ISMRA 2016
INTERNATIONAL SYMPOSIUM on MUSICAL and ROOM ACOUSTICS
September 11-13, 2016
La Plata, Buenos Aires, Argentina

Physics of musical instruments and voice:
Paper ISMRA2016-85

Non-stationary tones in reed instruments: A sequence of stationary states?

André Almeida[a,b]

[a] UNSW, Australia, a.almeida@unsw.edu.au
[b] Université du Maine, France

Abstract

Self-sustained instruments, such as the reed family, are capable of producing sustained, periodic notes, as the energy is provided throughout the entire life of the note. If it is too stable, however, the note will sound mechanical and uninteresting. During the course of an isolated note or a musical phrase, an oboist adjusts the blowing pressure, lip force and even the mouth cavity configuration to produce a note or a musical phrase envelope that makes the timbre, loudness and pitch evolve during this note or phrase. Moreover, he or she might use an intended faster and regular fluctuation in some notes that is usually called vibrato, and in some cases tremolo. Achieving this evolution can make the difference between a good and an expert musician. When studying these fluctuations in the time scale of a vibrato or a note, it is interesting to ask whether they can be considered as a continuous succession of the stationary regimes corresponding to instantaneous values of playing parameters (mouth pressure and lip force for instance). By using simulations and real instruments played by an artificial mouth, we investigate this quasi-static hypothesis in carefully controlled and archetypal time-evolutions of these two parameters..

Keywords: reed, vibrato, non-stationary

ISMRA 2016
INTERNATIONAL SYMPOSIUM on MUSICAL and ROOM ACOUSTICS
September 11-13, 2016
La Plata, Buenos Aires, Argentina

Non-stationary tones in reed instruments: A sequence of stationary states?

1 Introduction

Musical tones are most simply thought of as being a periodic sequence of pressure variations. The period of these variations roughly determines the pitch, while the energy contained in the oscillation characterises its loudness and the spectral components present in the oscillations characterise that part of the timbre determined by the sustained note. In real tones, however, the sequence is not strictly periodic, and the basic period of the oscillation can be seen to vary in length (and thus in pitch). The amplitude and spectral characteristics can also vary over a period. Vibrato[1] typically has a frequency of several cycles per second, so these can be typically thought as slow variations when compared to the rate of variation of the pressure, typically hundreds of Hz.

In a self-sustained instrument such as a reed-blown instrument, a single note corresponds to a constant geometry of the resonator. Variations in the characteristics of the oscillation (pitch, amplitude, spectrum) within a note are thus due to variations in the excitation system or to the resonator upstream from it (vocal tract).

From many previous studies [e.g. 1], it is known that different steady excitation parameters such as blowing pressure and lip force produce slight variations in pitch and larger effects in the amplitude and spectral composition of the periodic sound produced by the instrument. It is also known that slow variations in the excitation parameters at the scale of a vibrato produce variations in the sound at a similar time-scale. Mathematically, neglecting changes in the vocal-tract and some localised hysteresis [2]:

$$x = x(P_{mouth}, F_{lip})$$

where x can be frequency or amplitude of any of the harmonic components of the periodic sound.

The aim of the present work is to investigate whether in a vibrato or any other slow variation of exciter parameters the same relation measured in a static regime still holds, so that

---

1 On a violin, vibrato refers to cyclic oscillation in string length produced by rocking a finger of the left hand. This produces primarily a change in pitch. In contrast, tremolo refers to rapid alternation in the direction of bow movement, which produces a regular change in loudness. Hence some musicians reserve vibrato for change in pitch and tremolo for change in loudness. Players of wind instruments use vibrato to mean a regular change produced by change in the control parameters, including mouth pressure, so vibrato for a wind instrument player includes changes in pitch and loudness. This more general meaning of vibrato will be used here.

$$x(t) = x(P_{mouth}(t), F_{lip}(t))$$

Existing studies of vibrato [3] assume that this is the case. Alternatively, any change in this relation could mean that some of the components in the musical instrument have a natural 'inertia' resisting a change in parameters. Studies on reed instruments [4] have analysed the sound characteristics of the vibrato tone without analysing in detail their uniqueness or correspondence to stationary sound characteristics. Hajda [5] suggests that 'timbre', (here meaning the relative variation of harmonic amplitudes) is the most important time-varying characteristic in vibrato. This suggests the relevance of understanding how this variation is produced, physically.

