DOI: 10.61782/fa.2023.0533

forum acusticum 2023

VIBROACOUSTICS OF THE TROMBONE: HOW TO QUANTIFY THE EFFECT OF WALL VIBRATIONS?

M. Sécail-Géraud, F. Gautier
Le Mans Université,
Laboratoire d'Acoustique de l'Université du Mans, UMR CNRS 6613,
Av. O. Messiaen, 72085 Le Mans cedex 9

ABSTRACT

The walls of a wind instrument vibrate when the musician plays. These vibrations are all the more important as the wall is thin and the diameter of the pipe is important. Brass instruments with large bells or more particularly the trombone (J. Gilbert et al. DOI: 10.1007/978-3-030-55686-0) are therefore instruments where the effect of vibrations on the sound produced is possibly important. This question is controversial because of the complexity, multiplicity and also the smallness of the coupling mechanisms involved. In order to provide some answers, a model of the fluid/shell coupling is developed. It allows the calculation of the impedance of the vibrating duct, by perturbation, in 3 steps: 1/ calculation of the impedance of the rigid duct, 2/ calculation of the vibratory response from the modes of the duct, 3/ calculation of the impedance of the vibrating duct, from an effective speed of sound, dependent on the wall vibration. Experimental tests with a scanning laser vibrometer associated with numerical simulations show that the main impedance perturbation is induced by an axixymetric (piston) vibratory mode, whose frequency is located in the upper register of the trombone, which prefigures that the effect remains difficult to demonstrate.

Keywords: *Trombone, Wall vibrations, Vibrometry, Acoustic input impedance*

1. CONTEXT

The question of the influence of wall vibrations on the behavior of wind instruments has long been debated. In a playing situation, it is easy to notice that the body of a wind instrument vibrates. However, the influence of this vibration on the sound produced is not clearly established. In general, the vibrations of the body of the instrument give rise to two effects: an acoustic radiation from the wall towards the outside and a disturbance of the internal acoustic field, which gives rise to a radiation towards the outside, via its extremity. We thus distinguish an external vibroacoustic coupling and an internal vibroacoustic coupling. The direct radiation from the wall (external coupling is generally weak and can be neglected in front of the radiation from the open end of the instrument. Most of the published studies therefore concern the internal coupling.

In general, the vibroacoustic coupling mechanisms involved in these vibrations are difficult to study, because the fluid-structure interactions are weak in a light fluid. However, these vibrations are more important the thinner the wall and the larger the diameter of the pipe. Large diameter brass instruments and in particular the bell of the trombone are configurations where this interaction is likely to play a role [1]. Miller, in 1916 [2] experimentally analyzed the behavior of an organ pipe, surrounded by a water tank of variable height. The study, repeated a century later [3], confirms that the self-oscillations produced by the organ pipe in operation are disturbed by the vibrations of the walls, since they can be responsible for modification of the acoustic input impedance.

A literature review and a detailed analysis of the internal coupling has been proposed by [4] in the case of a cylindrical duct: the acoustic input impedance of a vibrating cylindrical tube is calculated; the model shows small perturbations of Z with respect to the value of this impedance when the duct is rigid. These perturbations are narrow band perturbation at the mechanical resonance frequencies of the duct, and are directly resulting from the acoustic flow pumped through the wall. The duct generally presents a large number of mechanical modes. Some of them are axisymmetric (breathing modes); Most of them, and in particular the first ones, have modeshapes that depend on the azimuth angle, being proportional to $\cos n\theta$. If there is no axisymetry defect in the duct (case of perfectly axisymetric cross section), the resulting vibratory field does not give rise to any coupling with the plane acoustic wave since the pumped flow is strictly zero. In the presence of a defect, the cross-section of the pipe can be described for example by a slight ovalization of the type $r = a(1 + \epsilon \cos 2\theta)$. It is then shown [4] that this small ovalization is then responsible for a non-zero flow pumped through the wall; this disturbs the input acoustic impedance. The specific case of the trombone bell has been studied in [5], which presents experimental observations and a simplified model of the wall effect on the acoustic impedance.

