Study of the relations between trumpets' sounds characteristics and the input impedance

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In order to study the influence of the bore's geometry of brass instruments on the sound produced, we developed a special trumpet leadpipe with a parameterised internal geometry. Using the same trumpet and the parameterised leadpipe, several hundred of different instruments, with notably different acoustical behaviour, can be designed. A set of such instruments has been evaluated in two ways: (1) a recording of the sound played by the instruments (by a musician or an artificial mouth) has been carried out, the playing frequency, the spectral centroid and the RMS pressure of the notes have been calculated. (2) the input impedance of each instrument has been measured. The objectives of this paper are (i) to study the influence of the input impedance on the playing frequency of the tones (because of the coupling between the buzzing lips and the instrument, the playing frequency is not exactly equal to the corresponding resonance frequency) ; (ii) to determinate in which extend the artificial mouth and a musician provide similar results ; (iii) to study the variance of the measurements (ANOVA) in order to detect if a "leadpipe effect" can or not be revealed by the artificial mouth or by a musician. For this, steady-state notes and crescendo notes have been recorded and analysed. As a result, the artificial mouth seems to be reproducible enough in order to provide an acoustical signature of the instrument.

1 Introduction

Studying the physical characteristics of musical instruments is particularly interesting to help their development and to improve quality assessment procedures. Concerning the brasses, the main physical measurement is the input impedance of the bore [1].

It's a very important property for the characterization of a brass instrument: it gives the magnitude of the acoustic response to a forced oscillation. In playing situation, the musician produces a note whose frequency (the playing frequency) is close to the resonance frequency of an impedance peak [2]. In first approximation, the playing frequency (which conditions the intonation) is mainly governed by the corresponding peak of the impedance. But although interesting information can be given by the impedance [3], it's a hard work to predict sound qualities of brasses only from the impedance.

A second interesting measurement which can be carried out on brass instruments is the recording of the sound produced in playing situation. Various parameters of the signal can be extracted in order to characterise the sound and the quality of the instrument. The main difficulties in this approach is to overcome the variability produced by the musician, and to be sure that differences between recordings are effectively due to the instruments, not the musician. In this context, artificial mouths are interesting devices to generate sounds with brass instruments in a reproducible way [4].

In order to isolate and finely control the influencing variables of the timbre quality of brass instruments, we decided to parameterise the shape of a very influential part of the resonator on the acoustic behaviour of the instrument: the leadpipe [5]. This part is roughly conical and is located between the mouthpiece and the tuning slide. Using this device and the same trumpet, we generated a set of instruments with notably different acoustical behaviour, varying only the internal geometry of the leadpipe. This set of instruments has been evaluated by two ways : (1) various parameters of the tones (played by a musician and an artificial mouth), have been assessed via signal processing techniques (Playing frequency, Spectral Centroid, RMS pressure P_{RMS}); (2) the input impedance of the instruments has been measured.

In this paper, we propose first to study the influence of the input impedance on the playing frequency of the tones. We propose next to determinate in which extend the artificial mouth and a musician provide similar results concerning the sound parameters. Finally, we studied the variance of the measurements in order to detect if a "leadpipe effect" can or not be revealed by the artificial mouth or by a musician.

2 Experimental devices

2.1 The parameterised leadpipe

From the measurements of the internal form of existing leadpipes (measured with calipers) [6], a parameterised leadpipe, made of 4 different interchangeable parts, each conical and parameterised by the radii r1, r2, r3, r4 (Figure 1), was designed.

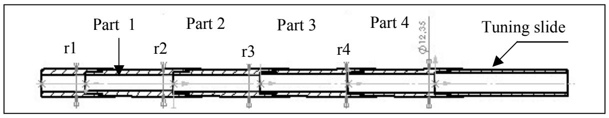

Figure 1 : design of the parameterised leadpipe

Several parts 1-2-3-4, with various values for the radii r1, r2, r3, r4, have been manufactured with a numerically controlled turning machine. The proposed values of r1, r2, r3, r4 correspond roughly to dimensions of marketed leadpipes, and the assembling of the parts allows the generation of various inner profile of leadpipes (many hundreds). A coding of each leadpipe, made of 4 letters (one letter for each part, the letter corresponding to a given dimension of the radius), has been defined in order to distinguish the leadpipes. So, using the same trumpet (*Bach* model *Vernon*, bell 43) and the parameterised leadpipe, several hundred of different instruments with notably different acoustical behaviour can be designed. With this device, we finely control the variation of the design parameter of the set of instruments. Five leadpipes, whose characteristics are presented in table 1, were studied.

