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2pEAb7. Active control applied to simplified wind musical instrument

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Active control is widely used in industry. However, there have been relatively few applications to musical instruments, particularly wind instruments. The aim of this study is to attempt to control the sound quality and playability of wind instruments, using active control. Active control makes it possible to modify the input impedance (amplitude and frequency) of an instrument and to modify the instrument's quality. Simulations and first experiments on a cylindrical tube, which is considered to be a simple wind instrument, with embedded microphone and speaker are presented. Finally, the effects on the sound and the input impedance of the instrument are studied.

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INTRODUCTION

Active control is widely used in industry, mostly to suppress vibrations or noise. However, there have been relatively few applications to musical instruments (Boutin, 2011; Hanagud and Griffin, 1998; Berdahl and Smith, 2012), particularly wind instruments (Guerard, 2002). Here, the goal is not to suppress vibrations, but to modify them. Using active control, musical instruments can be made to produce new sounds, while keeping the gestural input of the musician and still using the instrument as a radiator.

Applied to a cylindrical tube, which is considered to be a simple "wind instrument", active control enables modifications of the amplitudes and frequencies of its different resonances (Hull *et al.*, 1993; Nelson and Elliott, 1992). Consequently the sound emitted by this instrument may be modified. Active control also enables modifications of the input impedance of the instrument, so that the playability is modified. This control is done using collocated microphone and speaker, linked by a gain amplifier and a phase shifter (see Figure 1) (Chen and Weinreich, 1996).

The aim of this paper is to present measurements and simulations of the effect of the control.

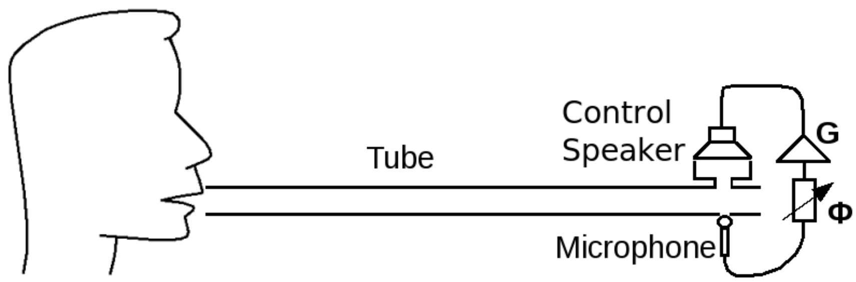

FIGURE 1: Cylindrical closed-open tube with control system : collocated speaker and microphone linked by a gain amplifier **G** and a phase shifter with value ϕ.

SIMULATIONS AND MEASUREMENTS

The studied system is a closed-open tube with length 1.18m and radius 11mm. The closed end has been chosen to imitate the effects of the musician on the resonances of the tube. The control system is composed of a collocated speaker and microphone and is placed 50mm from the open end of the tube. The speaker is linked to the tube by a cylindrical cavity of length 5mm and radius 20mm and a hole of mean thickness 1.5mm and radius 2mm. The components used in the control system are a 2" Tymphany LAT250 speaker and an Endevco piezoelectric pressure resistive model 8507C-5 microphone.

To simulate the control, the Rational Fraction Polynomials (RFP) algorithm (Richardson and Formenti, 1982) is used to identify the modal parameters of the system (Chomette, 2008) from a measurement of the transfer function of the uncontrolled system (referred to as the "open loop transfer function" H_{OL} in the following sections). These parameters enable the different resonances of the system to be calculated. Added together, these calculated resonances provide a calculated H_{OL}. The transfer function of the controlled system (referred to as the "closed-loop transfer function" H_{CL} in the following sections) is then determined using

$$H_{CL} = \frac{H_{OL}}{1 - H_{OL} G e^{j\phi}} \tag{1}$$

where G is the amplifier gain and ϕ the value of the phase shifter.

