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Amplitude, frequency, and timbre with the French horn

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Abstract

The French horn is used to introduce the three basic properties of periodic waves: amplitude, frequency, and waveform. These features relate to the perceptual characteristics of loudness, pitch, and timbre encountered in everyday language. Visualizations are provided in the form of oscilloscope screenshots, spectrograms, and Fourier spectra to illustrate the physics. Introductory students will find the musical relevance interesting as they experience a real-world application of physics. Demonstrations playing the French horn are provided in an accompanying video (Ruiz 2018 *Video: Amplitude, frequency, and timbre with the French horn* http://mjtruiz.com/ped/horn/).

Background

Students in introductory physics courses learn about amplitude, frequency, and harmonics of periodic waves on strings and pipes [1, 2]. On an oscilloscope, the amplitude is the maximum vertical measure, typically defined in physics texts as the height of the wave measured from equilibrium. The horizontal measure of one cycle is the period since the horizontal axis is the time axis. The frequency is the reciprocal of the period.

The timbre of a periodic wave is due to the various amounts of harmonics superimposed to form the shape of the repeating waveform pattern. Harmonics arise naturally as modes of vibration on strings and pipes. The timbre allows one to perceive the difference between a flute and violin when each instrument plays at the same loudness and pitch. Neglecting the fact that some frequencies sound louder than others [3], amplitude, frequency, and waveform are respectively correlated with loudness, pitch, and timbre [4].

The French horn

The French horn, often just called 'the horn', is a member of the brass family of wind instruments. It is made out of long, coiled up brass tubing that 'flares out' into a bell at the end. Therefore, the entire instrument ultimately has a quasi-conical shape to it. In contrast to a closed cylindrical pipe, which only has odd harmonics, a conical structure closed at one end produces both even and odd harmonics [5, 6].

The most commonly used variety of the horn, the double horn, is essentially two instruments in one, which can be easily switched using a trigger. One 'side' of the double horn is in the key of F, while the other is in the key of B-flat. The total tubing of the horn while playing on the B-flat side is shorter than when the performer is using the F side. The B-flat (B^b) side is pitched a perfect fourth above the F side, which corresponds to a frequency ratio of B^b:F = 4:3. An interval of a fourth spans five semitones.

As will be discussed, the player produces pitches by pressing rotors (valves) and exciting the resonance tube into higher modes in the harmonic series with lip technique. Higher adjacent pitches in the harmonic series are closer in frequency to one another, which makes it more difficult for the horn player to excite the intended resonance pitch. However, with the two sides of the horn, the performer can switch to the shorter B-flat side to more easily reach higher pitches. Since the B-flat side is pitched a perfect fourth above the F side, all of the frequencies in the harmonic series are shifted upward by a fourth. Therefore, if the performer wants to play a high note, the pitch will be lower in the harmonic series of the B-flat side compared to the F side.

To play the horn, a conical mouthpiece is attached to the front end of the tubing. The front end of the tubing is called the leadpipe. The player then blows air into the horn while 'buzzing' (vibrating) the lips against the mouthpiece so that the tube acts as a resonator. With a high level of approximation, the horn can therefore be treated as an air column with one end closed, producing different harmonics depending on the total length of the tubing. There are also rotors (valves) attached to the horn that can extend the tubing by different amounts so that the horn can access the full musical chromatic series of semitones. In this paper however, we will deal with the harmonic series produced by B-flat horn with no rotors pressed in order to simplify matters. This simplification is especially important because we desire to measure the harmonic frequencies produced by the natural resonances in the pipe. These frequencies satisfy the formula

$$f_n = nf_1 , \tag{1}$$

where f_1 is the frequency of the first mode of vibration (called the fundamental) and $n = 1, 2, 3, ...$. The horn player in practice will tweak things when necessary to make these frequencies better match the frequencies of equal-tempered tuning, i.e. concert pitches.

Dynamics and air

The volume of the sound produced by the horn player, also known as the 'dynamics', is primarily dependent on the amount of air flow into the horn. The lower the air flow, the softer the tone. Conversely, to achieve louder notes, more air is required. This feature holds true for both a prolonged note and short (staccato) note. While the former is played by a sustained flow of air and 'buzzing' of the player's lips (the 'embouchure'), the latter is created by a quick burst of air (assisted by the player's diaphragm) and a fast buzz of the lips. The higher the pitch, the more difficult it is to sustain the note due to higher frequencies requiring more pressure of the lip muscles on the mouthpiece. Similarly, the higher notes are more difficult to play softly.

