# PHYSICAL MODELING OF ORGAN PIPES WITH FREE REEDS

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ABSTRACT
Nowadays, striking reeds are commonly used for the reed pipes in organs, while in the 19th century free reeds were often used in Germany. After being banned during the *'Orgelbewegung'* at the beginning of the 20th century, free reed pipes are now being used frequently again. Because much of the experience concerning those pipes has been lost, the acoustical behavior of free reed pipes was simulated using an one-dimensional physical model so as to determine the optimal resonator and boot dimensions.

## 1. INTRODUCTION

The free reed was introduced into the organ by Abbé Vogler at the end of the 18th century. It differs in size of the reed and the frame from striking reed pipes which were used exclusively in organs beforehand. Free reeds are built in such way that the reed can oscillate freely through the frame and does not hit onto the shallot. Due to this alteration, their acoustical behavior is very much different from that of the striking reed pipes. Therefore, the dimensions of the remaining parts of the pipe (especially those of the resonator and the boot) have to be specially adjusted.

In the beginning of the 20th century, the free reed became unfashionable during the *'Orgelbewegung'*, a German movement that tried to restore the ideal of the barock organ. But nowadays, those type of stops are frequently considered again in new organs. However, some of the practical experience concerning those stops has meanwhile been forgotten and a number of experiments have to be carried out to restore this knowledge. To reduce the experimental effort, a one-dimensional model of a free reed pipe was developed and compared to existing data.

## 2. EXPERIMENT

<u>Method</u>

Two free reed pipes of the stop *Klarinette 8'* ($C_4$, Klais, Bonn) were used for the measurement that has already been presented at a meeting of the German Acoustical Society (Braasch et al., 2000). One of them had a cylindrical resonator of 38.5 cm length (the resonator length is here defined as the distance between the tuning wire in tuned position and the open end of the resonator). By fixing a second tube onto the resonator that was slightly wider than the resonator, its length could be adjusted to any length between 46 cm and 65 cm. The second free reed pipe that was used in the measurement had a conical resonator (40 cm length) which could be extended by 4 additional conical parts in steps of 5 cm to a maximum length of 65 cm.

The frequency of the reed of the cylindrical free reed pipe was measured using a laser vibrometer (Polytec OFV302 sensor head, OFV 3000 controller; Ono Sokki CF-360 Portable Dual Channel FFT Analyzer) at the Department of Physics at the Northern Illinois University, according to the method of Rossing et al. (1998). For all remaining measurements, the sound pressure of the pipe was recorded digitally on the intonation bank at the Klais organ workshop in Bonn using a microphone that was placed 50 cm above the outlet of the resonator.

