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NUMERICAL DESIGN OF A TRUMPET LEADPIPE: FROM THE NUMERICAL MODEL TO THE EVALUATION OF THE HARDWARE PROTOTYPE

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ABSTRACT

In a previous work, a machine learning model was trained using numerical simulations in order to predict intonation and playability descriptors of trumpets from the bore geometry [1]. Using this technology, a numerical design procedure was conducted where a new leadpipe geometry was proposed using a bi-objective optimization on the Equivalent Fundamental Pitch (*EFP*) and minimum blowing pressure (*Pth*), computed over five regimes. This recommendation led to a leadpipe numerical prototype that was manufactured by *Yamaha Corporation*, Japan. In this paper, we present recent investigations conducted on this hardware leadpipe prototype in order to compare the performances of the real instrument with the numerical expectations in the design phase. At first, impedance measurements of the prototype were performed, and sound simulations were computed from these measurements to assess the *EFP* and *Pth* descriptors. They were compared to the results of the numerical prototype. In a second step, playing tests with musicians were conducted in order to assess perceived differences between the original and prototyped leadpipe. These results are discussed in light of the potential sources of uncertainties through the whole procedure, from the model to the perception.

Keywords: *physics-based sound simulations, trumpet optimization, playing tests, instrument comparison.*

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1. INTRODUCTION

An interesting mean to study the objective quality of musical instruments is to carry out sound simulations by physical modelling [1]. They constitute a very interesting approach because they allow, by working on a virtual prototype, the exploration of the design space, by the creation of a large number of virtual instruments. The main interest of these simulations is that the sound result is driven by the causes that create the sound, as for a real instrument: if the physical model used is accurate enough to generate simulations in agreement with the real behavior (such as it is perceived by the musician), then the simulations can constitute a predictive tool for the development of the instrument (virtual acoustics) [2].
In recent years, machine learning (ML) has become an essential approach for the modeling of systems. Using this technique, we have developed in previous works [1,4] a procedure for optimizing the leadpipe of a trumpet. Two criteria were considered for the optimization: the Equivalent Fundamental Pitch (*EFP*), which may represent the global intonation of the instrument, and the minimum blowing pressure (*Pth*), which may represent the ease of emission of the note. The procedure led to the definition of an "optimized leadpipe", that was manufactured by *Yamaha Corporation of Japan*.
The objective of this paper is to give the first results about this new leadpipe, mainly by comparing the performances of the real prototype to the theoretical expectations in the design phases, and to compare it to the standard leadpipe.

Section 2 presents the background on the project, mainly the procedure defined to lead to the "optimal" leadpipe. A reminder of the physical model and the bore reconstruction process is proposed. In section 3, the first results are presented. They concern the simulation of instruments from measured or calculated impedances, and the analysis of differences between instruments when played by musicians.

2. BACKGROUND: OPTMIZATION OF THE TRUMPET LEADPIPE

2.1 Sound simulations

In this study, we use a classical elementary model of a brass instrument under playing conditions, described in [2]. The vibrating lips are modeled as a one-degree-of-freedom (1-DOF) outward-striking valve, non-linearly coupled to the air column of the brass instrument. From the input impedance *Ze* of the instrument (calculated or measured), different regimes of the trumpet can be simulated using different virtual musicians. The parameters used for the simulations are described in [1, 4]. Five regimes of the instrument were considered (regime 2 to 6), corresponding to the notes Bb3, F4, Bb4, D5 and F5 (concert-pitch) (Fig. 1).

Figure 1. Notes corresponding to the five different regimes simulated on a Bb trumpet (concert pitch)

To characterize the intonation of each regime of a virtual instrument, the Equivalent Fundamental Pitch (*EFP* – Eqn. 1), that represents the deviation in cent of the average playing frequency f_n from a reference frequency f_R, according to natural intervals, was calculated. The reference frequency was chosen arbitrarily according to the common tuning note of the instrument (the regime 4, Bb4) (with $f_R = f_4/4$, the *EFP* of the regime 4 is then necessarily equal to "0").

$$\overline{EFP_n} = 1200. log_2(\frac{\overline{f_n}}{n.\overline{f_R}}) \qquad (1)$$

To characterize the global intonation of each virtual instrument, the global average *EFP* was computed. It corresponds simply to the average value of the absolute values of the *EFP* of all the regimes (2 to 6) (Eqn. 2).

