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## Incorporating the wind-chest reservoir and a foot model to the organ pipe time domain simulation

G. Villegas Curulla<sup>a,b</sup> et F. Fabre<sup>a</sup>

<sup>a</sup>Sorbonne Université, Institut d'Alembert UMR 7109, LAM, Paris, France

<sup>b</sup>Sorbonne Université, ISCD, Paris, France



It is not new to pursue a closed formulation of the organ pipe operation that leads to a feasible solution in time or frequency. Research contributions in the 1950s-60s reprised the question of the nature of the aero-acoustic sources in such instruments well after the Rayleigh-Helmholtz dispute. Said contributions marked and accelerated a progress line : from the simple resonator with passive radiating ends to the mouth impedance, its coupling with the volume upstream behind the formation point of the jet, plus its receptivity, instability, and convection. If one neglects all other less prominent contributions to sound, all those finally lead to a dipole-like source in the labium at the mouth of the pipe (inwards / outwards). Most of these mechanisms are common with flute-like instruments. The contribution presented here seeks to obtain greater realism and a more accurate description : the incorporation of the pipe foot, whose response is coupled upstream with the reservoir (the wind-chest in the real organ) and downstream with the window cut into the resonator. Measurements are compared with the simulation of the model with the same geometry and dimensions. The stress is put into analysing the effect that the reservoir and the foot have in the hydrodynamic system with and without the coupling of the resonator.

## 1 Introduction

Flue organ pipes are discussed in the frame of self-sustained oscillation, flute-like instruments where the main distinction in the excitation system among families is given by the ratio  $W/h$  characterising the dimensioning of the window region. In organ pipes, this ratio can range from 4 – common with recorders – to 32, depending on their size and the family they belong to (further discussion in Chapter 10 in [1]). It is agreed to call  $h$  the thickness of the aperture between the pipe's foot and the resonator where the free-jet originates, while  $W$  refers to the window length between said aperture and the sharp labium where the jet alternately wafts inside and outside of the resonator giving rise to some of the aero-acoustic sources. Further detail on the geometry is provided in Section 3.

It has been common practice to approach the modelling of the organ pipe by describing a coupled system of (1) a hydro-dynamic part that injects mass into the foot of the pipe (or the mouth of the player in the case of a recorder) and (2) the acoustic part that includes the resonator, end the impedances of the window region and the passive end of the pipe – sometimes found to be closed in some stopped pipes.

This idealised initial condition of constant inflow has advantages in working out predictions focused on precise aspects of the acoustic system, mostly related to the description of phenomena linked to the jet evolution in the window region, the interaction with the rigid body of the resonator, and the field surrounding them.

The actual operation of the organ starts from a pressure supply system consisting of bellows and electric blowers, ducts and bends delivering the pressure to the wind-chests. At the final stage the pressure is supplied, firstly, to a shared reservoir at the base of each wind-chest called *laye* and secondly to a reservoir called *gravure* that is only common to pipes *speaking the same note* but belonging to different ranks that one can engage together into timbral mixtures operated by the same keyboard (see Figure 1). Nolle and Finch have described such systems and the influence of simultaneous multiple-pipe operation upon the stability of the delivered pressure [2, 3].

In the current paper we stress the influence of the reservoir and propose a time-stepping solution in the presence of acoustic oscillation. This is equivalent to saying

that we prepend an additional element to the developments found so far, which makes up for a larger agreement to the initial conditions of a pressure supply system of an organ, where the assumption starts by constraining a constant pressure delivered before the reservoirs.

Section 2 presents the geometry of the problem and the variables involved in most descriptions. Section 3 reviews relevant literature on the operation of the pipe that is assumed for building the current work. It is followed by the presentation of the hydrodynamic model proposed in this paper Section 4. Time integration results and measurements in Section 5. We conclude with some remarks and considerations for future work envisaged.