See figure 1 for an oscilloscope screenshot of a soft tone (left) next to one for a loud tone (right). The amplitude (measure from equilibrium to maximum) is less than 0.2 for the soft tone and about 1.0 for the loud tone. Units for a real oscilloscope are in volts. See LoPresto [7] for similar waveforms of the trombone and trumpet, relatives of the French horn in the brass family.

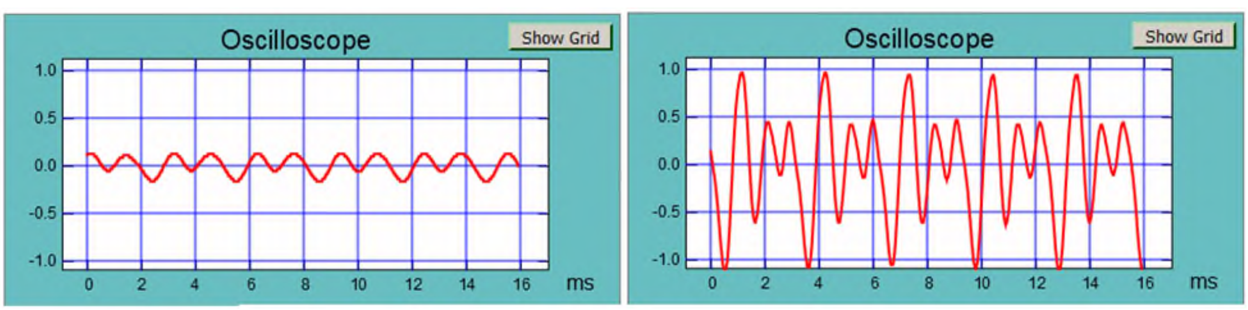

Figure 1. Oscilloscope view of a soft tone (left) and one for a loud tone (right).

Frequency and pitch

Manipulating the pitch of the horn is primarily dependent on two things: the player's embouchure and the rotors (valves) which can be pressed down. The player tightens the lips to increase the frequency of the vibration in order to raise the pitch of the horn, rising to the next tone in the relevant harmonic series. The opposite is done to lower the pitch. To achieve frequencies along the entire musical chromatic scale, not just a harmonic series, the player can press down any or all of the three rotor keys. Manipulating the rotors opens up or closes off small lengths of piping to slightly increase or decrease the full effective length of the horn. See figure 2 for coauthor Konz illustrating the use of the rotors where he is pressing on two of the three rotors and his forefinger is held above one rotor to avoid pressing it. A short sequence of rising semitones using the rotors is demonstrated in our video [8].

Figure 2. Coauthor Nick Konz pressing on two of the three rotors (valves). Pressing a rotor increases the length of the resonating tube.

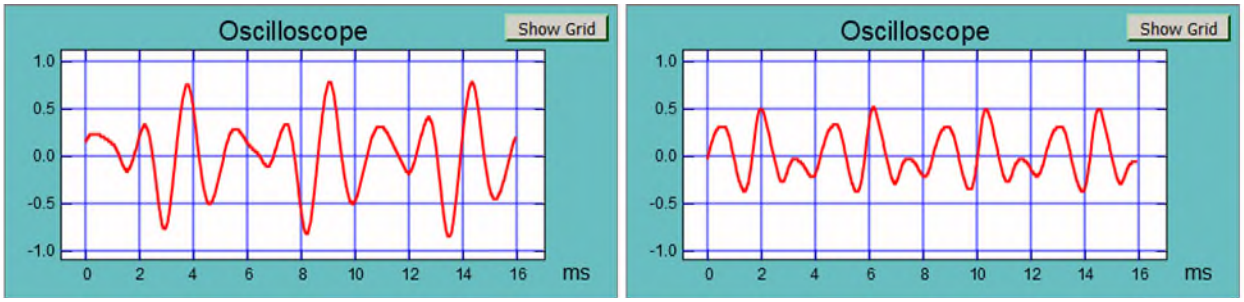

Figure 3. A lower pitch on the left (longer "wavelength" period) and a higher pitch on the right.

