PROCEEDINGS of ISMA 2019
International Symposium on Music Acoustics

13 - 17 September 2019 in Detmold, Germany

External sound field simulations and measurements of woodwind resonators

Erik Alan PETERSEN(1), Romane ROSSER(1)

(1)Aix Marseille Univ, CNRS, Centrale Marseille, LMA, UMR 7031, Marseille, France, petersen@lma.cnrs-mrs.fr

Abstract

The input impedance is a useful quantity to characterize the acoustic response of woodwind instruments and is efficiently simulated using the Transfer Matrix Method (TMM). However, the TMM does not calculate intermediate variables that are convenient for simulating the external sound field. Recent work by Lefebvre et al proposes the Transfer Matrix Method with external Interactions (TMMI) which accounts for the mutual radiation impedance of toneholes radiating into the same space and uses the acoustic flow through each aperture as the reference variable. Treating the flow through each tonehole as a source in a linear array, it is possible to calculate the external sound field such as the waveforms at a given receiver location and directivity patterns. Additionally, the efficiency of a resonator can be calculated as the ratio of the power at the input of the resonator and the sum of the power radiating from each aperture. This is a useful step towards understanding the competition between the energy that is retained within a resonator and facilitates the auto-oscillation of the reed, and that which radiates from the resonator. This topic is explored through simulation and measurements using simplified cylindrical resonators.

Keywords: Musical acoustics, radiation, cutoff frequency, clarinet.

1 INTRODUCTION

The tonehole lattice cutoff frequency is a well-known property of the clarinet and is generally considered to have an influence on the "character" of a given instrument [1]. However, it is not precisely known how the cutoff frequency influences the sound production and radiation. Recent work has shown that the cutoff frequency has a relatively small effect on the production of sound, primarily changing the spectral content of internal waveforms above the cutoff frequency [2]. It is hypothesized that the cutoff frequency will also change the radiation of a given resonator, an effect that could also determine the timbrel properties of an instrument. An early development of this idea is provided in the current paper where simplified resonators are excited at acoustically linear levels by a compression chamber. The pressure inside the resonators and at external points are measured in anechoic conditions. Transfer functions are then calculated and used to compare resonators with different cutoff frequencies and validate simulations.

2 SIMULATION OF EXTERNAL SOUNDFIELD

In order to predict the radiating characteristics of a resonator, the transfer function between a source inside the resonator and an external observation point is simulated. The simulation relies on the Transfer Matrix Method with external Interactions (TMMI) [3], a variant of the classic Transfer Matrix Method (TMM). The TMMI is designed to simulate the input impedance of a resonator by assuming a fictitious flow source U^s, and calculates the resulting pressure and flow P_n and U_n at each n^{th} radiating aperture, accounting for the mutual radiation load between sources that radiate into the same space. Therefore, the transfer function between the source flow U^s and each hole is simply

$$H_{u,n} = U_n/U^s, \tag{1}$$

where U^s has equal amplitude and phase for all frequencies.

The TMMI is readily exploited for radiation calculations because, in the process of simulating the input impedance, it provides the flow from each hole, already accounting for external interactions. Ignoring the presence of the body of the resonator, the holes can then be treated as an array of monopole sources. The pressure at some

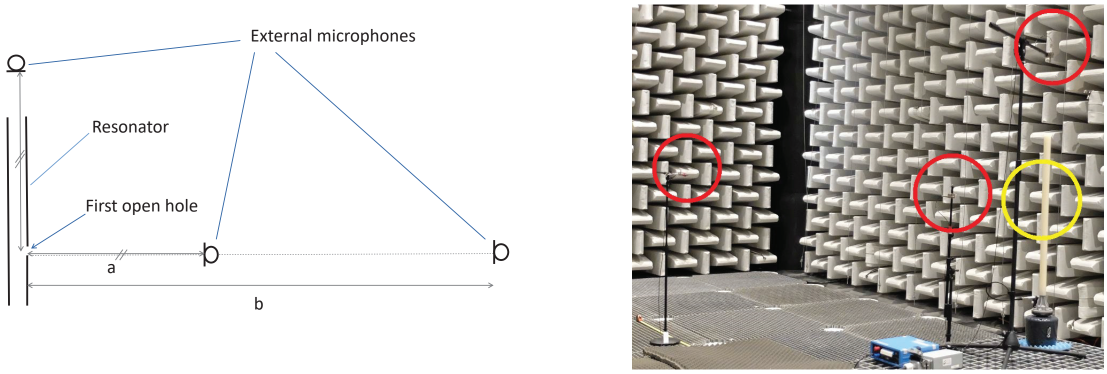

Figure 1. Three microphones (right, in red) are positioned around the resonator. The first two microphones are at the level of the first open hole (right, in yellow) and at a distance of b = 4 m and a = 0.7 m, respectively. The third is positioned above the end of the resonator at a distance a = 0.7 m from the first open hole.

