Strain to Displacement Calibration for Single-Reeds Using a High-Speed Camera

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ABSTRACT

Measurements of reed bending on the clarinet and saxophone have been used to qualitatively analyse the reed behaviour and its interaction with the player's tongue. A similar measurement technique is now aimed at obtaining quantitative information regarding the opening at the reed tip. This paper presents an experimental procedure in which the reed bending and reed-tip opening are simultaneously measured while the reed is artificially excited via a pressure-controlled blowing system. The reed bending is measured in terms of its surface strain and the reed-tip opening is obtained from processed high-speed camera images. For different blowing pressures and lip forces, a comparison of the measured signals indicates a linear strain-to-displacement relationship. Using a linear calibration model, the strain signal has been satisfactorily converted into reed displacement. This procedure opens up the possibility to measure the reed-tip opening under real playing conditions.

1. INTRODUCTION

Sound production in single-reed woodwinds is often characterised by the coupling between an excitation mechanism (reed-mouthpiece) and a linear resonator (bore) [1]. The reed-mouthpiece behaviour in the steady state is commonly described in terms of pressure difference, reed displacement, and volume flow [2]. Regarding the effect of the player's actions upon the excitation mechanism, the vocal tract and the tongue-reed interaction have been the focus of some recent studies [3, 4, 5]. The tongue-reed contact may determine the characteristics of the transient phenomena taking place during articulation of tones.

In order to analyse the reed behaviour during transients, Hofmann *et al*. developed a measurement setup based on the deformation of a strain gauge attached to the reed surface inside the mouthpiece [6]. This strain measurement varies according to the reed bending, leading to qualitative knowledge about the reed motion and its contact with the tongue, which was used to analyse playing techniques [4, 7]. The next step was to determine whether this setup could provide quantitative information regarding the reed-tip opening, a magnitude unavailable to previous physics-based analysis attempts [8, 9, 10]. To correlate strain-gauge signals to reed-tip displacement, static and dynamic tests have been previously performed [6, 11]. The static measurement tested two different lip configurations, whereas the dynamic measurement tested different vibrating frequencies. Both studies showed evidence of a linear relationship between the magnitudes and pointed out the need to corroborate this relationship under more realistic blowing conditions.

This study analyses the use of strain-gauge technology to obtain a calibrated measurement of the reed-tip opening during playing. A uniform displacement across the reed tip is assumed, as the reed is considered to vibrate as a clamped bar that operates below its first resonance frequency, hence the appearance of higher modes is avoided (as verified in [12]). The reed is excited under pressure-controlled artificial blowing conditions and it is simultaneously measured by the strain gauge and tracked by a high-speed camera (HS-camera). These two measurements are compared to establish the strain signal calibration (*i.e*. to transform strain measurements into reed-tip opening). Such a method would allow measurements of the reed-tip displacement in real playing conditions, where the reed vibration takes place inside the musician's mouth, hence no direct visual feedback is available.

2. EQUIPMENT AND METHODS

An artificial blowing setup is used to obtain single-reed vibrations in an artificial mouth (transparent plexiglass, 170 cm^3) allowing independent control of the blowing pressure and the lip force. The pressure in the artificial mouth is controlled by a proportional valve (PVQ33-5G-23 by SMC) in a feedback loop. The artificial lip is made out of soft rubber and its position and force can be adjusted. The experiments are performed on a synthetic clarinet reed (German cut, strength 3, by Légère) fixed on a Bb-clarinet German mouthpiece (W4 by Wurlitzer). The mouthpiece is coupled to a copper cylinder (length: 55 cm, diameter: 18 mm) representing the clarinet bore. The bending measurement is achieved by a strain gauge attached to the reed [6], and the reed motion is optically captured via a high-speed area-scan camera (V12.1 by Phantom). The strain-gauge signal, the blowing pressure, and the lip force are simultaneously recorded at 50 kHz using an acquisition platform (LabView by National Instruments). The camera images are recorded at 20000 frames per second (Camera Control Software by Phantom).

2.1. Strain-gauge reed setup

A strain-gauge sensor (length: 2 mm) is attached on the surface of a synthetic single-reed, inside the mouthpiece. This sensor gives a voltage related to the differences in compressive stress on the reed surface due to changes in the reed bending while it is vibrating. The sensor is placed between the lip position and the reed tip. In this study the sensor is at 11 mm from the reed tip whereas the artificial lip touches the reed at around 14 mm from the reed tip.

