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Design of a mechanical player system for fatigue-life evaluation of woodwind reeds

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Abstract

Research into synthetic replacements for woodwind reeds requires the consideration of several factors. To-date, comparisons between synthetic and natural cane reeds have mostly been limited to evaluations of their initial properties in an "unplayed" state. One important mechanical aspect of reed-life and durability is fatigue behaviour. Fatigue is primarily concerned with the degradation of mechanical stiffness over the lifespan of a reed and is important for understanding changing vibrational behaviour, for comparing differences between cane and synthetic materials, and for evaluating the return on investment for (relatively) expensive synthetic reeds. In this work an artificial player system is developed as the initial phase of a study to evaluate the long-term mechanical behaviour of cane and synthetic alto saxophone reeds. The artificial player will be used to "play" reeds on the system with control over playing time, input pressure and playing frequency. Using this setup, reeds can then be compared via several control parameters, including stiffness, mouthpiece pressure and mouthpiece spectral components during the course of the fatigue study, thus evaluating mechanical degradation rates between cane and synthetic reeds. Results will aid in understanding the importance of playing time and frequency on reed lifespan, fatigue-life differences between cane and synthetic reeds and the average return on investment (ROI) for synthetic reeds.

Keywords: Fatigue, reeds, artificial player

1 INTRODUCTION

Alternative materials to traditional Arundo donax L (cane) used for woodwind reeds are of interest for their reduced variability, reduced sensitivity to environmental conditions and their improved durability. The use of these alternative reeds is also of interest to those studying the performance of woodwind instruments for many of the same advantages mentioned above. For the musician (i.e., the consumer), a more unclear aspect of alternative reeds is the return on investment in terms of durability. Polymeric, composite and other alternative reeds all share a commonality with regards to monetary cost; they are all more expensive than their cane counterpart. Some companies sell their alternative reeds for several hundred dollars and thus it is important for the musician to understand the tangible benefits to such an investment in terms of reed longevity. Previous testing on the degradation of cane reeds has been limited to the isolated effects of moisture cycling [1], some of the chemical changes that occur in played reeds [2] and general measures of radiated sound spectra from a number of synthetic and cane reeds over a five day playing test [3]. The motivation for the present study concerns reed fatigue and the effects of playing on a real instrument with well-controlled and repeatable conditions, as reed fatigue-life and pertinent playing parameters is not well understood. For manufacturers, the degradation of mechanical stiffness and corresponding changes in radiated sound spectra are of particular interest.

The testing of reed longevity is complicated by several factors, including the need for a constant air supply, control over the input 'mouth' pressure, control over an applied lip force and the ability to reliably measure experimental parameters such as reed tip displacement and radiated sound pressure. This manuscript presents findings from an ongoing study investigating alto saxophone reed longevity in terms of fatigue life. Presently, the primary focus is on the experimental testing apparatus (artificial player) including the design of a well-controlled lip force system and an artificial 'mouthbox' through which an air supply system is coupled to a

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saxophone. Consideration is given to the types of measurements that need to be made for defining the fatigue life of alternative and cane reeds and to system modularity of the artificial player for use with other instruments and experimental tests.

2 EXPERIMENTAL DESIGN

This section provides an overview of the artificial player system design process, manufactured components and system calibrations that were required prior to the testing of reeds. Some details of the mouthbox design are provided to illustrate the design process of such a component when reed fatigue was the primary investigative objective.

2.1 Overall design

The artificial player system developed for fatigue testing here consists of a piston pump (air supply rated at 200 Watts, 13500 LPH flowrate, 47.9 kPa (6.96 psi) maximum gauge pressure), a pressure accumulator (pressure vessel), pressure regulator (manual pressure control), mouthbox assembly (artificial mouth and lip and mouthpiece coupling component) and finally the instrument (alto saxophone). These components are given in order of their placement in the artificial player air supply loop. Details of the mouthbox assembly components are provided in subsequent sections.

2.2 Mouthbox design

It was necessary to outline the main design requirements of the mouthbox component to ensure that investigative objectives (fatigue and aeroacoustic testing) would be fulfilled. The positioning of the mouthpiece in the mouthbox was important in order to provide sufficient space to obtain measures of reed fatigue at the reed tip. The overall volume of the mouthbox was designed with previous measures (between 27.14 and 45.79 cm^3) of average vocal tract volume in mind [4, 5]. This volume ($\approx$30 cm^3) needed to be increased approximately 15% to facilitate a modular mouthpiece coupling device. This device and the overall mouthbox design are shown in Figure 1. An overview of the experimental setup is provided in Figure 2 depicting the entire system in an acoustically isolated listening booth.

