Comparative Study of Different Physical Models Describing the Reed Behaviour in Real and Artificial Playing Conditions

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The aim of this work states at classifying the reeds according to their perceived quality. Knowing that a certain proportion of reeds is considered as unsatisfying by the musicians, it's interesting to dispose of a way to foresee the reeds quality, for both the musician and the manufacturer. The long term aim of this study is to understand which physical parameters determine the quality of the reeds.

The present work contains the study of the suitability of different physical parameters in order to describe the reed in quasi-static and dynamic state. A measurement bench has been developed in this purpose. Firstly, different positions of the reed are reached controlled by a vacuum pump, the difference of pressure between the mouthpiece and the atmosphere and the displacement of the reed being measured during the process. Secondly, these physical magnitudes are used to estimate the typical physical parameters of different physical models of growing complexity. Several linear and non-linear models are studied for a set of reeds perceived as very different, and their accuracy and relevancy are discussed. For each parameter associated to a model, its estimated values are qualitatively compared to the musicians' sensations.

1 Introduction

The musical quality of woodwind instruments such as clarinet or saxophone depends strongly on the reed quality. Quality of single cane reed may vary from a reed to another. Using our own experience of musician, we consider that 30 % of reeds in a box are good reeds, whereas 40 % are mean quality reeds and 30 % are considered as bad.

In a recent paper [1], we show that some equivalent parameters of reeds can be measured *in vivo* using an instrumented mouthpiece. These parameters are the reed channel height, the reed stiffness and damping. It seems that the reed damping could explain the subjective difference (easy and difficult reeds). However, this approach needs to do *in vivo* measurements involving musicians and can not be applied easily for industrial application.

The aim of this work is to study the feasibility of reed equivalent parameters estimation using an *in vitro* measuring bench. Previous measuring benches [2, 3] using a dynamic excitation at low level (about 100 dB SPL) do not enable to estimate reed parameters in a repeatable manner (due to hygrometric variation) and the estimated parameters do not correlate with subjective indicators. For this reason, this bench aims at characterizing reeds using a quasi-static and dynamic approach and at estimating the equivalent parameters of reeds using different physical models with a growing complexity.

2 System under study

The system under study (mouthpiece, reed, lip) is shown in Figure 1.

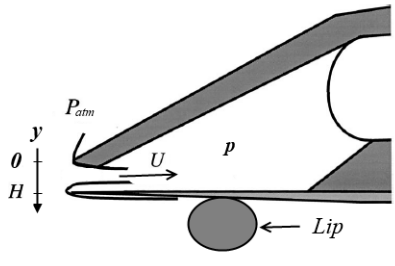

Figure 1: View of the system under study (from [4]).

It is based on the experimental system described in [5]. It is composed of the reed we wish to characterize, the mouthpiece and an artificial lip. As we expect to characterize different reeds easily, each reed should be mounted and unmounted quickly. Because of this we do not use any artificial mouth with a positive static pressure as described by Dalmont *et al* [4] or Almeida [6]. Instead, we create a negative pressure p using a vacuum pump, the equivalent mouth pressure being here the atmospheric pressure P_{atm}.

In this system, it is possible *a priori* to set-up two different configurations:

1. an artificial instrument working with a negative pressure which enables to create self sustained oscillations of the instrument and to characterize *in vitro* the dynamic response of the reed,
2. a system without any self-sustained oscillation which enables to measure the quasi-static response of the reed *in vitro*.

The aim of this paper is to know if both systems can be built and can provide with repeatable reed parameters.

3 State of the art

3.1 Physical models

3.1.1 Reed models

Reed Linear Modelling The usual physical model describing the reed assumes a linear behaviour for small amplitudes y. The reed motion y can be written

$$M\ddot{y}(t) + R\dot{y}(t) + K\left[y(t) - H\right] = \Delta P(t), \quad (1)$$

where

$$\Delta P(t) = p(t) - P_{atm}. \quad (2)$$

M, R, K are respectively the mass, damping and stiffness equivalent to the reed. Equation 1 shows that the reed is not beating for $\Delta P(t) > -KH$.

In this paper, we are going to implement the linear models of growing complexity named "K model" (taking $M = 0$ and $R = 0$ in Equation 1) and "$R\ K$ model" ($M = 0$ in Equation 1).

Reed Non linear modelling Results obtained in [1] show that the relation between the reed tip displacement y and the pressure drop ΔP is non linear even for small amplitudes (*piano* nuance).

