AN ATTEMPT TO USE AN ELECTRICAL CIRCUIT SIMULATOR TO BETTER UNDERSTAND THE RELATIONSHIP BETWEEN A BRASS PLAYER'S INTONATION AND THE INSTRUMENT'S INPUT IMPEDANCE

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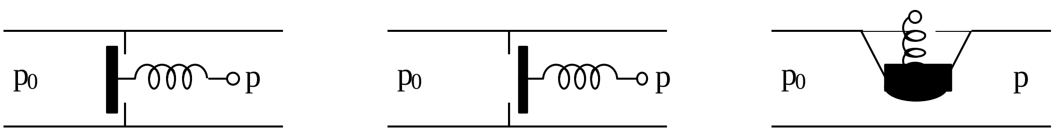
ABSTRACT

Understanding the mechanism of sound production is essential to predict intonation, response and sound of brass instruments. According to Ayers (visualising lip surface waves), Campbell (artificial lips), Adachi et.al. (physical modelling), tone generation on brass wind instruments cannot be satisfactory described by models ignoring lips as independent vibratory systems exhibiting wave propagation and being subject to sound pressure, Bernoulli force and even other forces. Transmission line modelling could be a way to model the distributed nature of lips and wave propagation in and on them. Simulation of such feedback loops including non-linear lip valves using the circuit simulator SPICE is presented.

INTRODUCTION

Understanding all essentials about the oscillator of wind instruments is keeping musical acousticians from all over the world busy up to now. Helmholtz [1] classified wood wind instruments as having reeds operating like inward striking doors tending to close with increased mouth pressure. This classification is obvious and has not been questioned in the past. On the other side, his classification of brass wind instruments as having lip reeds operating like outward striking doors, opening with the blowing pressure, has triggered ongoing discussions and arguments.

Much later in 1982 Elliot and Bowsher [2] raised the question about the role of the time-varying Bernoulli pressure, which has the ability to close the valve by applying a force perpendicular to the direction of air flow. This idea was elaborated by Saneyoshi et al. [3] introducing a third concept, which is now referred to as transverse model. The three concepts are illustrated in *Figure 1*, which was taken from publications of Adachi [4][5], where a much deeper investigation of these models can be found.



(a) **(b)** **(c)**

Figure 1: Classification of sound production mechanisms

A unified discussion of oscillation conditions for all three classes of oscillators was presented by Fletcher [6]. A linear theory of self-oscillation was published, reviewed and extended in [2] [7] [4].

The question, which of the three oscillator concepts applies to the sound production in brass instruments is still being investigated. Experiments with artificial lips made by Campbell's group [8] show that outward striking as well as inward striking action can be observed, depending whether a tone is blown above or below a natural resonance of the instrument. This is controlled by the player, who can lick a note up or down by changing the eigenfrequency of the lip oscillator.

Anyhow, observations made by Ayers [9], who presented detailed stroboscopic videos of lip action in different brass instruments, make it clear, that lip oscillation cannot accurately be described by simplified lumped models. It involves door-action as well as elastic and lossy deformation giving rise to surface waves with several modes of oscillation. On top of that, it is very likely that the lip motion inside the mouthpiece has a significant effect on the input impedance of the instrument, which is often considered as a well known and accurately measurable time-invariant quantity.

The model presented in this paper is far away from taking all these complex mechanisms into account. On one side it is just another simplified lip model based on the transversal concept, which seems to be a good approximation as long as blowing pressure is too small to enforce significant outward striking amplitudes. On the other side it is the first attempt to take the distributed nature of human lips into account by using a transmission line model instead of a lumped spring-mass system perpendicular to the flow direction.

The second and maybe even more interesting aspect of this work concerns the proposed method, to solve the non-linear system of differential equations. Small signal analysis in the frequency domain, operating point analysis, transient analysis in the time domain and even sensitivity analysis can most efficiently be made with the same equivalent circuit using an electrical circuit simulator.

Recent derivates of SPICE, the original and widely known public domain circuit simulator from the Berkeley University, have built-in sophisticated components models, like lossy transmission lines, non-linear elements like switches and dependent voltage/current sources which are specified by polynoms or arbitrary expressions of any number of other circuit variables or by tables, either related to time domain, frequency domain or to the z-domain of sampled systems.

