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1 Physical modelling of trombone mutes, the pedal note issue

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8 **Abstract**

9 Brass players use a variety of mutes to change the sound of their instrument for artistic
10 expression. However, mutes can also modify the intonation and the playability of the muted
11 instrument. An example is the use of a straight mute on a trombone, which makes it very
12 difficult to play stable pedal notes.

13 Previous studies have shown that using a straight mute establishes a parasitic acoustic
14 resonance in the trombone. To cancel this modification, an active control device was developed
15 and integrated into a mute, with satisfying experimental results [Meurisse et al., 2015]. With
16 this device, the perturbed pedal notes can easily be played again.

17 This paper investigates the ability of a physical model of brass instrument to reproduce
18 the behaviour of the trombone pedal *Bb* without mute, or with an "active" or a "passive"
19 straight mute. Linear stability analysis and time-domain simulations are used to analyse the
20 behaviour of the model in the parameter range corresponding to the pedal note. Numerical
21 results are compared for different models of instruments: a trombone, a trombone with a
22 straight (passive) mute, an a trombone with an active mute. It is shown that the simple
23 physical model considered behaves similarly to what is experienced with real instruments: the
24 playing of the pedal note is perturbed with a passive mute, whereas the model of trombone
25 with the experimental active mute gives results very similar to those obtained with an open
26 trombone.

27 **I Introduction**

28 A usual solution for changing the timbre of a brass instrument consists in using a mute, which is a
29 device plugged to the opening of the instrument bell, or held by hand just in front of the bell. The

30 shape and the material of the mute affect the pressure radiation of the bell, therefore modifying
31 the emitted sound [Campbell and Greated, 1994, p.398]. As a side effect, introducing an obstacle
32 in the bell, or close to it, also modifies the acoustical properties of the instrument [Backus, 1976].
33 This has various consequences, including modification of the instrument tuning and of the feeling
34 the musician has of his instrument.

35 Pedal notes are the lowest playable notes on a trombone. When the slide is fully closed, the
36 note played is a Bb^1 , corresponding to a playing frequency of $58Hz$ in equal temperament. These
37 notes are quite particular regimes of oscillation of the instrument, for which the playing frequency is
38 farther from the resonance frequency of the corresponding acoustical mode (the lowest one) than for
39 other regimes [Gilbert and Aumond, 2008, Velut et al., 2016b]. Furthermore, the lowest acoustical
40 mode is inharmonic with other acoustical modes. When a straight mute is inserted in the trombone,
41 playing stable pedal notes on the three first slides positions - Bb^1 , A^1 and Ab^1 - is uneasy and results
42 in a rolling, unstable sound [Sluchin and Caussé, 1991, Meurisse et al., 2015]. Measurements of the
43 input impedance of a trombone with a mute [Meurisse et al., 2015, Velut et al., 2016c] show the
44 occurrence of a parasitic acoustical mode between the first and the second modes.

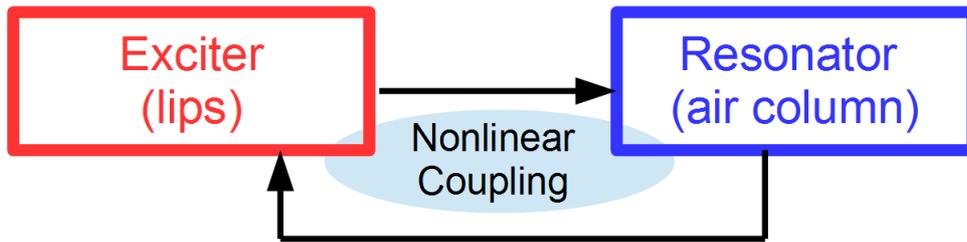
45 This paper will particularly focus on the pedal Bb^1 , corresponding to the slide fully pulled. It
46 will hereinafter be referred to as "the pedal note". An active control device has been previously
47 developed to remove this parasitic mode [Meurisse et al., 2015], which makes it possible to play
48 the pedal note with a straight mute. It consists of an "active mute", a commercial straight mute
49 equipped with an active control device which cancels the aforesaid parasitic resonance mode.

50 The purpose of this paper is to investigate to what extent a simple physical model of trombone
51 can predict the effect of a trombone straight mute on the pedal note and the effectiveness of the
52 active mute. The physical model of brass instrument is first presented. Then, linear stability
53 analysis (LSA) and time-domain simulations are used to analyse the behaviour of the pedal note
54 in this model. Analyses are conducted on an "open trombone" configuration (tenor trombone
55 without any mute), a "passive mute" configuration (the same trombone with a consumer straight
56 mute) and an "active mute" configuration (the same trombone with an identical straight mute
57 and the described active control loop). Results of this model are compared with the experimental
58 results from [Meurisse et al., 2015].

59 II Tools

60 II.A Brass instrument model

61 A physical model of trombone, suitable for a large class of music instruments, is presented in this
62 article. Following Helmholtz pioneering work [von Helmholtz, 1870], the trombone is modelled as
63 a closed-loop system consisting of an exciter and a resonator which are coupled, as illustrated in
64 Fig. 1. Such a system is able to self-oscillate in different oscillation regimes.



65

Figure 1: Closed-loop model in free oscillation, suitable for the description of most self-sustained musical instruments, including trombones. Self-sustained oscillations are generated by the localised non-linear coupling (here the airflow between lips) between a linear exciter (here the lips) and a linear resonator (here the air column inside the instrument bore).