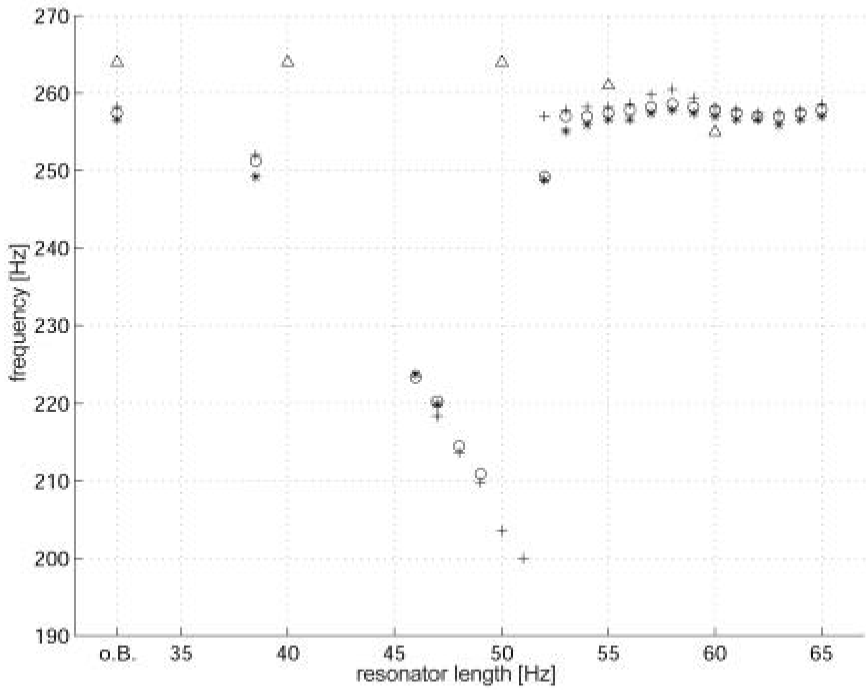


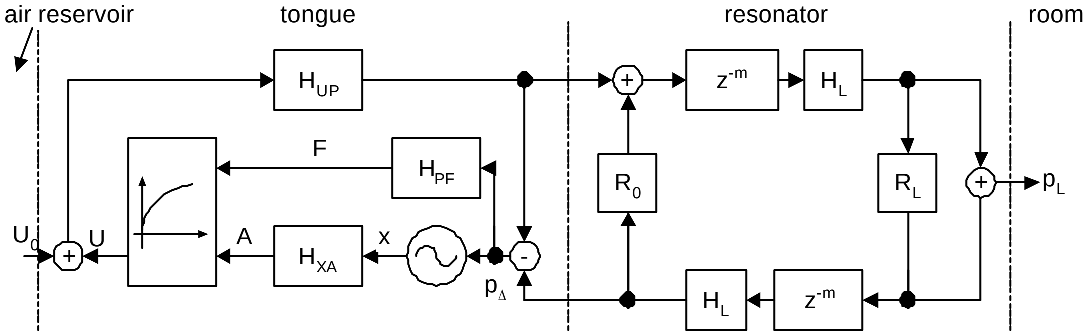

*Fig. 1: Fundamental frequency of the free reed organ pipes in dependance of the resonator length: '*': 50 mm/$H_2O$, '·': 70 mm/$H_2O$, '+': 90 mm/$H_2O$ (all with cylindrical resonators); D: 70 mm/$H_2O$, conical resonator.*

Results

Fig. 1 shows the dependance of the fundamental frequency of the pipe on the length of the resonator. As already mentioned by Töpfer/Allihn (1888) and Ellerhorst (1936), the fundamental frequency of the cylindrical pipe drops with increasing resonator length to a certain point, at which the pipe stops to sound (cylindrical pipes: 49-50 cm, 50 mm/$H_2O$; 50-51 cm, 70 mm/$H_2O$; no dead point, 90 mm/$H_2O$). After this dead point, the fundamental frequency jumps back to approximately the resonance frequency of the reed. The wind pressure had no noticeable effect on the frequency of the pipe. However, the range, in which the pipe does not sound, could be decreased by increasing the wind pressure. The conical resonator had a different effect on the pipe than the cylindrical one. Here, the fundamental frequency was less affected by the increase of the resonator length and the pipe only stopped to sound at a resonator length of 65 cm.

## 3. MODEL STRUCTURE

The proposed model is based on the free reed model of Tarnopolsky et al. (2000). The advantage of this model is that it simulates quantitative physical parameters. For the simulation of free reed organ pipes, the model had to be modified in two ways. Firstly, it had to be coupled to a resonator, which was not applied in the work of Tarnopolsky et al. (2000). Secondly, the free reed had to be turned into an inward striking type. In inward striking pipes, the wind pressure in the air reservoir creates a force that causes the reed to move into the direction of the air reservoir in the first place. In outward striking pipes the type which is found in Asian mouth organs as simulated by Tarnopolsky et al. on the other hand the reed moves into the opposite direction at their first move.




