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Comparative analysis of brass wind instruments with an artificial mouth: first results

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SUMMARY

We have developed in the past "artificial mouths" to study the behaviour of brass wind instruments (trumpet, trombone) in the playing situation, but without a musician. After using such devices to better understand the physical phenomena involved in brass instruments, we have built and used a new artificial mouth with the objective to test and set up instruments; the artificial mouth is considered here as a " test bench ". In this article, we describe the typical measurements that we have carried out on trumpets, in order to compare them (measurements of oscillation threshold, evolution of the playing frequency according to the dynamic level). As a first result, the artificial mouth allows one to show noticeable differences between instruments. We propose next some research paths which could be explored, in order to better control the quality of instruments and to insert in the future an artificial mouth in the design process of brass instruments.

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I. INTRODUCTION

Brass wind instruments (trumpet, trombone...) are musical instruments whose principle of operation is based on an aeroelastic valve for the sound source (vibrating lips of the trombonist), and on a tube of variable geometry (controlled either by a slide, or by the insertions introduced by valves) for the resonator [1, 2, 3, 4]. To avoid the difficulty of making measurements "in vivo", we have developed various models of artificial mouth [5, 6, 7, 8]. Initially, they were used for a fundamental research purpose; some significant results are reviewed in part II.1.We have built a new artificial mouth and propose to validate some measurements in order to use it as a " test bench " to assist brass instrument makers (part II.2). To achieve this aim, we first have to demonstrate that the artificial mouth can allow the detection of significant differences between instruments. We present in part III a preliminary study based on a comparative analysis between two trumpets.

II. BRASSWIND ARTIFICIAL MOUTHS

II.1. An experimental device for research purpose

The " artificial mouth " for brass winds primarily consists of " artificial lips " (latex tubes filled with water) whose vibration characteristics are mainly controlled by the pressure of water and the mechanical pressure exerted by an " artificial jaw ". The air overpressure in the “oral cavity” is another essential parameter for the control of the system. The first version of the artificial mouth was used for the study of high level sound [5] in a trombone and to check the relation between the " brassy sound " and the non-linear propagation phenomena inside the instrument.

