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An Exploration of Extreme High Notes in Brass Playing

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ABSTRACT

Some of the most striking examples of playing at the extremes of the high register of a brass instrument can be heard in modern commercial trumpet playing. Many other examples of very high brass playing are also found in the clarino writing for trumpets and orchestral horns in the late 17th and early 18th centuries. A distinctive acoustical feature of this style of playing is that the notes sounded are above what is normally considered to be the cut-off frequency of the instrument. This means that there is little or no reflection of the pressure wave from the bell of the instrument back to the player's lips, which is a requirement for establishing a strong coupling between the lips and the air column. Below the cut-off frequency, the threshold pressure for a played note is lowest close to one of the air column resonance frequencies; the corresponding experience of the player is that the lips are guided into pitch 'slots' close to the resonance frequencies. However, skilled players frequently claim that they can also experience distinct 'slots' when playing in the extremely high register. This paper explores three different approaches for investigating the physics of the lips, air column and resonator in playing extreme high notes: a recently developed multiple microphone technique has been applied to the separation of the forward and backward going waves in an instrument under playing conditions, high speed filming of the player's lips using specially designed mouthpieces with optical access has been utilised to examine the mechanics of brass playing in the high register, and a study has been undertaken of the transfer function between mouthpiece and bell at high frequencies and high amplitudes.

INTRODUCTION

Brass musical instruments feature the player’s lips, which act as a nonlinear valve to control the input of energy, coupled to an acoustic resonator. Players are able to play notes whose frequencies are close to those of one of the resonances predicted by linear acoustic theory. The resonances may be predicted by looking for peaks in the theoretical or experimental plot of the input impedance peaks. In general low frequencies reflect strongly from the open end of a trumpet and it is this process which is responsible for the formation or resonance and anti-resonance depending on whether the reflection is in phase or out of phase for the frequencies under consideration. Players’ lips can be buzzed close to the frequency of one of the input impedance peaks to create strong resonance, while attempting to buzz the lips at a frequency half way between peaks will not produce a convincing note, but rather the note will change during the initial transient into a note at one of the nearby peak frequencies. Players sometimes refer to the frequencies or pitches where they can play notes as ‘slots’. These ‘slots’ are essential to the performance and tuning of brass instruments.

Very high frequencies travel straight out of the bell due to the laws of diffraction. This explains why the number of strong input impedance peaks in brass instruments is limited. Very high notes on brass instruments are therefore expected to involve very little of the energy input to the mouthpiece being reflected back from the bell. This in turn implies that any note can be sounded by the lips, but only weakly. There will be a region in between the two extremes in which highly skilled players playing carefully designed instruments can get extremely high notes in spite of linear acoustics predicting a very small level of reflection of energy from the bell.

An example of the passive acoustic input impedance of a high quality modern trumpet and mouthpiece combination, typical of that used by trumpet players specialising playing in the highest register of the instrument, is shown in figure 1. The input impedance was measured using the commercially available BIAS system [1]. The figure shows a notional cut-off frequency at around the 12th resonant mode (corresponding to F_6). Close inspection of the impedance curve above this frequency reveals that there are small resonances at the frequencies we would expect but that these are much less well defined. It is not clear if these small peaks are sufficient for an experienced player to identify as useful ‘slots’, or if there are other, nonlinear effects, for example which provide slots for extreme high notes.

A long term aim of current research is to be able to determine when reflections are producing ‘slots’ available to the player.

In order to understand how trumpet playing works, and to assess how high in frequency we can expect reflections to occur, from a physics point of view it is useful to analyse and compare the acoustic pressure at different points along the instrument. This paper will explore the possible techniques that may be used for this purpose, namely wave separation, transfer function measurement along with high speed filming of players' lips.

