Spectral Sounds

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1 | Summary

Young pupils are often fascinated by music, not only because they listen to music on dozens of devices, but also because a number of them play musical instruments at different levels. For this reason music is a good way to explore wave phenomena and behaviour. And since waves are found in different areas of physics and science, music can be used to investigate a concept that is widespread in science. This activity is focused on studying what is called the spectrum of a sound, and in particular the entire range of frequencies produced by an instrument. It is this range which characterises any musical instrument.

- **Keywords:** sound, frequency, power, pressure, amplitude, note, pitch, timbre, graphs, logarithms
- **Disciplines involved:** physics, music, mathematics
- **Age level of students:** 16-18 years
- **Android apps:** Sound Spectrum Analyzer; n-Track Tuner
- **iOS apps:** iAnalyzer Lite
- **Further computer software:** freeware sound card oscilloscope SW, Scope 1.41

2 | Conceptual introduction

2 | 1 The science involved

Sound is a great way to study waves. Waves are common to different themes in science: sound, light, radio transmission and electromagnetic fields, plus any periodic phenomena—events repeating themselves at regular time intervals. Waves provide a good mathematical model for studying the behaviour of periodic dependencies. Laptops, tablets and smartphones are able to convert sound into a digital form, which means numbers, with the onboard microphone and an analogue-to-digital converter. And with the numbers on electronic devices, graphs can be plotted to show the waveforms and characteristics of the sound. Many oscilloscope apps based on smartphones' onboard microphones can be found for any operating system. Most of them offer the features that are necessary for a good study of waves. This is the reason why sound and smartphones offer quick access to an effective class activity focusing on waves. Many interesting characteristics of waves can be visualised using an oscilloscope app. As we conduct this activity, we will be studying and visualising waves in a time domain and, above all, in a frequency domain. Showing waves in a time domain means that we will basically see the sinusoidal graph of a wave, detecting its period, frequency and wavelength. Studying waves in a frequency domain is what in scientific language is known as studying the spectrum of a wave. This is what we will be most concerned with in this unit.

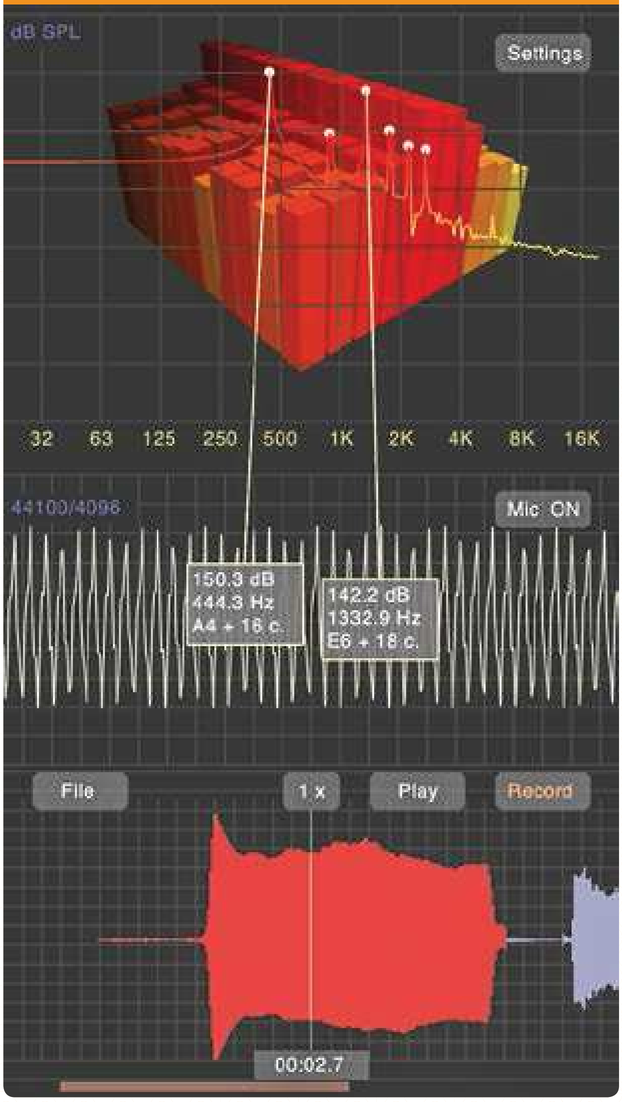
2 | 2 Relation to the curriculum

We assembled and conducted this project in Italy and France. Waves, as a general way of studying acoustics and optics, are studied in Italy in upper secondary schools with pupils aged 17-18. In France, acoustic music is taught in disciplines chosen by the students during the last year before the Baccalauréat (exams in secondary school in France). The concepts of intensity, pitch and timbre of a sound are studied by all students during the physics course in a topic called "Properties of waves" during the same year.

