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OPTIMAL ACTIVE CONTROL FOR A TROMBONE: A PARAMETRIC STUDY

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ABSTRACT

The main objective of this research is to perform an active control of the sound radiated by a trombone. For this instrument, most of the energy is radiated in the 50-3000 Hz frequency band, which is the framework for this study. The goal of the control, performed with several actuators placed near the bell, is to reduce the total radiated power and modify the directivity of the radiated pressure. The optimization of power reduction results from literature by a method using a model with monopoles. The study is further developed numerically beginning with a monopole model to finally get a more accurate model with a simplified trombone and control loudspeakers. This allows to take into account the diffraction of each part of the system. This models enable to compare and choose an optimal number of control loudspeakers as well as their optimal positions to get the targeted power radiation efficiency and directivity according to the frequency.

1. INTRODUCTION

The trombone is a musical instrument that can radiate up to 110 dB SPL at 1 meter [1]. For some applications the musician needs to reduce the sound level radiated by his instrument (training in apartment, change of timbre, ...).

Numerous mutes have been created in order to be able to act on the pitch, the loudness and the timbre of the instrument. Most of them are almost conical and placed in the bell. By blocking the bell, the low frequencies are attenuated, while the high frequencies are accentuated by the resonances of the mute [2]. An investigation also showed that mutes have an impact on the input impedance of the instrument [3]. During the last decades, active mutes have been studied. For example, one of them allows to reduce the radiated sound almost entirely in order to be only heard through headphones [4].

However, there is no mute that has the ability to reduce

¹Cup Mute, emeraldsread (visited on date 2019), https://en.m.wikipedia.org/wiki/File:Solo_Adjustable_Cup_Mute.jpg



Figure 1: Copper mute ¹

the power of the instrument without impacting the timbre or the input impedance of the instrument. The purpose of this research is to study an active control with loudspeakers which avoid to clog the bell so to minimize the influence on the input impedance. To do so, we choose to evaluate the performance of an external active system. Recent research has attempted to implement such a mute, but technological limitations related to the weight/power ratio of the loudspeakers have not yet allowed such a control [5]. The aim of this work is to propose a solution that could allow an active control.

The optimization of power reduction is first studied analytically by a simple model using only point sources [6]. Another study using a Boundary Element Method (BEM) is also investigated and compared to a point source model to study the effect of diffraction on the power attenuation. Then, a parametric study on the speaker position and number is performed.

2. SYSTEM UNDER STUDY

The system being studied is a trombone controlled by several loudspeakers as shown in Fig. 2.

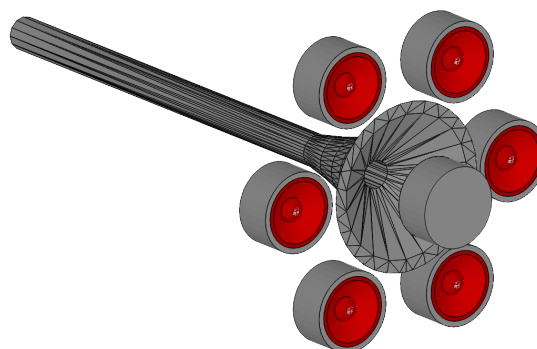


Figure 2: Active control system: in this example, the control is performed by 6 speakers located around the bell of the trombone and one in front of it.

The idea is to install as many loudspeakers as necessary to counterbalance the high sound level imposed by the trombone (± 110 dB SPL at 1 meter). The loudspeakers have been chosen according to the frequency response of the instrument [1]. Most of the energy being radiated in the

50-3000 Hz frequency bandwidth and looking to the constraints induced by the active control [1, 6, 7], the control is performed only for the first harmonics of the trombone spectrum.

Now, it is necessary to choose the number and positions of control sources in order to minimize the power of the musical instrument. For this, an analytical model (monopole sources) and a numerical model are implemented to evaluate the impact of the diffraction.

3. THEORY

The primary and control sources are first reduced to point sources to study a simple active control case [6] (see Fig. 3).

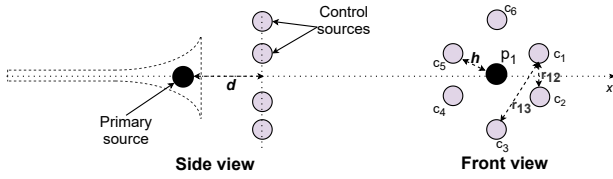


Figure 3: Schematic of the active control: the primary (trombone) and the control (loudspeakers) sources are considered as monopoles.

