

INTRODUCTION

Recent experiments on trombone players have highlighted performers' ability to create strong vocal-tract resonances and influence the regenerative process at the playing frequency, particularly in the high register of the instrument [1]. This vocal-tract tuning involves both amplitude and phase adjustments of the upstream system impedance at the fundamental frequency of the sound [2]. In order to evaluate the influence of amplitude and phase independently from each other, we propose to simulate the acoustical effect of upstream airways using an artificial trombone player system with an active control method inspired from previous experiments conducted on brass players [3]. This paper presents the experimental method, as well as first results revealing the high potential of this technique regarding the study of upstream coupling in wind instruments, improvement in the control of artificial brass player robots, and identification of artificial lip mechanical parameters.

METHODS

The active acoustic control method was implemented on an artificial brass player system developed at IRCAM [4]. This robot allows for precise feedback control of different control parameters: lip tension via adjustment of the volume of water inside the latex lips and the force applied by the mouthpiece on the lips, quasi-static flow via adjustment of a servo-valve connected to the artificial mouth cavity. A number of transducers also enable real-time monitoring of various state variables: P_d and P_u , the downstream and upstream acoustic pressure, measured respectively in the mouthpiece and in the mouth cavity, P_m the quasi-static mouth cavity pressure, F_e the force applied by the lips on the mouthpiece in the longitudinal direction, S_{lip} , the opening area of the lips measured by light transmission method, P_{l1} and P_{l2} the quasi-static water pressure in the artificial lips.

In order to simulate different conditions of acoustical coupling with the upstream cavity at the fundamental frequency f_0 of the sound, we rely on the assumption of air-flow continuity at the reed junction allowing to write Eq. (1) in the frequency domain (where Z_d and Z_u denote the input impedance of the downstream and upstream system respectively). By performing feedback control on the amplitude ratio and phase difference between P_u to P_d , we are therefore able to control the amplitude ratio and phase difference between downstream and upstream input impedances Z_d and Z_u at the playing frequency.

$$\frac{Z_u}{Z_d} = -\frac{P_u}{P_d} \quad (1)$$

The active control algorithm is implemented using the programming environment Max/Msp. The setup presented in Fig. 1 involves a downstream pressure transducer (Endevco 8507C-2) mounted in the mouthpiece cup, an upstream pressure transducer (Endevco 8507C-5) mounted in the mouth cavity just upstream from the lips, and a compression driver mounted on the mouth cavity. The feedback algorithm is implemented according to the following procedure:

- Once the system starts oscillating, the instantaneous fundamental frequency f_0 is extracted from the P_d signal using the Max/Msp external fiddle~.
- A sinusoidal signal at frequency f_0 is generated in the mouth cavity, where the amplitude and phase driving the loudspeaker are called A_c and Φ_c .
- A Max/Msp subpatch performs extraction of the instantaneous amplitude and phase at f_0 from the P_d and P_u signals.
- A_c and phase Φ_c are adjusted by a PID controller (proportional-integral-derivative controller), implemented in a Max/Msp subpatch, according to user commands on $\left|\frac{P_u}{P_d}\right|$ and $\angle P_u - \angle P_d$. The PID coefficients were tuned empirically prior to experiments.

This method enables independent control of the amplitude ratio and phase difference between Z_d and Z_u at the fundamental frequency of the sound during sustained tones. In this study, we focus on the highest pitch

tone (A4 b) we could produce without active control. As the volume of the mouth cavity is relatively large, the signal from the compression driver largely overrides the inherent acoustical effect of the mouth cavity at this playing frequency.