Table 1: description of the five leadpipes of the study

	Part 1		**Part 2**		**Part 3**		**Part 4**	
	r_1	r_2	r_2	r_3	r_3	r_4	r_4	r_5
AAAE	4.64	4.64	4.64	4.64	4.64	4.64	4.64	5.825
DKOS	4.64	5.45	5.45	5.5	5.5	6	6	5.825
CHMQ	4.64	5	5	5.5	5.5	5.7	5.7	5.825
IFJN	5	5.7	4.7	5.5	5.05	5.7	5.5	5.825
SPGA	6	5.825	5.7	5.7	5	5.05	4.64	4.64

Six leadpipes were considered for the study: the five home-made leadpipes presented previously and a leadpipe provided with the trumpet, called "original leadpipe".

2.2 The artificial mouth

The artificial mouth used in the study is described in [7]. The control parameters of the system, which can be adjusted independently and remain constant when one changes the instrument, are the air supply static pressure, the water pressure in the lips and the mechanical pressure on the jaw.

2.3 Input impedance measurements

Using the same mouthpiece (Yamaha 15B4), and the same remaining part of the trumpet (Bach, bell 43, model *Vernon*), the input impedance of the 5 trumpets were measured with the BIAS device [8] at ITEMM (Institut Technologique Européen des Métiers de la Musique, Le Mans, France). The frequencies of the peaks *f(i)*, from partial n°2 to partial n°10, are given in table 2.

Table 2: resonance frequencies of the peaks of the 6 trumpets (Hz)

Type	*f(2)*	*f(3)*	*f(4)*	*f(5)*	*f(6)*	*f(7)*	*f(8)*	*f(9)*	*f(10)*
AAAE	231.5	342	455	583	704	808	907.5	1036	1162
DKOS	229.5	350	471.5	592	703	813.5	920.5	1035	1157
CHMQ	231	350.5	470	590.5	702.5	814.5	924	1038	1158
IFJN	230	347.5	465	589	702.5	807.5	910	1033	1156
SPGA	229.5	347	463	579.5	689.5	801.5	911.5	1028	1146
original	224.5	337.5	460	596.5	723	811	912	1041	1161

2.4 Recording of the sounds

Several categories of tones, produced either by the artificial mouth or by a musician, were recorded. All the recordings (sampling frequency 44100 Hz, 16 bits) were made in the same room (same place, same temperature) with a Sennheiser e604 microphone. The microphone was placed in the axis of the bell (distance = 10 cm) and connected to the preamplifier and a Digigram Vx Pocket V2 sound card. The dynamic of the sound has been measured with a the sound level meter placed at the output of the bell.

For the six leadpipes, two notes, Bb3 and D4, were recorded. The position of the tuning slide was the same for all the leadpipes. Two kind of sounds were recorded:

- **Steady-state sound**: a note with the same dynamic *mezzo forte* (sound pressure level 100 dB). Duration about 4 seconds.
- **Crescendo sound:** a note starting from the threshold of oscillations until the loudest possible level. Duration about 30 seconds for the artificial mouth, 10 seconds for the musician.

Three replications of these recordings (take#1, take#2, take#3) were made. Two categories of tones were considered:

- **AM** : played by the Artificial Mouth. The embouchure remained fixed between the replications, only the air pressure of the artificial mouth was turned off (repeated measurements),
- **Musician** : played by the musician. In order to limit as much as possible the variability inherent to the musician, he was asked to play the note in the easiest and more natural way (without trying to adjust the height or the timbre of the tones).

For the steady-state sounds, a 3 seconds window of the signal, stable in pitch and amplitude, were selected from the recordings.

For the crescendo sounds, the signal was split into 20 windows of about 1 second, from the beginning to the end of the note.

These windows were the inputs of the signal processing analyse.

3 Signal processing of the sounds

Three main characteristics of the sounds were computed: the playing frequency, the Spectral Centroid, and the RMS pressure (Root Mean Square).

The playing frequency Fplay of the sounds was determined by computing the average period of the signals on a fixed number of periods. The variations of the frequency of the sounds being very weak (the pitch of the sounds is rather stable), this basic method provided satisfactory results (the standard deviation of the period was sufficiently weak).

