Examination of a novel organ pipe construction with blown open tongue

Péter Rucz[1], Judit Angster[2], András Miklós[2,3]

[1] Budapest University of Technology and Economics, Budapest, Hungary, Email: rucz@hit.bme.hu

[2] Fraunhofer-Institut für Bauphysik, Stuttgart, Germany

[3] Steinbeis Transferzentrum Angewandte Akustik, Stuttgart, Germany

Introduction

In a traditional pipe organ the pipe ranks are composed of labial (flue) and lingual (reed) pipes. Both kinds of ranks are tuned and voiced to a nominal windchest pressure. Changing this pressure not only affects the amplitude of the radiated sound but both the pitch and the timbre of the pipes. This means a strict limitation to the dynamic range of these pipe ranks.

In this contribution a new construction is examined that can possibly have an extended dynamic range: organ pipes with blown open free reeds. These pipes are referred to as "dynamic organ pipes" by their inventor, Ernst Zacharias [1, 2]. Contrary to traditional lingual pipes with blown closed beating tongues, the blown open free tongue can operate in a very wide range of driving pressures. The paper focuses on experimental investigations and discusses the results of laboratory measurements performed on experimental pipes. In addition, a simplified model of the new construction is established explaining the observed phenomena.

Experimental pipes and tools

The new pipe construction consists of three main parts which are the pressure tank, the tongue, and the resonator. From the windchest air is first conveyed into a small pressure tank which functions as the pipe foot (or boot). On the inner side of the pressure tank a blown open tongue is mounted. Contrary to the traditional lingual pipe design, the novel construction does not include a shallot: the pressure tank and the resonator are connected directly by the tongue. The other side of the tongue faces the resonator that can have different shapes.

All experiments reported in this paper were carried out on a total of three experimental pipes that are depicted in Figure 1. The three pipes have significantly different resonator constructions, as shown in Figure 1(a). Pipe #1 has a straight resonator, open on both ends. The resonator of pipe #2 is also straight with two open ends; however, it is turned into half, hence the two open ends are located side by side. Pipe #3 has a conical resonator with one open end. This cone is also turned into half. All three resonators are made of wood. In order to facilitate the measurement of the tongue vibration by means of a laser vibrometer the front side of the pressure tank of each pipe was made of plexiglas, as shown in Figure 1(b).

The experimental setup is depicted in Figure 2. All measurements were assembled and carried out in the pipe organ laboratory of the Fraunhofer Institute of Building Physics, Stuttgart, Germany. Throughout the experiments a model wind system (including the blower, the roller valve, the bellows, the wind duct, the windchest, and the fan control unit) was used. The fan control unit provided the desired constant windchest pressure and also controlled the valve inside the windchest for automated recordings. By changing the fan frequency and the weights on the bellows the windchest pressure could be adjusted between 50 and 1100 Pa.

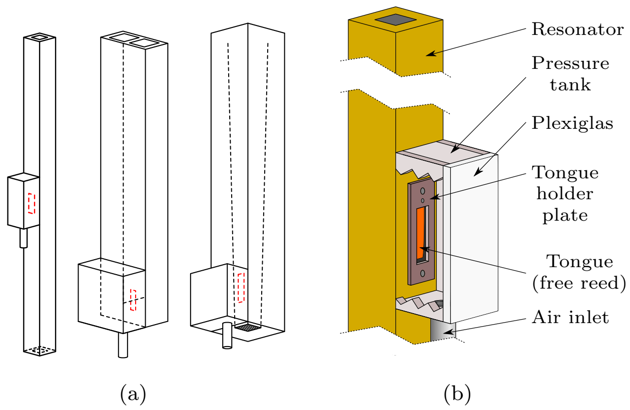


Figure 1: Experimental pipes. (a) Resonator shape of pipe #1, #2, and #3 (from left to right). The red dashed lines indicate the position of the tongue. (b) Illustration of the tongue construction.