66

67 For a brass instrument, the exciter is the lips of the musician, which act as a valve: the section of
 68 the channel between the lips depends on the pressure difference through these lips as well as on their
 69 mechanical characteristics. Multiple models of the lip reed have been proposed and used, with one
 70 degree of freedom [Elliott and Bowsher, 1982, Fletcher, 1993, Cullen et al., 2000, Silva et al., 2007]
 71 or 2 DOF [Adachi and Sato, 1996, Campbell, 2004, Lopez et al., 2006, Newton et al., 2008]. The
 72 model retained for this paper is the one-DOF valve model, usually referred to as the "outward-
 73 striking" model, also called (+, -) swinging-door model in the literature:

$$\frac{d^2h}{dt^2} + \frac{\omega_l}{Q_l} \frac{dh}{dt} + \omega_l^2(h - h_0) = \frac{1}{\mu}(p_b - p(t)), \quad (1)$$

74 where h is the height of the lip channel (m); p is the pressure at the input of the instrument, in
 75 the mouthpiece (Pa); p_b is the constant blowing pressure in the mouth (Pa); $\omega_l = 2\pi f_l$ ($\text{rad} \cdot \text{s}^{-1}$)
 76 is the lip resonance angular frequency; Q_l is the (dimensionless) quality factor of the lips; h_0 is the
 77 value of $h(t)$ at rest; μ is an equivalent surface mass ($\text{kg} \cdot \text{m}^{-2}$).

78 Although it does not fully reproduce all the observed behaviours of human or artificial lips, this
 79 model is sufficient for reproducing the normal playing situations [Yoshikawa, 1995], including the
 80 pedal note of the trombone [Velut et al., 2016b] and multiphonic sounds [Velut et al., 2016a]. As
 81 a limitation, this model is known to oscillate at higher frequencies than those at which a musician
 82 would play on the same acoustical mode. Even for this relatively simple model, choosing the lip
 83 parameters is challenging and requires a thorough bibliographical review. This was conducted in
 84 [Velut et al., 2016b]. The resulting set of parameters is given in table I.

h_0 (m)	W (m)	$1/\mu$ ($\text{m}^2 \cdot \text{kg}^{-1}$)	Q_l
$5 \cdot 10^{-4}$	$12 \cdot 10^{-3}$	0.11	7

85

86

Table I: Lip parameters retained in this study.

87 The resonator is the air column contained in the bore of the instrument. Given the low
 88 playing amplitude considered in this article, the brassiness phenomenon, related to non-linear

89 propagation in the instrument [Myers et al., 2012] is not taken into account. Under this hypothesis,
 90 the resonator can be fully described by its input impedance, which is by definition the ratio of the
 91 pressure $P(\omega)$ to the flow $U(\omega)$ at the input of the instrument, in the frequency domain:

$$Z(\omega) = \frac{P(\omega)}{U(\omega)}. \quad (2)$$

92 This value can be measured thanks to the sensor described in [Macaluso and Dalmont, 2011].
 93 In this paper, three input impedance measurements are used: the impedance of an open trombone
 94 (without any mute), the impedance of the same trombone with a "passive mute" (mute without
 95 active control) and the impedance of this trombone with an "active mute", with the feedback
 96 active control device enabled.

97 The input impedance can be considered as a sum of peaks, each peak corresponding to a
 98 resonance mode of the air column inside the instrument. Thus, it can be fitted with a sum of
 99 complex modes, corresponding to a sum of poles-residues functions:

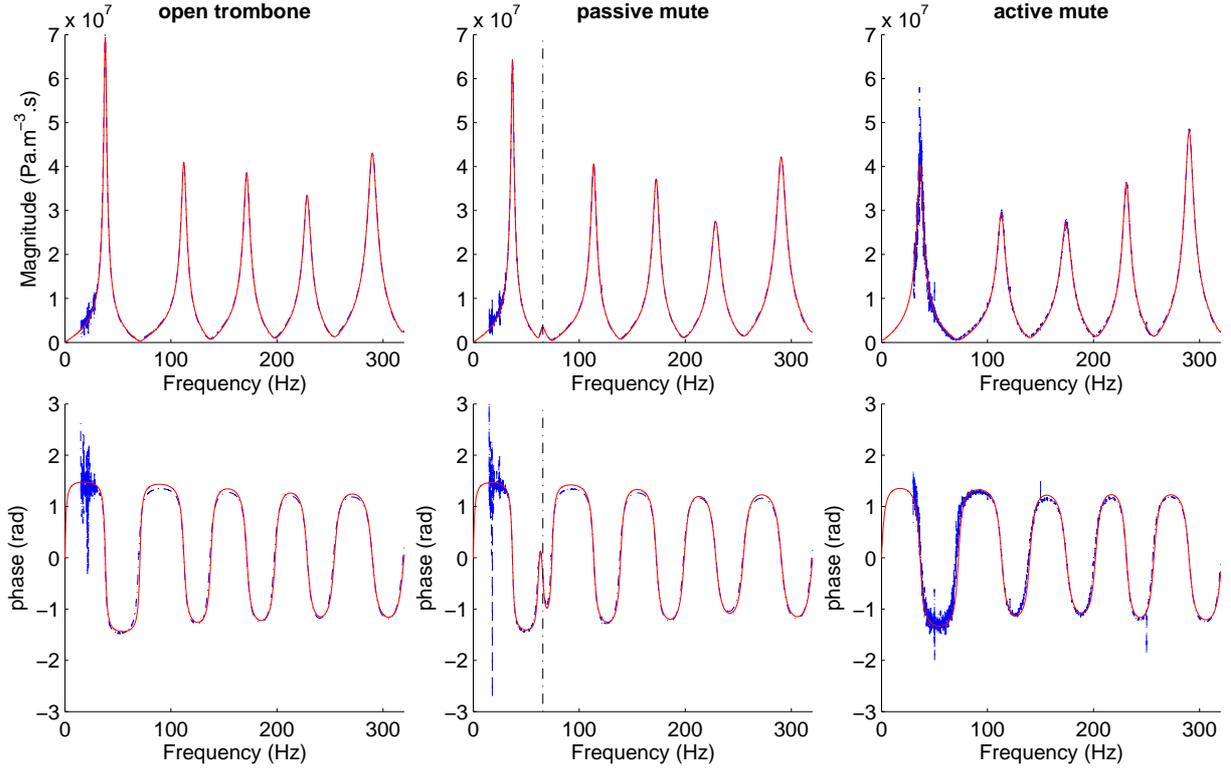
$$Z(\omega) = Z_c \sum_{n=1}^{N_m} \frac{C_n}{j\omega - s_n}, \quad (3)$$

