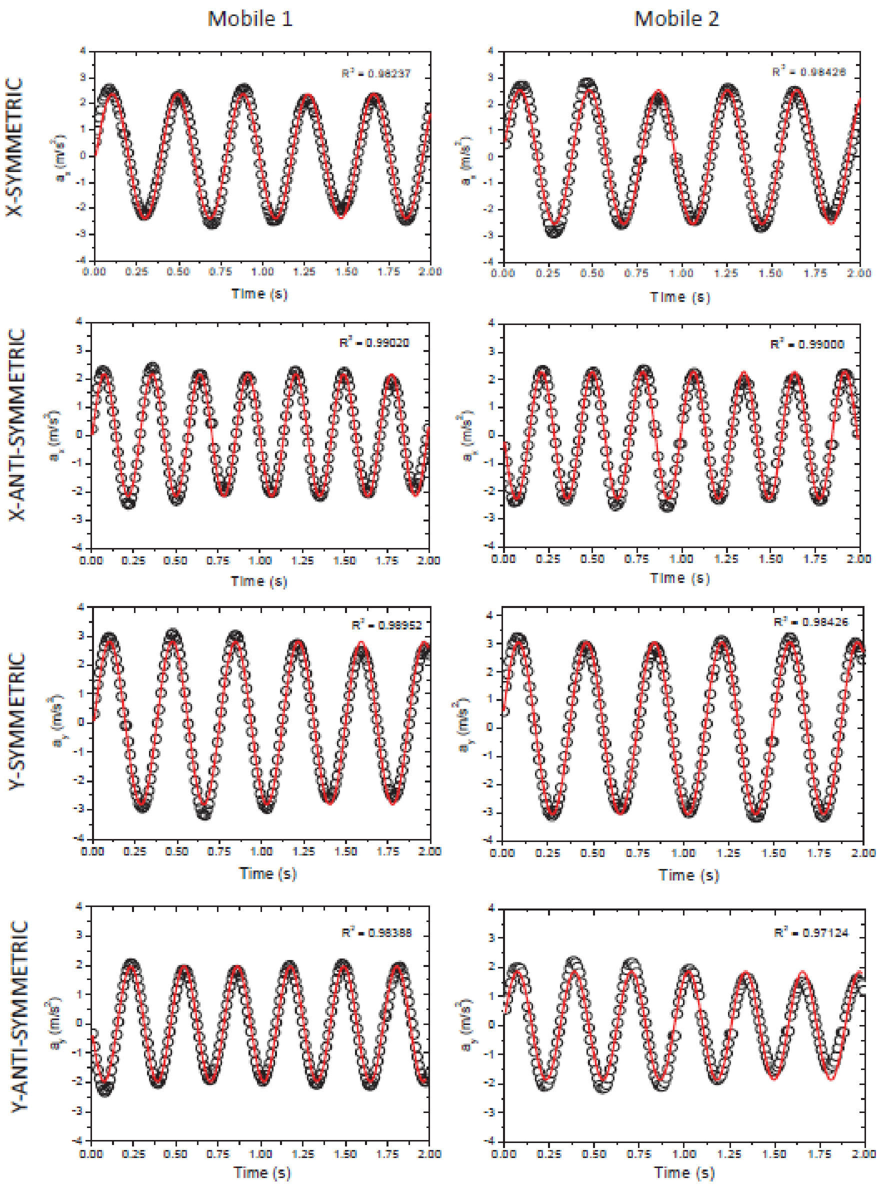

Figure 4. *Symmetric and antisymmetric acceleration oscillations of the smartphones 1 and 2 along x- and y- axes (open circles). The red solid lines indicate the fit. The square of the curvilinear correlation coefficient,* R^2*, has been included on the upper right hand side of each graph.*

There are 8 cases in total, where four eigenfrequencies correspond to each smartphone, for the symmetric and antisymmetric modes, respectively. The graphs of the acceleration measurements and the corresponding fit curve are included in Fig 4 for each smartphone, normal mode and axis.

The analogue values to the frequencies of the smartphones for the symmetric and antisymmetric modes and for the *x*- and *y*- axes are shown in Table II. The corresponding normal frequencies obtained from the Hessian matrix formalism are also included. A very good agreement is obtained between the experimental and the theoretical results.

	Experimental results	Hessian matrix formalism	Discrepancies (%)
ω_x^S (rad/s)	16.18±0.03	16.443	1.6
ω_y^S (rad/s)	16.79±0.02	17.038	1.5
ω_x^A (rad/s)	22.14±0.02	22.508	1.7
ω_y^A (rad/s)	19.92±0.04	19.804	0.6

Table II. *Comparison between the experimental results (average values from Table I) and those obtained from the Hessian matrix formalism.*

Finally, in the fifth experiment, an arbitrary oscillation is started by just shifting one of the mobiles out of the equilibrium position. It consisted of a diagonal displacement of the left-hand side smartphone while the other one was hold at the equilibrium position. Then, both smartphones were left free. In this case, the arbitrary oscillation (non-normal) of the studied system can be represented as a superposition of the corresponding four normal oscillations,

$$\begin{aligned}\vec{a}(t) = {} & [A_x^S \sin(\omega_x^S t + \varphi_x^S) + A_x^A \sin(\omega_x^A t + \varphi_x^A)]\vec{\imath} + \\ & + \left[A_y^S \sin(\omega_y^S t + \varphi_y^S) + A_y^A \sin\left(\omega_y^A t + \varphi_y^A\right)\right]\vec{\jmath}\end{aligned} \quad (8)$$

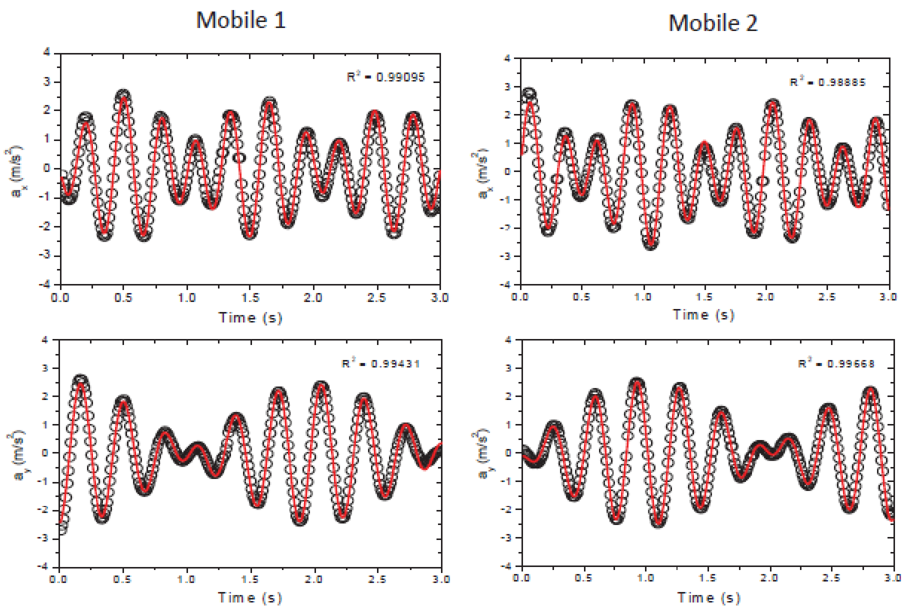

Figure 5. *Free oscillations of the smartphones (open circles). The red solid lines indicate the fit.*

Figure 5 shows the data points for an arbitrary oscillation (with open circles). A window of 3 s has been extracted from the total time series. The fitting for Eq. (8) (solid line in Fig. 5) was carried out in the same way as for the pure modes in Table I: that is to say by using the non-linear fitting algorithm Levenberg-Marquardt (Levenberg, 1944; Marquardt, 1963).

In all cases shown in Fig. 5 the values of R^2 are around 0.99 which indicates the good quality of the fitting procedure. The corresponding fitted frequencies are not shown (for brevity), since they are very similar as those reported in Tables I and II. Alternatively, the main frequencies of the system can be also explored by using the Fourier transform of a free oscillation of acceleration data. Our objective was rather to prove the validity of the Hessian matrix formalism in predicting the normal frequencies of a 2D coupled system. To connect basic and simple oscillation experiments like the one in this article with this formalism helps prepare the student's mindset for physics courses further in the syllabus.

5. Conclusions

The normal frequencies of a coupled two-dimensional system are studied both theoretically and experimentally. The normal modes were first calculated for a particle system from the Hessian matrix. An experimental setup using smartphones instead of particles and with real springs is used to test the theoretical model. The oscillation data were collected by the acceleration sensor of the smartphones. For all cases, the percentage discrepancies between the theoretical and experimental frequencies are within 1.7%.