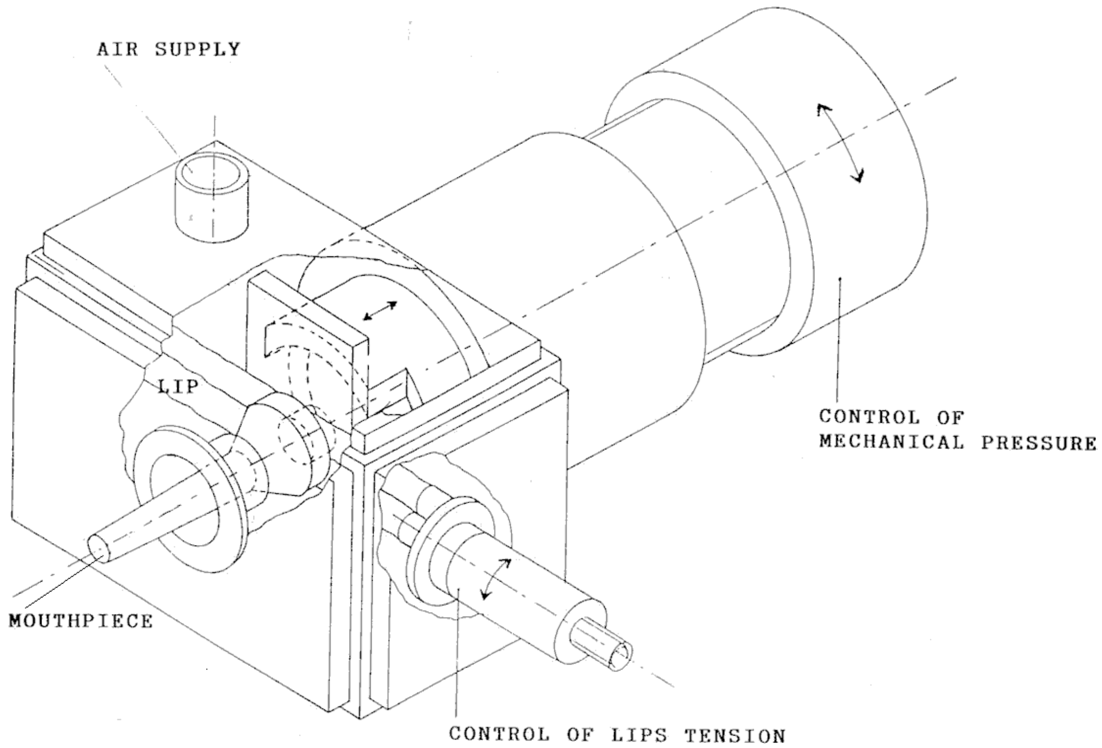

Figure 1. *Artificial mouth for brass instruments (version #2).*

The second version (fig. 1) was instrumented in order to obtain the mechanical response of the artificial lips in forced oscillation [6, 7]. Equivalent parameters of this oscillator (mainly the lip resonance frequencies) were extracted from the mechanical response, and the coupling between the resonator and the excitator was tested experimentally. Then the threshold frequencies of the coupled system, observed experimentally, were compared with theoretical thresholds frequencies coming from a linear stability analysis. As a major conclusion, it seemed unlikely that the observed behaviour near threshold can be explained by a lip model with only a single degree of freedom [8]. Future work has to include the implementation of threshold simulations based on a two-mass model for example, by adapting vocal folds models [9].

II.2. Towards a test bench for instruments making ?

The trumpets and trombones tested with the artificial mouth behave in the playing situation in a very realistic way. From this observation, we could imagine that an instrument maker will use it to design, set up and test a new instrument For this, we have developed a more compact and more convenient artificial mouth (fig. 2). The following table 1 presents some characteristics of the artificial mouths versions #2 and #3.

Table 1	Version #2	Version #3
Control parameters	Water pressure inside the lips Mechanical pressure on the jaw Control of the lips tension Air supply static pressure (between 0 and 500mbar)	Water pressure inside the lips Mechanical pressure on the jaw Opening of the jaw Air supply static pressure (between 0 and 500mbar)
Artificial lips	Latex tubes ∅ 20	Polyurethane tubes ∅ 12
Characteristics	Mainly for trombone	For many brass instruments (trumpet, trombone, horn, tuba, …)

Table1 : comparative technical data of artificial mouth versions #2 and #3

We have used version #3 to compare two trumpets of different makes. The results of this comparative analysis are presented in the following part.