2.2. High-speed camera image processing

A high-speed camera recording followed by digital image processing allows to analyse the vibrations of musical instruments. In this study, the reed and the mouthpiece are placed between a light source and the HS-camera, as schematised in Fig. 1. By doing so, a sharp contrast between the white background and the object –necessary for the image processing– is guaranteed. Magnification and fine focusing are required to assure the detection of single-reed vibrations, which are of the order of one millimetre, hence an optical lens and tube (length: 10 cm) are used. The conversion from pixels to millimetres is obtained by recording a 1-mm grid as a reference. In this study, the image resolution is 63 pixels per mm. The reed motion is then obtained using the following image-processing method.

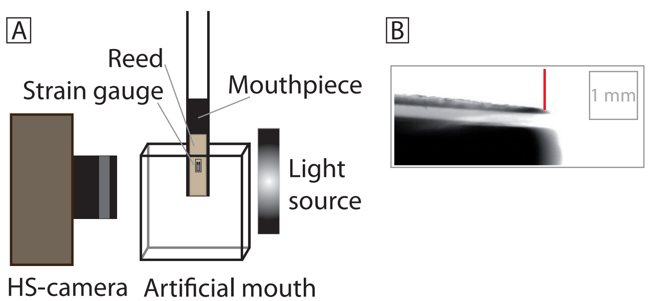

Figure 1. A: Scheme, seen from the top, of the high-speed recording setup. B: One of the recorded images. The red line indicates the vertical line tracked in the image processing.

We aim at measuring the reed-tip opening, *i.e.* the distance between the mouthpiece and the reed tip. The visualisation of the inner surface of the reed in the recorded images is more likely to be affected by shadows than the outer one. Considering that the reed material does not compress in the direction of the tip motion, the vibration can be measured by tracking the vertical motion of the outer side of the reed tip (red line in Fig. 1). An image processing approach has been designed in MATLAB (MathWorks Inc.) to automatically extract the reed tip motion from the recordings, in which the upper limit of the reed tip is detected according to a colour-threshold that discerns the dark objects from the white background. Afterwards, a quantitative measurement of the reed-tip opening is obtained by setting it to zero at the instant of the tip closure.

The setup has been checked to remain constant between image samples. First, the relative position between the camera and the reed-mouthpiece system does not vary, hence there is no need to consider the mouthpiece position. Rotation of the reed-mouthpiece system with respect to the camera view has been proven not to affect the output for angles up to 10°. Finally, the possible error introduced by changes in the shadow boundary during vibration does not present a significant impact on the recorded signals.

2.3. Experimental design

The measurements shown in this paper are performed with a strain-gauge equipped reed clamped to a mouthpiece. The reed-mouthpiece system is excited by controlling the blowing pressure and the lip force in the artificial mouth. The position of both the artificial lip and the reed is kept constant relative to the position of the mouthpiece along the experiment. The variables of the experiment are the blowing pressure and the lip force. For every blowing pressure setting, the lip force (and hence the equilibrium opening) is adjusted so as to obtain oscillations at the fundamental frequency (148 Hz). Four measurements are performed, where the blowing pressure ranges from 4.5 kPa to 7 kPa, and the lip force ranges from 0.5 N to 10 N, as shown in the legend of Fig. 2. An additional strain-gauge measurement is performed under real playing conditions with the same mouthpiece, reed, and cylinder.

3. RESULTS

This section presents a comparison between reed-surface strain and reed-tip opening signals and proposes a strain to tip-opening calibration procedure.

3.1. The linear correlation

Previous studies showed a linear trend between strain signals and reed-tip displacement in both static and dynamic regimes [6, 11]. We aim at validating such a linear correlation by comparing the strain signal to the reed-tip opening obtained from high-speed images in realistic artificial blowing conditions.

Figure 2A shows the original strain $\varepsilon(t)$ and reed-tip opening $h(t)$ signals for one measurement (blowing pressure: 6 kPa, lip force: 1.2 N, label number 3). The strain values are mirrored across the x-axis, so that bigger strain values correspond to reed opening and smaller to reed closing. The two signals are capable of describing the reed-tip motion, which has a closed phase ($h = 0$ mm) and an open phase. These signals are qualitatively comparable to a real playing signal (Fig. 3 bottom; obtained with the same reed and mouthpiece). Then, Fig. 2B plots the tip opening vs. strain for four measurements differing in blowing pressure and lip force. For all measurements, the previously observed linear relationship between strain and reed-tip displacement is confirmed.