$$\overline{EFP} = \frac{1}{5}.\sum_{k=2}^{6}|\overline{EFP_k}| \qquad (2)$$

To characterize the global ease of playing of the instrument, the threshold pressure $P_{th,k}$ of each regime *k* was obtained by Linear Stability Analysis (LSA) [5]. The sum of the threshold pressure P_{th} for all the regimes was calculated (Eqn. 3).

$$\overline{P_{th}} = \sum_{k=2}^{6}\overline{P_{th,k}} \qquad (3)$$

2.2 Optimization of the impedance

The general approach for the optimization of the impedance of a trumpet based on simulations and ML models consists of the following three stages:

Stage 1: Generation of sounds (section 2.1). Sound simulations by physical model are used to create a database of sounds (1000 trumpet samples), with the input impedance of the instrument as an input (modal parameters), and the sound signal as an output. Two descriptors are considered to characterize a virtual instrument: the global average *EFP* (Eqn. 2) and the threshold pressure P_{th} (Eqn. 3),

Stage 2: Supervised learning. ML models are fitted to the database, with the characterization of the impedance *Z* as an input (modal parameters) and the 9 different features as outputs (EFP_n (n =2, 3, 5, 6) and $P_{th,n}$ (n=2, 3, 4, 5, 6)),

Stage 3: Optimization. Using the previous ML models, the input impedance is optimized by a minimization of two descriptors: global average *EFP* and the threshold pressure P_{th}. A bi-objective optimization is considered, leading to a Pareto front, using a gradient-free method (Genetic Algorithms). An optimal target Z_{opt} was selected.

In addition to these stages, 2 more steps are necessary to obtain a real optimized instrument:

Stage 4: Bore reconstruction (section 2.3). The objective of this stage is to obtain the geometry of the bore that corresponds to the optimal impedance Z_{opt} identified in stage 3 (optimization),

Stage 5: Manufacture of the optimal instrument (section 2.4). Given the geometry of the bore (stage 4), a real instrument can be manufactured and tested with musicians, to assess the efficiency of the approach. Before manufacturing, a smoothing of the initial profile of the leadpipe was applied, to obtain a class C^1 profile (manufacturing of the trumpet leadpipe with a mandrel) Details of stages 1 to 4 are available in [1, 4].

2.3 Bore reconstruction

Instead of optimizing the whole bore of the trumpet (difficult to manufacture), it has been decided to focus only on an important part of the bore: the leadpipe. The leadpipe of a trumpet, located after the mouthpiece and before the tuning slide, plays an important role in the intonation. Its shape is evolutive, generally divergent. At the end of the process, only the leadpipe will need to be manufactured, resulting in a cost-effective and faster solution. The rest of the instrument corresponds to a Yamaha trumpet model for which accurate impedance measurements are available, and called in the next the "S" trumpet.
Six optimization variables were defined in the leadpipe, 5 diameters and one length (Fig. 2). The leadpipe is considered as a juxtaposition of truncated cones. The design variables are defined by vector X=(d_1, d_2, d_3, d_4, d_5, L).

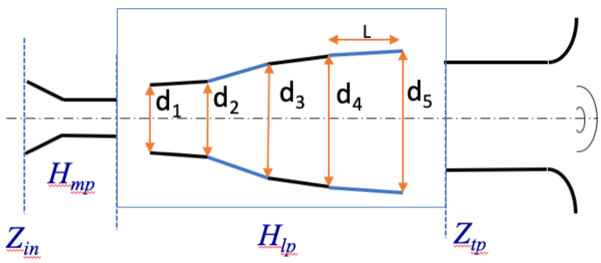

Figure 2. Overview of the bore of the trumpet (from the mouthpiece to the bell), with the definition of the design variables. The optimized part corresponds to the leadpipe, with the diameters d_1 to d_5 and the length L

To obtain the current input impedance of the trumpet, a transmission line model of the impedance has been used [6]. The input impedance of the instrument is a result of a calculation that involves three terms:

- The transfer matrix of the mouthpiece (Yamaha model), denoted as H_{mp}
- The transfer matrix of the four sections of the leadpipe, denoted as H_{lp}
- The input impedance Z_{tp} of the rest of the trumpet (a Yamaha model, S), measured with the CTTM impedance sensor at the entrance of the tuning slide.