model parameters:

| | | | |
|---|---|---|---|
| x | : reed displacement | $p_L$ | : radiated sound pressure |
| $p_D$ | : pressure difference $p_I$-$p_O$ | $H_{Up}$ | : transfer function airflow/pressure |
| F | : force onto the reed | $H_{xA}$ | : transfer function displacement/reed area |
| U | : air flow | $H_{pF}$ | : transfer function pressure/force |
| $U_0$ | : air flow into the boot | $H_L$ | : transfer function resonator delay line |
| A | : area of reed opening | $R_0$ | : reflectance resonator opening at reed |
| $p_I$ | : air pressure in the boot | $R_L$ | : reflectance resonator opening at outlet |
| $p_O$ | : air pressure in the resonator | $z^{-m}$ | : delay line |

*Fig. 1: Model structure*

In Fig. 1, the basic structure of the model, the physical parameters and their interactions are shown. The movement of the reed *x* is simulated in a mechanical oscillator circuit as a damped mass-spring system. The pressure difference $p_D$ between air reservoir and resonator at the reed creates a force *F* on the reed, which is simulated according to the Bernoulli force. The reed acts principally as a valve and its movement controls the air flow *U* through the pipe by gradually opening and closing. The value *U* greatly depends on the area of the reed *A*. Both the inner air pressure (sound pressure within the boot) $p_I$ and the outer air pressure (sound pressure in the resonator at the end of the reed) $p_O$ are dynamical parameters and therefore also the pressure difference $p_D$. The pressure in the boot $p_I$ varies greatly with the volume of the boot, the outer pressure $p_O$ with the dimensions of the resonator. The three main equations that have to be solved are:

$$m\frac{d^2x}{dt^2} + \frac{mw_0}{Q}\frac{dx}{dt} + mw_0{}^2x = 1.5WL(p_I + p_O) \qquad (1)$$

$$\frac{dp_I}{dt} = \frac{rc^2}{V}(U_0 - U) \qquad (2)$$

$$U = \sqrt{\frac{2(p_I - p_O)}{r}}CA \qquad (3)$$

In the calculation the equations are discretized and solved iteratively. The area of the reed opening *A* was estimated according to the equations 2 and 5 in Tarnopolsky et al. (2000). The physical parameters were chosen as follows:

| | |
|---|---|
| resonance frequency of the reed, ù: | 264 Hz |
| sharpness of resonance of the reed *Q*: | 50 |
| reed width, *W*: | 6.6 mm |
| reed length, *L*: | 22.4 mm |
| reed thickness: | 1,5 mm |
| reed material: | brass (ñ=8580 kg/m$^3$) |
| air flow into the boot, $U_0$: | 0.005 m$^3$/s |
| volume of the boot, *V*: | 0.3 liter |
| flow-contraction coefficient, C | 0.61 |

## 4. SIMULATION OF THE RESONATOR

The resonator is simulated using a digital waveguide model (Smith, 1998). It is assumed that a forward and a backward propagating wave exist. A delay line is used to model each. The solution for the whole resonator can be obtained by the addition of the values of all corresponding delay elements. Losses in the resonator are calculated either at the beginning or the end of the delay line $z^{-m}$. The reflectances $R_0$ and $R_A$ at both ends of the resonator had to be estimated to be able to simulate different resonator shapes. The reflectance at the open end of the resonator was calculated using the solution of Levine and Schwinger (1948) for the radiation impedance of open resonators. The diameters of the resonators with variable length *l* were chosen for the types: cylindrical, conical I and conical II as follows:

| | $\phi$ (reed) | $\phi$ (bell) |
|---|---|---|
| cylindrical | 4.5 cm | 4.5 cm |
| conical I | 3.2 cm | 6 cm |
| conical II | 3.2 cm | (12.9+*l*) 0.064 cm |