## 2 Study case : the physical organ pipe

### 2.1 Geometry

Figure 1 depicts the following description of the geometry and operation. The flow is allowed into a reservoir : in a real organ's wind-chest, this consists of a two-stage reservoir, as mentioned above, where the first one acts as a stagnation chamber for the multiple array of smaller ones connected to it and leading to the pipe's foot. The second one of those volumes starts receiving the pressure  $P_{res}$  delivered by the blowing system when a key-down is actioned in the console, and the flow passes through an inlet of cross-section  $S_{in} = \pi R_{in}^2$  into the foot, a conical cavity of volume  $V_f$  completely sealed except for a thin aperture of area  $S_{out} = Hh$  that leads to the window region. The pressure differences  $|P_{res} - P_{foot}|$  and  $|P_{foot} - P_{mouth}|$  cause the flow to progress downstream, where the second one of those governs the jet originating at  $S_{out}$ , whose center-line velocity is  $u_j$  ( $v_{out}$  hereafter).

From  $S_{out}$  the jet travels a distance  $W$  in the window region up until the interaction with the sharp edge called labium. The area of this region is thus given by  $S_w = HW$ . The labium is a straight-line profile over all its depth that is generally extended a few cm up to several dm onto a flattened surface carved or soldered to the resonator : its shape and size depend on style of manufacturing era, the organ maker school and the dimensioning of the rank where the specific pipe belongs to.

At the opposite radiating end of the resonator, otherwise

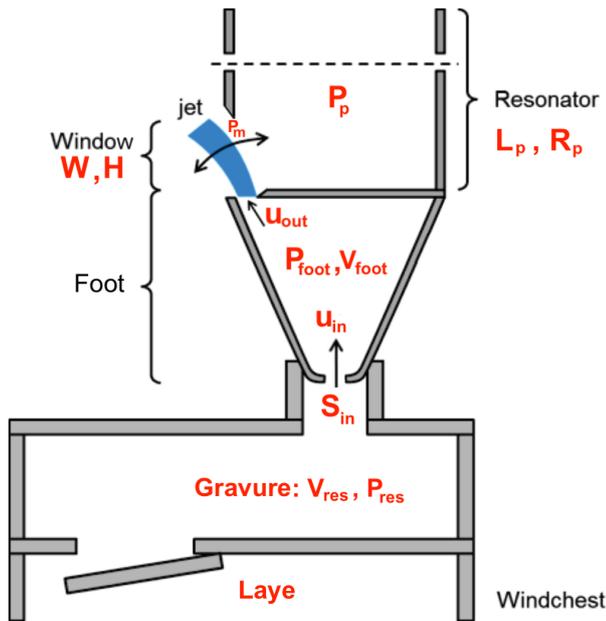


FIGURE 1 – Geometry of the reservoir and the organ pipe adapted from [4].

called passive end, the general terminations encountered are open-ended and closed. Coltman’s experiments [5] show that under general conditions, both radiating apertures are equivalent in terms of blowing current except for a  $n\pi$  phase-shift for the  $n^{th}$  mode. A third very common termination found is a mixture of the two : a chimney-like pipe is inserted through a perforation on the cap, thus modifying its spectral envelope.

### 2.2 Experimental setup

Dimensions of the study pipe are given in Table 1. The system consists of a pressure supply system whose flow we can regulate by means of a PID valve leading to the reservoir. Outlets from this reservoir are used for a pressure sensor and the inlet of the organ foot. Two more pressure sensors are flush mounted in the foot of the pipe and in the resonator 2 cm away from the window.

Excitation with a pressure supply system was carried under the following conditions : 4 bar were fed through a Brooks valve with  $SP = 40 \text{ L min}^{-1}$ ,  $[K_p, K_i, K_d] = [1.1, 12.0, 0.0002]$  and the offset and span were set to  $30 \times 10^3$  and  $12.5 \times 10^3$  respectively. The equipment employed for the measurements consisted of :

- Atlas Copco LFX Super-Flow air compressor
- A Brooks Smart Flow 5851S valve providing  $40 \text{ L min}^{-1}$
- Endevco signal conditioner 136 DC Amplifier
- Endevco transducers 8507 C-1 and C-2
- NI acquisition card 9234
- Steel wool inside the reservoir for noise attenuation

