Embouchure Interaction Model for Brass Instruments

Rares Stefan Alecu, Stefania Serafin and Silvin Willemsen
Multisensory Experience Lab, CREATE,
Aalborg University Copenhagen
ralecu18@student.aau.dk

Emanuele Parravicini and Stefano Lucato
Audio Modeling
Sovico, Italy
info@audiomodeling.com

ABSTRACT

A common approach for simulating brass instrument sounds is that of a mass-spring system strongly coupled to an air tube resonator of a certain length. This approach, while yielding good quality timbre results for the synthesized audio, does not aid expressive sound synthesis. An improvement of this modeling design is proposed, which takes into account the independent movement of the embouchure and its influence on the sound. To achieve this interaction, vortex-induced vibration (VIV) is taken into account as an additional source of excitation for the mass-spring system. In addition to this, the model also simulates breath noise of a brass instrument player, which is dependent of the embouchure's aperture dimensionality. The end result is a real-time VST application of a brass instrument with augmented embouchure interaction. The process loop of the VST is presented step-by-step and the application is evaluated both through informal listening and spectral measurements. From this evaluation, the model showcases a more varied and veridic timbre of brass sound, that supports a more expressive playing style.

1. INTRODUCTION

Among the families of musical instruments, brass wind instruments have been a popular subject of research, both in the study of their nonlinear physical behavior [1] and in simulation of said behavior. Part of the interest derives for the complex interactions present in the instrument, whose sound is produced by the vibration of the lips within the mouthpiece of the resonator. This excitation system is known as the *lip reed*. The motion of the lip reed helps shaping the air flow between the lips and through the tube of the brass instrument. This air flow in turn also influences the movement of the lips, which becomes synchronised to the vibration of the air column within the tube resonator. Thus, the player's embouchure and the resonator form a complex feedback system with bidirectional communication [2, 3]. Because of this, brass wind players require many years to train their embouchure in order to obtain a desirable pitch and intonation control.

Measurements of lip movement have been conducted in several studies in the past [2, 4] using high speed video footage of a player's embouchure. From these images, several relationships can be established between the variations of the lip reed aperture, the mouthpiece pressure and the air flow rate.

With this insight on the interaction, several implementations succeeded in emulating the whole system, consisting of the player's embouchure and the tube resonator [5–7]. The initial assumption of most implementations starts by simplifying the entire system as a pressure-controlled valve between two chambers: the mouth of the player and the mouthpiece of the instrument. Thus, a singular model is achieved where the embouchure and the brass resonator are locked in and emulated as a whole.

However, some important behavioral aspects are omitted from this type of approach. One of the main problems is the "quantization" behavior between the pattern of notes. For a certain length of the tube resonator, only notes that are harmonics of the tube's resonance frequency can be heard loudly, when the lips are in resonance with one of the tube's natural frequencies [1]. Because the lips are considered strongly coupled to the resonator, the lips are aided to vibrate louder when in resonance and less otherwise. Thus, only the harmonics of the tube's resonant frequency will be generated by the model and nothing will be heard while sweeping between notes.

In reality, the buzzing of the lip is not only aided by the air tube of the brass instrument, but the lips are also excited into vibration by the mouth-blown air flow itself. In a less common embouchure practice method, brass players are instructed to "buzz" their own lips without the aid of a resonator. With no resonator attached to the lip, a person is still able to vibrate its lips to a certain degree. This independent vibration is important in the sweeping between natural frequencies of the resonator, since the sound of the lip vibration can still be heard between these harmonics, and the transition is not as abrupt as in the previously mentioned approach. This detail is key in conveying a more natural sound timbre and in adding expressivity to the playing of the instrument.

Until now, implementations of the singular model were satisfying enough since many musicians resorted to using a standard MIDI keyboard to control the interface of their virtual instruments. With this type of control, only a series of independent notes defined within the equal-tempered scale are generated. Hence, less care was given to the behavior of a model during consecutive notes and their transients in-between. However, with the dawn of MIDI polyphonic expression (MPE) [8] and presence of commercial instruments that support said format (fx. ROLI Seaboard [9]), there is more than ever the need to offer virtual versions of instruments that aid expressive control and sound generation, while maintaining a realistic timbre quality. For this type of music-playing capabilities, it is essential to capture the details lost from the sterility of old standards to support the progress of music performance.