See figure 3 for a lower pitch (left) and higher pitch (right) on the oscilloscope. As mentioned earlier, the visual 'wavelength' is actually the period since the horizontal axis is the time axis. Students can be asked to give a measure of the time for one picture pattern. For the left wave, the first tallest peak is near 4 ms and the next similar peak is near 9 ms. Therefore, an estimate of the period is $T = 9 - 4 = 5\text{ ms}$. The corresponding estimate of the frequency is

$$f = \frac{1}{T} = \frac{1}{5\text{ ms}} = \frac{1000}{5\text{ s}} = 200\text{ Hz}. \qquad (2)$$

The harmonic series

A harmonic series can be produced on either the B-flat or the F side of the horn, with any configuration of valves pressed. To simplify things, we will only consider each harmonic series with no valves pressed. The F side, the lower side of the horn, has a lower pitched harmonic series, with the pitch of the fundamental frequency being a 'pedal' $F_1 = 43.7\text{ Hz}$ in concert pitch (i.e. the first F on the piano). The letters on the piano start with the first three white keys $A_0 = 27.5\text{ Hz}$, B_0, C_1, proceeding to G_1 and then repeating. A black key to the right of a white is designated with the white key name and the sharp symbol # such as $C_4^\#$ (for the black key to the right of C_4). A black key to the left of a white key is labeled with the flat symbol b such as

D_4^b, which is the same note as $C_4^{\#}$. The concert reference pitch of 440 Hz is A_4. In this paper, we avoid the complication that the French horn is usually written a fifth higher (seven semitones higher) in orchestral scores. All notes in this paper are referenced to the piano.

The $F_1 = 43.7 \text{ Hz}$ fundamental is extremely difficult to play. The B-flat side in turn has a higher fundamental pitch of B-flat, concert $B_1^b = 58.3 \text{ Hz}$. If your students are interested in calculating this frequency, start with $A_4 = 440 \text{ Hz}$ and divide by 2 three times to reach the note three octaves below at $A_1 = \frac{440}{2 \cdot 2 \cdot 2} = \frac{440}{8} = 55 \text{ Hz}$. Then multiply your result by the twelfth root of 2 to rise by a semitone to $A_1^{\#} = B_1^b = 58.3 \text{ Hz}$. The twelfth root of 2 ensures that rising 12 semitones, an octave higher, doubles the frequency.

The $F_1 = 43.7 \text{ Hz}$ and $B_1^b = 58.3 \text{ Hz}$ fundamentals are hard to play since it is difficult to manipulate and maintain the embouchure at these very low pitches. The embouchure required for these low pitches must be both relaxed and precise in order for the player's lips to buzz at the needed lower, 'slower' frequencies. The lower the desired note, the harder it is to synergize the embouchure and horn properly to achieve the desired low harmonic. The horn player usually plays in the vicinity of the third harmonics or higher. In the video, the first 12 pitches of the harmonic series for the B-flat side of the horn (no rotors held down) are played. These tones span from concert $B_1^b = 58.3 \text{ Hz}$ to $F_5 = 698 \text{ Hz}$, but note that the harmonic frequencies are not always a close match to concert pitches [9]. Concert pitches are based on the rule using the twelfth root of 2 described earlier, while harmonics are related by the integers of equation (1).

The frequencies measured with Audacity [10] are plotted in figure 4. The two red harmonics indicate that these harmonics do not fall close to their nearest concert pitches, but they fall extremely well on the straight line predicted by the physics of equation (1) for a conical pipe closed on one end [5, 6]. The experimental value is $B_1^b = 58\ \mathrm{Hz}$ from the slope of the excellent linear fit in figure 4. This experimental result is in agreement with the concert pitch $B_1^b = 58.3\ \mathrm{Hz}$ to two significant figures. Figure 5 is a spectrogram plot of the harmonics as they are played. The spectrogram shows the individual sine waves that are present in each harmonic. Fourier's theorem states that any periodic tone can be represented by its spectrum of harmonics (also called partials) where the fundamental pitch coincides with the pitch of the tone played. Note how the spacing of the partials increases with the rising pitches.