TABLEAU 1 – Dimensions of the test pipe in [mm]

$L_p$	$R_p$	$R_{in}$	$H$	$W$	$h$	$W/h$
422	25.9	3.7	39.4	9.72	0.72	13.5 $\emptyset$

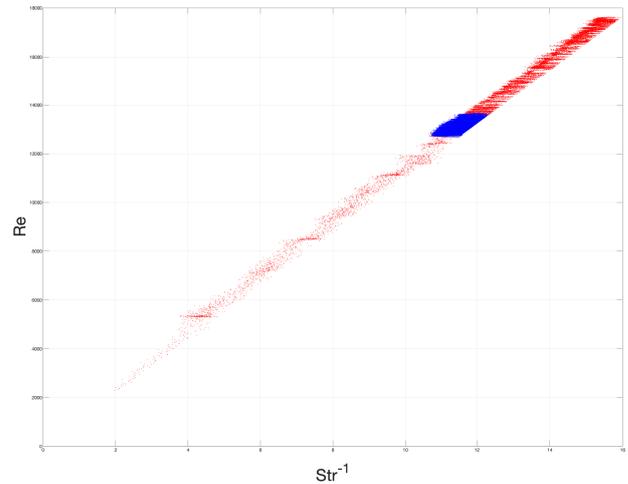


FIGURE 2 – Reynolds at the inlet of the pipe’s foot as a function of the oscillating regime at the mouth. Red and blue correspond to transient-state and steady-state, respectively.

### 3 A quick review of previous studies

A self-sustained oscillation instrument is composed of a closed-loop system, where a minimal model can be expressed with the following elements :

- Propagation and amplification of the air jet
- Aero-acoustic sources at the sharp-edge labium
- Passive resonances of the pipe

With respect to those areas of study and description of the organ pipe operation beginning at the constant inflow condition into the foot and downstream up to the resonator, the following assets have been abundantly explored and we will only succinctly summarize them next but we will not discuss the details.

General descriptions on the resonator as a wide pipe can be found in P. M. Morse, A. Chaigne-J. Kergomard, and A. Hirschberg-S. W. Rienstra [6, 1, 7], as well as the modal decomposition approach to the response of the pipe. Generalisations are then made towards providing pipe scaling criteria based on the Q-factor by N. H. Fletcher and later on by F. Blanc [8, 9].

M. J. Lighthill’s analysis [10] on the nature of the aero-acoustic sources was followed by contributions of A. Powell, J. W. Coltman, among others, on the edge-tone and driving mechanisms of the organ pipe up until the 1990s [11, 12, 13, 14]. A limitation on the oscillation amplitude at the mouth of the instrument is proposed when B. Fabre, A. Hirschberg and P. J. Wijnands investigate the vortex shedding at the labium [15].

After M. P. Verge’s work in the 1990s on confined

jets and pressure supply systems [16], C. Segoufin, P. de la Cuadra, R. Auvray and A. Ernoult have provided focused information into several critical aspects of the window region of the instrument [17, 18, 19, 20] : the instability of the jet, the impedance of the window seen by the injection of the jet, and the influence of the chamfers of the outlet in the interaction between the jet and the acoustic field of the resonator (otherwise called jet-receptivity).

It is worth noting that most of the elements mentioned have received equal attention in many collaborations by J. Angster and A. Miklós [21]. The reader is referred to [22] for a detailed overview on literature elements mentioned above up until the year 2000. However, it is also worth noting that to a certain degree, such advancements have been produced by experimental equivalents of the real instrument that made some parameters accessible to measurements but were constrained to not being playable as an instrument.