3 | What the students do

- The students download an app. They can choose amongst the apps mentioned above or find another one if they prefer.
- A set of instruments to be sampled is established. The students should preferably make the spectrum measurements on a set of instruments that includes string, woodwind, brass and percussion instruments. This is because the spectra they will get are slightly different, and different families of instruments produce different harmonic series.

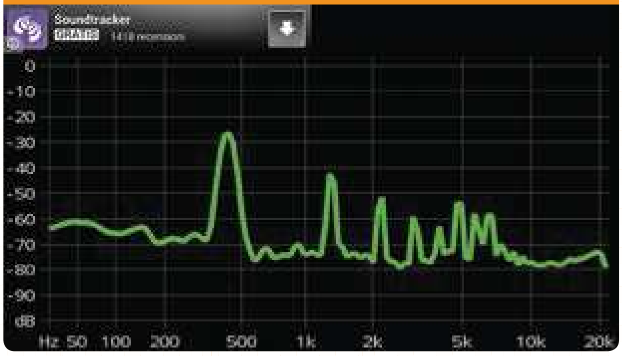
FIG.1 Screenshot: iAnalyzer Lite



One nice idea is also to register and analyse the spectra of a tuning fork, a tone produced by an electronic source and the human voice, for comparison with the instruments.

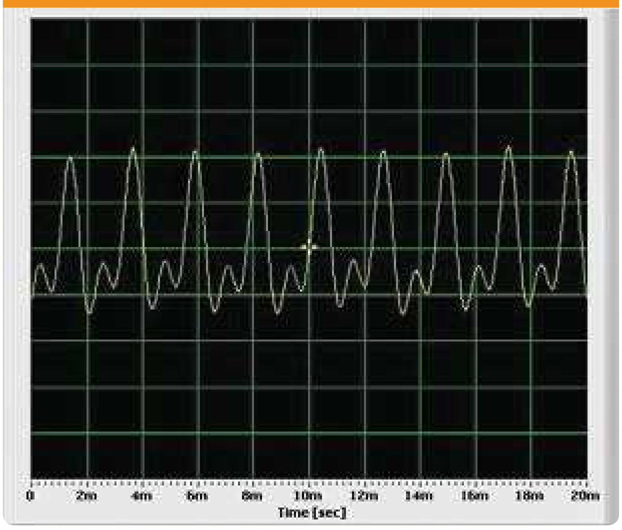
- A set of sampled frequencies must be chosen. These frequencies will be played by all the instruments. For instance, we agreed on C4, F4, G4 and A4, played by a violin, a guitar, a clarinet, an electronic keyboard (it can produce hundreds of sounds and timbres), an electric guitar and an oboe.
- The students can now start the recording phase. The pupil acting as the "musician" starts to play a note, and another pupil starts the app acquisition, putting the smartphone about one metre from the source of the music. After a few seconds, he or she stops the recording and saves the file or takes a screenshot.

FIG.2 Screenshot: Sound Spectrum Analyzer



- The students should be sure to save every recorded spectrum in a file with a meaningful name that will allow them to recognise the note and the instrument later.
- Since the students are likely to use different apps and smartphones, it could be useful to have a common reference for every spectrum, independent of the smartphone microphone's sensitivity and the app's time resolution. We used the freeware sound card oscilloscope SW, Scope 1.41. Amongst its features, it has a good spectrum analysis window that is fantastic for educational purposes.

FIG.3 Harmonics of a flute



- After recording the spectra for every note and every single instrument, the students analyse the graphs they have obtained, comparing each frequency spectrum obtained from every instrument. A table similar to **FIG. 4** can help them analyse differences and analogies.
- Before ending the recording session, the students can also record the spectrum of a tuning fork, the notes produced electronically (a wealth of software to produce tones is available for PCs or smartphones), and the voice

FIG.4 **A table can help to analyse differences and analogies. Write down your observations**

Instrument	Note			
	C4	F4	G4	A4/440
Guitar (Acoustic)				
Guitar (Electric)				
Violin				
Clarinet				

of the best singer amongst the students, all singing the same notes.

- Now they are ready to examine the spectra produced by the orchestra. It is very interesting to examine the graphs of the strings (guitar, violin), the woodwinds (clarinet, flute), the brass instruments (trumpet, horn), and the percussion instruments, and to try to spot the analogies and the differences.

At first glance, for every recorded instrument you will notice a number of prominent peaks in its spectrum. These are the amplitudes (y-axis) of the frequencies (x-axis) that make up the harmonic series of the played note. The lower frequency is usually the fundamental note, the one that was actually played. You will also observe that a tuning fork produces a perfect line in the graphs, while the human voice, no matter how clear it is, produces a more complex line. This line is the result of the sum of all of the frequencies produced by the student's voice.