The objective of this paper is to examine the effect of the vibrations of a trombone on the emitted sound. The elements presented are based on several works done at LAUM in Le Mans under the direction of our colleague Joel Gilbert. In section 2, the question of the importance of the sound radiated directly by the walls (external vibrocoustic coupling) is examined using Peter's experiment. In section 3, a model of the input impedance of a vibrating trombone is proposed (internal vibroacoustic coupling) and is compared to a measurement; In section 4, the spectrogram of a glissando in a playing situation finally allows to evaluate the effect.

2. SOUND LEVEL RADIATED BY WALLS

It is generally accepted that the sound radiated laterally by the vibrating wall of an instrument is negligible compared to the radiation from the end of the pipe. This radiation is complex to model and therefore to quantify. Peter Hoekje, researcher at Baldwin Wallace University, Ohio (USA), in collaboration with Joel Gilbert, researcher at LAUM has designed an experiment to estimate the importance of this radiation.

2.1 Principle of the Peter experiment

In the first phase of the experiment, a short musical sequence is played on the trombone by a musician (Fig. 1 (a)). The average acoustic level L_1 is measured with a sound level meter at $1m$ in front of the bell. At the same time, an accelerometer is placed on the bell and measures the level of acceleration of the horn (rms value).

In a second phase of the experiment (Fig. 1 (c)), the trombone is vibrated by means of a shaker, to which the acoustic signal recorded during the previous phase is applied, multiplied by a gain, adjusted so that the rms level of the acceleration measured is identical to the value measured during the previous phase. The acoustic signal emitted by the trombone is measured under these conditions (Level L_2).

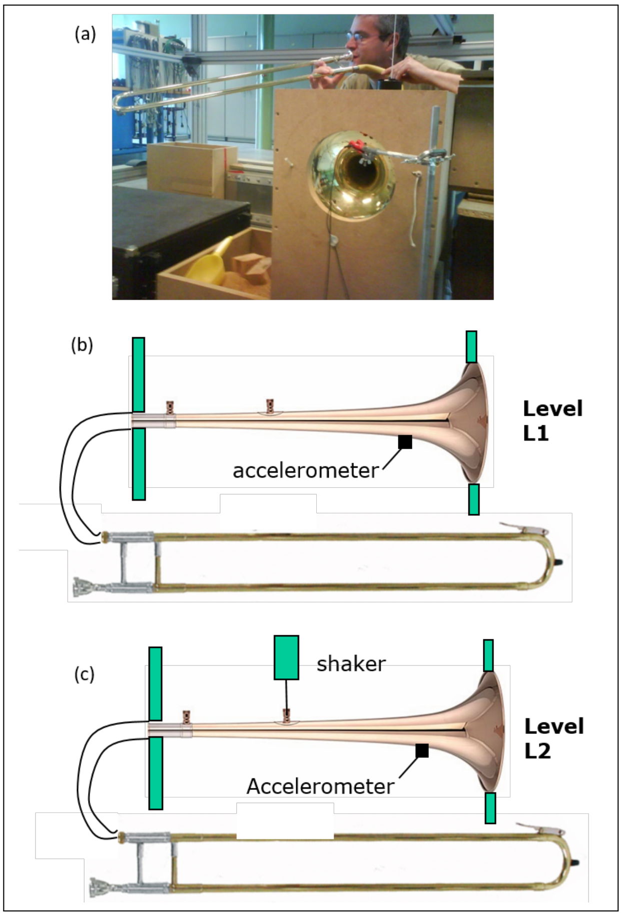

Figure 1. (a) Joel Gilbert playing the trombone for the Peter's experiment. (b) Measurement of the acoustic level emitted by the trombone played by the musician. (c) Measurement of the acoustic level emitted by trombone vibrated by a shaker at the same acceleration level than (b). The measured acoustic level is an estimation of the acoustic level radiated by the wall alone.

2.2 Order of magnitude of the pressure radiated by the wall

The Peter experiment, repeated many times, shows that the difference in levels $\Delta L = L_1 - L_2$ is of the order of $40dB$. The signal radiated by the wall, estimated by this simple test is of the order of a hundredth of the signal produced by the instrument.

In conclusion, the estimation of the order of magnitude of the sound pressure radiated directly from the wall shows that the coupling between the wall and the external fluid is small and insignificant compared to the radiation from the extremity (difference of 40dB). This coupling is therefore ignored in the rest of the analysis.