We define the Reynolds number ( $Re$ ) at the inlet and the reduced jet velocity in the window as

$$Re_{in} = \frac{v_{in} D_{in}}{\mu / \rho} \quad (1)$$

$$\theta = S_{tr}^{-1} = \frac{v_{out}}{W f_1} \quad (2)$$

The inlet diameter  $D_{in}$  is computed from the fitted value of  $R_{in}$  using Eq. 3 (see Table 1 for numerical values);  $\mu$  and  $\rho$  are the dynamic viscosity and the density of the air. The reduced jet velocity  $\theta$  is equivalent to an inverse Strouhal number  $S_{tr}$  and informs about the oscillation regime in the mouth. Together with the outlet of the foot and the alignment offset from the latter to the labium, the cross-section of the inlet constitutes one major tuning parameter for organ makers. Every adjustment made to the contour of the inlet makes it irregularly-shaped. We gained access to that parameter via the steady-state relationship

$$\langle v_{in} \rangle S_{in} = \langle v_{out} \rangle S_{out} \quad (3)$$

The velocity at the outlet is equivalent elsewhere in the literature to the jet center-line velocity at its origin. Lastly,  $f_1$  corresponds to the oscillation frequency of the first mode in the resonator, obtained from experimental data using the YIN algorithm [23].

An accumulated list of assumptions on the references cited a few paragraphs above can be summarized as follows :

- The air inside the foot behaves as a perfect gas under adiabatic compressibility regime
- Kinetic energy of the incoming flow is dissipated by turbulence
- A Kutta condition is assumed at the sharp edges of the inlet and outlet of the foot
- The air in the channel is considered incompressible, since the channel length is small compared to the distance travelled by sound waves during typical driving PRT
- The flow at the window section is laminar :  $Re_{out}$  in our test-case it is found to reach 2250 during transient-

state and settles for steady-state operation,  $Re_{out} \in [1500, 2000]$  during first oscillating regime

## 4 Continuous model equations

Verge et al. [24] establishes the initial dominance of the inertial terms  $\rho l_{(\cdot)} dv/dt$  over kinetic energy density, before the pressure differences reservoir-foot and foot-mouth reach the steady-state (the flue channel length  $l_{(\cdot)}$  can take the values  $l_{in}$  and  $l_{out}$  in this paper). Additionally, the pressure rise time at the transient will be crucial for the triggering of the acoustic modes in the body of the pipe. This is then the reason why we stress the importance of reaching a reliable physical model to start.

Much in the same way Verge et al. in [24] formulated the Bernoulli modelling of the outflow from the foot to the window, we do so for the inflow from the reservoir to the inside of the foot. We assume a homogeneously distributed pressure in a large reservoir to safely impose a negligible start velocity at the beginning of a streamline. As part of the assumptions pointed out in Section 2, we consider that the flow distribution inside the foot becomes turbulent, and the kinetic energy injected at the inlet is transferred onto smaller-scale vortex structures, thus bringing said velocity down to zero and interrupting the continuity of such streamline. Figure 2 provides information on the order of magnitude of the Reynolds number for a given operating regime in order to fulfil the last of the assumptions required in Sec. 3. The following equation modelling the proposed system is read as a Bernoulli at the inlet, conservation of mass inside the foot and a Bernoulli at the outlet :

$$\begin{cases} \rho l_{in} \frac{d}{dt} v_{in} + \frac{1}{2} \rho v_{in}^2 = P_{res} - P_{foot} \\ \frac{d}{dt} P_{foot} = \frac{\rho_o c_o^2 S_{in}}{V_{foot}} v_{in} - \frac{\rho_o c_o^2 S_{out}}{V_{foot}} v_{out} \\ \rho l_{out} \frac{d}{dt} v_{out} + \frac{1}{2} \rho v_{out}^2 = P_{foot} - P_{mouth} \end{cases} \quad (4)$$

where the constitutive equation  $p' = c_o^2 \rho'$  is used to express the mass conservation in terms of pressure, and where adiabatic compressibility regime is assumed inside the foot of the pipe, and heat exchange phenomena are neglected given a short time-scale under consideration here. Primed terms for pressure, density, and velocity under perturbation form are expressed as having a stationary value and an oscillating component :

$$p = \langle p \rangle + p' \quad (5)$$

Further assumptions are reinforced :

$$\langle P_m \rangle = P_{ref} \quad (6)$$

since the acoustic pressure originating at the resonator oscillates around a static point, namely the surrounding atmospheric pressure (*zero* for convenience); and an upper bound to the foot pressure in terms of the excitation is