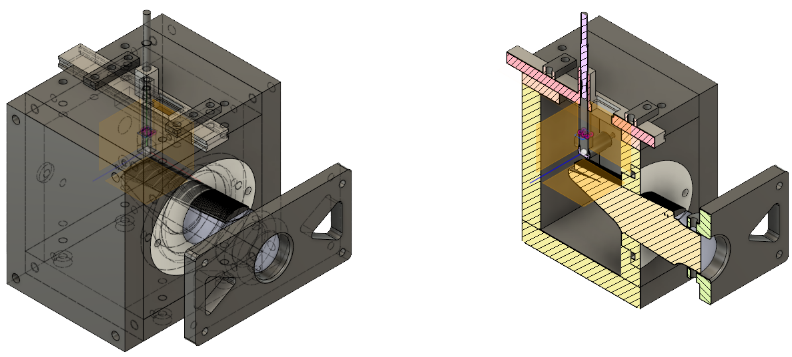


Figure 1. Left: Mouthbox assembly including the mouthpiece, mouthpiece retainer, lip-bar, lip positioning slider and mouthpiece coupling adaptor. Right: The mouthpiece assembly viewed as a cross-section depicting the internal orientation of the lip positioning relative to the mouthpiece.

The mouthpiece coupling adaptor provides flexibility for use of the mouthbox with soprano, alto and tenor saxophones. This modular component also provides sufficient space for the attachment of mouthpiece pressure

Figure 2. The artificial player system setup as will be used for reed fatigue testing in an isolated booth. All major components of the system can be viewed here, apart from the air supply pump that is to the left of the pressure vessel.

transducers and a hotwire probe for mouthpiece baffle flow measurements.

The artificial lip, here termed the “lip-bar", is oriented vertically with respect to the mouthbox and applies a compressive force on the reed. In this configuration, the mouthpiece is attached to the instrument rotated 180° relative to a normal playing condition to expose the reed tip for fatigue related measurements. The lip-bar was designed to allow for manual manipulation of applied lip force in this vertical direction and for control over the horizontal positioning with respect to the mouthpiece (i.e., to modify the vibrating reed tip length). A $\approx$5mm thick ethylene propylene diene monomer (EPDM) rubber material covers the lip-bar to act as a lip replacement material. Although other materials have been used such as synthetic polyester and polyurethane foam [6, 7], for a fatigue testing scenario, it is important to minimize the effects of creep and stress-relaxation in the lip material. Stress-relaxation in the lip would result in a reduction in applied lip force with time, changing the initial conditions of the experiment. To ensure that fatigue parameters are only reed dependent, EPDM rubber was used as it does not creep significantly with time (i.e., time independent elastic response).

The sliding component of the lip-bar also contains a small plexiglass window positioned directly above the reed tip. This window allows for laser doppler vibrometer (LDV) measurements to be taken while the system is in operation to quantify reed tip displacement. The LDV measures point velocity directly and thus a calibration was required to extract displacement data from the measured signal. Details of this calibration are given in a subsequent section (3).

Previous artificial mouth setups have included a similar artificial lip setup [8] or shaker-style systems linked to the lip [7, 6] in order to investigate the effects of tonguing articulation on several parameters, such as reed displacement, blowing pressure and radiated pressure. The mouthbox design presented above considered aspects of these previous works during iterative design and development, including a controllable lip force component [6], the consideration of lip materials and measurement instruments for reed displacement (i.e, strain gauges) [7]. As fatigue is the primary experimental interest of the present study, this had a significant influence on mouthbox design choices due to a number of complications that would be less critical to previous studies. These complications include air supply temperature fluctuations due to the long-term nature of fatigue experiments and artificial reed bending stiffness changes due to strain gauge placement. Air supply cooling was addressed via pump cooling using passive (heat sinks) and active (forced air) methods. Additional cooling was provided through passive heat dissipation methods in the pressure accumulator component of the supply loop. Strain gauges were not used directly on the reed tip to prevent the gauge and affixing epoxy from influencing long-term stiffness degradation. Another complication of the length of fatigue experiments is the need for humidified air in the case of cane reed testing. An ultrasonic humidification unit could not be added to the air supply stream as back-pressure would prevent the humidified air from mixing with the pressurized supply. Pump longevity concerns prevented the addition of humidified air to the intake side of non-pressurized ambient air. It was therefore decided to use saturated salt solutions (i.e., high purity potassium sulphate) providing passive levels of elevated relative humidity (≈97% between 28 and 38 °C) for the testing of cane reeds [9]. The design of a system to couple this solution to the mouthbox is still in development.