6. Acknowledgments

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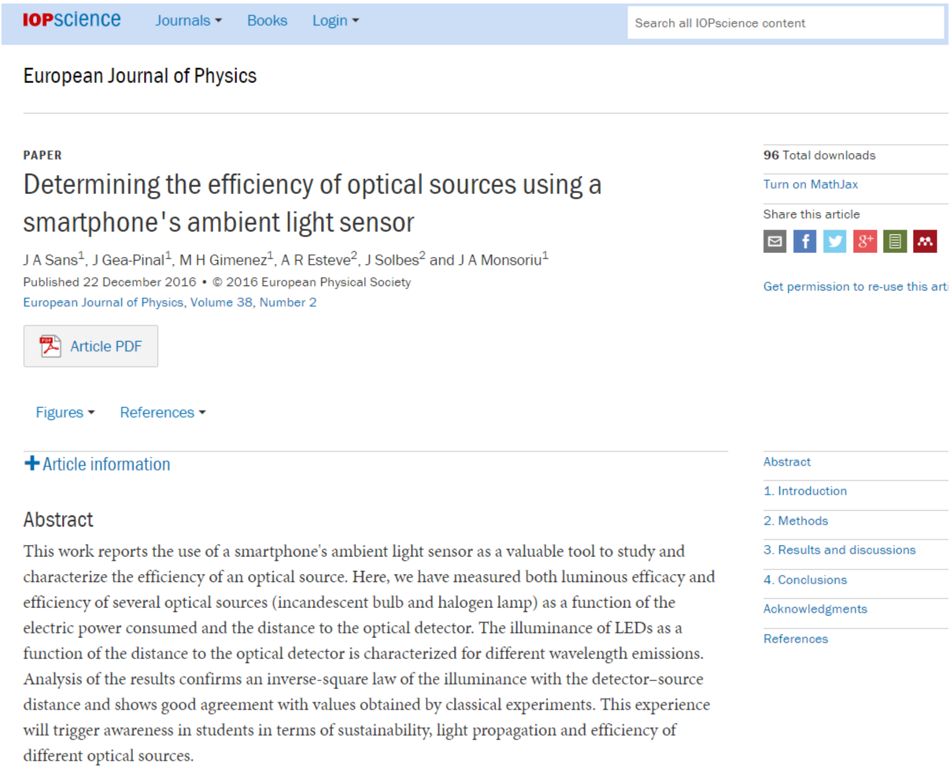
Determining the efficiency of optical sources using a smartphones's ambient light sensor



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PAPER

Determining the efficiency of optical sources using a smartphone's ambient light sensor

J A Sans[1], J Gea-Pinal[1], M H Gimenez[1], A R Esteve[2], J Solbes[2] and J A Monsoriu[1]

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Abstract

This work reports the use of a smartphone's ambient light sensor as a valuable tool to study and characterize the efficiency of an optical source. Here, we have measured both luminous efficacy and efficiency of several optical sources (incandescent bulb and halogen lamp) as a function of the electric power consumed and the distance to the optical detector. The illuminance of LEDs as a function of the distance to the optical detector is characterized for different wavelength emissions. Analysis of the results confirms an inverse-square law of the illuminance with the detector–source distance and shows good agreement with values obtained by classical experiments. This experience will trigger awareness in students in terms of sustainability, light propagation and efficiency of different optical sources.

Determining the efficiency of optical sources using a smartphone's ambient light sensor

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Abstract

This work reports the use of the smartphone's ambient light sensor as a valuable tool to study and characterize the efficiency of an optical source. Here, we have measured both luminous efficacy and efficiency of several optical sources (incandescent bulb and halogen lamp) in function of the electric power consumed and the distance to the optical detector. The illuminance of LEDs in function of the distance to the optical detector is characterized for different wavelength emissions. The analysis of the results confirms the inverse-square law of the illuminance with the detector-source distance and shows a good agreement with values obtained by classical experiments. This experience will trigger the awareness of the students in terms of sustainability, light propagation and efficiency of the different optical sources.

1. Introduction

The M-learning concept is widely extended among the teaching community and recently, together with the use of familiar equipment to the students, has been explored to perform new Physics laboratory practices more attractive to them. Electronic devices such as digital cameras (Monsoriu, 2005), webcams (Shamim, 2010), optical computer mice (Romulo, 1997; Ng, 2005) and game controllers (Vannoni, 2007; Tomarken, 2012; Ballester, 2013) allow to determine fundamental Physics properties through the design of new and interesting experiments. Among all these electronic devices, the widespread use of smartphones by most students and the large amount of sensors contained in them offer an invaluable opportunity to perform new teaching strategies. Moreover, the constant evolution of free apps to extract the information acquired by the smartphone's sensors is supporting this initiative. This attractive tool for scientific demonstrations and experimental measurements can 'enrich educational opportunities for learners in diverse settings' (West, 2013). Several examples on the design of new Physics laboratory practices have been recently presented showing the use of sensors contained in smartphones in physics education in different topics such as mechanics (Briggl, 2013; Castro-Palacio, 2013a; Castro-Palacio, 2013b; Klein, 2014; Vogt, 2014), optics (Van Domelen, 2007; Sans, 2013; Barreiro, 2014), and acoustics (Kuhn, 2013a; Gómez-Tejedor, 2014).

Regarding the exploitation of the different optical sensors of the smartphone, Hossain (2015) proposed the use of the camera of the smartphone like a fluorimeter with a good agreement between their results and the values obtained by a conventional fluorimeter. Vieira (2014) carried out a first approach to the use of the smartphone's ambient light sensor to describe the variation of the light intensity with the inverse-square law of the distance. Using this physics law, Sans (2013) has characterized the variation of the light intensity to describe the simple harmonic and damped oscillatory motion with the ambient light sensor. This paper paved the path for considering the smartphone's ambient light sensor as an accessible optical detector. On the other hand, the study of the electric power consumed by several optical sources could raise students' awareness about the importance of using more efficient devices.

In the present work, we go further presenting a new laboratory experiment based on the measurement of the luminous efficiency and efficacy of several optical sources by using the smartphone's ambient light sensor in order to compare their properties. We expect that the use of their own smartphones will trigger the students' interest and motivation to perform the laboratory practice and consequently, reinforce their curiosity to carry out their own homemade experiments.

2. Methods

The luminous efficacy of a light source defines how well a device transforms the electrical energy into luminous energy. It is determined by Eq. (1), which expresses the ratio between the luminous flux (ϕ) and electrical power (P),

$$\eta = \frac{\phi}{P} \tag{1}$$

Therefore, in the literature it is possible to find a similar parameter defined by light emitted in function of the maximum theoretical light emission (683 lm/W) defined at 555 nm (MacAdam, 1950). The choice of this wavelength is not random but is that at which the human eye is more sensitive. This value is obtained from the blackbody radiation and is called luminous efficiency, expressed as a percentage.

In the particular case of smartphones, they are usually equipped with a light sensor that allows adjusting the brightness of the display based on the environmental lighting to optimize their battery life. This light sensor uses a photodiode, in combination with a filter, to adjust its spectral sensitivity to the sensitivity of the human eye. This device is able to measure the illuminance (E), which is calculated by the luminous flux (ϕ) per unit area (A) as expressed in Eq. (2),

$$E = \frac{\phi}{A} \tag{2}$$

The size of the different optical sources used in this work, smaller than the detector-source distance, allows considering them as point sources. In this case, the energy in a certain region is determined by the amount of luminous flux that crosses a defined area. In the case of a point source, the luminous flux is propagated in all directions and is distributed over a spherical surface. Considering the smartphone's ambient light detector as a point detector, the illuminance measured is approximatively equal to the density

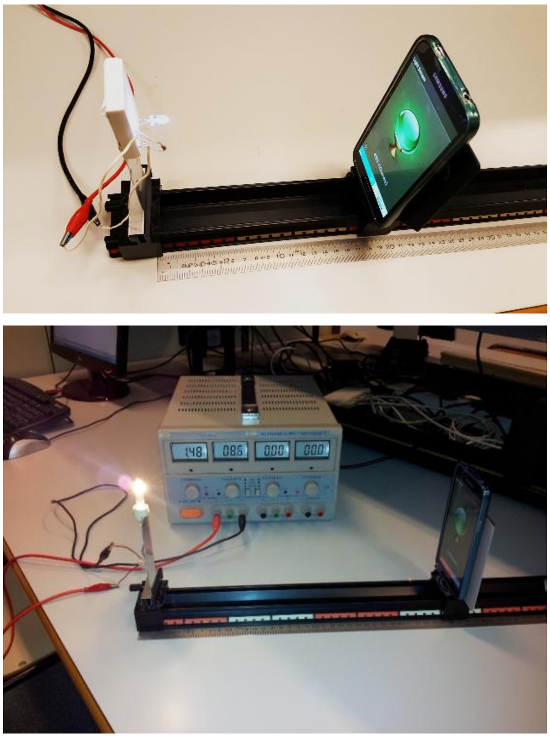

Figure 1. *Experimental set-ups to measure the luminous efficiency of an optical source using a smartphone's light sensor.*

of luminous flux projected by the optical source. Thus, the illuminance can be expressed as:

$$E = \frac{\phi}{4\pi r^2} \tag{3}$$

The experimental measurement of these magnitudes requires a point detector or with a small surface to determine the luminous flux and consequently, the illuminance. Here, we propose the simple experimental set-up shown in Fig. 1 in order to determine the illuminance of different optical sources. The optical source has been placed on the optical bench in a darkened room and connected to a variable power supply in order to control the electrical power provided to it. A smartphone (Samsung Galaxy S5) has also been placed on the optical bench with the center of its light sensor facing the light bulb. We have used the Android application *Sensor Box for Android*, version 5.0 (which can be downloaded from Google Play website*), to quantitatively determine the luminous intensity that reaches the smartphone's light sensor. The illuminance provided by the optical source was measured as a function of its distance to the light sensor, and as a function of the electrical power supplied.

