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How does a closed long chimney affect the sound of conical reed wind instruments?

Timo Grothe¹, Augustin Ernoult²

¹ *Erich-Thienhaus Institut, Hochschule für Musik Detmold, 32756 Detmold, Deutschland, Email: timo.grothe@hfm-detmold.de*

² *Project-team Makutu, Inria Bordeaux Sud-Ouest, 33405 Talence Cedex, France, Email: augustin.ernoult@inria.fr*

Introduction

Network analogies are helpful to understand the resonance behaviour of wind instrument air-columns. A tone hole is a side branch to the main duct and thus modelled as a parallel impedance. If the hole is closed by a finger or key, it acts as an open-closed tube. At its resonance frequencies, $f_0 = nc/(4l)$, ($n = 1, 3, 5, \dots$), it forces a large flow at the junction to the main duct, and thus a pressure node. This is comparable to a pressure node that an opening of the main duct would force. However, such an opening would radiate sound into the ambiance, while the closed chimney doesn't: It suppresses wave propagation in the main duct downstream the tone-hole position and thus acts as a notch filter. This effect can be used to design acoustic silencers [10]. On the other hand, the reflection at the closed chimney influences the wave propagation upstream of the tone-hole position. In a frequency band around its characteristic frequency, the presence of a closed chimney will disturb the main ducts resonance structure. This second effect of the chimney is strongly depending on its location in the duct: it can enhance or attenuate the pressure response at input end of the air column. Thus, the chimney might interact with the reed excitation, and this possible interaction is much less straightforward to understand compared to the passive notch filter effect.

It has been hypothesized, that the characteristic timbre of bassoons is related to the presence of long closed chimneys [6, 9], and this contribution aims to clarify which of the two effects is dominant for the radiated sound.

A simplified wind instrument

Among wind instruments, long tone hole chimneys are specific to the bassoon. They have been drilled obliquely into the wooden corpus to place them at acoustically correct positions inside the bore, while still being able to close them with fingers on the outside. Although many finger holes have been replaced by keys, three long-chimney tone holes remain in all bassoon designs until today. In the French bassoon, they are up to 45 mm long compared to up to 38 mm in the German bassoon [7].

To study the effect of the chimney length, a bassoon-like instrument has been designed as a cone with 2.15 mm input radius, 11 mm output radius and 940 mm length, with three tone holes of 3 mm radius, located at 500 mm, 570 mm, and 612 mm from the input end. These dimensions have been found by inverse parameter identification to approximate the input impedance of a bassoon fingered for the note C₃ ($f_0 = 153$ Hz), using the software OpenWind [2, 8].

Acoustic input impedance

The input impedance is the pressure response to unit flow excitation at the input end of an aircolumn. This end is of special importance because it is the driving point, the location where the exciter mechanism is connected to the aircolumn. Frequencies with at which the input impedance is large indicate possible sounding pitches, because here a small flow is sufficient to produce a large pressure response. Network analogies are a way to calculate the input impedance by "slicing" the aircolumn into short segments, determining their transmission behavior in terms of a complex impedance and connecting them. Expressions for the transmission matrix of a cylindrical duct, a conical duct and tonehole branching from a duct are readily available [1]. For plane wave propagation, these models are well validated. Such a model is very useful to modify single parameters and monitor their effect on the input impedance. For the calculations shown in this paper, an impedance calculation scheme in MATLAB [4] is used.

Artificial mouth

To investigate the influence of the chimney length on the sound, an artificial mouth was used to excite the simplified conical wind instrument with three tone-holes. For this instrument, the length of the closed chimneys can be varied from 0 to 100 mm by a piston. The pistons for each of the three chimneys have been fixed such that they can be moved simultaneously.