2.3 Fatigue and control parameters

In order to properly compare the fatigue life of alternative and cane reeds it is necessary to calibrate several systems of input parameters such that the initial conditions of each test are the same. This is required to ensure that comparisons between reeds are made using a fair test. Fatigue testing in an engineering sense typically considers the amplitude and rate (frequency) of a cyclic applied stress, and it is important to use this definition as guidance for measuring control parameters [10]. Reeds are mounted on the mouthpiece such that dynamic bending is the primary deformation regime, and in terms of cyclic applied stress reed tip displacement can be used as the stress amplitude component of fatigue life. In order to make fatigue tests comparable between reeds, the present study was designed such that the amplitude of initial reed tip displacement (in bending) was to be used as a control parameter. This displacement can be significant [11] with bending modes generating displacement amplitudes between 150-200% of reed tip thickness. Equal tip displacement is also dependent on the horizontal positioning of the lip mechanism as this controls the effective length of the unsupported vibrating beam (the last ≈5 mm of the reed tip) and this is recorded for each test. It was also desirable to note and record the applied lip force as this parameter required tuning in order to achieve steady-state conditions with the player system, including notes of different frequency and reeds of different strength. Mouthbox and mouthpiece pressure signals were also recorded using two Endevco miniature pressure transducers (mouthbox: 8510B-1 and mouthpiece: 8507C-1) and an Endevco Model 136 DC amplifier.

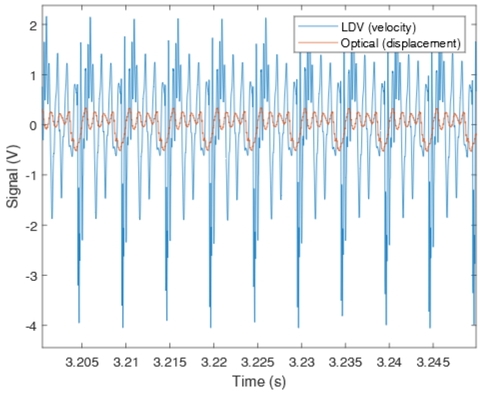
3 MEASUREMENTS AND CALIBRATIONS

Several mouthbox assembly components required calibration before any real fatigue measurements could be made. This section presents a number of these calibrations with respect to the corresponding mouthbox components.

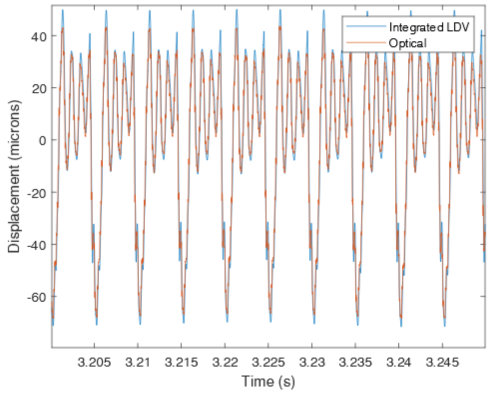
3.1 LDV reed displacement

A required parameter of reed fatigue characterization is the proper measurements of reed tip displacement. Although a confocal displacement sensor is present in the lab, it cannot fit inside the mouth box. Thus, an LDV was chosen, as its beam can be projected through a plexiglass plate. The LDV was calibrated for displacement measurements for two reasons mentioned here. The LDV exhibits a larger focused “spot" size than the optical sensor reducing its sensitivity to noise. Also, the working distance of the focused beam is substantially larger than the optical sensor and thus it was more suited to mouthbox measurements. LDV measurements were recorded using a Polytec PDV-100 instrument and recorded using a National Instruments USB-4431 signal acquisition board (recorded in MATLAB). For calibration purposes, both velocity and displacement signals were measured simultaneously on a vibrating alto saxophone reed (Légère signature series, 3.25-strength). The displacement signal was measured using a STIL Chromatic Confocal Sensor for non-contact measurements at a sampling rate of 10 kHz. Clamped reed excitation was achieved using a B&K Type 5961 handheld exciter (and stinger) attached to an Agilent 33220A function generator to maintain control over excitation frequency. Measurements of both velocity and displacement were made on opposite sides of the reed and focused ≈5 mm from the tip. A sheet of 4.76 mm (3/16 inch) plexiglass was placed between the incident LDV beam and the reed to simulate the conditions of the mouthbox configuration. Figure 3 presents a sample time-domain signal comparing LDV and optical displacement results.