This preliminary study is divided into three parts. First, an algorithm to measure spectra in tones with vibrato is tested using synthesised tones. Second, the sound properties of tones are investigated in a single instrument (an oboe, Yamaha YOB-441), for a single note (the trill fingering for C#5, with no keys engaged). Properties of stationary tones are compared with instantaneous properties of tones with an oscillating parameter (the mouth pressure). Third, a similar situation is investigated in a simulated system with resonator properties (input impedance) matching those of the note studied on the oboe.

2 Analysis protocol

In the following experiments, the recorded, simulated or synthesised tones are analysed using a phase vocoder algorithm developed in numeric Python [6]. Briefly, this divides the signal into frames with an overlap, then calculates their FFT using a window function (Hann). The amplitude of a partial is estimated by square summing the amplitudes of the five bins immediately adjacent to the corresponding peak. The frequencies are calculated by matching the phases of two consecutive frames, with an overlap of half the window size. The frequency values have a precision that is dependent on the window size. Typically the window size should be more than two periods long, so that two separate harmonic components appear as two distinct peaks in one FFT frame. In this article, the frequency of the note studied is, in the tempered scale, 552 Hz, meaning that the window should be more than 4 ms long.

In practice, a window of 1024 samples (20 ms) was used in the recordings (sampling frequency F_s = 51200 Hz) and 8192 in the simulations (16 ms) in the simulations (F_s = 484607 Hz). This typically allows for 10 measurement points in a period of a vibrato of 5 Hz.

More details are given in the last section, where this method is tested using synthesised signals.

2.1 Test signals

Some of the analyses presented in this work may be subject to systematic errors. For instance, frequency is a property that is defined for an infinite signal. However, the phase vocoder is designed to find the sum of sinusoids that can model the signal within a particular pair of frames. This method is obviously subject to possible artefacts when there are rapid variations of the frequency or amplitude of the partials within these two frames.

Instead of providing a systematic benchmark of the analysis method, this subsection presents an example of a signal synthesised from a sum of 15 harmonic partials whose amplitude, frequency and spectral envelope oscillate at a typical vibrato rate (5 Hz). The amplitudes of oscillation of the frequencies and amplitudes of the partials have a magnitude similar to those found in the subsequent sections of this work (Fig. 10). Here, however, they are randomly assigned to each partial in the synthesised sound. The phase of the vibrato oscillation of the amplitudes is also assigned randomly to the different partials (see figure).

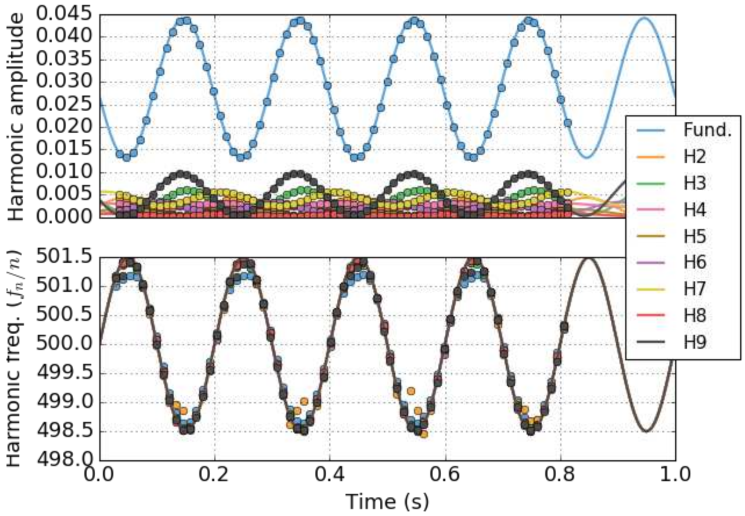

Figure 1 Comparison of amplitudes (top) and harmonic frequencies (bottom, divided by harmonic number) estimated (dots) by the phase vocoder analyses and those of the partials included in the synthesised signal (lines). For clarity, only the first 9 harmonics are shown. The fundamental and 2nd harmonic have the bigger deviations in the figure.

The signals are then analysed with phase vocoder method, in order to check that the modelled partial frequencies and amplitudes match those of the original partials in the sum.

A plot of partial frequencies (Fig. 2) and amplitudes estimated by the vocoder against the original values used in the synthesis show that partials are well estimated for a vibrato frequency of 5 Hz.

