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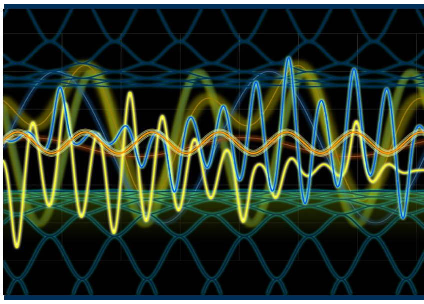

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Musical Acoustics: Session 12 - Brass, reeds and more

Physical modelling synthesis of a harmonium

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In this paper we present recent work on the development of a physical model of the hand harmonium, a bellow driven free reed instrument popular in South Asian music. Western free reed instruments like the accordion, the harmonica, the reed organ, etc. share many similarities with the hand harmonium in their physical structure and sound timbre. Previous models and experimental works on western free reed instruments are studied and revisions are proposed to the minimal model of free reeds described by Millot and Baumann (2007) to suitably match the physical setup and the sound timbre of a hand harmonium. The proposed changes allow the physical model to have the bellows pressure as a control parameter. A source-filter structure is suggested to model the acoustic effect of the wooden enclosure of a harmonium, which allows the realization of different timbres in the simulated sound.

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1. INTRODUCTION

Asian free reed instruments such as the sheng, the sho and the khaen have existed since ancient times. However, western free reed instruments such as the harmonium, the accordion and the harmonica are a relatively new category of musical instruments having originated in Europe about 200 years ago. Dwarkanath Ghose is generally credited to have modified the European harmonium to invent the Indian hand harmonium in 1884.[1] The hand harmonium has grown in popularity to become the instrument of choice for vocal accompaniment in North Indian (Hindustani) Classical music today. However, the use of the harmonium in Indian music has attracted a lot of criticism from musicologists.[2]

Figure 1: An Indian hand harmonium (top view)

Figure 2: A harmonium free reed

The harmonium (Fig. 1) is a standard western keyboard instrument that has a bellows pump to create pressure in a reed chamber. The press of a key on the keyboard raises a stop that allows air from the pressurized reed chamber to escape through the gap around a free reed. The escaping air sets up auto-oscillations in the reed which produces a sound.

The free reed in a harmonium (Fig. 2) is a thin metal strip riveted at one end to a support plate. There is a small clearance between the reed and the support so that it can freely vibrate as a beam without striking the support. This is quite different from a beating reed in a clarinet or a saxophone, where the reed is slightly wider than the mouthpiece opening. The reed in beating reed instruments has higher damping, allowing it to oscillate at a significantly lower frequency than its resonance frequency. The pitch or fundamental frequency of the sound is then primarily dependent on geometry of the resonator, e.g. the length of the cylinder in the case of a clarinet. In contrast, the metal free reeds used in free reed instruments have a lower damping and operate at a frequency close to their resonance frequencies. Hence, the metal reeds have to be tuned to get the right frequency for the musical notes.

Being a standard keyboard instrument, the harmonium can only play a discrete set of twelve notes per octave, usually spaced at an interval of one semitone with respect to each other. This is inconsistent with the non-equal temperament system in Hindustani music that uses 22 notes (a.k.a. shrutis) in one octave. The harmonium is also incapable of producing continuous pitch glides from one note to another as would be possible in a string instrument like a violin. This makes it impossible to produce essential ornaments in Hindustani music like meends, andolans and gamakas (elements similar to glissandos, portamentos, vibratos, etc. in Western music) on the harmonium. This paper is a part of a project to understand the critical parameters influencing the acoustic behavior of free reed instruments like the hand harmonium and to develop a natural sounding real time physics-based synthesis system that can add additional affordances like pitch glides and microtonality which cannot be achieved in a real harmonium.

2. RELATED WORK

While there has been a lot of research on the acoustics of beating reed instruments, free reed acoustics has not been as deeply researched. Cottingham[3] has given a description of the sound production mechanism in free reed instruments and provided a review of the prominent acoustic studies in this area.

