Musical acoustics for musicians

M. Campbell
University of Edinburgh, Acoustics and Audio Group, EH9 3JZ Edinburgh, UK
d.m.campbell@ed.ac.uk

Musical acoustics has traditionally been considered to be a scientific discipline, and musical acoustics research is frequently carried out in the physics or engineering departments of universities and technical institutes. However musical acoustics is an unusual science in that most of its principal topics of study, including the nature of musical sound and the functioning of musical instruments, are intimately bound up with the highly subjective activities and requirements of the practitioners of the art of music: the composers who create musical scores, the performers who bring the scores to life, and the craftsmen who provide the performers with the instruments through which music finds its voice. Communication and dialogue between scientists and musicians is vital if musical acoustics is to be relevant to musicians. One way in which this communication occurs is through the formal teaching of musical acoustics; courses of acoustics have been features of the academic training of musicians since the middle of the nineteenth century, and many acousticians have risen to the challenge of convincing classes of music students that science can enrich their understanding of music theory and practice. Another important route through which scientific ideas can be communicated to musicians is through specialised musical journals and web resources, which sometimes carry misleading or ill-founded ideas and claims. Fortunately there are many composers, performers and instrument makers who are fascinated by the scientific background to their art, and the involvement of such people in research projects contributes greatly to progress in musical acoustics.

1 Introduction

For more than a century it has been customary to include courses in musical acoustics in the curricula of university music degrees. Those of us who have taught such courses are well aware that, while some music students are sceptical about scientific approaches to their art, many are fascinated by the ways in which a little mathematics and physics can sometimes explain aspects of musical experience which are superficially baffling or counter-intuitive. The rapid growth of websites devoted to discussions of musical instrument behaviour is also a testament to the scientific curiosity of musicians; some of these are excellent and authoritative, but many still peddle quasi-scientific ideas long since discredited by the academic community.

There is clearly a need for continuing dialogue between the scientific research community and the composers, performers and instrument builders who between them create the music which is at the heart of all our endeavours. This dialogue between art and science is often surprisingly down to earth: musicians are practical people, and ask practical questions. Not uncommonly these questions turn out to be more profound than they first appear, and provide valuable spurs to new lines of scientific investigation. In this paper I recall a few of the questions which musicians have asked over the years, and briefly consider the scientific ideas which provide at least partial answers.

2 Why are some musical passages so hard to play in tune?

Some passages in orchestral and chamber music are notoriously difficult to play perfectly in tune. A particular problem arises when two flutes are playing high notes separated by a small pitch interval in an ensemble chord, such as the chord in bars 4 and 5 of Mendelssohn's "Overture: A Midsummer Night's Dream", illustrated in Figure 1. If the first and second flutes play equal temperament pitches E6 = 1319 Hz and G#6 = 1661 Hz respectively, the aural difference tone generated by the nonlinear behaviour of the human ear will have a frequency of 342 Hz. This is 80 cents higher than the note E4 = 329.6 Hz played by the second clarinet, creating a jarring discord which may be noticeable by the audience and will certainly be disturbing for the players.

The answer is for the first flute to play the G#6 14 cents flatter than equal temperament, at 1648 Hz. The difference tone between the two flutes is then in tune with the second clarinet's note, reinforcing rather than disrupting the E major tonality of the chord.

There are two reasons why the intonation of this chord is so critically dependent on the flutes. One is that they are playing in a frequency region in which difference tones are quite strongly perceptible [1]. The other is that while the pitch interval between two notes is determined by frequency division, the difference tone is determined by frequency subtraction. Since the difference tone frequency is approximately one fifth of the frequency of the first flute note, a small pitch correction by the flautist translates into a pitch change five times greater in the difference tone. Concentrating on the difference tone is therefore a useful tuning strategy for the player.

Figure 1: First five bars of Mendelssohn's "Overture: A Midsummer Night's Dream" (sounding pitches).

