Experimental Investigations on Double-Reed Quasi-Static Behavior

André Almeida[1], *Christophe Vergez*[2], *René Caussé*[1]

[1] IRCAM, CNRS/Centre G. Pompidou, 1. Pl. Igor Stravinsky, 75004 Paris
[2] LMA, CNRS, 31 Chemin Joseph Aiguier, 13402 Marseille Cedex 20
almeida@ircam.fr, vergez@lma.cnrs-mrs.fr, causse@ircam.fr

Abstract

Basic working principles of reed instruments are well-known and resulting models are able to produce realistic synthesised sounds. This is particularly true for single-reed instruments such as the clarinet or the saxophone. Double reed instruments however have specific geometric properties which can call in question some simplistic hypothesis which are justified for single-reed instruments.

Some models have been proposed in the literature to try to investigate the effect of the specificity introduced by the double reed. Experimental data is however more scarce than the models. Our current experimental work aims at characterising the double reed and its possible differences from the single reed.

As a first approach, the volume flow in the reed, the pressure difference across the reed, and the reed opening area are measured in the static regime, and their coupling is investigated.

1. Introduction

Since [1], most self-sustained musical instruments are usually described by a nonlinear exciter coupled to a linear resonator. In the case of a reed instruments, the exciter is the cane reed which modulates the volume flow entering the bore of the instrument (which is the resonator). Within the hypothesis of a linear behavior, the resonator can be easily characterized, either in the frequency domain (by its input impedance) or in the time domain (by its reflexion function). Lots of theoretical and experimental work have been done on this subject. In comparison the exciter has seldom been studied, especially from the experimental point of view. The usual way of characterising the exciter of a reed instrument is to describe the non-linear relation between two variables of acoustic relevance.

The ongoing experimental work reported in this paper is a step towards the evaluation of the generality of reed models currently used in musical acoustics ([2], [3]) and sound synthesis [4], and their relevance when considering the family of double reed instruments (this question has been addressed from the modelling point of view in [5] and [6]). This first approach is based on the static reed characteristics. In fact, we are interested in measuring two kinds of nonlinear characteristics for the double reed : firstly, the reed opening cross section S versus the pressure difference ($\Delta p = p_m - p_r$) between the mouth and the end of the backbore, and secondly the volume flow q versus the same pressure difference Δp. These two characteristics are further referred as the $(S - \Delta P)$ and $(Q - \Delta P)$ characteristics respectively. In playing conditions, these curves will have different forms depending on the rate of change of the variables. For lower playing frequencies of the instrument however, unstationnary effects of the flow and of the reed mechanics can be neglected, so that a statically measured characteristic can approximately describe the behavior of the exciter (i.e. both the flow and the material properties of the reed).

2. Measuring reed characteristics

2.1. Experimental device

2.1.1. Measurement of the $(Q - \Delta P)$ characteristics

The main difficulty is the measurement of the volume flow q. In theory, it would be possible to measure flow velocity at several points inside the reed (though not very easy, due to the reed dimensions), but it is practically too difficult because a high spatial resolution is needed (especially in the boundary layer). Flowmeters are otherwise available, but they are often too inaccurate for our purpose. A pressure based measurement of the volume flow has then been used. Indeed we adapt the work done by J. P. Dalmont, J. Gilbert and S. Olivier on the clarinet ([7]). A first pressure sensor is inserted in the artificial mouth, upstream of the reed, and measures the mouth pressure p_m. A second pressure sensor inserted at the end of the backbore, just before a diaphragm of area S_d (see figure 1) measures air pressure in the reed p_r. The Bernoulli theorem applied between this pressure sensor and the outlet of the diaphragm allows to deduce the volume flow q crossing the mouthpiece :

$$q = S_d \sqrt{\frac{2}{\rho} p_r} \tag{1}$$

where air velocity in the backbore has been neglected compared to air velocity in the diaphragm, whose cross section is small compared to the cross section of the backbore. Moreover, since a jet is supposed to form at the outlet of the diaphragm, there is no pressure deviation at the outlet of the diaphragm.