If we now consider, that engineers are nowadays simulating integrated circuits with thousands of non-linear elements (e.g. transistors) with such circuit simulators, it will become clear, that almost any model of vibrating lips can be implemented with little effort. This paper only wants to give an example, how an actual acoustical and mechanical model described by a set of differential equations can be transformed into an electrical equivalent circuit, ready to be analyzed in frequency or time domain.

MODEL AND EQUIVALENT CIRCUIT

The system, which was modelled to be simulated consists of a players lung, his air column, his mouth cavity, the vibrating lips and an open Bb trumpet with mouthpiece. The electrical equivalent circuit is shown in *Figure 2*. It is divided in three functional sub-circuits: The path of airflow from lung to trumpet mouthpiece, the oscillating lips and their effect on the airflow.

Little attention has been paid on the actual trumpet sound. It would be very easy to connect an additional element to the mouthpiece pressure *pmp*, which represents the complex transmission function of the trumpet – including even auditory acoustics, if you like. This element is driven by a table of frequency, magnitude and phase triplets, just like the element **H1**, representing the trumpet's input impedance.

The element **H1** converts an input current (the acoustical volume flow *u*) into an output voltage (the sound pressure level *pmp* in the mouthpiece) according to a given frequency domain table, which has been calculated from an actual trumpet bore using the lossy transmission line model published by Mapes-Riordan [10] and summarized by the author [11]. The magnitude spectrum is shown in *Figure 3*. The mapping between voltage [V] and pressure [Pa] and between current [A] and volume flow [m^3/s] requires acoustic impedance [Ω] to be specified following the mks convention.

The air flow originates in the lung, driven by the pressure source **V1**. For certain simulations the blowing pressure was varied between 1 and 6 kPa. A realistic throat resistance should be in the order of 4MΩ depending on throat area, the mouth cavity capacitance could be derived from C = u t / Δp with t being the time needed to change the pressure in an equivalent volume by Δp, when a constant volume flow u is flowing into the cavity. This was not done, so the effect of the mouth cavity was not taken into account properly.

The elements **E2**, **L1** and **E3** represent the modulation of the flow by the time varying lip orifice. According to Adachi, who excellently reviewed the applicable theory of fluid dynamics in [5], two distinct modulation regions have to be differentiated: The upstream contraction region, i.e., the mouth cavity and the lip orifice and the downstream expansion region, i.e., a thin region in the mouthpiece cup, where a jet is formed and energy is dissipated by turbulences until laminar flow is established again.

The conservation laws for energy and momentum in the laminar contraction region and for momentum only in the turbulent expansion region give the required relations between the pressures *pm* (mouth pressure), *plip* (the Bernoully pressure applying the driving force onto the lip) and *pmp* (the mouthpiece pressure, which is linked to the flow *u* by the instrument's input impedance), the flow *u* and the area of the lip orifice *slip* (***r*** = air density, D = length of lip orifice, SCUP = cross-sectional area at mouthpiece entry):

$$pm - plip = \frac{\mathbf{r}}{2}\left(\frac{u}{slip}\right)^2 + \frac{\mathbf{r}\,D}{slip}\frac{\partial u}{dt} \qquad plip - pmp = -\mathbf{r}\,u^2\left(\frac{1}{SCUP\ slip} - \frac{1}{SCUP^2}\right) \tag{1}$$