The data measured by the smartphone's ambient light sensor have been correlated with those given by a calibrated conventional luxometer. These results show a perfect agreement between both measurements. The analysis of the variation of the measurement with the angle has shown that the error in the position of the smartphone should not affect the value obtained. On the other hand, we checked the validation of the measurement with the ambient light sensor for different wavelengths and we observed a perfect agreement using a yellow filter in the lamp but an overestimation (underestimation) when using a red (green) filter. These correlation factors are important enough to be taken into account. The illuminance values presented in this work have been corrected using these factors (1.3 for red and 0.64 for green).

In this work, we have used an incandescent bulb, a halogen lamp and four light emission diodes (LEDs) to compare their illuminance ranges and the change of their efficiency with respect to the electric power supplied.

3. Results and discussions

3.1. Incandescent and halogen lamps

An incandescent bulb is formed by a wire filament through which an electric current passes, making the filament to heat up enough to radiate in the visible range. The bulb isolates the filament avoiding its oxidation by the presence of an inert environment or vacuum. Here, we have studied the illuminance of an incandescent bulb (Osram 7506) as it is the most common optical source used in a basic laboratory. The illuminance was measured as a function of the distance between the light source and the smartphone's

* https://play.google.com/store/apps

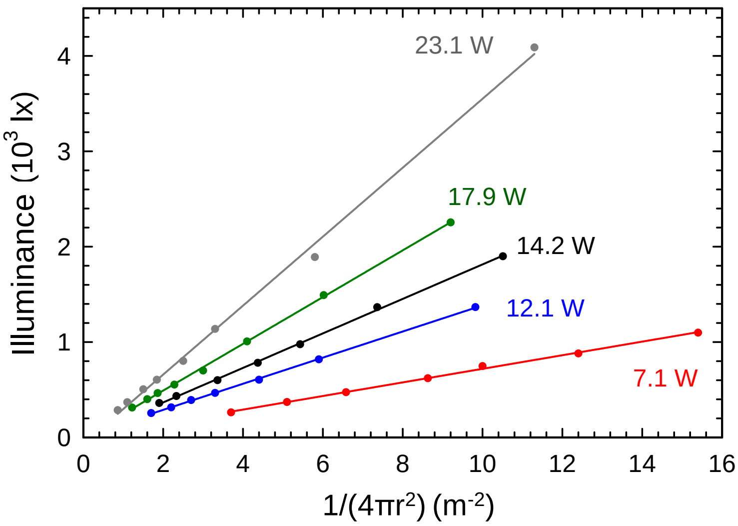

Figure 2. *Experimentally measured illuminance of an incandescent lamp versus the inverse of a spherical surface of radius r (symbols) for each electric power supplied. Least-square fits (lines) serve to obtain the values reported in Table I.*

light sensor, as well as a function of the electric power consumed. The distance range used between the light source and the smartphone's light sensor varied from (8.4±0.1) cm to (30.5±0.1) cm and the consumed electric power ranged between (7.10±0.19) W and (23.1±0.3) W. The experimental illuminance data collected by the smartphone's light sensor have been used to estimate the luminous flux according to Eq. (3), considering that the luminous energy is equally distributed along spherical surfaces.

The representation of the experimental illuminances at several electric powers as a function of the source-detector distance is shown in Fig. 2. These experimental data display a clear quadratic dependence with distance and can be fitted using least squares. All these fits show very good correlation coefficients close to 0.99. The large error observed in the y-intercept value given by the fit can be explained in terms of: i) the incandescent bulb cannot be considered as a point source at short source-detector distances and ii) the environmental light conditions, which should give a constant illuminance value. The luminous efficiency of the

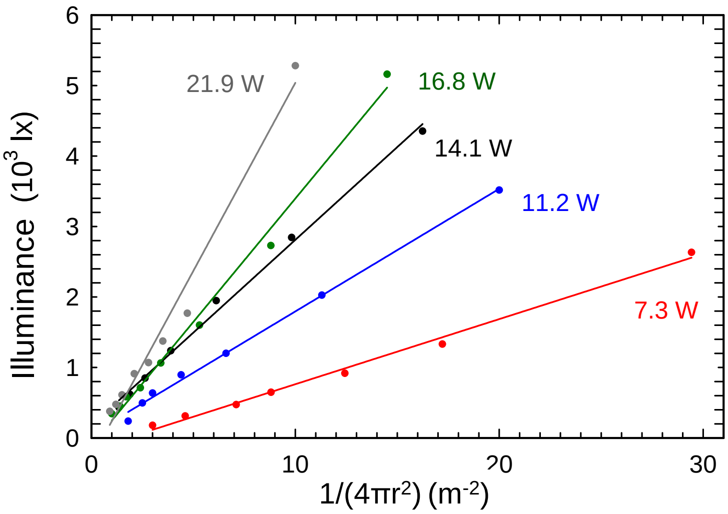

Figure 3. *Experimentally measured illuminance of a halogen bulb versus the inverse of a spherical surface of radius r (symbols) for each electric power supplied. Least-square fits (lines) serve to obtain the values reported in Table I.*

incandescent lamp increases with the increase of the electric current, which ranges between 1.5% and 2.3%.

The difference between the halogen lamp and the incandescent bulb lies in the presence of a halogen environment inside the bulb. This produces a halogen cycle chemical reaction with the material of the filament (typically tungsten) which is evaporated and redeposited back onto the filament. Thus the lifetime of the source is extended, allowing it to operate in a high electric power range and increasing its efficacy. In this experiment, we have characterized a halogen lamp (Osram 64427S-58663) using similar distance ranges between the light source and the smartphone's light sensor, (8.9±0.1) cm to (30.0±0.1) cm, and a similar consumed electric power range, (7.3±0.2) W and (21.9±0.3) W. The experimental illuminance is shown in Fig. 3 as a function of the source-detector distance for several electrical powers provided. As in the case of the incandescent bulb, the halogen lamp is considered a point optical source in first approximation. The correlation factors of the least-square fits exhibit values close to 0.99, which indicate the validity of the inverse-square law.

Eq. (1) and (2) allow to determine the luminous efficacy and efficiency for each electric power provided (Table I). The halogen lamp increases the luminous efficiency, which ranges between 1.1% and 3.4%, in good concordance with the efficiency reported (Gupta, 2001) for tungsten halogen lamps at highest electric power (3%). The efficiency obtained in the halogen lamp is higher than that of the incandescent bulb for similar electric power supplied, which shows that the presence of the halogen gas allows reaching higher temperatures to the filament.

	Consumed electric power (W)	Emitted luminous flux (lm)	Luminous efficacy (lm/W)	Luminous efficiency (%)
Incandescent	7.10±0.18	71.3±1.4	10.0±0.5	1.5
	11.9±0.2	136.9±1.2	11.5±0.2	1.7
	14.2±0.3	181±2	12.7±0.3	1.9
	17.9±0.3	245±2	13.7±0.3	2.0
	23.1±0.3	361±8	15.6±0.5	2.3
Halogen	7.3±0.2	92±3	12.6±0.8	1.9
	11.2±0.2	174±5	15.8±0.7	2.3
	14.1±0.3	263±8	18.6±1.0	2.7
	16.8±0.3	350±12	20.8±1.1	3.1
	21.9±0.3	530±30	24.3±1.8	3.6

Table I. *Luminous flux, luminous efficacy, and luminous efficiency of incandescent and halogen lamps obtained for different electric powers.*

Figure 4 shows a steady increase of the luminous efficiency as a function of the electric power for the incandescent and halogen lamps. The emission in incandescent bulbs behaves like an imperfect blackbody and requires certain temperature to emit in the visible range according to the Wien's displacement law. Both of them depends on the temperature reached in the tungsten filament. The increase of the electric power supplied leads to an increase of the temperature in the filament and, consequently, to the shift of the wavelength of the maximum optical emission towards values closer to

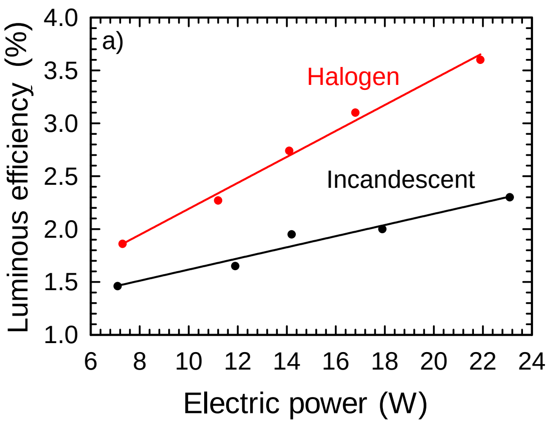

Figure 4. *Measured luminous efficiency of incandescent and halogen lamps.*

that of the maximum theoretical light emission (555 nm), causing an improvement of the efficiency (Hertel, 2014). The presence of a halogen environment allows to improve the efficiency of the halogen lamp with respect to the incandescent bulb due to the reconstructive effect of the halogen gas, which causes a higher filament temperature (higher illuminance) than the one obtained in the incandescent bulb. In this work, we have not exceeded the maximum electric power recommended by the manufacturer. Above the electric power recommended, the maximum optical emission could be at a higher wavelength than that at which the human eye is more sensitive (555 nm) or even the filament could evaporate too much degrading it. All these factors will trigger a decrease of the luminous efficiency.

