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Measurement of dynamic bending and displacement of clarinet reeds

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ABSTRACT

Novel equipment for single reed motion analysis with minimal intrusiveness has been designed in order to analyse the reed behaviour inside the player's mouth during performance. The experimental setup consists of a strain gauge sensor fixed on the flat side of the reed which gives a voltage signal proportional to the applied tensile or compressive stress, thus changing according to the bending of the reed. A former study analysed the relationship between the reed tip displacement and the reed bending under the effect of punctual static forces. Following that study, the question arises whether it is possible to extend the analysis to a dynamic configuration and experimentally characterise the bending-displacement relationship. In this study, the sensor reed is mounted on a mouthpiece which is coupled to a cylindrical tube representing the clarinet bore. An aspirated flow from the bore side induces the vibration of the reed. The reed motion is simultaneously captured by the strain gauge sensor and by a Laser Doppler Vibrometer (LDV). This configuration allows the measurement and further analysis of the dynamic bending and displacement of the reed. Two reeds with different stiffness are compared, showing a linear strain-displacement correlation at the tested frequencies and amplitudes.

1. INTRODUCTION

During the last century, many studies have focused on modelling and measuring both the resonator and the excitation mechanism in single-reed woodwind instruments. The resonator is generally understood as a linear passive element and the excitation mechanism is described as a lumped nonlinear element [1, 2, 3]. In the last decades experiments concerned the mouthpiece behaviour in the steady state which was described in terms of pressure difference and volume flow [2]. More recently the focus has shifted towards the role of the player, in order to consider the effect of the vocal tract [4, 5] and the articulatory actions of the player [6, 7, 8]. To fully understand and model the player-instrument interaction, the reed behaviour in transients needs to be established. Within this last goal, this paper analyses the use of strain-gauge technology to measure reed motion.

In order to analyse the reed behaviour during transients for real playing conditions in single-reed woodwind instruments, Hofmann *et al.* developed an experimental setup based on the deformation of a strain gauge attached to the reed [9]. Although these reed bending measurements have been successfully used to analyse playing techniques for both the clarinet and the saxophone [6, 7, 9], for further physical modelling applications, the question of whether one can accurately obtain the reed-tip displacement from the bending measurement still remains unanswered.

A first attempt to correlate the reed bending to the tip-opening was presented in [10], which explored static conditions for saxophone and clarinet reeds. The procedure consisted in adjusting the displacement of the reed by changing the position of a motor-driven table where the mouthpiece was fixed. The reed was pressed against a punctual force measurement head, causing the reed to bend; then the force measurement was repeated in an increasing path. The measurements took place in two configurations: at the lip position –where the lip was represented by the head force– and at the reed tip –where a soft clamp was fixed at the lip position–. For the second configuration, the results showed a linear correlation between the strain-gauge signal and the tip opening in static conditions. That study indicated that the observed linear trend was still not sufficient to define the sensor calibration in both static and dynamic ranges and suggested to perform such a calibration in artificial blowing conditions.

This paper analyses the strain-gauge capability of providing reliable information about the reed tip-opening in dynamic conditions with the aim of validating the extension of the bending-displacement relationship in the dynamic range. Establishing the sensor calibration would allow the strain-gauge signal to be used not only as a reference value but also as an indirect displacement measurement.

2. METHODOLOGY

This section presents the setup and experimental method used to simultaneously measure the reed bending and the reed-tip displacement in artificial blowing conditions for clarinet reeds.

Equipment

The measurements are performed on two synthetic clarinet reeds (German cut, by *Légère*) fixed on a Bb-clarinet mouthpiece (*Maxton* Na-1). The mouthpiece is coupled to a cylinder (length: 55 cm, diameter: 18 mm) representing the clarinet bore. The bending measurement is achieved by a strain gauge attached on the reed as presented in [9, 10], and the displacement is obtained by a Laser Doppler Vibrometer (LDV, *Polytec* IVS-400) pointing at the reed tip (Figure 1). The pressure in the mouthpiece is also recorded via a piezo-resistive pressure transducer (*Endevco* 80507C-2). The three signals are simultaneously recorded at 51.2 kHz using an acquisition platform (*National Instruments* LabView).

