Teaching about mechanical waves and sound with a tuning fork and the Sun

1. Introduction

Research in physics education has shown that students experience many difficulties in understanding basic concepts of mechanical waves. For instance, students often confuse the wave motion (direction and speed), with the oscillation of an element of the propagating medium (Wittmann, Steinberg and Redish, 1999, Wittmann, 2002). In other cases, students wrongly think that a wave carries matter or the "driving force" that created it, and only rarely wave propagation is associated with energy transfer. Students are also often unable to identify the physical quantity that is perturbed (Grayson 1996). At early school years, waves are conceptualized as solid objects, which "bump" and come back; accordingly, waves' superposition is often described as a collision between particles. Older students have problems in identifying the variables that mathematically describe a wave: they often focus exclusively on amplitude, ignoring frequency, and incorrectly relate velocity to intensity (Wittmann 2002). Most of the above difficulties seem to be due to the lack of understanding that the propagation of a mechanical wave is the response of a medium to a physical perturbation and that variables that describe such propagation depend only on the medium's properties and not on the specific perturbation.

Such alternative conceptions about wave propagation often shape students' understanding of sound, a phenomenon that is often used as context to teach about waves. Mazens and Lautrey (2003) found four mental models: *(i)* sound cannot *pass* through other objects, *(ii)* sound can be transmitted only if it is *harder* than encountered obstacles, *(iii)* sound is *immaterial*, *(iv)* sound is a vibratory process (scientific explanation). Most of these mental models attribute to sound a given property of matter, thus confounding wave properties with medium properties. Similarly, students may think that sound is a propagating substance-like *entity* carried or transferred by the molecules of the medium, seen only as a passive support (Linder and Erickson 1989, Linder 1992; Maurines 1992). Difficulties in dealing with sound propagation lead also to naïve conceptions about the sound velocity: students, for instance, may think that medium's particles slow down the sound propagation, or that the higher the density of the medium, the fastest the sound can propagate (Linder 1993). Finally, students may encounter problems with graphical representations of sound: for instance, often the $y(x)$ and $y(t)$ graphs, where y is the displacement of a medium element, x the abscissa and t the time, are not correctly distinguished by the students (Wittmann, Steinberg and Redish 2003)

Due to the complexity of mathematical formalism that describes wave propagation, usually high school teachers discuss the topic in a too qualitative manner that does not help students grasp a deep conceptual understanding of this fundamental topic for physics. In this paper, we address this issue presenting a module about mechanical waves, using sounds from tuning forks and the Sun as motivating contexts. The main reason is to show how physicists use the same technique (spectral analysis) to obtain information about very different phenomena.

2. Sound from a tuning fork

Tuning forks, invented by Händel's trumpeter, John Shore, in 1712, were very common amongst musicians as frequency standards, given their stability and small weight. With the increasing development of electronic equipment for music, digital tuners have gradually substituted them. However, they are a good teaching tool for introducing sound and the concept of vibration frequency. Tuning forks are usually made of two rectangular tines spaced of about 10 *mm* whose section is about 7 *x* 9 *mm;* length of the tines usually varies between about 70 *mm* and 170 *mm,* according to the desired frequency. A 45 mm long cylindrical stem of about 10 mm diameter joins the tines. A tuning fork may be modeled as a cantilever beam, which can vibrate in a symmetrical or anti-symmetrical mode in and out of the fork's plane. When the fork is set on vibration by a small hammer, the tines get close and turn away so they vibrate in a symmetrical mode. In-plane symmetrical modes have modal frequencies given by (Rossing, Russell and Brown 1992):

$$f_n = \left(\frac{\pi K}{8L^2}\right)\sqrt{\frac{E}{\rho}}\left[1.194^2, 2.988^2, 5^2, \ldots, (2n-1)^2\right] \tag{1}$$

where K is the radius of gyration of the beam cross section, L is the length of the tines, E is the Young modulus and ρ is the density of the material. The term:

$$\sqrt{\frac{E}{\rho}} \tag{2}$$

is the sound velocity v_s in the medium. Tuning forks are usually made of stainless steel, so v_s is about $5250\ ms^{-1}$. For a bar with a rectangular cross section as a fork, the radius of gyration is given by:

$$K = \frac{w}{\sqrt{12}} \tag{3}$$

where w is the thickness of the bar. Substituting (2) and (3) into (1) we have, for the fundamental mode:

$$f_1 \cong 0.162\frac{w}{L^2}v_s \tag{4}$$

Hence, for a tuning fork whose thickness is about 7 *mm*, tines length about 12 *cm*, we have $f_1 \cong 438.9Hz$, which corresponds to the central *A* tone.

In general, equations as (1) and (4) are a fundamental tool for the seismology analysis, since, from the frequency measurement, we gain insights about features of the system otherwise difficult to be directly accessed or measured.