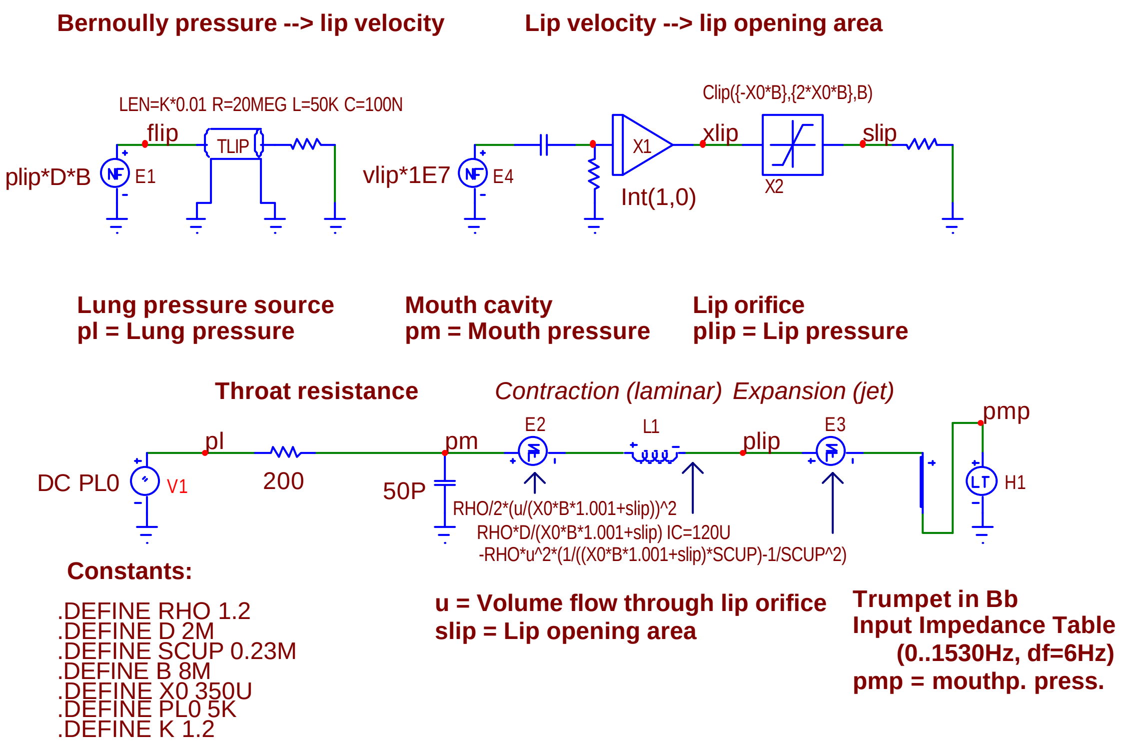


Figure 2: Equivalent circuit

Electrically speaking, the voltage drop between *pm* and *plip* is caused by a nonlinear voltage source **E2** and an inductor **L1** with time dependent inductance L= ***r*** *D / slip* and the voltage drop between *plip* and *pmp* is again caused by a nonlinear voltage source **E3**. In the simulation schematic *slip* denotes only the AC component of the time varying area, therefore the average lip opening *X0 ´ B* (*X0* = equilibrium lip opening distance, B = breadth of lip orifice) has to be added. Minimum and maximum lip opening areas are limited to avoid area numbers less or equal to zero.

The actual lip model is implemented by the transmission line **TLIP**. It is excited by the voltage source **E1**, which now represents a force rather than a pressure (Volt = Newton) and which duplicates the Bernoully pressure *plip* multiplied by the lip area *D ´ B*. Like any distributed dissipative mass / stiffness system, a transmission line conducts, damps and reflects input pulses and modulates the input current by its complex impedance, which depends on termination, length and material properties. It exhibits several resonance modes and it can even be arranged in a network to represent 2-dimensional, even 3-dimensional, distributed oscillatory systems. Acoustically the currents have to be interpreted as surface or node velocities.

The impedance of the lip has not been measured, therefore correct properties of the transmission line element are not known. Reasonable assumptions have been made about resonance quality and absolute scaling has been chosen in a way to get lip displacements in the expected order of magnitude. As a tuning parameter for the first resonance mode the factor *K* has been introduced which scales the original length of the line. Please note, that a big impedance magnitude causes a small current (=velocity) flow, it is therefore the minima not the maxima, where self oscillations can occur.

Lip velocity *vlip* has to be integrated (**X1,** gain=1, initial value=0) to get lip displacement *xlip*. In order not to integrate any DC offsets a simple high-pass filter has been put in front. The resulting displacement is limited and multiplied with the breadth of the rectangular lip orifice (**X2**, low=-*X0 B*, high=2 *X0 B*, factor=*B*) to get the AC lip orifice opening area *slip*.