Finally, the overall input impedance Z of the whole instrument is calculated as follows (Eq. 4):

$$H = H_{mp}.H_{lp}$$
$$[P_{in}\ U_{in}] = H.[Z_{tp}\ 1] \tag{4}$$
$$Z = \frac{P_{in}}{U_{in}}$$

The bore optimization problem of an instrument can be formulated as the search for the optimal geometry X* whose impedance Z fits as best as possible the target impedance Z_{opt}. A Genetic algorithm, NSGAII [7], with 300 individuals per generation, and a budget of 500 generations was used to solve this problem. From the Pareto front obtained at **stage 3**, which provides a range of optimal impedances that promote either a significantly lower *EFP* or a lower P_{th} than the training set and than the commercial trumpets, different target candidates were considered.
Nevertheless, one difficulty we have to face is to find, through bore reconstruction, leadpipe geometries that precisely produce the impedances of the Pareto front (or at least one impedance selected). Indeed, there is no guarantee that a solution to this inverse problem exists or can be easily reached, given the chosen design variables X=(d_1, d_2, d_3, d_4, d_5, L).
In this context, we could only obtain satisfactory bore reconstruction results by selecting a Z_{opt} with a lower *EFP* and P_{th} than commercial trumpets (namely the S trumpet), but located within the training set.
Different target instruments were considered for bore reconstruction. The optimal instrument $Z_{opt\text{-}rec}$ considered for the continuation of the study is presented in Fig. 3. Compared to instrument S, it presents a slight improvement of *EFP* and a decrease of P_{th} of around 70 Pa.

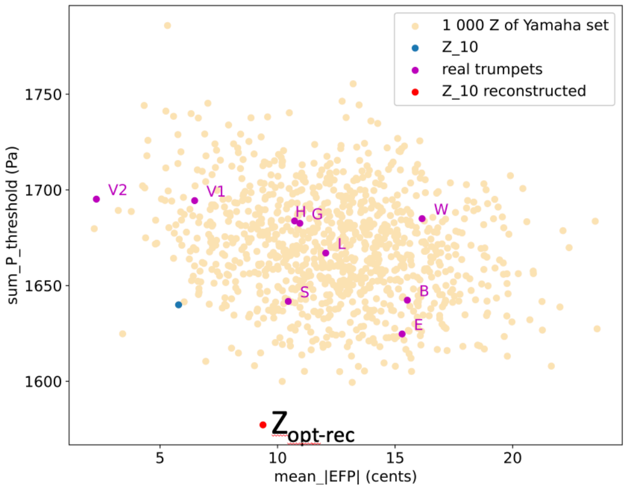

Figure 3. Position of different instruments in the plane of the two descriptors *EFP* and P_{th}: in particular, the Yamaha S trumpet, the reconstructed instrument $Z_{opt\text{-}rec}$ after re-simulation from the input impedance parameters. The training set counts 1000 instruments, corresponding to the beige colored points. The magenta points correspond to measured commercial instruments.

In perspective, one way to overcome this issue of "bore reconstruction" would be to compute a ML model of the descriptors directly from the design data (geometry of the leadpipe), and not from the modal parameters. We actually followed that strategy in another study not reported here, and that we conducted after this first phase of the project [9].

2.4 Manufacturing of the new leadpipe NL

The optimal leadpipe X* =(d_1, d_2, d_3, d_4, d_5, L)*, called NL, was communicated to *Yamaha Corporation* for the manufacturing (after a smoothing of the shape with a degree 4 polynom to have a class C^1 profile). A picture of the NL leadpipe is presented in Fig. 4, together with the current S leadpipe.

Figure 4. Picture of the NL new leadpipe and the S leadpipe

3. RESULTS: COMPARISON OF THE INSTRUMENTS

3.1 Simulations of S and NL

Impedance measurements of the NL prototype were performed, and sound simulations were computed from these measurements to assess the *EFP* and *Pth* descriptors.

Fig. 5 presents the results of the simulations for different versions of the instruments:

- S_{meas} corresponds to the S instrument, from the impedance measured on the real instrument,
- NL_{meas} corresponds to the NL instrument, from the impedance measured on the prototype,
- NL_{th} corresponds to the NL instrument, from the impedance calculated ($Z_{opt\text{-}rec}$) after bore reconstruction,
- $NL_{th\text{-}ycj}$ corresponds to the NL instrument, from the impedance calculated after a degree 4 smoothing of the optimal bore X* =(d_1, d_2, d_3, d_4, d_5, L)*.

Except for regime 6 (note F4), there is a remarkable degree of agreement between the position of the NL instruments resulting from impedance calculations and impedance measurements. This observation gives a good level of confidence in the quality of the Z models and the quality of the leadpipe manufacturing. The only difference is for regime 6, for which the P_{th} of the measured instrument NL_{meas} is slightly larger (+20Pa) than that of the theoretical instruments.

