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™ 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%.

Keywords: acoustic beats, sound level, smartphone.

Abstract in Spanish language

El presente trabajo expone un nuevo experimento docente sobre el Batido Acústico. En este sentido, hemos diseñado un montaje experimental para el estudio de la superposición de dos ondas de sonido con frecuencias muy similares, lo que da origen al fenómeno conocido como Batido Acústico. El micrófono del smartphone se utiliza para registrar las ondas de sonido emitidas por dos altavoces, los que se ubican de manera equidistante con respecto a este, y se conectan a generadores de corriente alterna. El smartphone se utiliza aquí como un instrumento de medición. Los datos del nivel sonoro se capturan con ayuda de una aplicación Android™, que se puede descargar de Google Play de manera gratuita. Finalmente, haciendo uso de técnicas de análisis gráfico y de ajuste, se obtiene la frecuencia del batido, la que a su vez se compara con las frecuencias emitidas por los generadores. Los valores de discrepancia obtenidos no superan el 1%.

Palabras claves: batido acústico, nivel de sonido, smartphone.

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.¹ Wireless devices such as wiimote have been also used in Physics teaching experiments.² 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.\textsuperscript{2,4} For instance, the acceleration sensor of the smartphones has been used to study mechanical oscillations, at both the qualitative\textsuperscript{3} and the quantitative\textsuperscript{4} 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 app.

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.\textsuperscript{5–7} The sound frequency spectrum captured by the smartphone microphone can be analyzed with a number of free applications, such as “Audio Spectrum Monitor”\textsuperscript{8} and “Spectrum Analyzer”.\textsuperscript{9} 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\textsuperscript{10} and the Doppler Effect for sound waves.\textsuperscript{11}

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\%.\textsuperscript{12} 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.\textsuperscript{13} 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 sound.\textsuperscript{14} By the study of destructive interference in a pipe it is also possible to adequately and easily measure the speed of sound.\textsuperscript{15} A soundmeter 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.\textsuperscript{16} 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 resulting in surprisingly sharp peaks that can be seen as time markers. The collected data allows the determination of gravitational acceleration.\textsuperscript{17}

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.\textsuperscript{18} 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.\textsuperscript{19} 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 App. “Physics Toolbox Sound Meter”.\textsuperscript{20} 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 $\varphi_1$ and $\varphi_2$,

$$x_1(t) = Asin[2\pi ft + \varphi_1],$$

$$x_2(t) = Asin[2\pi (f + \Delta f)t + \varphi_2].$$

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

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

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

$$A' = 2Acos(2\pi \frac{\Delta f}{2} t + \frac{\varphi_2 - \varphi_1}{2}).$$

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 $\lambda$,

$$I = \lambda A'^2 = 4\lambda A^2cos^2(2\pi \frac{\Delta f}{2} t + \frac{\Delta \varphi}{2}) = 2\lambda A^2 + 2\lambda A^2cos[2\pi \Delta ft + \Delta \varphi].$$

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

$$I = \frac{I_{\text{max}}}{2}[1 + cos[2\pi f_b t + \Delta \varphi]].$$

where $f_b = \Delta f$ is the frequency beat and $I_{\text{max}}$ is the maximum sound intensity. Therefore,
the resulting frequency of oscillation is the difference of the interfering oscillations. 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; $f + \Delta f = 10 + 1 = 11$ Hz). In panel a), the single oscillations are shown. In panel b), the superposition of the oscillations and envelope curve and in panel c), the amplitude squared.

3 Experimental results

The experimental setup used to carry out the experiments is shown in Figure 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 App. 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.

Figure 2: In the upper panel, a photograph of the experimental setup is shown. In the figure, the speakers (1 and 3), the smartphone (2) and the AC generators (4 and 5) are shown. In the lower panel, variations of the sound level of the acoustic beat as shown on the smartphones screen by the application “Physics Toolbox Sound Meter”.

First, the same effective voltage is set at both AC generators. The speakers were fed with signals of similar frequency and within the human audible range. We have used the frequencies 400 Hz and 401 Hz in the example shown in Figure 2 (lower panel). After checking that the beat can be heard, the mobile application is turned on. The beat oscillations are then observed on the mobile screen (Figure 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.

Figure 3: In panel a), the time series of the sound level in dB ($\beta$) (open squares) is shown and in panel (b), the time series of the sound intensity ($I(t)$ in Eq.5) (open circles), along with the fitted function (red solid line). Results correspond to a frequency difference of 1 Hz in the AC generators.

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 $\beta$ in dB to the sound intensity $I$ in
W/m² using the following expression: \[ I = I_0 10^{\beta/10}. \] (7)

where \( I_0 = 10^{-12} \) W/m² 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 (\( I_{\text{max}} \) and \( \Delta \phi \)) 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 \( \Delta f \) which is the difference of the frequencies from 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 Figure 3a of \( R^2 = 0.90 \). The resulting beat frequency is \( f_b = (1.008 \pm 0.002) \) Hz which corresponds to a discrepancy with respect to the frequency difference in the AC generator of 0.8 %.
Figure 4: In panel a), the time series of the sound level in dB (open squares) is shown and in panel (b), the time series of the sound intensity ($I(t)$ in Eq.5) (open circles), along with the fitted function (red solid line). Results correspond to a frequency difference of 0.5 Hz in the AC generators.

In order to provide further verification of the experimental procedure, several combinations of close frequencies ($f_b \approx \Delta f$) are used. For example, figure 4 shows the results for frequency differences in the AC generators of $\Delta f = 0.5$ Hz, where an experimental frequency beat of $f_b = (0.5020 \pm 0.0004)$ Hz with 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™ 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 analysis of 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. This has come up in our Physics courses where the students have experimented with different types of phenomena.4,10,11

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