$$P_{res} \geq P_{foot} \quad (7)$$

## 5 Results

Coltman [14] provides a pressure mapping starting from the inside of the resonator all the way out to the free-space, by which one can establish the estimation between the pressure in the pipe and the pressure at the mouth as :

$$P_m \simeq \frac{1}{2}P_p \quad (8)$$

Waveforms of the pressure signal at the reservoir, foot, and pipe levels are shown in Figures 3 4, and 5. They reveal the PRT steepness dependance on the dimensioning of the cavities  $V_{res}$  and  $V_{foot}$ . This dependancy is still apparent even when the operation of the resonator is avoided, thus not considering the influence of the  $P_m$  pressure term in the coupled system. Figure 5 shows that for a smaller reservoir, with a steeper PRT, the balance of filling-up times between the reservoir and the foot leads to the jet velocity overshooting during the transient and yields different gains for higher modes of the resonator.

The subdivision of each wind-chest inside the organ into *layes* and *gravures* provides an upper bound on the size of  $V_{res}$ . A pipe building principle imposes the equal foot height for all the pipes within the same rank, and they are then housed in a structure that supports them vertically called *faux-sommier* : these impose a bound on size of  $V_{foot}$ . Inspection of the spectra for the reservoir, foot and pipe reveals the strong dominance of the modal behaviour of the resonator over all cavities upstream (see Figure 6). A disturbance is found in the reservoir and foot signals after the valve aperture at 100 Hz : it is concluded that it responded to the compressor system utilised. The effect of the pipe's foot as a mixer between coupled volumes is apparent.

Measured data from the pressure in the reservoir and the resonator was used to provide the initial condition (IC) of the Equation 4 and to isolate the problem at hand from the rest of the acoustic system. The IC can be seen as a smoothed step function if one were only to consider reaching the steady-state. There are two considerations to be added : the initial overshoot responds to the tuning of the PID control of the valve and, on the real organ, to the opening of the valve in the wind-chest under the action of the transmission system from the keyboard to the pipe-ranks. The second observation concerns the oscillations after the transient. In the laboratory, this responds to the stabilisation of the PID and of the coupling reservoir-foot-pipe. In Section 2 many references have been provided where this behaviour is not only expected but also desired in some ranks of pipes within the organ.

Simulation of the the proposed model not only provided us with a preliminary means of validation, but also as a way to access parameters like the effective length of the inlet and outlet. It is also found in simulations that increasing the volume of the reservoir contributes to the steepness of the

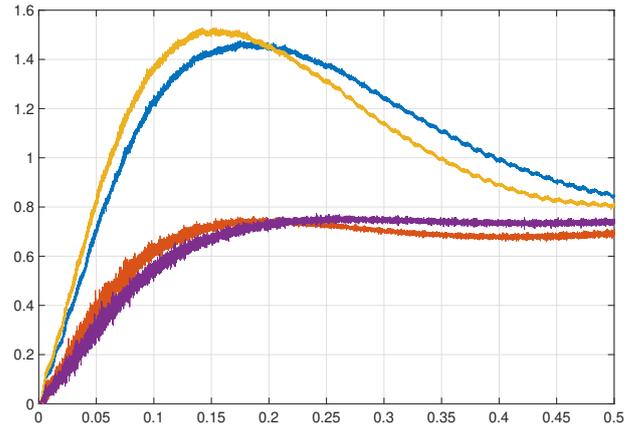


FIGURE 3 – Temporal evolution of the pressure measured in the reservoir during a span of 500 ms after detection of the onset. Solid blue and red lines correspond to reservoirs of 4 L and 20 L respectively under same blowing conditions. Pressure data is normalised by the pressure attained in steady-state. Additional data in yellow and purple is measured avoiding the resonator operation by blocking it with foam.