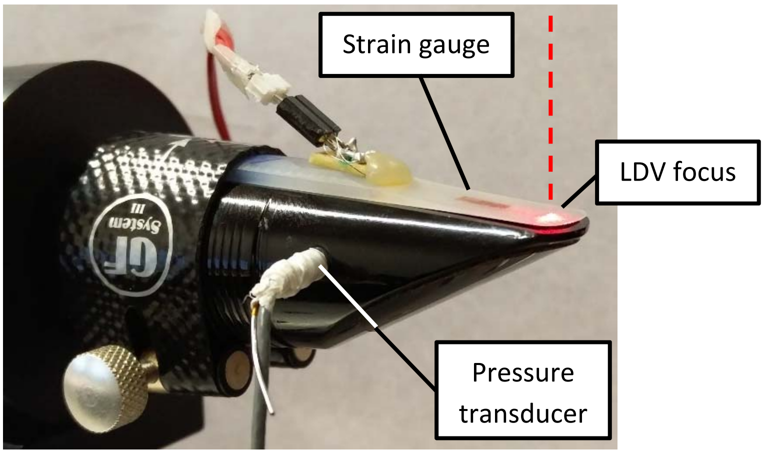

Figure 1. Setup with a strain-gauge sensor reed, a pressure transducer inserted to the mouthpiece and the LDV focus point at the reed tip. The vertical dashed line indicates the direction of the LDV light beam.

The excitation of the reed in the mouthpiece is achieved artificially. A vacuuming system is coupled at the end of the cylindrical tube, thus an aspirated flow induces the vibrations of the reed (used in *e.g.* [1, 11]). As these vibrations usually exceed the LDV measurement range, a flexible plastic tube is used for damping at the position of the lower lip of the player (around 1.3 cm from the reed tip). The power of the vacuuming system is kept constant during the experiment.

Strain Gauge Sensor. The strain gauge gives a voltage signal which increases when the gauge is under tensile stress and decreases when the gauge is compressed (compressive stress) [12]. When the reed vibrates, the gauge receives alternate tension-compression strength which modifies the gauge length and therefore changes in resistance are recorded. To convert the gauge voltage to the actual strain at the sensor position, a calibration procedure is established and presented in the Appendix.

Laser Doppler Vibrometer. A Laser Doppler Vibrometer allows a non-contact measurement of the instant velocity of a moving object taking into account the Doppler frequency shift of a laser beam after being reflected on the measured surface. After recording the velocity at the LDV focus point (see Fig. 1), the conversion into displacement is achieved by time-domain integration. The main drawbacks of this system are the limited measurement range (at 500 mm/s) and the fact that a measure of the instant velocity does not inform about the average position of the reed, thus resulting in displacements centred around the equilibrium position. Synchronisation between the LDV and the sensor signals is performed by means of a zero-crossing alignment of the AC-signals.

Experimental design

A comparison framework has been established to record reed bending and displacement. The bending is analysed in terms of the strain changes at the sensor position and the displacement is recorded at 2 mm from the reed tip (Figure 1). Two synthetic reeds with different stiffness (nominal strengths 2 ¾ and 3 ½) are used. A sensor is located at 8.8 mm from the reed tip for both reeds. Considering the LDV measurement range limitation, three vibrating frequencies are obtained by manually adjusting the applied damping force.

3. RESULTS

This section provides the results obtained for two different *Légère* synthetic reeds and compares the established strain-displacement relationships at different frequencies.

Strain-gauge reed of strength 2 ¾

Figure 2 (left) shows five periods of the transversal displacement at the reed tip and the longitudinal strain measured at the sensor position. According to the configuration of the setup, negative values in displacement correspond to the reed closing and positive values correspond to the opening. In view of the linear trend observed for static loads [10], a linear fit (Figure 2, right) is proposed as the mapping between these magnitudes.

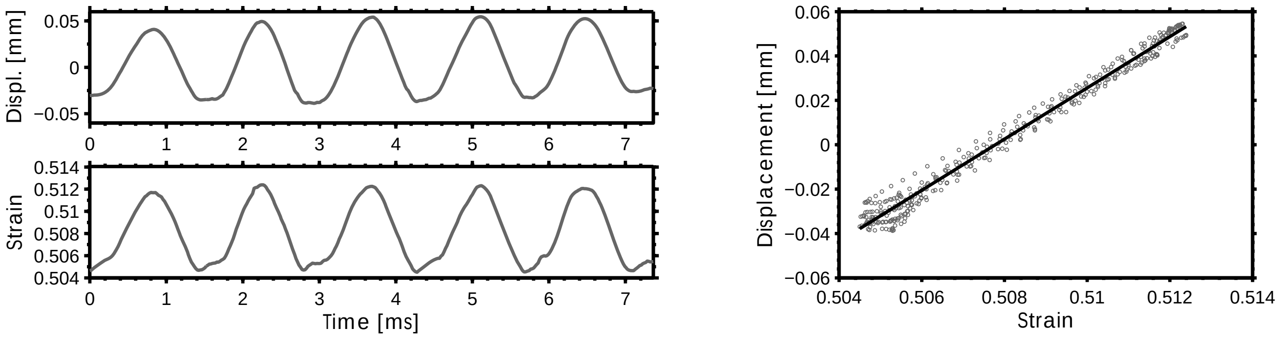

Figure 2. Evolution of displacement and measured strain (left) together with their linear correlation (right) for a vibration at 702 Hz (A in Fig. 3) of the reed of strength 2 ¾.

