Pitch bending technique on early horns by manipulation of the embouchure: A comparison between measured and predicted data.

Lisa Norman
University of Edinburgh
Acoustics and Audio Group
Lisa.Norman@ed.ac.uk

Jonathan Kemp
University of St Andrews
Department of Music
jk50@st-andrews.ac.uk

John Chick
University of Edinburgh
Acoustics and Audio Group
John.Chick@ed.ac.uk

Murray Campbell
University of Edinburgh
Acoustics and Audio Group
d.m.campbell@ed.ac.uk

ABSTRACT

Brass players sometimes adopt a technique whereby they adjust their embouchure in order to alter or bend the pitch of a note away from the centre of the resonance. The ease and control with which this can be achieved is an important factor in assessing the playability of a brass instrument. A good instrument will have well defined resonances, but experienced players do not like instruments with notes that are too 'stiff', and which lack sufficient flexibility for musical expression. The need for the ability to bend the pitch of a note is particularly important for natural trumpets and horns used in the baroque era, when instruments did not have valves and players were required to bend the pitch of some resonances (e.g. the 11th and 13th) by a significant fraction of a semitone. The instrument and player form a complex and closely coupled system. Using experimental data from playing tests on early orchestral horns, and comparing these results with those from a recently developed time domain model, it is possible to begin to identify features of an instrument and its interaction with a player which make it more or less susceptible to this type of manipulation.

1. INTRODUCTION

Arguably the most fundamental aspect of the acoustic design of a brass instrument is the creation of a bore profile whose acoustic resonances are harmonically related. The harmonicity of this series is important as it allows for a strong coupling between the resonances of the air column within the instrument, also known as a cooperative regime of oscillation [1]. This interaction helps to support the oscillation of the lip, a key function of the player's embouchure.

Although the internal shape of the instrument determines the frequencies at which the lips will most readily vibrate, the player still has the ability to exert some influence on the finer tuning of these resonances by 'bending' the pitch of notes using embouchure manipulation.

Pitch bending is commonly referred to by players as 'lipping', but the use of this term is perhaps slightly misleading. The technique involves the manipulation of the whole of the mouth and embouchure to change the pitch of the note; the lips, the tongue, the oral cavity, and mouthpiece pressure may all be brought into play when adopting this technique, and different musicians achieve this effect in different ways.

1.1 Historical context

Horns and trumpets from the seventeenth and eighteenth centuries do not have valves (the invention of which extended the range of notes available to the player), and so composers at this time were restricted to using predominantly pitches based on the natural resonances of the instrument.

Most of these pitches correspond to the notes of a diatonic scale whose tonic is the nominal pitch of the instrument, but the seventh, eleventh and thirteenth do not fit comfortably within this tuning system. Wayward pitches such as these were most likely problematic for musicians of the day, and they remain an issue for modern brass players interested in performing on natural instruments. In order to fine tune these pitches it is likely that a pitch bending technique was adopted.

Players of modern orchestral instruments are also interested in pitch bending, but at the more subtle level of musical inflection. Although significant for players in evaluating instruments, this usage is modest by comparison with baroque horn and trumpet playing. The focus of this paper is on the higher levels of pitch bending required for baroque horn playing.

1.2 The 11th resonance

Baroque composers do not seem to have made a particular effort to avoid these problematic pitches in their horn and trumpet writing. The written F♮ and F♯, see Figure 1, are two notes frequently used by composers around this time, and yet both notes share the same natural resonance, the eleventh, which falls somewhere in between the two pitches. Players would have been required to distinguish between these two notes and therefore would have had to 'bend' the pitch of the eleventh resonance up or down accordingly.

1.3 Harmonicity

There has been some discussion amongst players and scholars suggesting that early original brass instruments may have been better suited to the demands of eighteenth-century

Figure 1. Two notes, written F♮ and F♯, which are both played using the 11th resonance.

repertoire than their modern counterparts, particularly with regard to pitch bending potential. This is arguably because the resonant modes on these early horns and trumpets are not as harmonically aligned as on either modern instruments, or even copies of early eighteenth-century instruments [2, 3], and that this in some way aids the application of early performance techniques.

A related study exploring the acoustical properties of different trumpet mouthpieces, [4] has suggested that slight inharmonicity might in fact be a desirable quality in any brass instrument. From the point of view of pitch bending, misalignment in the series of resonant modes would result in weaker support from higher resonances and could thus, in theory, provide the player with greater flexibility of pitch, i.e. greater pitch bending potential.