Besides the steady increase of the luminous efficiency with the electric power, we have also observed a linear tendency between both parameters. Above 600 K, the temperature dependence of the tungsten filament with the electric power (Forsythe, 1925; Davis, 1962; Hill, 1966) follows a quasi-linear trend. This effect is due to the direct relationship between the electrical resistance of the cathode and the temperature raised to the power of 1.2 (Forsythe, 1925; Davis, 1962). According to the Wien's displacement law, an almost linear behavior of the temperature with the electric power supplied leads to an almost linear behavior of the maximum emission wavelength with the same electric power. If the maximum emission wavelength of the tungsten lamp is getting closer to the wavelength where the human eye is more sensitive (555 nm), then the optical efficiency should increase in the same way. This explanation allowed us to approximate the fit of our experimental results to a linear equation.

3.2. LEDs

A LED consists on the junction of two doped semiconducting materials (one p-type and the other n-type) forming a diode. Applying an electric current, the electrons flow from the n-type semiconductor towards the p-type semiconductor but not in the reverse. The electron is recombined when meets a hole, releasing energy in the form of a photon. The optimization of this process has permitted the manufacture of ultra-bright LEDs. These optical sources offer a higher illuminance for the same electric power. LEDs cannot be considered as a point source since they show directionality in their emission. This characteristic comes defined by the aperture angle (20º in this case) and the luminous flux is distributed over a spherical cap instead of a sphere. In this work, we have explored the efficacy of LEDs (825MR2C, 825MY8C, 825PG2C) emitting at different wavelengths and we have compared the results with an ultra-bright LED 10mm white LED (140000 mcd with ~15º of apex aperture). The efficacy of LEDs emitting in the red, yellow and green has been obtained from the variation of the illuminance as a function of the LED-smartphone distance, and these values have been compared with those obtained for an ultra-bright LED. The characteristics of these devices are shown in Table II.

	Voltage supplied (V)	Voltage in LED (V)	Current (mA)	Electric power (mW)	Emitted luminous flux (lm)
Green	24.0±0.2	2.4±0.1	18.1±0.4	43±3	0.15±0.02
Yellow	24.0±0.2	2.1±0.1	18.3±1.0	44±2	0.24±0.03
Red	24.0±0.2	2.0±0.1	18.4±0.8	44±2	0.54±0.06
Ultra-bright	24.0±0.2	3.4±0.1	19.2±1.2	65±2	11.9±0.7

Table II. *Voltage supplied to the circuit and voltage, current and electric power used by each LED, together with luminous flux calculated for each LED.*

LED-smartphone distances are in the same range for all the LEDs studied. In particular, the distance between the light source and the smartphone's light sensor is in a range from (7.7±0.1) cm to (34.0±0.1) cm, similar to that of the incandescent or halogen lamp. On the other hand, the electric current consumed by the LEDs is much lower than the values supplied (see Table II). In order to avoid effects of efficiency drop (Iveland, 2013), we have fixed the electric current to the optimal value provided by the manufacturer.

The comparison of these results with those given for incandescent and halogen lamps is inadequate since the origin of the light emission is completely different. as well as their kind of emission. The comparison of the results for the LEDs with those of the black-body radiation maximum in order to calculate their efficiency can be considered unfounded. LED emission is not given by the temperature of the component materials (as it happens with the incandescent and halogen lamps) but the recombination processes carried out between n-type and p-type semiconductors. On the other hand, the LED emission is by definition monochromatic. In the case of the white LED, several spectral lines are overlapped in order to cover most of the visible spectral range in contrast with the continuous emission obtained in both halogen and incandescent lamps. Thus, the values of the efficiency would be unreal. However, LEDs show the same dependence with the distance that the incandescent and halogen lamps because they can be considered as well point optical sources. Consequently, the light propagates through spherical surfaces. The low electric power consumed by LEDs give an average luminous efficacy higher than the incandescent and halogen lamps. Comparing LEDs emitting at several wavelengths (Fig. 5), one can clearly see that the ambient light detector is optimized for low photon energies. On the other hand, the illuminance measured for the ultra-bright LED is one order of magnitude higher than the values obtained for usual LEDs, which reveals the increase of the efficiency achieved with the same electric current.

4. Conclusions

We have successfully used the smartphone's light sensor and the Android application *Sensor Box for Android* to measure the illuminance of three different optical sources. We have proved the inverse-square law

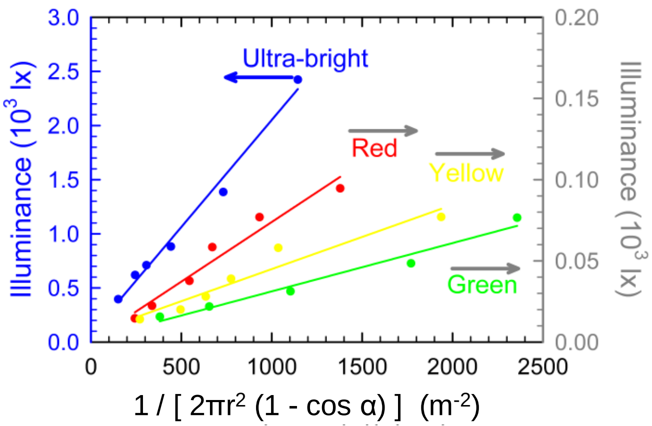

Figure 5. *Illuminance as a function of the detector-source distance for LEDs emitting in different wavelengths and compared with an ultra-bright LED device. Illuminance for read, yellow and green LEDs are associated to the right Y-axis whereas the values for the ultra-bright LED is associated to the left Y-axis.*

dependence of the illuminance with the detector-source distance for all the quasi-point optical sources. These measurements allowed us to determine the luminous efficacy and efficiency of both incandescent and halogen lamps as a function of the electric power supplied using a least-square fit. We observed a steady increase of the luminous efficiencies obtained with the supplied electric power for both sources which has been explained in terms of blackbody emission, Wien's displacement law and the relationship between resistance and temperature given in a tungsten filament.

On the other hand, we have also proved the validity of the inverse-square law dependence of the illuminance with the detector-source distance for LEDs emitting at several wavelengths. The comparison of usual LEDs with an ultra-bright LED showed an increase of one order of magnitude of the illuminance obtained by the latter. These results should stimulate students to use their smartphones to perform their own experiments at home, which will raise their awareness of the importance of the luminous efficiency.

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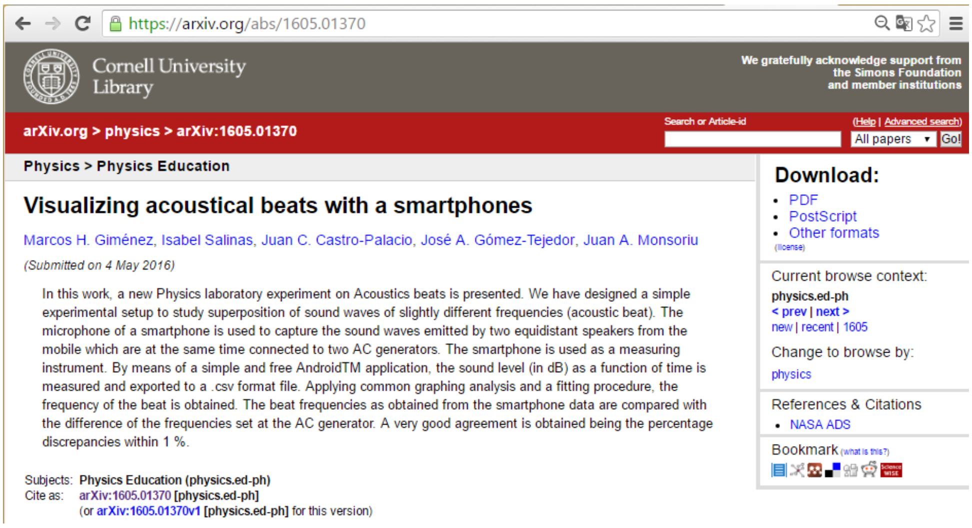
Visualizing acoustical beats with a smartphone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Marcos H. Giménez, Isabel Salinas, Juan C. Castro-Palacio, José A. Gómez-Tejedor, Juan A. Monsoriu

(Submitted on 4 May 2016)

In this work, a new Physics laboratory experiment on Acoustics beats is presented. We have designed a simple experimental setup to study superposition of sound waves of slightly different frequencies (acoustic beat). The microphone of a smartphone is used to capture the sound waves emitted by two equidistant speakers from the mobile which are at the same time connected to two AC generators. The smartphone is used as a measuring instrument. By means of a simple and free AndroidTM application, the sound level (in dB) as a function of time is measured and exported to a .csv format file. Applying common graphing analysis and a fitting procedure, the frequency of the beat is obtained. The beat frequencies as obtained from the smartphone data are compared with the difference of the frequencies set at the AC generator. A very good agreement is obtained being the percentage discrepancies within 1 %.