The choice of the diaphragm cross section is crucial. On the one hand, the diaphragm should be small enough

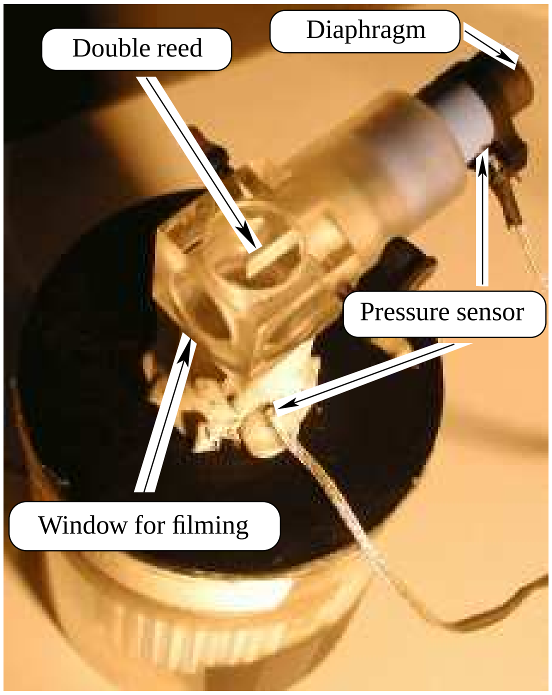

Figure 1: Experimental device

Figure 2: Video recorder to film the reed opening while the pressure blowing pressure is modified

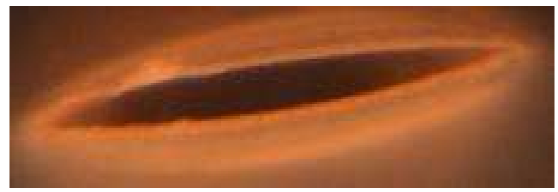

Figure 3: Sample picture of a video showing the variation of the double reed cross section at the inlet when blowing pressure is altered.

to allow significant pressure to be measured in the backbore, and to act as a nonlinear acoustic resistance to prevent the reed from oscillating. On the other hand, the head loss introduced by the diaphragm should not be too large so that the reed does not shut suddenly, therefore the diameter of the diaphragm should be as large as possible.

After many attempts, the closest solution to this compromise was a circular diaphragm, with a diameter of 1mm, with $45°$ chamfers upstream, to reduce head losses due to vena contracta.

2.1.2. Measurement of the $(S - \Delta P)$ characteristics

To measure the $(S - \Delta P)$ characteristics, a HI8 video recorder is used to film front views of the double reed through a transparent side of the artificial mouth (see figure 2). A program has been developed to analyse each image of the video (such as the one shown in figure 3) and extract geometrical dimensions of the reed opening.

2.2. Calibration

2.2.1. Pressure sensors:

Calibration of the pressure sensors (Entran EPE-54) is very demanding. Indeed, since they are highly sensitive to temperature and hygrometric conditions, they have to be calibrated for each new measurement. Their range of functioning is$[0, 35]$ kPa, and we have checked that their response is linear within this range and progressively deviates from linearity for larger pressures. Both sensors are calibrated for a zero pressure and a non-zero static pressure (known thanks to an additional manometer).

2.2.2. Diaphragms

At present, the diaphragm is being calibrated using a flowmeter. The value of the volume flow measured with the flowmeter has been compared to the value of the volume flow deduced from the pressure difference across the diaphragm through the Bernoulli theorem. However, this calibration should be more deeply investigated for future work, since the flowmeter used does not cover the whole range of volume flows measured into the artificially blown double reed. Therefore, diaphragms are only calibrated for the low-velocity range.

2.2.3. Video recorder:

The video recorder does not really need to be calibrated. However, since quantitative information on reed opening is deduced from image analysis, a comparison with an object with known geometry is required once the video recorder has been fixed. For this work, the width of the reed has been measured at rest.

Moreover, synchronising the video signal (stand alone recording) with the other sensors (automatically synchronised through the acquisition board) is not obvious. A rather satisfying synchronisation has been achieved using an interpolation between two events easily identified on both video and pressure signals, namely the beginning of the measurement and reed opening/closing transitions).

3. Experimental results

As explained in the previous section, the measured variables are the mouth pressure (p_m), the reed pressure (p_r)