3 Why do guitar "power chords" sound much lower in pitch than their component notes?

Figure 2: Ritchie Blackmore, guitarist with Deep Purple

Figure 3: Power chord introduction to "Smoke on the water"

Power chords, which contain fourths and fifths but no thirds, are dramatic ingredients in the electric guitar technique of heavy metal and hard rock musicians [2]. Their effectiveness is largely due the the generation of difference tones, not in the human ear but in distorting circuits deliberately introduced in the amplification process.

A classic example of the use of power chords is the introduction to "Smoke on the water" by the band Deep Purple [3]. The upper stave in Figure 3 shows the succession of fourths played by the guitarist (at sounding pitch). The difference tone, two octaves below the upper note of the dyad, is shown on the bottom stave. Bearing in mind that additional harmonics are also generated to some extent by the distortion process, the musical effect is to create a sequence of powerful root position chords.

4 How does the structure of a viol affect its timbre and "playability"?

The two centuries from 1500 to 1700 saw remarkable developments in the design and construction of bowed string instruments. The violin and viol families emerged around the beginning of the sixteenth century, and the form and method of construction of both types of instrument continued to evolve significantly for many years [4, 5]. In recent decades performers on the viol have become increasingly interested in the musical possibilities of the various types of instrument which developed at different stages in this evolution, and makers have responded by offering reconstructions of early viols. Few viols have survived from the sixteenth century, but copies have been made from instruments such as the Linarol tenor viol in the Kunsthistorisches Museum in Vienna (Figure 4). Sometimes instruments have been reconstructed from contemporary images: an example is the viol shown in Figure 5, which was based on a painting of around 1500 by Lorenzo Costa.

Figure 4: A set of viols made by Richard Jones following a tenor viol by Francesco Linarol c. 1550

Figure 5: Alison Crum playing a viol by Roger Rose based on a painting by Lorenzo Costa

Makers and players are interested in understanding more about how specific structural differences, such as the presence or absence of a soundpost, are related to the musically significant differences which are evident to players and listeners.

As part of a collaboration with Jim Woodhouse at the University of Cambridge, involving also the internationally renowned player Alison Crum and the viol makers Richard Jones and Anthony Edge, bridge admittance curves have been obtained for a considerable number of reconstructed viols based on models from the sixteenth and seventeenth centuries. The measurement technique, now standard for the study of violins [6, 7], employs a small pendulum-mounted hammer to deliver a light tap at the top bass corner of the bridge. An accelerometer in the hammer head measures the impulse imparted to the bridge, while a laser vibrometer focused on the treble top corner of the bridge measures the resulting bridge velocity. The ratio of these two quantities, Fourier transformed into the frequency domain, gives the bridge admittance curve.

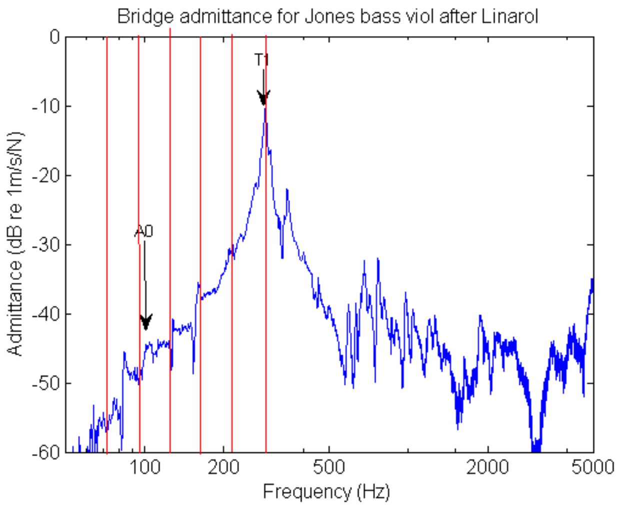

Figure 6: Bridge admittance curve for a six-string bass viol after Francesco Linarol

Figure 6 shows the bridge admittance for a bass viol based on the surviving Linarol tenor. This instrument has no soundpost, and all the strings are gut. The bridge admittance curve is dominated by one very large peak around 300 Hz. The vertical red lines on the graph indicate the frequencies of the six open strings; the strong resonance peak is close to the frequency of the first open string with pitch D4. From this it can be predicted that the instrument will be relatively powerful on its top string, and that upper harmonics will dominate the spectrum of notes played on the lower strings. These predictions are consistent with measurements; they are also consonant with the musical judgements of players, who welcome the clarity of sound of these instruments in renaissance polyphony.