The *spectral centroid* is commonly associated with the measure of the brightness of a sound. This measurement is obtained by evaluating the "centre of gravity" of the spectrum (1):

$$\mathrm{Sc} = \frac{\sum_{n=1}^{N} n.A n}{\sum_{n=1}^{N} A n} \qquad (1)$$

where A_n represents the amplitude of harmonic n of the spectrum and N the number of harmonics considered (in our case, N=6). The amplitudes of the harmonics were computed by two methods: with the Fast Fourier Transform (FFT) and with the synchronous detection method. The accuracy of the amplitudes obtained with the FFT method was rather weak. This implies an important error in the calculation of the Spectral Centroid. The synchronous detection method gave reliable results. For this reason, this method was chosen to calculate the Spectral centroid *Sc*.

The RMS pressure of the sound P_{RMS} (2) was computed:

$$P_{RMS} = \left(\frac{1}{nT} \cdot \int_0^{nT} p(t)^2 \, dt \right)^{1/2} \qquad (2)$$

n, number of periods ; T, period of the signal ; p(t), acoustical pressure.

4 Results and Discussion

4.1 Analysis of the steady-state sounds

4.1.1 Correlation F_{play} / F_{res}

The playing frequencies of the sounds corresponding to the 6 leadpipes, played by a musician or the artificial mouth, were computed. Results are presented in figure 1. The fourth resonance frequency of the input impedance of the trumpet, Fres4, corresponding to the played note Bb3, is also plotted on this figure 2.

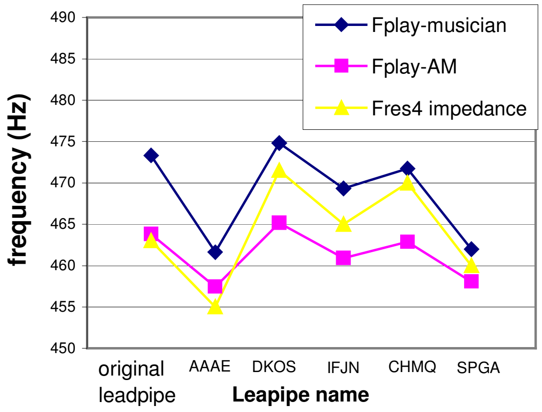

Figure 2: playing frequency and fourth resonance frequency of the different leadpipes

Firstly, the correlation between Fplay-musician and Fplay-AM is very good. The difference in the absolute value of the frequency can be explained by the difference of the temperature of the air blew by the musician (37°C) and the artificial mouth (20°C). In conclusion, concerning the playing frequency, the artificial mouth reveals differences between the leadpipes in accordance with the musician.

Secondly, the correlation between the playing frequency and the resonance frequency Fres4 is also very good. This confirms the fact that, in a first approximation, the playing frequency (which conditions the intonation) is mainly governed by the corresponding peak of the impedance [3]. The conclusions are the same for the note D4.

But the study of sound production in brass shows that the intonation of the instrument is not only controlled by the closest resonance frequency but possibly conditioned by upper resonance frequencies of the resonator (due to the complex aeroelastic coupling between the lips of the musician and the resonator. Further studies are needed in this area.

4.1.2 Variance analysis of the “leadpipe effect”

Three replications of the recordings on the same leadpipe were carried out, in order to test if the “leadpipe effect” can be distinguished despite the measurement error and the influence of other experimental factors. A one-way analysis of variance was employed to study the effect of the leadpipes on the playing frequency Fplay and on the Spectral Centroid Sc. The F-value was compared to the threshold value of the Fisher-Snedecor table with p-value = 0.05 ($F_{5\%(5\ ;\ 12)}$ = 3.11). The decision rule is: if $F_{obs} > F_{5\%}$, than the “leadpipe effect” is significant. Table 1 presents the results of the variance analysis for each playing condition (**AM** and **Musician**) for the note Bb3.

Table 1: variance analysis – Fisher test

		$F_{5\%}$	F_{obs}	Significant (5%)
Artificial mouth	Fplay	3.11	2.86	No
	Sc	3.11	2.9	No
Musician	Fplay	3.11	60.9	Yes
	Sc	3.11	2.14	No

Concerning the playing frequency, the effect of the leadpipe is clearly significant for sounds played by the musician. The musician was reproducible enough and provided weak variations of the playing frequency during the replications. For sounds played by the artificial mouth, the effect is not significant. This result is rather disappointing, because one of the main advantages of the artificial mouth lies in its reproducible embouchure. In fact, we noticed that the playing frequency always diminished between the successive recordings take#1, take#2 and take#3, even if the embouchure remains stable. The behaviour of the artificial lips depends on the duration of their use, and the mechanical properties of the material of the artificial lips (latex) seem to change when the material is stressed.