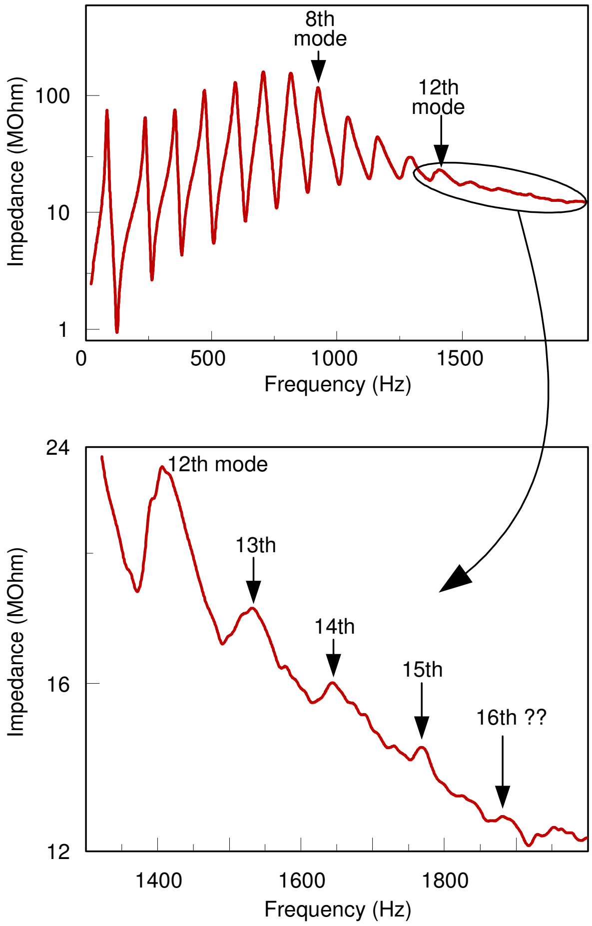


Figure 1. Input impedance of a modern trumpet and mouthpiece combination as used by specialist high players.

WAVE SEPARATION

The various different experimental approaches to measuring the acoustic behaviour of tubular objects have been reviewed by Dalmont [2] and in Dickens et al. [3]. Most techniques use more than one sensor to enable the determination of both pressure and volume velocity as the acoustic impedance is defined as the ratio of these two quantities. Most, including van Walstijn et al. [4] use frequency domain analysis using a pair of microphones. Multiple microphone spacings must be used to obtain a full frequency range analysis as there are singularities when the microphone spacing matches half of a wavelength.

Recently a technique has been developed which combines any number of multiple microphone recordings into a single time domain analysis algorithm [5]. This technique has been applied for the separation of the forward and backward going waves in horns while they are being played by a human player [6]. In the current work we briefly summarise the method and show results of wave separation while a trumpet is being played by a player.

Calibration

A cylindrical source tube is used and a schematic of the calibration measurement apparatus is shown in figure 2. Calibration may be performed by playing a logarithmic sine sweep through a Denon hi-fi amplifier out of a JBL 2426J compression driver loudspeaker. Sound input and output was handled with a Focusrite Saffire Pro 10 audio interface with PCB 106B microphones used for horn measurements and Endevco 8507C microphones used for trumpet measurements.

The signals at three microphones mounted in the source tube wall were recorded and analysed to determine the impulse-like time domain transfer function for travel between each pair of microphones [5]. This is achieved by using frequency domain division of the signals at each pair of microphones (with a smooth frequency domain low pass filter applied to minimise ripple) as described in Kemp et al. [5]. The source tube is cylindrical and extends for around 33 cm after the last microphone and time domain windowing is used to remove artefacts of multiple reflections from source tube ends [5]. The calibration is performed twice, once with the loudspeaker at each end of the apparatus to determine both forward and backward going versions of the time domain transfer functions, which differ due to unequal microphone gains and non-simultaneous sampling of soundcard inputs.