In order to carry out an active control on the system, the optimal volume velocity to be applied on the control sources is recalled [6]. To estimate the efficiency of this control, the acoustic power of the system with and without the active control is then estimated using two different methods.

3.1 Optimal control theory

To minimize the total radiated power, the optimal volume velocity q_{c_i} to be applied to the control sources is defined as :

$$q_{c_i} = -A^{-1}.b, \quad (1)$$

with A real and b complex numbers depending respectively on the transfer impedance matrices between control sources and between the primary source and each control one [6].

Pressure $p_m(\mathbf{r})$ radiated by a monopole is first defined as:

$$p_m(\mathbf{r}) = \frac{jZ_c k q}{4\pi} \cdot \frac{e^{j(\omega t - k|\mathbf{r} - \mathbf{r}_0|)}}{|\mathbf{r} - \mathbf{r}_0|}, \quad (2)$$

with $|\mathbf{r} - \mathbf{r}_0|$ the distance between the source placed in \mathbf{r}_0 and the observation point placed in \mathbf{r} , $Z_c = \rho_0.c_0$ and q the volume velocity of the monopole in $\text{m}^3.\text{s}^{-1}$. The $e^{j\omega t}$ factor is then omitted.

From Eq. (2), the expression of the transfer impedance Z_{ij} between the source i and the source j is deduced:

$$Z_{ij} = \frac{jZ_c k}{4\pi} \cdot \frac{e^{-jk r_{ij}}}{r_{ij}}, \quad (3)$$

with $r_{ij} = |r_i - r_j|$.

The vector $Z_{0,sj}$ represents the transfer impedance matrix between the primary source and the secondary (index s) sources:

$$Z_{0,sj} = \begin{pmatrix} Z_{01} \\ Z_{0j} \\ \vdots \\ Z_{0M} \end{pmatrix}. \quad (4)$$

The 0 index refers to the primary source and the 1 to n indexes refer to the control sources.

The matrix $Z_{si,sj}$ represents the transfer impedance matrix between the secondary source i and secondary source j :

$$Z_{si,sj} = \begin{pmatrix} Z_{11} & Z_{1j} & \cdots & Z_{1M} \\ Z_{i1} & Z_{ij} & \cdots & Z_{iM} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{N1} & Z_{Nj} & \cdots & Z_{NM} \end{pmatrix}. \quad (5)$$

Eq. (1) is redefined with $A = \frac{1}{2}.\Re[Z_{si,sj}(\omega)]$ and $b = \frac{1}{2}.\Re[Z_{0,sj}(\omega)].q_p(\omega)$ where q_p is the volume velocity of the primary source.

The volume velocity defined in Eq. (1) can be found analytically when control sources are placed at the same distance h from the primary one [7] or numerically when control sources are placed arbitrarily [6].

3.2 Power calculation

In order to estimate the efficiency of the active control, the power attenuation of the whole system is estimated. The acoustic powers delivered by the primary and the control sources are therefore estimated by two different methods. A first method consists to use the transfer impedance matrices of the system (see Section 3.1 and [6]). Another method consists to estimate the radiated power from the far field pressure of the system.

3.2.1 Transfer impedance matrix method

The total power is defined from the volume velocity of each of the sources composing the system [6]:

$$W = \frac{1}{2}.\mathbf{q}^H.\Re[Z_{ij}].\mathbf{q} \quad (6)$$

with \mathbf{q} the vector of primary and control source volume velocities and \mathbf{q}^H its Hermitian transpose.

Taking into account the model described in Section 3.1, the expression of the total power is developed as follows:

$$W = \frac{1}{2} \left[\mathbf{q}_c^H.\Re[Z_{si,sj}].\mathbf{q}_c + \mathbf{q}_c^H.\Re[Z_{0,sj}].q_p + q_p^H.\Re[Z_{0,sj}^T].\mathbf{q}_c + q_p^H.\Re[Z_{pi,pj}].q_p \right] \quad (7)$$

with $Z_{0,sj}^T$ the transposed of $Z_{0,sj}$ and $Z_{pi,pj}$ the impedance vector between the primary sources.