Overall the integrated LDV signal corresponds well to the independently measured displacement signal.



(a) Velocity and displacement signals.



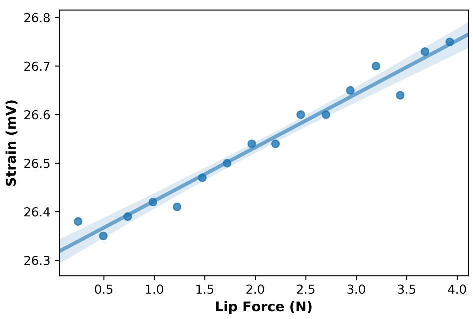
(b) Integrated LDV signal with reed displacement in microns.

Figure 3. Comparison of integrated LDV reed displacement results with those obtained via the optical sensor Note that data was acquired with a reed excitation frequency of 200 Hz and a peak-to-peak amplitude of 5V.

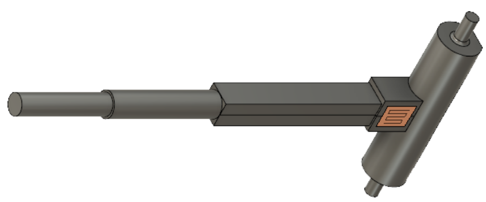
Comparisons between LDV measures with and without the plexiglass plate indicate that the plate does not introduce significant noise related errors to the signal. The LDV signal was conditioned using a lowpass filter with a cutoff within 10% of the reed excitation frequency. The integrated LDV signal was then mapped to known displacement values (in microns, µm) from the optical displacement sensor whereby future measurements using the mouthbox assembly could be made using only the LDV.

3.2 Lip-bar strain gauge calibration

The lip-bar was calibrated using a compression testing configuration by mounting the bar on the mouthbox sliding mechanism and clamping it to a rigid testing fixture (a large steel drill press table). The testing fixture was assumed to exhibit compliance several orders of magnitude lower than the 3D-printed lip-bar and therefore compressive strain during testing originated only in the lip-bar (with no error due to fixture compliance). The measurements were performed over a range of 0 to 3.5 N, similar to previous studies considering applied lip force versus playing frequency [6]. The configuration of the lip-bar and the corresponding calibration data is provided in Figure 4.



(a) Strain gauge output voltage in response to increasing compressive (vertical) load.



(b) Lip-bar with attached strain gauge.

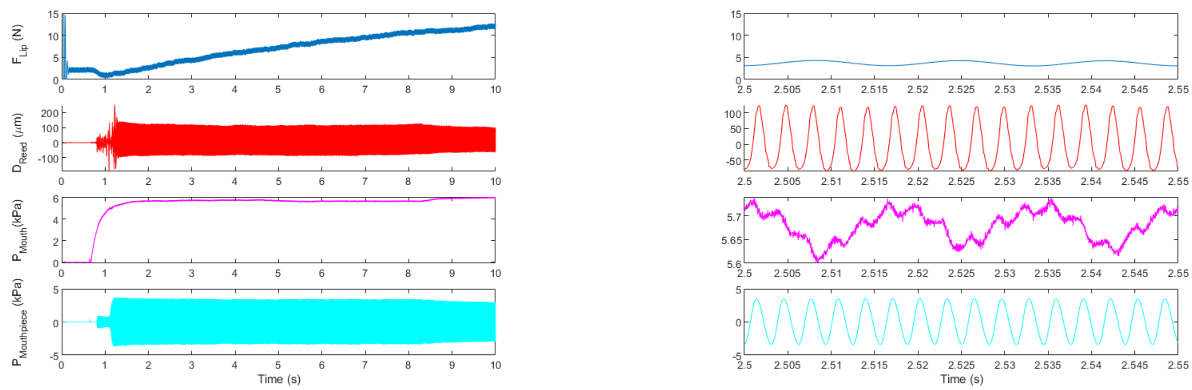
Figure 4. Overview of the lip-bar and strain gauge calibration results for lip-force with 95% confidence shown.

3.3 Piston-pump pressure pulsation

A piston pump supplies air to the artificial player system and offers a number of advantages over compressed air and blower systems, primarily reduced operational noise, improved pressure head (back-pressure tolerance), airstream temperature uniformity and ease of operation. There is a noted pulsing in the air supply stream generated by the pump due to a 60 Hz pump-rate. These pulses were minimized through the use of the pressure accumulator that produces a volume of air at a static pressure and mitigates the influence of dynamic pressure components to the output. Mouthbox pressure measurements taken with and without the included pressure accumulator confirm this.