The artificial mouth features fine control over the lip force via a micrometer screw. A pressure tank with a large diaphragm pressure regulator allows for precise adjustment of the blowing pressure and to sound the instrument at constant blowing over a few minutes. The reed pressure is measured with a piezoelectric differential pressure transducer (XCG093, kulite, Leonia, USA), and the sound in the room is measured with an externally polarized condenser microphone (Type 4190, Brüel & Kjær, Nærum, Denmark) The chimney length is adjusted manually and its position is captured continuously with draw-wire sensor (SP2, Celesco, Chatsworth, USA).

This setup allows steady blowing without change of the embouchure and blowing pressure. The chimney length can be varied during playing to measure its effects on the pressure spectrum inside the reed and in the room.

Results and Discussion

Impedance calculations and artificial mouth experiments have been conducted in form of parametric studies with variable chimney length. The results are displayed as a spectrogram of relative levels, referenced to the initial case of a pure cone, where all chimney have zero length. Figure 1 shows the disturbance of near-harmonic reso-

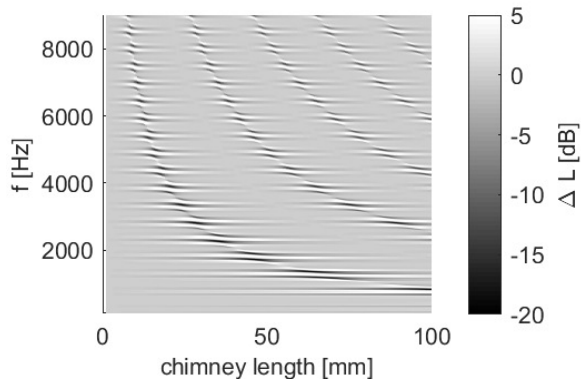


Figure 1: Effect of the chimney length on the input impedance of an open cone with one closed chimney.

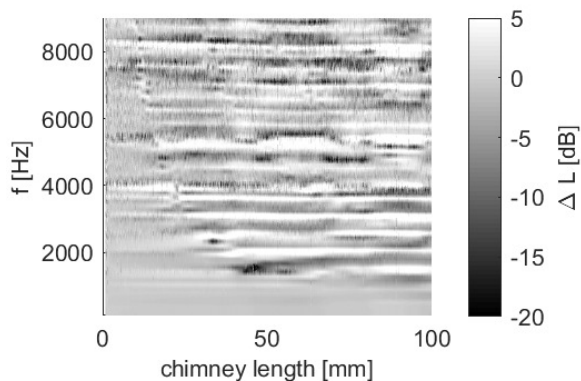


Figure 2: Effect of the chimney length on the reed pressure spectrum of an open cone with three closed chimneys of the same lengths.

nance structure of the truncated cone by the chimney resonance frequencies $f_{chim,n} \approx nc/(4l)$, $n = 1, 3, 5, \dots$. In the crossing region of chimney and cone resonance, a magnitude shift of the input impedance occurs. Apart from these regions, the cone's impedance remains nearly unchanged. Note, that the result shown here corresponds to a single chimney located 612 mm from the input end of the cone. For a different tone hole location in the main duct this impedance map may look very different, although the characteristic frequencies remain to be the same. The actual impedance magnitude may depend on the phase relation between the interacting resonators.

The effect of the chimney length on the sound spectrum is studied with continuous blowing, during which the chimney length was varied. After careful adjustment of the artificial mouth, a note was started and all three chimneys were matched to have the same length in each instance of time. The results of the mouthpiece pressure, and the pressure in the room are shown in Figures 2 and 3, respectively. In the room sound pressure spectrum, a notch filter effect is clearly observed at the chimneys resonance frequencies (compare Figs. 3 and 1). In a narrow band, the magnitudes differs by up to -20 dB compared to undisturbed cone. In the reed pressure spectrum, however, the variation is not clearly linked to the chimney resonance. One can still estimate the lowest chimney reso-

