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ACOUSTICAL BEHAVIOUR OF VENT HOLES ON BRASSWIND INSTRUMENTS

Marco Aragó Bishop [1*] **Arnold Myers**[2] **Murray Campbell**[1]

[1] School of Physics and Astronomy, The University of Edinburgh, Edinburgh, UK
[2] Royal Conservatoire of Scotland, Glasgow, UK

ABSTRACT

In most brass instruments, the acoustical resonator forms a cylindrically symmetric tube open at both ends. Sound is produced by the vibrations of the player's lips at the input end and radiates through the bell at the exit. Typically, these are the only two openings in brass instruments. However, in specific categories, such as the trumpets used in many modern performances by period orchestras, additional holes are drilled into the sides of the tube. The player can open or close these holes to improve the instrument's intonation and stability, particularly in baroque performances.

This paper studies the acoustical behaviour of two of the vent holes in a four-hole vented trumpet, for which the most notable behaviour is observed. The input impedance is measured using the BIAS system for all possible venting fingerings. These experimental results are compared with numerical simulations using the Openwind framework, with input data derived from mechanical measurements of the bore profile of the trumpet.

Keywords: *brass instruments, vented trumpet, input impedance, resonances, vent holes.*

1. INTRODUCTION

Brass instruments produce sound by modulating airflow through the player's vibrating lips at the mouthpiece, initiating oscillations in the air column within the instrument. This lip-driven excitation is what acoustically defines the family of brass instruments. Most modern examples, such as the trumpet, trombone, and tuba, are made of metal and incorporate valves or a slide mechanism to vary the effective tube length. By altering the tube's length, the player adjusts the instrument's resonant frequencies to match the lip vibration, allowing different notes to be played.

A notable exception is the natural trumpet, which lacks holes or valves, requiring players to rely solely on their embouchure and breath control to produce a range of pitches. The instrument's geometry is almost cylindrical, with an expanding bell at the end, requiring an appropriate mouthpiece to be played. With this configuration, the instrument can produce a series of pitched sounds close to that of a harmonic series, producing natural notes up to the 16$^{\text{th}}$ harmonic and beyond [1].

As with other brass instruments, the frequencies of the resonances of the natural trumpet form an approximately harmonic series. Nonetheless, even if they were perfectly harmonic, those pitches would not necessarily be considered "in tune" since neither the tempered scales nor the specific tuning requirements of a performance situation match a pure harmonic series. Consequently, natural trumpet players must be highly skilled to refine the pitch of the sound emitted by carefully adjusting embouchure, vocal tract, and breathing. Of particular difficulty is the high register, commonly known as the *clarino* register, which includes high-frequency notes that are closely spaced. This register is particularly challenging for players when performed at loud dynamics due to the instrument's resonances strongly dictating the pitches produced, which inherently limits the player's ability to control it with precision.

**Corresponding author*: phyarago@gmail.com.

The vented trumpet was invented in the second half of the twentieth century to facilitate stability and control of intonation in playing. Up to four vent holes were added, connecting the instrument's internal air column to the outside atmosphere, thereby reducing the amplitude of the pressure waves near the holes. This effect is comparable to cutting off the tubing portion below the hole for low frequencies. However, recent research has shown that the acoustical effects caused by opening the smaller vent holes are more subtle and require further analysis [2].

In this paper, the acoustical behaviour of two of the vent holes in an available four-hole vented trumpet crooked in D is presented. The analysis is restricted to the instrument's resonating air column, which is modelled in its linear regime through the input impedance Z_{in}, defined as the frequency-dependent ratio between the acoustic pressure and the volume flow at the instrument's entrance. The input impedance is measured using the BIAS system [3] for all possible venting fingerings. These experimental results are compared with simulations using the Openwind framework [4]. Input data for simulations is provided from mechanical measurements of the bore profile of the vented trumpet.

2. LINEAR ACOUSTICS OF RESONATOR

From a physical point of view, a wind instrument can be characterised by a non-linear excitation source coupled with a passive resonator, which is mainly reduced to its linear response. The latter provides a number of resonances, which interact with the non-linear source to produce the pitch and waveform of the played note [5]. In this study, the analysis is restricted to the linear acoustical response of the instrument.

To describe the system, we make use of the concept of acoustic impedance, which relates the acoustic pressure p to the particle velocity field $\underline{u}$. Since the velocity field is a vectorial quantity, the impedance is, in general, direction-dependent. However, in the case of tubular geometries and under the plane wave approximation, the particle velocity is assumed to be oriented along the longitudinal axis of the tube. As a result, the directional dependence of the impedance can be neglected. This approximation holds when the tube length is significantly larger than its radius, a condition satisfied by the vented trumpet examined.