In this case, for low frequency, the reed tip displacement can be written (ignoring damping and inertia effects) [7] using the convention given in Figure 1 :

$$K(y(t) - H) - k_c(\lfloor y(t) - y_c \rfloor)^{\alpha} = \Delta P(t), \quad (3)$$

where

$$\lfloor y - y_c \rfloor = 0, \; if \; y > y_c,$$
$$\lfloor y - y_c \rfloor = y - y_c, \; if \; y < y_c.$$

Coefficients k_c and α enable to describe the bending of the reed on the mouthpiece lay. In this work, parameter $\alpha = 2$ as suggested in reference [7].

Taking into account the non-linear stiffness, the dynamic behaviour of the reed can be described by

$$\begin{aligned} M\ddot{y}(t) + R\dot{y}(t) + K(y(t) - H) = \\ \Delta P(t) + k_c(\lfloor y(t) - y_c \rfloor)^{\alpha}. \end{aligned} \tag{4}$$

As in the previous section, in this paper we are going to implement the non linear models of growing complexity named "K_{nl} model" ($M = 0$ and $R = 0$ in Equation 4) and "R K_{nl} model" ($M = 0$ in Equation 4).

3.2 Reed characteristic measurements

The first characterization of the reed consists in determining the reed non linear stiffness while ignoring the damping and inertia effets.

For this, authors [4, 8] measure the different physical quantities (pressure drop ΔP, volume flow velocity U and reed displacement y) in a quasi-static manner. Their results obtained for a Plasticover reed (reed recovered with a film of plastic) and a Fibracell reed (cells filled with resin) show that the quasi-static characteristic of the reed obtained *in vitro* has a linear part, a non linear part (bending of the reed on the mouthpiece lay) and shows some hysteresis. Two typical results are presented in Figure 2.

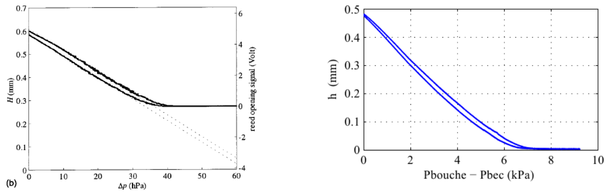

Figure 2: Quasi-static reed characteristic obtained by Dalmont [4] (left) with Plasticover reed and Ferrand [8] (right) with a Fibracell reed.

Measurements of reed characteristics in a dynamic regime has been made *in vitro* by Idogawa [9] with a Bari plastic reed mounted in an artificial mouth. The reed characteristic is shown in Figure 3.

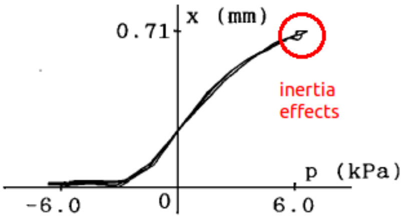

Figure 3: Experimental characteristic of a plastic reed measured *in vitro* with an artificial mouth (from [9]).

Figures 2 and 3 show that the expected characteristic of a reed is a non linear stiffness, *a priori* due to the bending of the reed against the lay of the mouthpiece. Damping (or viscoelasticity) effects seems to be slightly visible and the inertia effects are shown in Figure 3 by the small oscillations at the top of the curve.

All these results have been obtained for synthetic reeds. Nevertheless, our aim is to develop a system suitable for cane reeds.

4 Experimental system

The experimental system aims to estimate *in vitro* the reed parameters described in §3.1.1 in a repeatable and controlled manner. An important constraint for this system is that it must be able to measure different reeds quickly in order to develop the subjective tests and the *in vitro* measurements almost at the same time. For this reason, we can not use any artificial mouth made of a box supplied with a positive static pressure, which do not enable to mount and unmount reeds quickly.

Instead we propose to use a system which is opened on the mouthpiece side. Finally, the system is excited using a negative pressure inside the mouthpiece.

4.1 Description

The experimental system is made of an instrumented mouthpiece and an artificial lip. The mouthpiece is connected to a cylindrical resonator. The end of the resonator is connected to a vacuum cleaner with an adaptation system equipped with a valve. We did not use yet any air volume between the resonator and the adaptation system to reproduce the radiation impedance, so that the acoustic impedance of the resonator is not the impedance of a cylindrical tube.

The embouchure parameters can be adjusted by changing the artificial lip position in the horizontal and the vertical axis. The resonator length can be easily modified by changing the flexible tube between the mouthpiece and the adaptation system. The negative pressure can be adjusted by using the valve which controls the leakage.