In the following sections, two cases of control are studied; the first with gain only (no phase shifting) and the second with phase shifting (provided by an operational amplifier's phase

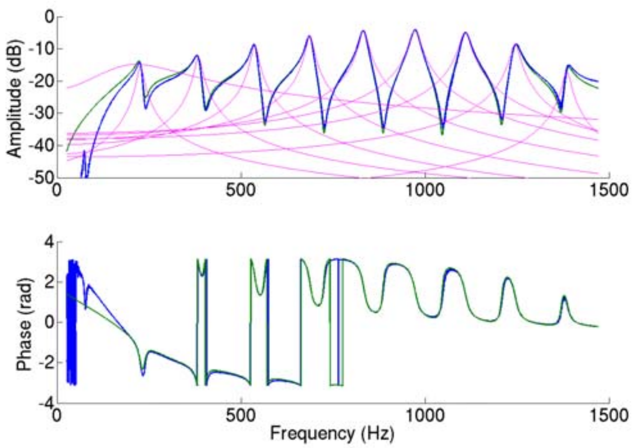

FIGURE 2: Top : Measured (blue) open-loop transfer function between the speaker and the microphone, calculated (green) open-loop transfer function obtained by adding the estimated first ten resonances obtained through RFP (pink). **Bottom** : Measured (blue) and calculated (green) phases of the open-loop transfer functions.

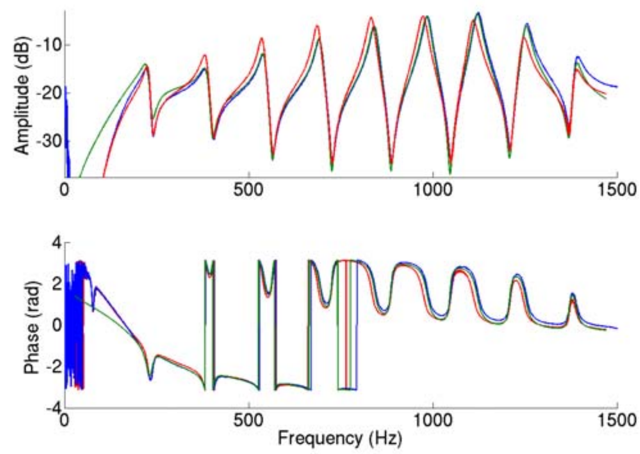

FIGURE 3: Top : Measured (blue) and calculated with eq.(1) (green) closed-loop transfer functions of the tube with gain G = 1.5 applied, and open-loop measured (red) transfer function. **Bottom** : Measured (blue) and calculated (green) phases of the closed-loop transfer functions, and open-loop measured (red) phase of the transfer function.

shifter) described by :

$$\phi = -2arctan(R.C.\omega) \quad (2)$$

with resistor $R = 1000\Omega$ and capacitance $C = 10\mu F$. A tool to qualitatively predict the behaviour of the system under control is then provided, followed by the study of the input impedance and, finally, an example of frequency windowed control is simulated.

First Example of Control : Gain Loop Without Phase Shifting

Figure 2 shows both the measured open-loop transfer function between the control speaker and the microphone and the calculated open-loop transfer function (obtained by adding the estimated first ten resonances obtained through RFP). As the system is a closed-open tube, the frequency of the n_{th} resonance is $f_n \approx f_1(2n-1)$. In the measured transfer function, the amplitude of the first resonance is very low (≈30dB lower than the other resonances). This may be due either to the location of the control system, close to the open end of the tube, or to the efficiency of the speaker. As a result of its low amplitude, the RFP algorithm does not identify it. The next nine resonances are identified however, as well as a supplementary one with a frequency of 215Hz (the flat one above the other resonances in figure 2); a hypothesis is that it is related to the main resonance of the control system (speaker + cavity + hole). The noise at low frequency corresponds to the frequencies where the speaker is not efficient. The phase of the transfer functions is not zero-centered and decreases as the frequency grows. At low frequencies, this may be primarily caused by the main resonance of the control system. Meanwhile, at higher frequencies, it is more likely to be due to a delay induced by the control system as a result of the distance between the control speaker and the microphone. Table 1 shows a comparison between the measured and calculated frequencies and amplitudes of the different resonances.

Figure 3 shows measured and calculated closed-loop transfer functions with a control gain G=1.5 applied, as well as the measured open-loop transfer function. Table 2 shows a comparison between the measured amplitudes and frequencies of the resonances in the closed-loop case and in the open-loop case. Table 3 shows a comparison between the measured and calculated frequencies and amplitudes of the different resonances in the closed-loop case.

