Finite element modeling of brass musical instruments

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ABSTRACT

This paper studies the contributions of mouthpiece and tubing to the acoustical properties of three nominally similar musical instruments from the brass family: trumpet, cornet and flugelhorn. Geometries of these instruments were used for an axisymmetric FEA simulations of the harmonic response to sinusoidal pressure at the mouthpiece. ANSYS software was used, with elements modelling the Helmholz equation. Frequency spectra for these instruments were obtained by FFT from sustained tones produced by advanced players under controlled studio conditions and significant differences were noted. While the FEA did not model the players' lips the sound transmission functions produced by these analyses again showed significant differences between instruments and generally favourable agreement with the measured spectra, in particular a strong 3rd harmonic for the cornet and a strong fundamental for the flugelhorn. Actual mouthpieces were not interchangeable but the FEA model was able to show that the mouthpiece and tubing each make a substantial contribution to the spectral differences. As expected the tubing had greater effect on the lower harmonics while the mouthpiece affected predominantly the mid range (around 700 Hz for the trumpet and cornet, and 1100 Hz for the flugelhorn).

INTRODUCTION AND BACKGROUND

Objectives

The objective of this paper is to model the sound produced by three closely related brass musical instruments and to attribute any timbral differences to particular geometrical differences. The sound generation mechanism (the player's lips and associciated apparatus) is of course a very important aspect of this problem but is not within the scope of this paper. The numerical model is validated by recorded sound from the same instruments.

The three instruments, B♭ trumpet, cornet and flugelhorn, were chosen because they are nominally similar in that they have the same tubing length, same tessitura, same means of sound production, and they are essentially interchangeable (any player who can play one can play all three equally well). However these three instruments have subtle geometry differences, mainly confined to the bell profiles and mouthpieces (described below). It is hypothesised that these geometry differences are responsible for measurable sound differences.

The acoustic model was created using the harmonic response tool in the finite element analysis software package ANSYS 12.1. Sustained notes were recorded in .WAV format and converted to frequency spectra using the Fast Fourier Transform (FFT) functions in MATLAB.

The timbres of these three instruments are generally distinguishable by experienced musicians in that the trumpet has the most sharp and penetrative sound, with the cornet slightly mellower than the trumpet, and the flugelhorn has a far mellower sound than either of the others (Backus, 1977). However due to the close family relationship of these instruments inexperienced listeners often have difficulty in positively identifying the instruments by their sounds, particularly when the initial attack of the note is removed.

Brass instrument acoustics

Brass instrument construction consists essentially of a length of cylindrical tubing with a mouthpiece at one end and a bell at the other. The method of sound production will first be described and the key features and purpose of the mouthpiece, tubing and bell will be discussed. The interested reader is referred to Wolfe (2012) for in depth acoustic details.

Method of sound production: A brass player generates sound by buzzing his or her lips into the instrument mouthpiece. The instrument greatly amplifies this sound near its reconant frequencies by modifying the input and output impedances with the mouthpiece and bell respectively (much like a transformer can amplify voltage or current depending on the attached impedances, or a lever can amplify a force or displacement). The instrument also tunes and colours the sound source by the natural resonances associated with the tubing length.

The natural response of brass instruments is to a good approximation described as a standing wave in pipe closed at one end and open at the other. The player's end is considered closed because it has a high input impedance. The player's lips do not allow significant oscillation of the air velocity, but create pressure oscillations, meaning the mouthpiece end of the instrument behaves as if it is effectively closed. In such a pipe a node (negligible flow) forms at the closed end and an anti-node (maximum velocity amplitude) at the open end. The pipe length thus represents an odd number of quarter-wavelengths, and the natural modes in the absence of a bell have frequency f_0, $3f_0$, $5f_0$ etc., where f_0 is the fundamental frequency for the pipe.

However a well-designed brass instrument, through the shaping of the bell, will have acoustics such that its resonant frequencies, or 'overtones', correspond to the 'harmonic series' (frequencies f_0, $2f_0$, $3f_0$ etc., where f_0 is the fundamental).

Bell: The main purpose of the bell is to make the sound of the instrument louder through the increase in area, and to modify the directivity of the radiated sound, although a side effect of the bell, as already stated, is to shorten the effective length of the tube, shifting the natural frequencies of the instrument slightly higher. Backus (1977) and Lapp (2010) report that the bell can be designed in order to shift the modes to fit the accepted frequencies for musical notes. Berg and Stork (2005) compare the frequencies of a B♭ trumpet with the equivalent plain tube with one end closed, showing actual frequency shifts.

Mouthpiece: The mouthpiece serves several acoustic and ergonomic purposes.

It has a wide opening relative to the main tube bore, comfortable for placing the lips, and sized to assist production of the appropriate range of source frequencies (deeper brass instruments such as the trombone and tuba have larger mouthpieces).