The linear regression is obtained as the least-squares fit between displacement (d) and strain (ε) and it is described as $d = m\,\varepsilon + n$. The obtained strain-displacement fits at three different frequencies are shown in Figure 3 (left). Taking these fits into account, the corresponding "mapped" strain-gauge signals are calculated and compared to the direct LDV measurement, as shown in Figure 3 (right).

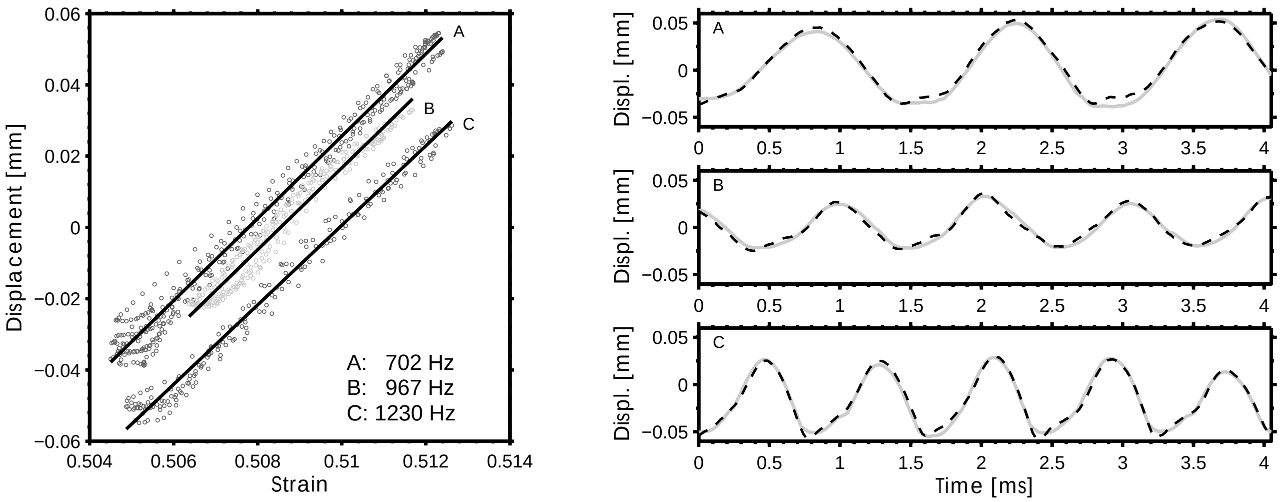

Figure 3. Strain-displacement fits for the reed of strength 2 ¾ at three frequencies (left). Corresponding displacement signals (right) of the mapped strain-gauge (dashed black) compared to the original LDV (grey).

Regarding Figure 3 (left), the slope of the fitted line (m) does not vary significantly between the different cases, but the d-intercept (n) does differ due to changes in the equilibrium opening of the reed. The equilibrium opening depends both on the closure of the reed due to the Bernoulli force induced by the aspirated flow (which might be much higher in this artificial setup, compared to real playing conditions) and on the artificial lip force applied on the reed.

According to these results, the presented calibration setup can be used to identify the magnitude of the vibrations, thus converting strain to relative displacement around their equilibrium position, but still a second measurement is needed to identify this equilibrium position. For example, a strain measurement when the reed completely closes can be used as a reference to establish the equilibrium opening under playing conditions, which would still depend on the lip force and on the Bernoulli force of the flow through the mouthpiece.

Strain-gauge reed of strength 3 ½

For a harder reed of strength 3 ½, displacement and strain signals and their linear fit are presented in Figure 4. The proposed fits at different frequencies (Figure 5, left) show less variability in the d-intercept than in the case of the softer reed (Figure 3, left). This can be due to the increase in stiffness of the reed or to a difference in the lip force.