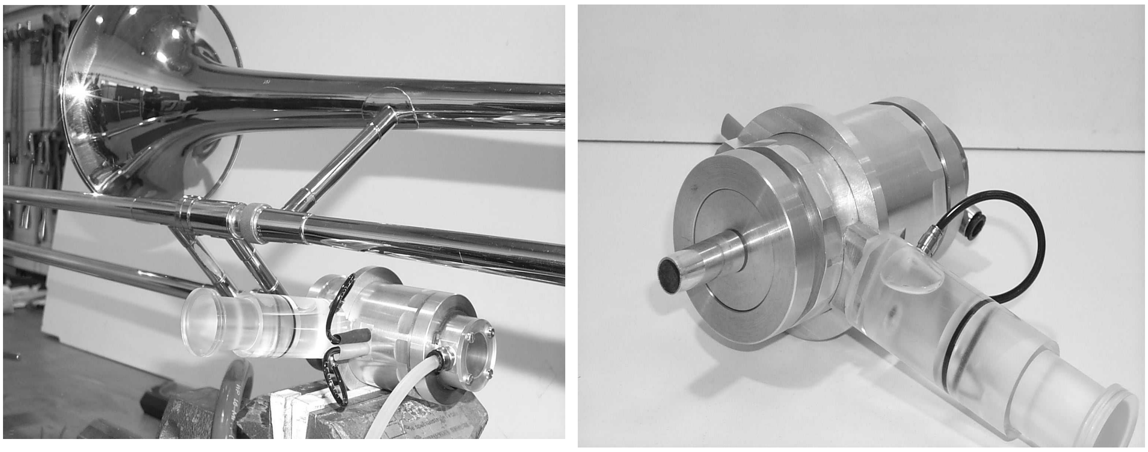

Figure 2. *Artificial mouth for brass winds (version #3).*

III. COMPARATIVE STUDY OF TRUMPETS

III.1. Input impedance

Brass wind instruments and more generally wind instruments are self-sustained systems which can be characterised by their input impedance. Figure 3 presents the input impedance (magnitude and phase) of a trumpet with no valve operated. This large frequency range measurement is done to estimate the values of the resonance frequencies. Thus accurate values of the resonance frequencies are obtained by measurements around each of them. The input impedances are measured by the apparatus described in [10].

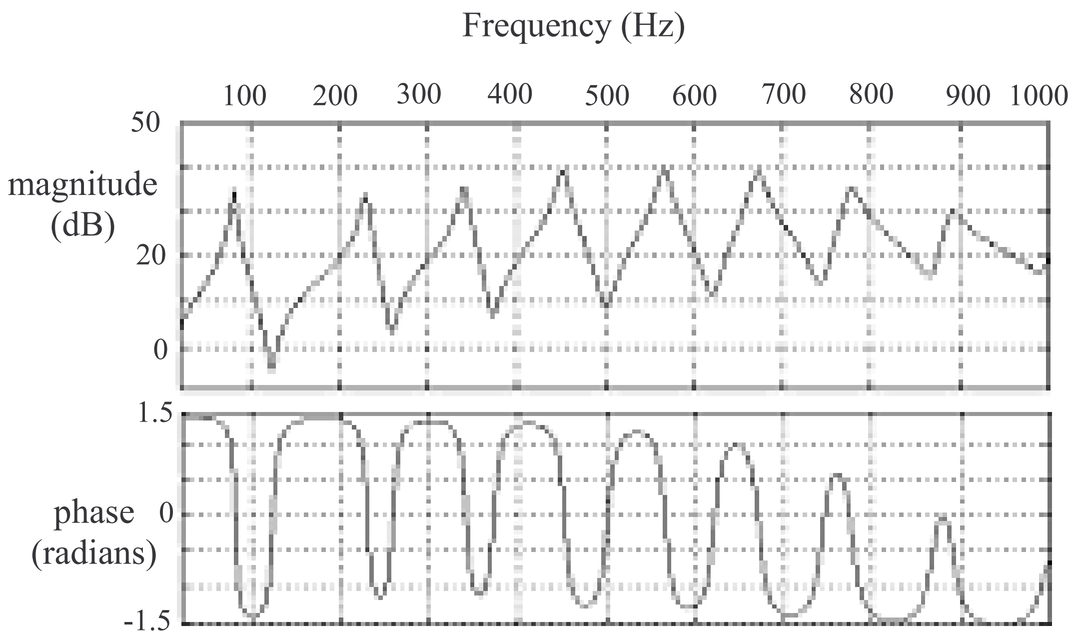

Figure 3. *Example of the measured input impedance of a trumpet (magnitude and phase).*

The frequencies corresponding to the maximum of impedance are the resonance frequencies of the air column of the instrument with its input section closed. In the playing situation, the musician produces a note whose frequency (the playing frequency) is close to the resonance frequency of the vibration mode that controls the self-sustained excitation process (fig. 4).