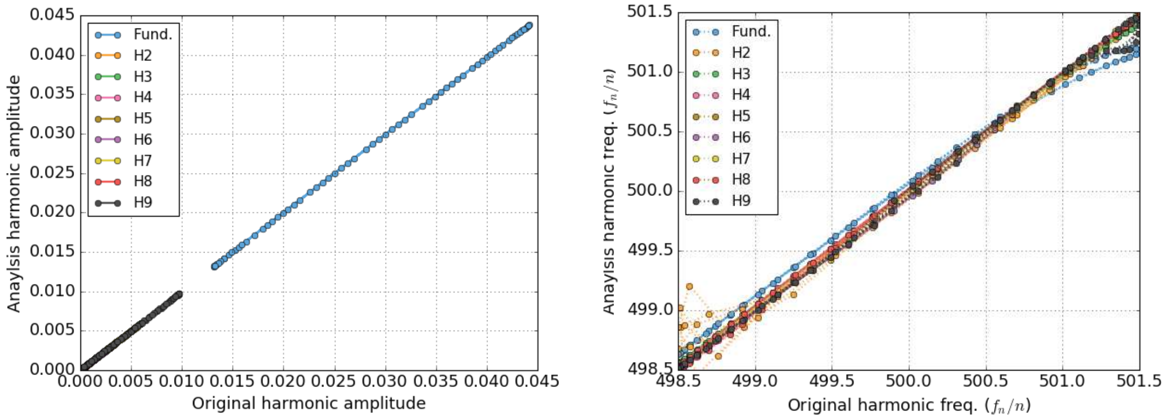

Figure 2 Estimated vs original partial amplitudes and frequencies

3 Artificially blown instrument

This section uses an artificially blown oboe (Yamaha YOB441) with a synthetic reed (Légère, Ontario). Its aim is to compare properties (frequency and amplitude of individual harmonics) of stationary tones at particular values of blowing parameters to instantaneous properties of tones played with blowing parameters varied only very slowly. In the simplest case, the parameter trajectory in the variable case could follow a path through parameters that were studied in the stationary case. In order to study this, the instrument is played in an artificial blowing machine where the blowing pressure and the lip force can be maintained with constant values in the stationary case. In the oscillating (vibrato) situation, the pressure is varied at a controlled frequency and the geometry that applies the lip force is unchanged. Since the lip is adjusted using a screw and lever system, it cannot be assured that this corresponds to a constant lip force. Moreover, the lip force is not measured. However, we assume that any variation in the force when the pressure is changed, should be the same for the stationary and vibrato cases, because the vibrato frequency is much slower than note frequency.

The blowing machine resembles the one used for systematic investigations of sound properties in a clarinet [1] although the lip system is here controlled by a system of screws accessible from the outside. Lips are adjusted independently for the upper and lower halves of the reed in order to produce a satisfactory tone over the maximum range of blowing pressures. In the current apparatus, it is observed that the best tone and largest playing range? is produced by lips located at different positions on the two halves of the reed..

3.1 Protocol

In the first experiment, the lip geometry is held constant, while the pressure is varied through the complete range of pressures for which the instrument plays the intended note. From these recordings, the mappings between the blowing pressure and the playing frequency and amplitude of individual harmonics are shown in Fig 3:

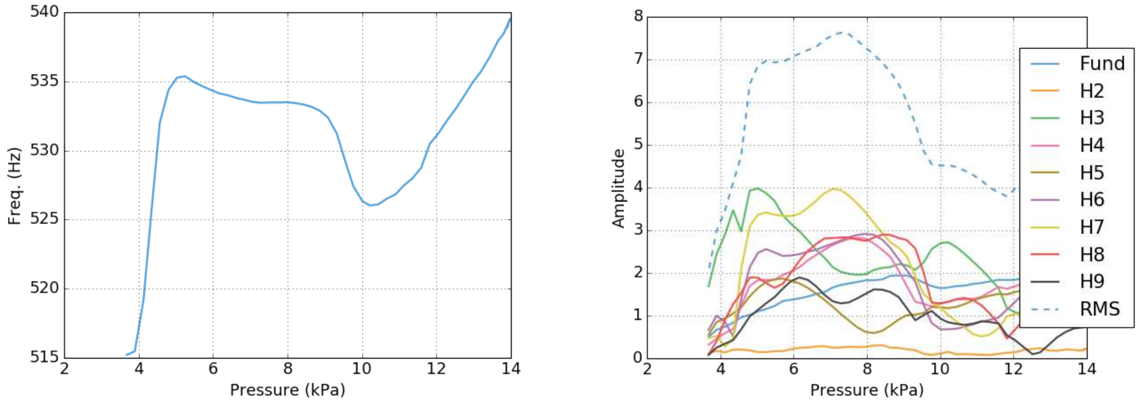

Figure 3 Fundamental frequency (left) and amplitude [Pa] of harmonics (right) plotted against blowing pressure. RMS amplitude is included for comparison. Amplitudes are obtained from signal radiated near the bell of the oboe