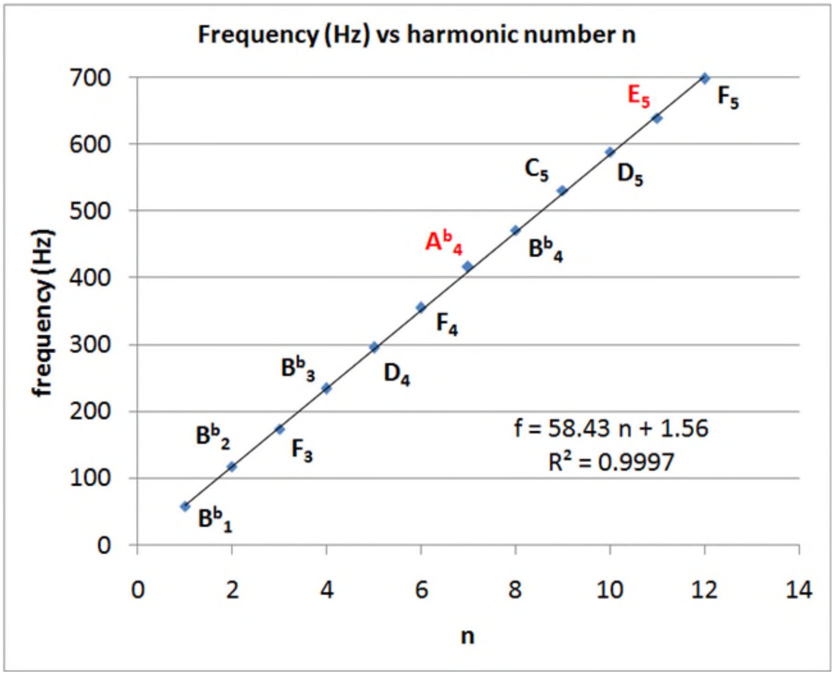

Figure 4. Measured frequencies of the French horn harmonic series starting on $B_1^b = 58.3\ \mathrm{Hz}$. The red indicates that the harmonic is slightly out of tune when compared to its corresponding concert pitch. The experimental value is $B_1^b = 58\ \mathrm{Hz}$ from the slope of the linear fit.

