Exploring Historical Scientific Instruments by Using Mobile Media Devices

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We describe an educational activity that can be completed with mobile media devices in order to understand the working principle of a pair of tuning forks, from the Historical Collection of Physics Instruments of the University of Palermo, and how they were used to explain acoustic interference and beats with the Lissajous optical method. This approach can be used with any tuning fork and it is a valuable teaching strategy that does not require specific laboratory equipment.

Introduction

The Historical Collection of Physics Instruments of the University of Palermo,[1] on exhibit at the Department of Physics and Chemistry-Emilio Segrè, in the historic building[2] of via Archirafi 36, keeps a rich collection of scientific instruments from the 19th century onwards. In the collection, about 20 acoustic instruments are preserved.[3,4] Most of these instruments have been bought from the instrument maker Rudolph Koenig (1832-1901), mainly in the second half of the 19th century, by the Italian physicist Pietro Blaserna (1836-1918), during his stay in Palermo as professor of Experimental Physics and Director of the Institute of Physics of the University.[3,4]

The exploration of historical scientific instruments is, in most cases, hampered by preservation conditions, since the direct use of the instruments inevitably modifies the environmental conditions (humidity and temperature) and it may cause damage to the instruments. Recently, three acoustic instruments of the collection have been examined by chemico-physical analysis,[5] in order to evaluate their preservation conditions. Thermal and structural properties of historical-wood samples have been investigated by Fourier-transform infrared (FTIR) spectroscopy and the results coupled with thermogravimetric analysis, in particular, micrograms of wooden samples of apparatuses from woods of different taxa: one sample extracted from the wooden base (*Swietenia mahagoni*) of a chronograph tuning fork with electromagnetic drive, one from the resonance box (*Picea abies*) of a tuning fork, and one from the wooden support (*Juglans regia*) for tuning forks. The thermal behavior of the wooden materials has been interpreted on the basis of specific indexes determined by the quantitative analysis of the FTIR spectra, providing a novel protocol to estimate not only the conservation state but also the conservation conditions of historical wooden artworks.[5,6]

To bypass the difficulties related to the direct use of historical instruments, one may resort to new technologies, in particular the use of mobile media devices (MMDs) such as smartphones or tablets. In the literature, an increasing number of papers are devoted to the use of MMDs as laboratory tools for school physics experiments,[7–11] since they are usually equipped with several sensors and controlled by appropriate software (apps) that allows one to perform accurate measurements.[12–15] In this article, we describe an educational activity that can be carried out by using MMDs, aimed at understanding the working principle of a pair of tuning forks and their historical use to explain acoustic interference and the phenomenon of beats.

The tuning forks and the phenomenon of beats

A tuning fork, or normal chorister, is an acoustic instrument having the form of a two-pronged fork formed from a U-shaped bar of elastic steel.[16,17] When struck, the tuning fork emits a sound at a certain frequency that depends on the length and the thickness of the prongs. Although the tuning fork was patented in 1711 by the English trumpeter John Shore (1662-1752),[18] it was only at the end of the 18th century that the German physicist Ernst Florens Friedrich Chladni (1756-1827) gave a scientific explanation of the vibration motions of the tuning fork, as a particular case of a straight rod bent in the center.[19] In 1854, the frequency of tuning fork used in music for tuning musical instruments was standardized.[20]

Fig. 1. Photo of the tuning forks on wooden (*Picea abies*) resonance box produced by Koenig and bought by Blaserna in 1868.[3,4] The insets show the resonance frequency and the manufacturer's monogram, engraved on the tuning forks. Historical Collection of the Physics Instruments of the University of Palermo, Italy.

The Historical Collection of the Physics Instruments of the University of Palermo owns the tuning forks shown in Fig. 1. They are mounted on a wooden resonance box. One of them emits a sound of frequency 1280 VS (640 Hz)[21] corresponding to the note MI_4, as indicated in the engraving shown in the

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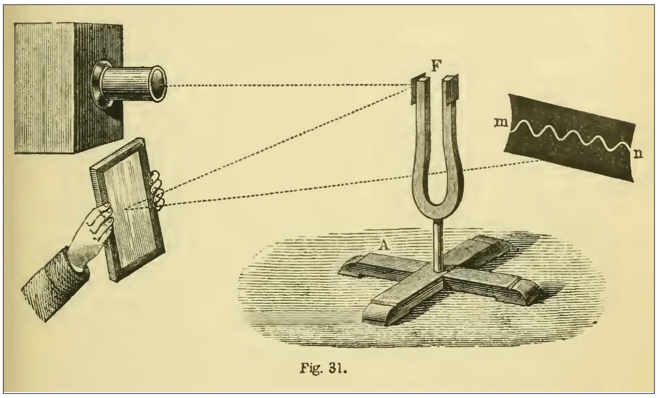