3. Sound from the Sun

In the Sun, sound pressure waves are stochastically excited by convective motion of gas in the region between 0.7 R_S (solar radius) and the photosphere. As for the fork, the study of these waves gives us a lot of information about the internal structure of the Sun or of a star. This branch of astrophysics is called helioseismology or astroseismology (see, for a review, Christensen-Dalsgaard 1988, 2010)

These waves travel under the surface of the Sun and depend on geometrical and physical parameters describing the interior structure of our star. The main consequence of propagation of such sound waves is a variation of the solar radius and hence of the radial velocity, measured through Doppler effect, of heavy elements[1] in the photosphere. Using solar models (Christensen-Dalsgaard 2003), it can be shown that the main frequency of such oscillations is given by:

$$f \propto \frac{M_S}{R_S^2\sqrt{T}} \tag{5}$$

where M_S is the mass of the Sun, and T is its effective temperature. With $R_S \cong 6.9598\times10^8\,m; M_S = 1.989\times10^{30}\,kg; T = 5777K$ one obtains $f \cong 3.05mHz$ (also known as *5-minutes* solar oscillations). The comparison between the observations and the theoretical model leads to inference of properties of the solar interior, such as the internal solar rotation and the speed of the sound waves. The latter can be expressed, in an adiabatic approximation, by the velocity v of sound in perfect ionized gas:

$$v = \sqrt{\gamma\frac{p}{\rho}} \tag{6}$$

where γ is a constant which depends on the gas, p is the pressure and ρ is the density of the gas. Using state equation

[1] In astrophysics, elements with atomic number greater than 2 are called "heavy"

$$pV = nRT = nk_B N_a T \tag{7}$$

where k_B is the Boltzmann constant and N_a is the Avogadro constant, and taking into account that

$$V = n\frac{\gamma\mu m_a N_a}{\rho} \Rightarrow V \propto \frac{1}{\rho} \tag{8}$$

where m_a is the atomic mass unit and μ is the mean molecular weight, a non-dimensional quantity related to the abundances of hydrogen and heavy elements in the Sun surface, equation (6) becomes in our case:

$$v_{sun} \propto \sqrt{T} \tag{9}$$

i.e., the speed of the sound wave in the Sun depends on its effective temperature and internal structure. Mean value for v_{sun} is about 23 cms^{-1} (Kjeldsen and Bedding 1995). In the next section, we show how we built on the analogy between sound and Sun oscillations to design our activities.

3. Connecting sound of the tuning fork to the sound of the Sun

The fundamental frequency of a sound wave can be written, in its most general form, as:

$$f = \frac{v}{\lambda} \tag{10}$$

where v is the sound velocity in the medium where the mechanical wave is propagating and λ is its wavelength. For sound emitted by a plucked string of length L with fixed ends, the wavelength of the fundamental frequency is related to the length of the string:

$$L = \frac{\lambda}{2} \tag{11}$$

As $\lambda \propto L$, we can write equation (10) as:

$$f \propto \frac{v}{L} \tag{12}$$

The core idea of the module is to generalize equation (12) to fork and Sun. To this aim we need to find the *effective length* of the two systems. For the tuning fork, because the radius of gyration K is related to the inertia moment[2] of the rectangular cross section of the bar which models the fork, we can define the effective length as:

$$L_{eff} \equiv \frac{L^2}{K} \tag{13}$$

which essentially represent a purely geometrical factor of the fork (it depends on the length of the tines and the cross section)[3]. Hence we can rewrite equation (12) in a more general form as:

$$f \propto \frac{v}{L_{eff}} \tag{14}$$

The meaning of equation (14) is that the knowledge of the vibration frequency of the fork allows us to gain some insights about its structure.

For the Sun, the formal derivation of equation (5) is not suitable for high school or basic astronomy courses students and is beyond the goals of these activities. Therefore, we decided to derive the equation starting from the general form (14). Kjeldsen and Bedding (1995) found that:

$$f \propto \frac{v_{sun}}{H_p} \tag{15}$$

[2] Here we refer to the second moment of area

[3] A similar reasoning applies for the physical pendulum, where the length of the simple pendulum is substituted with an "effective length" that depends on the mass moment of inertia and the distance between the centre of mass and the pole around which the pendulum is swinging.

where H_p is the pressure scale height (Kippenhahn and Weigert, 1990) in the photosphere of the Sun. The physical meaning of this parameter is that pressure and density drop with height by a factor equal to e^{-1} when height is increasing of H_p. Using an approximation of ideal gas behavior, it can be shown that:

$$H_p \propto \frac{T}{g} \tag{16}$$

where g is the acceleration gravity at the surface of the Sun. For the Earth atmosphere H_p is about 9 *km*, for the Sun photosphere is about 300 *km*.

To underline the relationships between equation (15) and the internal structure of the Sun, we make the following assumptions: sun oscillations are essentially determined by the thermodynamics of the Sun photosphere and by its scale height, which can be reasonably considered as the analogue of the effective length of the tuning fork. Using the expression for g:

$$g \propto \frac{M_S}{R_S^{\,2}} \tag{17}$$

the scale height of the sun oscillations in (16) can be written as:

$$H_p \propto \frac{R_S^{\,2}}{M_S} T \tag{18}$$

Using equation (9) we finally have for the frequency of sun oscillations:

$$f \propto \frac{v_{sun}}{H_p} \propto \frac{M_S}{R_S^{\,2}\sqrt{T}} \tag{19}$$

which is the same of (5). Hence, measuring f we can determine geometrical (radius) and physical parameters (mass, effective temperature) of the Sun.

4. Students' activities

The module is organized in two phases, with six activities of one hour each. Table 1 resumes timing, students' activities and didactical aims.