100 C_n and s_n being the dimensionless complex residues and poles of the complex modes of the
 101 fitted impedance, respectively. $Z_c = \frac{\rho c}{\pi r^2}$ is the characteristic impedance of the resonator, ρ is the
 102 air density, c the celerity of acoustic waves in the air and r the input radius of the mouthpiece.
 103 N_m is the number of modes used to fit the impedance fixed to $N_m = 13$ in this article. Translation
 104 of eq. (3) in the time domain leads to an ordinary differential equation for each complex modal
 105 component p_n of the pressure $p(t)$:

$$\frac{dp_n}{dt} = s_n p_n(t) + Z_c C_n u(t) \quad \forall n \in [1..N_m], \quad (4)$$

106 where $u(t)$ is the time-domain expression of the flow at the input of the instrument. Furthermore,
 107 $p(t) = 2 \sum_{n=1}^{N_m} \Re[p_n(t)]$.

108 The fit is optimised by a least mean squares algorithm. This results in a very good match
 109 between the measured impedance and the fit, as shown in Fig. 2.



110

Figure 2: (colour online) Comparison of the measured impedances (blue, dash-dotted) and their modal fits (red, plain) with 13 complex modes. Magnitudes (top plots) and phases (bottom plots) of the impedances for the three situations - open trombone (left), passive straight mute (middle) and active mute (right) - are displayed. The dash-dotted line at 65.7 Hz indicates the parasitic resonance.

111

112 The lips and the resonator are coupled through the expression of the flow $u(t)$ of the air jet through
 113 the lip channel:

$$u(t) = W.h(t) \cdot \sqrt{\frac{2 \cdot |p_b - p(t)|}{\rho}} \cdot \text{sign}(p_b - p(t)) \cdot \theta(h), \quad (5)$$

114 where W is the width of the lip channel and ρ the air density, sign is the sign function and
 115 $\theta(h)$ is the Heaviside step function. This non-linear expression of the flow was proposed in
 116 [Wilson and Beavers, 1974, Elliott and Bowsher, 1982] and has been used in almost every publi-
 117 cation about brasswind and woodwind physical models since.

118 The whole model can therefore be written:

$$\left\{ \begin{array}{l} \frac{d^2 h}{dt^2} + \frac{\omega_l}{Q_l} \frac{dh}{dt} + \omega_l^2 (h - h_0) = \frac{1}{\mu} (p_b - p(t)) \\ u(t) = W.h(t) \cdot \sqrt{\frac{2 \cdot |p_b - p(t)|}{\rho}} \cdot \text{sign}(p_b - p(t)) \cdot \theta(h) \\ \frac{dp_n}{dt} = s_n p_n(t) + Z_c C_n \cdot u(t) \quad \forall n \in [1..N_m] \\ p(t) = 2 \sum_{n=1}^{N_m} \Re[p_n(t)] \end{array} \right. \quad (6)$$