This opening is followed by a cup leading to a narrow throat, which increases the back pressure, hence input impedance. The depth of the cup alters the natural frequency of the mouthpiece, modifying the instrument sound and the ease with which certain notes are produced. The velocities in the throat may not be insignificant compared to the speed of sound, which may introduce nonlinear distortions. (Kuttruff, 2007).

The hypothesis is that the mouthpiece has as much influence on the sound as the instrument does, and would explain the difference in sound of trumpet and cornet, given that their tube and bell geometries are remarkably similar.

The resonant frequencies for mouthpieces are rarely documented, as is not a particularly relevant property to musicians, but was found in this study to be a significant factor in the instrument timbre. The Bach 1¼C trumpet mouthpiece used in this experiment, one of the more common mouthpieces, is stated to have a resonant frequency of approximately 800 Hz (Bach, 2011). A quick way to find the resonant frequency of the mouthpiece is by slapping an open palm on the mouthpiece inlet and listening to the frequency of the resulting “popping” sound.

Tubing: The tubing is generally cylindrical (excluding the mouthpiece and bell) with very narrow bore compared to its length. It essentially pads out the overall length to that necessary for the desired pitch. The bore diameters are reported below, but only the flugelhorn differed significantly, by 11%.

For ease of handling the tube for these three instruments is always coiled, but some historical or ornamental instruments have straight tubing.

The effect on the sound of the bends in the tubing is considered to be negligible compared to the effect of the bell and mouthpiece (Backus, 1977, Benade, 1990), although Brindley (1973) states that instruments with many sharp bends may have their resonances shifted a noticeable amount. For this reason, and because of the narrow bore, the instrument tubes are modelled in this study as being perfectly straight. This offers the substantial advantage of allowing an axisymmetric model without significant error.

Valves: As noted above, only certain notes can be obtained with a fixed length of instrument. The other musical notes are obtained but connecting extra lengths of tubing using valves. Valves are not considered in this study, which focuses on a single note (and its harmonics) produced by a fixed length of tube.

Geometry differences: Figures 1 and 2 below show the measured mouthpiece and bell geometries of the three instruments used in this study. The main differences were in the depth of the mouthpiece cups (trumpet being shortest, cornet longest) and the flare of the flugelhorn’s bell beginning earlier. As noted above the flugelhorn tubing bore was 11% narrower.

An essay by Stewart (2011) on the difference between trumpets and cornets goes into great detail on the popular misconception claimed to be perpetuated chiefly by brass musicians that cornets have a more mellow sound due to having a longer section of conical tubing than trumpets. Through analysis of many different makes of trumpets and cornets Stewart shows that the trumpet has a similar conical to cylindrical tubing ratio, and in many cases trumpets have a longer conical section than cornets. The conclusion of this report is that the trumpet and cornet are effectively the same instrument, and they produce virtually the same sound.

There were some minor questions regarding this essay, however the measured geometry of the trumpet and cornet used in this study confirmed there to be negligible difference other than the mouthpiece. Cornets are observed to have a mellower sound, and the spectra measured in this study show clear differences, hence the hypothesis above that the mouthpiece makes a significant contribution to the instrument’s timbre. The influence of the mouthpiece was tested by modelling the flugelhorn with the trumpet mouthpiece, and comparing this with the flugelhorn and trumpet each with its orthodox mouthpiece. These results could not be confirmed experimentally though because the trumpet mouthpiece could not be inserted into the flugelhorn without risking damage due to the different bore.

Previous studies

Hoffert, Chan and Johanning (2007) show via comparison of spectra of various notes played on the trumpet and clarinet that instrument identification is clearly possible. Musical sounds of defined pitch display significant spectral energy only at the harmonics (integer multiples of the fundamental frequency), thus the timbre of an instrument is characterised by relative strengths of each harmonic rather than in absolute frequency terms. Hoffert et al. highlight the consistency of the spectra for different notes played on the same instrument versus the relatively much larger differences observed for the same note played on the clarinet and trumpet, thus conclude the viability of instrument identification.

Their work however considered two instruments from different families. The present study expects to find more subtle differences looking at three very closely related instruments from the same family, so may pose greater challenges.

Kausel (1999) reports on the potential for numerical modelling of brass instruments. He developed a program, Brass Instrument Optimization Software (BIOS), that calculated the complex input impedance and sought to optimise the geometry of a brass instrument based on its resonance curve. Assumption were made on what was the ideal sound that brass instrument manufacturers strive to produce, but the resulting geometry was surprisingly realistic.

Kausel's paper noted that the Finite Element method could potentially produce better accuracy, but it required too much computing power to make it a viable optimisation tool for this problem at the time of his writing. However computing power has considerably increased in the intervening time, and the present study only requires analysis rather than optimisation, so FE has been chosen as the simulation method.