In a second experiment, the blowing pressure is set to an average value of 6.5 kPa, and the pressure forced to oscillate around this average value with different amplitudes of oscillation. A sinusoidal signal is applied to the control mechanism, but this does not produce a sinusoidal response in the mouth pressure, as shown in Fig. 4 for 3 different requested amplitudes of oscillation. In this case, the requested amplitudes of oscillation were in the ratio 1:1.75:2.5. The measured pressures, however, are in the ratios 1:1.9:2.5, showing a nonlinearity in the ratio of produced to requested pressure. The harmonic distortion in the real pressure signal is less than 20 dB.

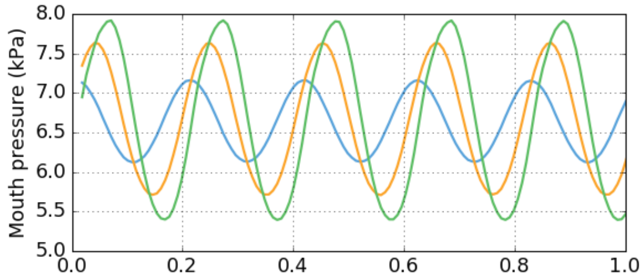

Figure 4 Oscillation of mouth pressure for the 3 vibratos analysed in this section

3.2 Results

Figures 4 and 5 show the variations of “instantaneous” harmonic frequencies and amplitudes for the notes produced with vibrato using the three blowing pressures curves shown in Fig 4. A black line shows the range of frequency values measured in the stationary case (i.e only very slow variation in pressure).

In the stationary case, Fourier components fall at almost exact multiples of the fundamental frequency, so that an averaged value is used. This is not the case during the vibrato and the "harmonic" components have slight systematic deviations from *n* times the fundamental with magnitudes that exceed uncertainties in the measurement. For some of the components (*n* above 2), this deviation seems to suggest a delay between the instantaneous harmonic frequency and the blowing pressure. This will be discussed later. The deviation is bigger for wider vibratos.

Some of the harmonic amplitudes (Fig. 6) also show a delay relative to the blowing pressure but these shifts are smaller than those of the harmonic frequencies.