1.4 Structure

Section 2 describes the experimental set up and the process for carrying out player tests while Section 3 includes a brief description of the computer model and how the playing properties of a brass instrument have been predicted. The results from measured and predicted data are discussed in Sections 4 and 5 respectively, and conclusions are proposed in Section 6.

2. EXPERIMENTAL SETUP

The horns used for the playing tests included five early orchestral horns from the Edinburgh University Collection of Historic Musical Instruments. Figure 2 shows a photograph of one of these early instruments, a horn from the mid-eighteenth century, made in England by Nicholas Winkings.

For the purpose of this investigation, all horns were crooked or pitched in D, a common key for horn players of the eighteenth century to play in, [1] and the tests were carried out without the hand in the bell in order to limit potential variables.

The photograph in Figure 3 shows the experimental setup for recording the playing tests. The radiated sound from the bell of the instrument was measured using a Bruël and Kjær 4192 pressure-field microphone, located one bell diameter from the plane of the bell of the instrument (approximately 230 mm depending on instrument used), on axis.

In addition to the radiated sound, the mouthpiece pressure was recorded using a 106B PCB Piezotronics dynamic pressure transducer located near the throat of a specially

[1] A horn crooked in D has a tube length of approximately 4.42 m, corresponding to a nominal pitch of D_1.

Figure 2. Photograph of a horn by the London maker Nicholas Winkings, from the mid-eighteenth century (GB.E.u, 2492).

Figure 3. Experimental set up, showing the positions of the microphones and sound-level meter.

modified mouthpiece as shown in Figure 4. The signals from both transducers were recorded at a sampling rate of 44.1 kHz.

Players were given a familiarisation period with each instrument before starting the recording process. Pitch bending capabilities were explored on a number of different resonances including the fourth, tenth and eleventh. In each

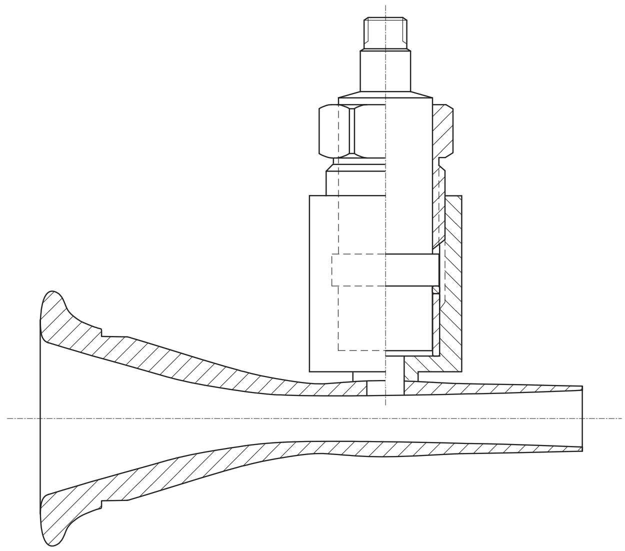

Figure 4. Diagram of a horn mouthpiece with a specially made fitting for a microphone.

case, players were asked to bend the pitch of the resonance downward and upwards as far as they could, until the note suddenly changed to the neighbouring resonance.

Typically the sound samples lasted for about two to three seconds. The test was played at a reasonably loud dynamic level, approximately forte, and was repeated at least four times. To assist the players with keeping the sound at a constant dynamic level over the duration of the pitch bend, they were provided with a sound-level meter (set to A-weighting). The players were asked to make no attempt to aim for a specific pitch, only to test the extremes of the flexibility of the pitch on the particular resonance.

The reason for testing the pitch bending capability of the fourth resonance is because it is relatively low in the playing range of the horn and therefore is easier to manipulate with the embouchure. The eleventh resonance was chosen because, although it is higher in the series and more difficult to bend, it is a particularly problematic pitch as mentioned earlier, which typically lies somewhere in between a written F$^\natural$ and F$^\sharp$. This resonance would certainly have been subjected to some form of pitch manipulation as composers include both these notes in their compositions.

After the playing tests, the initial analysis of the recordings was carried out using the pitch detection software Praat [5], a program originally developed for speech analysis, but found to work well for analysis of instrumental sunds. Further analysis was carried out by looking at the acoustic input impedance for each horn and mouthpiece combination. The equipment used to measure the acoustic input impedance of the various horns is the commercially available Brass Instrument Analysis System (BIAS) [6].

3. COMPUTATIONAL MODELLING

The use of computer simulation to assess the playing characteristics of an instrument has a significant advantage over player tests because it is non invasive, requires little contact with the instrument, and removes player subjectivity. Brass instruments are perishable and owners of collections are becoming increasingly sensitive to issues of excessive handling and contact.