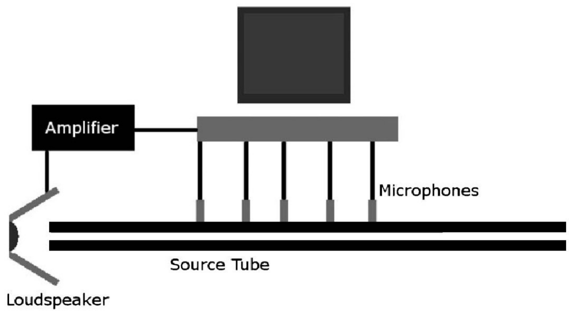
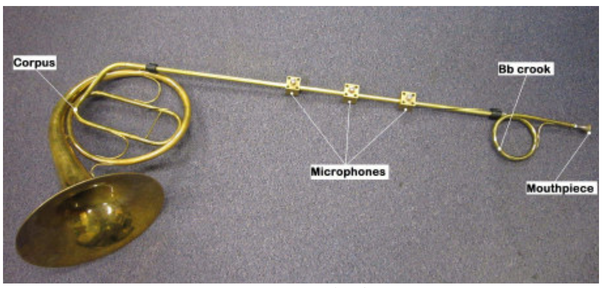


Figure 2. Schematic of calibration of the wave separation apparatus

Wave Separation in the Horn

Once the time domain transfer functions are known between each pair of microphones, the cylindrical "source tube" or "measurement duct" can be used as the middle section in the bore of a brass musical instrument such as a horn or trumpet. A schematic of such an arrangement for a natural horn made by Jiracek is shown in figure 3. Using the Bb crook in conjunction with the cylindrical source tube produces a bore very similar to that produced when the F crook is used as demonstrated in Reference [7].



Source: (Kemp et al. [5], 2010)

Figure 3. Photograph of apparatus used for playing conditions wave separation in horn

Signals recorded can then be analysed to determine the forward and backward going waves when the instrument is played by a human player. The player was encouraged to only play short notes (around 0.5 seconds) in order to prevent excess moisture and temperature changes from invalidating the calibration. In the longer term adaptive filter approaches may be used as discussed in work by van Walstijn and de Sanctus [8,9]. The analysis was performed using the wave separation algorithm described in Kemp et al. [5,6].

An example of the 5th mode of the Jiracek natural horn is shown in figure 4. It is interesting to note that the forward going wave as measured at the 3rd microphone (i.e. the microphone furthest from the mouthpiece) matches the measured signal until the reflections of that signal return from the bell after around three cycles of the forward going wave. Because the bell is an open end, the reflected energy is reflected with negative amplitude. A further five cycles later the amplitude of the forward going wave increases suddenly and this may be understood as being the result of the initial reflections from the bell having reached the mouthpiece in the appropriate phase to result in an increase in the forward going wave. The complex shape of the measured signal is found to be created by smoothly varying forward and backward going waves. It should be noted that the backward going wave matches the frequency of the forward going waves but has a lower amplitude due to radiation from the bell. The error term is determined by taking the standard deviation in the predictions of the forward going wave obtained by convolution of the forward going waves from the other microphones.

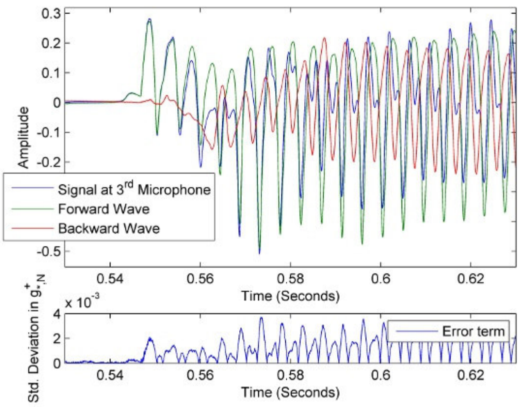


Figure 4. Wave separation for 5th mode on horn

Wave Separation in the Trumpet

In order to create a playable instrument, three microphones were mounted into the wall of the curved, constant cross-section tuning slide section of a trumpet manufactured by Smith Watkins trumpets. This tuning slide section was removable for calibration purposes. The results for the 4th mode of the trumpet are shown in figure 5. This sounds the pitch C_5 on the trumpet (concert Bb_4). Again the periodic waveform from the players lips reflect with negative sign, this time after around two cycles. The reinforcement of the forward going waves appear to occur after around four or five periods later.