The measuring system enables to measure the static and dynamic pressure inside the mouthpiece and to measure the reed displacement near the tip (not exactly at the tip, so the deformation of the reed while closed is also measured) on both sides (right, left). The characteristics of the measurement system are detailed in [1].

4.1.1 Instrumented mouthpiece

The instrumented mouthpiece has been made using a 3D printing system. An existing mouthpiece was scanned with a tomographic system (X rays) which enabled to obtain the CAD model of the mouthpiece. This CAD model was modified in order to allow the implementation of the different sensors as shown in Figure 4. The mouthpiece is built with a Nylon (PA12).

4.2 Reed equivalent parameters estimation

The pressure and displacement signals are used in order to estimate the reed equivalent parameters used in the different models (§3.1.1). As described in [1] and [10], the reed parameters are deduced from the comparison between

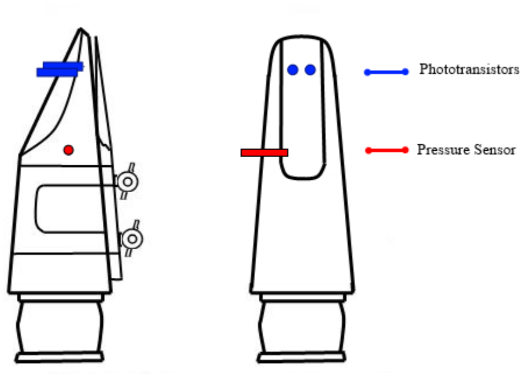

Figure 4: View of the instrumented mouthpiece.

the measured signals and signals deduced from the different models proposed above. The reed parameters are chosen in order to minimise the distance (least mean square) between the measurement and the model with a Gauss-Newton iterative method.

Four physical models are tested, as explained in §3.1.1.

4.3 Typical measured signals and reed parameters

We present here different signals obtained for one synthetic reed (carbon reed) and one cane reed for different resonator lengths.

4.3.1 Synthetic reed

The carbon reed is used with three different resonator lengths (1 m, 2 m , 7 m) and for a static pressure changing from 0 to the threshold pressure in 1 second.

For short resonators (1 m, 2m), we observe clearly the self-sustained oscillation of the reed at frequency near from the resonance frequency of the resonator. In Figure 5, a close view of some of the measurements shows the auto-oscillations.

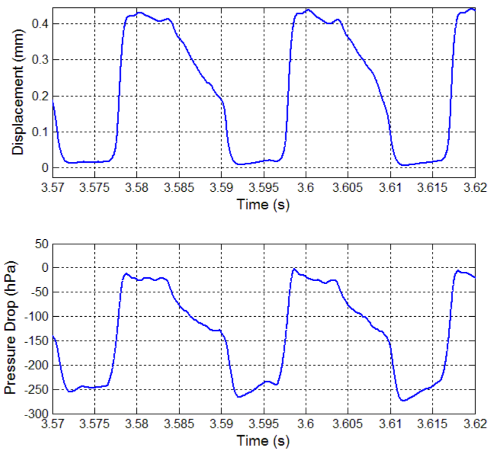

Figure 5: Close view of the measurements of the displacement of the synthetic reed and the pressure drop in the mouthpiece as functions of the time for the 1 m configuration.

It appears to be difficult to create auto-oscillation at a low static pressure (*piano* nuance), near the threshold pressure, probably due to the lack of harmonicity of the resonator. These same measurements are differently represented in Figure 6, where the damping, the inertia effects and the bending of the reed on the lay of the mouthpiece can be clearly seen.

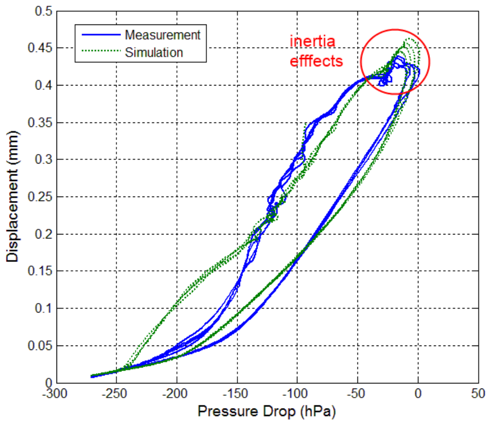

Figure 6: Measured displacement and estimated displacement employing the "$R\ K_{nl}$ model" for the synthetic reed as a function of the pressure drop in the mouthpiece for the 1 m configuration (5 periods).