The experimental pipes were stood upon the windchest and air was supplied to them using a pressure tube. Two calibrated condenser microphones (type GRAS 46AF 1/2") were used for recording the sound of the pipes. The microphone signals were amplified by a B&K Nexus 2690-OS2 amplifier. The tongue vibration was measured using a Polytec OFV3001 laser vibrometer pointing to the free tip of the vibrating reed. The pressure inside the small pressure tank was registered using a Honeywell 163PC01D36 pressure sensor. The latter pressure sensor could measure from DC to ≈ 1 kHz frequency. The signals were digitized using an 8-channel A/D card that operated with a sampling frequency of $f_s = 40$ kHz. The recordings were triggered by the signal that opened the valve inside the windchest. During each recording the pipe was sounded three times for 8 seconds with 2 seconds of pause between the sounds.

The recordings were evaluated using an in-house software tool called SoundAnalysis. This analysis tool provides signal processing routines for the precise determination of the fundamental frequency. Resampling and averaging

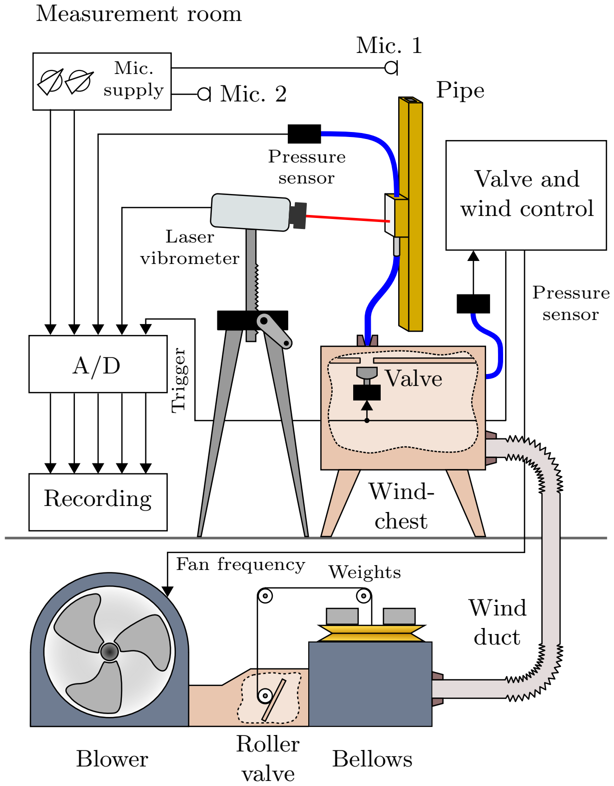


Figure 2: Experimental setup and tools.

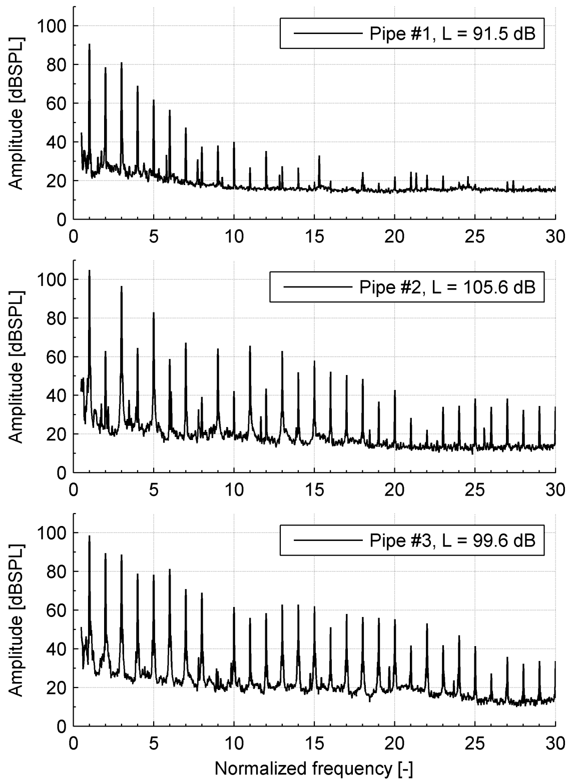


Figure 3: Steady state spectra of the experimental pipes at $p_{\mathrm{ref}} = 400\,\mathrm{Pa}$ blowing pressure.

were used for evaluating the steady state spectra. This led to a good signal to noise ratio with avoiding the spectral leakage and picket fence effects at the same time.