SIMULATION RESULTS

Looking at the results shown in *Figure 5* it can be observed that mode selection takes place. All natural tones with the exception of the pedal tone (which is even difficult to play in reality) are played properly, when the first anti-resonance of the lip oscillator is swept between about 100Hz and 700Hz. Comparing the lip resonance curves shown in *Figure* ***4*** with the sounding frequencies, it can be seen that the first anti-resonance of the lip is always lower than the sounding trumpet resonance. This explains the missing pedal tone, because a frequency well below 90Hz has not been reached during simulation. It is interesting, that the actually sounding frequency is nevertheless even higher than the trumpet's resonance.

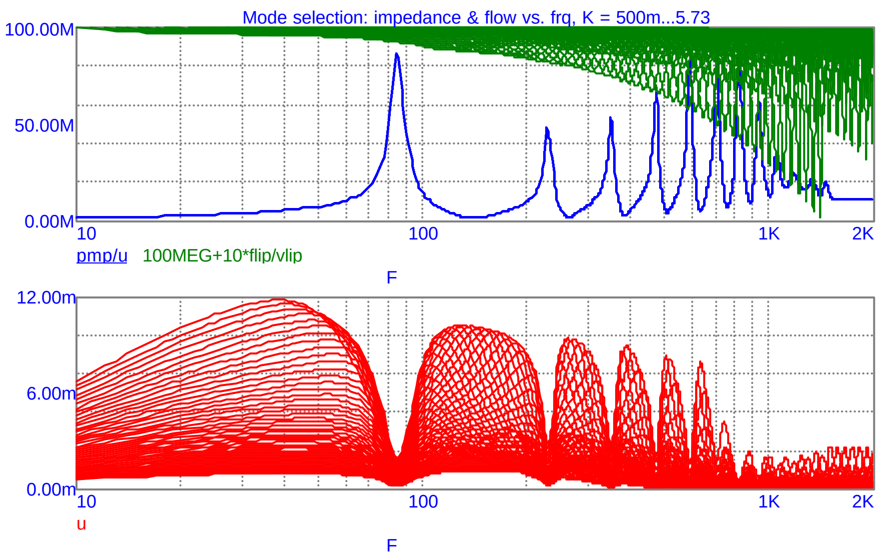


Figure 3: Trumpet impedance with varying lip impedance

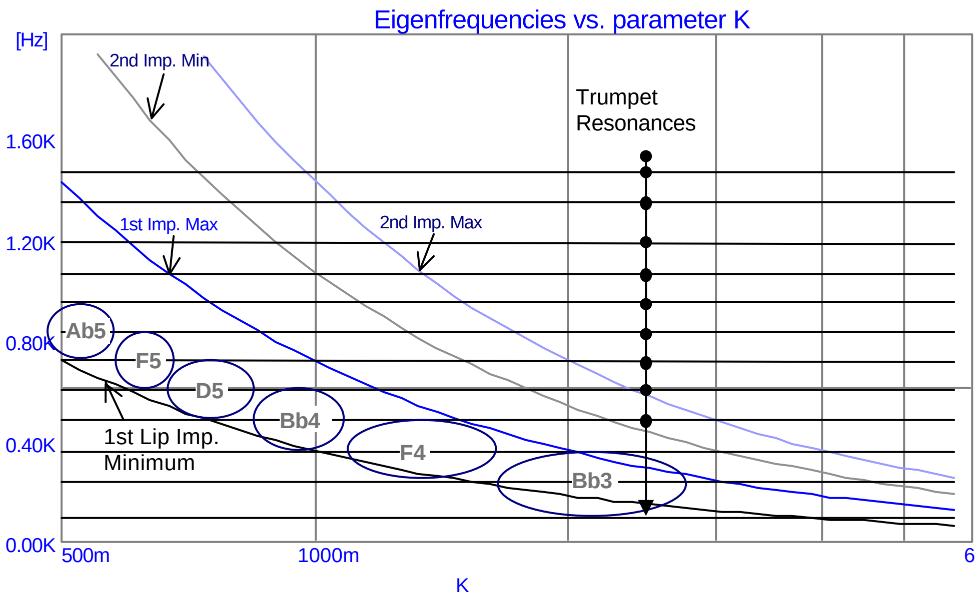


Figure 4: Lip eigenfrequencies and trumpet resonances

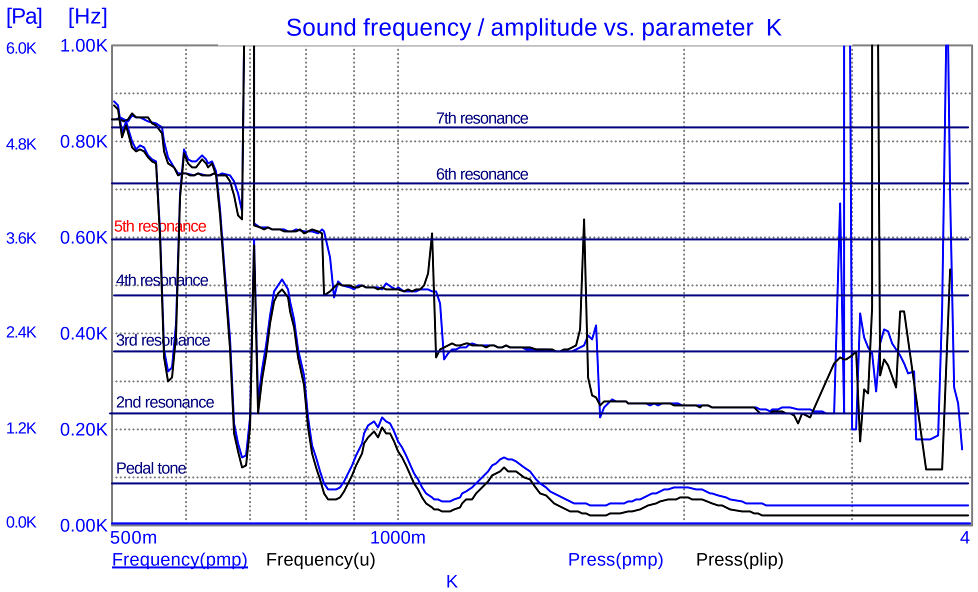


Figure 5: Mode selection (sounding frequencies and amplitudes)

This fact needs an explanation, especially because the opposite is usually attributed to the transverse model. Comparing with Adachi's results [5] it seems that the transversal model acts like a swinging-door model, when a transmission line is used to resemble the lips.

Maybe it is not the kind of model, which decides whether notes are blown on the rising are falling side of the resonance peak and whether lip resonance must be higher or lower than the played trumpet resonance. Maybe it is simply the question, whether pressure or flow related forces