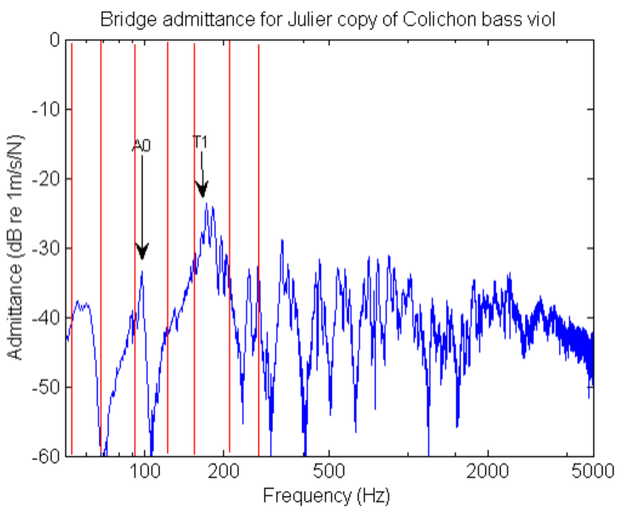

Figure 7: Bridge admittance curve for a seven-string bass viol after Michel Colichon

Figure 7 shows the bridge admittance of a very different type of bass viol, copied from an instrument of the late seventeenth century. It has a somewhat heavier construction, with seven strings. The string tensions are higher than on the Linarol, and several of the lower strings are overwound with silver. It has a soundpost. The resonances of this instrument are clearly more broadly distributed over the range of playing frequencies, with the consequence that the frequency spectra of notes played on the lower strings have stronger low harmonic components and the timbre is warmer and more rounded. This type of instrument is particularly suited to the virtuoso baroque repertoire for solo bass viol.

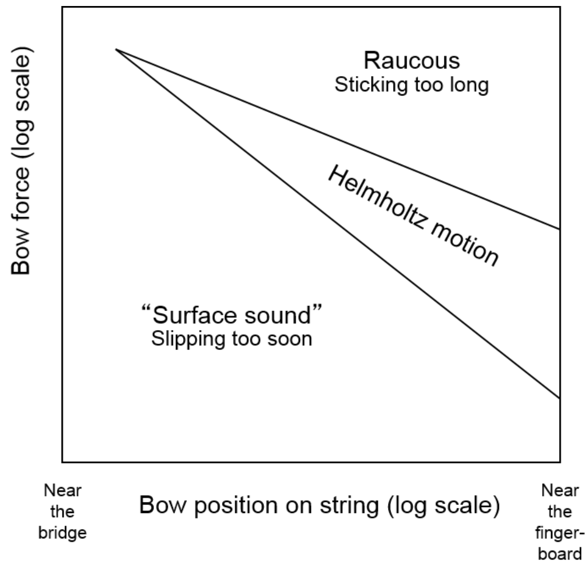

Figure 8: Schelling diagram

Jim Woodhouse has explored the relationship between bridge admittance and playability on bowed string instruments [8]. The famous Schelleng diagram (Figure 8) shows that for a given bowing distance from the bridge there is a minimum force which must be applied between the bow hair and the string if Helmholz motion (stable string vibration) is to be sustained. There is also a maximum bow force, above which the stick-slip cycle no longer synchronises with the string vibration frequency, giving a raucous sound [9]. While the maximum force line depends only on the properties of the string and the bow hair, the minimum bow force line translates vertically upwards as the bridge admittance increases. This reduces the permissible force range, making the instrument harder to control.