The player's lips are crucial to the sound production in brass instruments – simply blowing into the instrument produces no musical sound at all, and years of training are required to produce a professional quality sound. Thus on one hand a complete and accurate numeric acoustic model of a brass instrument must include a lip model, but on the other hand the lip behaviour is as much an art as a science, with many subtle and/or human factors, and it is expected to be extremely difficult to model accurately.

Fletcher (1993) developed linearised models of various valve types relevant to wind musical instruments and derives conditions under which oscillations may be initiated, but acknowledges the need to develop nonlinear models to describe such oscillations at their full amplitude.

Vergez and Rodet (1997) have measured a player's lip motion using a plexiglass model of the trumpet Bach 1½C mouthpiece and video camera. Yoshikawa (1995) performed similar experiments with pressure measurements and a strain gauge attached to the upper lips of trumpet and French horn players. These studies could be used to provide an empirical pressure time history as a mouthpiece boundary condition for the FE model of the instrument alone.

Kausel (2003) sought to model the lips from first principles, while Cullen, Gilbert and Campbell (2000) performed experiments with an artificial mouth. These give insights into the physics of the lip motion, necessary if one wished to integrate the lips directly into the FE model.

The lip model is outside the initial scope of the present study, though is recognised as a crucial area for future extension.

Fletcher and Tarnopolsky (1999) studied blowing pressure and its variation between players and in different registers of the trumpet. They found that maximum pressure varied considerably between players from 7 kPa to 15 kPa, and much higher pressures of up to 25 kPa were recorded for highest notes. This will be critical information if the present work is extended to include a lip model, but simulation results present below are linearised responses to sinusoidal excitation, and are normalised, so blowing pressure is not relevant.

NUMERICAL SIMULATION

Geometry definition, meshing and boundary conditions

To create relevant models of the three instruments, the geometry of each instrument was required. Neglecting the bends in the instrument, and only considering the instrument as it is when playing the note F_4, there are three key parts. The mouthpiece, the tubular section, and the bell.

Geometry definition: Exact dimensions of the mouthpieces for each instrument were available based on the mouthpiece model from New (2011). The length of the mouthpiece shaft which was inserted into the tubing of the instrument was noted during recording. The differences in mouthpiece shapes are as shown in Figure 1.

The tubular section inside diameter was obtainable using the instrument model, but was also checked manually to ensure that this inside diameter remained constant throughout the whole tubular section, which it proved to. The bore diameters were 11.66 mm, 11.68 mm and 10.50 mm respectively for the trumpet, cornet and flugelhorn, thus only the latter differs significantly, though the effect on the timbre is negligible.

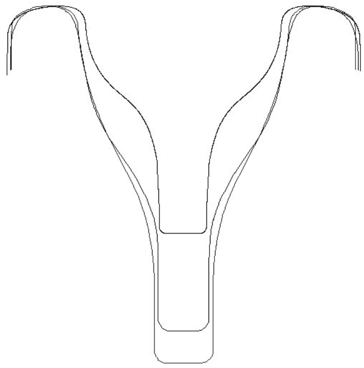

Figure 1. Profile of the Bach 1 ¼ C trumpet mouthpiece (short), the Bach 1 ½ C Flugelhorn mouthpiece (medium) and the Denis Wick 4B cornet mouthpiece (long)

The bell of each instrument, unlike the mouthpiece and tubing, was not readily available and had to be measured. The profiles are shown in Figure 2, up to the start of the cylindrical tubing.

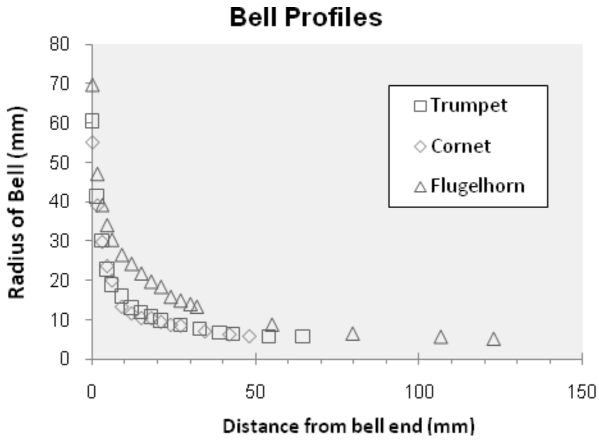

Figure 2. Measured bell profiles

By putting these three sections together, 3D models of the instruments were assembled as shown in Figure 3.

Figure 3. Revolved models of the trumpet (left), cornet (middle) and flugelhorn (right)

The FE model also included a surrounding 'room' which as discussed below is 8 m × 3 m.

Meshing: The element type used to model the air was the ANSYS FLUID29 element, a 4 node 2D axisymmetric harmonic acoustic fluid element, with the material properties shown in Table 1. This element type models the acoustic wave equation (Helmholz equation), i.e. compressible inviscid fluid with no mean flow.