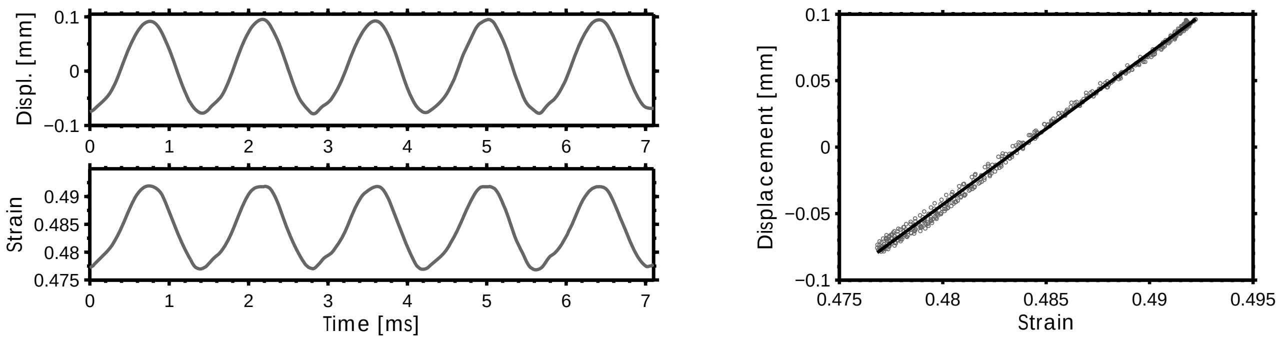

Figure 4. Evolution of displacement and measured strain (left) together with their linear correlation (right) for a vibration at 700 Hz (A in Figure 5) of the reed of strength 3 ½.

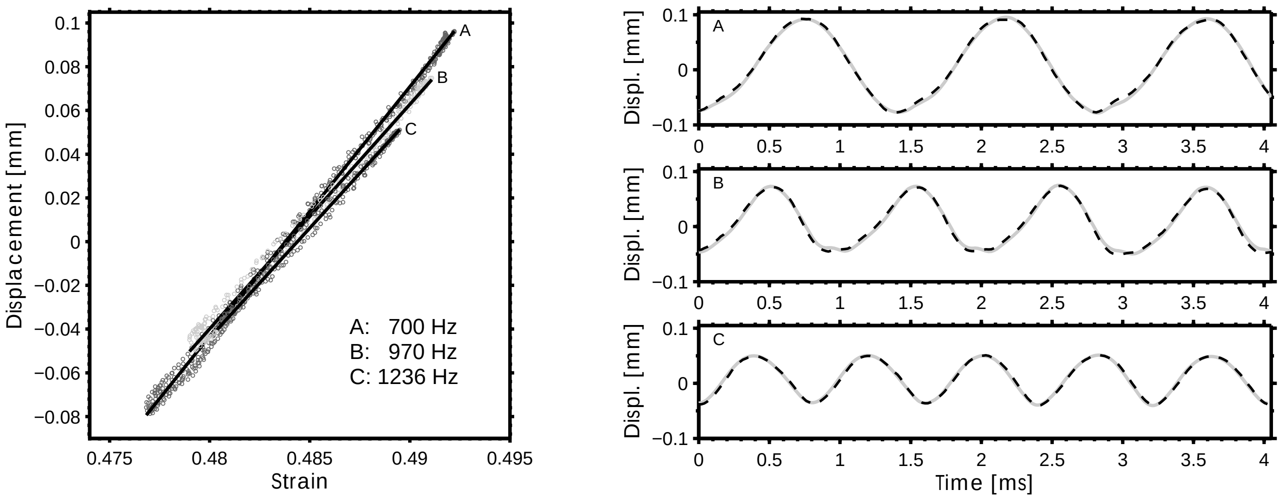

Figure 5. Strain-displacement fits for the reed of strength 3 ½ at three frequencies (left). Corresponding displacement signals (right) of the mapped strain-gauge (dashed black) compared to the original LDV (grey).

Another remarkable difference between reeds is the precision of the fit in the closed position (negative values in displacement). Whereas the soft reed presents an imprecise matching at this position (see C in Figure 3), the hard reed performs a better strain-displacement fitting at both opening and closing phases. This difference is due to the fact that high modes of vibration are reduced when the stiffness increases, thus resulting in a similar behaviour between bending of the reed and displacement at the tip. Still, this imprecision for the closing displacement-bending relation has been observed in both reeds (and in other tested reeds). A possible explanation lies in the difference from the present setup to the real playing configuration. The aspirated flow might bend the reed towards the mouthpiece lay in a different manner compared to real playing. This extra bending is reduced when the reed is harder, as the sensor is less free to bend.