Thus, the aim of this paper is to determine how adding movement independence to the lip reed can influence the sound of classical implementations and the interaction with the physical model. To achieve this behavior, inspiration was taken from theory regarding flow-induced vibrations. From it, a real-time VST application was designed that would prove to be efficient in computational costs and would extend the expressive capabilities of previous brass wind implementations.

2. THEORETICAL BACKGROUND

For any type of wind instrument, the source of oscillation represents the *reed*, a valve system that modulates the air flow that passes from the player's mouth to the instrument's mouthpiece [10].

The motion of the reed is complex, especially in the case of the elastic lip reed, which has several degrees of freedom in movement as confirmed in high speed video measurements [4]. On the topic of reed motion simulation, more degrees of freedom can influence the quality of the sound for higher harmonics [11, 12]. That being said, only the vertical component of reed's motion, perpendicular to the air flow, is considered in most studies. This component plays an important role in modulating the volume rate of the air flow passing through the reed aperture, which is essential in the sound generation of the instrument [13]. Thus, the reed can be represented as a simple one-mass harmonic spring (see Fig. 1), placed within a dynamic air flow, coupled to a resonator tube [7, 10].

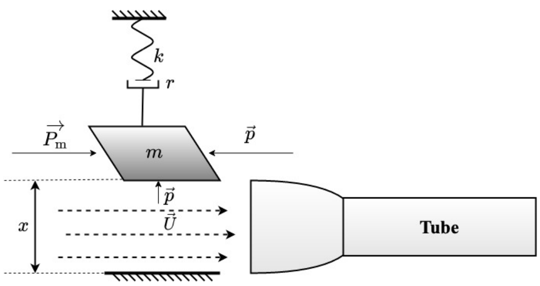

Figure 1. Mass-spring physical model of lip reed.

The movement of a single reed in this case is assumed to be similar to that of a forced harmonic oscillation, where the driving force is the resultant of the pressure forces on both sides of the reed, from the mouth and from the mouthpiece:

$$m\ddot{x} + r\dot{x} + kx = \sum F_{\text{aerodynamics}} \,, \tag{1}$$

where x represents the displacement of the mass-spring, m the mass of the lip reed, r the damping of the spring and k the elasticity of the spring. The dot operator describes a single derivative with respect to time.

While the pressure force coming from the mouth, defined as P_{m}, is considered static, the pressure on the exterior side of the reed p will vary in relation to the resonant frequency of the attached air tube. Thus, if the resonant frequency of the reed's mass-spring is near one harmonic of air tube's resonant frequency, then the oscillation will be larger in amplitude.

The variation of pressure is closely related to the modulation of the air flow by the reed and their relation can be determined by studying the dynamic properties of the flow. The volume flow rate of the air passing through the reed aperture $U(t)$ can be described as a highly nonlinear function of the pressure difference between the interior and exterior sides of the reed. It can be computed as the product between the surface of the reed opening $S(t)$ and the speed of the air flow $u(t)$ [2]:

$$U(t) = S(t) \cdot u(t). \tag{2}$$

Since the cross-sectional area inside the mouth is way larger than that of the reed opening channel, the velocity in the mouth cavity is neglected and $u(t)$ is considered uniform. Assuming there is no dissipation of the flow, i.e. the flow is quasi-stationary, incompressible and frictionless, the pressure drop across the reed channel is computed as a function of $u(t)$ using the Bernoulli equation

$$P_{\text{m}} + \frac{\rho v_1(t)^2}{2} = p(t) + \frac{\rho v_2(t)^2}{2} \,, \tag{3}$$

$$P_{\text{m}} - p(t) = \Delta P = \frac{\rho(v_2(t)^2 - v_1(t)^2)}{2} = \frac{\rho u(t)^2}{2} \,, \tag{4}$$

$$u(t) = \sqrt{\frac{2 \cdot \Delta P}{\rho}} \,, \tag{5}$$

where ρ represents the flow density, v_1 and v_2 are the flow velocities corresponding to the mouth and lip reed channels, respectively.

From eqs. (2) and (5), the volume flow rate is defined as [2]

$$U(t) = S(t) \cdot \sqrt{\frac{2 \cdot \Delta P}{\rho}} \,. \tag{6}$$

With the Bernoulli equation, the coupling between the reed valve and the tube resonator is achieved. The final step to describe the reed oscillation phenomena represents the method of computing the pressure from the reed channel $p(t)$. Considering pressure continuity on the front bottom corner of the mass (the corner closest to the tube as illustrated in Fig. 1), equivalence can be assumed between the pressure underneath the reed and the pressure applied on the reed towards the mouth. Additionally, under the assumption of a linear plane wave propagation within the brass tube, the pressure response $p(t)$ to the respective air flow can be computed through convolution as [6]

$$p(t) = (g * U)(t), \tag{7}$$

where g is the time-domain impulse response of the tube resonator.