3. ACOUSTIC IMPEDANCE OF A VIBRATING HORN

It has been shown in section 2 that the external vibracoustic coupling is weak. We are interested in section 3 by estimating the importance of the internal coupling, i.e between the wall and the internal fluid column: The acoustic input impedance is a key-characteristic of the instrument since the impedance peaks are providing the frequencies of self-oscillations and thus the possible playing frequencies. The question is to know how the wall vibrations affect the input impedance. For this purpose, we propose a model of the vibrating duct impedance, which can be used as input data for time-domain simulations to estimate the influence of wall vibrations (this type of analysis is not presented in this paper).

3.1 Modelling

Under the plane waves assumption and in harmonic regime ($e^{j\omega t}$, ω being the circular frequency), the acoustic pressure $p(x)$ and the acoustic axial velocity $V(x)$ verify the state equation

$$\frac{d.}{dx}\begin{bmatrix} P \\ V \end{bmatrix} = \begin{bmatrix} 0 & -j\rho_0\omega \\ -\frac{j\omega}{\rho_0\tilde{c}^2} & -\frac{1}{S}\frac{dS}{dx} \end{bmatrix}\begin{bmatrix} P \\ V \end{bmatrix}, \quad (1)$$

with $\tilde{c}(x) = c\left(1 + \frac{2Y(x)\rho_0 c^2}{j\omega r(x)}\right)^{-\frac{1}{2}}$, ρ_0 the air density, $S(x) = \pi r^2(x)$ the area of the cross-section at x. The notations are given in fig. 2 (a). The effective speed of sound $\tilde{c}(x)$ takes into account the vibration of the wall; it is slightly different from the sound velocity c and depends on the mobility of the duct $Y(x)$, averaged over the circumference at x:

$$Y(x) = \frac{\langle\dot{w}\rangle(x)}{P(x)}, \langle\dot{w}\rangle(x) = \frac{1}{2\pi}\int_0^{2\pi} \dot{w}(\theta, x)d\theta. \quad (2)$$

The normal velocity of the wall $\dot{w}(x)$ is described us-

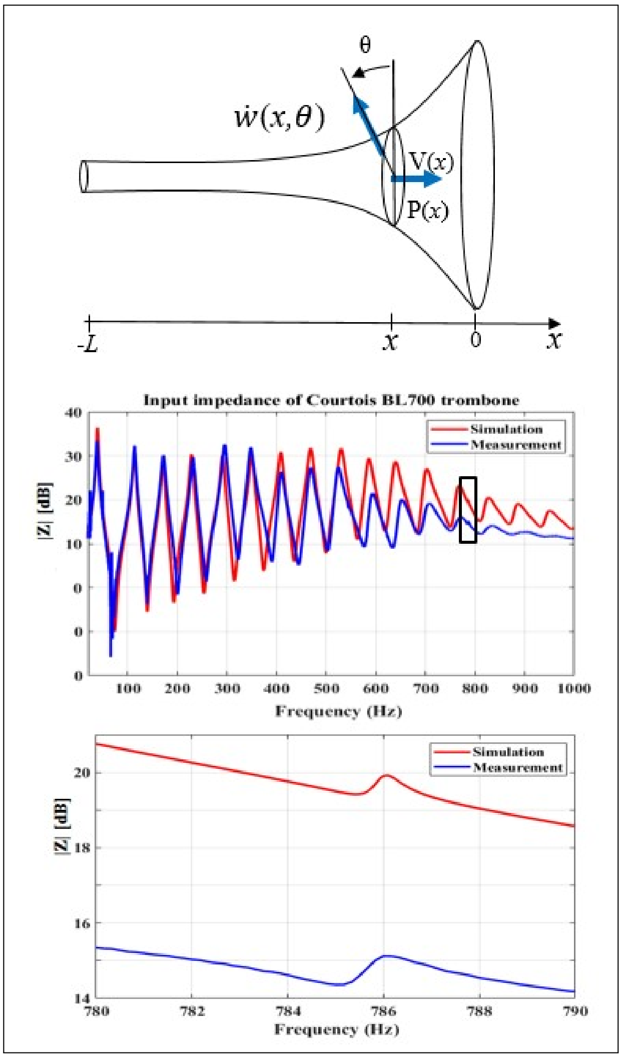

Figure 2. (a) Notations, (b) Impedance of a Courtois'trombone - model BL700, (b) zoom around the eigenfrequency of the piston mode (787Hz)