3.4 Sample measurements: Pressure, force and displacement

Initial measurements taken on the artificial player system are shown in Figure 5 for an alto saxophone played at ≈330 Hz (alto C#$_5$, concert E). For the Légère reed (strength 3.25) and lip material used, initial reed vibration begins at an input blowing pressure of approximately 2 kPa, although only 'squeaking' is produced at this level.



(a) Sample measurement of the four control parameters including the initiation of playing on the artificial player system.

(b) The same four control parameter measurements depicting reed displacment over a 50 ms duration.

Figure 5. An example of initial measurements taken using the artificial player system. These four signals represent the control parameters of interest for fatigue testing.

As blowing pressure increases above 5 kPa, reed oscillations reach a steady-state regime with a peak-to-peak displacement amplitude of 200 µm (a similar amplitude to that measured for a clarinet [11]) and an initial applied lip force of 2 N (compressive). In terms of reed fatigue, displacement amplitudes measured here represent ≈66% of the reed-tip thickness when a symmetrical strain amplitude configuration is considered (i.e., positive and negative direction). Through the cross-section of the tip, reed fatigue contains both compressive and tensile loading senses distributed perpendicularly to the neutral axis of the reed (for this setup considered a cantilever beam). For each cycle of reed vibration at the playing frequency these compressive and tensile strains at the outer tip surfaces represent the maximum and minimum strain amplitudes in a typical fatigue regime. For further long-term tests on reed fatigue life, the displacement amplitude of reed vibration (peak-to-peak) will define the maximum and minimum strain values, and the playing frequency the cyclic loading rate.

4 DISCUSSION

The current state of an artificial player system for the investigation of reed fatigue has been outlined above. The system design is modular and can be used with various sizes of saxophone or clarinet mouthpieces. Though primarily designed for fatigue studies, it can also be used for mouthpiece flow measurements. Many of the constraints that influenced the final mouthbox design were outlined in the context of fatigue experimentation. Calibration of fatigue control parameters was presented and included the use of LDV measurements for reed displacement and strain gauge voltage for applied lip-force.

Some initial fatigue-life control parameter measurements on the artificial player system (Légère signature alto reed, strength 3.25) have been presented in terms of changing mouthbox and mouthpiece pressure, lip-force and reed displacement. It was found that applied lip force increases with a decaying rate during initial playing measurements and this may be the result of viscoelastic effects in the reed-lip assembly and/or thermal drift in the strain gauge. The lip-bar and reed may exhibit a slowly increasing stiffness response with exposure to cyclic strain during an initial phase (during the first few minutes of playing) where viscous forces are not given sufficient time for relaxation, resulting in a temporarily increased effective stiffness. The time frame over which this process occurs will be investigated as the artificial player system is developed further as the influence of this effect on reed-tip displacement is important for quantifying fatigue-life.

There are a number of challenges associated with the evaluation of cane reeds that must be addressed before fair fatigue-life comparisons can be made to alternative reeds. Primarily, the injection of humidified air into the artificial player system requires careful consideration of pressure, air temperature and humidification source. The pressurized air delivered by the pump must be kept at constant temperature over the duration of the fatigue experiment (between 4 and 24 hours) such that fluctuations in temperature are minimized. Otherwise, measured pressure results may be difficult to compare between samples, and humidity levels may drift as the moisture capacity of air changes.

5 ONGOING AND FUTURE WORK

The design of an artificial player system for the fatigue testing of alternate (synthetic) and cane reeds has been considered in the context of control parameter measurements, measurement techniques, calibrations and initial system measurements. Some of the practical problems associated with fatigue experiments lasting over 12 hours have been discussed including air supply temperature, air supply humidity (for cane reeds) and lip-bar (and material) viscoelastic and creep effects. Continuing work on this project will include the design of a humidity chamber for attachment to the mouthbox assembly such that elevated levels of relative humidity (˜98%) could be maintained for the testing of cane reeds in a moist state. Complete simulation of playing conditions for cane reeds is challenging as the reed-tip is nearly saturated during playing, however very high values of relative humidity have been shown to swell and saturate the pores of natural Arundo donax L material [12] providing similar moisture conditions to playing. The results of fatigue testing will include the comparison of synthetic and cane reed performance using the control parameters mentioned (tip displacement, input blowing pressure, mouthpiece pressure) and a number of other measurements that manufacturers are interested in (namely radiated sound pressure level and spectral components). These results will be used to evaluate the ROI of synthetic reeds, average reed lifespan for a given playing frequency, decay rates of reed stiffness and changes in timbre more generally (via saxophone radiated sound measurements).

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