For the 7 meter resonator, we achieve a quasi-static movement of the reed, except when the reed is up to a critical point (at 0.22 mm). At this small distance, the reed becomes unstable as described by Almeida [6]. This can be seen in Figure 7.

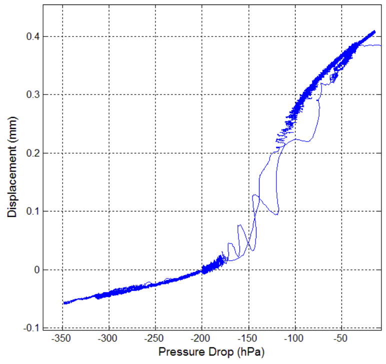

Figure 7: Measurement of the displacement of the synthetic reed as a function of the pressure drop in the mouthpiece for the 7 m configuration.

Comparison between Figures 6 and 7 shows that the hysteretic effects are less important in the quasi-static measurements, which have the same aspect than the results by Idogawa [9], with the only difference that our measurements shows the deformation of the reed inside the mouthpiece once it's closed.

4.3.2 Cane reed

As previously for the synthetic reed, the cane reed is used with the three resonator lengths. For this reed, it is very difficult to obtain a stable oscillation regime. We observe an *in tempo* regime (oscillation at the resonance frequency of the reed) at the beginning of the oscillation, followed by an oscillation synchronized with the resonator first resonance frequency. For the resonators of 1 m and 2 m, the *in tempo* regime has different durations.

For a long resonator (7 m), it is difficult to observe a proper quasi-static displacement of the reed as for the carbon reed. Instead of this, after the quasi-static displacement regime, we observe a reed resonance in the closing regime (see Figure 8).

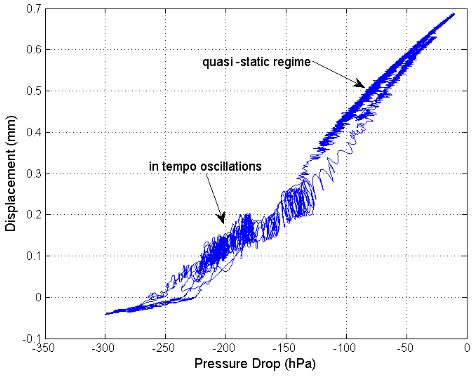

Figure 8: Measurement of the displacement of the cane reed as a function of the pressure drop in the mouthpiece for the 7 m configuration.

5 Accuracy of the different physical models

The estimation method minimizes the error e between the measurement and the simulation, this parameter e being a good indication of the accuracy [10]. The comparison between the measurements and some simulations for one representative measurement are presented in Figure 9.

In light of these results, the most accurate model tested in this paper is the $R\ K_{nl}$ model ($e \approx 4\%$), as expected from [1].

6 Repeatability of measuring bench

The aim of this section is to estimate the variance of the reed parameters due to the variance of the experimental system setup, more particularily due to :

- the embouchure parameters changes without any change of embouchure setup (mechanical lip parameters),
- the reed mounting and unmounting with a constant embouchure setup ,
- the embouchure setup (different positions in the x and y directions).

These experiments are conducted with a cane reed and a resonator of length 1 m.