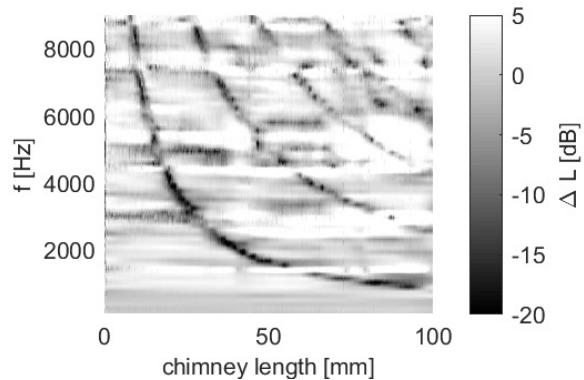


Figure 3: Effect of the chimney length on the sound pressure spectrum radiated from an open cone with three closed chimneys of the same lengths.

nance from Fig. 2. For higher frequencies, the levels vary without a clear pattern. The largest level variation is found at a chimney length between 40 and 50 mm (-20dB at 45 mm). The result is much less clear here and the comparison of Figs. 2 and 3 implies, that the non-linear reed exciter is very sensitive to impedance variation not only near the fundamental air column resonance.

The previous results account for the academic example of a pure cone; the chimney length has been exaggerated in order to demonstrate the effect. In real wind instruments, for example the French and German bassoon, the longest chimney lengths differ by less than 10 mm. Figure 4 shows the pressure spectra in the reed mouthpiece and in the room, for the pure cone at two chimney lengths 45 mm and 38 mm, respectively, corresponding to the maximum chimney lengths found in French and German bassoon. For comparison, the chimney impedance is added to the plot. We expect the largest effect at the chimneys input impedance minima, and indeed slight shifts in the spectral envelope of the sound in the room can be observed. However, the effect is subtle. Inside the mouthpiece, the reed pressure spectrum is nearly unchanged.

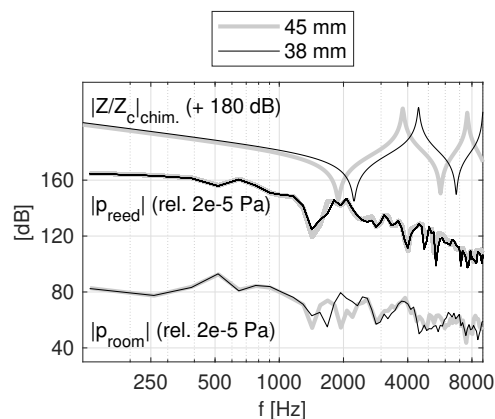


Figure 4: Spectra of reed pressure and sound pressure in the room for two different chimney lengths. The impedance of the closed chimneys is shown for comparison (top, shifted for better readability)

Conclusions

The closed chimney effect is quite pronounced for a simplified reed wind instrument. In a pure cone with three chimneys of the same length, we find a comb-filter like attenuation of the radiated sound by -20 dB at characteristic frequencies of the closed chimney. When varying the chimney length, changes in the reed pressure spectrum where much smaller at these frequencies and the comb-filter pattern is hardly detected. Therefore, the passive acoustic filter effect appears to dominate over the disturbance of the exciter.

However, when the geometrical complexity of the air column approaches that of a real wind instrument, the effect becomes more and more blurred. A 10 mm difference in chimney length corresponding to the difference found between French and German bassoon has only a small effect on the sound spectrum. It is well in the same order of magnitude than variations due to the instruments directivity [5].

Simulations of the sound generation [3] are in good qualitative agreement with the experiments. As the spectral components of the reed pressure are hardly affected in magnitude (Fig. 4), it is tempting to regard the long chimney effects as a purely passive acoustic effect. However, the overall effect is rather small, and the observed shifts in the spectral envelope do not exactly coincide with the chimneys input impedance minimum. The chimney length variation further leads to changes in driving frequency (not shown) which although subtle might be more significant for the playing behaviour in terms of intonation than the slight shifts in the spectral envelope are for the perceived sound.

Therefore, the effect of the chimney length on wind instrument timbre should be discussed with caution.

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