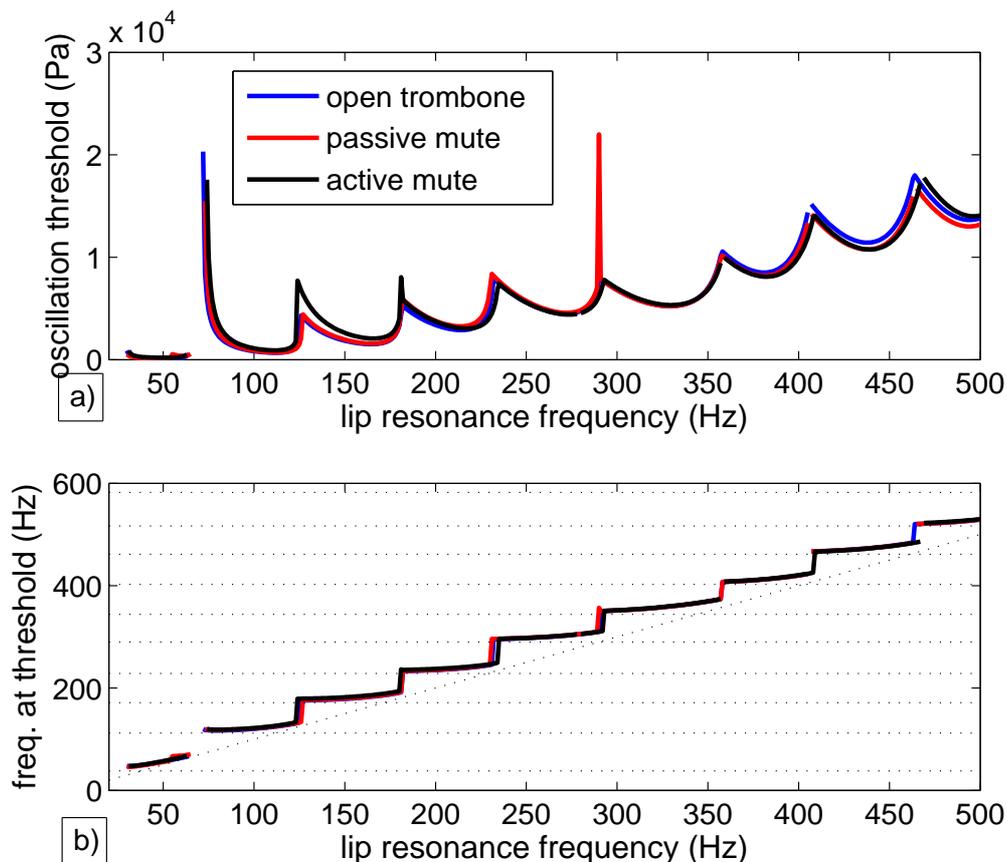
119 II.B Linear stability analysis

120 The model described above has a variety of possible behaviours. One of them is a static solution,
121 all variables being constant. The stability of this static solution is a useful piece of information, as
122 instability of the static solution indicates possible emergence of oscillating solutions through Hopf
123 bifurcations. This stability analysis can be carried out on a linearised model: non-linear equations
124 are linearised in the vicinity of the static solution. Then, the stability of this static solution is
125 assessed through computation of the eigenvalues of the Jacobian matrix. If at least one eigenvalue
126 has a positive real part, any perturbation of the static solution will grow exponentially, which by
127 definition means the solution is unstable. Details on the method applied to brass instruments can
128 be found in [Velut et al., 2016b].

129 This method is used to find the lowest blowing pressure value leading to an unstable static solution.
130 This p_b value is hereafter called p_{thresh} . The imaginary part of the same eigenvalue indicates the
131 oscillation angular frequency for $p_b = p_{thresh}$, provided that the oscillating solution is periodic. The
132 corresponding frequency is noted f_{thresh} .

133 LSA has been used for flute-like instruments [Auvray et al., 2012, Terrien et al., 2014] as
134 well as reed woodwinds [Wilson and Beavers, 1974, Chang, 1994, Silva et al., 2008] and brass-
135 winds [Cullen et al., 2000, Velut et al., 2016b]. This method does not provide information about
136 the stability of the oscillating solution which results from the destabilisation of the static solution.
137 The only piece of information about the resulting waveform is f_{thresh} , which is only valid if said
138 solution is periodic.

139 An example of results is given in Fig. 3: p_{thresh} (a) and f_{thresh} (b) are plotted against the lip
140 resonance frequency f_l , which is a control parameter used by the musician to change the note
141 played with the trombone. As observed in [Velut et al., 2016b], the plots can be divided in several
142 f_l ranges corresponding to U-shaped sections of the p_{thresh} curves and very lightly growing plateaus
143 of f_{thresh} just above the acoustic resonance frequencies of the resonator.



144

Figure 3: (colour online). Linear stability analysis results: p_{thresh} (a) and f_{thresh} (b) are plotted against f_l . Results for the open trombone (blue), the passive mute (red) and the active mute (black) are displayed. Black dotted lines of the bottom plot are the resonance frequencies of the open trombone (horizontal) and the bisector of the axes ($f_{thresh} = f_l$). The qualitative behaviour of the open trombone, the passive mute and active mute are very similar at this scale.

145

146 II.C Time-domain simulation

147 To get more information about the nature of oscillating solutions of the instrument model, solving
 148 the non-linear equation system Eq. (6) is required. Numerical differential equation solvers provide
 149 simulated values of the system variables. Simulated values of the pressure at the input of the
 150 instrument p have been obtained with the open-source Python library called MoReeSC [Mor, 2016],
 151 which has been developed specially for time-domain simulation of self-oscillating reed and lip valve
 152 instrument models [Silva et al., 2014].

153 To illustrate the additional information provided by time-domain simulation, waveforms and spec-
 154 tra of two simulated pressure signals are given in Figure 4. The simulation in Fig. 4 (a) and (c)
 155 was computed with $f_l = 90$ Hz while the one in Fig. 4 (b) and (d) was computed with $f_l = 110$ Hz,
 156 each one on an open trombone, with a blowing pressure 10% higher than the oscillation threshold.
 157 While LSA results for these two situations are very close to one another, numerical resolution of

158 the complete model shows a difference in the nature of the oscillation: while the oscillation is
 159 periodic for $f_l = 90$ Hz, it appears to be quasi-periodic for $f_l = 110$ Hz.