The system formed by eqs. (1), (6) and (7) represents a simplified description of a general reed interaction with the air flow of a wind instrument. The discretization of this system of equations shall be referenced further as the state-of-the-art (SOTA) implementation. For woodwind instruments, a cane reed is used and the playing frequency of such instruments is mainly controlled by the resonator and not strongly influenced by the reed itself [10]. Contrary to this, the lip reed for a brass instrument plays a bigger role in obtaining correct musical notes. The resonance of the lip reed is influenced by instrumentalists through subtle muscle control of the lips and needs to be related to the natural frequencies of the resonator, resulting in a strong coupling between the reed and the air tube. Additionally, the lip reed's elastic properties helps in shaping the reed's opening, which is not as linear as the rigid cane reed's rectangular aperture. This detail adds to the nonlinear complexity of the lip reed model [2].

As stated, a topic of interest in this case is to study self-oscillation of the lip reed without the aid of an object. Keeping the same mass-spring structure described previously, the driving force applied on a harmonic oscillator has to be oscillatory in nature to achieve system vibration [14]. In the context of brass, if P_m is constant and the resonator's air tube influence is eliminated, the resulting aerodynamic forces become static. In theory, the lip reed would not be permitted to vibrate, reaching an equilibrium immediately. Thus, an additional force acting upon the lip is needed to obtain an oscillatory motion.

This topic guides us into the field of *vortex-induced vibration* (VIV), which is scarcely studied in the field of sound and music computing, but heavily discussed in the field of structural engineering. Consider a bluff [1] nonrotating object placed within a travelling flow, as seen in Fig. 2. As the flow moves with a certain speed, oscillation of the object can occur due to instabilities formed in the layer around the object [15]. From these instabilities, alternating flow vortices on opposite sides of the object are formed, which change the pressure distribution along the object's surface, resulting in a pseudo-periodically varying lift force in the transversal direction [16, 17]. This phenomenon is present for example in aeolian vibration, such as power lines "singing" during strong winds [18].

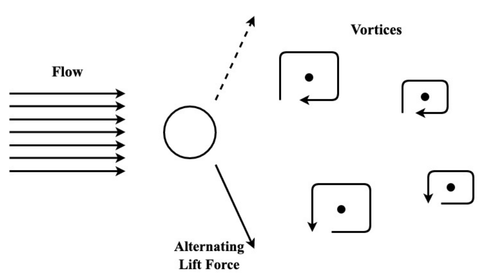

Figure 2. Vortex-induced vibration scheme, excited by a moving flow.

[1] The term "bluff" can be crudely considered the opposite of "aerodynamic", describing a body placed within a fluid stream which generates separated boundary flows over a significant part of its surfaces [15]. This results in strong drag forces acting upon the body.

3. RELATED WORK

Literature on brass instruments mainly focuses on modeling the upper lip of the mouth, since it moves during the interaction significantly more than the lower lip [4]. Of particular interest is the model proposed by Rodet and Vergez in several works [6, 19], which takes the modeling approach of equivalating the movement of the upper lip as the interaction between a mass-spring and an air flow, as shown in Fig. 1. The chosen model consists of a parallelepipedic object of mass m attached to a spring k and damper r. The object is presumed to have defined areas for its front, rear and bottom faces. The vertical displacement of the mass-spring is denoted with $x(t)$, the pressure response at the entry of the mouth piece $p(t)$ and the incoming volume air flow rate $U(t)$.

Inspired by eqs. (1), (6) and (7), the authors of [6] propose a similar lip-air tube coupling system, additionally taking into account lip collision during aperture closing and the fact that the air flow can travel in both directions:

$$m\ddot{x} + (1 + 4\theta)r\dot{x} + (1 + 3\theta)kx = F, \tag{8}$$

$$p(t) = (g * U)(t), \tag{9}$$

$$U = S \cdot (1 - \theta) \cdot \mathrm{sgn}(P_\mathrm{m} - p) \cdot \sqrt{\frac{2|P_\mathrm{m} - p|}{\rho}}, \tag{10}$$

$$F = \gamma(P_\mathrm{m} - p) + A_\mathrm{b}(1 - \theta)p, \tag{11}$$

$$\theta = \begin{cases} 1 & \text{when } x \leq 0 \\ 0 & \text{when } x > 0 \end{cases}$$

where A_b is the bottom area of the mass-spring, F is the resultant of the pressure forces applied on the reed and γ represents the effective area of the pressure forces parallel to the flow, which includes the angle of the parallelepipedic mass. The Heaviside variable θ denotes whether the lips are closed ($x \leq 0$) or open ($x > 0$). When the lips close, the mass-spring system becomes more rigid to simulate collision, while the air flow $U(t)$ and the force applied underneath the lip become null.