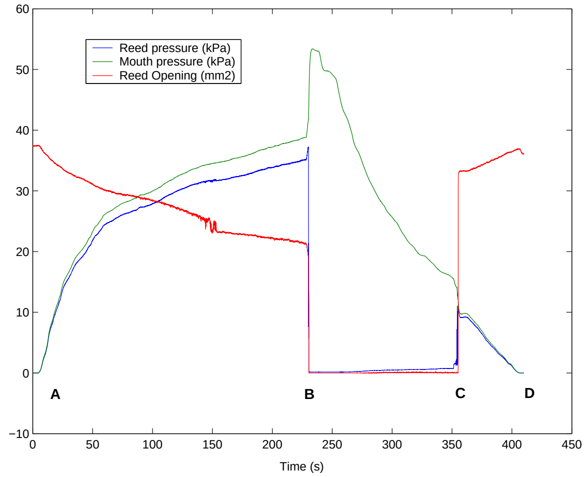

Figure 4: Time variation of the measured variables

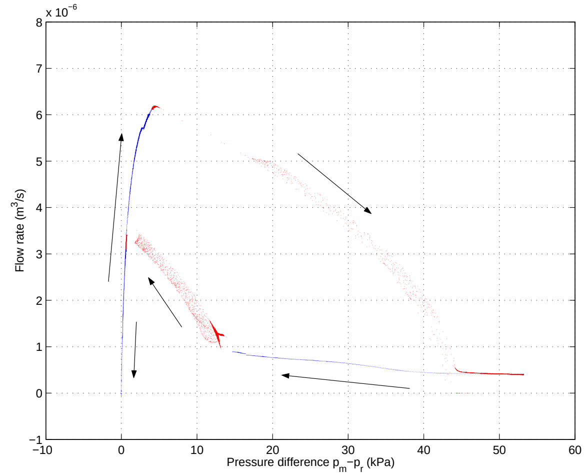

Figure 5: $(Q - \Delta P)$ characteristic curve corresponding to the data shown in figure 4

and the reed opening (S). Figure 4 shows an example of the evolution of these variables in the time domain. Before the beginning of the acquisition, both pressure sensors are calibrated with the same pressure value by obstructing the diaphragm, thus preventing any flow.

The acquisition begins (**A**) with a zero pressure on both sensors which also acts as a second calibration pressure. The mouth pressure is then increased slowly, forcing the reed to close progressively. At a certain point (**B**) the pressure difference destabilises the reed forcing it to shut suddenly after oscillating for a few periods (for scale reasons, these oscillations are not visible on figure 4). Due to the stopping of the flow through the reed, mouth pressure p_m suddenly and strongly increases, and reed pressure p_r drops to 0.

Once the reed has shut, the mouth pressure is progressively decreased. The reed remains closed for a certain range of mouth pressures, until p_m is sufficiently low (**C**) to allow the reed stiffness to reopen the reed. The transition to the open state is also accompanied by a short sequence of oscillations (again not visible on figure 4). The mouth pressure quickly decreases due to the leaking through the reed. Reed pressure increases as the flow through the diaphragm is resumed.

The mouth pressure is continuously decreased till zero (**D**) and the calibration is checked to remain valid.

3.1. Deriving the flow characteristics

From the analysis of the data shown in figure 4, we can trace the characteristic curve $(Q - \Delta P)$. The complete curve shown in figure 5 shows some scattered points (blue) in the red regions which correspond to the quick transition between closed and open reed states, typically accompanied by a few periods of auto-oscillation. The red points correspond to the transition periods, sampled at a higher frequency. In fact, pressure data shown in figure 4 were acquired at a sampling rate of 20000 Hz and downsampled to 40 Hz to reduce the volume of the analysis.

The transition points shown in red seem to correspond to a different regime in the flow. The fast oscillations of both measured pressures (p_m and p_r) are probably affected by unstationnary effects of the flow and of the reed mechanics. However, they are worth being seen since they stress the fact that there is an hysteresis in the experience, causing the system to follow a very different trajectory in the phase-space.

Another interesting feature is that the reed never closes completely for the pressure range we studied. On the acquired images we can see that a very thin slit remains open[1] generating the residual flow which can be seen on figure 5 around 50 kPa. Another interesting behavior (shown in figure 5) appears when decreasing the blowing pressure p_m while the reed is still *closed*. Indeed, there is a subtle, yet not negligible, increase in the flow (up to $1e^{-6}$ m^{3}s^{-1}) before the destabilisation of the reed. This can also be observed on the recorded images, where the opening of the reed starts to increase progressively when p_m is decreased, before the destabilisation of the reed occurs, causing a jump of the reed opening.

3.2. Stationary flow and reed opening data

It has been stressed in the previous section that the current experimental device does not allow a complete scanning of the reed characteristics in quasi-static conditions. We are forced to use tight diaphragms so that the reed does not oscillate during the experiment. This has the effect of drastically increasing the pressure drop fraction that takes place in the diaphragm. As a consequence, when we achieve the maximum of the $(Q - \Delta P)$ characteristic curve, the pressure drop in the reed quickly increases forcing the reed to shut suddenly (point B in figure 4).

