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PHYSICAL MODELING SOUND SIMULATIONS FOR THE STUDY OF THE QUALITY OF WIND INSTRUMENTS

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Physical modeling sound simulations can be potentially interesting for instrument design as far as they are representative of the functioning of the real instrument. This work studies to what extent sound simulations of a brass instrument (the trumpet) are predictive of certain playing characteristics of the instrument (intonation, timbre). The physical model used is based on an acoustical modeling of the resonator (characterized by its input impedance), a mechanical model of the excitor (one degree of freedom outward striking valve for the vibrating lips), and an aeroelastic coupling between the excitor and the resonator. Two simulation methods are implemented: (1) the harmonic balance technique (a frequency method for the calculation of sounds in permanent regimes) and (2) time-domain simulations based on the impulse response of the resonator. Different trumpets, obtained by small variations of the geometry of the leadpipe (tube connecting the mouthpiece to the tuning slide) are on the one hand simulated on different regimes, and on the other hand played by a real musician on different notes. Different descriptors (intonation, spectral centroid) of the played notes are extracted to characterize differences between the trumpets. A comparison of the results is conducted in order to assess to what extent sound simulations are able to predict certain dimensions of the quality of the instrument when it is played.

Keywords: musical acoustics, auto-oscillating system, intonation, computer aided design

1. Introduction

The study of the quality of musical instruments is particularly interesting to help their development. The quality can be evaluated by physical measurements on the instruments (objective quality) [1]. Concerning brasses, the main physical measurement is the input impedance of the bore [2]. In playing situation, the musician produces a note whose frequency (the playing frequency) is close to the resonance frequency of an impedance peak. But the timbre of a note is also conditioned by upper resonance frequencies of the resonator [3]. Although interesting information can be given by the impedance, it is a hard work to predict sound qualities of brasses only from the impedance. A second interesting measurement that can be made on brass instruments concerns the analysis of sounds produced in playing situation. Various parameters of the signal can be extracted in order to characterise the sound. The main difficulties in this approach are to overcome the variability produced by the musician, and to be sure

that differences 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]. Another mean to study the objective quality of instruments is to carry out sound simulations by physical modelling [5]. Assessing the brightness of trumpet sounds by a comparison of simulations, an artificial mouth and a real musician, has been for example presented in [6].

Our work is in this context. We focus here on the ability of simulations by physical modelling to represent certain dimensions of the quality of a trumpet (mainly intonation and timbre). Our objective in this paper is to study if simulations are accurate enough to show differences between instruments that are in agreement with a real playing of the trumpet with a musician.

In order to create two instruments with controlled differences, we parameterised the shape of a very influential part of the resonator on the acoustic behaviour of the instrument: the leadpipe. Two different leadpipes have been manufactured, played by a real musician and simulated using the physical model. The two leadpipes differ in their internal geometry. Results according to the intonation and the timbre of the instruments were compared.

In this paper, we present the geometry of the different leadpipes used for the simulations, the physical model and the temporal simulation method. A preliminary analysis of the produced sounds is provided, studying intonation metrics and sounds spectral centroid.

2. Material and methods

2.1 Parameterised leadpipe

The leadpipe, located between the mouthpiece and the tuning slide of the trumpet, is an important part in quality of a trumpet. It is roughly conical and has a great influence on the intonation of the instrument. From the measurements of the internal shape of existing leadpipes (measured with calipers), a parameterised leadpipe was designed, made of 4 different interchangeable parts, each conical and parameterised by the radii r_1, r_2, r_3, r_4 (figure 1).