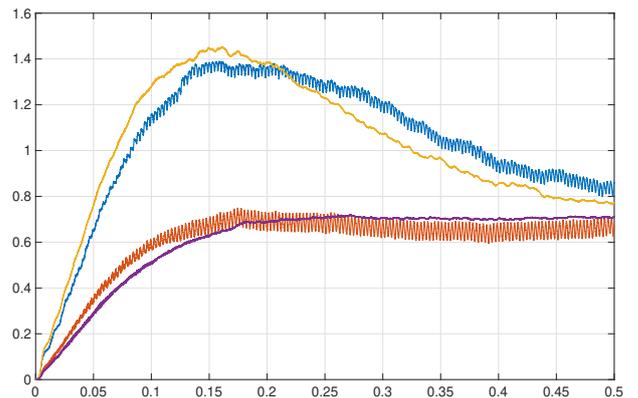


FIGURE 4 – Temporal evolution of pressure measured in the foot during a span of 500 ms. In normal operation, blue and red solid lines reflect 4 L and 20 L reservoirs. Yellow and purple reflect the same measurements neglecting the acoustic operation of the resonator.

pressure rise time in the foot, which was already intuitive. For example, the ratio between the inlet and outlet channels used in the simulation whose results appear in Figure 7 was  $l_{out}/l_{in} = 1.5$ . Solving the non-linearity of the reservoir and foot converged within a tolerance of  $10 \times 10^{-9}$  after 3 Newton-Raphson iterations per sample on a personal computer with 16 GB of memory and a 2.2 GHz processor, using less than 400 ms of runtime per 1 s of simulation in MATLAB. Once steady-state was reached, the oscillating regime was  $\langle \theta \rangle = 9.6$ .

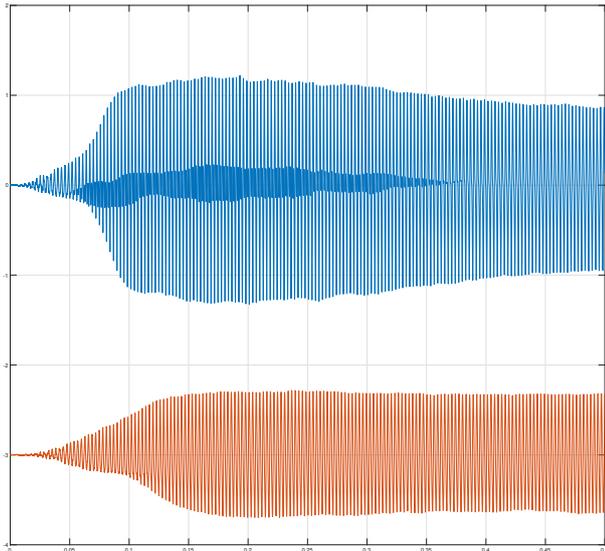


FIGURE 5 – Time evolution of the pressure measured in the pipe spanning the first 500 ms using a reservoir of 4 L (blue) and 20 L (red). Data has been offset for the purpose of visualisation.

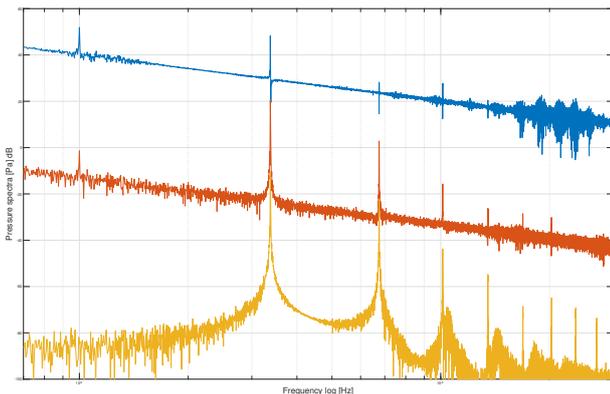


FIGURE 6 – Spectra of measured  $P_{res}$ ,  $P_{foot}$ ,  $P_m$  with a 4 L reservoir (blue, red, and yellow solid lines) during steady-state. Data are expressed in dB ref 1 and have been offset 50 dB and 95 dB for visualisation purposes.