Concerning the Spectral Centroid, the effect of the leadpipe is clearly not significant, either for the musician nor the artificial mouth. The conclusions are the same for the note D4. Several explanations can be proposed:

- For the musician, his embouchure changes between the replications, and he is not able to play exactly in the same way. For the artificial mouth, the mechanical properties of the lips change between the replications,
- the leadpipes are too similar relatively to the spectral centroid they can produce and the spectral centroid may be too basic to show differences between the leadpipes,
- a last and important possibility must be envisaged: the way the leadpipes are played is possibly too simplistic to exhibit differences in the spectral centroid: steady-state sounds are possibly too rough and unable to reveal “subtle” differences between the instruments

For this reason, we decided to play the instruments with a crescendo (from *pp* to *ff*), with a note starting from the threshold of oscillations until the loudest possible level.

4.2 Analysis of the *crescendo* sounds

4.2.1 Playing frequency *Fplay*

The variations of the playing frequencies of the sounds during the crescendo, corresponding to the 2 leadpipes (CHMQ and SPGA), played by the artificial mouth, were computed. Figure 3 presents the evolution of the playing frequency of the note Bb3, according to the pressure P_{RMS}. Similar curves were obtained for the note D4. The musician produced curves of the same type, but the reproducibility between the takes was weaker.

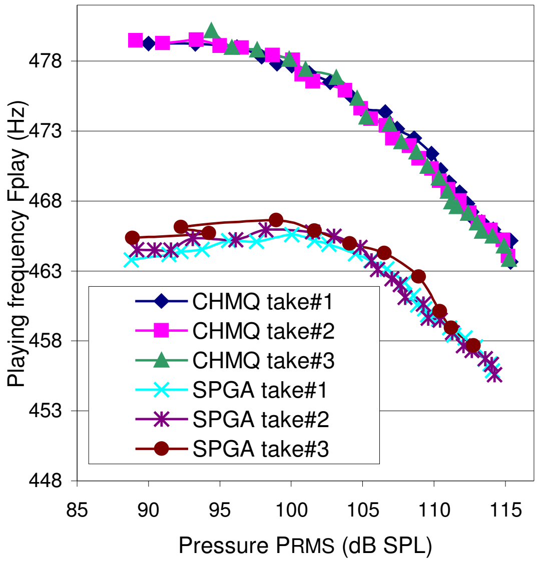

Figure 3: Playing frequency.vs.RMS pressure for two leadpipes CHMQ and SPGA, played by the artificial mouth.

For the two leadpipes, the playing frequency decreases when the intensity of the sounds increases.

The differences between the replications (take#1, 2, 3) is clearly lower than the differences between the leadpipes. In conclusion, with crescendo sounds, the artificial mouth is able to shows the effect of the leadpipe concerning the playing frequency.

4.2.2 Spectral centroid Sc

Figure 4 presents the evolution of the Spectral centroid Sc according to the pressure P_{RMS} of the tones, for the 2 leadpipes (CHMQ and SPGA), played by the artificial mouth (note Bb3). Similar curves were obtained for the note D4.

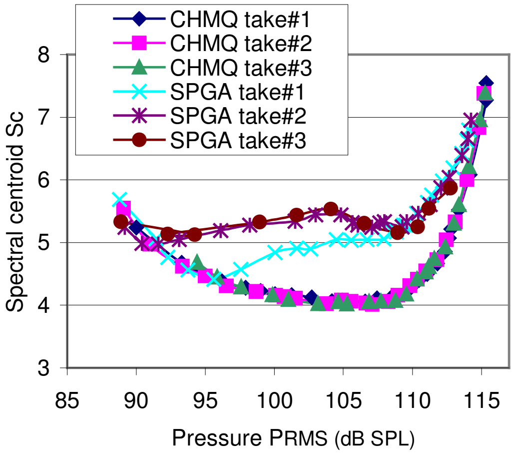

Figure 4: Spectral centroid.vs. RMS pressure for two leadpipes CHMQ and SPGA, played by the artificial mouth

For the two leadpipes, beyond a certain threshold, the spectral centroid globally increases when the intensity of the sound increases. This is in accordance with the sensation: louder is the note, brighter is the sound.