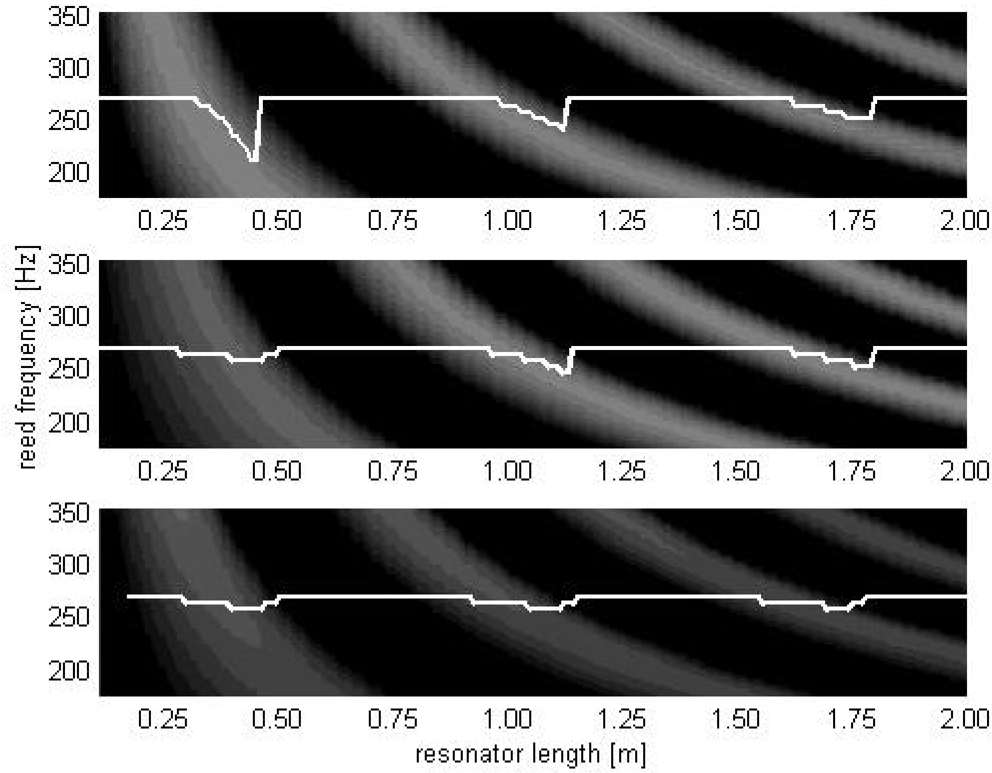



*Fig 2.: Reed frequency (white lines) of the model at different resonator length (top: cylindrical; center: conical I; bottom: conical II). The resonance frequencies of the resonators are shown in the background (light gray).*

## 5. MODELING RESULTS

Fig. 2 shows the fundamental frequency of the reed as a function of the resonator length *l* for three different resonator shapes (cylindrical, conical I with constant conical angle, conical II with constant diameters at both ends). The gray curves show the resonance frequencies of the resonators. The frequency of the reed is affected most if it is in the range of a resonator frequency as it was proposed by the solutions of Weber (1828) and Helmholtz (1865).

The influence of the cylindrical resonator ($\phi$=4.5) on the fundamental frequency of the pipe is larger than the influence of the conical resonator. This was already observed for a real organ pipe (Fig. 1). However, the influence is not only determined by the shape of the resonator, but also by its diameter, and in the simulation the influence of the conical resonator I on the reed frequency was larger than the influence of the conical resonator II.