It is already the case that many eighteenth-century horns are no longer in playing condition due to large dents, leaks, or cracks in the metal. A thick layer of dust inside the tubing or a trapped foreign object could alter the acoustics of an instrument, so in the case of instruments that have already experienced significant wear and tear, and are no longer in playing condition, extrapolated measurements of their bore profiles can be used as the input to computational models in order to predict the acoustic behaviour of the instruments.

The vibration of the lips of brass players can be modelled by considering the lip to be a single mass able to move in two dimensions and obeying a forced damped harmonic oscillator equation which is given by Adachi and Sato [7] as:

$$\frac{\partial^2 \vec{\xi}}{\partial t^2} + \frac{\omega_0}{Q}\frac{\partial \vec{\xi}}{\partial t} + \omega_0^2 \left(\vec{\xi} - \vec{\xi}_{equil}\right) = \frac{2b}{m_{lip}}\left((p_m - p_0)\left(\vec{\xi} - \vec{\xi}_{joint}\right)^{\perp} + p_{lip}\vec{e_y} d\right). \quad (1)$$

Here m_{lip} is the mass of the lip, ω_0 is equal to the natural angular frequency of the lip, Q is the quality factor of the lip, b is the lip width (perpendicular to the axial direction, x, and the vertical direction, y) and d is the lip thickness in the x direction. The vectors are two dimensional along x and y, with $\vec{\xi}$ giving the displacement of the bottom corner of the lip, $\vec{\xi}_{joint}$ giving the fixed position of the top corner of the lip and $\vec{\xi}_{equil}$ being the equilibrium position of the bottom corner of the lip in the absence of air pressure differences. Bernoulli forces must be taken into account in calculating the pressure beneath the lip, which is denoted by p_{lip} while p_m is the pressure in the mouth, p_0 is the pressure in the mouthpiece immediately beside the lip and $\vec{e_y}$ is the unit vector in the y direction.

The lip model was run with the natural frequency of the lip, ω_0 ramping linearly, either upwards or downwards through the appropriate range for the transient being modelled. The value of Q was multiplied by a factor of $0.25\sqrt{3}$ and values of ω_0 multiplied by a factor of $\sqrt{3}$ when the vertical displacement of the lip was negative (corresponding to the lips overlapping) [9].

Parameters chosen were mainly the same as those found in Adachi and Sato [7], with the lips assumed to be just touching in the absence of an air pressure difference (vertical equilibrium of zero). The lip mass (in kg) depends on lip natural frequency, f_{lip}, according to the empirical formula taken from Adachi and Sato [7]:

$$m_{lip} = \frac{1.5}{f_{lip}(2\pi)^2}. \quad (2)$$

The static mouth pressure was taken to be 6 kPa. This model was then coupled to the Finite Difference Time Domain (FDTD) model of Bilbao [8] which simulates lossy linear wave propagation based on the bore profile. Full details of numerical model, including the FDTD model for wave propagation in the bore, the method of coupling the lip model and values of the constants used are found in Kemp et al [9]. The results in this case will be the same as that which would be obtained from measuring or computing the instrument time domain reflectance and coupling this to the lip model (within the accuracy of computation or measurement).

4. MEASURED RESULTS

The results from player tests revealed a subtle but measurable variation with regard to the pitch bending potential of specific notes on certain instruments. A horn by the maker Hofmaster (see Figure 5 for a photograph) was relatively amenable to pitch bending on the 11th resonance. Figure 6

Figure 5. Photograph of a horn by the London maker Christopher Hofmaster, from the mid-eighteenth century (GB.E.u, 3297).

shows an example of the change in pitch as the 11th resonance on the Hofmaster horn is bent downwards till the note drops to the the resonance immediately lower.

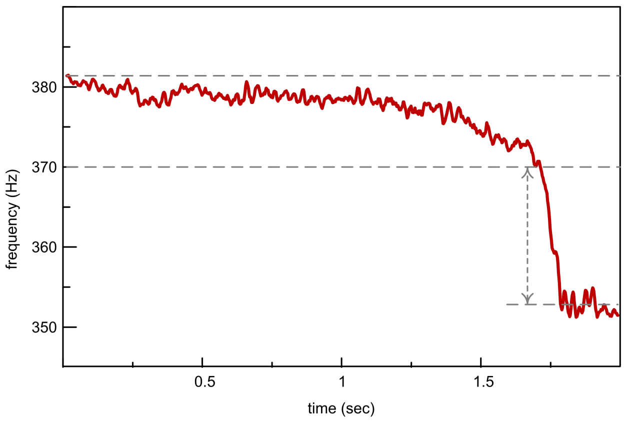

Figure 6. Graph showing the change in pitch as the eleventh resonance is lipped downwards until it drops to the tenth resonance, played on a horn by the maker Hofmaster.