Measurement results

The steady state spectra of the three experimental pipes at the reference blowing pressure $p_{\mathrm{ref}} = 400\,\mathrm{Pa}$ are shown in Figure 3. For the sake of better comparability the spectra are shown in a nondimensional frequency scale, where the unit is the fundamental frequency of the given pipe. As it can be seen, the fundamental is the strongest partial in the steady state in case of all pipes. At the same time, the envelope and hence the timbre of the pipes are remarkably different.

In case of pipe #1 the octave is weaker than the third partial, which is due to the fact that the position of the tongue is near to a pressure node of the even modes of the resonator. In the steady state spectrum of pipe #2 the even partials have significantly lower amplitudes than the odd ones. This phenomenon can be explained by the destructive interference occurring in case of even modes: the standing pressure waves in the air column have opposite phases at the two ends of the resonator for these modes. The steady state spectrum of pipe #3 contains a large number of strong partials. Among these, the 9$^{\mathrm{th}}$ harmonic has a locally minimal amplitude.

The attack transients of the pipe sounds were also analyzed. It was found that the speed of the attack is similar to that of traditional organ pipes; about 20 to 50 periods were needed to reach the steady amplitudes. It was also observed that the order of the amplitude of the partials remains the same during the whole attack as in the steady state pipe sound.

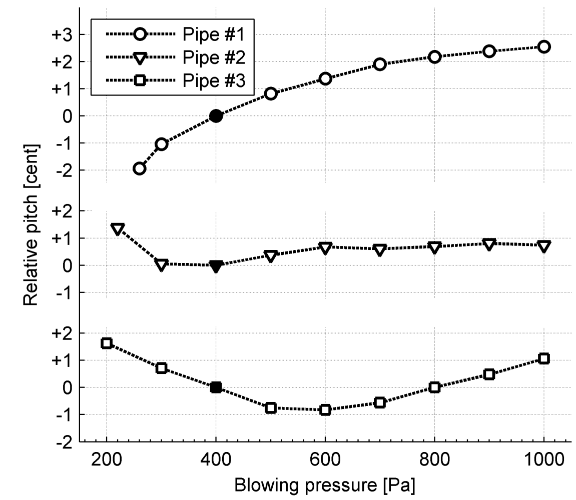
Dynamic organ pipes should be playable at different blowing pressures. Ideally, the pipes should produce the same pitch and timbre for all windchest pressures. As it is seen in Figure 4(a), the stability of the fundamental frequency is very good for all three experimental pipes. The maximum deviations from the reference pitch are less than ± 3 cent. As a comparison, the pitch of a labial pipe would change in a similar extent due to a $\pm 1°\mathrm{C}$ fluctuation of the ambient temperature.

The minimal blowing pressure of pipes #2 and #3 is around 200 Pa. Pipe #1 requires $\approx 260\,\mathrm{Pa}$ pressure in the windchest to provide a stable steady state sound; however, close to the minimal pressure the attack of the sound is slow and unstable. In the stable region, the amplitude of the fundamental component of the steady state pipe sound increases by 12–15 dB with increasing the blowing pressure, as shown in the top graph of Figure 4(b). The amplitude of the tongue vibration also varies in the same range.

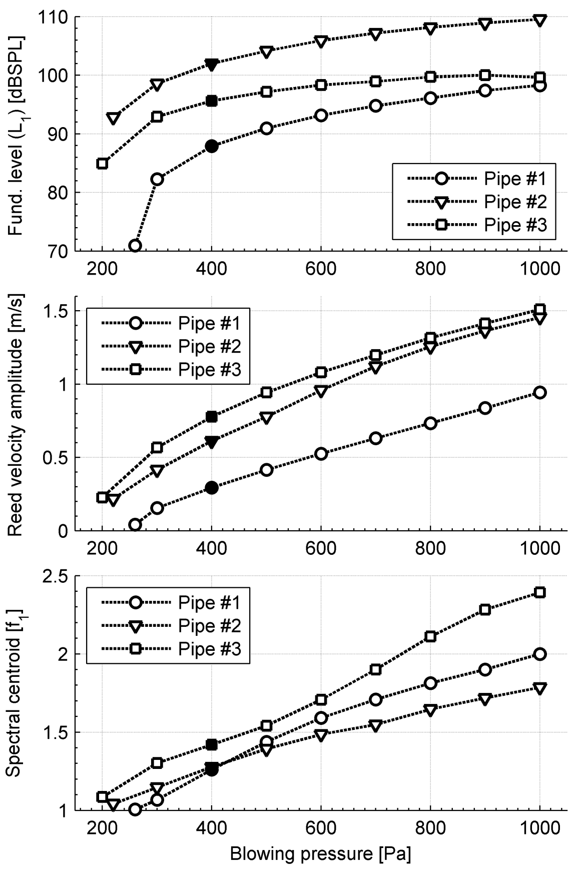
For each setup the centroid C of the steady state power spectrum $X(f)$ was calculated from the amplitudes of the first $N = 20$ harmonics as