In particular, the input impedance is of special interest, offering a convenient way to analyse brass instruments, as the magnitude of the input impedance explicitly shows the frequencies and amplitudes of the resonances on which the played notes are based [6]. It is, therefore, used as an invaluable way to characterise the instrument. Furthermore, it is possible to express the input impedance in terms of modal parameters [5],

$$Z_{in}(\omega) = i\omega \sum_m \frac{p_m^2(0)}{\omega_m^2 + i\omega\omega_m/Q_m - \omega^2}, \tag{1}$$

where each linear term only depends on the angular frequency ω_m, amplitude $p_m^2(0)$ and quality factor Q_m of resonance m. This approach allows for efficient analysis of the resonator and hole effects, as specific resonances can be either boosted or suppressed depending on the playing requirements. In this framework, the behaviour of the vent holes can be analysed through the variation of the modal parameters associated with each resonance, providing a means to characterise their influence on the overall acoustical response.

2.1 Vent Holes

When opening a hole in an axially symmetric tube, the intended musical purpose must be taken into consideration. For vent holes, this corresponds to a strategically placed hole that is not used to define a new fundamental frequency but instead, when opened, helps with intonation correction, response improvement, or sound clarity.

The hole is studied by considering the component as an additional short tube in the instrument's geometry. In energetic terms, when a sinusoid travelling down the pipe encounters a hole, some of the energy is transmitted towards the bell end, some is radiated from the hole, and the remaining energy is reflected to the input. Therefore, the shape of the standing wave formed within the air column changes along the length of the instrument, even if the radius of the tube is constant throughout.

A proper parameter to characterise the energy in the system is the sound power transmission T, defined as the fraction of sound energy which is transmitted past the hole [7],

$$T = \frac{1}{1 + (cb^2/4\pi h_e r^2 f)^2}, \tag{2}$$

where c is the speed of sound, f is the frequency of the sound wave, b is the hole radius, and h_e is the effective acoustic length of the side branch.

At low frequencies, the power transmission rapidly approaches zero, indicating an effective cutoff of the main bore's right section. As the frequency increases, the transmission tends toward unity, with most of the sound propagating through the pipe, behaving as a high-pass filter. As a consequence, the effect of the hole on each resonance will vary depending on its frequency relative to this filtering behaviour. A useful parameter to characterise the hole is the cutoff frequency, defined as the frequency at which $T = \frac{1}{2}$. Resonances below the cutoff frequency will be significantly affected by the presence of the hole, while those above it will remain largely unaffected.

3. CALCULATING INPUT IMPEDANCE

The simulations performed on the vented trumpet rely on an accurate description of the instrument's bore profile, as well as ambient conditions matched to those of the experimental measurements. To maximise reproducibility between experiments and simulations, all relevant elements of the instrument were carefully measured. Assuming the main bore of the instrument is an axially symmetric tube, the geometry can be fully characterised by the radius as a function of the axial position. Accordingly, both the length of the pipe and the variation of its radius along the axis were measured mechanically using bore gauges. A three-dimensional reconstruction of the trumpet bore is shown in Fig. 1.

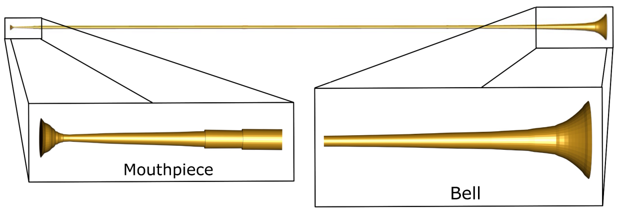

Figure 1. 3D model of vented trumpet geometry used in the Openwind simulation. A zoomed view of the shape of the mouthpiece and bell is shown. The total length of the bore is $L = 2.25\,\mathrm{m}$.

In this setup, following a systematic asymptotic analysis [8], the Webster horn equation, describing wave propagation in pipes of varying cross-sectional area, is reformulated as a pair of Telegrapher equations to model the system while accounting for viscothermal losses [9,10]. A Finite Element Method (FEM) approach, implemented in the Openwind framework, was employed to solve the system numerically. This method allows for the computation of the input impedance, as well as the pressure and volume flow fields along the bore, which were used to analyse the behaviour further.

The scheme enables the definition of the ambient conditions. For consistency with the experimental measurements, the temperature was set to $17\,^{\circ}\mathrm{C}$, and a radiation impedance for an infinitely flanged pipe was imposed as the boundary condition at the pipe end [11].

4. MEASURING INPUT IMPEDANCE

The input impedance was measured using the Brass Instrument Analysis System (BIAS), which offers a fast and accessible method to perform many successive measurements on the impedance of brass instruments [12]. It relies on a capillary-based technique, where two microphones are positioned on either side of a high-impedance capillary, which is then connected to the mouthpiece [3]. The experimental setup of the BIAS head mounted with a vented trumpet is shown in Fig. 2.