A. ACOUSTICAL MODELS AND EXPERIMENTAL STUDIES

Early acoustic studies on free reeds focussed on understanding how the vibrations in free reeds are established. Self-sustained oscillations can be set up in reeds if an unsteady pressure difference can be developed between the two sides of the reed. As the reed oscillates, the aperture area changes, leading to velocity fluctuations in the air flow through the reed. The velocity-dependent pressure changes can be found using the Bernoulli equation. However, this mechanism in isolation cannot develop the asymmetric pressure differences required to set up self-oscillations. In highly damped reeds with strong coupling with the resonator as in the case of a clarinet, the pressure asymmetry is provided by the acoustic response of resonator. This mechanism is however absent in the case of a free reed instrument.

The mechanism that sets up self-oscillations in a harmonium reed was first investigated and published in a series of experimental and theoretical studies by Hilaire.[4–6] The studies proposed that the primary mechanism to set up the self-oscillations is the inertial effect of the upstream air flow. Since the air flow in the reed happens through a narrow jet, there is much less mass in the jet as compared to the upstream section. As a result the pressure near the reed changes rapidly as compared to the upstream pressure.

Experimental studies by Tarnopolsky[7,8] and Ricot[9] agree with the upstream inertial effect theory proposed by Hilaire. Ricot also gave an acoustic model based on a two-dimensional potential flow for synthesizing accordion sound.

Johnston[10] studied the mechanism for reed coupling and pitch bending in a diatonic harmonica. While most of the prior studies considered that the free reeds operate only at the principal eigenfrequency, an experimental study by Biernat and Cottingham[11] has shown that the presence of other modes of oscillation could be significant in the initial transients. In particular, Cottingham proposes that the first torsional mode and the second transverse mode may have a significant role in the initiation of the reed oscillation during the initial transient.[12]

B. PHYSICAL MODELING SYNTHESIS

Physical modeling synthesis is a popular method to synthesize the sounds of musical instruments in real-time. In this method, we typically model a musical instrument as a simplified physical system, develop its governing equations and devise an efficient numerical solution scheme to solve these equations and yield the audio samples in real-time. The emphasis is on capturing most of the properties of the sound of the instrument while keeping the model computationally simple enough to generate the samples at audio-rate. Since we model the underlying physical behavior rather than the sound itself, physical modeling synthesis can result in highly realistic sounds. Physical modeling synthesis is frequently employed to develop virtual acoustic instruments. In virtual instruments, some of the control parameters in the governing equations may be provided as real-time input by the user to allow interaction with the system as in a real musical instrument.

Hikichi et al.[13] developed a physics-based time-domain simulation model to synthesize the sound of a ‘sho’, an ancient free reed instrument that has pipe resonators coupled to the reed.

Millot and Baumann[14] have given a generic one dimensional model for simulating the sound from any free reed instrument and have also described a numerical scheme to solve the system in real-time. Parameters to synthesize the sound for a harmonica reed have been provided and the synthesized time-domain waveforms are presented. The paper also provides a discussion on the stability of the numerical solution and the dependence of pitch and dynamics of the synthesized sound on the control parameters in the model. We will summarize the Millot-Baumann model here and propose adaptations to simulate the harmonium sound using this model.

C. MINIMUM MODEL BY MILLOT-BAUMANN

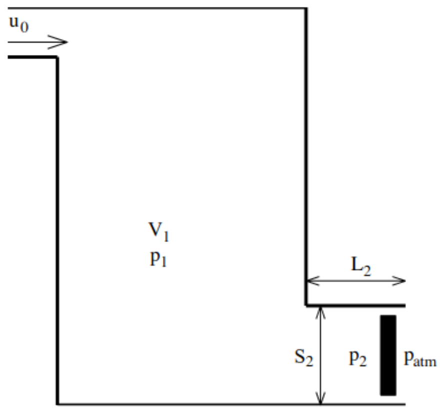


Figure 3: Configuration for minimum model by Millot-Baumann[14]

As established in previous studies, it is the inertial effect of the upstream air that is responsible for establishing self-oscillations in lightly-damped free reeds that are not acoustically coupled to a resonator. The minimum model, as shown in Fig. 3, models the upstream as a large volume V_1 where the pressure p1 is assumed to be uniform. The volume V_2, with pipe of length L_2 and cross-sectional area S_2 represents the narrow jet through which the air flows across the reed. The reed is modeled as a lumped mass-spring-damper system that oscillates sinusoidally. Depending on the equilibrium position of the reed, this setup can describe a blown-closed (-+) or a blown-open (+-) reed (as per the convention by Fletcher[15]). The region downstream from the reed is exposed to atmospheric pressure. The system is excited by the volume flow u_0 entering the volume V_1.