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Visualizing acoustical beats with a smartphone

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Abstract

In this work, a new Physics laboratory experiment on Acoustics beats is presented. We have designed a simple experimental setup to study superposition of sound waves of slightly different frequencies (acoustic beat). The microphone of a smartphone is used to capture the sound waves emitted by two equidistant speakers from the mobile which are at the same time connected to two AC generators. The smartphone is used as a measuring instrument. By means of a simple and free Android^{TM} application, the sound level (in dB) as a function of time is measured and exported to a .csv format file. Applying common graphing analysis and a fitting procedure, the frequency of the beat is obtained. The beat frequencies as obtained from the smartphone data are compared with the difference of the frequencies set at the AC generator. A very good agreement is obtained being the percentage discrepancies within 1 %.

1. Introduction

Portable devices' sensors offer a wide range of possibilities for the development of Physics teaching experiments in early years. For instance, digital cameras can be used to follow physical phenomena in real time since distances and times can be derived from the recorded video (Monsoriu, 2005). Wireless devices such as wiimote have been also used in Physics teaching experiments (Tomarken, 2012). The wiimote carries a three-axes accelerometer which communicates with the console via Bluetooth™. More recently, smartphones have been incorporated to this variety of portable devices (Kuhn, 2012; Castro-Palacio, 2013). For instance, the acceleration sensor of the smartphones has been used to study mechanical oscillations, at both the qualitative (Kuhn, 2012) and the quantitative (Castro-Palacio, 2013a) levels. These works show very simple experiments where the smartphone itself is the object under study. The acceleration data are captured by the acceleration sensor of the device and collected by the proper mobile application.

All smartphones are equipped with a microphone, which can be used to record sounds with a sample rate of 44100 Hz, and in some new devices up to 48000 Hz. This allows to analyze different acoustic phenomena with the smartphone microphone (Kuhn, 2013a). The sound frequency spectrum captured by the smartphone microphone can be analyzed with a number of free applications, such as *Audio Spectrum Monitor*[*] and *Spectrum Analyzer*[†]. Also, the fundamental frequency of a sound wave can be measured with very high precision, which allows to study a frequency-modulated sound in Physics laboratory (Gómez-Tejedor, 2015) and the Doppler Effect for sound waves (Gómez-Tejedor, 2014).

Using smartphone devices, several methods to measure the velocity of sound have been proposed. For instance, by means of the Doppler effect using ultrasonic frequency and two smartphones the speed of sound can be determined with an accuracy of about 5% (Klein, 2014). Based on the distance between the two smartphones and the recording of the delay between the sound waves traveling between them, the actual speed of sound can be obtained (Parolin, 2013). Using economic instruments and a couple of smartphones, it is possible to see nodes and antinodes of standing acoustic waves in a column of vibrating air and to measure the speed of

[*] https://play.google.com/store/apps/details?id=my.sample (retrieved on April 15th, 2016)

[†] https://play.google.com/store/apps/details?id=com.raspw.SpectrumAnalyze (retrieved on April 15th, 2016)

sound (Parolin, 2015). By the study of destructive interference in a pipe it is also possible to adequately and easily measure the speed of sound (Yavuz, 2016). A sonometer application can be used to measure the resonance in a beaker when waves with different wavelengths are emitted by the smartphone speaker. This application can also be used to measure and analyze Doppler effect, interferences, frequencies spectra, wavelengths, etc. or to study other phenomena in combination with some other fundamental physics laboratory equipment such as Kundt or Quincke tubes (González, 2015). On the other hand, measurements with the smartphone microphone can be used to analyze physical process not directly related with acoustic. The sounds made by the impacts of a ball can be recorded with the microphone. The impacts result in surprisingly sharp peaks that can be seen as time markers. The collected data allow the determination of gravitational acceleration (Schwarz, 2013).

In order to measure the acoustic beat, two mobile phones can be placed at a short distance from each other and then play previously recorded tones with a constant frequency with the MP3 function. The signal can be captured using a microphone and by the line-in of a sound card in a computer, and then, the recorded signal can be analyzed with suitable audio software (Kuhn, 2013b). In a similar way, three smartphones can be used to analyze the acoustic beat: two of them produce the sine tones with slightly different frequencies and the third device detects and analyzes the overlapping oscillation (Kuhn, 2014). In this kind of experiments, oscillogrammes are recorded and the acoustic beats are derived from the varying envelope amplitude.

In the present work, a more intuitive procedure is presented in order to characterize acoustic beats with a smartphone. When two sound waves of very close frequencies are superimposed, a “vibrating” tone is perceived. This is the basic principle behind the tuning of musical instruments. Instead of using oscillogrammes, we propose to capture the perceived vibrating tone by using the smartphone as a sonometer. The sound waves are generated by two independent speakers connected to AC generators, although two other smartphones may be also used to generate the sine tones. By means of the free application *Physics Toolbox Sound Meter*[*], the students are able to measure the sound intensity (in dB) of the acoustic beats as a function of time.

The resulting sound intensity variations are directly displayed on the mobile screen and the frequency beat can be quantitatively obtained. Moreover, the recorded sound levels can be exported to a PC for a more quantitative analysis, i.e. by email, cable or Bluetooth connection. In this way, the varying intensity of the vibrating tone is derived from the sound level measurements and fitted to a harmonic function in order to accurately obtain the corresponding frequency beat. The results are compared with the frequency difference of the superimposing AC signals, and a very good agreement is obtained.

2. Basic theory

Let $x_1(t)$ and $x_2(t)$ be two harmonic oscillations of equal amplitude A, very close frequencies f and $f + \Delta f$, and initial phases φ_1 and φ_2,

$$x_1(t) = A\sin[2\pi f t + \varphi_1] \tag{1}$$

$$x_2(t) = A\sin[2\pi(f + \Delta f)t + \varphi_2] \tag{2}$$

After some basic mathematical manipulations, the superposition of both oscillations gives rise to,

$$x(t) = x_1(t) + x_2(t) = A'\sin\left[2\pi\left(f + \frac{\Delta f}{2}\right)t + \frac{\varphi_1 + \varphi_2}{2}\right] \tag{3}$$

The frequency of the resulting oscillation is the average value of the superimposing oscillations. The resulting amplitude is,

[*] https://play.google.com/store/apps/details?id=com.chrystianvieyra.physicstoolboxsuite (retrieved on April 15th, 2016)

$$A' = 2A\cos\left(2\pi\frac{\Delta f}{2}\mathrm{t} + \frac{\varphi_2 - \varphi_1}{2}\right) \tag{4}$$

The intensity of the wave resulting from the interference of the initial oscillations is proportional to the amplitude squared. Let us denote the proportionality factor as λ,

$$I = \lambda A'^2 = 4\lambda A^2\cos^2\left(2\pi\frac{\Delta f}{2}\mathrm{t} + \frac{\Delta\varphi}{2}\right) = \\ = 2\lambda A^2 + 2\lambda A^2\cos(2\pi\Delta f\mathrm{t} + \Delta\varphi) \tag{5}$$

where $\Delta\varphi = \varphi_2 - \varphi_1$. The above equation can be rewritten as,

$$I = \frac{I_{max}}{2}[1 + \cos(2\pi f_b\mathrm{t} + 4\Delta\varphi)] \tag{6}$$

where $f_b = \Delta f$ is the frequency beat and I_{max} is the maximum sound intensity. Figure 1 shows the example of $x_1(t)$ and $x_2(t)$ which are oscillations of the same amplitude, $A = 1$ m, close frequencies $f = 10$ Hz and $f + \Delta f = 10 + 1 = 11$ Hz, and initial phases $\varphi_1 = \varphi_2 = 0$ rad. The frequency of the amplitude squared A' (and so of the intensity $I = \lambda A'^2$) is $\Delta f = 1$ Hz.

All the theory explained above is applicable to sound waves such as those generated by speakers placed at equal distances from the microphone of the smartphone. The speakers are fed with slightly different signals of same effective voltage from two independent AC generators.