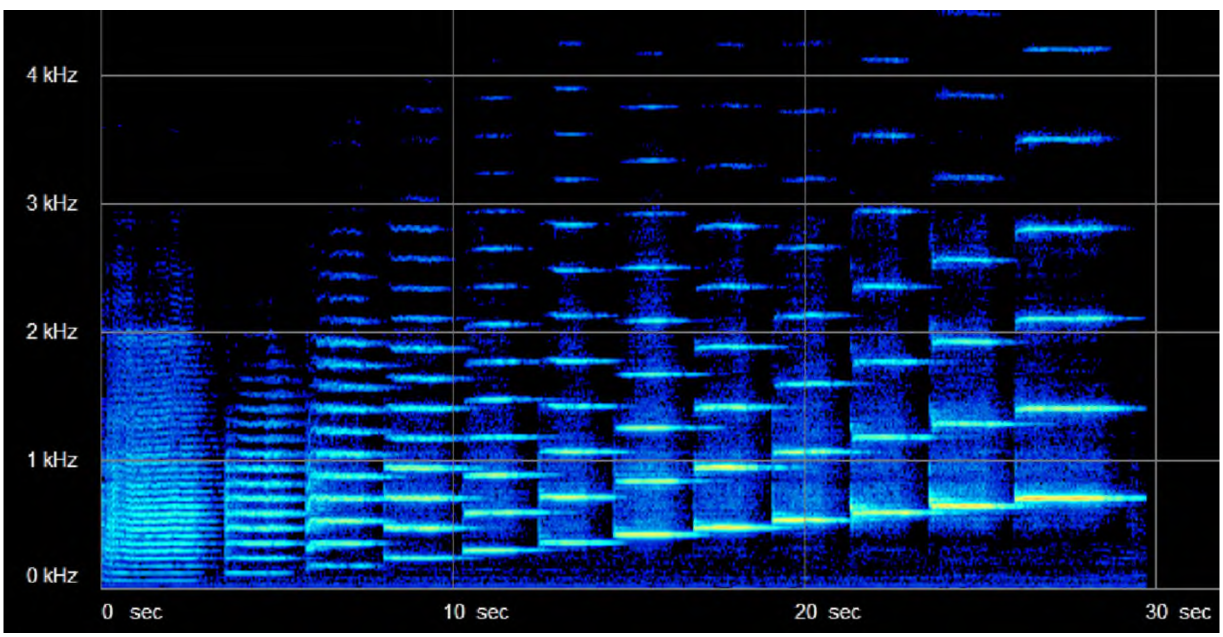

Figure 5. Spectrogram of the first 12 tones of the French horn harmonics beginning on $B_1^b = 58.3\ \mathrm{Hz}$. The PC desktop app is *Spectrogram 16* by Richard S. Horne.

Timbre

The timbre can be affected by placing the hand or a device referred to as a mute into the bell opening. See figure 6 for a photo of a mute inserted into the bell and the right hand partially inside the conical bell section. Inserting the hand into the open end of the horn also adjusts the pitch to some degree. For normal playing, the right hand is slightly cupped and inserted into the bell to only barely affect the pitch. But if desired, the hand can be inserted further into the bell until the palm covers the majority of the opening, lowering the pitch by as much as a half step. This technique is called playing 'stopped horn' and it also dramatically alters the timbre of the tone.

Figure 6. A mute inserted into the bell (left image) and the right hand partially inside the bell.

The timbre can be dramatically adjusted using a mute, a cone-shaped device usually constructed of wood and cork. The mute is inserted directly into the horn's bell to cover the entire airway, which does not affect the pitch like stopping the horn does, but makes the horn sound much more muffled. Figure 7 shows both the spectrogram and oscilloscope waveform for regular playing (left, 0-2 s) and when the hand is inserted far into the bell (right, 2-4 s).