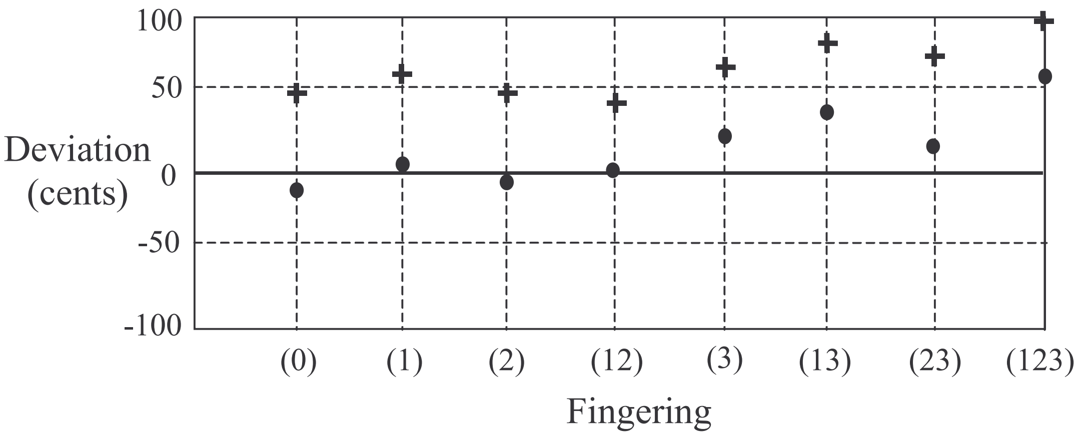

Figure 4: *Compared intonation accuracy of the 3rd resonance frequencies of a trumpet (o) and the 3rd regimes played by a trumpet player (+) corresponding to the 8 fingerings. The intonation accuracy is defined as the deviation in cents of the analysed frequency (resonance frequency or playing frequency) relatively to an ideal location (based on the equally tempered scale with A4= 440Hz).*

There is a noticeable mean difference, around a quarter-tone, between the resonance frequencies and the playing frequencies. This difference is mainly due to differences in the experimental temperature conditions (which influence the sound celerity and thus the frequencies) ; part of the difference can be due to the complex aerodynamic coupling between the lips of the player and the trumpet. The intonation accuracy of the instrument is primarily controlled by the accuracy of the resonance frequencies of the resonator. Thus, the input impedance curve is a good objective indicator of certain qualities of a brass instruments [11, 12]. Moreover, the calculation of the input impedance can be made by a theoretical approach, based on the transmission line modeling [13]. The comparison between theory and experiment is in this case sufficiently good to envisage the use of predictive models for certain qualities of brass, and the use of Computer Aided Design software for the design of new wind instruments [14, 15, 16]. This approach necessitates the establishment of correlations between subjective responses given by a musician (which represent certain dimensions of the quality) and measurements extracted from the impedance curves of a set of instruments [17]. These experiments are difficult to carry out, because one must finely control which parameters vary between members of the set of instruments, in order to be sure that the differences observed in the subjective assessment are effectively due to these variations [18].

Furthermore, it is not easy to predict qualities in playing conditions (ease of emission, quality of timbre) from information extracted from the input impedance. Many mathematical expressions, which aggregate information from the input impedance curve (mainly the resonance frequencies, quality factors and magnitude of the impedance) have been proposed to predict with more or less success certain qualities of brasses [19].

We propose in this article a complementary approach to the impedance measurements, based on tests with the artificial mouth. Our objective is to check that measurements with the artificial mouth make it possible to discriminate between two instruments, and that the interpretation of measurements is in conformity with certain perceptual assessments of the musician [20].

III.2. Measurements with the artificial mouth

a) Measurement of the playing frequency

We compared two trumpets of different makes, marked by C and Y on the following figures. Initially, after having measured their input impedance, the resonance frequencies were compared with the playing frequencies of the corresponding regimes, obtained either with the artificial mouth (for a given embouchure adjusted in order to obtain realistic sounds with the two trumpets), or with a trumpet player. The correlation obtained between these measurements is excellent; the frequencies obtained by the three methods indicate a very similar relative intonation behaviour of the trumpets. Thus, the artificial mouth gives relative playing frequencies which are coherent with the playing frequencies produced by a musician, or with the resonance frequencies. Table 2 indicates the deviation in cents of the frequency (resonance frequency or playing frequency) relatively to an ideal location based on the equally tempered scale for two notes F4 and D5, and all possible fingerings of these notes on the trumpet. In all cases, pitches given are played rather than written notes. There is no contradiction in the relative responses given by the three methods. These first measurements validate the use of the artificial mouth for predicting the intonation of brasses.