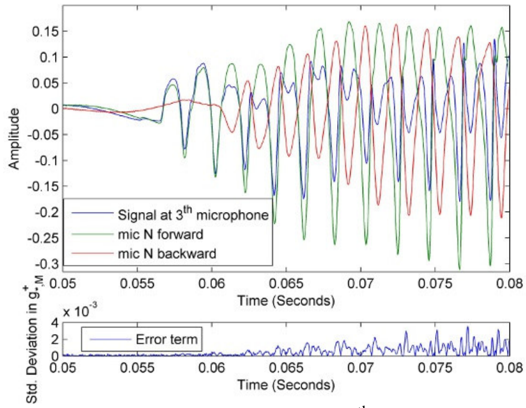


Figure 5. Wave separation for the 4th mode on trumpet

TRANSFER FUNCTION MEASUREMENT

It is useful to compare the signal measured in the mouthpiece and the signal radiated from the bell in the frequency range of interest. In order to achieve this, a JBL 2446H horn loudspeaker driver was used to drive the mouthpiece of a trumpet using a 10 second linear sine sweep from 900Hz to 2500Hz. The input pressure was measured using a PCB 106B microphone located in a cylindrical cavity to which the mouthpiece of the trumpet was connected, and a Brüel and Kjær 4192 pressure-field microphone recorded the signal on axis in the plane of the trumpet bell. Recordings were made at a sample rate of 51.2 KHz and the resulting signals were split into sections of 1000 samples for analysis. The transfer function for each section of the sweep was then calculated by taking the ratio of the root mean square pressures in the plane of the bell and at the mouthpiece.

The results are plotted in figure 6. The dips observed in the transfer function, marked by arrows, correspond to resonances of the instrument. The frequencies are lower than those of the peaks in the input impedance curve shown in Figure 1; this reduction is attributed to the effect of the microphone cavity which effectively increases the volume of the mouthpiece. The transfer function curve confirms that there are weak resonances at least up to the 16th mode in the trumpet. Further testing using techniques such as wave separation will be required to prove if these resonances are sufficient to influence the lips of the player.

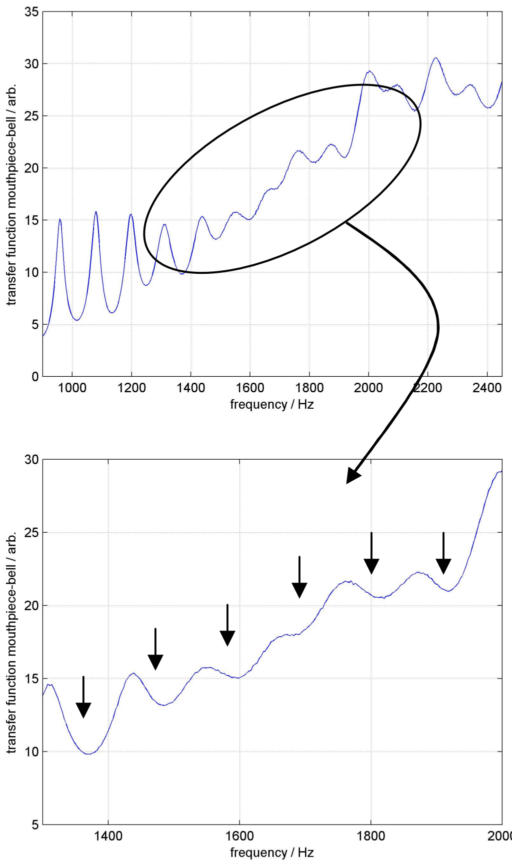


Figure 6. Transfer function between mouthpiece and outside bell for a modern trumpet and mouthpiece combination as used by specialist high players

HIGH SPEED FILMING

To gain a better understanding of the mechanics of the player's lips when playing in the high register, a high speed video camera was used to focus on the lips through a transparent mouthpiece. This was a commercially available shallow cup trumpet mouthpiece injection moulded from an undyed polycarbonate. From the outside of the mouthpiece, in the region of the cup, some material had been machined away to make the walls of the cup thinner and so reducing optical distortion.