Fig. 2. Historical experimental method to make visible the harmonic oscillations by using a tuning fork and the Lissajous optical method.[17]

inset of Fig. 1. The other one emits a sound of frequency 1536 VS (768 Hz) corresponding to the note SOL_4, as indicated in the engraving shown in the inset of Fig. 1. On one end of one prong of both tuning forks, a small mirror is glued, most likely, to carry out experiments on acoustic interference with an optical method. Both sound boxes are signed "*Rudolph Koenig à Paris*" and the manufacturer's monogram is engraved on both the tuning forks, as shown in the inset of Fig. 1. In 1851, Koenig started to work in Paris as an apprentice to the famous violin maker Jean Baptiste Vuillaume (1798-1875), where he acquired his great skill working with metal and specific wood varieties that possess tonal properties. Seven years later, Koenig left to set up his own business making acoustical instruments, but his real interest was the science of acoustics. Inspired by the publication of the German physicist Herman von Helmholtz (1821-1894) and in personal communication with him, Koenig soon devoted himself to the research on acoustics and to the design of acoustical instruments.[22] The tuning forks of the collection were bought by Blaserna, from Koenig, in 1868.[3,4]

The tuning fork gives the simplest vibrations that are harmonic oscillations. Historically, to make these oscillations visible, a tuning fork was used, as illustrated in Fig. 2. A small mirror attached near the extremity of one of the tuning fork's prongs and a counterweight to the other one allows one to use the optical method invented by the French physicist Jules Antoine Lissajous (1822-1880). Blaserna[17] in his book of 1876 says:

> A ray of solar light introduced into the room is made to fall on the mirror of the tuning-fork, and is reflected thence on to a concave mirror, and thence again is reflected on to a diaphragm of translucent paper. An image of the hole in the window shutter is thus obtained on the diaphragm under the form of a luminous spot. This spot remains at rest as long as the tuning-fork is at rest, but when the latter vibrates, its mirror takes part in the vibration, and there appears a vertical luminous line instead of the spot on the diaphragm. This line is caused because our eyes are not able to follow the rapid movements of the luminous spot … if the concave mirror be rapidly moved by hand, so that it turns round a vertical axis, the different luminous spots, which correspond to different points of time, strike different parts of the diaphragm, and a beautiful curve is thus formed, which represents the form of the vibrations … if the mirror be turned with a suitable velocity, neither too fast nor too slow, a most beautiful sinuous curve is obtained, which exactly represents the form of the simple vibrations.

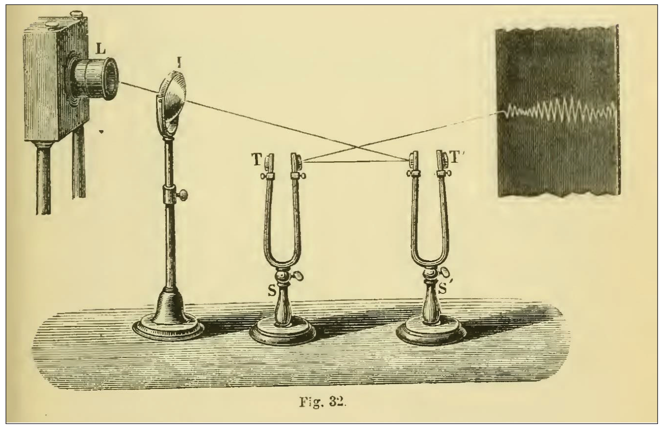

Fig. 3. The Lissajous optical method to perform experiments on the acoustic interference and beats.[17]

The Lissajous optical method allows one to perform several experiments. One can perform experiments on acoustic interference and in particular on the phenomenon of beats, which consists of the superposition of two sounds of nearby frequencies and is perceived as a periodic variation in volume. Figure 3 shows the experimental arrangement described by Blaserna[17] for the study of acoustic interference.