A least-squares fit is then formulated as $h = a \cdot \varepsilon + b$, where the parameters a and b express an amplitude factor and an offset factor respectively (straight lines in Fig. 2B). The four linear fits in Fig. 2B present the same slope but a different strain offset, due to the effect of the lip force on the equilibrium position of the reed, and thus on the static bending of the reed. The linear relationship can be corroborated by considering the overlapped signals in Fig. 2C, corresponding to the reed-tip opening obtained from the camera signal and the strain signal after using the linear fit. The fitted signal (blue) accurately describes the reed-tip motion during the whole period. This result suggests that the a and b parameters obtained by performing one reference measurement can then be used to

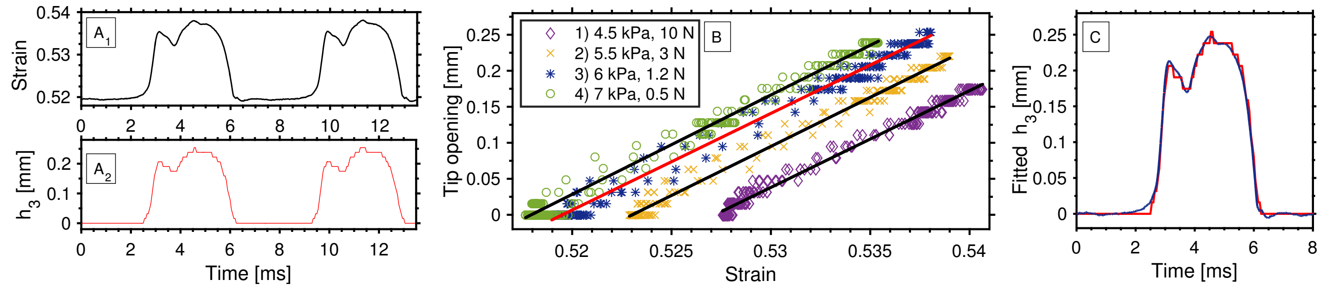

Figure 2. A: Original strain (ε) and its corresponding reed-tip opening (h_3) seen by the HS-camera for the measurement at 6 kPa and 1.2 N (label number 3). B: Reed-tip opening vs. reed strain at different pressures (kPa) and lip forces (N) and their linear fitting model; model 3 (red) is taken as the reference for the calibrated signals in Fig. 3. C: Reed-tip opening from the camera (red) over the fitted strain signal (blue) for measurement number 3.

calibrate other strain signals recorded by the same strain-gauge sensor-reed, as is next analysed.

3.2. The calibration procedure

Using the described setup, the strain at the reed surface and the reed-tip opening have been simultaneously recorded for calibration purposes. The calibration process is realised in four steps: synchronisation of the two signals, extraction of the a and b calibration parameters using a reference signal (a_3 and b_3 for measurement number 3, chosen as the one with the largest displacement amplitude), fitting the desired strain signals (measurements i = 1, 2, 4) by applying the linear fit with the reference parameters $h_i(t) = a_3 \cdot \varepsilon_i(t) + b_3$, and adjustment of the reed-tip opening offset, to attain the minimal opening at $h = 0$ mm.

The plots at the left of Fig. 3 show the three reed-tip opening signals $h_i(t)$ obtained after applying the reference fitting model, plotted over the tip opening seen by the HS-camera. As expected from the constant slope and the varying offset in Fig. 2B, at this stage of the calibration process we obtain an accurate relative displacement but not an absolute one, that is why the offset needs to be adjusted so as to obtain $h = 0$ mm at the position of the reed tip touching the mouthpiece.

The offset adjustment requires a measurement of the strain at the reed closure. When the reed tip closes against the mouthpiece at every period, beating occurs. In this case, the recorded strain signal can be used to determine the reed-tip closure. Hence, for the present study, the reed closure is determined at the instant of minimal strain (*e.g.* for h_1 in Fig. 3 this offset is equal to 0.109 mm). Then, by subtracting this value from the fitted signals, the calibrated signals result in a satisfactory matching to the camera signals, as it is shown at the right of Fig. 3.