Many measurements were done in the area of lip movement for brass excitation, in order to observe a certain relationship between different parameters of the interaction. In the work of Boutin et al. [4], important insights are presented on how the lip pressure varies with lip aperture, along with the variation of the bore impedance in regards to the playing frequency. Additionally, the experimental measurements of lip surface conducted by Bromage et al. [2] show similar findings, along with an interesting proposal to mathematically define the lip surface variation. From empirical observations, a general lip opening area-displacement formula can be derived as

$$S(t) = S_0[x/x_0]^q, \tag{12}$$

where S_0 and x_0 represent reference mean values of the lip opening area and displacement, and q is an exponent value between 1 and 2.

On the topic of VIV, the literature proves to be pretty scarce in this domain. With the exception of a few studies on vibration produced on cavity holes for pipe organs [20], vibration for more flexible objects seems to not be a field of interest for the sound computing field. A better understanding of the phenomena can be viewed in studies on structural engineering problems, such as [16].

4. IMPLEMENTATION

The following is an overview on the implementation and the control parameters of the resulting real-time VST application, developed in C++ using the JUCE framework [21]. Initially, the implementation focused on discretizing the system of equations defined in Section 3, without considering the influence of VIV. After achieving this approach, the VIV phenomenon is added as a separate part of the discretization process.

The mass-spring vertical displacement x can be determined using finite-difference time-domain methods. The update formula for the next step of x at a predefined sampling frequency f_s is as follows:

$$x[n] = \frac{1}{a_1}(F + a_2 \cdot x[n-1] + a_3 \cdot x[n-2]), \quad (13)$$

where

$$\begin{cases} s = \frac{1}{f_\mathrm{s}} \\ a_1 = \frac{m}{s^2} + \frac{(1+4\theta)r}{2s} \\ a_2 = \frac{2m}{s^2} - (1+3\theta)k \\ a_3 = \frac{(1+4\theta)r}{2s} - \frac{m}{s^2} \end{cases}$$

Taking inspiration from Rodet's work on brass simulation [7], the resonant frequency of the lip influences the mass and the elasticity of the spring, which are scaled using a tension factor ζ, a ratio between the desired frequency f_lip and a reference frequency f_0, defined for a reference mass m_0 and elasticity k_0:

$$f_\mathrm{lip} = \zeta \cdot f_0 = \zeta \cdot \frac{1}{2\pi}\sqrt{\frac{k_0}{m_0}}\,, \quad (14)$$

$$k = k_0 \cdot \zeta, \quad (15) \qquad m = m_0/\zeta. \quad (16)$$

After finding the next sample of x, the Heaviside variable θ is updated if the state of the lips have changed. To minimise unwanted behavior of the model during frequent switching between the lip states, a sharp hysteresis function is implemented with P_m-dependent thresholds. The switching limits of the hysteresis are modulated by a "jitter noise", which consists of a white noise generator whose variance depends on the blowing pressure. The modification of the hysteresis limits only occurs at the passing between the two states of the Heaviside variable θ.

The lip aperture surface at the next time step is calculated using eq. (12), where $q = 1.3$ was chosen in this current implementation, since it proved to yield satisfying results.