> [A] pencil of rays of solar or artificial light is caused to enter the room, and having been suitably concentrated by the lens **I**, falls upon the mirror of a tuning-fork **T'**, thence by reflection on to that of a second tuning-fork **T**, and thence, finally, on a diaphragm of paper, where the image of a luminous spot is formed. The tuning-fork are both equal, and give the same note. If the tuning-fork **T** be now rubbed with a violin bow, it vibrates and changes the luminous spot on the diaphragm into a long vertical line; but if the other tuning-fork **T'** be also rubbed, the vertical becomes longer or shorter, according as the vibratory movements of the two tuning-forks are made in the same or in reverse directions at the same instant of time, and therefore reinforce or enfeeble each other's effect. This being so, if a small coin be attached by means of a little wax to the tuning-fork **T**, it will be retarded in its vibrations, and will thus give with the other **T'** very marked beats. The vertical line will then be of variable length sometimes long and sometimes short, and one of these changes to each beat. … This vertical line can easily be converted into an undulating line by rapidly moving the tuning-fork **T**.

The two tuning forks of the collection were used, most probably, for the study of the acoustic interference and the phenomenon of beats by the Lissajous optical method described above.

The use of mobile media devices to explore historical instruments

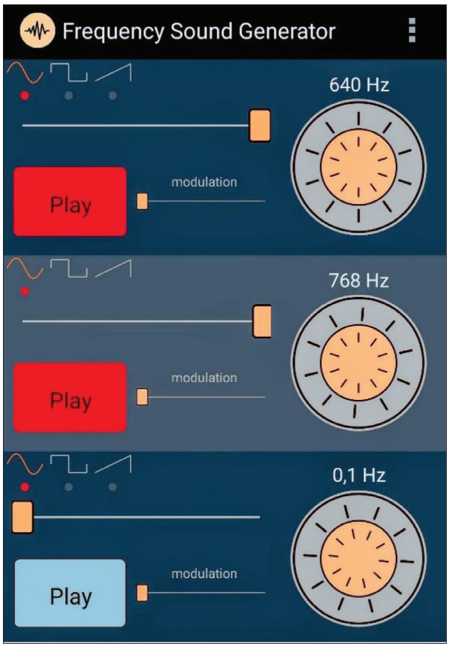

Fig. 4. A screenshot of the free Frequency Sound Generator app,[23] which shows the setting to reproduce the sound of the tuning forks to observe the phenomenon of acoustic beats. The tone generator at 0.1 Hz is switched off. The app allows one to regulate separately the intensity of the waves so as to faithfully reproduce the sounds of the two tuning forks.

To explore the working principle of historical scientific instruments, considering the difficulties to directly use them in the experiments, one may resort to new technologies and in particular the use of MMDs, such as smartphones or tablets. These devices are usually equipped with several different sensors controlled by appropriate software, and therefore they can be used to perform measurements, as well as to generate sound waves of defined frequency and intensity. This opens the possibility of arranging low-cost laboratories where expensive devices, as well as historical scientific instruments in not good preservation conditions, can be replaced by MMDs.

Here we describe how to use MMDs to understand the working principle of a pair of tuning forks and their historical use to explain acoustic interference and the phenomenon of beats. Figure 4 shows a screenshot of the free Frequency Sound Generator app.[23] This app is a simple sound-wave generator from 0.1 Hz to 20 kHz, easy to use, that allows one to generate simultaneously three tones of definite frequencies and intensity. By generating one tone, it is possible to reproduce the emitted sound of one tuning fork. Whereas by generating two tones, it is possible to reproduce the emitted sound of a pair of tuning forks, which gives rise to the phenomenon of acoustic interference and beats. In our case, we first set the frequencies respectively $f_1 = 640$ Hz and $f_2 = 768$ Hz that are the frequencies of the tuning forks shown in Fig. 1 and play one tone at a time. Then, we play both sounds simultaneously to reproduce the beats, which now can be heard. This setting is shown in Fig. 4. The app allows one also to regulate separately the intensity of the generated tones, by a slide knob, so as to reproduce the sounds of the two tuning forks either in frequency and in intensity. Furthermore, the historical experiment can be reproduced faithfully by using two different MMDs, each generating a tone of different frequency and intensity.