The governing equations for the model are as follows:

- Mass conservation for volume V_1

$$\frac{V_1}{c_0^2} \cdot \frac{d(p_1 - p_{atm})}{dt} = \rho_0(u_0 - u) \tag{1}$$

- Bernoulli equation for volume V_2

$$p_1 = p_2 + \rho_0 \cdot \frac{L_2}{S_2} \cdot \frac{du}{dt} \tag{2}$$

- Bernoulli equation for the upstream and downstream of the reed

$$p_2 = p_{atm} + \frac{1}{2}\rho_0 v_j^2 \tag{3}$$

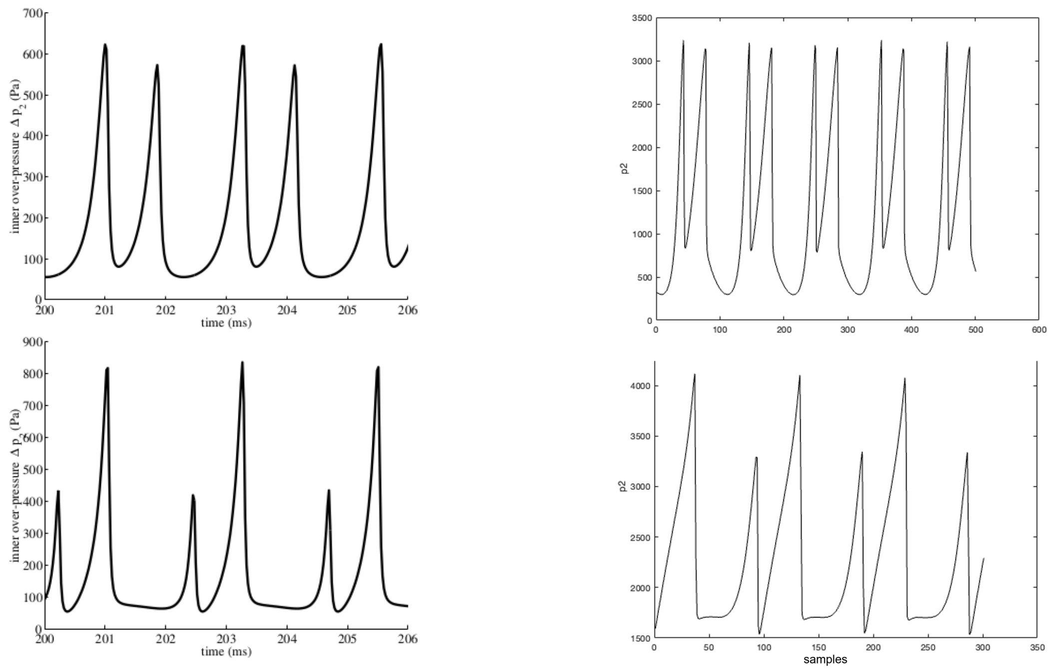
- Equation of the reed motion as a lumped mass-spring-damper

$$\frac{d^2\zeta}{dt^2} + Q^{-1}\omega_0\frac{d\zeta}{dt} + \omega_0^2\zeta = \mu(p_2 - p_{atm}) \tag{4}$$

- Total volume flow rate as the sum of jet flow and pumped flow due to reed motion

$$u = S_r \cdot \frac{d\zeta}{dt} + \alpha S_u v_j \quad (5)$$

where ,
ζ : displacement of reed from equilibrium position
α : vena-contracta factor
S_u : useful area of the aperture
c : speed of sound in air
v_j : particle velocity in air jet
ρ_0 : air density
ω_0 : eigenfrequency of the lumped reed



(a) Waveforms presented by Millot et al.[14]

(b) Waveforms observed in our implementation

Figure 4: Comparison of reed over-pressure waveforms for (-,+) and (+,-) between original and our implementation

We discretized these equations and solved them using the numerical scheme described by Millot. The time domain plots for the reed over-pressure (p_2) for the blown-closed and blown-open reeds presented by Millot-Baumann can be compared to those obtained through our implementation in Fig. 4. Although the magnitude of the over-pressure is about five times in our implementation, it can be seen that the waveforms are quite similar. Since the useful area of aperture S_u used by Millot to obtain these results is not specified, we used a simplified aperture given by $S_u = |y| * W_r$, where y is the position of the reed tip and W_r is the width of the reed. We believe that this difference in useful aperture area may have resulted in the higher magnitude of over-pressure obtained.