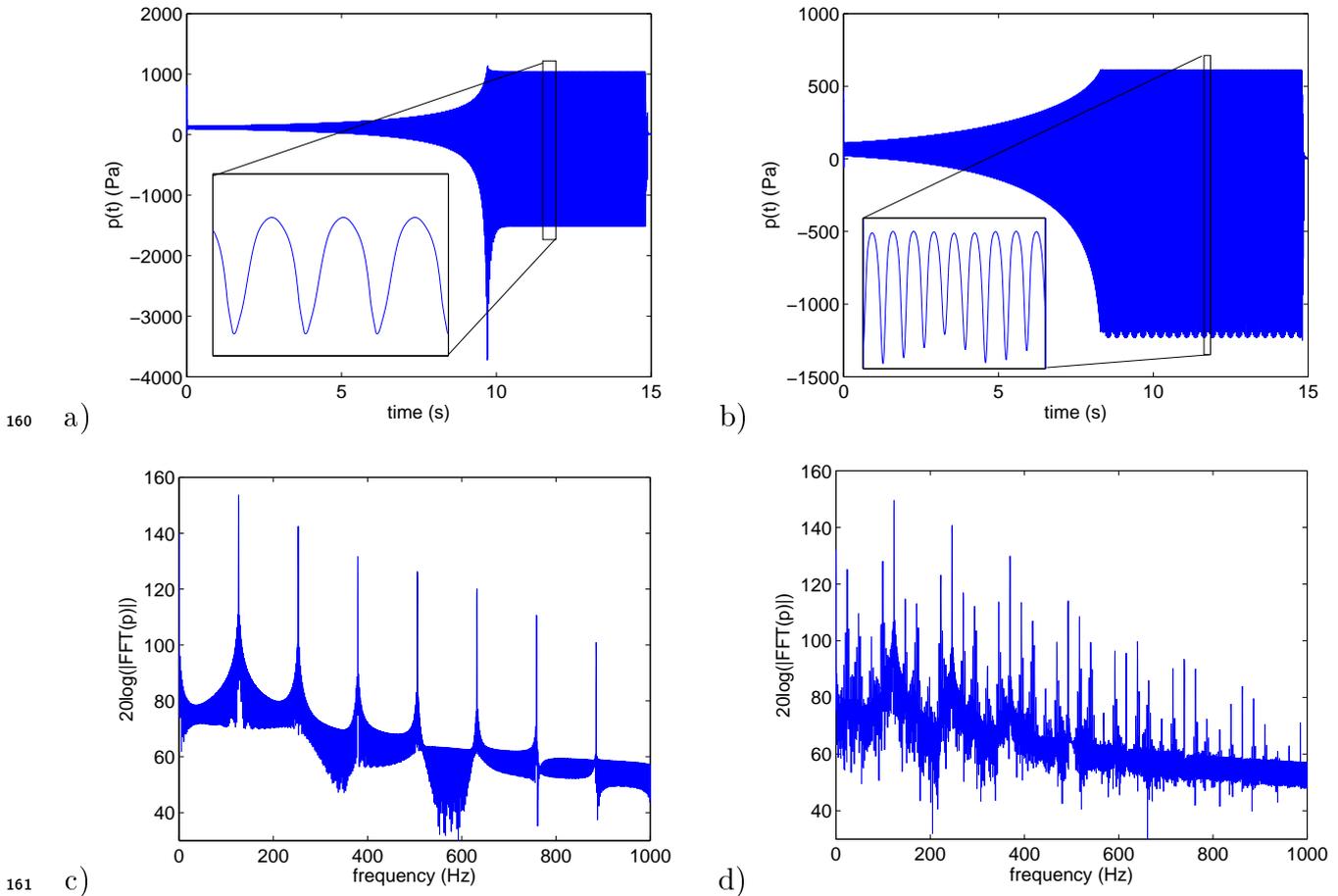


Figure 4: Waveforms of simulated p signals for $f_l = 90$ Hz (a) and $f_l = 110$ Hz (b) with zooms on some periods, along with spectra of their respective sustained regime in c) and d). For each simulation p_b is set to $1.1 \cdot p_{thresh}$. $f_l = 90$ Hz results in a periodic oscillation while $f_l = 110$ Hz
 162 results in a quasi-periodic oscillation with well defined secondary peaks.