acting on the lip resonator are dominating and whether resonances or anti-resonances of the lip oscillator are required to self-oscillate. An indication for this hypothesis is, that by adding flow and pressure related forces, Adachi succeeded to balance both effects [4].

Another simulation detail is shown in *Figure 6*. By increasing the blowing pressure it is possible to switch to the next resonance mode without changing the tension of the lips, a fact, trumpet players probably know and most probably dislike.

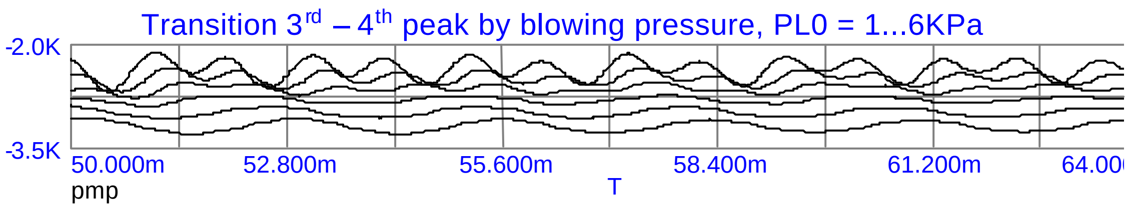


Figure 6: Mode transition by blowing pressure

CONCLUSIONS AND OUTLOOK

A player – trumpet system was successfully simulated using a standard electrical circuit simulator. The lip was modelled as a distributed damped mass/stiffness system according to the so called transversal model. Realistic mode selection has been observed, but new questions about model classification and related oscillation conditions have been raised.

Further work will be necessary to get deeper insight into the most interesting relation between an instrument's input impedance and a typical player's opinion about its response and intonation. By extending the model predictions of radiated sound spectra, attack and decay properties will be possible.

The lip model can be extended to a more dimensional distributed network of transmission lines exhibiting surface waves with velocity components perpendicular and in the direction of the flow. In the second case a mouthpiece layer with lip modulated volume could be modelled.

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