The extreme case occurs when the ratio of minimum to maximum bow force approaches unity. Helmholtz motion becomes impossible, resulting in a rapid low frequency beating which is usually described as a "wolf note". Since this occurs for high values of the bridge admittance, powerful instruments are particularly prone to wolf notes.

Figure 9 is a plot of the minimum to maximum bow force ratio as a function of playing frequency for the Colichon bass viol copy by Anthony Edge. There is a separate curve for each of the seven viol strings; these overlap, since a given note can usually be played on more than one of the strings. The peak at 185 Hz, corresponding to the body resonance marked T1 in Figure 7, shows that the note F#3 is most susceptible to wolfing. The minimum bow force increases with the wave impedance of the string, so the wolf is more likely when the note is played on the G2 and C3 strings with relatively large mass density. On the lighter E3 string the minimum to maximum bow force ratio is just over 0.06, and the risk of a wolf is very low. These predictions are

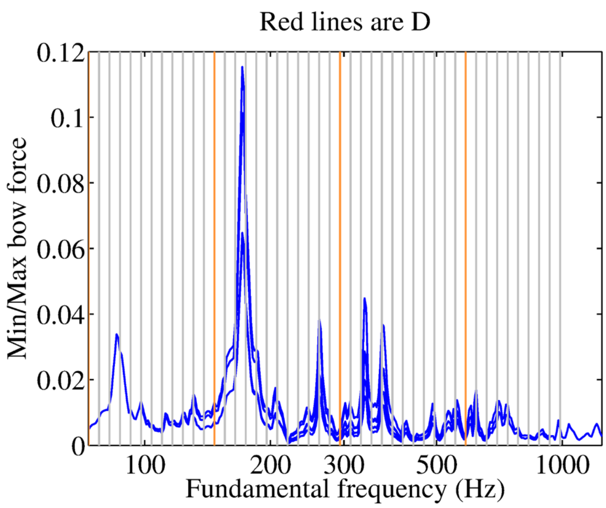

Figure 9: Wolf susceptibility diagram for a seven-string bass viol (Woodhouse).

confirmed by playing experience.

5 Why is my cornetto unstable on G5?

The cornetto is a conical wooden tube around 63 cm long, either straight or (more commonly) in a gentle curve. It has six finger holes and one thumb hole, and is sounded by the player's lips vibrating against a small cup mouthpiece. The instrument has a playing range of two and a half octaves, and creating an instrument that will play with good intonation and stability over this range demands great skill from the craftsman. Several makers have asked whether scientific analysis could pinpoint the reason for specific problems which arose during manufacture.

The passive resonant behaviour of a wind instrument can be characterised by the input impedance, which is the ratio of the acoustic pressure to acoustic volume velocity at the entrance plane of the instrument's mouthpiece. There are various techniques available for measuring this quantity; the curves in Figure 10 were obtained using the commercially produced BIAS system [10]. The blue curve shows the input impedance for a cornetto which was found to have an unstable G5 (frequency 784 Hz); when attempting to play that note the player risked slipping on to a note approximately a tone higher. The red curve was measured on a cornetto which did not have this problem.

The note G5 is obtained on the cornetto with only the thumb hole and the second highest finger hole covered. The tone hole lattice cutoff frequency for this fingering is around 800 Hz. Below this frequency the highest open finger hole effectively vents the tube, so a wave travelling down the tube is reflected at that point. Above the cutoff frequency, the wave continues to travel down the tube, being reflected at the open lower end. The smaller peaks which occur just above 800 Hz are caused by these reflections; they also provide the explanation for the misbehaviour of the cornetto represented by the blue curve. The first extra peak in the faulty instrument is relatively high in amplitude, and less that two semitones away from the G5 peak, while the corresponding peak in the red curve is less than half the amplitude and considerably further away in pitch. It is possible (at least in principle) to use computer modelling software to propose an adjustment