Phase 1 – Analysis of the sound of a tuning fork (3h)

In the first activity (1h) the students are introduced to the basic concepts of sound propagation by driving questions as *"what is sound and how do we produce it?"*. The aim of this activity is to introduce the concept of sound as a perturbation of the medium in which the wave is propagating and to recognize that the perturbed physical quantity is the pressure of air particles that oscillate around their equilibrium position. Then, students listen to three sounds produced by the same tuning fork with a small mass put at different heights of one tine[4]. The students, without looking at the video, are asked to hear the sounds and to describe the differences between them. Once the students recognize the differences in the pitch of the sounds, they are told that the sounds are produced by the same tuning fork in different configurations. A model of tuning fork as two joined bars at one end is introduced; then, students are asked to describe how they would investigate sounds to find information about the different configurations and to hypothesize about possible relationships between configurations of the fork and sounds. Finally, the teacher introduces the physical quantities that describe a sound: intensity, time, frequency, period, and wavelength.

In the second activity (1h), students are first asked *"how would you graphically represent a sound?"*: after a brief discussion, the students are introduced to a digital audio editor (in our case the freeware software GoldWave[5]). The intensity *vs*. time graph of the three sounds is hence displayed (Figure 1).

[4] The file can be found at https://www.youtube.com/watch?v=NGyyhJZNqdk
[5] www.goldwave.com

Table 1 - Overview of the students' activities.

Phase	Activity	Time (h)	What students do	Intended didactical objectives	Driving Questions	Support materials
1	Analysis of the sound of a tuning fork	1	Listen to three sounds produced by the same tuning fork Describe the differences between the three sounds Hypothesize possible relationships between fork's configurations and the different sounds.	To introduce the concept of sound as a perturbation of the medium and the physical quantities that describe a sound: intensity, time, frequency, period, and wavelength.	*"What is sound and how do we produce it?"*	Sound samples
		1	Use the digital audio editor Discuss the intensity *vs.* time graph of the three sounds Discuss the role of frequency to describe the sound Analyze the waveform, spectrum and spectrogram graphs Estimate the fundamental frequency of the sound from the *I(f)* graph	To show that an exponential decay in the time waveforms is due to the energy dissipation in air To introduce *I(f)* graph (*spectrum*) and *f(t)* graph (*spectrogram*) To understand what kinds of information are inferred from the three graphs To characterize the tuning fork as source of a "pure" sound	*"How would you graphically represent a sound?"*	Software: GoldWave
		1	Estimate the velocity of the sound wave in the tuning fork from the length of the tines and the section of the fork	To understand that sound velocity depends on the geometry of the fork (length and cross section of the tine).	*"How can we change the frequency of a sound?"*	Software: GoldWave
2	Sound of the Sun	1	Listen to the sound of the Sun Discuss about birth and shape of stars and what are the physical processes involved in a star Discuss what causes sound waves in the Sun	To understand that the stability of a star is a consequence of hydrostatic equilibrium, mass conservation, energy transfer and energy conservation To understand that pressure is the physical key quantity whose variations cause acoustical waves in the Sun	*"How do stars work?"*	Sound samples
		1	Qualitatively discuss physical process inside the Sun Use the digital audio editor Estimate the frequency of sound oscillations	To recognize that the pressure forces in the Sun cannot be only related to the thermodynamic processes, but also to radiation pressure; To recognize the same spectral analysis can be performed for different physics phenomena	*"What are the pressure forces in the Sun?"*	Software: GoldWave
		1	Discuss on what could depend the estimated frequency of the Sun sound Further discuss about stability of the Sun Estimate the velocity of the sound wave in the Sun and compare it with that obtained for the tuning fork.	To understand that the sound waves in the Sun are related to processes that happen within the Sun and that the frequency is related to geometrical factors (radius) and physical properties (mass and temperature)	*"On what does the frequency of the Sun sound depend?"*	Software: GoldWave