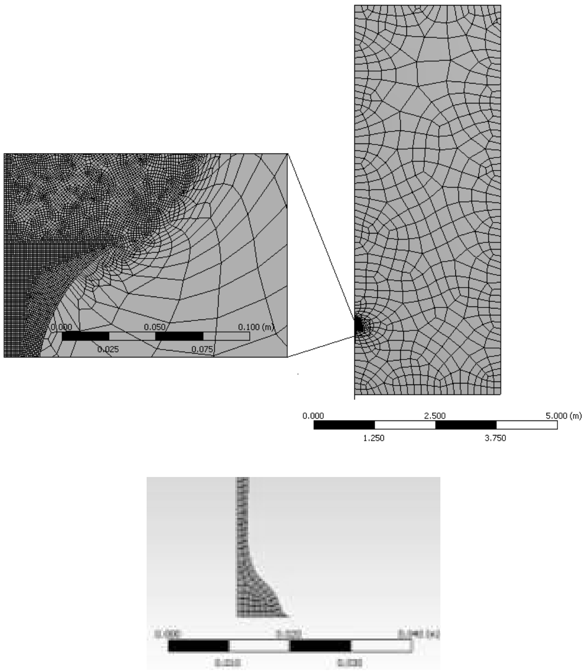

Figure 4: FEA mesh (bell region, complete and mouthpiece)

As shown in Figure 4 the mesh was reasonably fine within the instrument, with at least two elements across the radius of the tubing at any cross section, i.e. about 2.6–2.9 mm depending on the instrument. Much larger elements were used in the 'room' surrounding the instrument. Altogether there were around 25,000 axisymmetric elements. This gave results independent of the mesh.

Table 1. Material properties of air used in simulation

Density	1.205 kg/m^3
Speed of Sound	344 m/s
Boundary impedance ratio	1 (but overridden by specified conditions)

Boundary Conditions: In the geometry setup of the models, there were two 2-dimensional bodies of air, or FLUID29, present. These two bodies had two distinct connections. One was the connection at the bell outlet, and the other was the connection along the profile.

The connection along the bell outlet was defined as 'bonded', so the interior and exterior air behave as a single continuum over the bell interface. The connection between the trumpet profile and its adjacent air either side was defined as frictionless, so air within the tube of the trumpet would not be affected by the exterior air, and this bond effectively replaced the instrument thickness.

The boundary conditions for the simulation of the air flow were as follows.

- Sinusoidal pressure at inlet with constant amplitude independent of frequency
- No displacement of instrument profile in tangential or normal direction
- No displacement of central axis in normal direction
- No displacement of room borders in their respective normal directions

Modal analysis and Harmonic response

Two main types of analyses were performed using the finite element model, a modal analysis and a harmonic response analysis. The modal analysis evaluates the natural frequencies and mode shapes (unforced vibrations) of the modelled fluid domain, while the harmonic response analysis then evaluates the response to forced excitation.

In this problem there is little damping, hence the resonances are very sharp – musical instruments in fact rely on this being the case in order to produce clear tones of well defined frequency. The method chosen for the harmonic response was therefore the mode superposition technique with clustered harmonic analysis option, which solves the uncoupled system of equations by performing a linear combination of the mode shapes obtained from the already performed modal analysis. A consequence of this is that since the resonant peaks in the spectra are used there is generally limited information about the bandwidth, but on the other hand as the bandwidth of the instrument resonant peaks will be narrow the alternative method of using a fixed frequency increment will very likely miss or not fully excite the very narrow peaks of the extremely important natural modes and badly misrepresent the true peak values.. By using the known modes this guarantees that there are excitations at the natural frequencies Use of techniques that use points evenly spaced but otherwise arbitrarily distributed across the frequency domain is therefore not recommended for problems of this type.

It should be noted that the instrument on its own would typically display few natural frequencies within the audible range, with wavelengths corresponding to simple multiples of the instrument length (with end corrections for the bell). However in this simulation the instrument was modelled with a surrounding 'room', hence there were dozens to hundreds of natural frequencies of the system in between each that could be classified as a natural frequency of the instrument alone. The mode superposition technique used is therefore able to capture the interaction of the instruments with its surrounds just as well as any of the other techniques available.

The modal superposition method does however require a damping value, but by defining a damping ratio of 10^{-5} the damping factor becomes negligible.

Model validation

There are some significant differences between the FE model and the experiments reported below, the key ones being the room geometry and characteristics, the microphone placement and response, and the excitation source (player's lips). Of these the latter is by far the greatest approximation.

