A PHYSICAL MODEL OF LIPS AND TRUMPET

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Abstract

We describe a physical model of the trumpet, of the lips of the trumpet player and of the interaction between the two, that we have developed at IRCAM. The bore is simply, yet accurately, represented by a linear system. The lip is represented as a non-linear oscillator with two degrees of freedom, moved by pressure from the mouth and from the mouthpiece. The model exhibits behaviors comparable to natural trumpet playing and produces sounds with typical brass quality. We also underline the necessity of a *playing* or *control* model.

Introduction

We have implemented the trumpet model in terms of a linear system for the bore and a model of the lips of the player [Rodet 90]. Lips are represented by a non-linear oscillator moved by pressure from mouth and from the mouth piece. This leads to a system of five non-linear differential equations. The problem is particularly challenging since we have to deal with air flow, nonlinear oscillators, numerical resolution and acoustics, and also because lip parameters are difficult to measure while the player is performing.

Our point of departure has been a model of trumpet designed by W. Strong in the course of a sabbatical visit at IRCAM. We have redesigned this model and studied its behavior according to different possible design choices. In particular, we have experimented with modifications of the computation of volume velocity and pressure around the lips.

It is interesting to compare sound production in the trumpet and in the voice. Although of different size and mass, vocal cords are comparable, in their behavior, to the lips. A *one-mass model of vocal cords* is found inadequate to portray vocal sound production in certain vocal tract configurations [Ishizaka 68]. A very interesting *two mass model of vocal cords* has been developed by Ishizaka and Flanagan. [Ishizaka 72]. The main difference between the vocal system and the trumpet system is that the driving point impedance of the vocal tract is much smaller than the impedance of the trumpet bore. In consequence, the glottis is weakly coupled to the vocal tract and vibrates rather independently of the vocal tract configuration. The lips being pressure controlled, vibrate better at a frequency just under a peak of the trumpet bore impedance [Fletcher and Rossing 91], [Rodet 90] .

Model of a vibrating lip

In the two mass model, vocal cords are assumed to vibrate essentially orthogonally to the trachea, even though in reality they also have a clear motion in the direction of the trachea. The movement of the lips for the trumpet is discussed in [Yosikawa 88]. It then seems that two movements are possible, may be as a function of register. The first movement is orthogonal to the mouthpiece axis - we will call it *up and down* - and is comparable to the movement of the vocal cords. The second movement assumes a lip is rotating around an axis situated at its basis, parallel to the lip, so that the extremity of the lip moves essentially back and forth (Figure1). The vertical movement is measured by y and the rotation by θ. The mouth pressure MP induces an open area A between the lips:

$$A = a_1 + a_2 \cos\theta + a_3\, y \qquad (1)$$

Through the area A, air flows with a volume velocity Ul. From this volume velocity the pressure in the mouthpiece TP can be computed by convolution of Ul with the impulse response Ir(t) of the trumpet at the mouthpiece for a given position of the pistons:

$$TP(t) = Ir \otimes Ul\,(t) \qquad (2)$$

More precisely, a lip is modeled as rigid parallelepiped with length L_L, width L_W, thickness L_T and mass M (Figure 2). This mass can move along two degree of freedom acoustically coupled, but for sake of simplicity we decided for no mechanical coupling. The two movements are represented by two mechanical oscillators with one degree of freedom. Each oscillator is characterized by its inertia, stiffness and damping factor resulting in some natural frequency F_r and Q factor for each oscillation type. The movement of the upper lip only is considered, the lower is assumed fixed (this seems reasonable for high notes [Saneyoshi 87]).

The lip itself is thus considered a linear system, except when lips come into contact. That is, if the area A computed from y and θ is less than some minimum (e.g. 10^{-5} cm^2), damping factors are multiplied by 5 and stiffness is increased by a factor of y^3 or θ^3. The contact of the widely opened lip with the mouthpiece is ignored. In an experiment done at IRCAM, the movement of the lip was filmed using a transparent mouthpiece and a stroboscope. The film shows that the upper lip can come in contact with the mouthpiece. It is thus necessary to take this nonlinearity into account when the opening is higher than some threshold.

In the linear regime, the Q factor is fixed with a value of 5 [Yoshikawa 88]. The resonance frequency and the natural frequency are then close together, and the resonance frequency F_r is chosen as the parameter of an oscillator, since its value is relatively easy to measure for a trumpet player [Yoshikawa 88]. In our first experiments, the F_r's for y and θ movements are chosen equal, but we discuss different values below.