Figure 2. Experimental setup of the BIAS head mounted with the vented trumpet in the anechoic chamber.

Impedance data was collected using the Versatile Instrument Analysis System (VIAS) software, which allows for higher energy in the excitation signal and user-selected time and frequency range for each measurement. Measurements were performed using a logarithmic sweep from $20\,\mathrm{Hz}$ to $4\,\mathrm{kHz}$ with a period of $600\,\mathrm{s}$ using a sinusoidal excitation signal, ensuring adequate time for standing wave formation at lower frequencies.

Using this experimental configuration, the input impedance of the vented trumpet was measured systematically by opening one vent hole at a time. To replicate the opening and closing of holes as a player would with their fingers while ensuring consistency across measurements, all holes were appropriately sealed and maintained airtight closure except for tests when a single hole was opened. To ensure this was the case for all measurements, a reading of the impedance with all holes closed was taken at the beginning and end of the sessions, verifying the stability of the procedure.

5. RESULTS

The positions along the bore and dimensions of two vent holes on the vented trumpet are listed in Tab. 1, referred to as the thumb hole (hole 1) and octave hole (hole 4), with hole 1 having the larger radius. Due to the curved instrument surface, chimney height was defined as the maximum distance from the surface to the top edge of the hole, measured along the local normal and assumed constant across the hole.

Table 1. Position, radius, and chimney length of holes 1 and 4. Errors indicated in parentheses.

Hole	Position [m]	Radius [mm]	Chimney [mm]
Hole 1	1.1920(1)	3.72(5)	0.68(5)
Hole 4	1.0455(1)	1.75(5)	0.63(5)

Thus, opening hole 1 is expected to significantly alter the instrument's resonances. The measured input impedance in this configuration is shown in Fig. 3, where each peak corresponds to a resonance.

The large radius results in minimal energy transmission beyond the hole, leading to a general upward shift in resonance frequencies. In particular, the hole dimensions translate to a cutoff frequency of approximately 1913 Hz, which is well above the intended playing frequencies with the hole open. Consequently, the hole significantly alters the resonance structure in this frequency range. Moreover, Fig. 3 reveals a general trend in the impedance magnitude: odd resonances exhibit increased amplitude due to constructive interference of pressure waves upstream of the hole, whereas even resonances are attenuated as a result of destructive interference, leading to a reduction in the input impedance amplitude. These effects progressively diminish for resonances approaching the cutoff frequency.

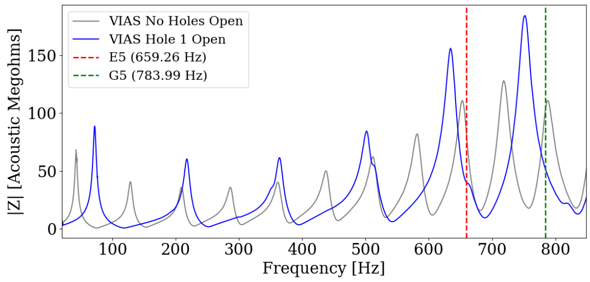

Figure 3. Input impedance magnitude measured for the vented trumpet with hole 1 opened (blue), and all holes closed (grey). The vertical dashed lines indicate the frequencies of the pitches for which the hole is opened, as indicated in the legend.

The intended playing frequencies with the hole open are occasionally E5 and, more importantly, G5, primarily improving playing security and intonation of the notes. However, in both cases, the nearest resonances (nine and eleven) undergo significant frequency shifts, reducing their amplitudes near the playing frequencies. At first glance, considering a simplistic approach in which the pitch is determined mainly by the closest resonance to the playing frequency, this suggests a negative impact on playability. Yet, analysis of the pressure and flow fields for the weak resonance just above G5 reveals a distinct acoustic effect which must be taken into account.

Fig. 4 shows the pressure and volume flow fields comparison between the large resonance with all holes closed at 790.30 Hz and the small resonance with hole 1 opened at 829.19 Hz, those closest to the G5 playing frequency. The apparent small pressure amplitude for the weak resonance with respect to the large resonance at the input is responsible for the small impedance magnitude observed previously.

A closer inspection of the pressure field reveals greater constructive interference occurring between the hole and the instrument's bell rather than between the input and the hole, thus increasing the amplitude of the standing wave pattern downstream of the hole. This suggests that the segment extending from the hole to the bell supports a robust resonance with pressure nodes at both boundaries near the resonance frequency. Consequently, a high flow amplitude is expected at the bell end, consistent with the bottom plot of Fig. 4. The intensified standing wave pattern downstream of the hole corresponds to an increased energy concentration in that region. Given the relatively high flow amplitude at the bell compared to the overall wave amplitude, significant acoustic energy is radiated efficiently from the bell, facilitating the stable production of the G5 pitch despite the small amplitude of the associated resonance.