The experimental set-up is as shown in figure 7. A high speed camera (Vision Research Inc. Phantom v4.1 camera), set to take 10000 frames per second, was focused on the player's lips. Necessary additional illumination was provided by a fibre optic 'cold' light source. A 106B PCB Piezotronics dynamic pressure transducer was used to measure the pressure in the backbore mouthpiece. Radiated sound from the bell of the instrument was measured using a Brüel and Kjær 4192 pressure-field microphone, located one bell diameter from the plane of the bell of the instrument. Signals from both transducers were fed to a Brüel and Kjær PULSE system for data acquisition and synchronisation with the high speed video data.

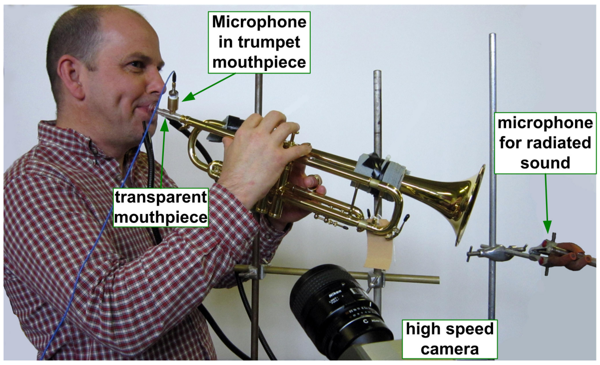


Figure 7. Experimental set-up for high speed filming

Each frame from the high speed film is 'binarised' such that the open area of the lips can be identified and isolated from the rest of the image. Despite the inevitable image distortion resulting from a combination of refraction through the wall of the mouthpiece together with the indirect camera angle, a pixel count of the open area in each frame would provide a qualitative assessment of the movement of the lips.

The open area as a function of time, for the 8th and 12th resonant modes can be seen in figure 8. The figure shows that the lips are opening and closing once per cycle and that there are no sub-harmonic or other unusual phenomena occurring for notes played in the high register.

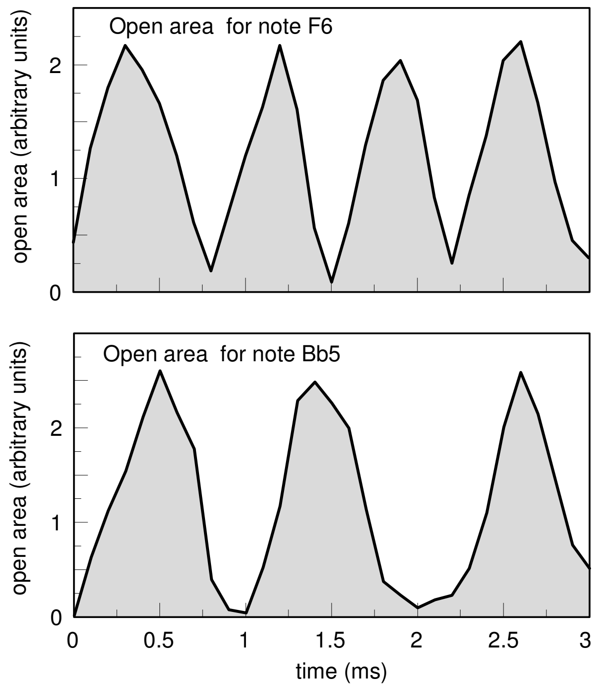


Figure 8. Open area as a function of time for the 8th and 12th modes

CONCLUSIONS

The physics involved in playing super high notes on brass instruments is currently being illuminated by various different techniques, It is apparent from standard linear analysis and measurement techniques that the air column resonances become increasingly weak with increasing frequency. Skilled players extract extremely high notes, such as the 16th mode of a trumpet air column, in a frequency range where the experimentally determined input impedance ceases to show strong harmonic peaks. Techniques such as multiple microphone wave separation, high speed filming and transfer function analysis have the potential to determine the interaction between the reflections within the air column and the motion of the player's lips. Further work will involve designing improved mouthpieces with optical access in order to facilitate accurate high speed filming of super high notes and assessment of the effect of non-linearities on wave separation and transfer function techniques.

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