Now that $x[n]$ can be computed, the rest of the unknown variables in the lip motion (the pressure within the flow p and the air flow volumetric rate U) are calculated from eqs. (9) and (10). Since the focus is on modeling the excitation process, the tube resonator model will be simplified, using only the formula for the impulse response of a normal cylindrical tube, inspired from [19]

$$g(t) = Z \cdot \delta(t) + 2Z \cdot \sum_{i=1}^{\infty} \mu^i \cdot \delta(t - iT), \quad (17)$$

where Z represents the characteristic impedance of air at the lip aperture, $\delta(t)$ the Dirac impulse function, T the resonant period of the air tube of a certain length and μ is the feedback reflection coefficient, which ranges between -1 and 0. This impulse response does not take into account any bore variation similar to a real brass instrument resonator, nor does it consider any scattering effects caused by the size mismatch between the lip reed aperture and the cross section of the tube resonator. The input impedance is calculated as

$$Z[n] = \frac{\rho \cdot c}{S[n]}, \quad (18)$$

where ρ and c are the air density and the speed of sound in air, respectively. For a very small lip aperture, the input impedance becomes very large, up to very unrealistic values, compared to real-life measurements [3, 4]. This results in occasional destabilisation of the physical model. If the lips are closed, the calculated impedance tends to infinity, which is propagated in the feedback path of the model. As such, a capping function is implemented, to limit the impedance to a maximum possible value. The maximum limit decreases nonlinearly in terms of playing frequency, according to

$$Z_\mathrm{max} = \frac{5 \cdot 10^{10}}{6 \cdot f_\mathrm{lip} \cdot 10^{-2} + 1}\,. \quad (19)$$

The function follows the behavior found in previous impedance measurements [3, 4] and fine-tuned empirically to obtain the best sound quality for all parametric conditions of the physical model.

With x known, the next step is to compute p. First, with the formulated impulse response, eq. (7) can be rewritten as

$$p[n] = Z \cdot U[n] + 2 \cdot Z \cdot \sum_{i=1}^{\infty} \mu^i \cdot U[n - i \cdot T \cdot f_\mathrm{s}]. \quad (20)$$

By writing $\mathrm{sgn}(y) = y/|y|$, eq. (10) can be formulated as

$$U[n] = S[n] \cdot (1-\theta) \cdot (P_\mathrm{m} - p[n]) \cdot \sqrt{\frac{2}{\rho}\frac{1}{|P_\mathrm{m} - p[n]|}}\,. \quad (21)$$

By replacing volume flow rate U as a function of pressure p in eq. (6) and computing the convolution in eq. (7) the following equation is obtained:

$$p[n] = A \cdot (P_\mathrm{m} - p[n]) \cdot \frac{1}{\sqrt{|P_\mathrm{m} - p[n]|}} + C, \quad (22)$$

where

$$A = c \cdot (1-\theta) \cdot \sqrt{2\rho}, \quad (23)$$

$$C = 2 \cdot Z \cdot \sum_{i=1}^{\infty} \mu^i \cdot U[n - i \cdot T \cdot f_\mathrm{s}]. \quad (24)$$

Here, A can be seen as a variable that describes the flow's physical characteristics and C represents the summation of all reflected pressure waves from the air tube at time step n. This summation is computed with the aid of a simple interpolated delay line buffer, as seen in Fig. 3. The length of the buffer depends on the user-defined tube resonant frequency of the brass model. Before continuing to the next step of the process, the air tube contribution is passed through a one-pole low pass filter to prevent any aliasing caused by sudden changes of the delay buffer's length. To counteract the filter's influence on the tube's resonance, the delay buffer needs to be defined shorter than its theoretical length.

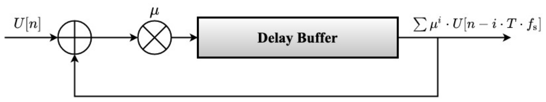

Figure 3. Delay buffer implementation for computation of air tube contribution.

By writing an equivalence in $\sqrt{|P_\text{m} - p[n]|} = y$, eq. (22) becomes a solvable second order polynomial, but whose results depend on the absolute value of the pressure difference. From a computational point of view, the sign of the difference between P_m and p cannot be determined in real time. Thus, two situations need to be considered when computing p: when the air flow is moving from the mouth into the mouthpiece ($P_\text{m} > p$) and vice versa. The former case describes an "outward" behavior of the air flow, while the latter describes an "inward" behavior.