This method can nevertheless only be used if the impedance matrix is known, which is easy when using an analytical model with monopoles.

3.2.2 Source overlay principle

For the case of a numerical calculation or a measurement where only the pressure field $p(r, \theta, \phi)$ on a sphere is obtained, it is necessary to use the source overlay principle to estimate the whole studied system power.

The pressure being calculated numerically in far field at N points equally distributed in spherical coordinates by the radius r , the azimuth ϕ and the elevation θ , the acoustic power is defined by:

$$W(r, \theta, \phi) = \frac{1}{2} \sum_{i=1, j=1}^{N_\theta, N_\phi} \frac{p(r, \theta_i, \phi_j) \cdot p^*(r, \theta_i, \phi_j)}{Z_c} r^2 \sin \theta d\theta d\phi. \quad (8)$$

4. BOUNDARY ELEMENT SIMULATION

A numerical method based on a boundary element method that can take into account the geometry of the trombone and the speaker boxes is considered using the software *Akabak* [8]. Using the optimal volume velocity estimated with Eq. (1), this numerical approach enables to calculate the pressure in far field and to deduce the power of the system with realistic sources.

4.1 Geometry of the model

Several configurations are considered. A monopole source controlled by n monopole sources is first simulated to confirm the power calculation developed in Section 3.2.2.

A more realistic model with a trombone controlled by several loudspeakers is then built. For this last model, the mesh of the system geometry shown in Fig. 4 is defined: radiating elements are modeled as flat pistons and their rear bodies are cylindrical tubes. Each flat piston simply imposes a velocity, so it is a rigid body when the velocity is equal to zero. In order to have reliable results, the minimal distance between two points of the mesh is the tenth of the maximum frequency wavelength.

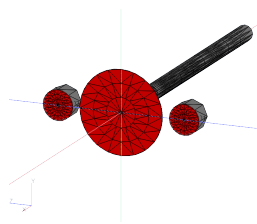


Figure 4: Mesh of trombone controlled by 2 loudspeakers. The radiating elements are red.

4.2 Power calculation

An optimal volume velocity (defined with Eq. (1)) is imposed for each flat piston. The pressure radiated by the vibration of each diaphragm is then derived from the Helmholtz equation [8].

The pressure emitted by each source is calculated in the far field on N points equally distributed on a sphere of radius r , azimuth ϕ and elevation θ . The resulting pressures are then extracted from the software and summed to calculate the total radiated pressure on a sphere. Following the same principle described in Eq. (8), the power can then be calculated from the pressure estimated by this model. This method has the advantage to take into account the diffraction produced by the elements of the system (see Fig. 5).

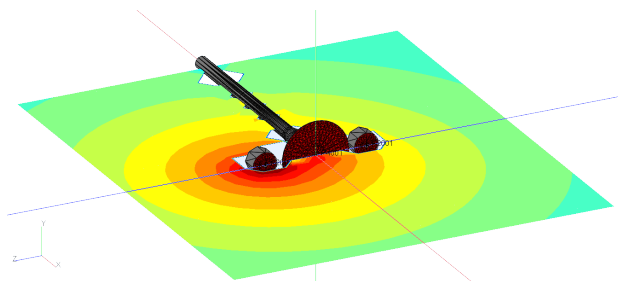


Figure 5: Pressure field for the case with 2 control sources. Case for which only one control source is activated.

4.3 Validation of the boundary element model

As a first step, a comparison between the two different methods (Section 3.2.1, Section 3.2.2) used to calculate the power produced by the different sources is carried out. The power of a primary point source is estimated with and without a control by 2 point sources separated of $h = 0.16$ m from either side of the primary source as in Fig. 5. For each method, the calculation of the optimal volume velocity for the control source is similar, see Eq. (1). As expected, the resulting attenuation of the system is the same regardless of the method. The boundary element model is therefore validated for this simple case of point source (results are not shown in this paper).