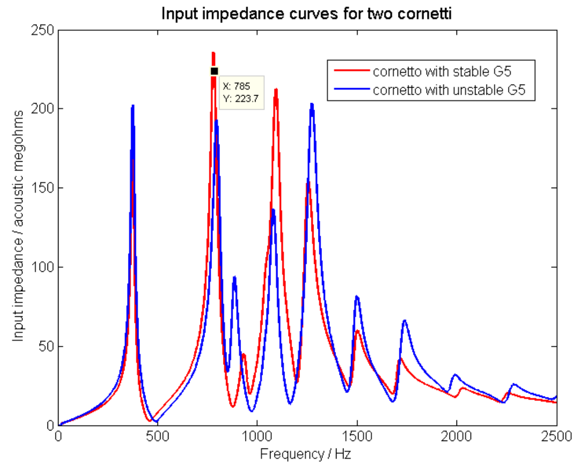

Figure 10: Input impedance curves for two cornetti. Blue curve: unstable G5. Red curve: stable G5

of the bore to eliminate or reduce problems of this type [11].

6 What frequencies are generated in trombone multiphonics?

Multiphonics [12] can be played on the trombone using two techniques. The player can sing into the instrument while playing it conventionally; this results in a modulation of the air flow into the mouthpiece by the vibrations of the vocal folds, superimposed on the normal modulation by the lip vibration. In a "lip multiphonic" the player finds an unconventional lip oscillation regime involving simultaneous modulation of the open area between the lips with two different periodicities.

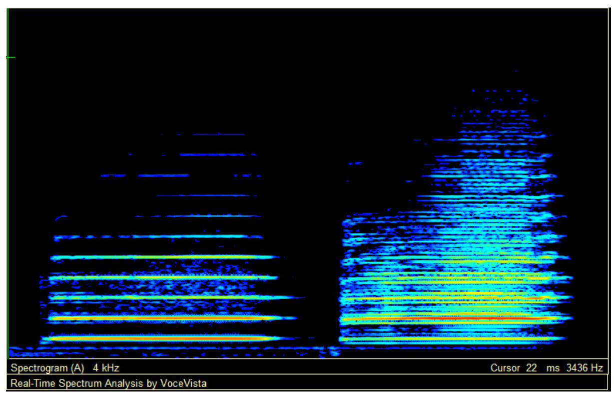

Figure 11: Trombone lip multiphonic

Figure 11 shows the spectrogram of two notes played on a tenor trombone. The first is a normal B♭3; the second is a lip multiphonic based on the same acoustic resonance but with an additional, much lower periodicity superimposed.

In 1992 the composer Paul Keenan commenced a PhD at the University of Edinburgh, studying with Nigel Osborne. He became fascinated by lip multiphonics played by the trombonist John Kenny, and developed a compositional style influenced by highly detailed spectral analysis of these sounds [13].

7 Why does the pitch of a wind instrument change in a warmup?

"Warming up" a wind instrument by playing it for a few minutes is a procedure with which all performers are familiar. The colloquial term used to describe this method of preparing the instrument for performance implies that the main effect of the exercise is to increase the mean temperature of the instrument. How does a rise in temperature influence the pitch of a wind instrument, and are there significant factors other than temperature which come into play when the instrument is blown?

As the temperature of a wind instrument increases, it expands. An increase in length leads to an increase in the wavelengths of standing waves in the instrument and a flattening of the pitches of the acoustic resonances; however, this effect is negligible in practice. The significant effect of a rise in temperature is the increase in the speed of sound; this results in a sharpening of the acoustic resonance pitches by around 3 cents per degree Celsius. .