3. METHODS

Although the Millot model gives a good first approximation for a free reed, it does not account for the acoustic effect of the wooden enclosure in which the harmonium reed is placed. So, the timbre of the sound synthesized with this model is quite different from that of a harmonium. We could change the dynamics of the synthesized sound by varying the excitation signal u_0. However, we found that the range of permissible values of u_0 to set up stable reed oscillations was very narrow. We also observed that the response (i.e. the change in loudness) to a change in u_0 is more gradual than that observed while bellowing a real harmonium. It could be possible that we think of the input air flow rate as a control parameter for dynamics in a harmonica, but for a harmonium it is more intuitive to think of bellows pressure as the control parameter.

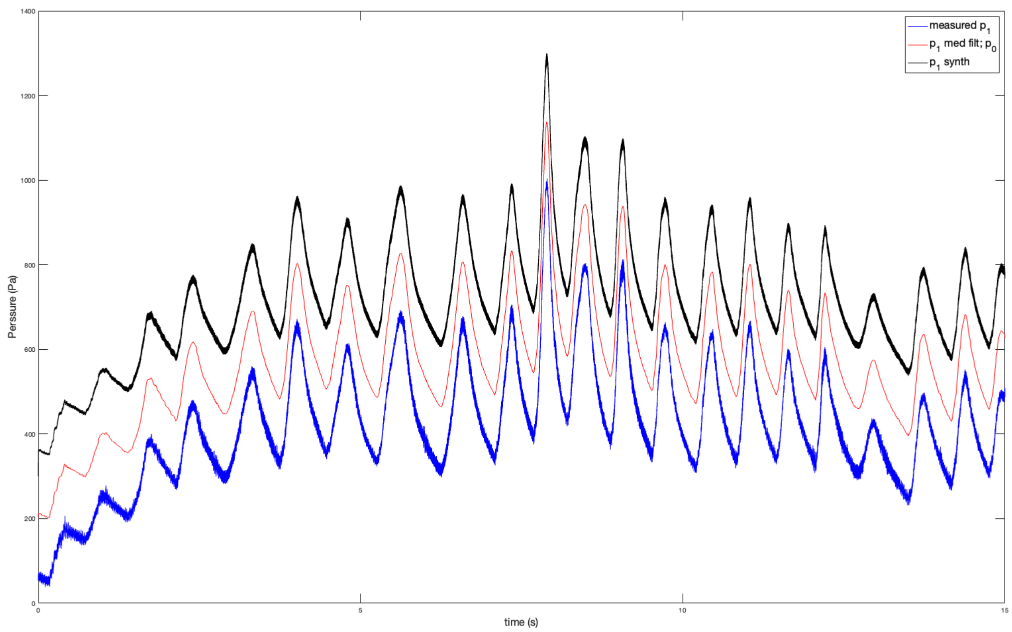


Figure 5: Reed chamber pressure measured using a pressure transducer (blue); median filtered version of raw reed pressure, also used as p_0 for bellow simulation (red); p_1 simulated using the proposed model(black); p_0 and simulated p_1 plots shifted in y axis by 150 Pa and 300 Pa for better visibility