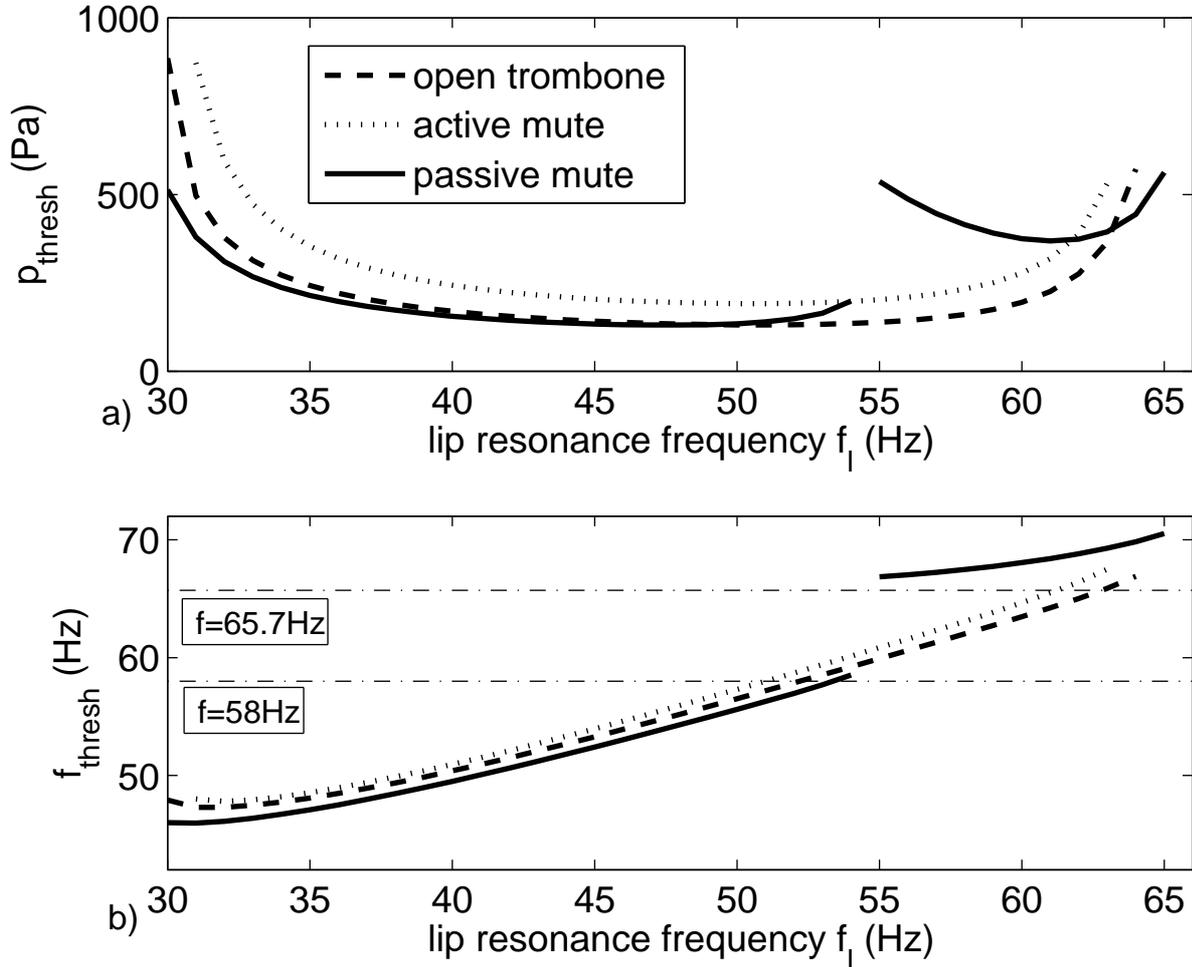
163 The f_l and p_b values for simulations are chosen thanks to LSA, avoiding a long and cumbersome
 164 search for the oscillation threshold with multiple simulations. The complementarity of these
 165 methods quickly provides a lot of information about relevant points of the oscillation regime.

166 III Results

167 III.A LSA

168 Linear stability analysis was performed on the three configurations studied: open trombone, passive
 169 mute, and active mute. Choosing a configuration consists in choosing C_n and s_n values among
 170 the three sets obtained by fitting, all other parameters of the model remaining the same. Lip
 171 parameters were taken from Table I. LSA was performed within the pedal note range, for f_l from

172 30 Hz to 65 Hz. This results in f_{thresh} values corresponding to an oscillation sustained by the first
 173 acoustical mode of the open trombone. Figure 5 is a zoom on Fig 3 in the considered f_l range.
 174 Fig. 5a) showing the threshold pressures p_{thresh} , while Fig. 5b) is the frequency at threshold f_{thresh} .



175

Figure 5: Results of LSA in the vicinity of the pedal note (zoom of Fig.3). Results with an open trombone (dashed line), a passive mute (solid line) and the active mute (dotted) are plotted together. (a) is the oscillation threshold pressure p_{thresh} , (b) is the oscillation frequency at threshold f_{thresh} , against f_l . Horizontal dash-dotted lines in (b) indicate 58 Hz (playing frequency of the pedal Bb) and 65.7 Hz (resonance frequency of the parasitic mode of the passive mute). While open trombone and active mute have very similar behaviours, the oscillation regime expected for the trombone with the passive mute becomes different above $f_l = 55$ Hz with a sudden increase in the p_{thresh} and f_{thresh} values.

176

177 The open trombone and the active mute behaviours are similar: the $p_{thresh} = F(f_l)$ plot is U-
 178 shaped. f_{thresh} is above the trombone's first acoustical resonance frequency (39 Hz) and grows
 179 monotonously with f_l . Within this f_l range, the oscillation threshold of the active mute trombone
 180 is about 75 Pa higher than that of the open trombone, and f_{thresh} is also 0.5 to 1.5 Hz higher.
 181 For $f_l \leq 54$ Hz, the results for the trombone with a passive mute are similar to those for the other
 182 configurations. But from $f_l = 55$ Hz, both the pressure threshold and the expected playing fre-

183 quency increase significantly: p_{thresh} suddenly jumps from 198.6 to 536.9 Pa, while f_{thresh} increases
184 by 8.3Hz (13%, i.e. slightly more than a tone), to reach 66.8 Hz. This value is just above the
185 resonance frequency of the parasitic peak induced by the passive mute.

186 f_{thresh} covers a range of frequencies around the expected playing frequency of a pedal $B\flat = 58$
187 Hz. The results for the open trombone and the active mute configurations are very close to
188 one another, the only difference being a rather small offset in p_{thresh} and f_{thresh} . In contrast,
189 the passive mute results stand out from the two other configurations: for f_l values above 55
190 Hz, p_{thresh} and f_{thresh} increase suddenly. The f_{thresh} value obtained is above the acoustic reso-
191 nance frequency of the parasitic mode related to the passive mute, and so the regeneration con-
192 dition [Elliott and Bowsher, 1982, Campbell, 2004] is satisfied for an oscillation supported by this
193 parasitic mode.