ing a modal expansion, $\dot{w}(x) = j\omega\sum_k A_k\Phi_k$, k being the modal index, A_k the modal amplitude,Φ_k the modal shapes of mode k, having the eigenfrequency ω_k and the modal damping ξ_k. The average of $\dot{w}(x)$ over a circumference can be written as

$$\langle \dot{w} \rangle (x) = j\omega \sum \frac{\int_{-L}^{0} P(x) r(x) \quad 2\pi \langle \Phi_k \rangle (x) dx}{m_k \left(-\omega^2 + 2j\xi_k\omega_k\omega + \omega_k^2\right)} \langle \Phi_k \rangle (x) \tag{3}$$

The objective is to calculate the input acoustic impedance of the vibrating duct, $Z(-L) = P(-L)/V(-L)$ which results from the resolution of the 3 coupled governing equations (1), (2), (3). Since $Z(-L)$ is equal to the input pressure $P(-L)$ when $V(-L) = 1ms^{-1}$, the impedance is obtained by considering the excitation condition $V(-L) = 1ms^{-1}$ and the boundary condition $Z(0) = Z_{Rad}$. The impedance Z_{Rad} denotes the imposed radiation impedance of the end of the duct. The equations (1),(2), (3) are solved using a perturbation method, in 3 steps.

- Step 1 : Equation (1) is solved in the absence of vibration, i.e. considering that $\tilde{c} = c$. This is a rigid duct impedance calculation which can be performed for example by means of the impedance matrix method [6]. The pressure field $P(x)$ resulting from $V(-L) = 1ms^{-1}$ is obtained in the whole rigid waveguide. This pressure is the called the blocked pressure.
- Step 2 : The blocked pressure is used to compute the wall velocity $\langle \dot{w} \rangle (x)$ using eq. (3). This calculation is straightforward if the modal basis of the trombone, i.e. the set of modal parameters ω_k, ξ_k, m_k, Φ_k is known.
- Step 3 : The wall impedance $Y(x)$ is then calculated using eq(2) and the result is inserted into 1 to get an updated estimation of the internal pressure, which takes into account wall vibrations.

3.2 Trombone vibration modes

The description of wall vibrations requires knowledge of the modal basis of the instrument. In practice, this can be determined by the finite element method or by means of experimental tests. In this study, we use a vibrometric scan carried out by means of the Robovib platform (3 Polytech PSV500 scanning vibrometers mounted on a 6m travel arm). The vibratory scan is obtained on the entire surface of the instrument (see 3(a), i.e. including the cylindrical part of the trombone and all the complex shape of the bell. Excitation is achieved by means of a shaker applied to the mouthpiece in an oblique direction. The scan is performed in 3D, providing the vibrational components in all 3 directions, and in particular the normal velocity. An experimental modal analysis (not detailed here) is then performed and provide the modal features. The results