[1]This is deduced by direct observation of the pictures. However, the algorithm developed to automatically measure the reed opening fails to give signifi cants results for so small openings, which explains that reed opening plotted in fi gure 4 is zero between points B and C

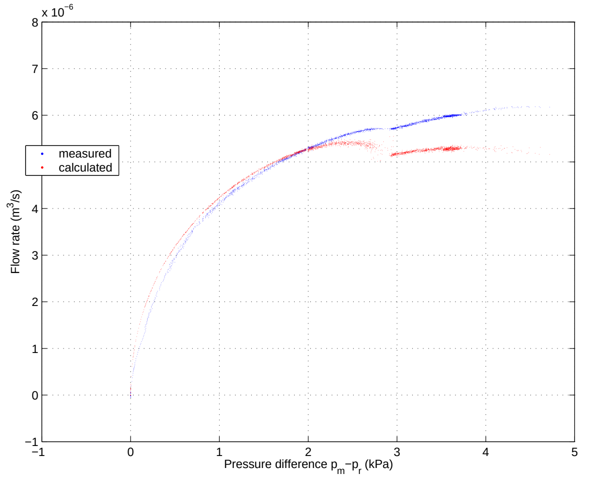

Figure 6: Comparison of the measured $(Q-\Delta P)$ characteristic with the one calculated using the measured pressure difference and reed opening according to eq. (2)

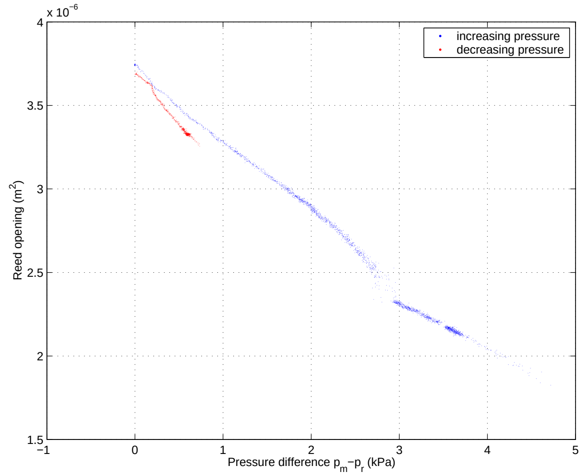

Figure 7: Measured $(S-\Delta P)$ characteristic. We distinguish the trajectory of the increasing pressures (closing reed) and that of the decreasing pressures (opening reed)

Nevertheless, the first portion of the $(Q-\Delta P)$ characteristic curve can be obtained and some comparisons with a physical model remain possible. We consider in the following the most simple physical model where the reed is modeled by a spring and the flow calculated from the pressure difference across the reed through the Bernoulli theorem (see [3]). This model has proved to rather well match the single-reed experimental $(Q-\Delta P)$ characteristic recently measured by J. P. Dalmont et al.([7]).

Figure 6 shows two $(Q-\Delta P)$ characteristic curves. For the blue one, the flow was measured using the technique described in section 2.1.1. The red one is calculated from the measured pressure difference between the mouth and the reed $(p_m - p_r)$ and the measured reed opening cross-section (S) using the Bernoulli formula:

$$q_B = S\sqrt{\frac{2}{\rho}(p_m - p_r)} \tag{2}$$

It can be checked that the measured volume flow q is slightly smaller than the calculated one q_B for lower pressures. At the top of the characteristic however q_B drops below q, indicating that a better calibration of the diaphragm for this range of pressures is probably needed.

Figure 7 traces the reed opening versus the pressure difference. We recall that in a Backus-like [2] reed-model, the relation is linear (the coefficient being the reed stiffness). In the figure we distinguish the points referring to the increasing of mouth pressure (blue) and the decreasing (red). The different path followed by the reed is most probably due to visco-elastic effects of the reed material.

4. Conclusion

The analysis of the data presented in this article can hardly indicate that the static behavior of the double reed is significantly different from that of a simple reed. However, only a complete measurement of the reed characteristic will allow to draw more complete conclusions on this subject. Moreover, as explained above, the flow measurement should be more precise after the diaphragm has been calibrated on all its range of functioning.

5. Acknowledgements

The authors would like to thank very sincerely J. P .Dalmont and J. Gilbert for useful discussions during the preparation of the experiments.

6. References

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