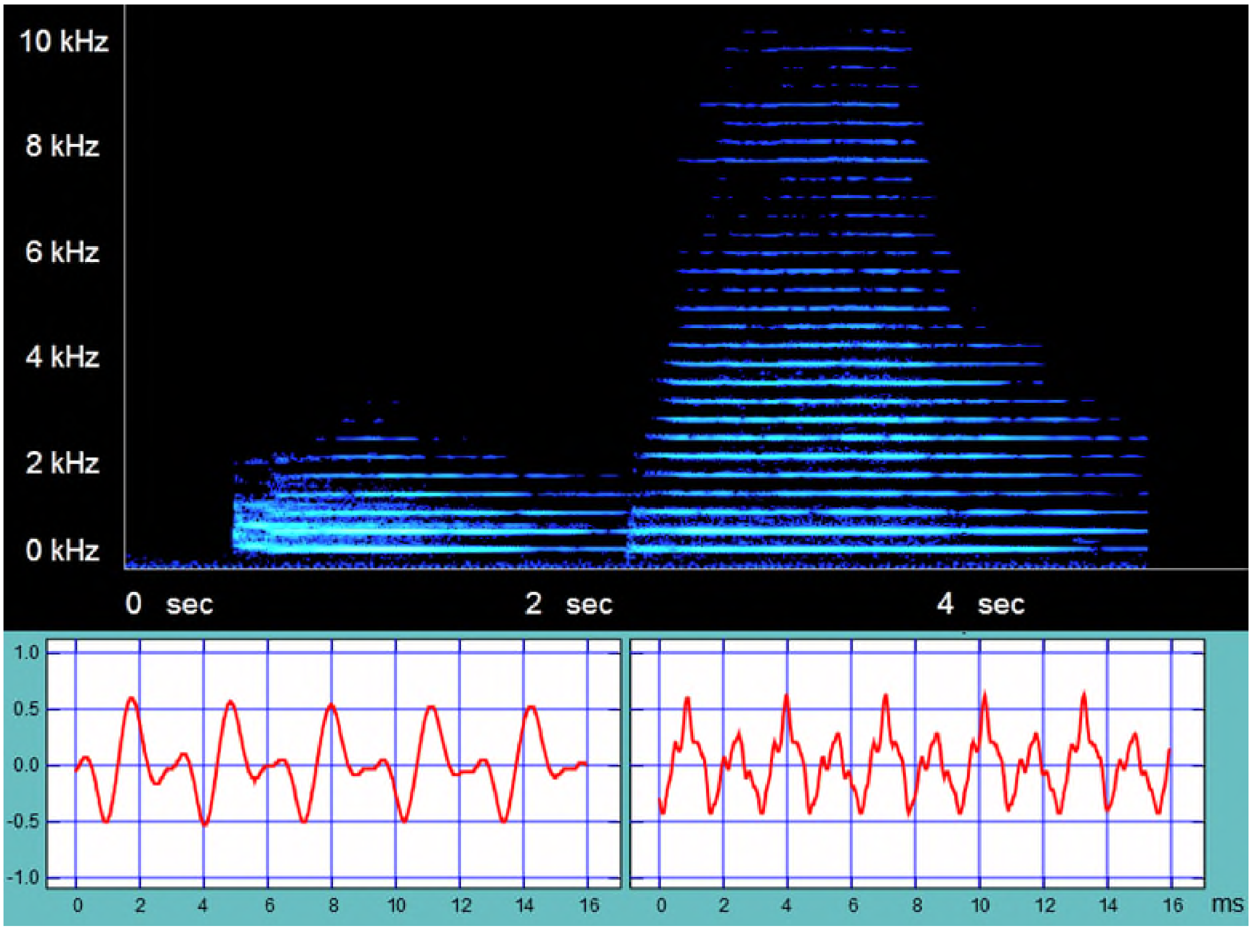

Figure 7. Spectrogram and oscilloscope waveform for normal playing (left) and playing with the right hand deeply inserted into the bell (right). Note the drastic change in timbre (waveform) appearing on the oscilloscope and the addition of many partials for the richer wave on the right.

Figure 8 is a plot of the strength of each partial against harmonic for the two timbres in figure 7, using the software Audacity. The richness of the tone with the inserted hand is prominent in both figures 7 and 8. There are many additional higher partials that appear when the hand is inserted into the bell. Note the higher frequency ripples modifying the basic waveform in the oscilloscope display of figure 7 for the tone with strong higher partials.

