This research work deals with the active control of the sound radiated by a brass instrument. The general goal is to reduce the radiated sound level without altering the input impedance of the instrument. This paper focuses only on the active control of the radiated power. The control is performed by several loudspeakers located outside close to the bell. In order to choose control loudspeakers, measurements of the pressure field produced by a trombone played by a non-professional musician are carried out. This enables to estimate the properties of the equivalent point source of the trombone (volume velocity and position) for different frequencies and levels. Knowing the volume velocity delivered by the control loudspeakers, maximum excursions and input electrical powers are deduced for various loudspeakers types. A dedicated type of loudspeakers is chosen to perform the control. The trombone radiation is modelled by a point source (the interior acoustic field of the trombone is not studied). Considering a lumped element model of the suitable control loudspeakers, the optimal control is applied to determine the pressure field radiated by the bell with analytical models (4 control sources in the shape of a tetrahedron).

Keywords: musical acoustics, brass instruments, loudspeakers, active control, acoustic radiation

1. Introduction

The sound rendering of a musical instrument is essential for the musician who must be able to control the power and the timbre as he wishes. In the brass instrument family, the sound can be modified or attenuated with a mute, often inserted in the bell of the instrument (see Fig. 1). This tool, available in various shapes, has an impact on both timbre and power of the radiated sound.

The "classical" mute starts to be considerably commercialised at the beginning of the 20th century with the birth of jazz. Musicians mainly use it to produce sound effects such as the "wah-wah" effect highlighted by Duke Ellington. It can also be a way to reduce the radiated sound level so that the musician can play without disturbing the neighborhood. More recently, Yamaha launched the Silent Brass™ mute which allows to play a brass instrument while keeping mainly the acoustic energy inside the horn. The sound is picked up in the mute by a microphone and then transmitted through earphones to the player’s ears.
A common impact of these mutes is that the musician’s playability inevitably changes. The player must therefore adapt his way of playing. In addition, when the musician’s intention is only to reduce the sound power of his instrument, the timbre of the latter is also denatured.

A study on the active control for a trombone and for a clarinet has been done as part of Meurisse’s thesis [2]. A feedback control has been implemented to a trombone mute modifying both the frequency and the damping factor of the mute customizing the musician’s playing. However, it cannot effectively control a system with several degrees of freedom, as opposed to a modal control then studied on a clarinet, which allows significant changes in the sound and input impedance of the instrument [3].

Recently, an investigation has been done to study the effect of an active control over the radiation of a waveguide [4]. The objective is to reduce the radiated power with an active control with 2 control sources, to observe the impact on its directivity and the input impedance. The following research is a continuation of this work.

The aim of this research work is to perform an active control of the sound radiated by a brass instrument. The general goal is to reduce the radiated sound level without altering the input impedance of the instrument.

This paper focuses only on the active control of the radiated power and the shaping of the directivity for a real trombone (see Fig. 2), the control of the input impedance is not studied here.

In order to choose control loudspeakers, measurements of the pressure field produced by a trombone played by a non-professional musician are carried out. This enables to estimate the properties of the equivalent point source of the trombone (volume velocity and position) for different frequencies and levels.

Knowing the volume velocity delivered by the control loudspeaker, maximum excursion and input electrical power are deduced and studied.
2. Trombone volume velocity

In order to control the power radiated by the trombone, it is first necessary to know the volume velocity it can produce, as the control loudspeakers will have the same total volume velocity [5].

This quantity is not often measured. A measurement of the sound level radiated by the trombone in function of the distance is therefore implemented. These data permit to deduce a volume velocity value for a note played by the trombone. It is also possible to determine the equivalent acoustic center from which the radiated wave is released (as it has been done for the trumpet with an optical method [6], and using a spherical array of microphones [7]), which is necessary for further work (see Section 4).

To find the volume velocity of the primary source $q_p$, the radiated pressure is measured. A recent study [8] show that a trombone is omnidirectional up to $\pm 500$ Hz. The pressure amplitude can thus be given by:

$$ p(k, r, r_p) = H(k, r, r_p) \cdot q_p(k), $$

with

$$ H(k, r, r_p) = \frac{jk\rho e^{-jk(r-r_p)}}{4\pi(r-r_p)}, $$

$r$ the distance from the horn ($r = 0$) to the observation point, $r_p$ the position of the primary source, $k$ the wave number, $\rho$ the density of the medium and $c$ the speed of sound in air.