4.4 Effect of diffraction

The goal is then to figure out possible impacts coming from different type of sources and geometries by the boundary element method. A new geometry is built where the trombone becomes more accurate: a 8" diameter flat piston replaces the point source without (case 1) or with (case 2) a 1.31" diameter and 2 m long cylinder placed at the back to simulate the end of the trombone body. The control sources become 3" flat pistons without (case 1) or with (case 2) a 5 cm long rear cylindrical cavity. This choice is made to simulate the loudspeakers that will be used later for experimental work. The powers without and with control for a case where 2 control sources are placed at $h = 0.16$ m from either side of the primary source are calculated with Eq. (8). The resulting power attenuations are shown in Fig. 6.

The power attenuation appears to be the same as with the point source model Eq. (2) for case 1. For that case, the rear part of the radiating element is considered as closed. It appears furthermore that there is no differences between

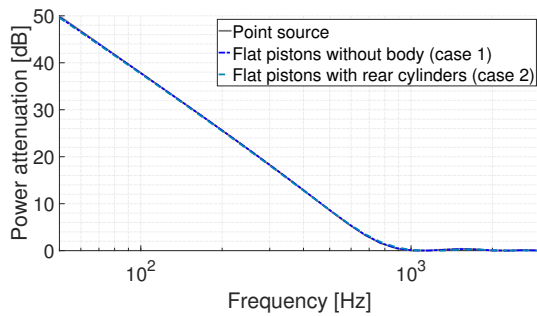


Figure 6: Power attenuation by boundary element method (2 control sources at $h = 0.16$ m): comparison between a point source model and one with flat pistons without (case 1) or with (case 2) rear cylindrical tubes.

a point source model and case 2 up to 3 kHz (see Fig. 7), the error being less than 0.4 dB.

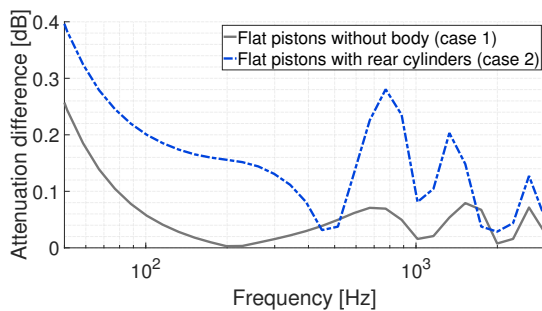


Figure 7: Attenuation difference on the power attenuation estimated by boundary element method (2 control sources at $h = 0.16$ m) for flat pistons without (case 1) or with (case 2) rear cylindrical tubes according to a point source model.

Diffraction may be highlighted by observing on Fig. 8 the differences of pressure emitted by the primary source with or without control sources.

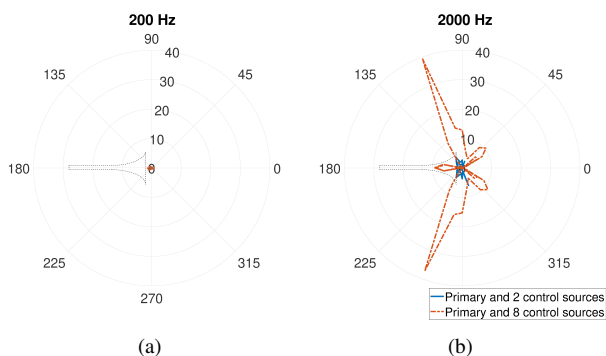


Figure 8: Relative difference (in %) on the pressure emitted by a trombone in farfield in presence or absence of control sources at 200 Hz (a) and 2 kHz (b). The diffraction is only present in high frequencies and focused on the sides at the back of the source.

In Fig. 8, the added control sources are considered as

closed boxes. Their impact on the far field is noticeable at 2 kHz in Fig. 8b: diffraction causes drops of pressure at 110° and 200° (0° being the axis of propagation of the trombone radiation). However, if diffraction has an impact by the presence of control sources, it slightly affects the pressure in low frequency where the active control is efficient.

Hence diffraction seems not to impact the attenuation in this frequency range. The monopole model appears to be sufficient for the analysis of power attenuation in the studied frequency range. Diffraction is nevertheless not taken into account in the calculation of the optimal volume velocity with transfer impedance matrices. For the rest, the optimal volume velocity calculated with Eq. (1) is kept for the parametric study though.

5. APPLICATION

The calculation of power attenuation being validated by several methods, a parametric study is carried out. The position as well as the number of control sources is modified in order to optimize the control system to be set up. In a second step, a control of directivity is studied, which permits to highlight the effect on the power attenuation.