Compare this with Figure 8 which shows an example from a different horn; this graph shows the pitch contour for an instrument by the maker Sandbach (see Figure 7 for a photograph) which proved to be less flexible on this resonance. [2]

Figure 7. Photograph of a horn by the London maker Sandbach, from the early nineteenth century (GB.E.u, 203).

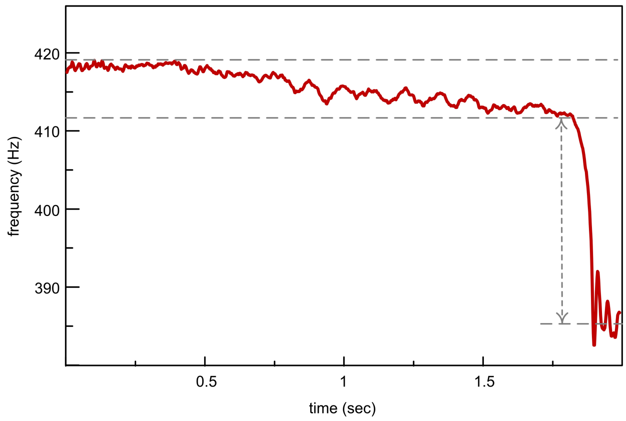

Figure 8. Graph showing the change in pitch as the eleventh resonance is lipped downwards until it drops to the tenth resonance, played on a horn by the maker Sandbach.

The comparison of upward pitch bends on both of these horns showed a similar response to the downward pitch bend results; the Hofmaster instrument responded more readily to embouchure manipulation technique than the Sandbach horn. The maximum range of flexibility on the eleventh resonance, summing the flexibility in the upward and downward directions and taken as an average from all relevant sound clips, was 82 cents for the horn by Hofmaster and 56 cents for the horn by Sandbach.

As an example, the grey lines in figure 6 show the note being lipped in the downward direction from around 382 Hz to around 370, a change of 55 cents to 2 s.f. before the note transitioned rapidly to the tenth resonance (producing a total change in pitch of around 136 cents during the course of the recording). In the case of the Sandbach horn,

[2] Note: these two horns are from different time periods and therefore have slightly differing nominal values of concert pitch

the example shown in figure 8 shows the frequency produced by the player varying from around 419 Hz to around 411 Hz, a change of 33 cents before the rapid transition to the tenth resonance (giving a total change of 146 cents during the course of the recording). It should be noted that the pitch range analysis based on these graphs is an estimation; sometimes there is not a clearly defined point at which the note appears to make the sudden transition to the neighbouring resonance. This is particularly apparent on the the graph in Fig 6. If the pitch bend was to be carried out at a slightly slower speed, the point at which the transition occurs might be more apparent.

5. PREDICTED RESULTS

The results shown in Section 4 were then compared to predictions from the time domain computer model described in Section 3. Predictions of pitch bending by the model are shown in Figure 9, based on bore profile measurements from the Hofmaster horn, and Figure 10, based on those from the Sandbach horn.

Since the time scale shown (in seconds) for the simulated data transitions is smaller than that for the playing tests, the slope corresponding to the rapid transitions between resonances is shallower, and the exact point of transition harder to establish. A reasonable estimate for the modelled transition for the Hofmaster horn shown in figure 9 gives the frequency changing from 385 Hz to 373 Hz before the rapid transition, corresponding to a downward pitch bend of 55 cents to 2 s.f. (agreeing with the pitch range shown in the player results shown in figure 6). In the case of the Sandbach horn, the modelled transition shown in figure 10 includes a pitch bend from 420 Hz to 410 Hz, giving a variation of 42 cents to 2 s.f., somewhat larger than the 33 cents observed in the player generated note transition shown in figure 8 but agreeing with the conclusions of playing tests with regard to the fact that lipping note pitch is easier on the Hofmaster horn.