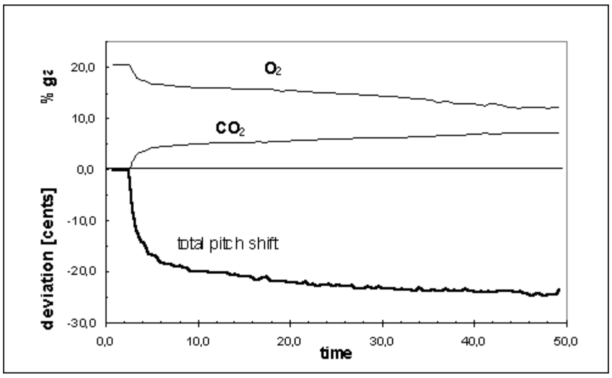

Figure 12: Above: measurements of the percentages of oxygen and carbon dioxide in exhaled breath during a sustained musical note. Below: prediction of consequential pitch change in acoustic resonances. From [15]

There is however another effect which occurs when the player blows air into the instrument: the composition of the gas inside the instrument tube changes [14]. In a paper presented at the ISMA 1997 meeting in Edinburgh [15], Leonardo Fuks reported measurements of the relative proportions of oxygen and carbon dioxide present in exhaled air during a note sustained on a woodwind instrument for 50 seconds. Since carbon dioxide is heavier than dry air, an increase in the proportion of carbon dioxide leads to a reduction in the speed of sound and a flattening of the pitches of the acoustic resonances. Fuk's measurements are shown in Figure 12. Also in this figure is a curve predicting the drop in pitch of the acoustic resonances during playing, taking into account the additional effect of water vapour in the player's breath. It can be seen that in the first 10 seconds of playing the pitch of the resonances is predicted to drop by around 20 cents.

Recent measurements on trombone warmups by Amaya Lopez-Carromero have broadly confirmed the predictions of Fuks. Figure 13 shows results for a King tenor trombone. The frequencies of the first 12 impedance peaks were measured after the instrument had been left unplayed for 24 hours; the temperature inside the trombone leadpipe before the start of warmup was the ambient laboratory temperature

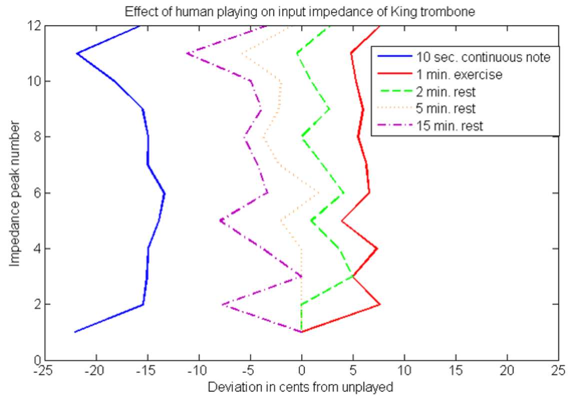

Figure 13: Pitch changes in acoustic resonances of a tenor trombone after human playing.

of 23°C. A continuous F3 was the played for 10 seconds; impedance measurements made a few seconds after the end of this playing showed a flattening of between 15 and 20 cents (blue curve). The instrument was then given a conventional warmup for 1 minute; this consisted of an alternation of long and short notes, and slow arpeggios from B♭1 to B♭4, with breaths taken every 5 to 10 seconds. At the end of the warmup the acoustic resonances were on average 6 cents sharper than in the unplayed state. Over the course of the next 15 minutes the instrument was left unplayed. The acoustic resonances at the end of this period were around 5 cents flatter than in the unplayed state, suggesting that some carbon dioxide was still present in the instrument.

8 Conclusion

The results of research on the behaviour of musical instruments and the perception of musical sounds must satisfy two essential criteria: they must be scientifically valid, and they must be musically relevant. Ultimately, choices of intonation, timbre, type of instrument and playing technique are made on musical grounds by musicians, but science can illuminate the objective factors which underly these choices. The interchange of ideas, information and questions between scientists and musicians (who are sometimes the same people) is an essential activity which underpins and invigorates progress in this fascinating and interdisciplinary quest for understanding which we call musical acoustics.

Acknowledgments

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