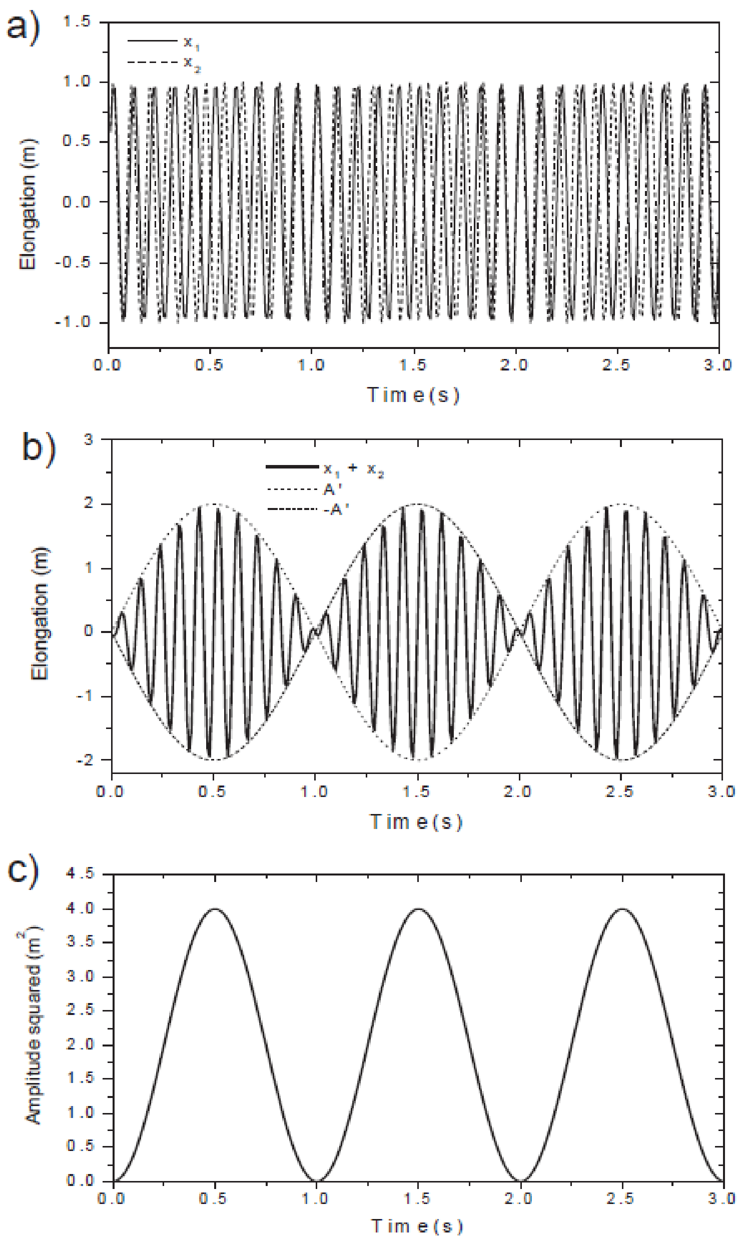

Figure 1. *Superposition of two oscillations $x_1(t)$ and $x_2(t)$ of the same amplitude ($A = 1\,m$) and close frequencies ($f = 10\,Hz$; $f+\Delta f = 11\,Hz$). The figure shows: a) the two single oscillations; b) the superposition of the oscillations and the envelope curve; c) the amplitude squared.*

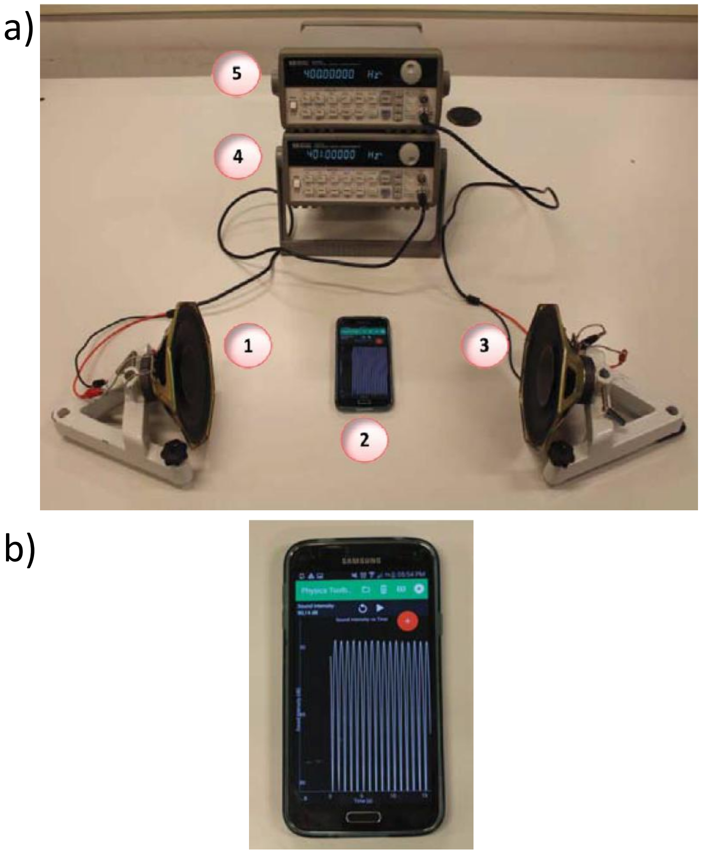

Figure 2. *a) Photograph of the experimental setup: the speakers (1 and 3), the smartphone (2) and the AC generators (4 and 5). b) Variations of the sound level of the acoustic beat as shown on the smartphone's screen by the application Physics Toolbox Sound Meter".*

3. Experimental results

The experimental setup used to carry out the experiments is shown in Fig. 2a. It consists of two AC generators (model 33120 A of Hewlett Packard), two identical speakers (model AD70800/M4 from Philips) facing each other, and the necessary cables to get all appliances connected. Finally, the smartphone is placed in the mid-way between both speakers. Two other smartphones with an application for generating a sine tone, could be also used. The Android application *Physics Toolbox Sound Meter*, capable of measuring the sound level of the waves coming from the speakers, was previously installed on the smartphone.

First, the same effective voltage is set at both AC generators. The speakers were fed with signals of similar frequencies and within the human audible range. We have used the frequencies 400 Hz and 401 Hz in the example shown in Fig. 2b. After checking that the beat can be heard, the mobile application is turned on. The beat oscillations are then observed on the mobile screen (Fig. 2b). It can be verified that, even when there is a small level of background noise, and the sampling frequency can not resolve the minimum values of the signal, the periodicity of the oscillations are still observed.

After recording the sound level for several seconds, the registered data, previously exported to a .csv file, can be sent to a PC for further analysis. For this purpose, different ways can be used, namely, cable connection, Bluetooth or email. In order to derive the beat frequency, the first step is to convert the registered sound level β in dB to the sound intensity I in W/m^2 using the following expresion (see Tipler, 2003),

$$I = I_0 10^{\beta/10} \tag{7}$$

where $I_0 = 10^{-12}$ W/m^2 is the standard value of the intensity threshold of the audible range in humans. Later, an interval of 5 s is chosen from the central part of the time series recorded by the smartphone. This segment of data for $I(t)$ is fitted using a least-squares algorithm to the Eq. (6). The only relevant quantity to this work is the beat frequency, f_b, although the other two parameters (I_{max} and $\Delta\varphi$) can be also obtained from the fitting procedure.

The use of sine or cosine functions in the fitting does not make any difference since it affects only the initial phase and not the frequency of the acoustic beat which is our objective function. Based on the values of frequency obtained from the fitting, the frequency of the beat f_b can be determined and compared with Δf which is the difference of the frequencies from the AC generators.

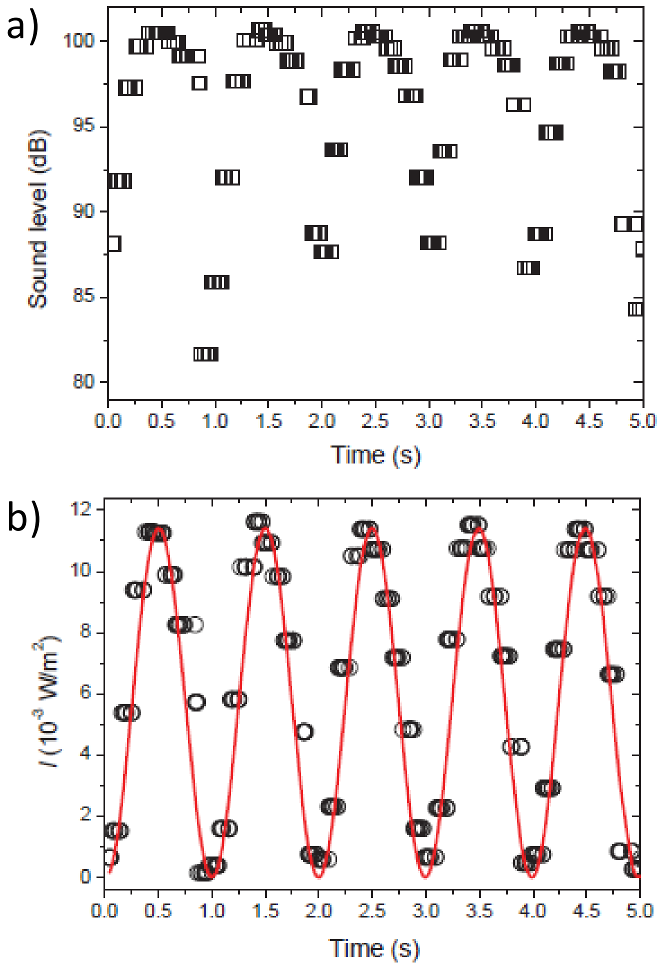

Figure 3. *a) Time series of the sound level in dB (β) (squares). b) Time series of the sound intensity (I(t) in Eq. (5)) (circles), along with the fitted function (red solid line). Results correspond to a frequency difference of 1 Hz in the AC generators.*

Figure 3 shows the results for a frequency difference in the AC generator as 1 Hz. First, the central interval of the time series of the sound level (in dB), registered with the smartphone is represented in Fig. 3a. The resulting beat frequency is $f_b = (1.008 \pm 0.002)$ Hz with a regression coefficient $R^2 = 0.90$.