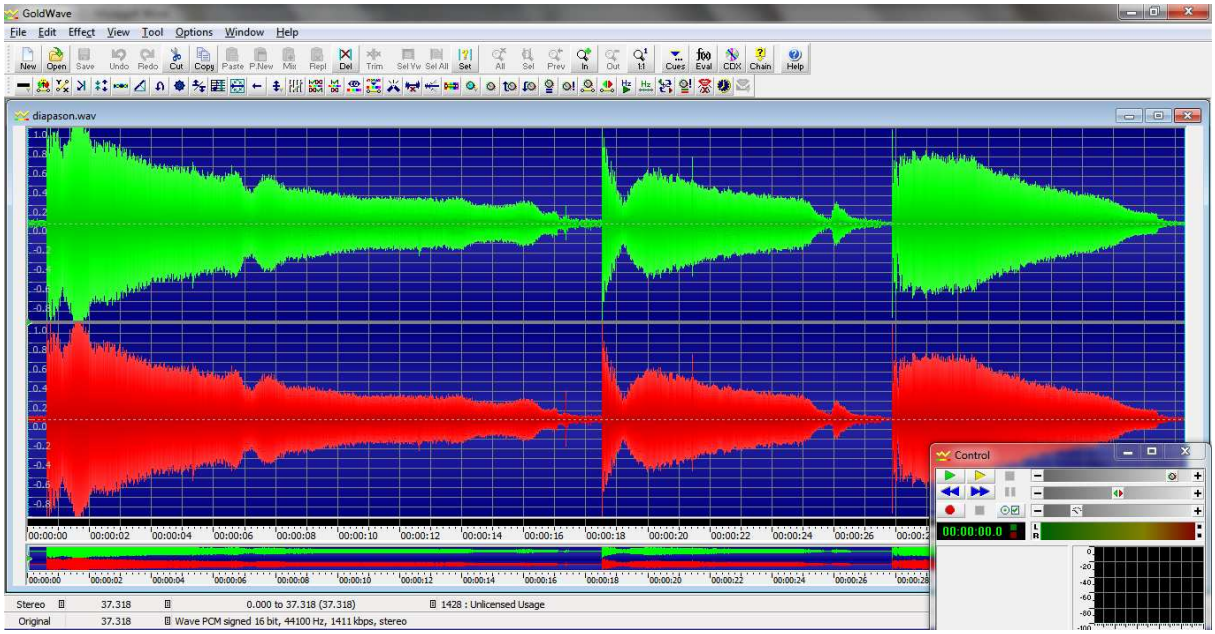

Figure 1. Waveforms produced by a tuning fork in three different configurations. First sound is from t =0 *s* to t = 17 *s*, second one from t = 17 *s* to t = 27 *s*, third one from 27 *s* to 37 *s*. Time between the three experiments was cut from the waveform

The students are first asked to describe the graph and focus on the different phases of a sound (attack, sustain, decay). The graph is useful to investigate the duration of each sound and its intensity. In particular, it graphically shows an exponential decay, due to the energy dissipation in air. However, the graph cannot provide information about why the three wave functions sound different. After a brief discussion to recall the physical quantities that describe a sound, they are guided to *split* the *I(t)* graph into two different ones: an *I(f)* graph (*spectrum*) and a *f(t)* graph (*spectrogram*) graph, where *f* is the frequency of sound. The students are asked to sketch the graphs starting from the *I(t)* graph and to discuss the qualitative relationships between these graphs and the *I(t)* one. Then, both graphs are displayed (Figures 2a, 2b and 3) and the students are hence asked to describe the main differences between the three graphs.

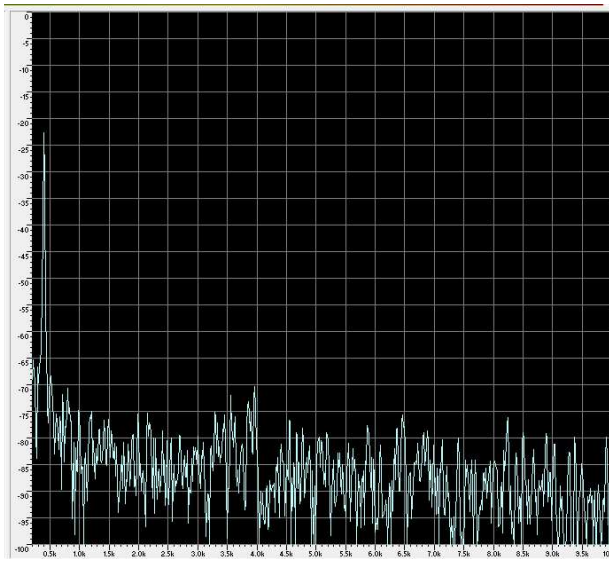

Figure 2a: screenshot of the spectrum of the waveform represented in Figure 1 at time *t* =1.3 *s*; *y-axis*: intensity in decibel; *x-axis:* frequency

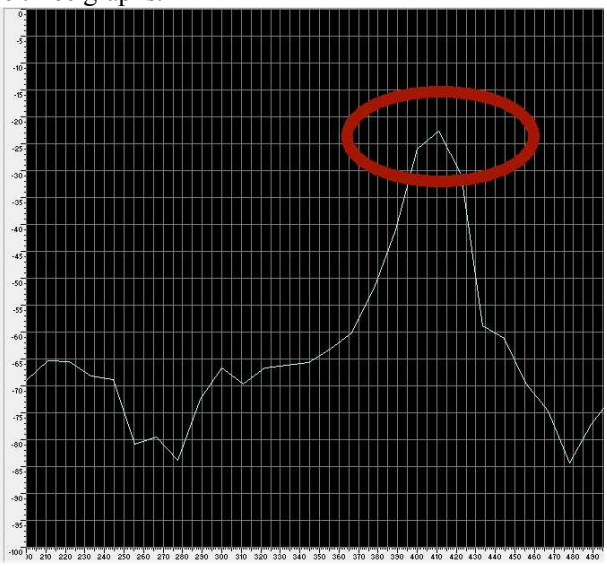

Figure 2b: zoomed portion of the spectrum in Figure 2a around the main frequency of the waveform in Figure 1 at time *t* =1.3 *s*. The maximum is -25 *db* at about 410 *Hz*