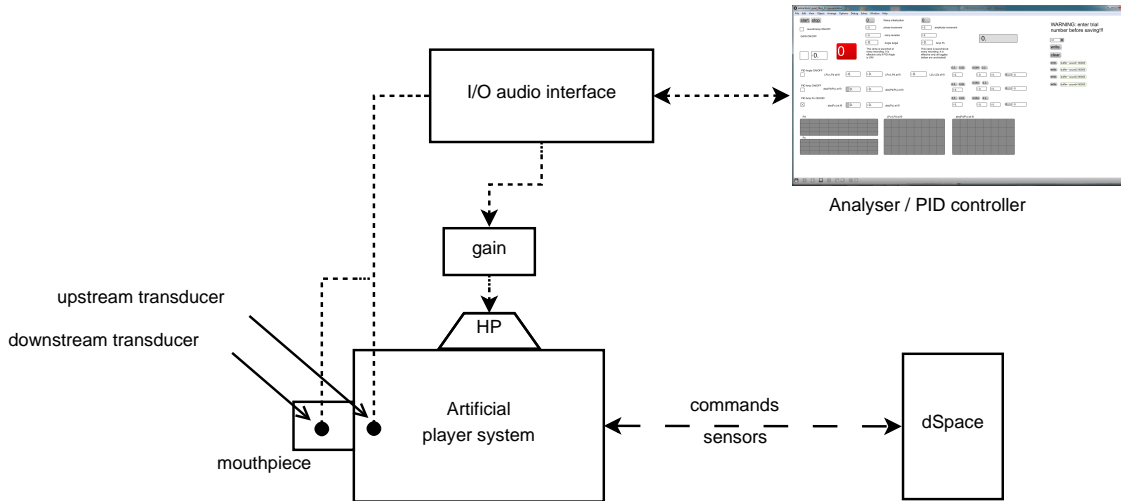


FIGURE 1: Diagram of the experimental setup. Signals from the downstream and upstream pressure transducers are recorded by an audio interface running at 44.1kHz and used for the active control. The artificial player commands and control parameters are transferred through a dSpace module working at 1kHz.

In this paper, we report the results obtained according to the following protocol:

1. Find a proper control parameter setting (input volume flow, lip tension) to obtain a steady and clear tone without active control.
2. Preset active control parameters to the observed phase difference between P_u and P_d resulting from the weak coupling with the mouth cavity.
3. Set a command value for $|P_u|$ (constant upstream acoustic energy condition) or for $\left| \frac{P_u}{P_d} \right|$ (constant Z_u to Z_d amplitude ratio condition).
4. Turn the active control on.
5. While maintaining a constant amplitude condition, sweep linearly the phase difference $\angle P_u - \angle P_d$ over a range of 240° .

RESULTS

Experiment 1

Data from a 60 seconds recording with constant upstream energy condition ($|P_u|$ is a constant) are presented in Fig. 2. As the pressure transducers are capturing both acoustic and quasi-static pressure, the quasi-static mouth pressure P_m is derived from low-pass filtering of the upstream transducer signal simultaneously input to the dSpace (running at 1kHz). We first notice that the linear sweep of the phase difference $\angle Z_u - \angle Z_d$ and the constant upstream acoustic energy are well achieved for the first 38 seconds. The system maintains stable oscillations for 38 seconds before entering into a more turbulent regime, certainly due to the destructive phase tuning imposed by the controller and not supported by the lips. At time 46 seconds, active control is stopped and the lip oscillations return to their initial, sustained condition.

Regarding the stable sounding section (from 0 to 38 seconds), we observe that despite a constant acoustic energy on the upstream side, the linear phase shift induces significant f_0 variations, as well as a maximum

of downstream pressure energy correlated with a minimum of quasi-static mouth pressure. From the measurement of the complex input impedance Z_d of the trombone, we observe that this downstream pressure maximum does not match with a $|Z_d|$ peak value. This observation suggests that this maximum in downstream pressure is not due to an increase of downstream support but rather to a beneficial phase tuning of Z_u relative to Z_d at f_0 .

Experiment 2

Data from a second experiment with constant $\left|\frac{P_u}{P_d}\right|$ condition are presented in Fig. 3. As in the previous experiment, significant f_0 variations are observed with variations of the phase difference $\angle Z_u - \angle Z_d$. A maximum of downstream and upstream energy is observed around $t=28$ seconds, matching with a minimum of quasi-static mouth pressure.