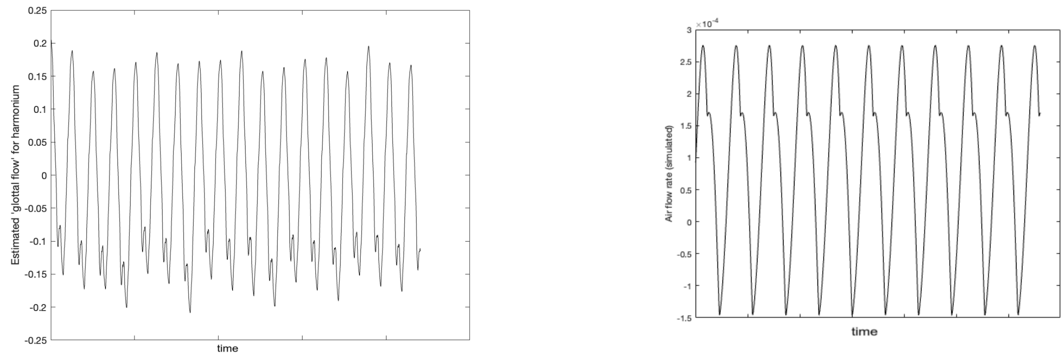
Using a pressure transducer we measured the operating pressure inside the reed chamber of a real harmonium while playing some melody as in a regular performance. As can be seen in Fig. 5, we observed that the reed chamber pressure (p_1 in the Millot model) ranges from 200-1000 Pa. The pressure rises rapidly when the bellows are operated and then as the air escapes (through the reed or other leakages in the structure), the pressure drops approximately like an exponential decay. Importantly, if we compare the pressure with its median filtered version (the orange curve in the plot), we see that there is only a small variation in the reed chamber pressure with respect to the long term average values. This is quite in contrast to the p_1 values observed in the simulation (Fig. 10a) where we observe a variation of $\pm$ 500 Pa with respect to a mean value of 900 Pa.

To better suit the physical setup and sound timbre of the hand harmonium we propose two adaptations to the Millot model, namely the adoption of a source-filter model and introduction of an extra pressure chamber to the Millot model. We describe these in the following sub-sections.

A. SOURCE-FILTER MODEL

The source-filter model for speech production[16] represents voiced speech as a combination of a periodic excitation signal generated by the glottis that is filtered by a linear filter representing the vocal tract. The fundamental pitch of the voice is determined by the glottal source signal while the timbral characteristics are determined by the formants of the vocal tract. The sound production mechanism for a harmonium is very similar to that of voice with lungs, the vocal chords and the vocal tract being analogous to the bellows, the reeds and the downstream wooden enclosure.

The iterative adaptive inverse filtering (IAIF) algorithm developed by P. Alku[17] can be applied to a speech signal to simultaneously estimate the air flow at the vocal folds ('glottal flow') and the all-pole vocal tract filter. The derivative of glottal flow can be considered as the excitation pressure signal that is convolved with the vocal tract filter to resynthesize the speech. We applied the IAIF algorithm using the implementation in COVAREP Toolbox[18] to estimate the "glottal flow", i.e. the air flow at the reed in a recorded harmonium sound.



(a) Reed air flow rate estimated by IAIF algorithm

(b) Reed air flow rate in simulation

Figure 6: Comparison of estimated and simulated reed air flow rate

The air flow at the reed estimated by the IAIF algorithm can be compared with the corresponding reed air flow simulated with our implementation of the Millot model in Fig. 6 which shows a snapshot of the flow patterns during the steady phase of a note. The waveforms of both plots have similar features and in particular show a discontinuity within each period that is assumed to occur when the reed passes from one side of the support plate to the other. The magnitude of airflow is varying considerably in the flow estimated by the IAIF in the recorded sound. This is expected since the excitation signal cannot be maintained perfectly constant in a real harmonium. Given the similarity in the structure of the estimated and simulated airflow, we propose that we can consider the simulated airflow to be analogous to the 'glottal flow' in speech and the 'vocal tract' filter estimated by the IAIF algorithm as the linear all-pole filter representing the wooden enclosure of the harmonium. To match the timbral quality of a recorded harmonium in the synthesized sound, we can then convolve the derivative of the simulated air flow with the 'vocal tract' filter estimated by the IAIF algorithm.

B. EXTRA PRESSURE CHAMBER FOR BELLOWS CONTROL

(a) Reed chamber of a harmonium. The four small holes connect the reed chamber with the spring-piston chamber

(b) Harmonium piston-spring chamber

Figure 7: Inside a hand harmonium

Using the inlet airflow as the control parameter for loudness modulation was found to be difficult and unintuitive. When the bellows are pumped in a hand harmonium, the incoming air compresses a piston against a spring (Fig. 7b). The enclosure housing the piston-spring assembly acts as a source of compressed air. Harmonium players attempt to maintain a constant pressure in the bellows while performing which keeps the air in the spring chamber at a roughly constant pressure during a performance. The compressed air from the spring chamber enters the reed chamber through small holes connecting the two chambers (Fig. 7a), with the air flow rate dependent on the pressure difference between the two chambers. The inlet airflow to the reed chamber is thus indirectly controlled with the bellows pressure.