## 6 Discussion and future work

We have presented a hydrodynamic system that models the behaviour of the reservoir and the foot. Further analysis on stability and energy conservation is to be carried out in order to assert that the system proposed is behaving physically. A starting point is proposed by the unforced system from Eq. 4

$$\frac{d}{dt} \left( \frac{P_{foot}^2}{2} + \frac{\alpha_1}{2} v_{in}^2 + \frac{\alpha_2}{2} v_{out}^2 \right) = -(\alpha_3 v_{in}^3 + \alpha_4 v_{out}^3) \quad (9)$$

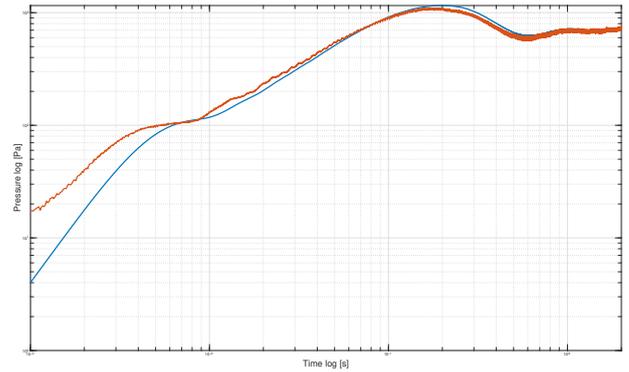


FIGURE 7 – Measured and simulated pressure in the foot of the pipe during transient-state (blue and red solid lines respectively). The sample rate used was 51.2 kHz in both cases.

with  $\alpha_i$  real positive coefficients. We can recast Eq. 3

$$\langle v_{out} \rangle = \langle v_{in} \rangle \frac{S_{in}}{S_{out}} \quad (10)$$

to give a bound on the system's energy in steady-state operation and use linearisations of the form of Eq. 8 to obtain

$$\begin{aligned} \frac{d}{dt} P_f &= \frac{d}{dt} (\langle P_f \rangle + P'_f) \\ \frac{d}{dt} v_{in} &= \frac{d}{dt} (\langle v_{in} \rangle + v'_{in}) \\ \frac{d}{dt} v_{out} &= \frac{d}{dt} (\langle v_{out} \rangle + v'_{out}) \end{aligned} \quad (11)$$

We seek further opportunities for relevant linearisation points with the hope of delivering a computationally efficient time-stepping solution for polyphony simulation of the normal organ operation : multiple pipe ranks are engaged in timbral mixtures during performance.

We have investigated the time and spectral evolution of the reservoir, the foot, and the pipe by

- Changing  $V_{res}$
- Blocking the resonator with foam to avoid its acoustic operation
- Removing the steel wool from the reservoir

and we are led to believe that the parameters to which an organ maker has access for design and tuning, namely  $(V_{foot}, S_{in}, S_{out})$ , majorly govern the frequency content of the excitation system proposed (Eq. 4) when coupled with the acoustic system.

We have shown that the filling-up of cavities has an impact in the steepness of the PRT. In former models such as those described in Sec. 1 with a prescribed constant inflow, linearisation led to proposing a Helmholtz-like resonator for  $V_{foot}$  with the outlet channel  $l_{out}$

$$\omega_o^2 = \frac{c_o^2 S_{out}}{V_f l_{out}} \quad (12)$$

in good agreement with their measurements. We seek to propose a closed-form expression while prepending  $V_{res}$  to the system in order to estimate a realistic IC for the aforementioned system. A family of functions such as

$$P_{H,res}(t - t_o) = \frac{1}{1 + e^{-2k(t-t_o)}} P_{o,res} \quad (13)$$

can be a preliminary suggestion, but further study is required in order to incorporate estimations on PRT, stabilisation time, and overshoot for a given set of parameters ( $V_{res}$  and  $V_{foot}$  among others), whose effect during the transient will yield different gains to the 2<sup>nd</sup> and 3<sup>rd</sup> modes of the pipe.

Lastly, the study pipe used for validation of the current model has to be taken to the buffet of a real instrument (e.g. St. Elisabeth d'Hongrie) and used in the place of one in the same *teessiture* in order to asses the level of realism achieved by the experimental reservoirs and decisions on the PID flow control.

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