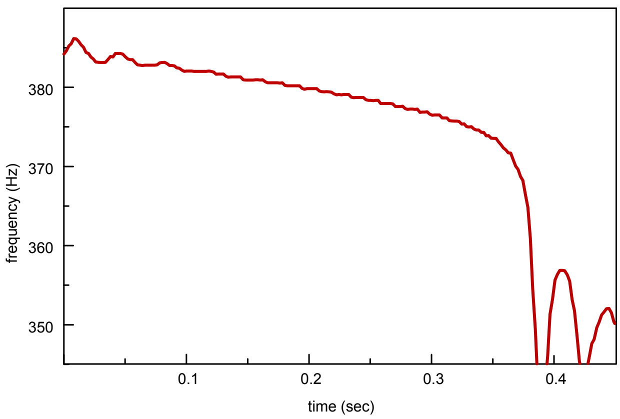

Figure 9. Graph showing the predicted change in pitch, comparable to the measured results in Figure 6, for a horn by the maker Hofmaster.

Lipping notes above or below the input impedance peak for an instrument was achieved by adjusting the value of f_{lip} in the two dimensional lip model. This process features hysteresis in that different playing frequencies are possible when the lip frequency is adjusted in an upward or downward direction. The degree to which notes can be bent was also found to vary with the quality factor of the lip resonance.

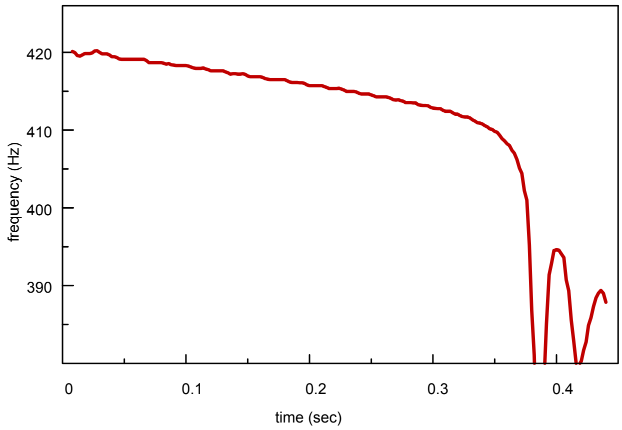

Figure 10. Graph showing the predicted change in pitch, comparable to the measured results in Figure 8, for a horn by the maker Sandbach.

Figure 11 shows the pitch contour obtained from analysing the pressure in the mouthpiece, taken from the computer model where the lip frequency has been simulated to produce an upward pitch bend over the 10th resonance based on bore profile measurements of a horn by the maker Winkings. Results are plotted for both $Q = 3$ and $Q = 5$.

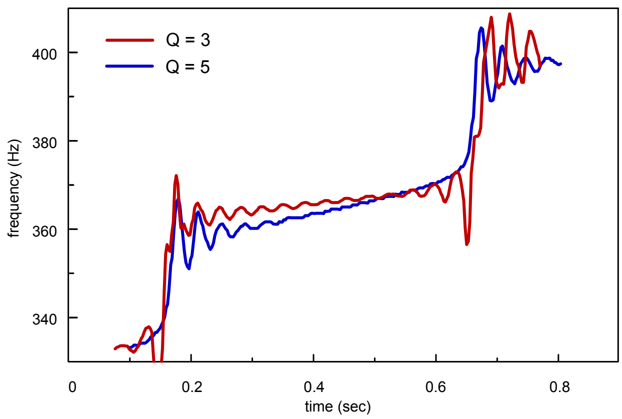

Figure 11. Graph showing a comparison of predicted change in pitch of the 10th resonance with two different values of Q for the lip.

It may be noted that larger values of lip quality factor produce a greater range of sounding frequencies when increasing the lip frequency, while the different quality factors produce very similar ranges of sounding frequency when decreasing the lip frequency.

6. CONCLUSIONS

The results of playing tests and modelling showed broadly similar behaviours for note transition phenomena. While players may vary a large number of control parameters to perform lipping, there was nonetheless a similar range of frequencies available during lipping in the physical model when adjusting only the lip frequency (and frequency dependent lip mass). Since the quality factor associated with the lip model has an impact on how far a note may be lipped in an upward frequency direction, further work may involve studying whether conclusions can be reached over the quality factor associated with the lip model in different playing ranges, in order to provide input parameters for realistic physical modelling synthesis of such phenomena.

Playing tests confirmed that the mid-eighteenth horn by Hofmaster was easier to lip than the nineteenth century Sandbach horn, at least for the notes studied in this project. The results of FDTD time domain simulations using the measured bores of these instruments were in qualitative agreement with the playing tests, demonstrating that the difference in lipping behaviour was not dependent on specific human players and their expectations. Future work will attempt to identify the features of the instrument bores, and their associated input impedance curves, which are responsible for these musically significant differences in playability.

7. REFERENCES

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