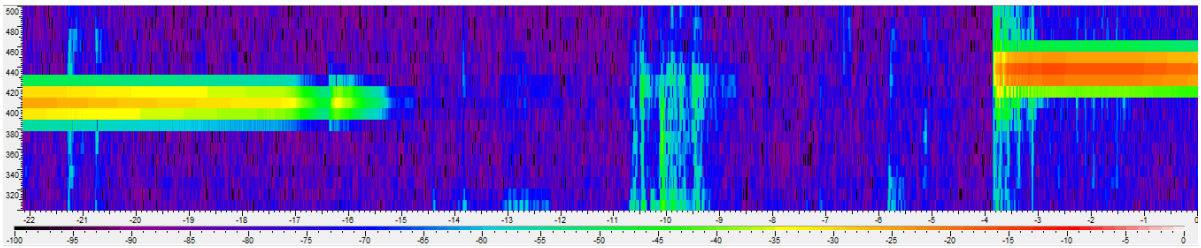

Figure 3. screenshot of the spectrogram of the waveform represented in Figure 1 at time *t* between *22s* and *28s*; *y-axis*: frequency; *x-axis:* time. Colour of the bars is related to sound intensity (colours, in increasing magnitude, are black, purple, blue, cyan, green, yellow, red, and white. A deep purple point, for example, has lower magnitude than a yellow point). Left-end bar represents the second sound, right-end bar the third sound.

Focusing on the *I(f)* graph, students are first guided to recognize that the *y-axis* shows a different scale for the intensity, namely a *decibel* scale[6], which is introduced as a useful tool to compare different sounds and establish reference values. Then, the nature of human ear is discussed to help students to understand that we can hear sounds only within a range of frequencies between 20 *Hz* and 20 *kHz*, and hence the *x-axis* is limited to this range. Finally, students are asked to focus on the peaks of the graphs and to estimate their positions on the *x-axis*. In such a way, they can recognize that, as they hear the sounds, the position of the peaks on the axis slightly changes, and hence, such position can be used to distinguish the three sounds. A similar discussion is made for the *f(t)* graph. Every student then estimates with the audio software functions the frequencies at which the *I(f)* graph presents the highest peaks (with a value greater than -70 *decibel*, which we adopted as noise threshold) and is asked to comment about the obtained results. In our case, each of the three sounds presents two frequencies for which the intensity is significantly higher than the other ones. During the rest of the activity, the first of the two frequencies is referred to as "the fundamental", while the second one is referred to as the "second harmonic" (if a third peak is distinguishable, then it will be the third harmonic, and so on)[7]. The students are guided to notice that the intensity of the second harmonic quickly decreases while the intensity of the fundamental remains more or less constant. Therefore, the students can focus only on the fundamental frequency.

The fact that the three sounds can essentially be described by only one frequency is used by the teacher to define the tuning fork as a physical system that approximately emits a "pure" sound, i.e., a sound with only one frequency.

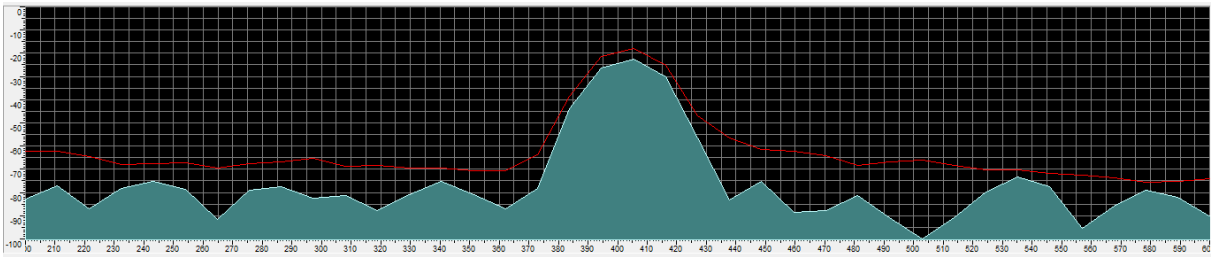

Figure 4. Zoomed screenshot of the spectrum of the first sound (from 0s to 17s) produced with the tuning fork. The frequency can be estimated as $f_1 \cong 410Hz$. Uncertainty is about 20 *Hz* (half total width at half height of the peak)

[6] The intensity of a sound in decibel is defined as $I_{db} = 20\log_{10}\left(\frac{I}{I_0}\right)$ were I_0 is the standard threshold of hearing

[7] A possible explanation for the creation of the second harmonic is that as the two tines of the fork move back and forth, the stem moves up and down twice. The amplitudes of the harmonics in the stem depend on the amplitude of vibration (Rossing, Russell and Brown 1992)

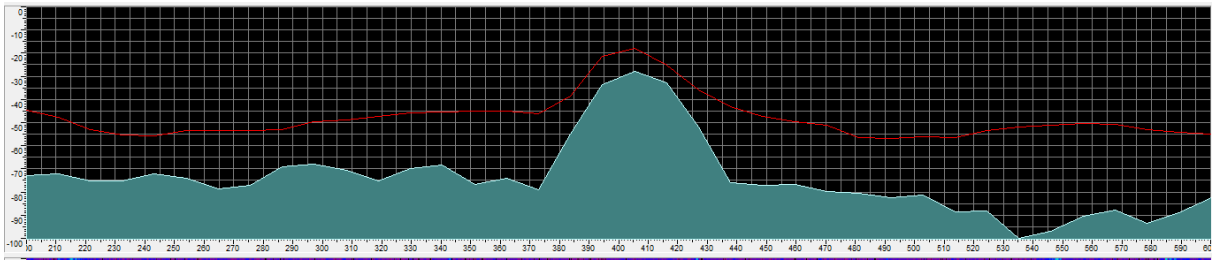

Figure 5. Zoomed screenshot of the spectrum of the second sound (from 17s to 27s) produced with the tuning fork. The frequency can be estimated as $f_1 \cong 405Hz$. Uncertainty is about *20Hz* (half total width at half height of the peak)