2.1 Experiment

To get the distance dependance of the pressure, a trombone note is measured by 14 microphones in the axis of the instrument along 4 meters hold on a thin metal stand, and perpendicular to propagation to avoid diffraction below 10 kHz [9] (see Fig. 3).

![Figure 3: Principle of the measurement: the microphones are arranged in a decreasing logarithmic manner.](image)

To get an accurate value of the pressure, the experiment takes place in an anechoic room in order to avoid any reflection from the walls. Its cutoff frequency is around 100 Hz. Below this frequency, the measured pressure does not fit the model (see Eq. (1)).

The musician plays four notes covering the instrument fundamental frequency range: $[58;117;233;466]$ Hz corresponding respectively to the notes $[B0_b;B1_b;B2_b;B3_b]$. These notes are also chosen so that the musician does not have to move the trombone slide. They are played in crescendo in order to evaluate also the instrument dynamics. Each note is played four times in order to be able to estimate the average value and the standard deviation of the measure.
For each played note, we choose to focus on the 6 first harmonics containing the majority of the energy radiated by the instrument. The frequency bandwidth is therefore from 58 to 2736 Hz. The metal stand is small enough to avoid its diffraction in the studied frequency range. The trombone is also placed on a stand to ensure that it is directed towards the axis of the microphones. This stand is adjustable on all 3 axes to settle precisely the position of the instrument. The latter is held by the hand and the shoulder of the musician sitting on a stool. The trombone is not totally attached so that the musician can easily play.

### 2.2 Interpretation

Thanks to a FFT analysis of the measured signal, the pressure decrease over the distance is estimated for each harmonics (see Fig. 4).

![Sound Pressure Level](image)

**Figure 4**: Sound pressure level over the distance for the note $B_3^\#$ ($f = 466$ Hz).

From Eq. (1), it is possible to deduce $q_p$ with the following equation:

$$ q_p(k, r_p) = H^\dagger(k, r).p(k, r_p, r), $$

with $H^\dagger(k, r)$ the pseudo inverse of $H(k, r)$, such that $A^\dagger = (A^H.A)^{-1}.A^H$.

The optimum acoustic center position is estimated by minimizing error between the theoretical pressure at $r_p$ and the measured pressure.

The estimated trombone volume velocity $q_p$ is then represented as a function of its acoustic center $r_p$ on Fig. 5.

The acoustic center positions are between -13 and 2 cm. For each harmonic, they remain coherents between themselves whatever the input level. The trombone acoustic center moves toward the mouthpiece as frequency increases as it has been shown for a trumpet by Rendón et al. ([6], Fig. 3). Hence, the equivalent primary source should be around the horn between -10 and 0 cm.

For each point, the uncertainties of the volume velocity and the acoustic center are defined as twice the standard deviation calculated on 4 measurement samples for the same note and sound level.

For this work, only the volume velocity modulus is investigated. The maximum value on all played notes is $q_p \simeq 0.01$ m$^3$.s$^{-1}$ (see Fig. 6). The estimation is accurate enough for the further work: once the trombone volume velocity is known, the choice of a sound source giving at least the same amount of volume velocity is investigated.
3. Loudspeaker volume velocity

3.1 Thiele and Small parameters

In order to determine the characteristics and the number of loudspeakers required to do an active control of the musical instrument, an electrodynamic loudspeaker is modelled analytically. A lumped element model gives the volume velocity that the loudspeaker can deliver as a function of its excursion and/or input power. The loudspeaker is mounted in a sealed enclosure.

Based on the Thiele & Small model [10], the volume velocity delivered by speaker is given by [11]:

$$q_c = \frac{U_g S_d}{Q_e Bl} \frac{G_e(j\omega/\omega_c)}{j\omega/\omega_c},$$

with $U_g$ the generator voltage applied to the speaker input, $S_d$ the diaphragm surface, $Q_e$ the electric quality factor, $Bl$ the coupling factor, $G_e(j\omega/\omega_c) = \frac{(j\omega/\omega_c)^2 + Q_t^2(j\omega/\omega_c)^2 + 1}{(j\omega/\omega_c)^2 + Q_t^2(j\omega/\omega_c)^2 + 1}$, $\omega_c$ the angular frequency of the loudspeaker and its enclosure and $Q_t$ the total quality factor.

By adding a closed box to the speaker and by working above the speaker resonance frequency, the limiting factor is not the diaphragm excursion but its maximum admissible power.