Note		**F4: 349Hz**		**D5: 587Hz**		
Fingering		*(0)*	*(13)*	*(0)*	*(3)*	*(12)*
TP C	*Tp player*	+ 25	+45	+15	+25	+30
	Res Freq	-45	-15	-60	-39	+69
	Artif. Mouth	+14	+29	+14	+23	+26
TP Y	*Tp player*	+60	+110	+55	+75	+100
	Res. Freq.	0	+63	-21	+9	+49
	Artif. Mouth	+53	+105	+46	+66	+80

Table 2: deviation in cents of the frequency (resonance frequency or playing frequency), obtained with 3 different methods: 1) Trumpet player, 2) Resonance frequency, 3) Artificial mouth.

b) From oscillation threshold toward high level

Secondly, with the artificial mouth, the trumpets were subjected to a crescendo, starting from the oscillation threshold, for a given embouchure adjusted in order to obtain realistic sounds with the two trumpets. The playing frequency of a Bflat3, obtained with all valves depressed, is represented according to the mouth overpressure (fig. 5).

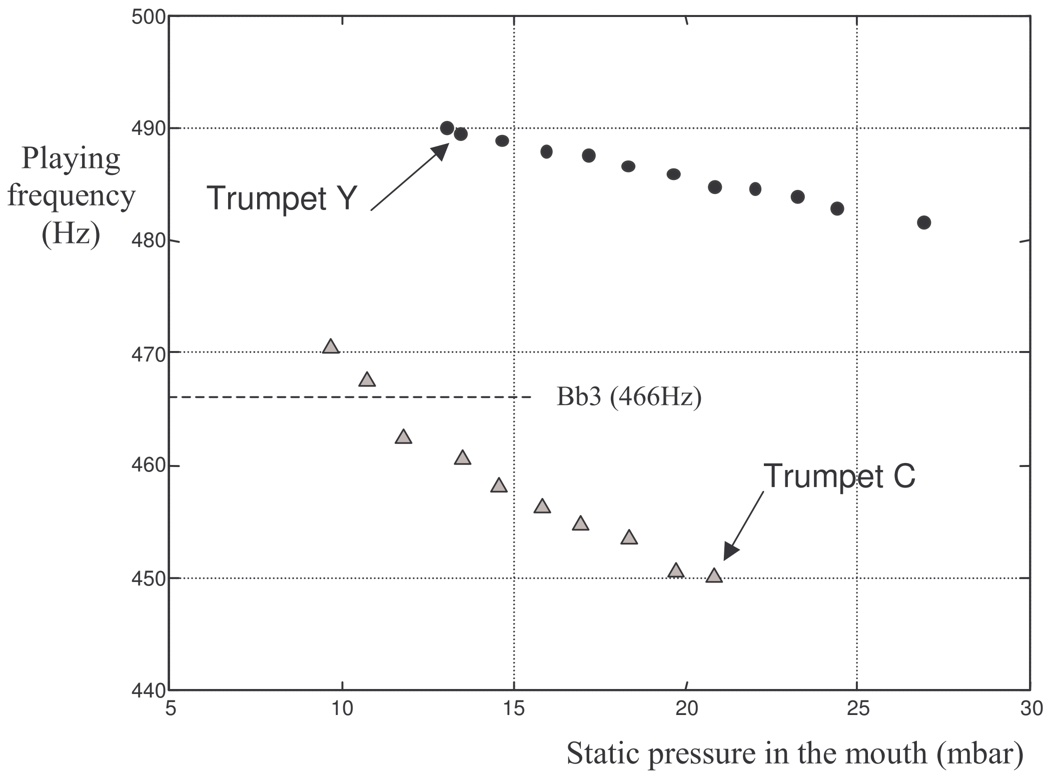

Figure 5. *Evolution of the playing frequency for the same fingering, for two trumpets C and Y. Bflat3 is played with the artificial mouth with the same embouchure. The playing frequency (in Hz) is represented according to the mouth overpressure (in mbar).*