Room geometry: The modelled room was by necessity a cylinder since the FE model as a whole was axisymmetric. Axial symmetry is an excellent approximation to the instrument geometry (assuming the tube to be unrolled into a straight line, which is stated to have negligible effect on the instrument acoustics due to the very small radius of the bore compared to that of the bends (Backus, 1977, Benade, 1990) and has a major advantage of reducing the problem computationally by one dimension without introducing approximations other than those mentioned. However while the instrument may be modelled well it is a gross approximation to assume an axisymmetric room.

The impact of the room geometry is reduced by ensuring that its dimensions are large enough not to affect the solution field within the instrument, and further by the incorporation of wall damping. The latter is important since a cylindrical boundary, being concave, will create a focal point on the axis of symmetry. In our model we extended the room boundaries to beyond the point where there was an observable impact on the solution within the instrument. The chosen room dimensions were 8 m in length and 3 m radius (for reference the instrument tube length is 1.4 m).

For future work ANSYS has the capability of modelling a fully absorbent boundary, which would effectively replace the 'room' with an infinite space, equivalent to playing the instrument outdoors or in an anechoic chamber. This would certainly be recommended when some of the more critical approximations are addressed (particularly the player's lip model), however it was not considered warranted in this study.

Microphone placement: The impact of the room geometry may be further reduced by using results close to the instrument bell. In physical terms this means placing the microphone close enough to the instrument to capture the direct sound field and render the reverberant field negligible.

In the FE model the output pressures were averaged over the plane bounded by the rim of the bell, minimising the room effect, while in the physical experiments the microphone was placed some distance away and off centre so as not to damage the sensitive microphone (details below). While this does not invalidate the results, a more physically accurate FE model would again be recommended when the lip model is implemented.

Lip model: A musical instrument, in spite of its inherent resonances, will respond entirely differently depending on the excitation source. The excitation model used in this study is a very crude approximation to a reality in which even subtle differences will have a profound effect (e.g. in this context a good player versus a bad player could arguably be considered a 'subtle' difference). However, as will be seen in the results, the results produced by this crude model are extremely promising.

In the present study the input pressure at the mouthpiece simulates 'white noise', a sinusoidal input swept over all frequencies, though obviously this is simulated by a large number of discrete frequencies. Because the modal superposition technique was used the input frequencies are the natural frequencies of the whole system comprising the instrument and surrounding room. The frequency increment was therefore variable, averaging around 3–4 Hz over the 250–1700 Hz range, but up to 20 Hz at higher and lower frequencies. These values depend primarily on the room dimensions – a larger room would give a higher frequency resolution.

By contrast the excitation produced by a real player is clearly periodic but highly non-sinusoidal – there is typically a regular explosive pressure pulse produced by the player, alternating with an interstitial period of relatively shorter but more intense low pressure caused by the instrument's response during the period of closure of the player's lips. (Yoshikawa, 1995) The lips behave as an elastic valve, and their behaviour is highly dependent not only on the player, but on the response of the instrument – in fact a good player will exploit the resonance of the instrument rather than force the instrument to respond against its natural tendency – so the instrument in this sense is primarily what ensures that the excitation is at a particular frequency.

Furthermore, accompanying each 'explosion' of the player's lips is a small input of fluid, so that over time there is an average nett flow through the instrument. This is significant because nett power is input into the instrument, hence sound energy is radiated from the bell. The modal analysis on which the FE solution is based, by contrast, models standing waves and not transport of energy. This has consequences for detection of the output sound (i.e. comparison of the sound pressure measured by the microphone with nodal pressure solutions in the FE model). This is another reason why, as stated above, a microphone model can't be fully developed until the lip model is improved.

FEA OUTPUT AND INTERPRETATION

By necessity measurable output of the experimental and numerical results are not the same, hence are not directly comparable, so some means of interpreting the numerical results is required.

In the experimental results the response detected by the microphone is the response of the instrument to forced vibration, with the player's lips and air flow providing the sound source. A good player exploits the natural resonances of the instrument, so that there is an interaction between the instruments and the lips. Nevertheless the source is periodic (thought non-sinusoidal), hence regarless of the instrument's natural resonances the only frequencies that can be present in the recorded signal are exact integer multiples of the excitation frequency.

By contrast, in the FE simulation, in the absence of a lip model or some equivalent periodic vibration source, the excitation is swept over all frequencies. However it is noted that there will be strong resonances. In a well designed instrument these resonances (or overtones) will be approximately, but never exactly, integer multiples of some fundamental frequency, so will not in general coincide exactly with the spectral peaks in the real sound. Forcing near these resonant frequencies should produce significant response.

It is hypothesised that the relative spectral magnitudes of the periodically forced (real) response correlates with the ease of production of a particular frequency, which in turn is related to the strength of the resonance. As explained above, a brass instrument approximates a pipe closed at one end, so strong resonances will be characterised by a pressure maximum at the mouthpiece (node) and pressure minimum at the bell (antinode).