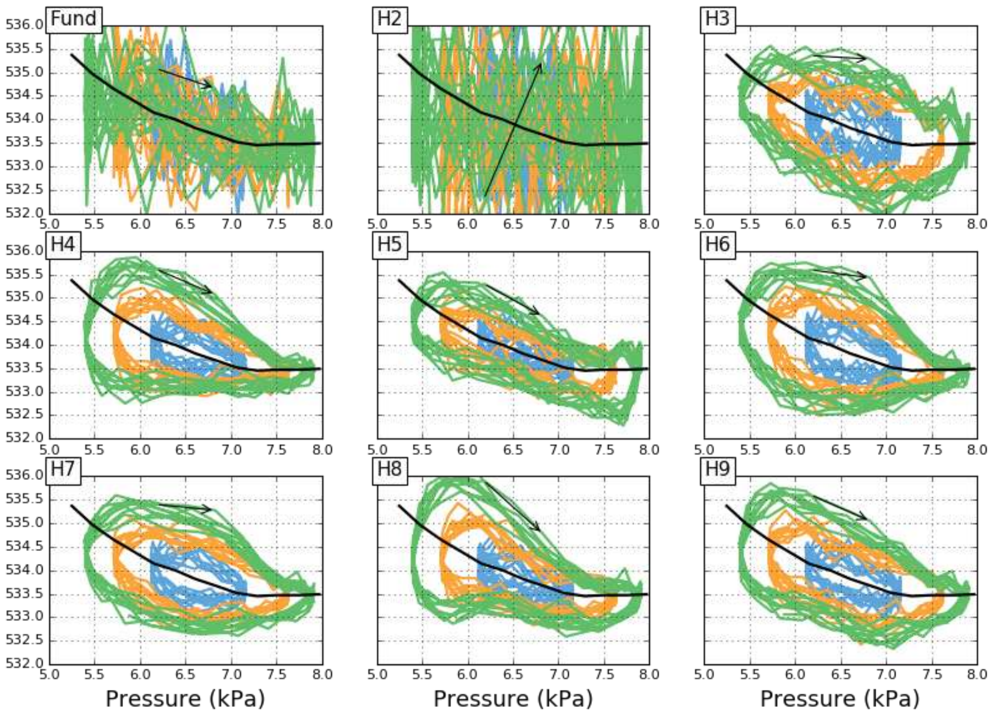

Figure 5 Frequency of partials obtained in the 3 vibrato signals, plotted against the instantaneous mouth pressure. Frequencies of higher partials are divided by the partial number. For comparison, the frequency corresponding to the steady state for the blowing pressure value is shown as a thick black line. The thin black arrow shows the direction of the cycle, by joining two adjacent anaysis points.

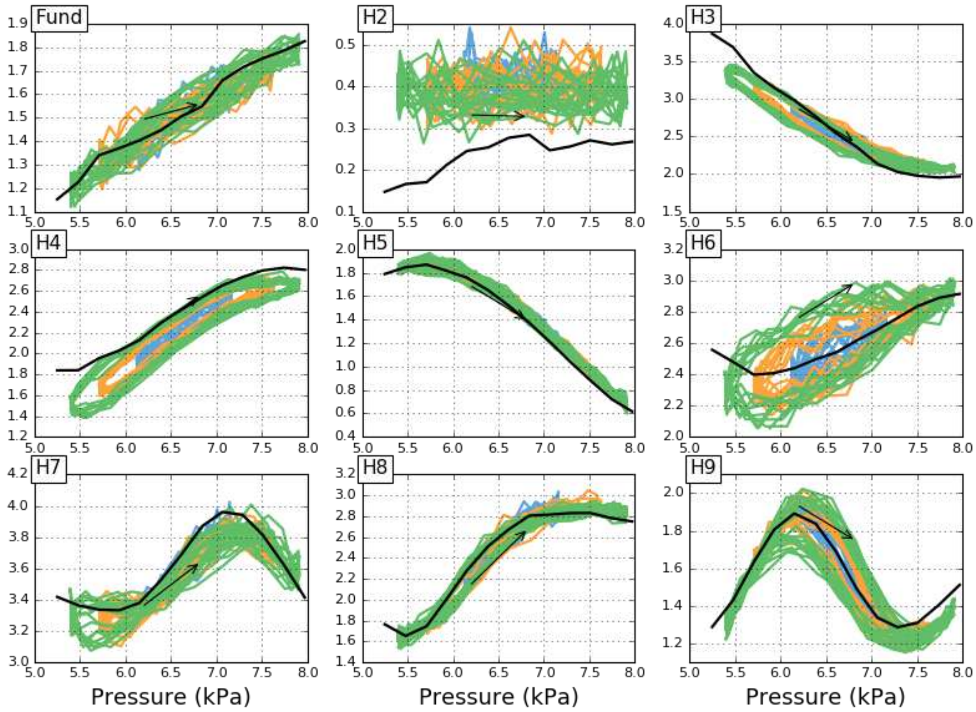

Figure 6 Amplitude in Pa of partials obtained in the 3 vibrato signals, plotted against the instantaneous mouth pressure. For comparison, the amplitude corresponding to the steady state for the blowing pressure value is shown as a thick black line. The plotting range in the amplitude axis is adjusted for each partial. Notice that the 2nd partial exhibits a much smaller range than the others.

4 Simulations

The phase shifts observed in harmonic frequencies and amplitudes observed in an experimental situation could in principle be due to a delay between the measured pressure and the actual consequence on the playing parameters of the instrument, for example, lip position having to adapt for the new pressure. To test for this hypothesis we reproduced features of the experiment in a simulated instrument. In order to maintain the acoustic characteristics, the measured input impedance curve is used, with some adaptations, in the simulation.

4.1 Simulation algorithm

The simulation algorithm is based on Silva [7]. The acoustic element and the reed are simulated as a sum of modes (several for the acoustic resonator, but only one for the reed). The reed is coupled to the acoustic resonator through the Bernoulli equation and the pressure difference acting on the reed opening (i.e. flow = $(2PA/\rho)^{1/2}$, where P, A and ρ are the blowing pressure, the reed aperture and the density of air). More details can be found in [7]. This simulation generates the pressure inside the reed, which is rather different from that radiated, because of the cut-off/ cut-on frequency of the bell (and the tone-hole array).