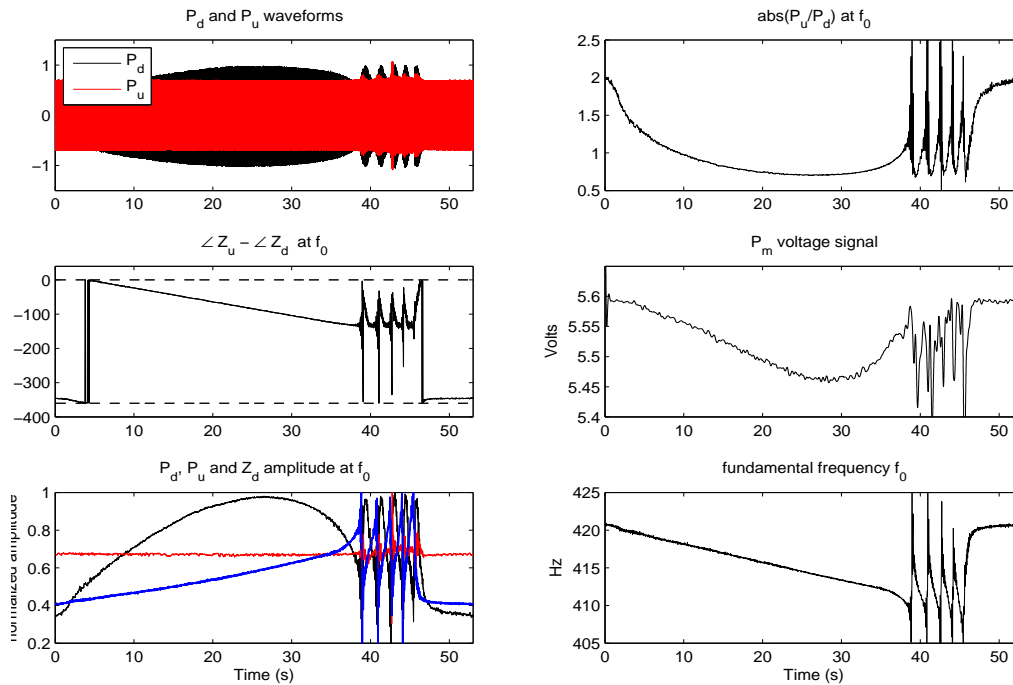


FIGURE 2: Sustained A4b with linearly varying phase difference between P_u and P_d at f_0 and constant acoustic upstream energy. Left column from top to bottom: P_d (black) and P_u (red) waveforms; phase difference between Z_u and Z_d at f_0 ; P_d (black), P_u (red) and Z_d (blue) normalized amplitude at f_0 . Right column from top to bottom: P_u to P_d amplitude ratio at f_0 ; quasi-static mouth pressure P_m (output voltage of the transducer), instantaneous fundamental frequency f_0 .

Comparison between Different Experimental Conditions

Two other experiments were conducted according to the protocol of experiment 1 ($|P_u|$ is a constant) but with different values of upstream energy in each experiment. For all experiments, the amplitude of the pressure difference across the lips $\Delta P = P_u - P_d$ and P_d amplitude were plotted against $\phi = \angle Z_u - \angle Z_d$ and against f_0 . The frequency and phase ϕ at $|\Delta P|$ maximum and $|P_d|$ maximum were extracted. Results are presented in Table 1. In the four conditions, we note that the phase ϕ was swept linearly by the same amount (145°) before stable lip oscillations could no longer be maintained.

Focusing on the three first conditions, we observe that an increase in the level of upstream energy increases the Δf_0 range covered, as well as the range of variations of the quasi-static mouth pressure. Although