Again, the differences between the replications (take#1, 2, 3) is clearly lower than the differences between the leadpipes. In conclusion, with crescendo sounds, the artificial mouth is able to shows the effect of the leadpipe concerning the spectral centroid.

The results with the musician were not so clear because playing a crescendo during several seconds (8 to 10 seconds with a crescendo seems to be a maximum), and being reproducible in the way the crescendo is played for the replications is rather a hard task.

4.2.3 Harmonic spectrums of the sounds

The spectral centroid is a monodimensional description of the spectrum of a note and may in certain case be inadequate to reveal differences between sounds. In order to get a more accurate description of the spectrum of the crescendo notes, the evolution of the magnitude of the harmonics H1 (fundamental), H2, H3, H4 of the note were computed.

Figure 5 and 6 present the evolution of the magnitude of the harmonics, according to the magnitude of the fundamental for the leadpipe CHMQ and SPGA respectively.

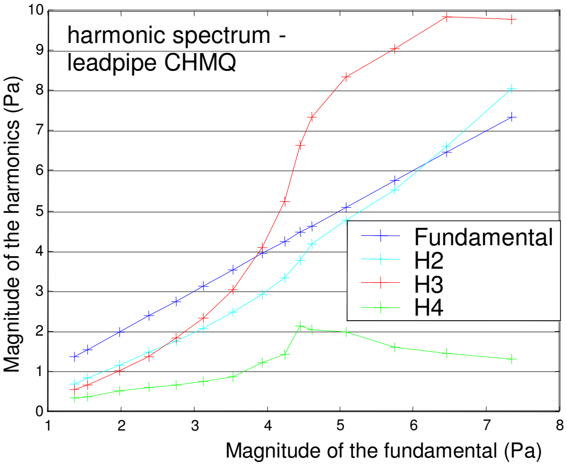

Figure 5: Spectrum of the harmonics (leadpipe CHMQ)

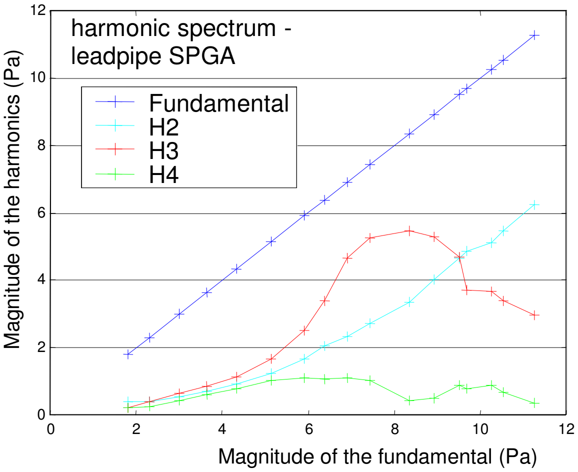

Figure 6: Spectrum of the harmonics (leadpipe SPGA)

By comparing these two figures, the differences in the harmonic spectrum between the leadpipes during a crescendo are easily noticeable. Leadpipe SPGA is clearly less “bright” than CHMQ, the spectral enrichment is significantly weaker. These figures are relative to take#1 of the recordings, but similar figures were obtained with the others replications. It seems that the harmonic spectrum of the trumpet is, in a large extend, characteristic of the trumpet, and relatively independent to the way the instrument is played (musician or artificial mouth) [9].

5 Conclusions

We presented in this paper a study of trumpets sounds characteristics, played either by a musician or by the artificial mouth. We used for this a parameterised leadpipe and we studied the influence of weak differences in the internal geometry of the leadpipe on the sound characteristics.

For steady-state notes played with a mezzo-forte dynamic, the results show firstly that the playing frequency of the notes is correlated with the resonance frequency of the impedance curve. This confirm a result generally assumed in several studies. Secondly, we showed using variance analysis that the effect of the leadpipe on the characteristic of the sound (playing frequency, spectral centroid) is not clearly visible: several non-controlled factors (variations in the embouchure of the musician, variations in the mechanical properties of the artificial lips) create variations in the sound of the same order of those created by the leadpipe.

For crescendo notes, the artificial mouth has a paramount advantage on the musician: the possibility to play crescendo during a long period of time [8]. The results show that, during a crescendo note, the evolution of the spectral centroid is characteristic of the leadpipe and that a “leadpipe effect” can be revealed with the artificial mouth. Our results show that the harmonic spectrum of a note is more conditioned by the instrument than by the way it is played. An acoustic signature of the instrument could be designed with signal processing of notes played with the artificial mouth.

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