The modes of the resonator are extracted from input impedance spectrum measured on the instrument, after adding a parallel compliance to represent that of the air trapped inside the missing reed in parallel with the compliance of the reed itself (neither of which is included in the measurement). (Adding these compliances brings the impedance peak closer to the playing frequency measured in the real instrument). After these corrections and the mode extraction process, the measured and simulated impedance curves are given in Fig. 7.

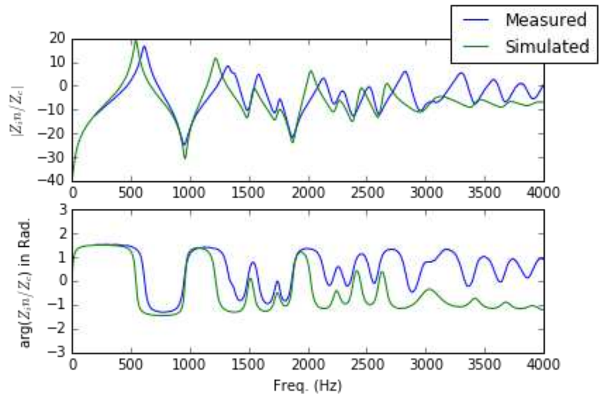

Figure 7 Measured input impedance of the oboe used in the previous experiment. The impedance corresponding to the modal decomposition used in the simulation in this section is plotted in green. This has a reed compliance added in parallel to correct for the reed, which was absent in the measurement.

Similarly to the experimental situation, the simulation is first run for a series of constant parameters until, for each, the system stabilises in a periodic regime. Next, the simulation is run again for one of the pressure values used for the stationary case, and once it stabilises in the periodic regime, the mouth pressure is made to oscillate within the range of stationary values measured before. An example of the mouth pressure applied to the simulation is shown in Fig. 8. Note that in the simulation the pressure is non-dimensional (γ), where $\gamma = 1$ corresponds to the value of pressure that would close the reed in the absence of oscillations.

This example produces the following time-course of harmonic frequencies, when divided by their harmonic number. The reason for the spikes in the sixth harmonic is not known to us.

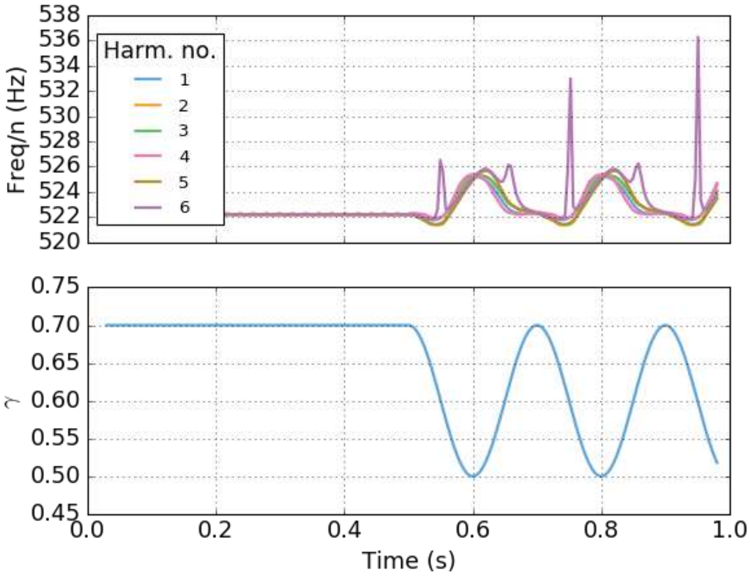

Figure 8 Time course of the frequencies of partials of the signal simulated with the mouth pressure profile shown in the previous figure. Each frequency is divided by its harmonic number

4.2 Example analysis of simulations

Similarly to the experimental analysis, it is possible to compare the trajectory of harmonic amplitudes and frequencies between vibrato and stationary cases. Once again, the harmonic frequencies do not follow the stationary case, but a cycle around them. The deviation is also higher for some of the higher harmonics than it is for the fundamental, but the cycle shapes seem different from those seen in the experimental case. Harmonic amplitudes also show a phase shift relative to the blowing pressure, although smaller than that shown by the frequencies. This was also the case in the experimental section.