5.1 Power control

The parametric study is carried out with a point source model. Several parameters can enhance the efficiency of the active control. The impact of the position as well as the number of control sources is studied below.

Five configurations are investigated (Fig. 9) and the resulting power attenuations on the system are shown in Fig. 10. For each case, the number and the positioning of sources is different.

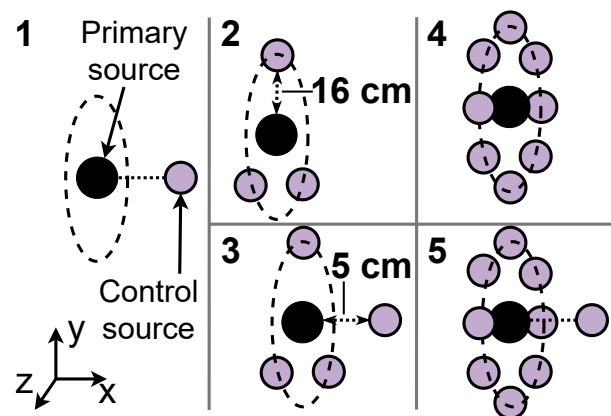


Figure 9: Scheme of possible setups used for active control: the control sources can be placed around the primary source or in front of this last one.

In this parametric study, the calculation of the volume velocity comes from transfer impedance matrices Eq. (1). The resulting power attenuations are calculated with Eq. (6).

First of all, increasing the number of control sources (from 3 to 8 sources - cases 2 and 4) produces nearly the

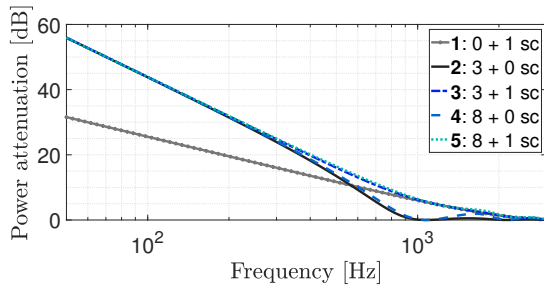


Figure 10: Power attenuation with point sources in 5 cases (see scheme in Fig. 9). **1:** 1 source is at 5 cm front of the primary source, **2:** 3 sources are at 16 cm from the primary source equidistant in a ring, **3:** case 2 with a 4th source in front of at 5 cm, **4:** similar to case 2 with 8 sources, **5:** similar to case 3 with 8 sources on the ring.

same low-frequency attenuation. It is only from $kh = n\pi$ ($f \simeq 1000$ Hz, h being defined in Fig. 3) that a slight increase takes place for the case 4, but remains negligible compared to the attenuation at low frequencies before $kh = n\pi$. The ring is more efficient in low frequencies due to the high distance between the primary and the control source, making impossible an efficient control in high frequencies. Increasing the number of sources allows nevertheless to prevent reaching maximum excursion and nominal power of the loudspeaker.

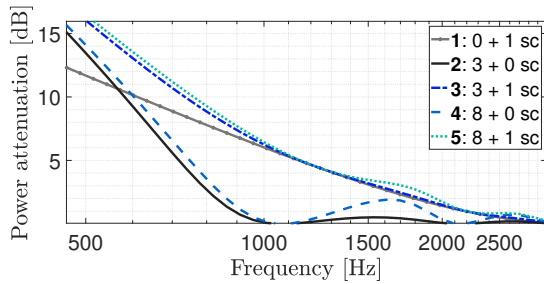


Figure 11: Power attenuation with point sources for the 5 cases presented in Fig. 9: zoom on $kh = n\pi$.

Secondly, the addition of a control source on the axis of the trombone (cases 3 and 5) increases the attenuation around $kh = n\pi$, up to 6 dB. This can easily be explained by the fact that this added source is closer to the primary source ($h = 0.05$ m) compared to the control ones located at $h = 0.16$ m. This is emphasized on the zoom around 1 kHz on Fig. 11.