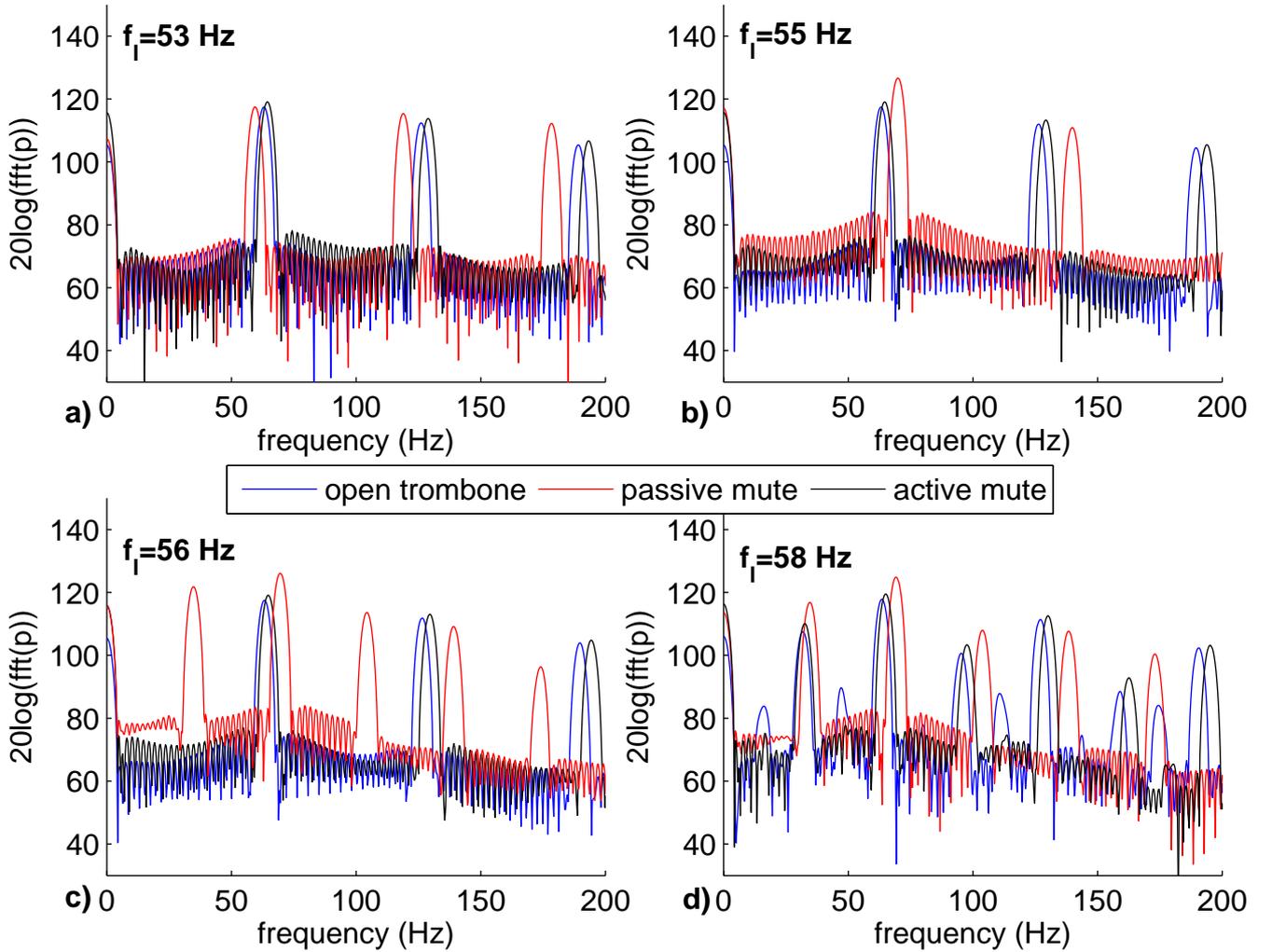
194 These results can account for the difficulty of playing a stable pedal note with a passive mute: the
195 LSA indicates a perturbation of the oscillation frequency at threshold, for parameters which could
196 be those used for the pedal note. However, experimental results shown in [Meurisse et al., 2015]
197 suggest a non-periodic oscillation when a musician tries to play a pedal note with a passive mute.
198 As LSA cannot predict the nature of the oscillation, further investigation on the complete non-
199 linear model is needed. This is the purpose of the numerical simulations presented in the following
200 section.

201 III.B Time-domain simulations

202 Time-domain simulations were carried out within the same range of f_l as for LSA, in 1 Hz steps,
203 for each configuration: trombone alone, trombone with a passive mute and finally trombone with
204 active mute. The blowing pressure was set to $p_b = 1.1 \cdot p_{thresh}$ as in [Velut et al., 2016b] in order to
205 keep manageable transient times. This value is close enough to p_{thresh} so that cautious comparisons
206 can be carried out between these simulations and LSA.

207 Simulated pressure signals were separated into a transient and a sustained regime with the help of
208 the "mironsets" function from MIRtoolbox [Lartillot and Toiviainen, 2007]. The spectra of all the
209 sustained regimes were computed. Figure 6 plots spectra of $p(t)$ for representative values of f_l .