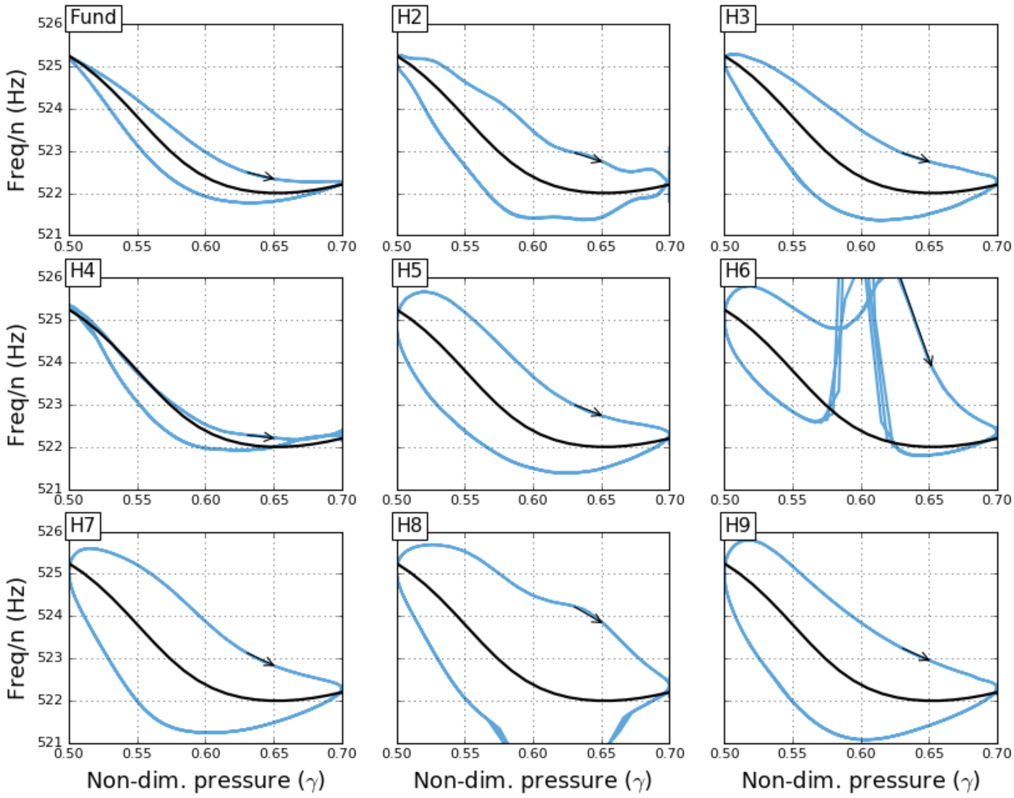

Figure 9 Partial frequencies of the simulated vibrato signal plotted against corresponding steady-state values