observation point M is proportional to the time derivative of the summation of the contributions of each U_n, accounting for a propagation delay and spherical spreading:

$$P_M = \frac{d}{dt}\sum_{n=1}^{N}\frac{H_{u,n}U^s}{r_n}e^{-j\omega r_n/c}, \tag{2}$$

where r_n is the distance between the n^{th} hole and M, ω is the angular frequency, and c is the speed of sound in air. This model assumes anechoic conditions and ignores absorption in air.

Because this is a linear model, at each step we have the option to choose the acoustic variables P or U, related by the impedance. It is numerically equivalent to consider pressure sources P^s and P_n, from which the external pressure P_M is calculated. Therefore, equations 1 and 2 can just as easily be written in terms of pressure sources, which is less physical but more convenient when comparing with measurements because a microphone measures pressure inside resonator.

3 MEASUREMENTS

3.1 EXPERIMENTAL RESONATORS

The resonators used in this work are designed to have the same first impedance resonance, but different tonehole lattice cutoff frequencies [2]. The global cutoff frequency is fixed by choosing the geometry of each cell to have an equivalent local cutoff frequency [4]. Three resonators $\mathscr{R}_{1.0}, \mathscr{R}_{1.5}$, and $\mathscr{R}_{2.0}$ are used in the current work. All have first impedance peaks at 185 Hz, and cutoff frequencies at 1000, 1500, and 2000 Hz, respectively. The distance between toneholes is the same for all three resonators, and the cutoff frequency is changed only by varying the radius of the toneholes.

3.2 EXPERIMENTAL DESIGN

The transfer function in pressure from inside the resonator to the external sound field was measured experimentally. The resonators were connected to a compression chamber using a 3D printed adapter piece with a 6 cm cylindrical portion in which the microphone is mounted. The pressure measured by this microphone is treated as the source pressure P^s in Section 2. The pressure was measured at three external locations, the positions of which are shown in Fig. 1.

Pure sinusoidal excitation signals were used to force the resonator from 100 Hz to 4000 Hz in steps of 10 Hz.

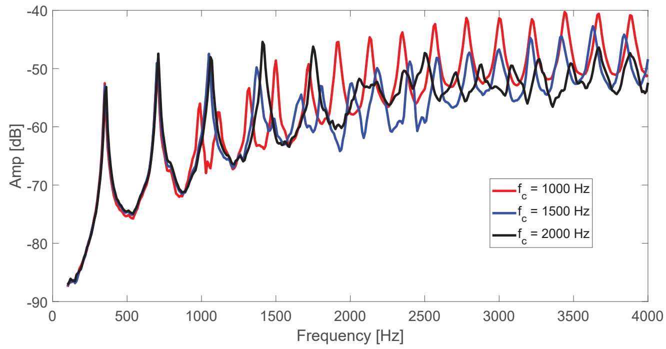

Figure 2. Transfer function between interal pressure and external pressure at the overhead microphone location. The resonators with f_c = 1000, 1500, and 2000 Hz are shown in red, blue, and black, respectively.

This signal choice was chosen instead of a frequency sweep because the radiation from the resonator, particularly at frequencies corresponding to the impedance troughs, is very weak. The coherence function calculated using a sweep type signal was only robust in the vicinity of the impedance peaks.

The measured signals are band filtered from 50 Hz to 6000 Hz and windowed to retain only the stable portion of the signal. Peak amplitudes of the i^{th} harmonics are extracted using synchronous detection

$$P_M(\omega_i) = |2 < p_m(t) \cdot e^{-j\omega_i t} >|. \tag{3}$$

This method is valid because the frequencies are precisely known and stable. In the following analysis only the fundamental frequency ($i = 1$) is considered.

3.3 MEASURED TRANSFER FUNCTION FOR THREE RESONATORS

The transfer function between internal pressure and three external observation points described in Section 3.2 was measured for all three resonators. Figure 2 shows the transfer function between the internal pressure and the microphone that is located 0.7 m above the first open hole for each of the three resonators. All three resonators radiate similarly at frequencies below the tonehole lattice cutoff frequency, with peaks that are harmonically related to the first peak. This is because at low frequencies the main acoustic source of the resonator is the first open tonehole, which radiates as a monopole. As the frequency increases up to and past the cutoff frequency of a given resonator, the transfer functions become more complicated. This transition is particularly abrupt for resonator $\mathscr{R}_1$, where the cutoff frequency happens to coincide with an existing peak.