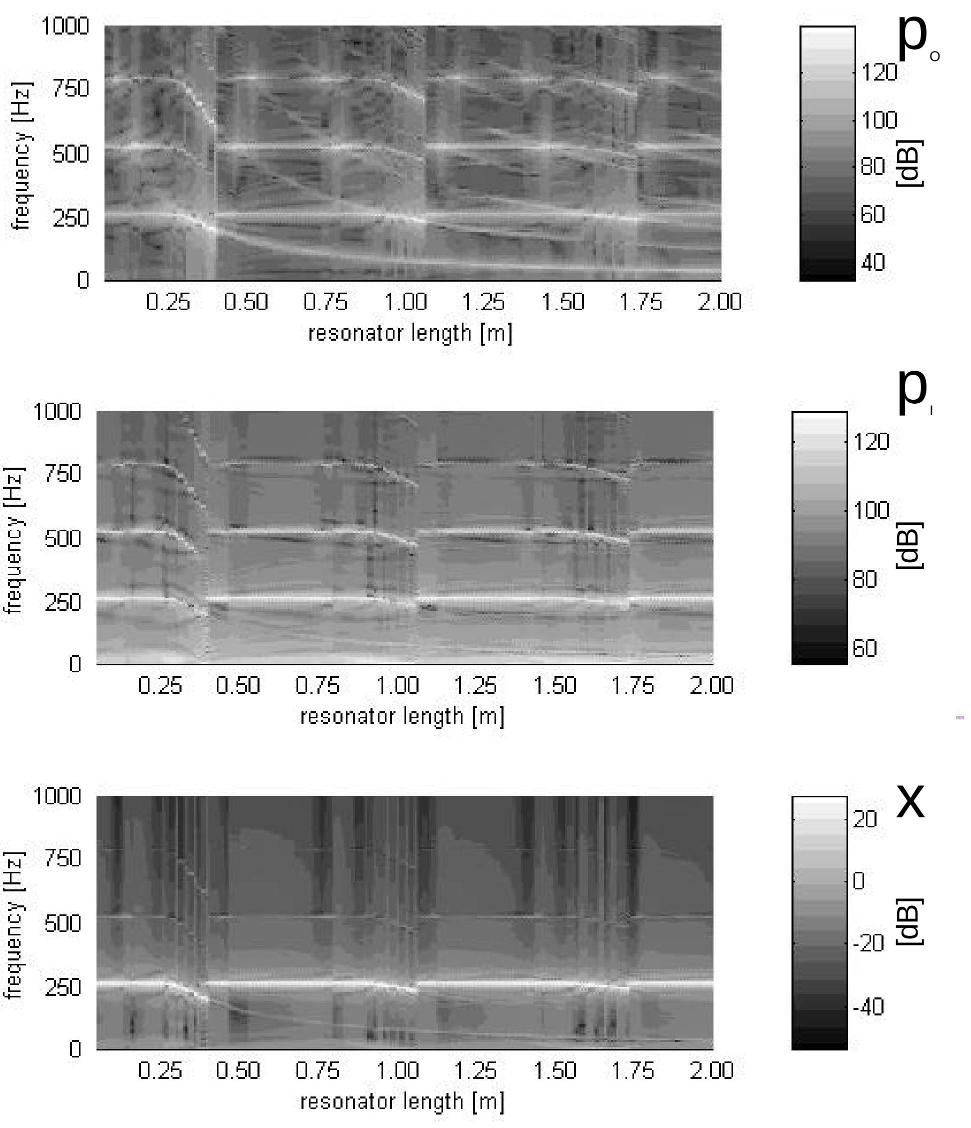



*Fig. 3: Spectrograms for three different simulated physical parameters (top: $p_O$, the sound-pressure amplitude in the resonator at the reed; center: $p_I$, the sound-pressure amplitude in the boot at the reed; bottom: x, the amplitude of the reed displacement).*