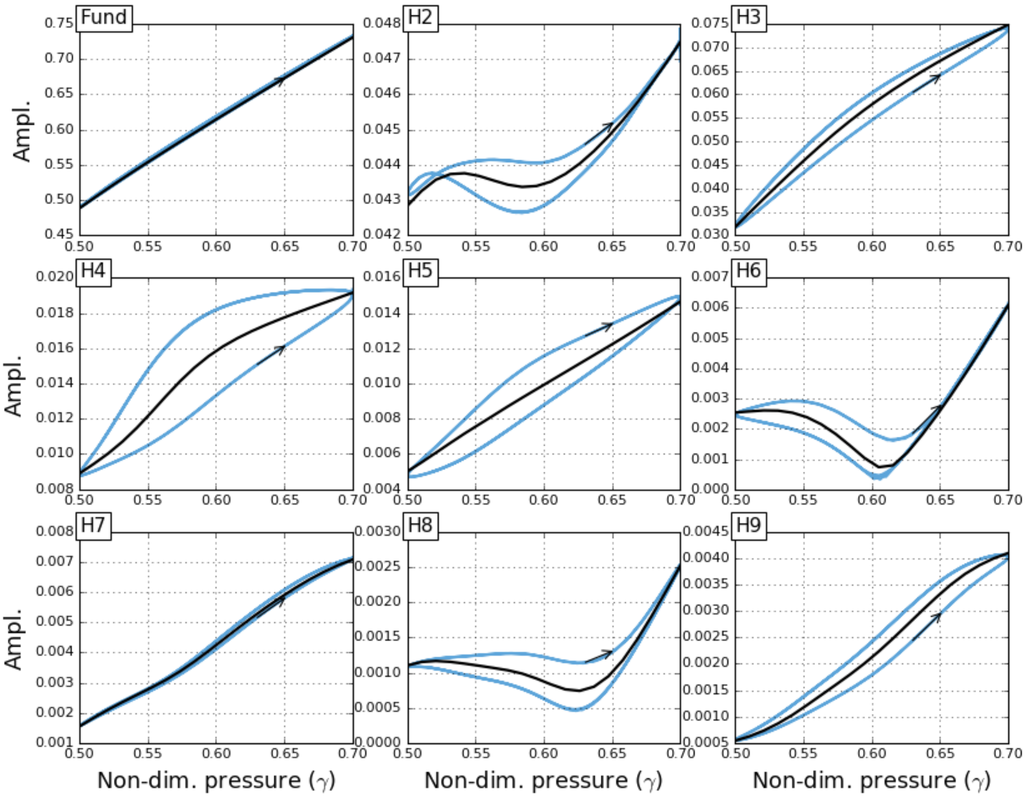

Figure 10 Partial amplitudes in the simulated vibrato signal plotted together with corresponding steady state values

4.3 Comparison with experiments and observations

Notice the very different amplitude relations when compared with the experimental results: in the simulation, the first harmonic has a much higher overall amplitude than the other harmonics. In the experiment, the sound was measured in the radiated field close to the bell, whereas in the simulation, the calculated pressure is that acting upon the reed. Although in principle it would be possible to calculate the pressure anywhere else in the resonator, or radiated by the bell, this requires further experiments. We choose not to in this preliminary work, as it is for now only of secondary importance to match the simulated amplitude results to the ones in the experimental case. (Note that the cutoff frequency of the tone hole array and bell, as measured for this note, lies between the 2nd and 3rd harmonics: see Fig. 7.)

On the other hand, the simulations seem to show that the delay between the properties of harmonic components, and the inharmonicity in the vibrato is not exclusively a consequence of any delay between the measured pressure and its consequence on the system. On the contrary, in this simulation, any changes in the pressure have immediate consequences on the exciter. The possibility that the reed inertia prevents it from adapting instantaneously to the pressure change remains but note that the reed's characteristic frequency is set to 2500 Hz, its time scale being much shorter than that of the vibrato oscillation (5 Hz).

5 Discussion and conclusion

The analysis method based on a phase vocoder seems well suited to the analysis of the vibrato signals studied in this work, with the estimated partial amplitudes within 2% of the original, and the frequencies less than 1%.

Analyses of both experimental and simulated signals in a reed instrument show that frequencies and amplitudes in these signals do not follow exactly the harmonic amplitudes and frequencies measured in stationary signals for the same playing parameters. The differences relative to the stationary parameter case are up to 0.5% for frequency values and up to 10-20% for the values of the harmonic amplitude.

Additionally, the analyses show that, in simulated and experimental signals, the partial frequencies are not exactly harmonic. The spread of partial frequencies divided by partial number are typically less than 0.2%, but the phase vocoder estimates some spikes in inharmonicity of the simulated signal that can be much larger than this value, up to 1%. It is not clear whether these spikes are an artefact of the method or if they have physical meaning.

Acknowledgments

The authors thank the Australian Research Council Discovery Project DP140102340 for support of this project, Yamaha for the oboe and Légère for the reeds.

References

[1] Almeida, 2013. Almeida, A., George, D., Smith, J., & Wolfe, J. (2013). The clarinet: How blowing pressure, lip force, lip position and reed “hardness” affect pitch, sound level, and spectrum. The Journal of the Acoustical Society of America, 134(3), 2247-2255.

[2] Li 2016: Li, W., Smith, J., Wolfe, J., & Almeida, A. (2014). Tongue, lip and breath interactions in clarinet playing: a study using a playing machine. In Proceedings of the 21st International Congress on Sound and Vibration, ICSV21, Beijing, China.

[3] Verfaille, V., & Guastavino, C. (2005). Perceptual evaluation of vibrato models. In *Proceedings of Conference on Interdisciplinary Musicology*.

[4] Gilbert, J., Simon, L., & Terroir, J. (2005). Vibrato of saxophones. *The Journal of the Acoustical Society of America*, *118*(4), 2649-2655.

[5] Hajda, J. M. (1999). The effect of time-variant acoustical properties on orchestral instrument timbres. PhD Thesis

[6] Almeida, 2016. PyPeVoc, a phase vocoder algorithm for Numeric Python. Public GitHub repository: https://github.com/goiosunsw/PyPeVoc

[7] Silva 2014: Silva, F., Vergez, C., Guillemain, P., Kergomard, J., & Debut, V. (2014). MoReeSC: a framework for the simulation and analysis of sound production in reed and brass instruments. Acta Acustica united with Acustica, 100(1), 126-138.