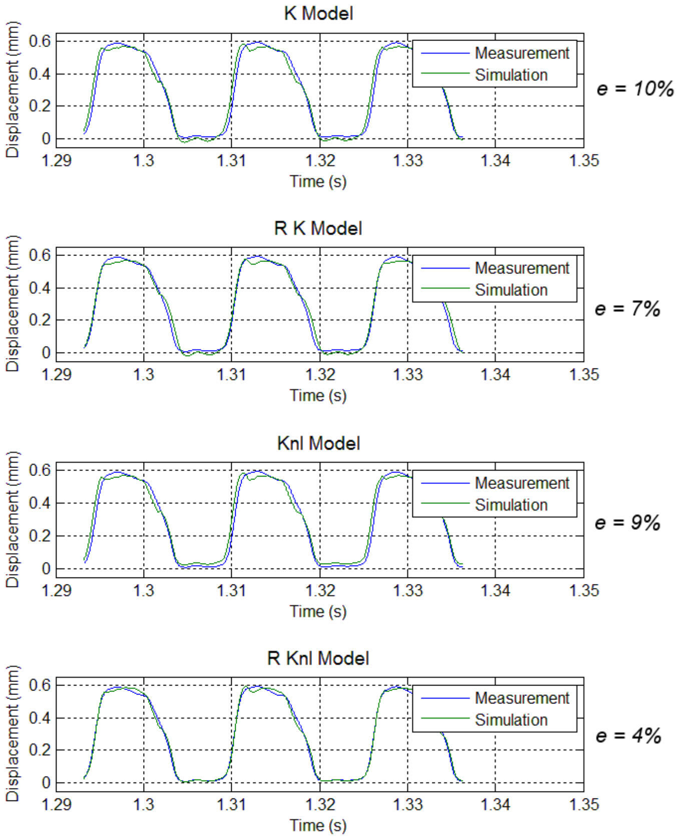

Figure 9: Comparaison of the simulated signal and the measurement for the parameters estimation.

6.1 Results of the study of the repeatability

For each of the three studies of repeatability within the controlled variation of the configuration of the system, a set of 5 measurements was analysed, and the reed parameters were estimated in three regions of each measured signal (beginning, middle and end) containing around five periods. The standard deviation of the estimated parameters is analysed in this section.

The results of the first study of stability, without any change in the configuration of the system, show a good stability (the highest variation is 5%, the dampings and the parameters k_c and y_c being the less stable).

The results of the study of stability of the parameters when unmounting and mounting again the cane reed show a high dispersion on the parameters k_c and y_c of the non linear model ($\overline{\sigma} \in [9, 21]\,\%$), while the others have a dispersion lower than 6%.

Aiming to understand the role of the artificial lip in the variability of the measurements, two sets of 5 measurements in different heights were carried on. The results show that the higher is the position of the lip, the lower is the variance of the parameters. However, increasing the value of this set up parameter can lead to unrealistic playing conditions. The global analysis of the measurements reveals that the configuration parameters controlling the embouchure have a very important role for the estimated parameters ($\overline{\sigma} < 16\%$ for the parameters of the linear model, and $\overline{\sigma} \in [16, 26]\,\%$ for the parameters of the non linear stiffness).

7 Analysis of different reeds

7.1 Description

In this section, we use six cane reeds considered as subjectively different by the musician. These reeds are the selected from the same brand, with the same shape and the same strength (Tenor Vandoren ZZ 3). Three of them are considered as easy to play and produce a bright sound and three are considered as difficult to play and produce a dull sound. All the reeds are “played” by the negative blowing pressure machine using the lowest static pressure it was possible to obtain. However, it is not possible to play with acoustic level as low as it’s obtained *in vivo*.

7.2 Reed parameters analysis

The parameters presented in §3.1.1 are estimated for each reed. The maximal pressure reached when the reed is closed is also obtained, as the product $K \cdot H$.

A preliminary study of the relevancy of the estimated parameters developed with the free software *Tanagra* [11] shows that the parameters K, R and $K \cdot H$ obtained with the non linear model allow to discriminate properly the reeds by HAC (Hierarchical Ascending Classification). The parameters R and $K \cdot H$ are found uncorrelated in a PCA (Principal Component Analysis). This two parameters form a 2-dimensional space in which the subjective perception of the quality of the reeds may be explained.

8 Conclusion

A measurement bench has been developed, allowing to excite a reed preserving its accessibility. Two different configurations of the system can be implemented to produce dynamic or quasi-static oscillations. An experimental limit is that, in the actual state, our experimental system produces only *forte* nuances. The recently developed instrumented mouthpiece permits to measure the pressure drop in the mouthpiece and the displacement of the reed.

Some experimental problems which complicate the control of the movement of the reed have been identified. The adaptation duct between the acoustic resonator and the vacuum cleaner needs to be modified in order to supress the coupling between these two parts. A more stable and easily removable system for the artificial lip, which has revealed crucial, has to be developed to facilitate the control and reproduction of the playing conditions.

A method to estimate the reed parameters corresponding to different physical models has been developed. The estimation error of the model is almost 4 % in the case of the most complicated model (damping and non linear stiffness).

The study of the repeatability using different configurations shows that the standard deviation of the parameters used in the linear model do not exceed 16 %, whereas non linear parameters (describing non linear stiffness) shows a larger variability (up to 26 %).

The pertinence of these parameters in order to describe the subjective differences about quality are studied. Finally, the 2-dimensional space composed by the estimated parameters R (damping) and $K \cdot H$ (closing pressure) of the non linear model has provided a preliminary classification of the reeds.

9 Acknowledgments

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