4. DISCUSSION

In order to extend the use of the strain-gauge equipped reeds presented in [9], a calibration procedure in the dynamic regime has been presented in this paper. To extract the reed tip displacement from the bending measurement, a linear fitting procedure has been established. This procedure allows the calibration of the reed displacement around its equilibrium position. The restriction of the proposed setup to measure absolute displacements does not allow to consider the differences in the opening of the reed due to external forces (aspirated flow and lip force). That is why a reference measurement of the reed bending should be performed in order to feed a known position to the fitting model.

The different tested reeds have resulted in satisfactory linear correlations at the experimented frequencies and amplitudes. For the two exposed reeds, which had the same sensor position on the reed, differences have been reported in terms of correlation precision at the reed closure. According to the results, hard reeds allow a more precise correlation than soft reeds. This phenomenon is explained by an increase in effective stiffness.

Despite the linear trend presented in the static range [10] and the linear fit at dynamic vibration presented in this work, the limitations imposed by the equipment may restrict the extension of the here-stated correlations to real playing conditions. The main restriction is the direction of the flow (aspirated instead of blown), which might cause changes in the reed behaviour with respect to the real playing configuration. An artificial blowing setup is envisaged in order to overcome this restriction as well as to attain lower frequencies and larger amplitudes, looking for a better representation of the real playing conditions.

APPENDIX

Strain gauge calibration

A strain-gauge sensor allows a measurement of its deformation or strain (ε), proportional to the change in resistance (ΔR) caused mainly by a change in length (ΔL), neglecting the changes in width (w_g). The sensor sensitivity to strain is given by its Gauge Factor (GF). Defining the strain as the normalised change of length ($\varepsilon = \Delta L/L$), the relation between strain ε and the resistance change ΔR can be defined in the linear range as [12, Chap. 1]:

$$GF = \frac{\Delta R/R_g}{\Delta L/L_g} = \frac{\Delta R\ /R_g}{\varepsilon} \tag{1}$$

where R_g and L_g are the nominal gauge resistance and length. These two characteristics are not needed for the calibration itself, as the GF factor is given by the gauge manufacturer. The gauges used in this study have nominal values $R_g = 120\ \Omega$, $L_g = 2$ mm, $w_g = 1.6$ mm and $GF = 2$.

In order to amplify the voltage signal in small resistance variations, the strain gauge signal acquisition is completed with a quarter-bridge circuit [12, Chap. 5], as represented in Figure 6. The relation between the four resistances in the quarter-bridge circuit is described by Eq. (2):

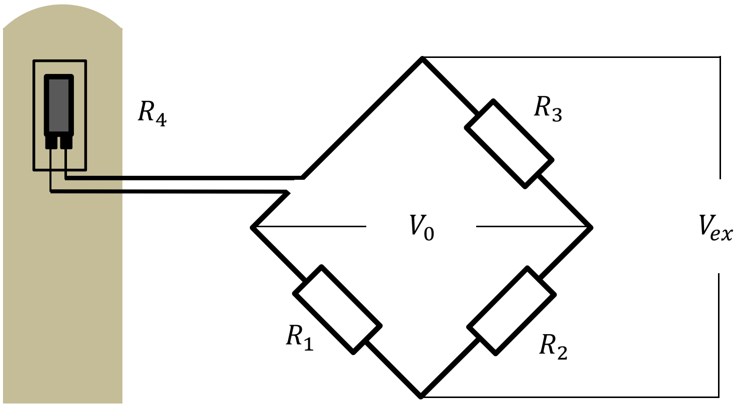

Figure 6. Quarter-bridge circuit with a strain gauge attached to the reed (adapted from [12]).

$$V_0 = \left(\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2}\right) V_{ex} \quad (2)$$

where V_0 is the measured voltage and V_{ex} is the external voltage (here $V_{ex} = 5$ V). The fourth resistance is replaced by the strain gauge, whose changes in resistance ($R_4 = R_g + \Delta R$) cause the unbalance of the bridge and therefore the measurement is possible.

Considering that the four resistances are set to the condition $R_1/R_2 = R_g/R_3 = 1$ and introducing Eq. (1) to Eq. (2), the relation between the measured voltage V_0 and the strain-gauge strain ε is:

$$\frac{V_0}{V_{ex}} = \frac{-GF \cdot \varepsilon}{4} \left(\frac{1}{1 + \frac{GF \cdot \varepsilon}{2}} \right) \quad (3)$$

whence the strain ε can be obtained. To summarize, the strain gauge allows a measure of its normalised increase in length (strain) considering its gauge factor GF and the change in resistance. For amplification, a quarter-bridge circuit fed with an external voltage V_{ex} is used. Then, the voltage within branches V_0 is measured and calibrated to obtain the strain.

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