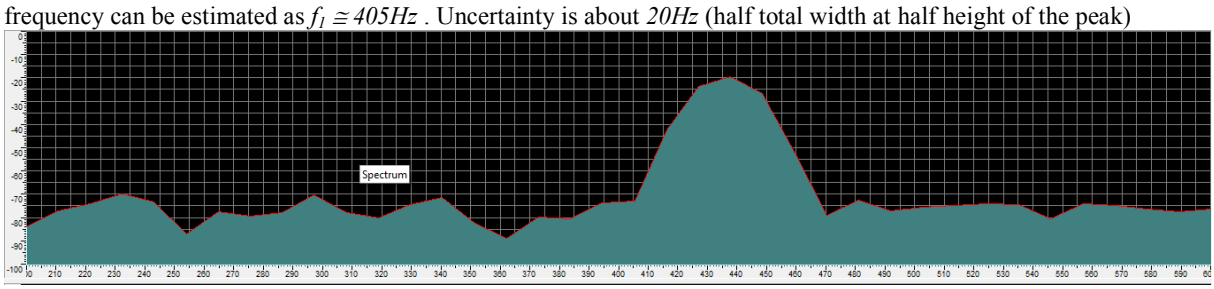

Figure 6. Zoomed screenshot of the spectrum of the third sound (from 17s to 27s) produced with the tuning fork. The frequency can be estimated as $f_1 \cong 440Hz$. Uncertainty is about *20Hz* (half total width at half height of the peak)

For our case, the first two sounds have very similar frequencies (respectively 410 and 405 *Hz*), the third one has a slightly higher frequency, 440 *Hz*. A similar measurement can be obtained from the spectrogram graph (Figure 3). The conclusion of the activity is that frequency content may be used to characterize sounds.

At the beginning of the third activity (1h), the students watch the video of the tuning fork and see how the three sounds were obtained. The video can be useful to introduce a discussion about *"how can we change the frequency of a sound?"*. To this concern, equation (14) is derived and the parameter L_{eff} introduced to take into account the fact that to move the small mass results in a change of the heard frequency. Students are guided to understand that L_{eff} is a parameter that takes into account the geometry of the fork (length and cross section of the tines). Using the model, since the third sound has a greater frequency than the previous two, it follows that the effective length decreases, which is in agreement with the fact that the small mass, which constrains the oscillation of the free end, is moved from the top to the bottom of the tuning fork. The activity ends with a paper-and-pencil task in which students, using equation (4), estimate the velocity of the sound wave in the tuning fork (without additional mass) from the length of the tines and the section of the fork.

Phase 2 – Sound of the Sun (3h)

In the first activity (1h), the students listen to the sound sample of the Sun acoustical wave, recorded through a Michelson Doppler Imager (MDI) mounted on the SOHO spacecraft[8]. The chosen sound sample corresponds to a one-mode oscillation. Students are then told that data related to the sound wave were collected from the Sun surface and digitally treated so to produce a sound file that could be listenable to human ear. The activity is guided by the general question *"How do stars work?"* and in particular by the specific questions*: "what are stars?", "how they are created"* and *"what is their shape and why?"*. The aim is to help students understand the basic reason for which stars can be thought of as spheres that contain a certain volume of gas, described by thermodynamics variables as volume, pressure, temperature. Then, the students are asked to justify why stars are stable. After a brief discussion, the students are guided to understand that the stability of a star is a consequence of four conditions: hydrostatic equilibrium, mass conservation, energy transfer and energy conservation. Conditions about energy lead to a relationship between the solar temperature and solar luminosity, while mass conservation and hydrostatic equilibrium lead to a relationship between the pressure and density. Drawing on these relationships, the students may

[8] The sound samples, which we have used in the student activities, can be found at http://solar-center.stanford.edu/singing/singing.html. The procedure used to generate the sounds is described at http://soi.stanford.edu/results/sounds.html

hence recognize that, as for air particles, pressure inside the stars varies due to internal processes and, consequently, acoustical waves can be generated. The activity ends by asking the students to hypothesize what causes pressure forces in the inner layers of the Sun.

At the beginning of the second activity (1h), the teacher recalls the conclusion of the previous activity and asks the students *"what are the pressure forces in the Sun?"* to discuss their hypotheses. To this aim, the students are guided to compare centripetal force on a small volume element of mass m at the surface of the Sun with the resultant of all forces acting on it (gravitational and pressure forces due only to thermodynamic process). If necessary, the students may recall the reasoning used in hydrostatics when calculating buoyancy of an object in a fluid. After a qualitative discussion, the students should be able to recognize that pressure forces cannot be only related to thermodynamic processes but also to radiation pressure. Finally, the students estimate the frequency of Sun sound oscillations from the spectrum and spectrogram graphs. Using the software facilities, the students may identify from the spectrum an envelope centred around *143 Hz* and with a *24 Hz* width (Figure 7). Hence, the estimation of the fundamental frequency is $(143 \pm 12)\,Hz$. By using a multiplying factor for the velocity of reproduction[9], one obtains for the Sun sound frequency $(3.4 \pm 0.3)\,mHz$ which is in good agreement with the expected value given by equation (5).