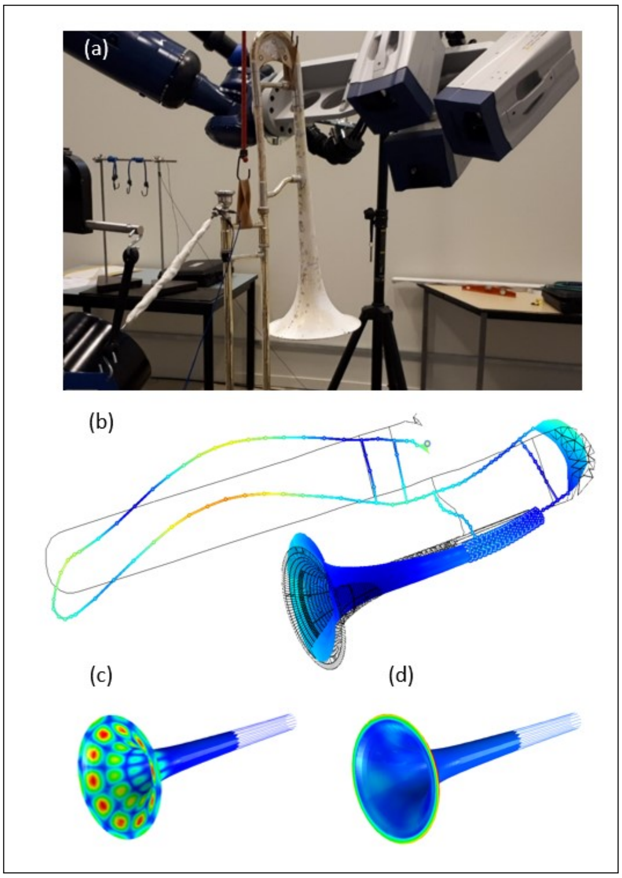

Figure 3. Polytech Robotvib platform for scannning vibrometry at Le Mans Université, Ecole Nationale d'Ingénieurs du Mans (a), measured modeshapes, (b) example of bending mode of the slide ($142Hz$), (c) example of bell mode with azimuthal variation ($1002Hz$), (d) piston mode ($787Hz$).

show a large number of modes. The first trombone modes (below $200Hz$) are bending modes of the slide and tube: the whole instrument vibrates in a similar way to a long beam (see an example of mode at $142Hz$ in fig. 3(b)).

At higher frequencies (above $200Hz$, the trombone modes are located in the bell, which is the most flexible part of the instrument. They have complex shapes characterised by variations in shape close to $\cos n\theta$, θ being the azimuthal angle (see an example of mode at

$1002Hz$ in fig. 2(a)). The axisymmetric modes of the horn are few. The first of these is a piston mode at 787Hz, shown in fig. (3)(d). All non-axisymmetric modes give rise to weak coupling, that is a mean value $\langle\Phi_k\rangle(x) = 1/\pi\int_0^{2\pi}\Phi_k(\theta,x)d\theta$ which is small but not equal to zero in eq. (3). These small but non-zero values are due to the loss of exact axisymmetry induced by defects (material weld line, shocks). In contrast to the non-axisymmetric modes, the value of $\langle\Phi_k\rangle(x)$ for the piston mode is large, which is a signature of the fact that the piston mode and the internal plane acoustic pressure are naturally coupled.

3.3 Experimental validation

The methodology is applied to the a Bb played in first position of the trombone (117Hz). The measured and the simulated input impedance curves are presented in Fig. (2b). The measured impedance reveals artefacts due to wall vibrations, visible on the zoomed Fig. (2c). The most important artefact is related to the presence of the piston mode (787Hz). The difference in level between the simulated and measured impedances is related to the value of the impedance Z_{Rad}, which describes approximate radiation conditions, which in particular do not take into account the diffraction of sound by the horn itself. A more advanced radiation model, beyond the scope of this paper, would be required to update Z_{Rad}. Fig. (2c) demonstrates that the proposed methodology provides a model of the impedance of a vibrating duct, able to describe accuratly the perturbations due to wall vibrations : it is thus shown that wall vibrations generate disturbances in the input impedance of the order of 1dB at $787Hz$, which corresponds to the upper register of the instrument.

3.4 Acoustic glissando around the piston mode

The perturbations of the input acoustic impedance by wall vibrations are likely to affect the sound produced: Fig. (4) shows the spectrogram of a glissando played by Joel Gilbert. The ambitus of the glissando is chosen so that the frequency of the piston mode is within the excursion of the playing frequency. When coincidence with the frequency of a mechanical mode (piston mode or one of the bell modes) occurs, this mode responds clearly (see white arrows in fig. (4a)). However, this coincidence is not clearly visible on the acoustic signal (see Fig. (4b)). The wall vibration is thus generated by the coupling but does not give rise to a significant acoustic effect for the particular case studied. Considering the model, we can conclude that a thinner or lighter wall, with lower damping, or the case of a coincidence between a piston mode with an acoustic mode, is likely to give rise to greater coupling.