From table 2, it can be seen that the control decreases the amplitudes of resonances 2 to 6 by

TABLE 1: Measured (M) and calculated (C) amplitudes and frequencies for the open-loop case (H_{OL}) and differences between them. The values are taken from the blue (measured) and green (calculated) curves in figure 2.

Resonance	Amplitude M (dB)	Amplitude C (dB)	Difference (dB)	Frequency M (Hz)	Frequency C (Hz)	Difference (Cents)
2	-14.3	-13.8	0.5	224	223	-5.4
3	-12.1	-12.1	0	380	380	0
4	-8.6	-8.6	0	535	535	0
5	-5.9	-6	0.1	686	686	0
6	-4.3	-4.4	-0.1	833	832	-1.4
7	-4.1	-4.1	0	974	973	-1.2
8	-4.9	-5	-0.1	1110	1110	0
9	-8.5	-8.6	-0.1	1248	1247	-1
10	-15	-15.7	-0.7	1390	1391	0.9

TABLE 2: Measured amplitudes and frequencies for the closed-loop case (H_{CL}) with gain G = 1.5 applied and differences with the measured values for the open-loop case (table 1). The values are taken from the blue and red curves in figure 3.

Resonance	Amplitude (dB)	Difference (dB)	Frequency (Hz)	Difference (cents)
2	-15	-0.7	220	-21.6
3	-15.2	-3.1	379	-3.2
4	-12	-3.6	538	6.7
5	-9	-3.1	691	8.7
6	-6.2	-1.9	841	11.5
7	-4	0.1	985	13.5
8	-3.3	1.6	1122	12.9
9	-5.6	2.9	1255	6.7
10	-12.4	2.6	1394	3.5

TABLE 3: Calculated amplitudes and frequencies for the closed-loop case with G = 1.5 applied and differences with the measured values (table 2). The calculated values are taken from the green curve in figure 3 while the measured values are taken from the blue curve.

Resonance	Amplitude (dB)	Difference (dB)	Frequency (Hz)	Difference (cents)
2	-14	1	219	-5.5
3	-14.8	0.4	380	3.2
4	-11.9	0.1	538	0
5	-8.7	0.3	691	0
6	-6.1	0.1	840	-1.4
7	-4.1	-0.1	983	-2.4
8	-3.5	-0.2	1120	-2.1
9	-6.1	-0.5	1253	-1.9
10	-13.8	-0.6	1392	-1.7

as much as 3.6dB, while it increases the amplitudes of resonances 7 to 10 by as much as 2.9dB. Resonances 2 and 3 have their frequencies decreased, especially the second resonance which is flattened by nearly an eighth of a tone. The other resonances have their frequencies increased by as much as 13.5 cents (a semi-tone is 100 cents). It is clear that the control seems to modify the sound of the instrument.

From tables 1 and 3 it can be seen that, in both open and closed loop cases, the modelled values are close to the measured values, with maximum differences of 5.5 cents and 1dB. These very little differences can be explained by the differences between the measured and estimated

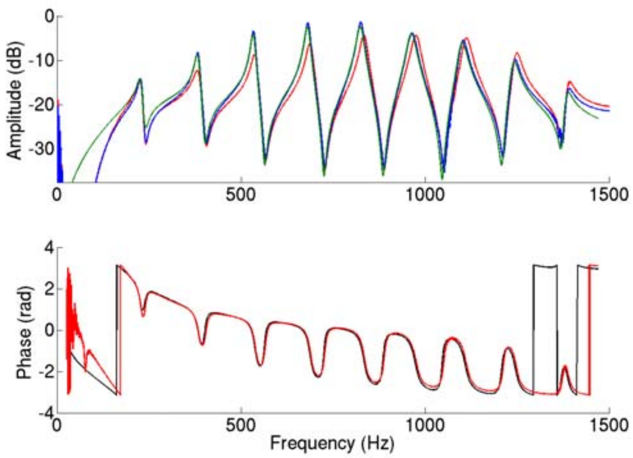

FIGURE 4: Top : Measured (blue) and calculated with eq.(1) (green) closed-loop transfer functions of the tube with gain G = 1.32 applied, and open-loop measured (red) transfer function. **Bottom** : Measured (red) and calculated (black) phases of the open-loop transfer functions with phase shifting applied.