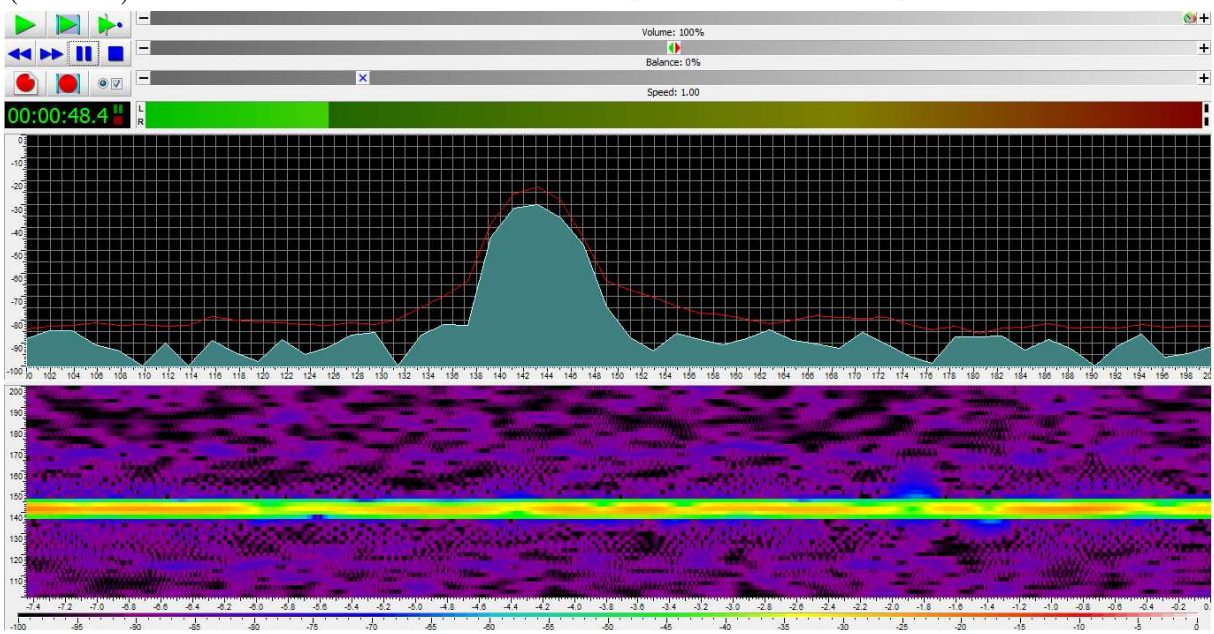

Figure 7. Zoomed screenshot centred around the fundamental frequency of the spectrum (above) and spectrogram (below) of the Sun sound http://soi.stanford.edu/results/one_mode_1_1_2_30s.au available at http://soi.stanford.edu/results/sounds.html. In the spectrogram graph, colour intensity of the bars is related to sound intensity (yellow means higher intensity, deep purple lower intensity).

In the third activity (1h), the students use the general equation (14) to answer the question *"on what does the frequency of the Sun sound depend?"*. The teacher first recalls that the sound wave is generated in the inner shells of the Sun (or the star) and propagates towards the photosphere and it is indirectly measured via luminosity changes or Doppler shifts. Then, using stability conditions, and building on the analogy with the fork, the students are guided to understand that the effective length for the sound waves in the Sun must be related to both geometrical factors and physical processes that happen within the star. Pressure height H_p parameter and equation (18) are first discussed: in particular, the students are guided to understand that the radius of the Sun is the parameter that takes into account geometrical factors, while its temperature and mass

[9] The factor was used to make the Sun sounds listenable to human hear. As reported at http://soi.stanford.edu/results/sounds.html this factor is about 42000

are used to take into account processes that happen within the star. Hence, equation (19) is briefly discussed and similarities/differences with the tuning forks are deepened.

Several paper-and-pencil tasks can be proposed at this point: - to estimate the velocity of the sound wave in the Sun using (15) and to compare it with that obtained for the tuning fork; - to calculate the mass (or the radius or the temperature) of the Sun using (19). As an extension, using again equation (15), the students can estimate the physical properties of other stars for which the frequency of the sound oscillations is known in order to compare the physical parameters of different types of stars.

The activities end by recalling that spectrum analysis was used to gain information about the system that generated the perturbation, information otherwise difficult to obtain, and that such indirect measurement technique is frequently used in several research fields in physics as astrophysics, nuclear physics, optics.

5. Implications and conclusions

Research in physics education has shown that lecture-based instruction is not sufficient to help students to grasp an adequate conceptual understanding of mechanical waves and sound propagation (Wittmann 2002). In this paper, we have presented an innovative module that aims at addressing common students' misconceptions in this area of physics blending a traditional context as the sound produced by a tuning fork with an unusual one as the sound produced by the Sun. The proposed module can be integrated by laboratory activities about sound generation and propagation in materials (Hernández, Couso and Pintó 2011) or ICT-based measurements of sound velocity (Parolin and Pezzi 2015). The activities can also support students' learning about advanced mathematical topics as Fourier analysis.