Considering the former case, the pressure within the air tube p can be computed as follows:

$$|P_\text{m} - p| = P_\text{m} - p = y^2, \tag{25}$$

$$p = P_\text{m} - y^2. \tag{26}$$

Eq. (22) becomes:

$$(P_\text{m} - y^2) \cdot y = A \cdot y^2 + C \cdot y, \tag{27}$$

$$y^2 + A \cdot y + C - P_\text{m} = 0. \tag{28}$$

From the roots of the eq. (28), only one of the roots of the polynomial is chosen as the solution for p. To find out in which behavioral case the process is, the deltas of both cases need to be calculated and compared

$$p_{1,2}[n] = P_\text{m} \mp \left(\frac{-A + \sqrt{\Delta_{1,2}}}{2}\right)^2, \tag{29}$$

where

$$\Delta_{1,2} = A^2 \mp 4C \pm 4P_\text{m}. \tag{30}$$

Since A is always positive, both Δ_1 and Δ_2 can never be negative at the same time. If Δ_1 is negative, then Δ_2 is obligatorily positive, meaning the air flow has an inward behavior. The opposite is also true. However, both deltas can also be positive at the same time. For this situation, the choice between the two methods is dependent on the previous behavioral case. For example, if both deltas are positive and the previous behavioral case was outward, then the computational method for an outward flow is chosen.

After p is determined at the current time step, the value is inserted back into eq. (10) to compute U. This completes the process loop of the physical model.

As it can be observed, the air tube contribution can be removed if μ is set to 0. But in the current configuration, it would result in an unrealistic behavior, where the pressure within the air flow p would become constant, depending only on the static variables A and P_m. In parallel, the lip displacement x is still varying in this case, opening and closing the aperture. This drawback is caused by the SOTA design of lip reed simulation, since it is always presumed that a tube resonator is attached to the reed.

To obtain the self-oscillation of the mass-spring without coupling it to a resonator, the previously discussed VIV phenomena has to be added to the process. According to theory in this domain [17, 22, 23], a periodic lift force applied to a damped oscillator can be described mathematically as follows:

$$m\ddot{x} + r\dot{x} + kx = L(t), \tag{31}$$

$$L(t) = -L_\text{a}\ddot{x} + L_\text{v}\dot{x}, \tag{32}$$

$$(m + L_\text{a})\ddot{x} + (r - L_\text{v})\dot{x} + kx = 0, \tag{33}$$

where L_a represents an added mass term and L_v an added damping term from the lift force. Both terms are dependent on the speed of the air flow, which is in turn proportional to the volumetric flow rate U and lip displacement x.

Since most of the case studies in VIV researches are focused on cylindrical objects and the lift force terms also depend on characteristics of said object, it would be too inaccurate to consider that what works for cylindrical pipes also works for the model's parallelepipedic mass-spring. Hence, a mathematical study on fluid dynamic interaction for this type of object is necessary to have a veridic simulation.

To avoid a complete redesign of the model or an exhaustive research on the area of fluid dynamics, a more empirical approach is implemented to emulate VIV. Firstly, L_a is ignored in this implementation, since the added mass would affect the real vibration frequency of the mass-spring and would reduce the musical utility of the model drastically. Secondly, the added damping term was calculated as a nonlinear function of x. The modified damping coefficient for eq. (8) becomes [23]

$$r = \max(r_\text{spring} - w_r \cdot \left|\frac{x_0}{x}\right|^d, 0), \tag{34}$$

where r_spring is the user-defined spring damping amount, w_r a weight coefficient of the added damping term and d the order of dependency on the lip displacement. With this modification, self-oscillation of the mass-spring is achieved.

A final detail is the application of breath noise modulation on the embouchure model, as seen in Fig. 4. The modified parameter in question is the mouth blowing pressure P_m and the parameter's modulation depends on both lip displacement and blowing pressure itself. The pressure is modulated with a "pulsed noise", i.e., a white noise generator passed through two parametric biquad filters, one bandpass (BPF) and one highpass (HPF). The amplitude of the modulated noise depends on normalized lip displacement $|x/x_0|$ and the user-defined blowing pressure P_{m0}. The HPF's cutoff frequency is scaled in regards to the lip aperture's surface. When the surface increases, the cutoff frequency becomes lower. This behavior reflects a fundamental relationship between the physical dimension of an object and the vibration frequency produced in fluid dynamics [20].

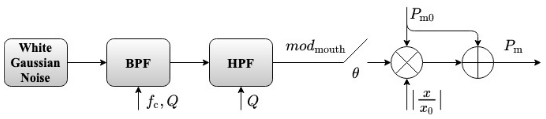

Figure 4. Diagram for noise modulation.

The output of the model is the pressure variable p, scaled to be within the audio amplitude range. Pressure is considered as the best variable from which the output is computed, due to the relation between human hearing mechanism and pressure variation related to sound propagation. Due to the complex nonlinear processing, oversampling is required in order to get better audio quality and stability.

The VST provides an interface for the user to control the characteristics of the lip mass-spring, air tube, mouth blowing pressure, noise modulation and the added VIV damping term.