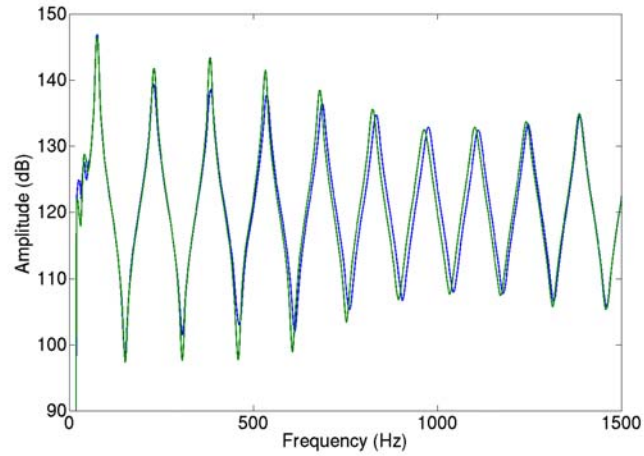

FIGURE 5: Input impedance without control (blue) and with phase shifting and control gain G = 1.32 applied (green).

phases and because the first resonance is not estimated.

Second Example of Control : Gain Loop With Phase Shifting

Figure 4 shows an example of measured and calculated closed-loop transfer functions between the speaker and the microphone with phase shifting and a control gain G = 1.32 applied. The phase shifting is directly calculated using equation (2) and applied to the calculated transfer function of figure 2 (bottom, green). Table 4 shows a comparison between the measured amplitudes and frequencies of the resonances in the closed-loop case and in the open-loop case. Table 5 shows a comparison between the measured and calculated frequencies and amplitudes of the different resonances in the closed-loop case.

TABLE 4: Measured amplitudes and frequencies for the closed-loop case (H_{CL}) with gain G = 1.32 applied and differences with the measured values for the open-loop case (table 1). The values are taken from the blue and red curves in figure 4.

Resonance	Amplitude (dB)	Difference (dB)	Frequency (Hz)	Difference (cents)
2	-14.1	0.2	226	10.7
3	-8.2	4.1	382	6.3
4	-3.3	5.3	534	-2.2
5	-1.5	4.4	681	-8.8
6	-1.3	3	825	-11.6
7	-3.8	0.3	964	-12.4
8	-5.4	-0.5	1103	-7.6
9	-9.8	-1.3	1245	-2.9
10	-16.3	-1.3	1392	1.7

From table 4, it can be seen that the control increases the amplitudes of resonances 2 to 7 by as much as 5.3dB, while it decreases the amplitudes of resonances 8 to 10 by as much as 1.3dB. Resonances 2, 3 and 10 have their frequencies increased by as much as 10.7 cents. The other resonances have their frequencies decreased by as much as 12.4 cents. It is clear that again the control seems to modify the sound of the instrument.

TABLE 5: Calculated amplitudes and frequencies for the closed-loop case and differences with the measured values (table 4) with G = 1.32 applied. The calculated values are taken from the green curve in figure 4 while the measured values are taken from the blue curve.

Resonance	Amplitude (dB)	Difference (dB)	Frequency (Hz)	Difference (cents)
2	-14.2	-0.1	225	-5.3
3	-8.7	-0.5	381	-3.2
4	-4.1	-0.8	533	-2.3
5	-2.3	-0.8	681	0
6	-2.3	-1	824	-1.5
7	-3.9	-0.1	963	-1.3
8	-6	-0.6	1102	-1.1
9	-10.3	-0.5	1243	-1.9
10	-17.2	-0.9	1390	-1.7

Again, the modelled values are close to the measured values, with maximum differences of 5.3 cents and 1dB. The calculated values are all lower than their measured equivalents (both amplitudes and frequencies), which is probably due to a lack of precision with the phase shifter. However, the model generally provides good estimations and enables the effect of a control to be predicted.