More importantly, the module here presented introduces as teaching tool a digital audio editor, which helps students deepen the relationships between the waveform of sound and its frequency content using spectrum and spectrogram graphs. The first aim of using such graphs is to address students' alternative conceptions about the frequency of mechanical waves (e.g., the frequency changes as the wave travels in a medium) using a multi-representation of the same phenomenon, which is an important step toward the construction and validation of personal mental models to represent real phenomena. The use of the three graphs (waveform, spectrum and spectrogram) may also help students understand the meaning of the typical sinusoidal shape of sound waves in the time domain and how such mathematical relationships is represented in the frequency domain (see Figure 8).

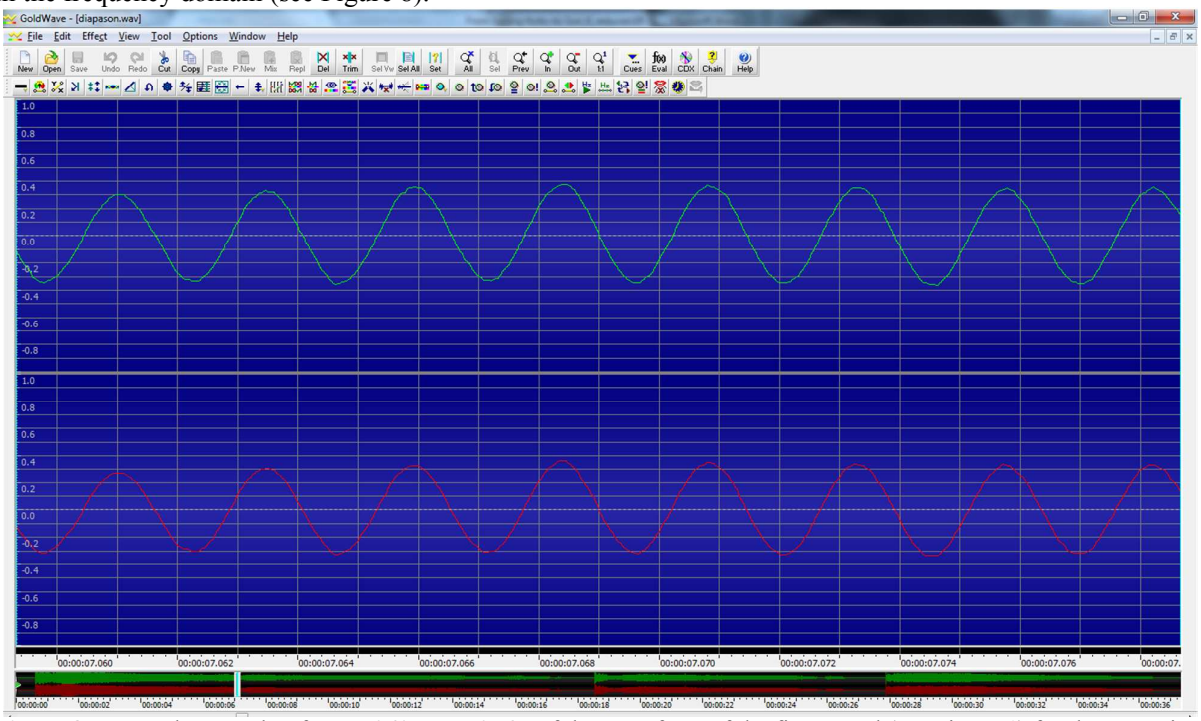

Figure 8. Zoomed screenshot from 7.060 *s* to 7.076 *s* of the waveform of the first sound (see Figure 1) for the extension activity. Note that the measured period is 2.43 $*10^{-3}$ *s*, which corresponds to a frequency of about 411 *Hz*

As an extension activity, students may measure the period from the waveform graph and compare it with the value of frequency estimated from the spectrum graph. With such comparison, it is possible to strengthen the link between the two representations and to understand that the frequency of a sound depends solely on the source that produced it.

Finally, with the spectrum and spectrogram graphs we aimed also at familiarize students with indirect measurement methods, as spectral analysis, which are widely used in many physics research fields. In particular, students may understand that in the case of spectral analysis, they can infer about the properties of materials that produce sounds. For instance, the relationship between the speed of a sound wave and the density of the material in which it is propagating, often misunderstood by students (e.g., the denser the medium, the faster sound propagates) can be more clearly explained. The spectral analysis, carried out with the digital audio editor, can facilitate the measurement of a physical variable (in this case, the frequency of the sound) that models the behavior of very different phenomena as the mechanical oscillations in a bar and the functioning of a star like the Sun.

Used in combination with traditional experiments with tuning forks, spectral analysis provides students also with a quick interpretation of the collected data, thus strengthening the link between experiments and the process of modeling and formalization.

As next step, we are now designing an assessment tool based on those already validated in literature to investigate the effectiveness of the module's activities. As further step, we plan to improve the part of the module devoted to astrophysics, first deepening the discussion about the models of star stability (equilibrium between hydrostatics and radiation pressure) and including analysis of spectra to infer more general properties about the physics of the stars.

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