$$C = \frac{\sum_{n=1}^{N} nX(nf_1)}{\sum_{n=1}^{N} X(nf_1)} \qquad [f_1], \qquad (1)$$

where f_1 denotes the fundamental frequency of the pipe.



(a) Fundamental frequency



(b) Amplitudes and spectral centroid

Figure 4: Effects of changing the blowing pressure. The reference case with $p_{\text{ref}} = 400\,\text{Pa}$ is highlighted by the filled markers.

The result of the calculation is shown in the bottom diagram of Figure 4(b). As it can be seen, the centroid of the spectrum significantly increases with increasing the blowing pressure. This effect can also be heard in the subjective comparison of pipe sounds: with normalizing the amplitude of the recordings the change of the timbre becomes obvious to the listener.

	Value [mm]		
Parameter	#1	#2	#3
Physical length	597	1 181	1 188
Inner circumference	56.0	113.3	63.9 – 172.9
Effective radius	7.9	16.0	9.0 – 24.4
Effective length	610	1 207	1 170

Table 1: Physical and effective dimensions of the resonators.

		Value		
Component	Parameter	#1	#2	#3
Sound	f_{sound} [Hz]	278.4	139.8	108.9
Reed	f_{reed} [Hz]	247.8	127.1	98.5
	Q_{reed} [−]	151.8	218.5	108.0
Resonator	f_{res} [Hz]	284.4	143.7	110.5
	Q_{res} [−]	44.2	62.1	50.8
Difference	$f_{\text{sound}} - f_{\text{reed}}$ [cent]	+202	+165	+175
	$f_{\text{sound}} - f_{\text{res}}$ [cent]	−37	−48	−25

Table 2: Parameters of the experimental pipes.

While the stability of the fundamental frequency and the playable amplitude range of the experimental pipes is quite pleasing, the change of the timbre with the blowing pressure is unsatisfactory. To be able to improve the pipe construction regarding the latter aspect, a physical model of the sound generation needs to be elaborated first. This model is introduced in the following section.

Basic physical model

The physical and effective dimensions of the resonators are listed in Table 1. The effective length is calculated by making use of the length corrections at the open ends of the resonator. The radiation impedance and the length corrections are evaluated based on the effective (acoustic) radius of the pipe. In case of pipe #3 the reed is shifted by $\approx 85\,\text{mm}$ from the closed end (see Figure 1(a)), which reduces the effective length. Viscothermal losses can be calculated from the inner circumference of the pipes.

The most important parameters of the experimental pipes are listed in Table 2. The sounding frequency f_{sound} is given for 400 Pa blowing pressure. To obtain the natural resonance frequency and the quality factor of the reed, the resonators were damped by inserting sound absorbing material into the open ends. The pipes were sounded with damped resonators but all of them produced strong steady state sounds. The frequency was lower and the steady state spectrum changed remarkably in all cases compared to the original sounds. Then, the parameters of the reed were determined from the decay phase of the reed motion when the tongue is in free vibration. The first eigenfrequency and the quality factor of the resonators were approximated using a simple one-dimensional waveguide model that incorporated viscothermal and radiation losses. It should be noted that all pipes have very narrow scaling, i.e., the ratio of effective radius to effective length is quite small compared to