A Prediction Tool : The Phase of the Open-Loop System

The previous sections showed that the control system does not have the same effect on each resonance. Many other simulations and measurements have revealed that the effect of the control system when providing gain is dependent on the phase value at the peaks of the open-loop system. Figure 6 shows how the changes in amplitude and frequency of a peak are influenced by its phase value.

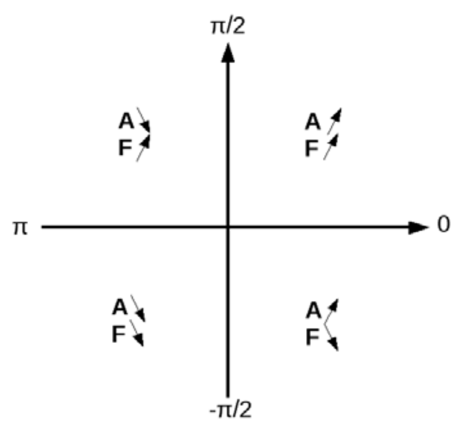

FIGURE 6: Amplitude (A) and frequency (F) modifications regarding to the phase value at the peak of the open-loop system. If the phase is on one of the axes, there is only one modification; $\phi = 0 : A \nearrow; \phi = \pi : A \searrow; \phi = \pi/2 : F \nearrow; \phi = -\pi/2 : F \searrow$.

When the phase value at the peak of the open-loop system is between $-\pi/2$ and $\pi/2$, gain injection will cause the amplitude to increase, while when the phase value is between $-\pi$ and $-\pi/2$ or between $\pi/2$ and π, gain injection will cause the amplitude to decrease. Meanwhile, when the phase value at the peak of the open-loop system is between 0 and π, gain injection will cause the frequency to increase, while when it is between $-\pi$ and 0, gain injection will cause the frequency to decrease. If the phase value at the peak of the open-loop system falls on one of the axes, there is only one modification; when $\phi = 0$, only the amplitude increases; when $\phi = \pi$, only the amplitude decreases; when $\phi = \pi/2$, only the frequency increases; when $\phi = -\pi/2$, only the frequency decreases.

Effect on the Input Impedance

The input impedance of a wind instrument shows the resonance properties of its air column (Backus, 1974). It gives information about the intonation, the timbre and the playability of the instrument. The input impedance is defined by $Z{=}p/U$, where p is the acoustic pressure and U the acoustic flow. Over the frequency range of interest, its amplitude gives peaks and hollows; the playable notes of the instrument have frequencies near these peaks. The height of a peak gives an indication of the ease of playing the associated note.

Figure 5 shows the input impedance of the closed-open tube for the case presented previously, with control gain G = 1.32 and phase shifting applied and without control. Measurements were done using the $BIAS^{®}$ system. Table 6 shows a comparison between these input impedances.

TABLE 6: Amplitudes and frequencies of the peaks in the measured input impedance for the open-loop (OL) case and closed-loop (CL) with G = 1.32 case and the differences between them. The values are taken from the curves (OL: blue; CL: green) in figure 5.

Resonance	Amplitude OL (dB)	Amplitude CL (dB)	Difference (dB)	Frequency OL (Hz)	Frequency CL (Hz)	Difference (Cents)
1	146.9	146.5	0.4	76	76	0
2	139.4	141.8	2.4	229	230	5.2
3	138.6	143.3	4.7	384	383	-3.1
4	137.7	141.5	3.8	537	533	-9
5	136.4	138.5	2.1	688	681	-12.3
6	134.7	135.6	0.9	834	825	-13
7	132.9	132.5	-0.4	976	964	-14.9
8	132.4	132.8	0.4	1111	1102	-9.8
9	133.3	133.7	0.4	1247	1242	-4.8
10	134.5	134.9	0.4	1387	1386	-0.9

It can be seen from figure 5 and table 6 that the control has little effect on the first resonance. However, it has an effect on peaks 2 to 5, as their amplitudes are all increased by as much as 4.7dB. It can be hypothesised that the control system modifies both the playability and the sound of the instrument.