If both trumpets behave qualitatively in the same way (decreasing of the playing frequency with increasing mouth pressure), it appears that trumpet C gives a greater variation of frequency. One can expect that the trumpet player with the trumpet C will have to compensate a little bit more with his embouchure and to control it carefully to remain in tune during the crescendo If a given embouchure has been chosen to compare the two trumpets in the same conditions, a real player would adapt his embouchure to each trumpet. And we might assume that he would look for a suitable embouchure in order to play with the lowest blowing pressure. For this reason, we have found out for each trumpet the embouchure which give the minimum threshold pressure. This is done by modifying the adjustments of the artificial mouth (water pressure inside the lips, and force on the artificial jaw) and tracking the minimum of pressure. We have noticed experimentally that the embouchure's parameters which correspond to this minimum of pressure are unique. Table 3 presents for both trumpets the minimum threshold pressures, obtained with different embouchures, and various notes. Each particular embouchure is found by determining the artificial mouth's control parameters' adjustments which lead to the lowest pressure magnitude.

Minimum threshold pressure	Trumpet C	Trumpet Y
Aflat3	15,7mbar	18,6 mbar
Eflat4	9,9mbar	10,6mbar
Aflat4	13,5mbar	19,2mbar

Table 3: minimum threshold pressures, obtained with different embouchures, and various notes

Assuming that the threshold pressure is one way to characterise the "ease of playing", then trumpet C seems easier to play than trumpet Y (the minimum oscillation threshold pressure is the lowest for trumpet C), but these conclusions has to be studied more carefully with users' tests and subjective assessments in future work.

In addition to these results, it is possible to analyse the acoustic pressure radiated at the bell for example (a microphone is placed on the bell axis, in the output section of the bell). The acoustic output level is displayed according to the mouth overpressure (fig. 6).