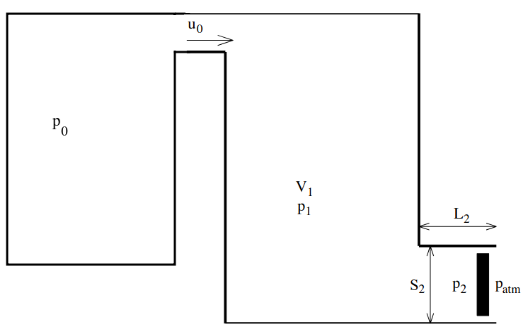


Figure 8: Adapted model with extra pressure chamber for bellows control

To model this physical structure and to get the expressive dynamics control of the bellows, we propose to add another chamber representing the spring-piston chamber in the Millot-Baumann model as can be seen in Fig. 8. The pressure p_0 in this chamber represents the bellows pressure and is a control parameter in our simulation model. We assume that at each time step 'n' in the numerical simulation, the inlet airflow rate to the reed chamber ($u_0(n)$) is given using the current bellows pressure $p_0(n)$ and the reed chamber pressure at the previous time step $p_1(n-1)$ from the following equations.

$$p_0(n) - p_1(n-1) = \frac{1}{2}\rho_0 v_0^2(n) \tag{6}$$

$$u_0(n) = S_0 \cdot v_0(n) \tag{7}$$

where,
S_0 : reed-chamber inlet aperture area.
v_0 : air particle velocity for the reed inlet airflow

4. RESULTS AND DISCUSSION

Using the changes proposed above, we synthesized sounds to simulate the sound of the note F4 ($f_0 \approx 349Hz$) from two different harmoniums and compared their sound timbres.

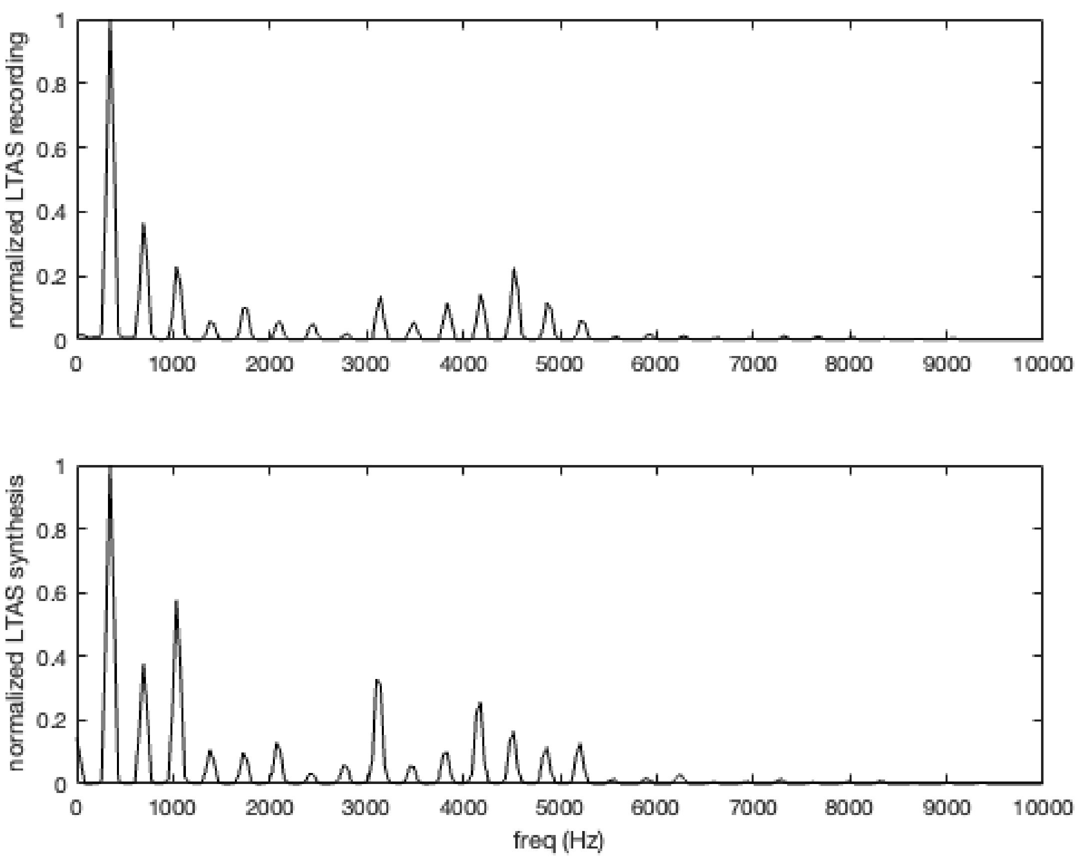
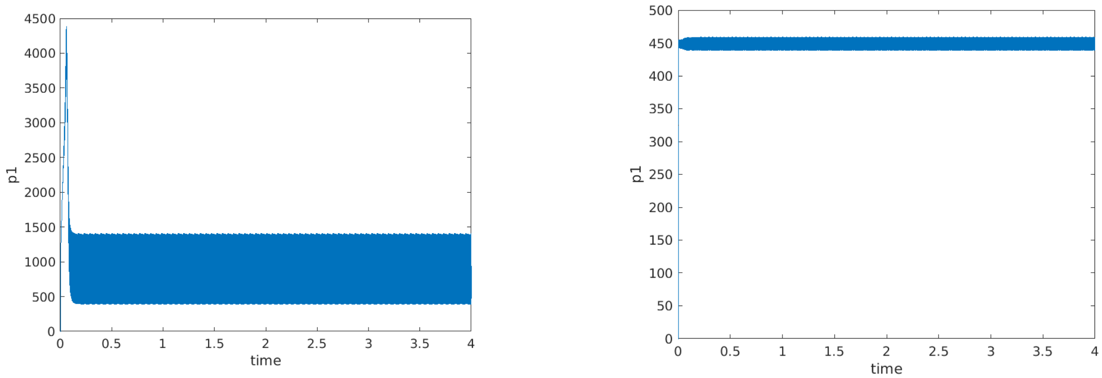