A numerical measure of this resonance is the 'Sound Transmission Funcction' (STF), defined as the ratio of the inlet (mouthpiece) pressure over the outlet (bell) pressure. The FE models clearly show particular frequencies that produce a simultaneous maximum inlet (mouthpiece) pressure and minimum outlet (bell) pressure, as were predicted for instrument resonances. In between these peaks (the vast majority of data points) the STF typically varies around 30 orders of magnitude less. These would correspond to room resonances.

However we note that the STF will produce peaks corresponding to *all* the 'open' notes (no valves depressed) available on the instruments, a harmonic series based on B♭ , or approximately multiples of 116 Hz (but excluding the fundamental). The experiments on the other hand were based on the note F_4 (349 Hz) and only exact integer multiples of this will be in the spectrum, thus only resonances that are near integer mutiples of this note will be excited, i.e. every third possible overtone. The other overtones will be inactive when this note is played.

The STFs presented below therefore will only include overtones of F_4 (349 Hz) since the STF is being used as a proxy for the instrument spectrum. The peaks are shown as single points since, as explained above, all other data are negligible. Figure 5 shows the results for the three instruments.

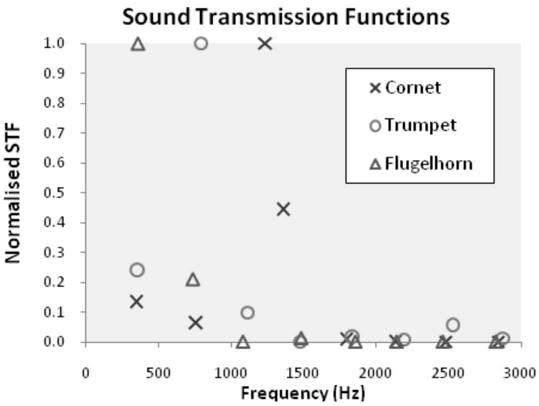

Figure 5. Sound transmission functions of the three instrument FE models (only overtones of the note F4 shown)

EXPERIMENTAL WORK

Procedure

The objective was to record representative sounds produced by an expertly played B♭ trumpet, cornet and flugelhorn, and to identify distinguishing features of the frequency spectra attributable specifically to the instruments, in order to validate the numerical model presented later.

Two musicians were used in this recording in order to quantify, and hopefully substantially rule out, the influence of the player on the results. Both of these musicians were classically trained Honours students at the Tasmanian Conservatorium of Music.

To achieve the aim of identifying differences attributable to the instruments it was essential to maintain reproducible experimental conditions, so standard conditions were defined to eliminate variables such as playing style, pitch, attack and envelope, make and model of the instruments, room conditions, microphone quality and recording quality.

Each musician was asked to play and sustain the note F_4 (nominally 349 Hz in equal tempered tuning referenced to A440) at a mezzoforte (i.e. moderately loud) level on each of the three instruments. This pitch was chosen because it is a mid-range 'open' note (no valves depressed). Players were also instructed to use the same playing technique for each instrument. As the two players shared the same trumpet, cornet and flugelhorn we will define 'instrument' throughout the paper generically to mean one of these three without needing to specify the make or model. The length of the mouthpiece which was inserted into the instrument was also noted during this stage.

The instruments were recorded in the main recording studio of the Conservatorium of Music at the University of Tasmania. This is an acoustically dry space (though not anechoic) so the microphone, placed approximately 100 mm longitudinally and offset 30 mm from the centreline of the bell outlet, was in the near field, capturing predominantly direct sound with negligible colouration from the reverberant field.

The temperature of this room was 21^{o}C. The microphone used was a highly sensitive Naked Eye "Roswellite" ribbon microphone, and it was located as close to the bell as possible without damaging the microphone. The recording was done on Pro Tools 9 for Mac and saved as high resolution .WAV files.

Results

The FFTs of the notes showed very little difference from player to player. As shown in Figures 6 and 7, on the cornet, the amplitude of the third harmonic is significantly larger than the rest, followed by the first, second and fourth harmonics, which were approximately equal. The higher harmonics all had progressively much lower amplitudes.

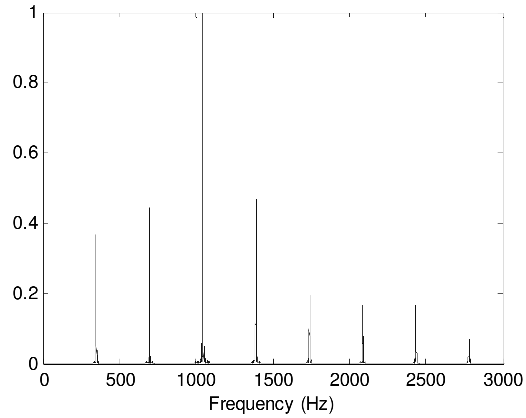

Figure 6. FFT of sustained F_4 note on cornet by Player 1, normalised with respect to dominant spectral peak.