Fig. 12 compares volume velocities: primary source (trombone), control sources and loudspeakers available on the market. The primary source volume velocity is an estimation of the trombone spectral envelope coming from a measurement of 4 notes [$B0_b; B1_b; B2_b; B3_b$] played at a high intensity (± 110 dB SPL at 1 meter) [1]. This estimation enables to deduce the optimal volume velocities of 4 control sources using Eq. (1). The four sources positions are given by Fig. 9, case 3 with $h = 0.16$ m. These optimal velocities are compared to the ones delivered by 3

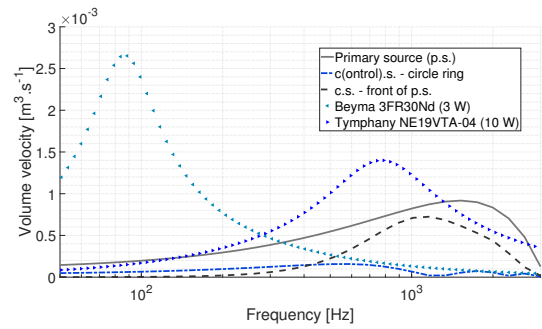


Figure 12: Comparison of the required volume velocity for each control source according to their position to the primary source for the case 3. Two curves are added to show different loudspeaker volume velocity capacities.

loudspeakers Beyma 3FR30Nd mounted on a 1 liter box (on the ring) and 1 loudspeaker Tympany NE19VTA-04 (on axis).

The maximum volume velocity of the "axis" control source is more than 4 times higher the maximum volume velocity of the "ring" control sources.

The "axis" control source should have a resonance frequency around 1200 Hz to control the high frequency range whereas the "ring" control sources resonance frequency should be around 600 Hz.

This comparison shows that the two loudspeakers references can be used as control sources if they are respectively supplied with 3W and 10 W. The Beyma 3FR30Nd mounted on a 1 liter box has a sufficient excursion to control the low frequency range while the Tympany NE19VTA-04 can handle enough electric power to control high frequencies.

The resulting directivity (normalized for $\theta = 0$) for such a control (case 3) is shown in Fig. 13.

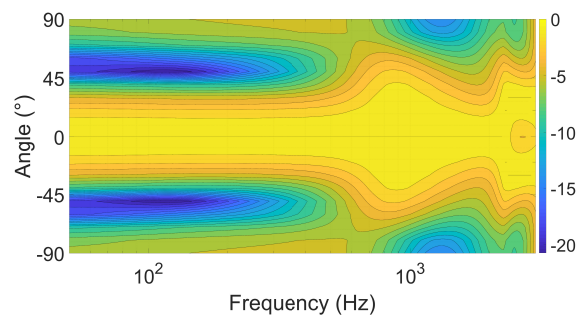


Figure 13: Directivity pattern (with 3 control sources at $h = 0.16$ m and 1 at $h = 0.05$ m) at 1 meter on the y/z plane (trombone radiation is at 0°). The pressure attenuation is minimal on axis is maximum while there are drops of pressure at $\pm 50^\circ$ up to 500 Hz.

Looking to Fig. 13, there is a drop of amplitude of ± 10 dB at 50° up to 500 Hz. When the goal is to minimize the power with Eq. (1), the closer one get to the axis of prop-

agation of the trombone (at 0°), the less the sound level is attenuated. This depends on the position and the number of control sources around the primary one.

To conclude, it is possible to improve the power attenuation of the system on a given target frequency range by placing several layers of loudspeakers around the trombone. These ones must be tuned according to their frequency range of operation to deliver an appropriate volume velocity.

In addition to the power attenuation, it is interesting to be able to control the directivity of the system.

5.2 Directivity control

The goal is now to make a control on the directivity of the system in order to focus the sound towards a desired localization. Let's take the example of a musician who would like to hear the sound of his instrument louder. The directivity would then have to be adapted so that the sound would be louder only towards the musician.

Considering solutions used to achieve cardioid loudspeakers for sound reinforcement, the control source layer is shifted by a distance d on the x axis with respect to the primary source (see Fig. 14).

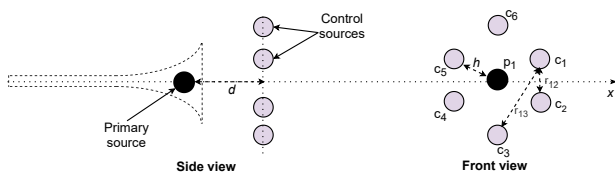


Figure 14: Simplified presentation of the system: a ring, composed of control sources separated of a distance h from the primary source originally in the same plane, can be shifted on the axis x by a chosen distance d .