Simulation of Frequency Windowed Control

In the previous sections, gain G and phase shifting are applied over the whole frequency range. It would be more useful to change the parameters of each resonance independently, in order to design the sound of the instrument.

Figure 7 shows a simulation where only two resonances are controlled : the amplitude of the third resonance is increased by 7.5dB with an increase in frequency of 2Hz (6 cents), and the frequency of the seventh resonance is decreased by 34Hz (-43cents, nearly a quarter of a tone) with an increase in amplitude of 0.1dB.

To obtain these results, band limited phase shifting and gain filters were used. The simulation was computed using four frequency "windows" in Matlab.

For both resonances, a Tukey window was used to shift the phase. This window is close to the rectangular window but has smooth transitions to its limits; it enables the translation of a

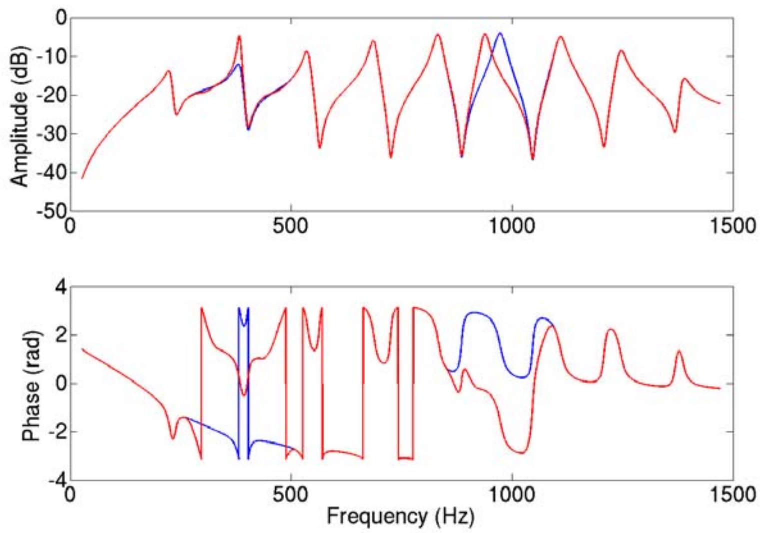

FIGURE 7: Top : Simulated transfer functions in open-loop (blue) and closed-loop (red); Frequency of the 7th resonance is modified and amplitude of the 3rd resonance is modified. **Bottom** : Phase of the transfer functions in open-loop (blue) and closed-loop (red).

whole section of phase. The length of each window was 250Hz and they were centered on the resonance peaks. The target shifting was $\phi = 0$ for the third resonance, so that only an increase of the amplitude was achieved. It was $\phi = -\pi/2$ for the seventh resonance, so that only a decrease of the frequency resulted.

The gain applied to the third resonance was through a Hanning window, which provides gain specifically at the frequency of the resonance. To obtain this result, the maximum gain was 2.5. The gain applied to the seventh resonance was through a Tukey window, which provides gain to the peak even if the frequency of the peak is changed. To obtain this result, the gain was 5. Again, the length of the windows was 250Hz and they were centered on the peaks.

Practically, such results may be obtained using Max/MSP software (Max, last viewed 22 Jan. 2013). The only problem is the latency between the input and output of a computer. This latency can be taken into account but it will not allow control of the transients, only the steady states will be controlled.

CONCLUSION AND PERSPECTIVES

A simulation of a control system to change the playability and sound of a simplified wind instrument using gain and phase shifting, has been proposed and validated experimentally.

The measurements presented have shown that the amplitudes and frequencies of all the resonances can be adjusted simultaneously using the control system. The possibility of adjusting the amplitudes and frequencies of each resonance independently has also been demonstrated. The alterations to the resonances demonstrate that the sound of the instrument may be modified by control.

Input impedance measurements gave information regarding the playability of the controlled instrument, demonstrating that both the playability and the sound of the instrument may be modified by control.

Simulations have been proposed to make a more advanced control.

The next stage of the work will involve controlling each resonance of the simplified wind instrument independently using Max/MSP. Playing and perceptive tests with musicians will then be carried out to validate the control musically.

Adapting the control to real instruments, like the bass clarinet, will be the next step, as well as trying other control methods, such as modal active control.

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