A MIDI mapping implementation is also achieved for the plugin, which aids expressive control of the lips, tube and blowing pressure parameters. The MIDI note frequency, pitch bend and modulation messages influence the air tube and lip resonant frequencies, while blowing pressure is controlled via note velocity and a MIDI expression value (extracted from data associated with Aftertouch or an expression pedal), which dictates the amount of added pressure to the initial value determined from note velocity.

5. EVALUATION

The following section presents the evaluation of the model, from the perspective of interaction control and quality of the audio behavior. The model's VST application was tested in the digital audio workstation REAPER [24] at 48 kHz sampling frequency and 24-bit audio depth. The oversampling is set at 4 times the VST host's sampling frequency. The model's parameters are modified continuously through the interface's control knobs.

5.1 Interaction

When interacting with the model without the air tube coupling, achieving self-oscillation of the lips proves to be a difficult task. To simulate similar control behavior to that of a brass player, simultaneous control of the model's parameters is required. In the current context of the project, this aspect is hard to obtain, since the correlation between parameters is difficult to define. A solid vibration of the lip model is achieved by balancing between the amount of pressure and the mass-spring's parameters. However, vibration becomes much easier to generate when the air tube is added. In this situation, vibration is easier to achieve as the reflection coefficient of the tube increases. As the reflection coefficient tends to -1, the air tube contribution increases and the influence of the embouchure augmentations on the sound is reduced, reverting to the SOTA behavior.

Once the right sound of brass is obtained, the parameters for lip mass-spring attenuation, lift force component, noise modulation and air tube reflection can be left unchanged. Thus, for real time control, to generate different notes of similar timbre, only lip resonant frequency, blowing pressure and tube resonant frequency need to be modified.

5.2 Sound and behavior

Timbre and behavior evaluation is done through informal listening and spectral measurements of the model's output in MATLAB. The listening was conducted by the authors and the personnel at Audio Modeling [25], who collaborated for the development of this model. Recordings that are showcasing the model's output can be heard at [26].

Overall, the model's output resembles strongly that of a generic brass instrument. The tube resonant frequency can be set within a large range, thus the model's behavior can vary from that of a bass trumpet to a "trombino". A positive aspect of the model is the quality of the sweeping between the natural frequencies of the tube, resulting in a less abrupt "quantization" behavior. By adjusting the reflection coefficient, the quality of the transients is heavily modified, becoming more elongated as reflection is decreased. The transients can become long enough to create a beating effect between nearby consecutive resonances while sweeping.

The prolonging of the transients also aids expressiveness, achieving sounds that are not just the natural frequencies of the tube. This is similar to how real brass players are capable of "lipping" sounds around the resonant frequencies of the instrument. Thus, the model has the potential of supporting a vibrato-playing style or creating a legato pattern of notes between consecutive resonances. Based on these observations, it seems that adding independence to the lip reed does influence the timbre and behavior of the model, obtaining a more veridical sound. For the current implementation, the model can easily excite a large number of tube harmonics, even higher than 2 kHz, which is considered beyond the capabilities of most experienced brass players in the world. However, at such high frequencies, aliasing becomes much more noticeable, degrading the quality of the sound.

Another confirmation to the model's quality of a brass sound is seen through waveform comparison between the synthesized output and the bore pressure measurements from previous research [2, 4], which seem to be similar in nature. Examples of the waveforms can be seen in Fig. 5.

Without the lip lift force aid, the model reverts to the SOTA implementation and its strong "quantization". The sweeping between the notes is clean with short transients and the number of audible generated tube harmonics is less than with the aid of the lift force.

Without the air tube, the self-oscillating lip model seems

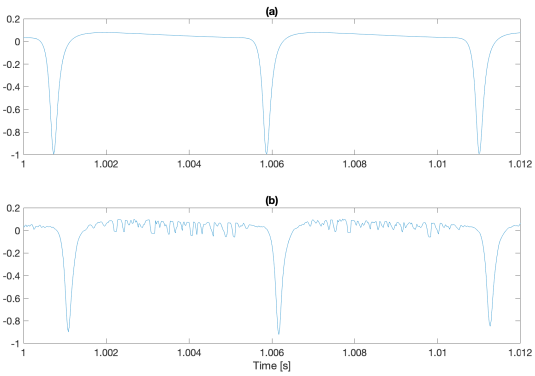

Figure 5. Time-domain representation of synthesized brass sound without (a) and with (b) mouth pressure noise.

to generate a "buzzing" sound. Online videos and recordings of "lip buzz" have been chosen as reference while evaluating the simulated sound. For lower frequencies, the model's sound resembles to real life examples, but the behavior becomes less natural when the lips vibrate at a higher frequency. However, high frequency buzz examples are not that common, since it is hard for a brass wind player to generate such a sound without any additional aid. Thus, it is difficult to ascertain what is the expected behavior in this context.