A delay $\tau = \frac{d}{c}$ is added to the optimal volume velocity (estimated previously in Section 3.1) to modify the directivity and the power of the primary source. Adding a delay, however, has a negative impact on the power attenuation, as shown in Fig. 15.

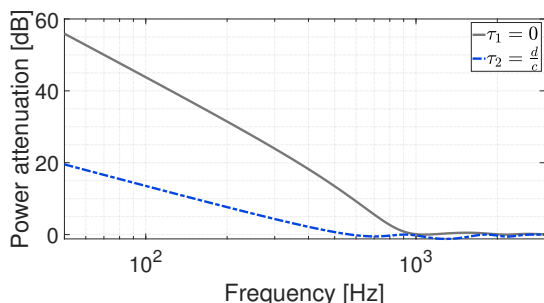


Figure 15: Power attenuation for two different time delays (3 control sources at $h = 0.16$ m and $d = 0.1$ m).

The greater the added delay, the less effective is the power attenuation (-6 dB per doubling of τ). In Fig. 15,

when a delay is added, the power attenuation becomes lower in low frequencies: $W_{att} \geq 6$ dB up to 250 Hz only. This is the result of the volume velocity calculation (Eq. (1)) which is not optimal anymore in this case and should be estimated again.

In the case of Fig. 15, the directivity becomes cardioid (see Fig. 16). The acoustic energy is attenuated in $+x$ and increased in $-x$.

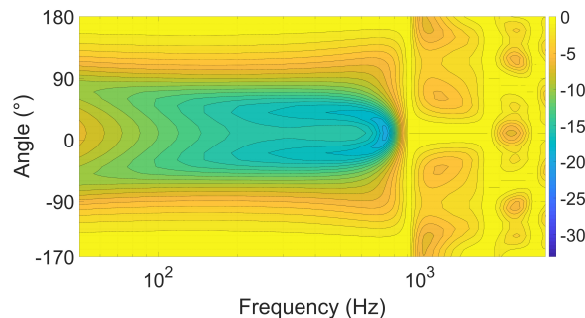


Figure 16: Directivity pattern (with 3 control sources at $h = 0.16$ m and $d = 0.1$ m) at 1 meter on the y/z plane (trombone radiation is at 0°). The added delay $\tau = \frac{d}{c}$ corresponds to the flight time between the primary source and the control one on the x axis. The pressure attenuation is maximal on axis up to 1 kHz.

The cardioid directivity allows concentrating the acoustic energy towards the musician and thus avoids as much as possible radiation in the room. Fig. 16 shows that this targeted shape is respected in low frequency, the sound level is especially attenuated in front of the primary source. There is finally a limit at $kh = n\pi$ where the targeted shape disappears and the pressure is no more attenuated on axis.

6. CONCLUSION

In this paper, an active control system has been studied in order to reduce the acoustic power of a trombone. This system is made of secondary loudspeakers placed near the bell. Assuming that all the sources can be considered as monopoles, the theory of optimal control enabled to get the optimal volume velocities emitted by the loudspeakers knowing the volume velocity of the trombone for four notes played at high sound pressure level. The optimal voltage of the loudspeakers was deduced from a simple T&S model.

The optimal configuration uses two groups of loudspeakers, a ring around the bell (group 1) and a loudspeaker in front of the bell (group 2). Each group of loudspeakers needs to be tuned to deliver the optimal volume velocity, the first group being used for low frequencies and the second for higher frequencies. The optimal power attenuation is between 40 dB at 100 Hz and 6 dB at 1 kHz.

The study of a configuration using a ring of loudspeakers placed in front of the bell fed with the optimal voltage and a time delay showed that it is possible to modify the

directivity of the system. In this case, the power attenuation is reduced suggesting that the simultaneous control of power and directivity is a compromise.

In parallel, this study showed that the use of a BEM model is not necessary to estimate the power attenuation, the effect of diffraction being negligible in the frequency range under study.

For the future, it will be necessary to optimize the choice of the control loudspeakers for all the notes of a trombone, to assess the performances of the active control with an experimental work. Moreover, other optimization techniques could be used ([9], [10], [11], [12], [13]) to control simultaneously the power and directivity of the system.

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