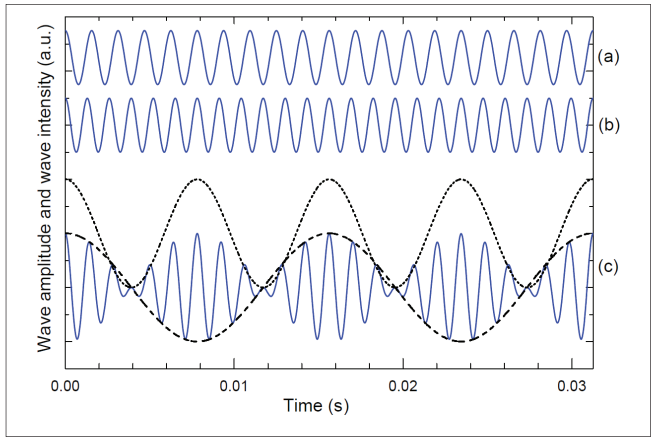

Fig. 5. Sound waves. (a) Single wave at frequency 640 Hz. (b) Single wave at a frequency 768 Hz. The frequency values are those of the tuning forks of Fig. 1. (c) The continuous line is the sum of the two single waves; the dashed line indicates the amplitude variation, which reproduces the acoustic beats and oscillates at frequency $|f_1 - f_2|/2 = 64$ Hz. The dotted line is the square of the wave that gives the sound intensity (volume) and oscillates at frequency $|f_1 - f_2| = 128$ Hz.

To mathematically explain the origin of the beats, one can sum two cosine waves of unit amplitude and frequency f_1 and f_2, respectively.[24] By using prosthaphaeresis formulas, one obtains

$$\cos(2\pi f_1 t) + \cos(2\pi f_2 t) = 2\cos\left(2\pi \frac{f_1 + f_2}{2} t\right)\cos\left(2\pi \frac{f_1 - f_2}{2} t\right).$$

Figure 5 shows the sound wave obtained by the sum of two single sound waves, which reproduce the acoustic beats. If the two original frequencies are quite close, the frequency of the cosine of the right side of Eq. (1), that is $|f_1 - f_2|/2$, is perceived as a periodic variation in the amplitude of the first term and not as an audible tone. It can be said that the lower-frequency cosine term is an envelope for the higher frequency wave, i.e., that its amplitude is modulated. The frequency of the sound is $(f_1 + f_2)/2$, that is, the average of the two frequencies. Since the human ear perceives the sound volume (intensity), which is proportional to the square of the amplitude of the sound wave, the beat frequency f_B will be equal to the absolute value of the difference in frequency between the two interfering waves, $f_B = |f_1 - f_2|$. The general mathematical description of interference and beats of two waves of different frequency and amplitude can be found in Ref. 24.

A physical interpretation of the acoustic beats is that when the two sound waves are nearly in phase, they interfere constructively and their maxima sum up, raising the perceived volume. When the two waves are out of phase of about 180°, they interfere destructively, the maxima of one wave cancel the minima of the other, and a reduction of the perceived volume occurs.

Discussion and conclusion

The role of history of science and of historical scientific museums is central to improve the learning of scientific concepts.[25–27] The understanding of physical phenomena can be bolstered by using pedagogical paths[28] starting from a historical approach and including the study of working principles of the historical scientific instruments[29–31] as well as historical-based laboratory activities[32,33] to improve student attitudes toward science.[10,11] During the last decades, there has been a rising interest in the preservation of historical scientific instrument collections and the development of research activities related to them.[28–33] The restoration of physics cabinets and historical laboratories, the replication of historical experiments[25] and science communication events, as well as the online display of collections are only some examples. Nevertheless, exploration of historical scientific instruments is hampered by preservation conditions, since the direct use of the instruments inevitably modifies the environmental conditions, which may cause damage to the instruments. The use of MMDs may help to overcome these difficulties and it may help to increase the attention of students. Furthermore it provides a precious educational resource and a more comprehensive way to approach the teaching of science. This different approach certainly contributes to students' learning of science concepts and stimulates the interest of students towards physics.[10,11] On the other hand, the use of MMDs as measurement devices opens the possibility of arranging low-cost setups for physics experiments, which may foster students' active learning,[34] enhancing engagement and interaction during lessons.[35] Indeed, the students' interest in smartphones, as well as their expertise to use such devices, can result in a powerful tool to bolster active learning[34,35] and reinforce their interest in learning scientific issues.[10,11]

In conclusion, we have described an educational activity that can be done by using mobile media devices in order to understand the working principle of a pair of historical tuning forks and how they were used to explain the acoustic interference and beats with the optical method invented by Lissajous.

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