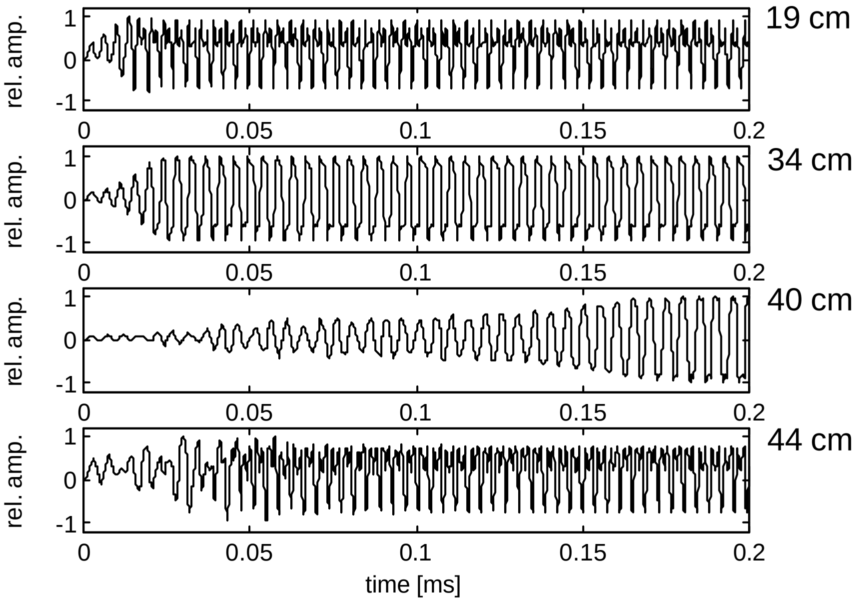



*Fig. 4: Onsets simulated for different resonator lengths for a cylindrical resonator.*

Fig. 3 shows the spectrograms for three different physical parameters (top: $p_O$, the sound-pressure amplitude in the resonator at the reed; center: $p_I$, the sound-pressure amplitude in the boot at the reed; bottom: $x$, the amplitude of the reed displacement). In each of the three figures, the resonance frequency of the reed and the resonator are clearly visible. In contrast to the real pipe, a strong decrease of the reed amplitude in those cases where the frequency is significantly smaller than the reed resonance frequency is not observed in the model simulation. It is aimed to improve the model in the future to show this effect. However, it can be observed that $p_I$ increases in those cases where the reed frequency is near its resonance frequency,while $p_A$ increases in those cases where the reed frequency is determined by a resonance frequency of the resonator.

Also concerning the onset oscillation some typical characteristics of the free reed organ pipe could be simulated. The oscillation can be modified through the resonator in a similar way as it was observed in the experiment. The onsets of the reed displacement for four different cylindrical-resonator lengths (Ö=4.5) are shown in Fig. 4. As it was already observed for real pipes, the onset slope turns out to be more regular, if the resonator is set to the right length (here from 19 cm to 34 cm). Moreover, the onset time is increased if the fundamental frequency drops significantly, when the resonator length is increased (here 40 cm). After the fundamental frequency of the reed switches back to its resonance frequency, the onset is irregular for the first few centimeters.

## LITERATURE


J. BRAASCH , C. AHRENS, J.P. COTTINGHAM and T.D. ROSSING **(2000)**: *Der Einfluß der Becherlänge bei Orgelpfeifen mit Durchschlagzungen*, in: Fortschr. Akust., DAGA 2000, Oldenburg, p. 242-243.

W. ELLERHORST **(1936)**: *Handbuch der Orgelkunde*, Einsiedeln.

H. HELMHOLTZ **(1865)**: *Die Lehre von den Tonempfindungen*, Braunschweig.

H. LEVINE and J. SCHWINGER **(1948)**: *On the radiation of sound from an unflanged circular pipe*. Phys. Rev. 73, p. 383-406.

T.D. ROSSING, J. ANGSTER, A. MIKLÓS **(1998):** *Reed vibration and sound generation in lingual organ pipes*, J. Acoust. Soc. Am. 104, p. 1767-1768.

J.O. SMITH **(1998)**: *Principles of digital waveguide models of musical instruments*, in: Applications of digital signal processing to audio and acoustics (ed. M. Kahrs and K. Brandenburg), p. 417-466. Kluwer Academic Publishers, Boston/Dordrecht/London.

A.Z. TARNOPOLSKY, N.H. FLETCHER and J.C.S. LAI **(2000)**: *Oscillating reed valves: An experimental study*, in: J. Acoust. Soc. Am. 108, p. 400-406.

J.G. TÖPFER **(1888)**: *Die Theorie und Praxis des Orgelbaus*, Max Allihn (ed.), reprint of the second edition, Netherlands 1972.

W. WEBER **(1828)**: *Theorie der Zungenpfeifen*, in: Annalen der Physik und Chemie 93 (ed. J.C. Poggendorff), Leipzig 1828, p. 193-246.