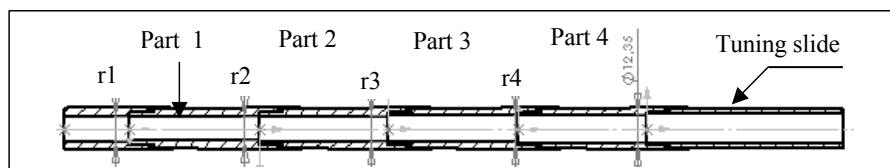


Figure 1: design of the parameterised leadpipe

Several parts 1-2-3-4, with various values for the radii r_1, r_2, r_3, r_4 , have been manufactured with a numerically controlled turning machine. The proposed values of r_1, r_2, r_3, r_4 correspond roughly to dimensions of marketed leadpipes, and the assembling of the parts can generate many hundreds of different inner leadpipe profiles. A naming system has been defined to distinguish every leadpipe. The leadpipes are named after a 4 letters code, each letter corresponding to the radii dimension of the corresponding part. So, using the same trumpet (*Bach*, bell 43, see figure 1) and the parameterised leadpipe, several hundred different instruments with notably different acoustical behaviour can be designed [7]. Two leadpipes (**AAAE** and **CHMQ**) were studied, whose characteristics are presented in table 1.

Table 1: description of the dimensions (in mm) of the two leadpipes **AAAE** and **CHMQ** 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 |

| | | | | | | | | |
|-------------|------|---|---|-----|-----|-----|-----|-------|
| CHMQ | 4.64 | 5 | 5 | 5.5 | 5.5 | 5.7 | 5.7 | 5.825 |
|-------------|------|---|---|-----|-----|-----|-----|-------|

Using the same mouthpiece (Yamaha 15B4), and the same remaining part of the trumpet (*Bach*, bell 43), the input impedance Z of the 2 trumpets were measured with the BIAS device [8] at ITEM (Institut Technologique Européen des Métiers de la Musique, Le Mans, France). This measurement, characteristic of the instrument, is the input of the sounds simulations.

2.2 Physical model of the trumpet

The physical model is based on the 3 following equations (Eq. 1-2-3), which involve three periodic variables; the opening height $H(t)$ between the two lips of the player, the volume flow $v(t)$ at the entrance to the mouthpiece ($v(t)=0$ if $H(t)<0$), and $p(t)$ the pressure in the mouthpiece (for more information, refer to [9]):

$$v(t) = b.H(t) \sqrt{\frac{2(P_m - p(t))}{\rho}} \cdot \text{sign}(P_m - p(t)) \tag{1}$$

$$\frac{d^2 H(t)}{dt^2} + \frac{\omega_L}{Q_L} \frac{dH(t)}{dt} + \omega_L^2 H(t) = \frac{P_m - p(t)}{\mu_L} \tag{2}$$

$$p(j\omega) = Z(j\omega) \cdot v(j\omega) \tag{3}$$

Numerical solutions of the physical model are obtained using an adaptation of the method presented in [10]. This adapted method computes the discrete time series $p[n]$ and $u[n]$ using a discrete convolution of the resonator impulse response and an explicit numerical scheme of the discrete nonlinear coupled problem.

The parameters of the simulations, that represent the “virtual musician”, are presented in table 2.

Table 2: parameters of the simulations

| Control parameters | | | Lips parameters | | |
|--|------------------------------------|---|---|------------|-------|
| definition | notation | typical value | definition | notation | value |
| Pressure in the mouth | P_m (Pa) | 4000 to 14000 | width of the lips | b (mm) | 10 |
| Resonance frequency of the lips | $f_L = \omega_L/2\pi$ (Hz) | Variable, according to the regime simulated | rest value of the opening height | H_o (mm) | 0.05 |
| Inverse of the mass per area of the lips | $\nu_L = 1/\mu_L$ (m^2kg^{-1}) | 0.5 to 3 | Quality factor of the resonance of the lips | Q_L | 5 |

Different regimes of a Bb trumpet were simulated (Figure 2). Results are presented in this paper for the regimes 3 (note F4), 4 (note Bb4) and 5 (note D5).



Figure 2: different regimes of a Bb trumpet (concert-pitch), with regime 3 (F4), regime 4 (Bb4), and regime 5 (D5)

2.3 Comparison criteria

Two criteria, calculated from the sounds generated (either simulated, or played by a musician), are considered.