3.2 Comparison with the trombone

Now, the volume velocity of the loudspeaker Beyma - 3FR30Nd [10] is compared to that of the trombone (see Fig. 6) to estimate how much loudspeakers are needed to deliver as much volume velocity as the instrument is producing.

The volume velocity delivered by the control loudspeaker $q_p$ shown Fig. 6 is represented for a wideband excitation in contrast of $q_p$ which is characterized by the harmonics of the trombone (estimated from the measurement, see Section 2.1).

Nevertheless, it may be noticed that a single speaker would not be sufficient to deliver enough volume velocity to play the 6 first harmonics of the note $B3_{♭}$ ($f = 466$ Hz).
In this case, it is more accurate to calculate the power $P$ required to be applied to the loudspeaker to deliver enough volume velocity. Hence, the power for one speaker is calculated as a function of the volume velocities of the primary (see Eq. (2)), the control sources (see Eq. (3)) and the number of speakers:

$$P = \left( \frac{Q_e.Bl}{S_d.N_s} \right)^2 \cdot \frac{1}{2.Z_e} \cdot \sum_{i=1}^{N_h} \left| \frac{q_p(\omega_i).\omega_i}{G_c(\omega_i)} \right|^2,$$

(4)

with $Z_e$ the rated impedance of the speaker, $N_h$ the number of harmonics and $N_s$ the number of speakers.

From Eq. (4), the required power as a function of the number of speakers is deduced Table 1.

<table>
<thead>
<tr>
<th>Number of speakers</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power needed (W)</td>
<td>476</td>
<td>119</td>
<td>53</td>
<td>30</td>
<td>19</td>
<td>13</td>
<td>10</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Table 1: Power required to deliver a sufficiently high volume velocity quantity for the six first harmonics of $B3\flat$ ($f = 466$ Hz) of the trombone as a function of the number of speakers.

Knowing that this loudspeaker has a nominal power of 30 W, 4 speakers are needed to be able to perform the active control.

4. Active control model

A particular case of active control is studied for $r_p$ being the acoustic center position of the fundamental. 4 control sources are equally spaced (in the shape of a tetrahedron) from the primary source [5]. For this model, the distance between the primary and the control sources is $r_{p,c_i} = 10$ cm.

The equation giving the minimum power output $\frac{W_0}{W_p}$ of each control source is given by:

$$\frac{W_0}{W_p} = \frac{1 - 4.sinc^2(k.r_{p,c_i})}{1 + 3.sinc(k.r_{c_i,c_j}),}$$

(5)

with $r_{c_i,c_j}$ the distance between a control source $i$ and a control source $j$. 
Looking to Eq. (5), the power attenuation depends on the distance between the primary source and the control sources [5]. Also, the further the control sources are apart from each other, the smaller the power attenuation frequency range (here, \( r_{c_i,c_j} = 15 \text{ cm} \)). Furthermore, Fig. 7 is showing that the greater the frequency, the smaller the power attenuation. The consequence is observed between 500 Hz and 2000 Hz where there is no power attenuation anymore.

For higher harmonics, the power attenuation is lower because their equivalent primary source positions are shifted.

5. Conclusion

To conclude, the position and volume velocity of an equivalent monopole to the radiation of a trombone were estimated using measurement results and an equivalent source model.

For the maximum volume velocity corresponding to note \( B3_b \) \( (f = 466 \text{ Hz}) \), a Thiele and Small model of the loudspeaker is used to estimate the minimum number of speakers.

In the case of the loudspeaker Beyma - 3FR30Nd [10], 4 speakers are required. In the case where there are 4 control sources (shape of a tetrahedron), the calculation of the power attenuation shows that the control is effective up to 500 Hz (due to the position of the control sources) thus affecting only the low frequencies, so the fundamental of each note.

In the future it will be necessary to optimize the position of the control sources (for example with a ring as in [12]) in order to control the radiated power of the fundamental frequency and higher harmonics. Moreover, the effect on a delay applied on control sources will be studied to enhance the directivity of the instrument equipped with the active mute.

Finally, it will be necessary to take into account the non-linearities of the speaker: indeed, even if it has a low harmonic distortion ratio in the specifications, its distortion should be higher when it has to support its nominal power. This brings other constraints in the development of a good active control [13]. This will add a selection criterion to choose the loudspeaker which fits for this application.

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REFERENCES