In addition to this, the resulting oscillation is unstable in terms of maintaining a constant amplitude or fundamental frequency, at constant parameters.

f_{lip} [Hz]	f_{out} [Hz]	$f_{\text{lip}}/f_{\text{out}}$
220	333.98	0.6587
440	641.60	0.6858
880	1315.43	0.6690

Table 1. Observations on discrepancy between user-defined lip frequency f_{lip} and output's fundamental frequency f_{out}.

As seen in Table 1, the generated lip buzz has been measured and studied spectrally. There is a discrepancy between the user-defined lip resonant frequency and the output's fundamental frequency. The ratio between the two frequencies seems to be constant and this reflects the physical constraints of previous models, presented in [27]. Because of the lips collision simulation and of the varying spring attenuation, the lip model vibrates at a higher frequency than expected. This behavior is proven also when having an air tube attached, where, despite defining the resonant lip frequency at a natural harmonic of the tube resonator, the next higher harmonic is instead excited.

The breath noise modulation yields convincing results if adjusted to a low amplitude, giving the impression of a real air flow passing through the tube resonator.

Modifying the resonant frequency of the air tube is equivalent with modifying the length of the brass tube with a slide. While a slide usually offers a deviation of a few semitones from the original starting pitch with this model, radical changes in length can be simulated with the model. These extreme adjustments yield an interesting repeating portamento behavior, varying across an octave.

The model encounters some problems when it comes to simulating lower dynamic sounds. It is expected that the higher the blowing pressure, the higher the amplitude of the vibration and the more noticeable the presence of higher harmonics in the sound, as heard in trumpet crescendo performances. In the model, the amplitude of the fundamental does increase, but the higher harmonics are decreasing. This behavior is explained by the damping variation caused by the lift force. As blowing pressure increases, the lip displacement x also increases, which may lead to a higher damping amount once x becomes larger than the calculated mean displacement value x_0. As a result, the increase in damping also attenuates the high harmonics.

At a lower blowing pressure level, there is a higher chance of getting short bursts of distortion when sweeping between resonances. The distortions are caused by the impedance capping method, which changes in accordance to lip frequency, but not to blowing pressure or lip aperture surface. For low blowing pressure, the resulting lip displacement and aperture surface are small. Thus, the surface-dependent impedance is too high in this case, which leads to a stronger air tube contribution in comparison to the mouth pressure force.

6. CONCLUSIONS

A real-time physical model of a brass instrument with embouchure independence is obtained, which showcases a beneficial augmentation of previous work. While the model matches the quality of timbre from previous implementations, it increases greatly the expressiveness potential of the brass instrument model. By studying both theoretically and empirically the physics acting upon an embouchure, an independent model is obtained by taking into account the VIV phenomena as a source of mass-spring excitation. When coupled with the resonator, an improvement on the transient behavior between natural frequencies of the air tube is achieved.

With this accomplishment, the model could become a versatile digital instrument, that would be able to support a player's needs for more expressive sound generation of a virtual brass instrument. However, due to the nonlinear complexity of the embouchure and the empirical approach of modeling self-oscillation, the model proves to be unstable at certain points, creating unwanted distortions, bursts or timbre evolution. An important amount of fine tuning is required to obtain a stable model with a proper sound at the current state.

For future consideration, several in-depth studies on certain aspects of the modeled embouchure could yield improvements. A possible study topic is the behavior of springs with variable elasticity and damping, in order to have a better expectation on the output's fundamental frequency and to adapt the model to the expected frequency. In addition to this, a better insight on input impedance variation and VIV can result in stabilizing the model's behavior while interacting. Though, this research may result in discarding the current mass-spring assumption for lip modeling and replacing it with a more complex design.

After improving the embouchure model, the next steps should concern the refinement of the resonator part of the model. In order to obtain a full-fledged brass instrument, some details of the resonator need to be added to the current implementation. An example of a research topic in this sense can be the bell of the brass tube with a user-modifiable curvature.

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