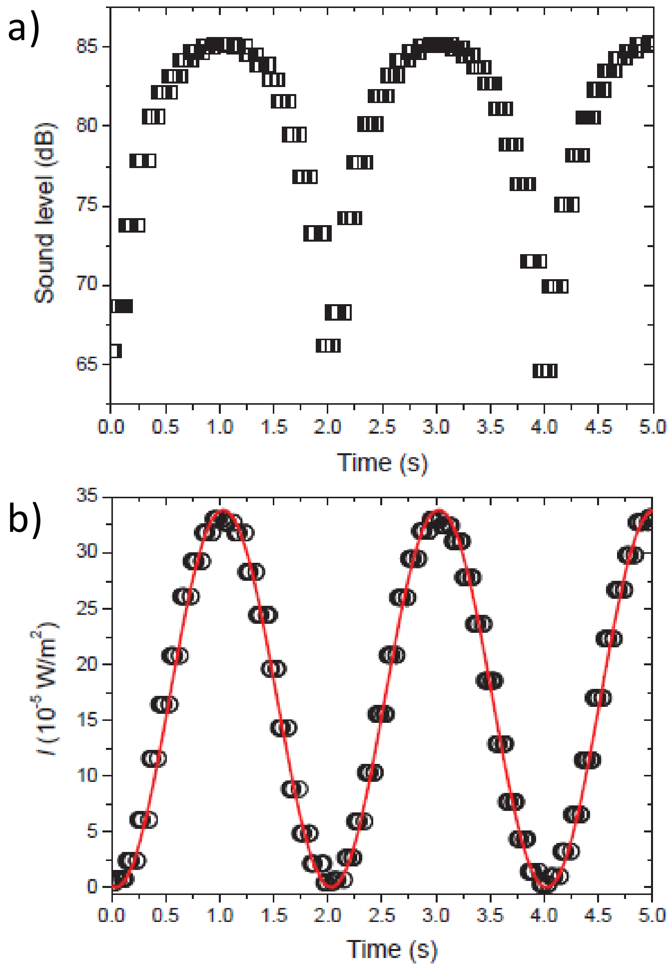

Figure 4. *a) Time series of the sound level in dB (β) (squares). b) Time series of the sound intensity (I(t) in Eq. (5)) (circles), along with the fitted function (red solid line). Results correspond to a frequency difference of 0.5 Hz in the AC generators.*

The discrepancy with respect to the frequency difference in the AC generator is 0.8%.

In order to provide further verification of the experimental procedure, several combinations of close frequencies ($f_b \approx \Delta f$) are used. For example, Fig. 4 shows the results for frequency differences in the AC generators of

$\Delta f = 0.5$ Hz, with an experimental frequency beat of $f_b = (0.5020 \pm 0.0004)$ Hz and a regression coefficient $R^2 = 0.99$. The quality of the fit can be seen in the value of R^2 which is close to 1. In this case, the discrepancy with respect to the expected value is 0.4%.

We repeated the proposed experimental procedure to characterize the acoustic beats with frequency differences in the AC generator between 0.5 and 1.5 Hz and main frequencies between 400 and 700 Hz. In all cases, the discrepancies were lower than 1%. Therefore, the precision of the frequency measurements was reasonably enough to capture the acoustic beat phenomenon. This is not itself the goal of this work but to show the students a Physics teaching experiment based on a smartphone, a very familiar device to them.

4. Conclusions

A new Physics teaching experiment for first years university students has been presented in this work. A smartphone with an Android^{TM} application has been used as sonometer to measure the sound intensity of the beats formed by the superposition of sound waves generated at speakers connected to AC generators. The interfering waves had the same amplitude and very close frequencies. The time series generated from the measurements with the smartphone are further analyzed by the students in order to determine the frequency of the beats. The beat frequency obtained from the smartphone data reproduces the value calculated from the AC generators frequencies within 1 %. The use of smartphones in Physics teaching experiments is a very motivating experience for the students.

5. Acknowledgments

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Capítulo 3

Discusión de los resultados

Como se ha comentado anteriormente, el objetivo fundamental de este proyecto de Tesis es extender el uso de los sensores de los teléfonos móviles inteligentes (*smartphones*) en el área de la Física y la Tecnología. En este apartado se resumen brevemente las aportaciones desarrolladas junto con los primeros resultados de la evaluación de las experiencias, tanto por parte de alumnos de universidad como de educación secundaria.

Aportaciones realizadas

Tal y como se ha comentado en la Introducción, en el laboratorio de Física se realizan prácticas de laboratorio en las cuales los alumnos estudian desde el punto de vista experimental leyes físicas con las que han trabajado previamente en las clases de teoría y problemas. El objetivo de las prácticas de laboratorio es doble: por un lado reforzar los conocimientos teóricos adquiridos, y por otro habituarse a las técnicas experimentales propias de laboratorio (manejo de aparatos de medida, toma de datos experimentales, análisis de los mismos, cálculo de incertidumbres, etc.).

En el laboratorio de Física se utiliza multitud de aparatos de medida. Algunos son muy sencillos (cronómetro, regla) y otros más complejos (multímetro, osciloscopio, ordenador). Es muy importante para la correcta formación del alumno de grados tecnológicos, que adquiera habilidades en la utilización de dichos instrumentos de medida así como en el análisis matemático de los datos obtenidos.

En ocasiones, los alumnos encuentran rutinarias y poco motivadoras las prácticas de las asignaturas relacionadas con la Física. Esto conlleva falta de interés en las mismas y que traten de realizar las mínimas medidas exigidas en el menor tiempo posible, de manera mecánica, y sin reflexión crítica sobre el trabajo realizado. Por otro lado, el uso de material antiguo y/o ajeno al día a día del alumno aleja a éste de la propia experiencia.

En este contexto, con la intención de paliar los problemas indicados, en esta Tesis se ha propuesto una serie de experiencias innovadoras donde se utiliza el *smartphone* como dispositivo de medida, de tal forma que los alumnos descubran que este dispositivo tecnológico puede tener muchas más aplicaciones de las que ellos conocen. Las prestaciones de los *smartphones* actuales permiten registrar medidas de magnitudes físicas, y exportarlas a un ordenador para su posterior análisis.

Las aportaciones realizadas (recogidas en Capítulo 2) se pueden clasificar en tres bloques en función del sensor utilizado. En primer lugar, se ha considerado el sensor de aceleración. Se trata del sensor más conocido de los integrados en los teléfonos inteligentes, principalmente porque es el que más se utiliza, por ejemplo, en diversas *Apps* recreativas o para controlar la rotación automática de la pantalla. La función principal del acelerómetro es, como su mismo nombre indica, medir la aceleración con la que desplazamos linealmente el teléfono en las tres dimensiones del espacio, lo que ha permitido desarrollar las siguientes experiencias:

- Determinación de la constante elástica de un muelle a partir de las oscilaciones armónicas que describe un *smartphone* unido al mismo (Artículo 1).
- Determinación del tiempo de relajación del movimiento de un *smartphone*, unido a un muelle, que oscila en un medio viscoso (Artículo 1).
- Determinación de la frecuencia de batido de las oscilaciones mecánicas de un *smartphone* suspendido de un muelle cuyo otro extremo está unido a un vibrador (Artículo 2).
- Caracterización de los modos normales de oscilación de dos *smartphones* acoplados por sistema de muelles (Artículo 3).

El segundo sensor considerado en las experiencias de laboratorio desarrolladas ha sido el de luz ambiente. La principal función de este sensor es detectar la intensidad de la luz ambiente para poder ajustar el brillo de la pantalla de forma automática, haciéndola más clara o más oscura según se requiera. Este sensor ha permitido proponer una nueva experiencia de laboratorio en la que se caracteriza la eficiencia energética de diversas fuentes de luz (incandescente, halógena y *leds*) actuando el *smartphone* como luxómetro (Artículo 4).

Finalmente, con el micrófono que incorpora y con una *App* adecuada, el *smartphone* puede operar como sonómetro, lo que ha permitido caracterizar el fenómeno del batido acústico (Artículo 5).

Evaluación de los resultados

Algunas de las experiencias propuestas ya han sido realizadas por grupos piloto, tanto en educación superior como en educación media, lo que ha permitido evaluar el grado de aceptación por parte de los alumnos. A nivel preuniversitario, el curso 2014/15 se impartió el Taller "*Experimenta la Física con tu smartphone*" a 30 alumnos de primero de bachillerato y a otros 30 de cuarto de la ESO que participaron en el *Campus Científico de Verano de Valencia* VLC-CAMPUS* organizado conjuntamente por la Universitat Politècnica de València y la Universitat de València durante el mes de julio. En el taller (de 1,5h de duración) los alumnos pudieron realizar diversas experiencias, entre las cuales se incluían la de caracterizar el movimiento armónico simple mediante el sensor del aceleración, y la de verificar mediante el sensor de luz ambiente la ley del inverso del cuadrado de la distancia. Tras la realización de las experiencias, los estudiantes cumplimentaron una breve encuesta cuyos resultados (sobre 10 puntos) se muestran en la Tabla I.