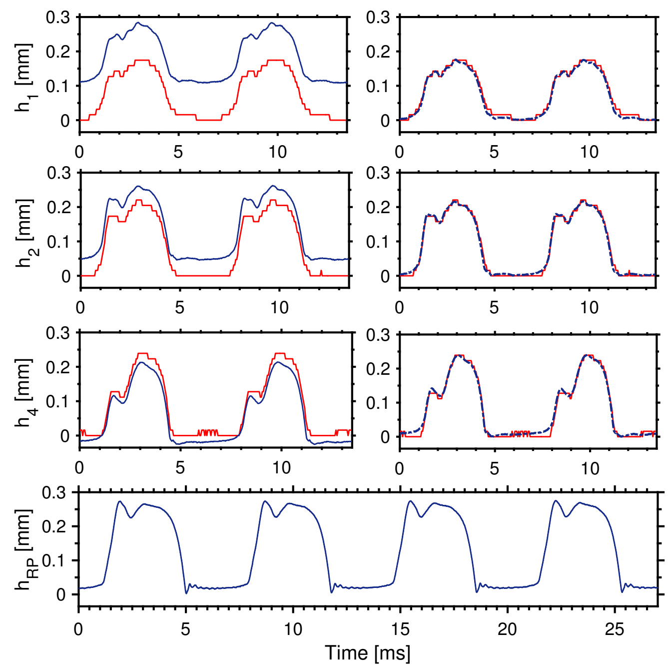

Figure 3. Reed-tip openings obtained after fitting the strain signals (blue) and their corresponding HS-camera signal (red), for measurements 1, 2 and 4, using the fitting model 3 as a reference. At the right, the calibrated signals (blue) are obtained after adjusting the reed-mouthpiece closure ($h = 0$ mm). At the bottom, a calibrated real-playing strain signal, which cannot be compared with a camera signal.

4. DISCUSSION

This paper analyses the use of strain-gauge technology to measure the reed motion and its capacity to provide a calibrated measurement of the reed-tip opening during playing. The use of an artificial blowing setup allows to excite the reed and to perform a high-speed recording of the tip opening. This setup is used to compare the strain at the reed surface with the reed-tip opening, showing a linear relationship between the two magnitudes.

The experimental setup has been improved with respect to [6, 11] by exciting the reed in an artificial mouth and recording its motion using a HS-camera. The artificial blowing conditions allow to reproduce the role of the player's lower lip, which controls the reed equilibrium position, its vibrating length and the amount of damping applied to the reed [1], and to control the pressure in the artificial mouth. By comparing the real playing signal (bottom of Fig. 3) to the artificially obtained signals, it can be deduced that the artificial blowing machine generates reed oscillations that are qualitatively equivalent to those obtained under real playing conditions and may hence be used to analyse the presented sensing technique.

The experimental design consisting of simultaneously measuring the reed strain and tip opening via a HS-camera results in a satisfactory comparison framework. Although the tip-opening signal obtained from the HS-camera images presents a significant level of quantisation, this quantised signal is only used for calibration and comparison, but will not be used as a measurement tool once the strain gauges are calibrated.

Different blowing pressures and lip forces are tested for one lip position and one tone. The obtained linear fits present the same slope (parameter a) but differ in strain offset, as the reed is preconstrained by the presence of the lip. This is the main drawback of such a setup, implying the need of using the instant of reed closure as a reference strain value. A similar consideration was also pointed out for the optical measurements proposed in [13]. Nevertheless, a minimum in the strain signal might not correspond to the reed closure for different playing configurations. For a real-playing calibrated signal (Fig. 3 bottom) it has been observed that when the reed closes against the mouthpiece (*e.g.* at $t = 5$ ms), the body of the reed experiences a damped vibration at low amplitude. Furthermore, it cannot be guaranteed that the reed will always beat against the mouthpiece lay. Therefore, in the absence of a HS-camera, a complimentary measurement of the reed closure is needed, which can be another instant where beating is forced to occur under the same configuration of the reed-mouthpiece-lip system.

After adjustment of the fitted-strain offset, the calibration procedure results in a satisfactory extraction of the reed-tip opening from the strain signals within the range of this experiment. Future experiments may include an extension of the calibration procedure to the overblown register as well as to transient phenomena. The aim is to calibrate signals in real playing conditions using a reference signal obtained in artificial blowing conditions. Therefore, the fact that under real playing conditions the lip force may vary should also be taken into account. Furthermore, a more accurate determination of the reed closure in both real and artificially obtained signals would allow to better readjust the offset of the fitted signals.

Single reeds equipped with a strain-gauge sensor may be used for obtaining the reed-tip displacement under real playing conditions. As already shown in [7, 12], mounting such strain-gauge sensors on single reeds does not disrupt the performance of woodwind players. This information about the reed displacement is of paramount importance for physics-based synthesis/analysis applications regarding the characterisation of the excitation mechanism in woodwind instruments.

5. ACKNOWLEDGEMENTS

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