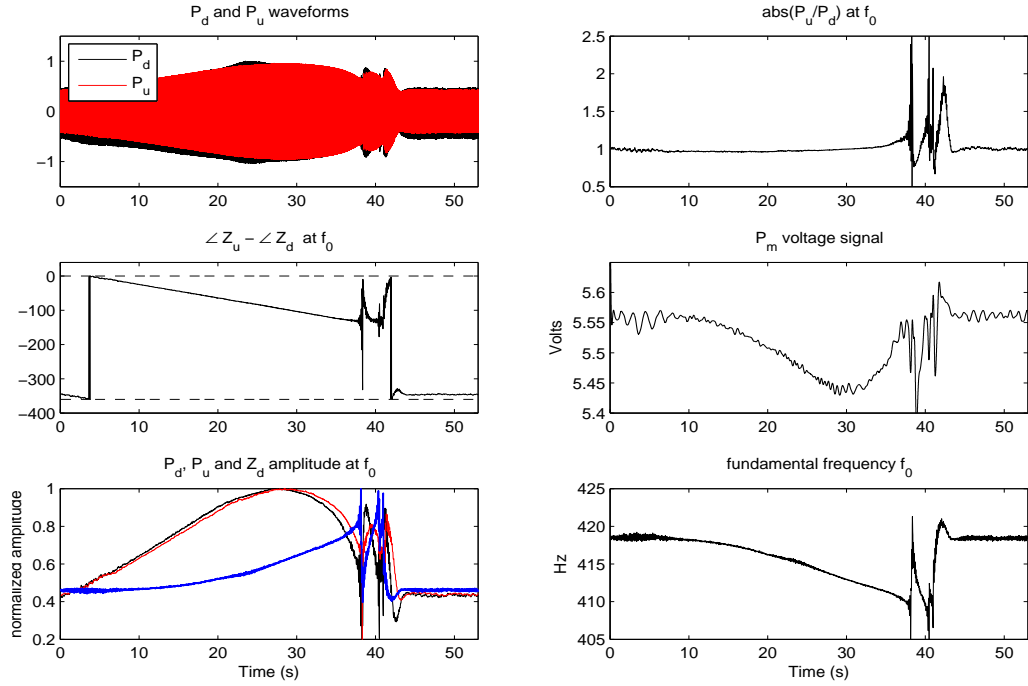


FIGURE 3: Sustained A4b with linearly varying phase difference between P_u and P_d at f_0 and amplitude ratio of P_u to P_d maintained constant and equal to unity. Left column from top to bottom: P_d (black) and P_u (red) waveforms; phase difference between Z_u and Z_d at f_0 ; P_d (black), P_u (red) and Z_d (blue) normalized amplitude at f_0 . Right column from top to bottom: P_u to P_d amplitude ratio at f_0 ; quasi-static mouth pressure P_m (output voltage of the transducer), instantaneous fundamental frequency f_0 .

TABLE 1: f_0 variations, frequency and phase ϕ at which the pressure difference across the lips is maximum, frequency and phase ϕ at which the downstream pressure is maximum, maximum and minimum values of P_u to P_d amplitude ratio, and quasi-static mouth pressure variations (in % of the maximum value of P_m recorded during the stable part of the tone), extracted in three conditions of constant upstream energy (normalized to the condition of maximum upstream energy) and one condition of constant upstream to downstream energy ratio. For all conditions, ϕ was swept linearly over a range of 145° .

Condition	Δf_0	$f(\Delta P_{max})$	$f(P_{d,max})$	$\phi(\Delta P_{max})$	$\phi(P_{d,max})$	$\frac{P_u}{P_d} _{max}$	$\frac{P_u}{P_d} _{min}$	ΔP_m
$ P_u = 59\%$	6.5Hz	416.6Hz	414.5Hz	-36°	-88°	1	0.54	1.6 %
$ P_u = 85.6\%$	10Hz	417Hz	414.2Hz	-45°	-90°	2	0.7	2.5 %
$ P_u = 100\%$	14Hz	417.5Hz	414.1Hz	-44°	-91°	3	0.78	3.0 %
$\left \frac{P_u}{P_d} \right = 1$	8.5Hz	416Hz	414Hz	-67°	-92°	1.1	0.96	2.2 %

P_d and ΔP energy peaks occur at different ϕ values across experiments, P_d and ΔP peak frequencies are observed at relatively similar values. These observations support the two following conclusions: 1) Given a constant amount of acoustic energy provided from the upstream side, an optimal phase tuning of upstream airways may significantly increase the acoustical efficiency of the lips and maximize the downstream acoustic pressure generated. It may also slightly reduce the quasi-static blowing pressure required to maintain a given level of oscillations. 2) Stable peak frequencies observed may suggest that lip motion is maximized at a given playing frequency, possibly matching with a resonance frequency of the lip-reed system.

Simultaneous measurement of lip opening area S_{lip} would enable calculation of lip transfer function $\frac{\Delta P}{S_{lip}}$ and possibly determine whether observed peak frequencies correspond to a lip mechanical resonance. Although S_{lip} monitoring was performed during our experiments by light transmission method, some uncertainties remain regarding the synchronization between S_{lip} and pressure transducer signals, as well as regarding the exact relationship between photo-transistor signal and the absolute lip opening area. Solving

these issues will enable investigation on the possible application of this active control method to the estimation of lip resonance frequency under playing conditions.

CONCLUSIONS

We have presented a method for the simulation of different upstream coupling conditions during sustained tones played on an artificial trombone player system. This method appears to be robust for a slowly varying control of the relative phase and amplitude at f_0 of the downstream and upstream input impedance. It seems to facilitate the production of high tones with the artificial mouth and clearly demonstrates the importance of a careful phase tuning on the production of downstream pressure. Further work on this setup will involve: improving the reliability of the phase and amplitude estimation of lip opening area, investigating the possibility to apply this method for the estimation of lip resonance frequency during playing, and evaluation of technical solutions to improve the velocity of the active control feedback allowing the study of transitory upstream tuning.

ACKNOWLEDGMENTS

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