3.4 COMPARISON WITH SIMULATION

The simulated and measured transfer functions between internal pressure and all three microphone locations is shown in Fig. 3 for $\mathscr{R}_1$. Because the simulation is normalized (ie the flow source $U^s = 1$), the amplitude of the simulation is shifted so that the minimal point between the first two peaks is at the same amplitude as the measurement. The peak amplitude was not chosen as the reference point because the measurements (in steps of 10 Hz) do not fully resolve the peak.

The simulation matches the measurements at low frequencies. At high frequencies, the shape of the simulation aligns reasonably well with the measurements, but the amplitude is not adequately captured. The simulation under-predicts the amount of radiation. This is also noticed in the impedance measurements (not shown). Around the cutoff frequency there is a marked shift in frequency between the simulation and measurement. This may be an interesting topic for further developing the model.

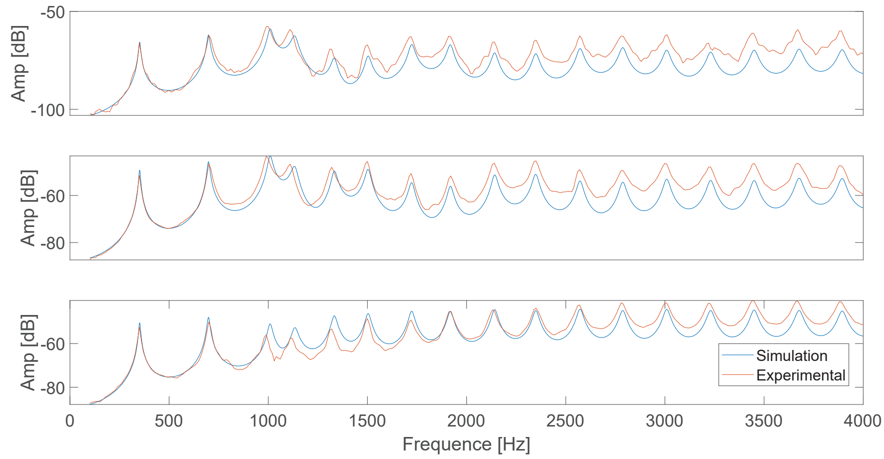

Figure 3. Simulated and measured transfer function for resonator $\mathscr{R}_1$ between internal pressure and external pressure at three microphone locations (see Fig. 1).

4 CONCLUSIONS

The effect on radiation of the tonehole lattice cutoff frequency is investigated. It is found that the cutoff frequency has a considerable impact on the transfer function between internal pressure and pressure at multiple points external to the resonator. This implies that the cutoff frequency could act as a filter of the sound that is radiated from an instrument, irrespective of its influence on sound production. It is also found that it is possible to extend the TMMI calculation to simulate external pressure waveforms. This use of the TMMI is adequate at low frequencies but is only approximate at high frequencies. This is a logical place to search for an improved model. Future work could involve repeating the experiment at sound pressure levels that are high enough to induce nonlinear effects. This would be done with a compression chamber or artificial blowing machine.

ACKNOWLEDGEMENTS

The authors would like to thank Patrick Sanchez and Clément Rabau for their help with the experimental aspect of this work, and in particular for designing the adapter piece that connects the compression chamber and the resonators. We would also like to thank Guy Rabau for piercing the resonators. Finally, we acknowledge the many helpful discussions with Marc Pachebat, Fabrice Silva, and Philippe Guillemain. This work has been partly supported by the French Agence Nationale de la Recherche (ANR16-LCV2-0007-01 Liamfi project.)

REFERENCES

[1] Benade, A. H., Fundamentals of Musical Acoustics Oxford University Press, London (1976).

[2] Petersen, E. A.; Guillemain, G.; Kergomard, J.; Colinot, T., The effect of the cutoff frequency on sound production of clarinet-like instruments, Journ. Acoust. Soc. Am (to appear, accepted 2019).

[3] Lefebvre, A.; Scavone, G. P.; Kergomard, J., “External tonehole interactions in woodwind instruments,” Acta Acustica united with Acustica **99**, 975-985 (2013).

[4] Moers, E.; Kergomard, J., “On the cutoff frequency of clarinet-like instruments. Geometrical versus acoustical regularity,” Acta Acustica united with Acustica **97**, 984-996 (2011).