We would suggest that at this point you introduce some good inquiry-based learning (IBL) activity with the students in order to guide them toward spectrum analysis. This would be based on a form including questions such as the following:

- Describe what you see in the picture.
- Why do you think that some frequencies are more prominent than the others?
- Can you infer a dependency or a relationship amongst the prominent frequencies?
- Can you explain the dependence?

Further activities could include:

1. Inspect the mathematical construction of the tempered scale and deduce the pitch of the sound of an instrument.
   - The students could propose a protocol to verify the relationship between the different notes of the 4th tempered scale. They can find the proper formula in several documents.
   - They are then asked to find a linear relationship expressing the height of one of four notes of the scale and the number n of this note in the range. For this, a table giving the number of the note can be provided.
   - Then, after downloading the mobile application, they record different sounds provided by a pitch pipe. They can deduce the pitch from the spectrum they obtain.
   - Finally, they draw a graph on a spreadsheet showing the relationship between log (fn) and the number n of the notes in the tempered scale. They must obtain an affine function whose leading coefficient is log(a). They can then return the value and compare it with the theoretical value.

2. Discover that the pitch of the sound of a pan pipe is inversely proportional to the length of the tubing.
   - The students find the theoretical relation between the pitch of the sound emitted and the length of the pan pipe.
   - Then they propose a protocol to verify this relation using the pan pipes, the spectrum analyser of their smartphone and a spreadsheet to plot a graph. Finally they implement their protocol.

3. Highlight the fact that the pitch of a note on a xylophone is proportional to the length of the respective bar.
   - The students suggest an experimental protocol that can verify the influence of the small bar's length on the sound's frequency. This protocol must include the plan of a graph with a modelling.
   - Then the students have to implement their protocol.

4 | Cooperation option

Students from different schools can work together to analyse the spectra of different instruments. They can also analyse the same instruments and compare their results. Another idea is that the different schools could focus on different kinds of instruments, i.e. one school could analyse woodwinds, while another could analyse brass instruments, and then a spectral comparison can be performed, underlining differences and analogies.

If a musical instrument workshop is located in your area, you might want to measure the spectra of the instruments directly where they are assembled. For example, in Italy there is a centre of violin production in and around Cremona, thanks to the Stradivari tradition. Samples of spectra can be acquired at different stages of instrument assembly, so that the students can understand how the components influence the spectrum and the harmonics produced.

5 | Conclusion

Students can learn to understand the complex world of periodic events and wave phenomena by exploring the easiest and most visible part of it: acoustics. In particular, the activity shows them how a sound is composed of several frequencies, and how different frequencies can be assembled to produce a sound. They acquire the know-how that is required to analyse a sound spectrum, recognise the harmonics of a note, and understand how the amplitude depends on the frequency. They then will be able to analyse a light spectrum and an electromagnetic spectrum. This activity is also meant to motivate young students to study the production of sound in different instruments—the different harmonic formation in wind, string and brass instruments, and the waves and resonance in strings compared to pipes.

Personal experience

If you start examining a wave in the time domain together with students, you will show them a plain sinusoidal wave. In the frequency domain they may meet with some difficulties, because they see only lines. You might want the students to be able to understand logarithms: the amplitude (pressure or energy) is always measured on the Y-axis in decibels, so they should know how to read the decibel scale. Students have to practice the use of apps in order to be able to spot harmonics and understand them as multiples of the fundamental frequency. Usually a background noise is recorded together with the notes unless you are in a very professional musical studio, so the students have got to recognise the background level and be able to get rid of it. Moreover, the premium apps usually offer the ability to save a spectrum as a file, but in a free app version the pupils have to take a screenshot of the graph, and this could lead to some logistical difficulties.

Since not all the apps shown in the list offer the option of saving the spectrum as a file, at least in the free versions, the pupil playing the instrument needs help from another pupil in order to take a screenshot of the recorded data. The graphs obtained are usually examined as pictures.

The spectrum of the oscilloscope running on a PC is always useful as a common reference for all the apps.

You might also want to explain to the students what the harmonics, pitch, loudness and timbre of a note are.

If you use an amplifier (i.e. for a guitar or an electronic keyboard), you have to consider that it can act as a filter, taking away some of the harmonics, volume or bass elements.

Please note that your spectrum might contain some unwanted noise. In particular, if some important electric activity is going on close to the location where you are carrying out this activity, you might notice that a 50Hz frequency is present in your spectrum. This is the (European) main electricity frequency, which might also cause some acoustic interference.

We started this project after introducing the topics of waves and sound. It received a good response from students who were able to play musical instruments.

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