Computation of the volume velocity Ul

Between the lips, air flows in a channel of area A, length L_T (thickness of the lip) and width L_W. The flow is supposed to be irrotational, which is certainly oversimplified at the opening of the channel into the mouthpiece. But we neglect the turbulent phenomena here happening. The mouth pressure MP is computed by considering the acoustic tube from lungs to lips as a simple resistive load R, even though, in reality, it could have some important effect on the oscillator property. The Bernoulli pressure P_B on the lip is then calculated as a function of MP, Ul and A. As a result, we have a differential equation in Ul:

$$(a/A)Ul' - (b/A^3)Ul - (g(\theta)/A^2)Ul^2 = LP - R.Ul - TP \quad (3)$$

Mechanical differential equations

The forces exerted on y and θ oscillators are computed according to stiffness, damping factor and mass deduced from Q factors and resonance frequencies, and from MP, TP (pressure in the mouthpiece) and P_B. This gives two differential equations:

$$My''+a_y y'+k_y y = s_1(LP - RUl - TP)\sin\theta + s_2(LP - RUl - (d/A^2)Ul^2 - (e/A^3)Ul) \quad (4)$$

$$j\theta''+a_r\theta'+k_r(\theta - \theta_0)=v_1(LP\text{-}RUl\text{-}TP)+v_2(LP\text{-}RUL\text{-} (d/A^2)Ul^2 - (e/A^3)Ul)\sin\theta \quad (5)$$

We therefore have a system of 5 equations in (y', y, Ul ,θ, θ'). The other parameters, even though they can be modified, are assumed to vary slowly and are fixed for the solution of the system. Different numerical methods have been tested (Backward Euler, Adams prediction and correction, Runge Kutta 4-4 and discretised Ricatti). No method has been found totally satisfactory. However, the simplest methods (Backward Euler and Adams prediction) seem to work the best.

First results

The model is of high order and difficult to solve, and tests are far from being complete. However, some interesting results have been obtained.

- For a given resonance frequency, the lip starts oscillating when the mouth pressure gets above a certain threshold.
- Usually, the vertical movements play a more important role than the rotation movement. The maxima of volume velocity are much better aligned with the maxima of y than with the maxima of θ. Yoshikawa has observed a movement more important in y, or θ, when the oscillation frequency is under, or above (respectively), a mode of the trumpet. We have not observed such a behavior but this feature may be lost in the simplifications of our model.
- At certain resonance frequencies F_r, the system enters a particular regime where, in addition to the fundamental frequency, the signal is modulated at a very low frequency (10 to 30 Hz). The fundamental frequency can be unstable if the lung pressure drops too low.

Fundamental frequency and energy as functions of LP and F_r

In this section, we consider LP and F_r as the only parameters of the model that the users have at their disposal. Usually they want to obtain some fundamental frequency F_0 and energy E. The mapping between F_0 and E on one side, and LP and F_r on the other has been established by a program on a grid function on the LP-F_r plane. For each couple (LP,F_r), the system output is computed and F_0 and E are measured [Rodet 91]. Figure 3 shows F_0 as a function of LP and F_r, $F_0=G_F(LP, F_r)$, in the interval [240, 600 Hz] and [1000, 100000 Pascals] respectively. Note the influence of the modes: for low pressure specially, F_0 is forced around the frequency of the peak of the trumpet impedance. Figure 4 shows E as a function of LP and F_r, $E = G_E(LP, F_r)$. The energy is particularly high in the vicinity of the peaks of the impedance. This corresponds to the case of playing the instrument on the modes.

Resonance frequency of the oscillators

Until now, for simplicity, we have considered the resonance frequencies F_{ry} and $F_{r\theta}$ of the oscillators as equal. Let us now draw E in the F_{ry}-$F_{r\theta}$ plane. This shows whether a large amplitude stable oscillation occurs. Figure 5, for LP=30000 Pascals shows how this happens effectively when both resonance frequencies are in the vicinity of the peaks of the impedance.

Learning to play and estimation of the parameters

The musical use of a model requires that one can play it in a controlled and expressive way and at a given F_0. We know that learning to play an instrument is usually a difficult process. The physical parameters, such as lung pressure or lip mass and tension, are related to the features of the produced sound, such as fundamental frequency or loudness, through a non-linear and complicated map which usually needs to be learned or modeled.

Here we have two control parameters, LP and F_r, and we assume that the sound output is entirely described by its F_0 and E characteristic. We have obtained the functions $F_0 = G_F(LP, F_r)$ and $E = G_E(LP, F_r)$. To be able to play the instrument we have to get the inverse functions $LP = G_L(F_0, E)$ and $F_r = G_r(F_0, E)$. We have written a program to do this inversion starting from a section of the surface $F_0 = G_F(LP, F_r)$ by the plane $F_0 = f$. The exact values F_0 and E are then computed by interpolation. Another appealing method for learning this nonlinear mapping between (F_0,E) and (LP,F_r) would be to train an Artificial Neural Network [Thouard 90] on the data obtained from the model.

Feedback loop

In the previous section we have described a procedure to adjust the parameters of the model according to the desired sound output characteristics. However, this procedure is insufficient if the model exhibits some hysteresis, as can be observed on our models. In this case, it is necessary to introduce a feedback loop to continuously adjust the parameters according to the measured sound output characteristics.

Conclusion

The model has been simplified in order to retain the most important features. Consequently, it exhibits behaviors comparable to natural trumpet playing and produces sounds with typical *brass* quality. However, much more work is needed to better analyze the physical processes involved, to understand and represent them in a model powerful enough to render all the subtlety of natural sounds, yet simple enough to compute and control [Rodet 92].

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