PREGUNTA	1ª Bach.	4º ESO	MEDIA
1. Los profesores parecen dominar la temática de la sesión.	9,75	9,75	**9,75**
2. Me han resuelto las dudas con claridad y precisión.	8,39	8,02	**8,21**
3. Me han animado a participar activamente en la sesión.	8,58	8,00	**8,29**
4. Han conseguido despertar mi interés por la temática de la sesión.	7,42	7,33	**7,38**
5. Los objetivos a conseguir se han indicado al inicio de la sesión.	9,22	8,25	**8,74**
6. La duración de la sesión es adecuada.	9,00	7,75	**8,38**
7. La metodología empleada y las actividades realizadas son adecuadas.	9,33	9,00	**9,17**
8. Los materiales utilizados son los adecuados.	9,42	9,50	**9,46**
9. Mi valoración general de la sesión es buena.	9,08	8,92	**9,00**

Tabla I. *Valoración media del Taller "Experimenta la Física con tu Smartphone" dirigido a estudiantes de primero de Bachillerato y cuarto de la ESO.*

* https://www.campuscientificos.es/pdf/proyectos/Resumen_proyectos_VLC.pdf

A la vista de los resultados anteriores podemos concluir que la valoración general del Taller por parte de estudiantes de educación media fue muy buena (9 puntos), destacando fundamentalmente la metodología seguida (9,17) y los materiales (sus propios *smartphones*) utilizados (9,46). La temática (Física) ha sido la que ha obtenido la puntuación más baja (7,38). Sin embargo, hay que tener en cuenta que en esta sesión transversal participan todos los estudiantes del campus científico, independientemente del proyecto en el que estuvieran inscritos (Física, Matemáticas, Química o Medicina).

A nivel universitario, se ha evaluado la práctica de laboratorio "*Determinación de la constante de un muelle*". Tradicionalmente, los alumnos estudian el movimiento armónico simple mediante un muelle del cual se suspende una masa conocida a la que se hace oscilar. A partir de la medida del período de oscilación, los alumnos determinan la constante elástica del muelle. De forma alternativa, mediante el acelerómetro incorporado en el *smartphone*, se puede registrar la aceleración que experimenta el teléfono suspendido de un muelle. Así, los alumnos disponen de una información mucho más rica (serie temporal de la aceleración) para el estudio del movimiento armónico simple.

Para evaluar los objetivos alcanzados, hemos realizado una encuesta de satisfacción a los alumnos. Como se disponía de docencia en varios grupos, se ha comparado los resultados de la encuesta en los grupos tradicionales, con los obtenidos en los grupos donde se ha introducido la innovación (smartphone). En la Tabla II se muestran las preguntas planteadas, así como la valoración realizada en cada grupo de alumnos, en una escala de 0 a 10. La encuesta se ha realizado a un total de 269 alumnos de la Escuela Técnica Superior de Ingeniería del Diseño de la Universitat Politècnica de València, de los que 132 han utilizado el *smartphone*, y 137 han seguido la metodología tradicional. Se puede observar en general, una calificación mucho más alta en todos los apartados de la encuesta por parte de los grupos que han realizado la práctica con teléfono móvil inteligente, en comparación con los que han seguido el método tradicional. Únicamente la pregunta relacionada con el tiempo disponible para la realización de la práctica obtiene una puntuación un poco menor. Esto se justifica por el tiempo requerido para la instalación de la aplicación en el teléfono móvil, la familiarización de los alumnos con la misma, el envío de los datos del teléfono móvil al ordenador, y el uso de una hoja de cálculo para el análisis de dichos datos.

PREGUNTA	**Tradicional**	***Smartphone***
1. La práctica se adecua a la temática general de la asignatura.	7,6	9,0
2. Los objetivos a conseguir se han indicado claramente al inicio de la práctica.	7,1	8,3
3. El tiempo disponible para realizar la práctica es adecuado.	6,3	5,9
4. La metodología empleada y las actividades realizadas son adecuadas.	6,6	8,2
5. El material utilizado me ha resultado motivador.	5,8	8,2
6. Me ha sorprendido el procedimiento de medida.	4,9	8,1
7. El profesor ha resuelto las dudas con claridad y precisión.	6,5	8,5
8. Esta práctica me ha resultado más interesante que las anteriores.	5,7	8,1
9. Mi valoración general de la práctica es buena.	6,8	8,5

Tabla II. *Valoración media de la práctica de laboratorio "Determinación de la constante de un muelle" por alumnos que han seguido la metodología tradicional, comparada con la calificación dada por los alumnos que han utilizado su smartphone.*

No obstante, el *smartphone* permite comprender mejor el fenómeno físico estudiado, ya que los alumnos pueden visualizar el movimiento armónico simple analizado, y no se limitan únicamente a cronometrar oscilaciones.

Capítulo 4

Conclusiones

En este capítulo de conclusiones se analiza el nivel de cumplimiento de los objetivos de investigación planteados en la introducción, y se exponen las perspectivas futuras.

Cumplimiento de los objetivos

Tal y como se indica en el Capítulo 1, el objetivo fundamental de este proyecto de Tesis es proponer diversas aplicaciones de teléfonos móviles inteligentes en el área de la Física experimental, aprovechando los diversos sensores que estos dispositivos incorporan y la creciente disponibilidad de *Apps* gratuitas que los controlan. Como objetivos particulares, se planteó el desarrollo de experimentos que hicieran uso del sensor de aceleración, el sensor de luz ambiente y el sensor acústico como instrumentos de medida.

Los Artículos 1, 2 y 3 incluidos en el Capítulo 2 corresponden al primero de los objetivos particulares mencionados, al desarrollar experiencias en las que se utilizan series temporales de aceleraciones registradas, en unos casos por un *smartphone* (oscilación libre, oscilación amortiguada, batido mecánico) y en otros por dos acoplados (sistema bidimensional configurado mediante un conjunto de muelles).

El Artículo 4 desarrolla un experimento en el que se utiliza el sensor de luz ambiente del *smartphone* para comprobar la dependencia de la iluminancia con la inversa del cuadrado de la distancia al punto de emisión, así como comparar la eficiencia de diversos tipos de fuente.

Por último, en el Artículo 5 se hace uso del micrófono del *smartphone* en una experiencia que permite caracterizar el fenómeno del batido acústico.

El conjunto de trabajos incluidos en el compendio de publicaciones posibilita la consecución del objetivo fundamental planteado. Las experiencias propuestas son adecuadas en general para asignaturas de Física de primer curso de universidad, con la excepción del estudio de las oscilaciones acopladas, que resulta más conveniente para estudiantes más avanzados. Varias de estas experiencias, tales como la oscilación libre, los batidos mecánico y acústico, o el estudio de fuentes de luz, resultan también adecuadas para educación secundaria, aunque quizá con alguna simplificación de la base teórica y del análisis de datos.

Dado que se pretende que estas experiencias supongan una alternativa que resulte más interesante y motivadora que los procedimientos tradicionales, un aspecto relevante de cara a la consecución del objetivo principal es la opinión de los propios alumnos. En este sentido, las encuestas realizadas, cuyos resultados en incluyen y comentan en el Capítulo 3, ponen de manifiesto la valoración positiva de los estudiantes, tanto universitarios como de educación secundaria.

Perspectivas futuras

Como se ha comentado en el punto anterior, se han propuesto diversas experiencias aprovechando diferentes sensores de los *smartphones* tales como el acelerómetro, el sensor de luz y el micrófono, utilizando *Apps* libres. Sin embargo, el abanico de posibilidades que ofrecen los teléfonos inteligentes en mucho más amplio y se puede hacer uso de otros dispositivos como el giroscopio, el sensor de proximidad, el de campo magnético, o el de temperatura y humedad que incorporan algunos *smartphones*, para proponer nuevas prácticas de laboratorio. En este sentido, como perspectiva futura nos planteamos el desarrollo de nuevas experiencias de Física tales como:

- *Magnetómetro*: Los teléfonos móviles disponen de un sensor magnético, capaz de medir la intensidad del campo magnético en los tres ejes en el rango de los mT. Sin embargo, se han realizado pocos estudios de este sensor y desarrollado muy pocas experiencias a nivel educativo. Mediante este sensor podemos desarrollar una práctica para la medida del campo magnético creado por diversos elementos como imanes, conductores de geometrías diversas, bobinas, etc.
- *Ley de Malus*: Esta ley establece la intensidad de un haz de luz polarizado linealmente, cuando atraviesa un polarizador, en función del ángulo del mismo. Utilizando el luxómetro incorporado en el teléfono móvil, podemos medir dicha intensidad para verificar así la ley de Malus. Otra práctica más avanzada podría ser la medición de la dependencia de la intensidad lumínica con la distancia considerando distintos frentes de onda: esférico para una fuente puntual, cilíndrico para una fuente lineal, etc.

- *Ley de Gay-Lussac*: Algunos teléfonos móviles incorporan sensores de temperatura, humedad y presión, que permiten predecir el tiempo como lo hacen las estaciones meteorológicas digitales. Estos sensores permiten realizar sencillas prácticas de termodinámica si se tiene en cuenta que la mayoría de teléfonos móviles operan entre 0 y 50 ºC (aunque el Samsung Galaxy S II puede soportar -22 ºC), que pueden operar con grados de humedad entre el 0 y el 100%, y que pueden medir presiones hasta varias atmósferas. Así pues, usando un recipiente de volumen fijo y encerrando en él el teléfono móvil, se puede contrastar el cambio de presión cuando cambia la temperatura (ley de Gay-Lussac). Esta práctica se puede implementar con un pequeño recipiente acoplado a una placa Peltier que permite calentar o refrigerar dependiendo del sentido de la corriente.

Adicionalmente, también se pretende desarrollar *Apps* propias que permitan controlar mejor los sensores de los teléfonos móviles y tabletas. Así por ejemplo, las *Apps* disponibles hoy en día para discernir frecuencias sonoras tienen muy poca resolución espectral, por lo que se pretende crear aplicaciones propias que exploren los límites de sensibilidad de todos los sensores. Las *Apps* a desarrollar se realizarán para ser operadas en el sistema Android™.

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