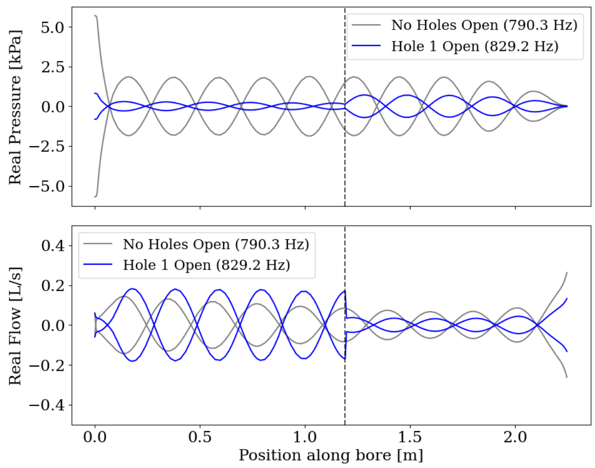

Figure 4. Top: Real part of complex pressure field along the bore for the resonance frequencies closest to G5. Bottom: Real part of the complex volume flow field along the bore is for the resonance frequencies closest to G5. The grey line indicates the closest resonance with all holes closed. The blue line indicates the closest resonance with hole 1 opened. The vertical dashed line indicates the hole position.

A similar behaviour was observed for hole 4. From Tab. 1, hole 4 has the lowest radius, thereby having the smallest cutoff frequency at 817 Hz. The qualitative behaviour of the fourth hole was found to be equivalent for both even and odd resonances. However, due to the small dimensions of the hole, these effects are drastically reduced as the resonances approach the cutoff frequency, giving a significantly different input impedance as compared to hole 1. For instance, the suppression of the even resonances is highly reduced near the cutoff frequency.

Hole 4 comprises the playing of notes corresponding to the even harmonics of D2. Fig. 5 shows three of these notes (D5, F♯5, A5) with their corresponding playing frequency to exemplify the acoustic behaviour of the hole. By opening hole 4, the resonances closest to the even harmonic playing frequencies have been shifted in frequency closer to these, notably improving the intonation of the notes. However, as for the case of hole 1, these resonances are somewhat suppressed by the hole. Therefore, the playability of the notes could be compromised.

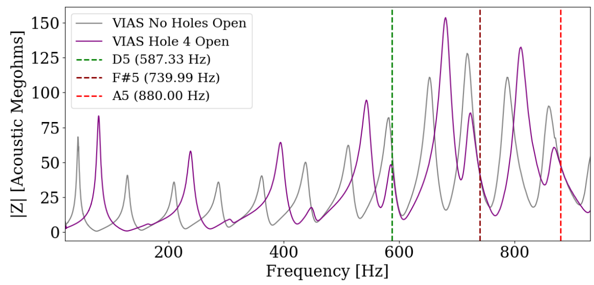

Figure 5. Input impedance magnitude measured for the vented trumpet with hole 4 opened (purple) and all holes closed (grey). The vertical dashed lines indicate the frequencies of the pitches for which the hole is opened, as indicated in the legend.

Nonetheless, the same reasoning applied to hole 1 extends to the acoustic pressure field and volume flow in this case. For the even resonances, a stronger standing wave pattern develops downstream of the hole, increasing flow amplitude at the bell and boosting sound radiation, thereby improving the stability of the even harmonics of D2.

6. CONCLUSION

The acoustical behaviour of the thumb and octave vent holes in an available four-hole vented trumpet has been examined. Under a linear approximation, the input impedance was used to determine the behaviour of the resonances of the system by observing variations in the amplitude, frequency and quality factors of each resonance when a hole was opened along the tube. The input impedance was measured experimentally using the BIAS system, and numerical simulations using the FEM were used to analyse the behaviour of each resonance in greater detail.

The opening of the thumb hole (hole 1) showed the nearest resonances to the intended playing frequencies to undergo a significant frequency shift and an evident reduction in their impedance amplitude, which suggested, at first instance, a negative impact on the playability. However, the acoustic pressure and volume flow fields calculated from the simulations on the instrument for these resonances showed a constructive interference occurring between the hole and the instrument's bell rather than across the input and the hole, thus increasing the amplitude of the standing wave pattern downstream the hole. The intensified standing wave pattern corresponds to an increased energy concentration in that region, and, as a result, significant energy is radiated efficiently from the bell, facilitating the stable production of the notes for which the closest resonances were observed to reduce their amplitude. A similar behaviour was observed for the octave hole (hole 4).

7. ACKNOWLEDGMENTS

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