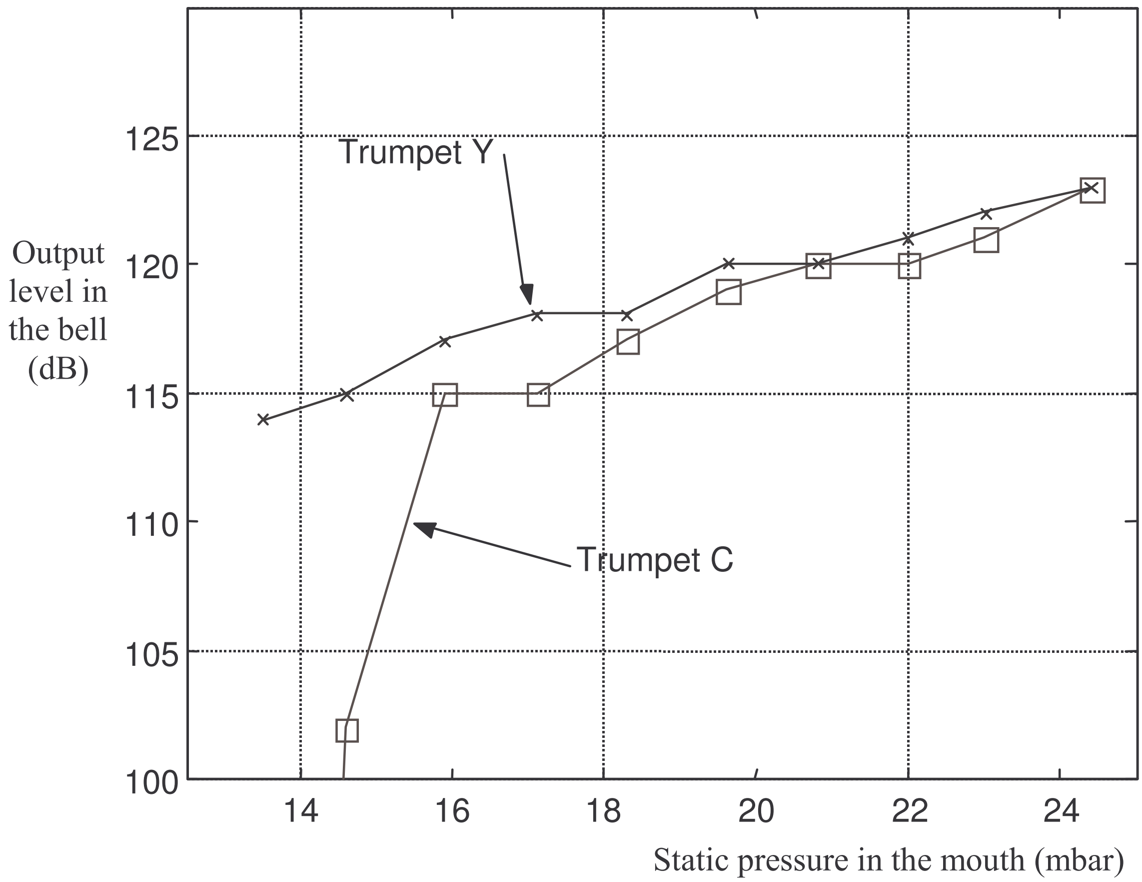

Figure 6. *Variation of the acoustical output level in the bell of the instrument (in dBspl) according to the mouth overpressure (in mbar). The note played with both trumpets C and Y using the artificial mouth is F4.*

Far from the oscillation threshold, the two trumpets behave in quite the same manner. With the same embouchure, trumpet Y is always more sonorous than C. On the other hand, in the vicinity of the threshold, the trumpet C shows stable regimes with very low acoustical level.

c) Comparison of several fingerings

After a comparison of our trumpets according to the makes, we have analysed several fingerings on the same trumpet. Thus, three different fingerings make it possible to play a D5 (one usual fingering and two substitution fingerings). With the artificial mouth, the trumpet was subjected to a crescendo from the oscillation threshold to the extinction of the played note, the same embouchure being preserved for the three fingerings. Figure 7 shows the playing frequency as a function of the mouth overpressure. Measurements for the three fingerings show a similar frequential behaviour (a decreasing function with a total variation of 15 Hz). There is a systematic difference between each fingering; these differences are identical to those obtained from the measured resonance frequencies.