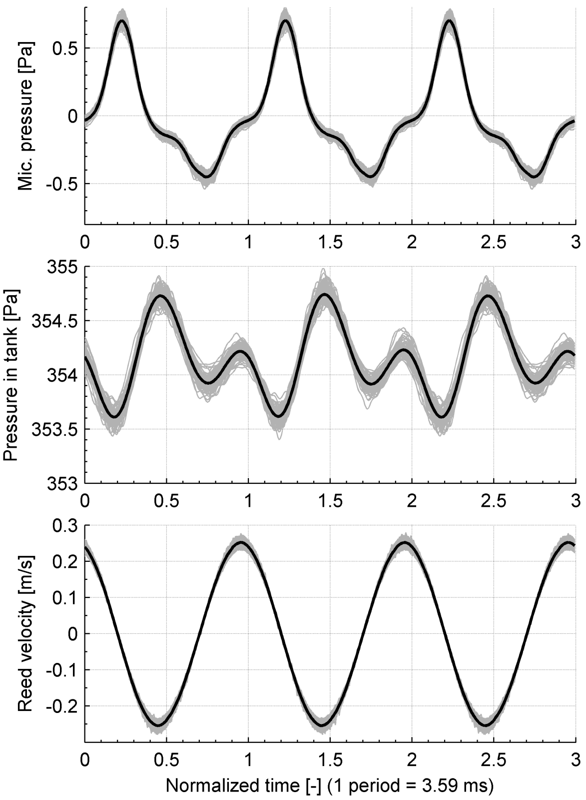


Figure 5: Steady state signals of pipe #1 at 400 Pa blowing pressure. Top: Nearfield microphone. Middle: Pressure inside the pressure tank. Bottom: velocity of reed vibration. Gray lines: 100 periods plotted over eachother. Black lines: average of 100 periods.

a usual setup. Thus, the quality factor of the resonator is determined by the wall losses. As seen, the quality factor of the tongue is significantly greater than that of the resonator for all three pipes: $2.1 \leq Q_{\text{reed}}/Q_{\text{res}} \leq 3.5$.

Interestingly, the sounding frequency (f_{sound}) is about 150 to 200 cent higher than the reed frequency (f_{reed}) in all cases. However, the sounding frequency is closer to the first eigenfrequency of the resonator (f_{res}) which is about 25 to 50 cent greater than f_{sound}. It can be assessed that the tongue and the resonator act as a strongly coupled oscillator in case of these experimental pipes. This behavior is different from the usual construction of lingual pipes with free reeds, where strong coupling is usually avoided and hence the sounding frequency is very close to the first natural resonance frequency of the tongue [3].

A minimal model of free reed instruments was established by Millot & Baumann [4]. This model describes the motion of a free reed as an Euler−Bernoulli beam operating in its first bending mode. In particular, the model incorporates the precise calculation of the so called useful section, the area through which air can flow under the tongue. Naturally, this area is dependent on the actual position of the tongue. The configuration introduced in [4] does not contain a resonator: the upstream section of the reed is connected to a pressure tank by means of a short pipe, while the downstream section is on the outside of the instrument where atmospheric pressure is assumed. It is assumed that the air flow separates from the tongue forming a thin jet of air. The velocity of the air jet is calculated by means of the Bernoulli equation.

The same setup was implemented by the authors for the time domain simulation of the movement of the tongue. Without the resonator being included in the model the results cannot be compared quantitatively to measured data; nevertheless, the measurement results displayed in Figure 5 show good qualitative agreement with the simulations. As it can be seen in the bottom diagram of Figure 5 the reed vibration is sinusoidal during sound generation. This is consistent with the simulation results (see e.g. Figure 17 of [4]) and justifies the single-mode reed model. The other interesting property of the free reed configuration is that the jet formation can occur twice each period of the sound: (1) when the tongue is inside the instrument the jet appears on its downstream face, and (2) when the tongue is outside the jet appears on the upstream face. Since the geometry of the setup is not completely symmetrical (see e.g. the tongue holder plate shown in Figure 1(b)), the two jet formations give different jet velocities, as also seen in Figure 19 of Ref. [4]. Although the jet velocity was not measured in our setup, the typical characteristics of the jet formation can also be identified from the time signal of the pressure inside the pressure tank. Due to the double jet formation, this pressure signal has two local minima and maxima in each period. This behavior is seen in the middle diagram of Figure 5 and also reproduced by the simulation model.

It can be assessed that the basic free reed model by Millot & Baumann [4] is capable of reproducing the essential phenomena observed in the measurements. However, further and more detailed investigations would require incorporating a resonator model and the reed–resonator coupling into the simulations. This task is out of the scope of this paper, but it is among the future plans of the authors.

Acknowledgments

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