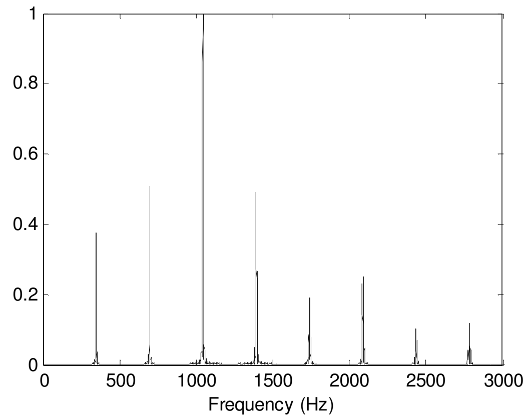

Figure 7. FFT of sustained F_4 note on cornet by Player 2, normalised with respect to dominant spectral peak.

Similar agreement between Player 1 and Player 2 spectra was observed on the other two instruments also, and it was concluded that the players were not affecting the sound significantly, thus presented results below are for Player 1 only (i.e. Figure 6 corresponds to Figure 9 later).

Figures 8 and 10 show spectra for the other two instruments. The three spectra clearly show distinguishing features, the most obvious being the dominant harmonic, which is the third for the trumpet and cornet, and the first for the flugelhorn. This confers with the aural observation that the flugelhorn has a mellow timbre while the trumpet and cornet have a much brighter timbre – the presence of the higher frequencies creates the brighter sound much like turning the treble up on a stereo.

The trumpet and cornet differ most in the relative magnitudes of the secondary peaks (1^{st}, 2^{nd}, 4^{th} and 5^{th} harmonics), which are significantly stronger for the trumpet.

RESULTS AND DISCUSSION

Spectral amplitudes

Figures 8–10 compare the simulated STF peaks with the measured spectra for each instrument.

The agreement is remarkably good considering the approximations made, in particular the absence of a lip model. Of particular note is the identification of the dominant spectral peak for the cornet and flugelhorn on the third and first harmonics respectively.

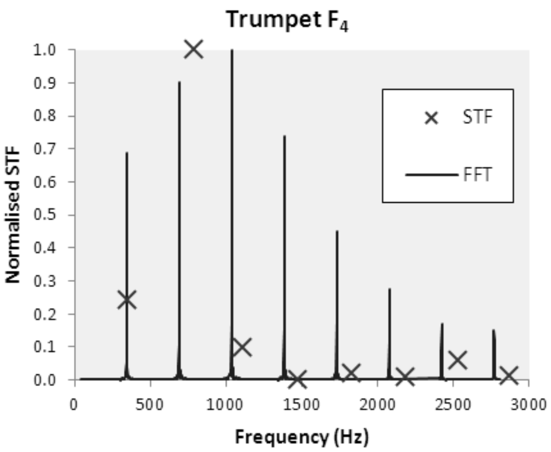

Figure 8. Sound Transmission Function of the trumpet FE model compared with the recorded FFT of the sustained F_4 note on the trumpet played by Player 1, normalised with respect to dominant spectral peak

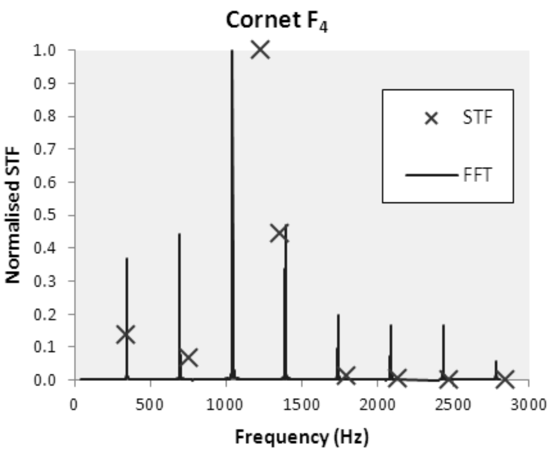

Figure 9. Sound Transmission Function of the cornet FE model compared with the recorded FFT of the sustained F_4 note on the cornet played by Player 1, normalised with respect to dominant spectral peak

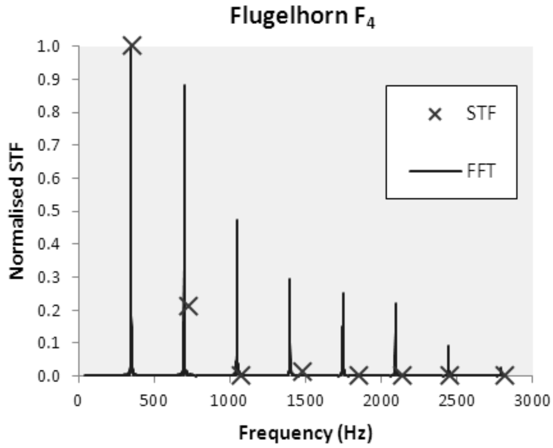

Figure 10: Sound Transmission Function of the flugelhorn FE model compared with the recorded FFT of the sustained F_4 note on the flugelhorn played by Player 1, normalised with respect to dominant spectral peak

There are also some significant discrepancies, to be expected. Most notably the FE model fails to predict the strong third harmonic of the trumpet spectrum.