The agreement between the theoretical leadpipe NL_{th} and its version with a degree 4 smoothing $NL_{th\text{-}ycj}$ is excellent, indicating that this regularization has no

visible effect (in fact, it only changes the geometry of the leadpipe by a few hundredths of a millimeter).
The comparison between the S and the NL leadpipes leads to the following comments:

- The pitch of the Bb3 note is slightly higher for the S leadpipe (+30 cents), so the octave Bb3-Bb4 is closer to a theoretical octave (Ratio 2) for the NL instrument than for S. For the other notes, the EFP are very similar for the 2 leadpipes,
- For the note D5, the threshold pressure is higher for the S instrument than for the NL (+ 50Pa). For the other notes, pressures are comparable (lower than 30 Pa).

These results provide indications on the nature of the differences between the S and NL instruments, which must be confirmed by tests in playing conditions.

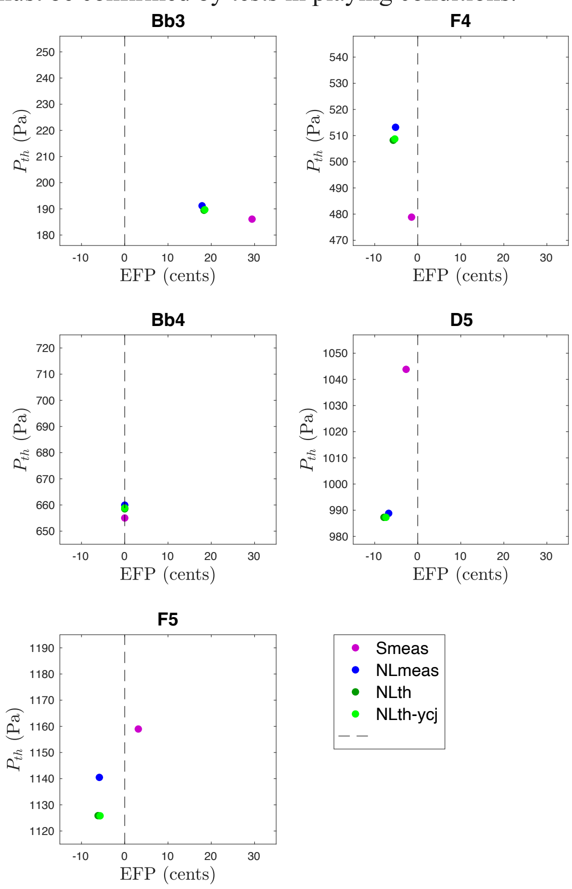

Figure 5. comparisons of the NL and S instruments for the different regimes. Different versions of the NL instruments are considered to estimate the deviation between theoretical and real instruments.

Fig. 6 presents a comparison of the input impedance of instrument NL, measured (*NL_{meas}*) or calculated (*NL_{th-ycj}*).

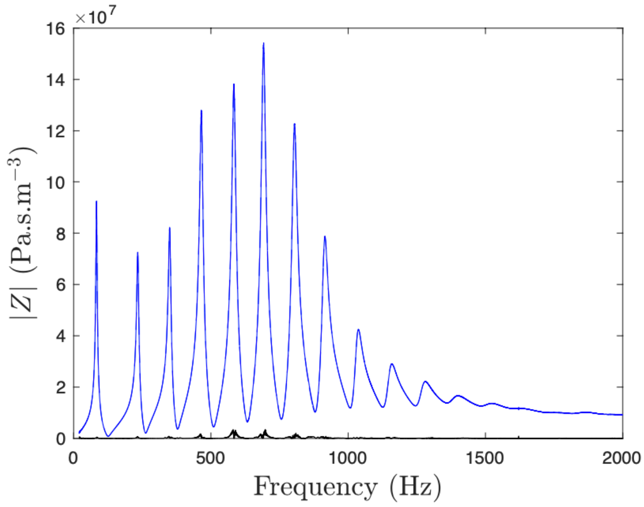

Figure 6. comparisons of the magnitude of the impedance of instrument NL, either measured or calculated. The difference between the 2 curves is presented in black lines.

Results show that the two impedance are very close and that the model agreement between the calculation and the measurements is large.