The first one, the Equivalent Fundamental Pitch (*EFP* – Eq. 4), represents the deviation in cent of the playing frequency f_n of the regime n from a reference frequency f_R . 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”.

$$EFP = 1200 \cdot \log_2 \left(\frac{f_n}{n \cdot f_R} \right) \quad (4)$$

The second one is the spectral centroid Sc of the sounds (Eq. 5), with a_k and f_k corresponding respectively to the amplitude and the frequency of the harmonic k (equation 5):

$$Sc = \frac{\sum_{k=1}^N f_k \cdot a_k}{\sum_{k=1}^N a_k} \quad (5)$$

3. Results

The results are presented for the time domain simulations only (simulations with the harmonic balance method are presented in the poster).

For each instrument and each regime, several simulations with slight changes in the control parameters of the simulations (changes of f_L and of $v_L - Pm$ being constant) were carried out (10 repetitions). Similarly, 10 repetitions of the same note, played by the musician, were considered. The instruction given to the musician was to play a steady state note with a *mf* dynamics.

The average *EFP* of the notes (across the 10 repetitions), corresponding to the regimes 3, 4, 5, are presented in table 3, together with the *EFP* of the resonance frequency of the corresponding impedance peak.

Table 3: comparisons of the average EFP for regimes 3, 4 and 5

| | | Regime 3 | Regime 4 | Regime 5 |
|--|--|----------|----------|----------|
| | | | | |

| | | | | |
|--------------------------------|----------------------------------|-------|---|-------|
| Simulated | CHMQ (<i>EFP</i> – cent) | +3.9 | 0 | +15.8 |
| | AAAE (<i>EFP</i> – cent) | +33.9 | 0 | +51.7 |
| Played | CHMQ (<i>EFP</i> – cent) | -7 | 0 | -6 |
| | AAAE (<i>EFP</i> – cent) | +24.3 | 0 | +22.9 |
| Resonance frequency (Z) | CHMQ (<i>EFP</i> – cent) | -12 | 0 | +12 |
| | AAAE (<i>EFP</i> – cent) | +6 | 0 | +42 |

Results show that for the simulated sounds, the trumpet **AAAE** is less in tune than the trumpet **CHMQ**: regime 3 (+33.9 cents) and regime 5 (+51.7 cents) are too high. From the simulations, the conclusion is that the intonation of trumpet **CHMQ** is more satisfying. For the sounds played by the musician, the conclusions are similar: trumpet **AAAE** is less in tune when played (regime 3: +24.3cents – regime 5: +22.9 cents) than trumpet **CHMQ**. Simulations and played notes lead to the same conclusion: trumpet **CHMQ** is more in tune than trumpet **AAAE**. Conclusions are not so clear for the resonance frequencies of the impedance peaks, even if trumpet **AAAE** is in average less in tune than **CHMQ**. More regimes should be taken into account to confirm this behaviour.

The average spectral centroids of the instruments are presented in table 4.

Table 4: comparisons of the average spectral centroid Sc for regimes 3, 4 and 5

| | | Regime 3 | Regime 4 | Regime 5 |
|------------------|--------------------------|----------|----------|----------|
| Simulated | CHMQ (Sc – Hz) | 523 | 689 | 833 |
| | AAAE (Sc – Hz) | 561 | 643 | 729 |
| Played | CHMQ (Sc – Hz) | 680 | 953 | 1129 |
| | AAAE (Sc – Hz) | 671 | 946 | 1066 |

Results show that for the simulated sounds, the trumpet **CHMQ** is brighter (higher spectral centroid), except for regime 3. For the played sounds, the trumpet **CHMQ** is brighter for all the regimes. There are of course differences in the absolute values of Sc that is always higher for played sounds. This can be explained by non-linearities in the behaviour of the instrument (brassy sound) that are not taken into account by the physical model.

4. Conclusions

The experiments carried out in this study show a noticeable agreement between simulations and a real playing of the instruments. Concerning intonation, the physical model is accurate enough to provide pitch differences that are in agreement with a real playing of the instrument. The simulations seem to be a better predictor of the intonation of the instrument than the resonance frequencies of the impedance. Concerning the timbre, an agreement is also noticed with the spectral centroid, that needs to be confirmed by taking into account more regimes, more musicians, and more timbre descriptors. A more thorough processing of the variability of the musician (real and virtual) would be necessary to confirm these results.

One perspective of this study will be to take into account spectro-temporal descriptors, in order to study differences according to transient regimes of the instruments.

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