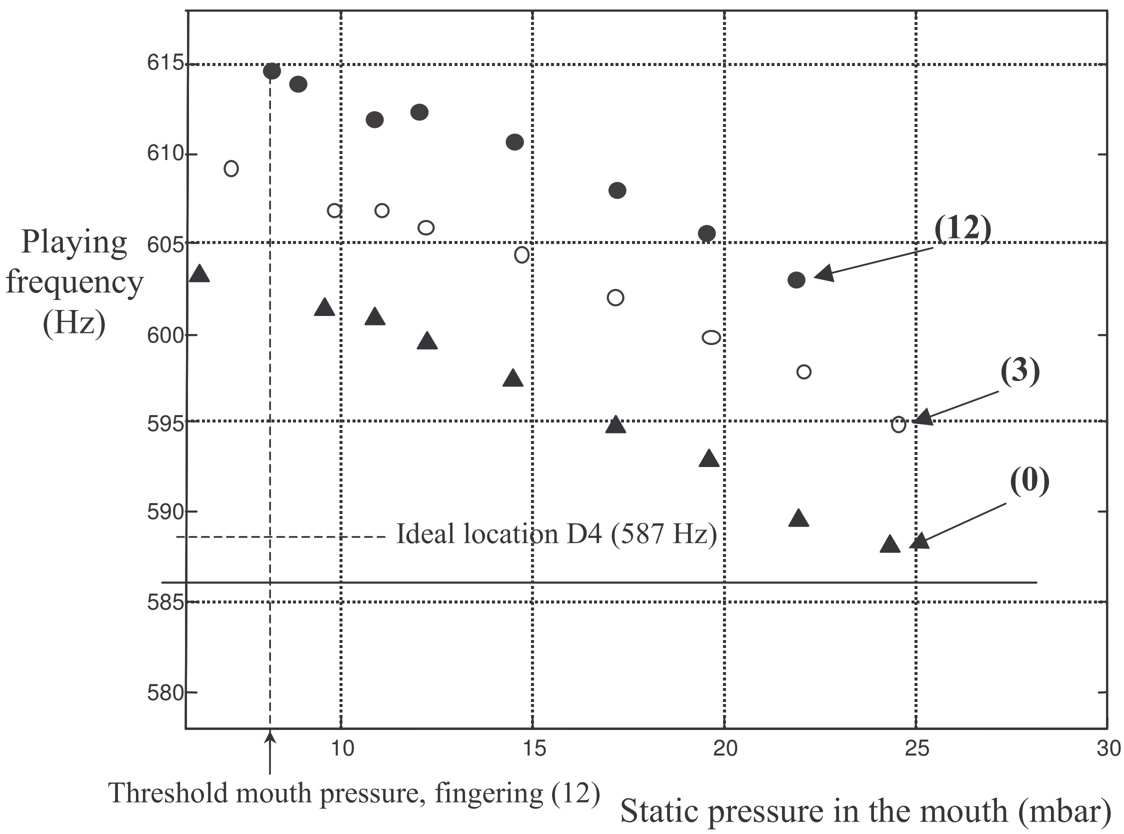

Figure 7. *Variation of the playing frequency for three fingerings of the trumpet Y for the D4 played using the artificial mouth, with increasing mouth overpressure. The three different fingerings are:*

the usual one with no valves depressed (0) ; the two substitution ones: valves 1 and 2 depressed (12), and valve 3 depressed (3).

A given embouchure has been chosen to compare the three fingerings of the studied trumpet. In such a way, the three fingerings are compared under the same conditions. It is then possible to compare the playing frequency obtained with different fingering, to evaluate the relative intonation of the trumpet, and to detect eventually fingerings which are abnormally inaccurate. Indeed, the multiple experiments we have made with the artificial mouth have shown that a rank according to the playing frequency, obtained with a given embouchure and the same air pressure, stays always the same whatever embouchure is used.

From Figure 7, one can deduce that the playing frequency (real and artificial) for fingering (12) is higher than for fingering (0), a conclusion which conformed to the trumpet player's assessment. But we deduce that fingering (12) is higher than fingering (3) too, which was not obvious to the trumpet player. The artificial mouth gives in this case a quantitative and objective answer to a question the answer to which was previously subjective and dependent on the musician.

The determination of the minimum threshold pressure has been done by finding, for each fingering, the most suitable embouchure (Table 4) :

Table 4	(0)	(12)	(3)
Minimum threshold pressure	8,2 mbar	10,5mbar	12,9 mbar

Table 4: minimum threshold pressures, obtained with different embouchures, and various fingerings, for the note D5.

The lowest minimum threshold pressure corresponds to the usual fingering (0), which is coherent with the trumpet player's experience.

IV. CONCLUSION AND PROSPECTS

We have developed a new artificial mouth for brass wind instruments, more compact and easier to handle than previous versions. Our objective is to use it as a "test bench" for instrument making. Preliminary comparative measurements on trumpets have been carried out. The artificial mouth makes it possible to test brass instruments under realistic playing conditions. Moreover it makes it possible to discriminate between instruments having quite similar internal bores. The analysis of these measurements can bring additional and complementary information to that from professional musician testers. Eventually, the test bench "artificial mouth" may make it possible to highlight subtle differences when one makes very small modifications to an instrument, differences that seem to be very difficult to evaluate by the tester . An instrument maker could use these measurements to compare a new instrument with a reference instrument, evaluated as very good by musicians or testers. In order to increase the efficiency of the artificial mouth as a "test bench", and to allow the realisation of tests during long period of time, the problem of the reliability of the latex lips or the polyurethane lips has to be solved. Even if polyurethane is less subjected to ageing than latex, an even more stable material has to be used.

In perspective, we will to complete the present study by defining how the measurements carried out with the artificial mouth can be used in the design process of a new instrument, and to apply it to a given case of new instrument development.

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