210



211

Figure 6: (Colours online) Spectra of the simulated $p(t)$ signals, for $f_l = 53$ Hz (a), 55 Hz (b), 56 Hz (c) and 58 Hz (d). p_b is set to 110% of the oscillation threshold. For each f_l value, results with the open trombone (blue), the passive mute (red) and the active mute (black) are displayed. The results for the open trombone and the passive mute are noticeably similar.

212

for $f_l < 55$ Hz, the three configurations - open trombone, passive mute, active mute - lead to a periodic oscillation, as illustrated for $f_l = 53$ Hz by (Fig. 6a). The oscillation frequency is a bit higher than f_{thresh} : 7.5% for open trombone and active mute, and 2.5% higher for the passive mute. Oscillation frequencies higher than f_{thresh} when $p_b > p_{thresh}$ is coherent with the fact that a musician's playing frequency gets higher when he increases his blowing pressure. The trombone with a passive mute has a lower oscillation frequency than the open trombone, which has itself a slightly lower oscillation frequency than that of the trombone with the active mute. The oscillation frequencies range from 60 to 64 Hz, a bit higher than $Bb = 58$ Hz. This is sensible since this model is known to oscillate at higher frequencies than those at which a musician plays.

At $f_l = 55$ Hz (Fig. 6b) the oscillation frequency of the passive mute configuration suddenly jumps from 59.4 to 69.6 Hz, making it play sharper (nearly a minor third) than the two other configurations. This is consistent with the LSA results, where f_{thresh} suddenly increases by 8 Hz

224

225 for this f_l value. The oscillations are still periodic and above the acoustical resonance frequency
226 of the first mode; but for $f_l = 56$ Hz and above (illustrated by Fig. 6c) the fundamental frequency
227 of the passive mute falls to 34.8 Hz. This is nearly half its former value, and under the trombone's
228 first acoustic resonance frequency (39 Hz). Finally, for $f_l \geq 58$ Hz (Fig. 6d), all configurations
229 result in fundamental oscillation frequencies about half, or a quarter, of the oscillation frequencies
230 obtained for lower f_l values.

231 Simulation and LSA results are consistent: when f_l reaches 55 Hz, the oscillation frequency of
232 the trombone with a passive mute suddenly increases. This is related to a regime change in the
233 instrument: for $f_l < 55$ Hz, the oscillation is mainly supported by the trombone's first acoustical
234 mode, while above, the parasitic mode at 65.7 Hz caused by the mute becomes the main supporting
235 mode of the oscillation, which explains the increase in the oscillating frequency.

236 Above $f_l = 56$ Hz, however, the oscillation frequency of the passive mute decreases to half of its for-
237 mer value. As the oscillation frequency is under the trombone's first acoustical resonance frequency,
238 the regeneration condition of a model with outward-striking valve is not satisfied [Campbell, 2004].
239 This situation suggests a period-doubling phenomenon [Bergé et al., 1995]. When increasing f_l
240 again, the three configurations appear to undergo period doubling, which is even doubled for the
241 open trombone with a fundamental frequency of 16.2 Hz. Sub-harmonic cascade has already been
242 put in evidence for trombones [Gibiat and Castellengo, 2000], notably in a previous study with
243 the very same model and parameters [Velut et al., 2016b].

244 These results confirm the existence of a parasitic regime of oscillation for the passive mute
245 configuration, which could explain why musicians experience difficulties when trying to play
246 the $B\flat$ pedal in this situation. This parasitic regime is sustained by the parasitic acoustical
247 mode brought by the mute. Furthermore, in accordance with the experimental results published
248 in [Meurisse et al., 2015], the simulation results are qualitatively the same for the open trombone
249 and the active mute, with very close oscillation frequencies. The range of f_l leading to periodic
250 oscillations near the pedal note frequency is quite wider for the open trombone and the active
251 mute than for the passive mute.

252 IV Conclusion

253 Playing a stable $B\flat$ 1 on a trombone with a straight mute is very difficult. An active mute has been
254 developed [Meurisse et al., 2015] to deal with this issue. Two analysis tools, LSA and time-domain
255 simulation, are used to investigate to what extent the chosen brass instrument model reproduces
256 the experimental behaviour of the trombone pedal note when the trombone is equipped with a
257 commercial, passive straight mute, and when using the said active-control mute. LSA and time-
258 domain simulation results are quite identical for the open trombone and the trombone with an
259 active mute. The model is therefore able to predict the efficiency of the active control device
260 which makes the pedal note easily playable again. Results of the model of a trombone equipped
261 with a passive mute, however, are clearly different from those of the open trombone model: the

262 pedal note is disturbed by a new oscillation regime, which seems related to the parasitic acoustical
263 mode added by the mute. Hence, even a "small" perturbation of the input impedance, such as a
264 peak 20 times smaller in amplitude than surrounding peaks, can strongly affect the behaviour of
265 a resonator.

266 As in a previous paper [Velut et al., 2016b], this study shows a rather good agreement between
267 LSA results and time-domain simulations, within the limits of the LSA method. This study on
268 mutes also shows the relevance of the chosen brass instrument model, which is able to predict a
269 number of behaviours of the trombone, including particular playing regimes [Velut et al., 2016b,
270 Velut et al., 2016a] and, in the present case, the influence of modifications of the instrument bore.
271 The methodology proposed seems relevant, as beginning a study with LSA very quickly gives an
272 overview of the potential behaviour of the system under given conditions. This fast computation
273 already provides interesting results, which can be interpreted alone. However, if further exploration
274 of the oscillation regime is required, LSA results give hints for choosing f_l and p_b values for
275 initialising other analysis methods.

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