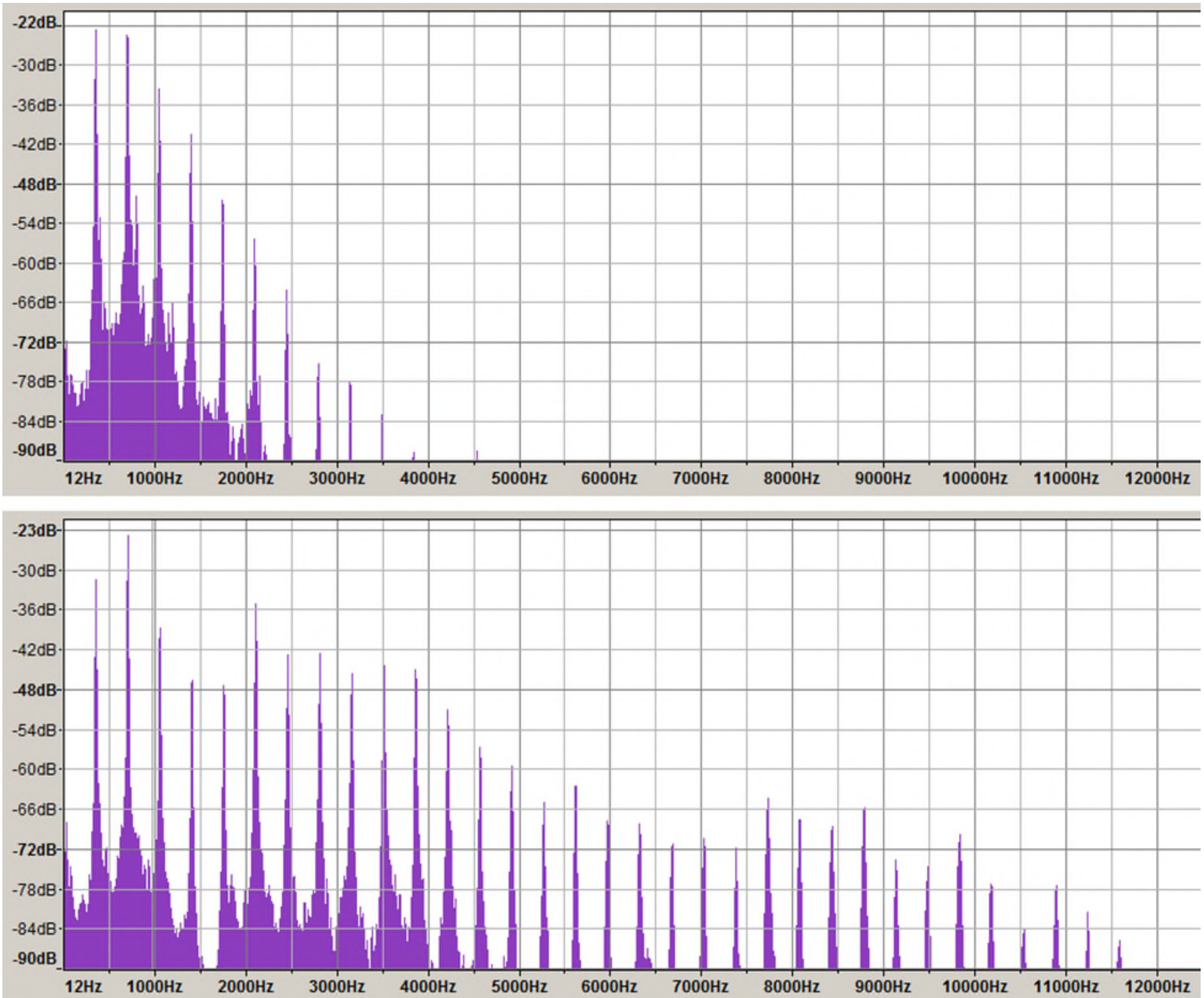

Figure 8. Strengths of partials against their harmonic frequencies for the normal tone of the French horn (top) and the sound produced when the right hand is inserted significantly into the bell.

Conclusion

This interdisciplinary paper illustrates how principles of physics are realized in the real world of music, using the French horn. The discussion includes examples of the three basic properties of periodic waves: amplitude, frequency, and waveform. These three characteristics correlate with corresponding perceptual terms used in everyday language: loudness, pitch, and timbre [4].

Introductory students will be familiar with these descriptions of musical tones, which will enable them to more easily master the physics. The paper includes three main ways to visualize wave properties: the oscilloscope display, the spectrogram, and the Fourier spectrum. The last visualization plots the strength of each partial against its harmonic frequency or number. Students learn that periodic waves are superpositions of sine waves from the harmonic series. The harmonic series emerges naturally as the standing waves in a conical pipe with one end closed and the other open [5, 6]. Finally, a short video is provided that demonstrates all the features of this paper [8].

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https://iopscience.iop.org/article/10.1088/1361-6552/aabbc1

References

[1] Crundell M, Goodwin G and Mee C 2014 *Cambridge International AS and A Level Physics* 2nd edn (London: Hodder Education) pp 101-25

[2] Freedman R A, Ruskell T G, Kesten P R and Tauck D L 2018 *College Physics* 2nd edn (New York: W H Freeman) pp 521-54

[3] Fletcher H and Munson W A 1933 Loudness, its definition, measurement and calculation *J. Acoust. Soc. Am.* **5** 82-108

[4] Berg R E and Stork D G 2005 *The Physics of Sound* 3rd edn (Upper Saddle River, NJ: Pearson) pp 8-9

[5] Ayers R D, Eliason L J and Mahgerefteh D 1985 The conical bore in musical acoustics *Am. J. Phys.* **53** 528–37

[6] Ruiz M J 2017 Hearing the transformation of conical to closed-pipe resonances *Phys. Educ.* **52** 035012

[7] LoPresto M C 2003 Experimenting with brass musical instruments *Phys. Educ.* **38** 300-8

[8] Ruiz M J 2018 *Video: Amplitude, Frequency, and Timbre with the French horn* http://mjtruiz.com/ped/horn/

[9] Holmes B and Ruiz M J 2017 Twenty-four tuba harmonics using a single pipe length *Phys. Educ.* **52** 025005

[10] Audacity at SourceForge 2016 https://sourceforge.net/projects/audacity/ or the Audacity website at http://www.audacityteam.org (Accessed: 1 April 2018)

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