3.2 Recordings of the instruments and first analysis

The two instruments S and NL were played and recorded by 5 musicians. A series of five notes was recorded, in an ascending then descending arpeggio (Fig 7).

Figure 7. Sequence of notes played be the musicians (Bb writing)

Players were instructed to play as naturally as possible (without pitch corrections). The sounds were recorded with a Zoom H4 recorder (48kHz, 24 bits). Three repetitions of each sequence were performed, for each instrument S and NL.
From the audio recordings, the playing frequency of each note was estimated with the YIN algorithm [7], and similarly to the *EFP*, the deviation (in cent) from natural intervals was computed.

The intonation diagrams of the different notes are presented in Fig. 8, with the error bars corresponding to the 95% confidence interval calculated on the sample size of 3*2*5 = 30 observations.

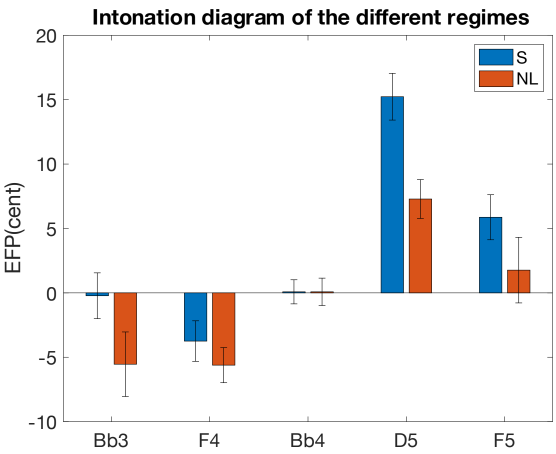

Figure 8. Intonation diagram for the different notes of the trumpet (in cent), with the 95% confidence intervals – Bb4 is the reference note (tuning note).

There are slight differences in intonation between the two instruments:

- Octave Bb3-Bb4 is larger with NL than with S
- Notes D4 and F4 are slightly higher with S than with NL

It is interesting to mention that this relative position of the played notes is in agreement with the relative positioning of the simulated sounds (Fig. 5): simulations can make interesting predictions of the pitch, at least from a relative point of view.

To characterize the spectrum of each instrument, the spectral centroid Sc_n of each regime n was considered, calculated as the power-weighted average spectral frequency (Eqn. 5).

$$\overline{Sc_n} = \frac{\int_0^\infty f.\left|\overline{S(F)_n}\right|^2 df}{\int_0^\infty \left|\overline{S(F)_n}\right|^2 df} \tag{5}$$

The diagrams of the spectral centroid for the different notes are presented in Fig. 9, with the error bars.

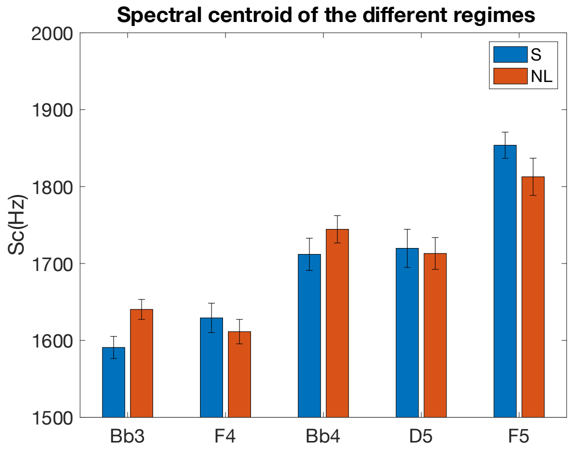

Figure 9. Spectral centroid of the different notes of the trumpet (in Hz), with the 95% confidence intervals.

Concerning the spectral centroid, instruments S and NL are extremely similar and no clear difference can be highlighted. Further investigations are needed to determine whether timbre differences are significant.

4. CONCLUSIONS

The work carried out in this article allows us to study to what extent theoretical differences, observed on a prototype of a virtual instrument, remain valid when the instrument is actually built. A trumpet leadpipe, developed and optimized using physical model simulations, was produced and mounted on an instrument. It should be noted that it is extremely rare in musical acoustics to be able to compare performances on virtual instruments to performances on a real instrument, as instrument manufacturing requires extensive resources and advanced know-how. This work constitutes a pioneering contribution. The first results show that the performances between virtual instruments and real instruments are rather in agreement, in particular with regard to playing frequencies. The continuation of this work will consist of determining whether the differences between the initial instrument and its optimized version are actually noticeable in playing conditions.

5. ACKNOWLEDGMENTS

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