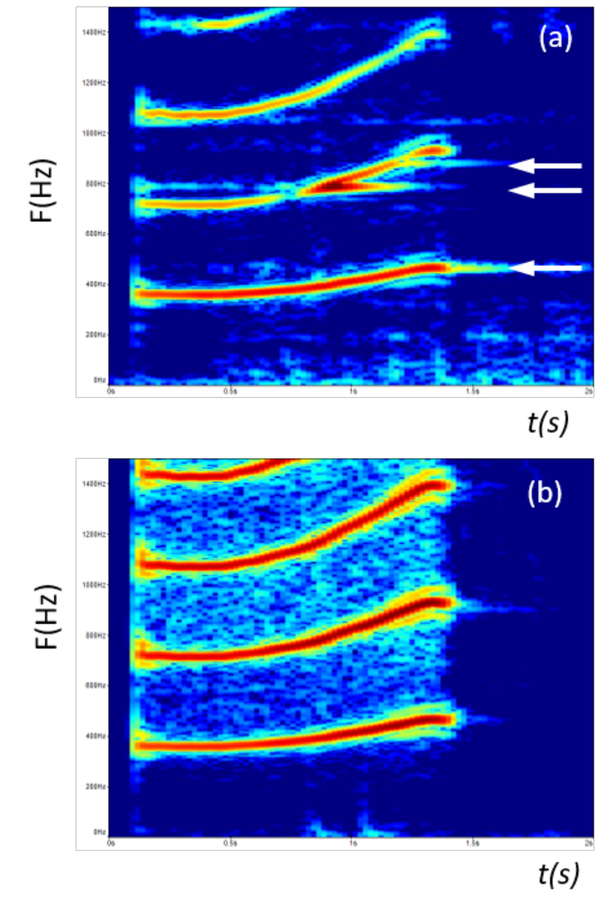

Figure 4. Glissando played by Joel Gilbert. (a) acceleration of the bell, (b) acoustic pressure measured at $1m$ in the axis of the instrument.

4. CONLUDING REMARKS

The vibrations of a trombone, played by a musician are clearly measurable. However, the influence of these vibrations on the sound produced is not clearly established. This paper provides elements to quantify this effect. Peter's experiment makes it possible to evaluate the level radiated directly by the cylindrical tube or the bell. This radiation is 40dB lower than the sound directly produced by the end of the instrument. In addition, an acoustical input impedance model, taking into account wall vibrations, is proposed. For the tested configuration (Bb of a Courtois BL700 trombone), this model predicts a modification of the order of 1 dB, in the vicinity of the frequency of the piston mode of the bell ($787 Hz$, i.e in the upper register of the instrument). In a playing situation, an experimental glissando shows that this disturbance leads to measurable vibrations but is not audible. Other configurations could be investigated for which the coupling between the shell and the internal fluid could give rise to an audible effect since it gives rise to greater coupling : a thinner or lighter wall, a lower damping, or the case of a coincidence between a piston mode and an acoustic mode,

5. ACKNOWLEDGMENTS

This paper is dedicated to the memory of Joel Gilbert. The authors would like to thank Peter Hoekje, Kees Nederveen, Levy Leblanc, Jean-Pierre Dalmond for their collaboration and fruitful discussions.

6. REFERENCES

[1] M. Campbell, J. Gilbert, and A. Myers, *The Science of Brass Instruments*. Modern Acoustics and Signal Processing, Springer International Publishing, 2021.

[2] D. Miller, “The influence of the material of wind-instruments on the tone quality,” *Science*, vol. A, no. B, pp. 111–222, 2010.

[3] F. Gautier, G. Nief, J. Gilbert, and J. P. Dalmont, “Vibro-acoustics of organ pipes—Revisiting the Miller experiment (L),” *The Journal of the Acoustical Society of America*, vol. 131, pp. 737–738, 01 2012.

[4] G. Nief, F. Gautier, J.-P. Dalmont, and J. Gilbert, “Influence of wall vibrations on the behavior of a simplified wind instrument,” *The Journal of the Acoustical Society of America*, vol. 124, no. 2, pp. 1320–1331, 2008.

[5] W. Kausel, D. W. Zietlow, and T. R. Moore, “Influence of wall vibrations on the sound of brass wind instruments,” *The Journal of the Acoustical Society of America*, vol. 128, pp. 3161–3174, 11 2010.

[6] S. Felix and V. Pagneux, “Multimodal analysis of acoustic propagation in three-dimensional bends,” *Wave Motion*, vol. 36, no. 2, pp. 157 – 168, 2002.