Figure 9: Comparison of normalized LTAS of a HQ-recorded note (top) and a synthesized note (bottom)

The comparison of the normalized Long Term Average Spectrum (LTAS) of a high quality recorded sound of the F4 note and its corresponding simulated sound can be seen in Fig. 9.

More sound samples and their simulated versions can be accessed at https://pninad.github.io/ViennaTalk2022/ We observed that the synthesized sounds have clearly distinct timbres and also have a close resemblance to the harmonium sounds that they were supposed to simulate. Importantly, the simulated sounds have the characteristics of a 'natural' harmonium sound.



(a)** p_1 **variation in our implementation of Millot model

(b)** p_1 **variation in adapted model

Figure 10: Comparison of simulated reed chamber pressure

Figure 10b shows that the reed chamber pressure (p1) was observed to have a smaller variation of $\approx \pm 20$ Pa for a mean pressure of 450 Pa as compared to the larger variation seen in the original model (Fig. 10a), showing consistency with the behavior observed in our pressure measurement.

The main motive behind adding the pressure chamber was to have bellows pressure control as a parameter to our model. We ran another simulation where we assumed that the median filtered version of our measured pressure represents the time varying pressure in the spring-piston chamber (p_0) achieved using bellows. Using this p_0 value as the input for our proposed model we obtained the reed pressure values as seen in Fig. 5. We see that by varying p_0 as per a measured value from a real harmonium, the reed chamber pressure p_1 in the simulation is very close to the measured pressure values. Also, the simulated sound closely resembled a harmonium played with strong bellowing actions thus achieving our objective.

5. CONCLUSION

This paper has presented the adaptations to a state of the art free reed model done to simulate harmonium sounds. Our proposed model allows for the use of bellows control as in a real instrument. The model parameters can be tuned to produce any microtonal note in keeping with the requirements of Hindustani music where the harmonium is predominantly used. The effectiveness of a source-filter based model to synthesize sounds from harmoniums with different timbres was demonstrated.

Future work would involve the development of a real time synthesis system coupled to a suitable physical interface that would enable performing music while exploiting the added affordances not available in a real instrument. Experimental studies to understand more complex features of free reed motion are underway. Suitable updates to the physical model can be made based on these experiments to capture finer details observed. Research on filter design to yield parametric control of timbre is also planned.

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