The low STF for high frequencies is also a consistent trend. This may be due to the linear solution. As noted earlier there may be nonlinearities introduced in particular by the throat of the mouthpiece, which could account for the increased spectral energy in the higher frequencies of the measured results.

Clearly however the FE models were able to capture significant differences between instruments, and these are broadly consistent with measured results, hence the numerical modelling confirmed that the instrument geometry does play an important role in shaping the timbre of the instrument.

Relative influences of instrument, mouthpiece and player

In view of the negligible difference noted earlier between the trumpet and cornet tubing and bell geometry, yet significant difference in both measured and simulated spectra, a further model was created to test the influence of mouthpieces on the sound of the instrument. This model consisted of the trumpet mouthpiece connected to the flugelhorn tube and bell. However this could not be reproduced experimentally since the instruments had different bores and (even if an effective seal could be created) there was a risk of damage to the instruments and mouthpiece.

The inlet (mouthpiece) pressure spectra provided further evidence for the influence of the mouthpiece. The trumpet (illustrated in Figure 11), cornet and flugelhorn inlet pressures showed dominant spectral peaks at around 790 Hz, 660 Hz and 1150 Hz respectively.

Figure 12 shows a comparison of the STFs of the standard trumpet and flugelhorn, and the modified flugelhorn. The modified instrument has its dominant peak at the first harmonic, as the original flugelhorn does, however the second harmonic of the flugelhorn increases from around 20% to 75% with the change to the trumpet mouthpiece, much sloser to the original trumpet's peak. This shows the trumpet mouthpiece to be a significant factor in influencing the strong second harmonic.

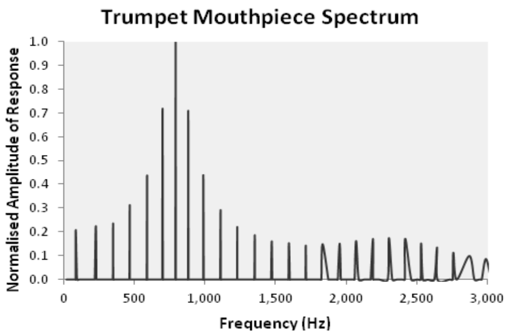

Figure 11. Normalised inlet pressure spectrum of the trumpet FE model

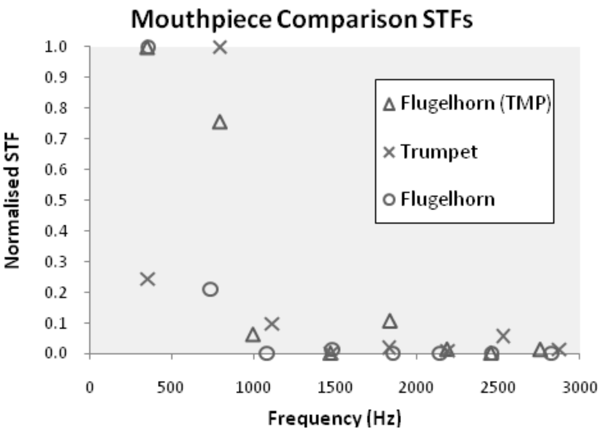

Figure 12. Sound Transmission Function of the modified flugelhorn FE model with trumpet mouthpiece (TMP) compared with the standard trumpet and flugelhorn (using the orthodox mouthpieces)

RECOMMENDATIONS AND CONCLUSIONS

Clear measurable differences were observed between the three instruments by both the experiments and the simulations.

The numerical modelling was successful, resulting in surprisingly good correlation between the FEA and measured results in spite of the simplifications made and that not identical quantities were being compared. This is very encouraging for further work.

The sound transmission function proved to be a useful way to quantify the ease with which a given frequency is excited when the instruments were played.

The tube and mouthpiece geometries were both shown to have a profound effect on the characteristic sound of each instrument. As might be expected the tube influenced more the lower frequencies while the mouthpiece had a greater influence on the mid-range frequencies (around 800Hz).

It is hoped to extend this work to model the lips and hence the sound generation mechanism. It is expected that this will further improve predictions by three mechanisms: through enabling different notes to be explicitly selected, through forcing the harmonics to be integer multiples of the forcing frequency, and through accounting for nonlinearities in the forcing function. However the same lip model would be applicable to all instruments so this does not invalidate the findings of the relative differences between the instruments.

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