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CONTROL OF AMPLITUDE, FREQUENCY AND PHASE OF AN HARMONIC ANTI-NOISE PNEUMATIC SOURCE

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In active sound control, loudspeakers are typically used to attenuate the noise emitted by a primary unwanted noise source. But the fragility and low sound pressure level produced at low frequency make electromechanical loudspeakers unfit for industrial applications of active control of tone noise (e.g. fan noise, turbomachine noise,...). The technological limitations of loudspeakers led to the development of compact anti-noise sources capable of generating high sound pressure levels sufficiently robust to work in extreme conditions. On the other hand, high sound pressure levels can be generated by pneumatic sirens with compressed air. But such periodic noise sources cannot be used in active noise control applications because they are not controllable in amplitude and phase. The objective of this work was to design an alternative pneumatic source perfectly controllable in amplitude, frequency and phase. The presented concept is an electro-mechanical chopper of compressed air in order to generate a pulsed flow. The paper presents a prototype of the device and its control both in amplitude and phase. The developed prototype was characterized in a semi-anechoic chamber for different configurations of downstream flows (pressure 60-90 Psi). The experimentally measured characteristics are roughly consistent with the theoretical predictions. The pneumatic source radiated noise as a monopolar sound source in harmonic regime at the frequency range of 500 Hz. The radiated noise was perfectly controlled in phase with the precision of 6 degrees. The sound pressure level (at 1 meter) was controlled in the range of 80-110 dB by controlling the mean flow in the range of 20-100 scfm. So, it can be concluded that such a device can be used for active noise harmonic control. Further works will be required to improve this original device and to implement it in practical applications.
Keywords: no more than five words (e.g. building acoustics, finite element methods)

1. Introduction

Over the years, different methods were developed to eliminate or reduce undesired noises. They can be grouped as passive or active. Passive methods have proved their effectiveness in the attenuation of mid to high range frequencies, using absorbent materials, shock absorption, resonators, etc. However, the low frequency range is still a challenge [1].

Active methods are efficient to reduce harmonic low frequency noises. On the other side, these methods require controllable anti-noise sources with a power level comparable to the noise to be canceled. Loudspeakers or shakers are typically used in an active control system to generate the anti-noise dedicated to attenuate the unwanted primary noise. But the fragility and low sound level produced at low frequency make them unfit for many real applications in harsh environments, particularly in which air temperature is high. Consequently, the problem is to design an alternative loudspeaker for real applications such as industrial ventilators. The main hypothesis is that pneumatic sources must be favorably considered for a new concept of harmonic anti-noise source.

Very few research has been conducted to design a robust anti-noise source with a pneumatic source. By using a flap oscillation in a flow, it is possible to actively attenuate a pulsed flow of fluid in an exhaust pipe of a combustion engine [2,3]. Hence, a secondary harmonic source of anti-noise can be implemented in real harsh environments by using an oscillating flap as an aeroacoustic source. Another similar technology is to use an electro-pneumatic transducers, also called pneumatic sound generator or compressed-air loudspeakers. The basic idea of such a device is based on the air powered sirens [4,5]. A rotary device open and close an orifice which module the head loss in the device, hence modulating the incoming air flow. In final, the flow modulation produces a pure tone. Webster et al. [6] reported a sonic electro-pneumatic transducer used as a speech and alarm system on the flight deck of an aircraft carrier. Fiala et al. [7] designed a linear sonic electro-pneumatic transducer producing 6kW of acoustic power. Hooker and Rumble [8] and Kumar et al. [9] have built similar devices to generate a pulsed-flow, where the compressed air is supplied to a rotary device which periodically obstructs the airflow. Prek described a valve with a variable section [10]. It generates a powerful jet noise (>130 dB), but this jet produces a wide band noise which is difficult to control.

The first comprehensive theory of the electro-pneumatic transducer was proposed by Meyer only in a graphical form [11]. In 1990, Chapman and Glendinning, developed an explicit determination of the amplitude and phase of the acoustic pressure at the source output [12]. In 1999, Blondel and Elliott, a theoretical analysis was developed with a view to using an electro-pneumatic transducer as a secondary actuator in an active noise control system [13]. Experiments with a subsonic generator was shown highly non-linear but highly efficient: attenuation of 25 dB for sinusoidal primary sound fields at frequencies below 100 Hz [14].

The first objective of this study is to experimentally demonstrate that the pneumatic transducers can be used to produce high anti-noise source with primary sound fields at frequencies superior to 100 Hz. Hence, the frequency target of the developed device is 500 Hz, which corresponds to the tonal noise generated by classical industrial ventilators.

The challenge with this objective is to be able to maintain the perfect control of the amplitude and the phase of the electro-pneumatic source (and so on the frequency). In order to reduce the noise emitted by a primary source, the canceling noise emitted by the controllable secondary source must meet some basic criteria, related to the amplitude of the sound generated and the precision of the phase between both sources. It is well known that a 10dB of active attenuation can be reached if the ratio of amplitude is within 80 to 120% and the phase precision is ±10 degrees. A 20 dB of active attenuation can be reached but the phase precision must be ±5 degrees and the ratio of amplitude within ±0.6 dB [15]. So, a noise attenuation implies a high precision both on the phase and amplitude of the anti-noise pneumatic source.

The concept of the device is presented and detailed in the section 2. In section 3, the device is described including its phase controller. In section 4, experimental results illustrate the phase tracking ability of the controller and the amplitude control of the sound generated.

2. Theory

Figure 1 illustrates the concept of the device. The compressed air from the reservoir takes the route marked 0, 1, 2, 3 and then emerges out of the duct into the atmosphere. The rotating flap (located between the marks 1 and 2) is used to modulate the equivalent cross section area (illustrated in Fig. 2). A motor is used to put the flap in rotation in order to chop the airflow hence producing a periodic unsteady flow. For a rotating valve turning at the constant rotation speed of N rpm, the airflow is obstructed 2 times per turn generating a pulsation at $30N$ Hz. Hence, if a 500 Hz tone needs to be generated, the axe must rotate at 15,000 rpm, which is a high rotation speed for an electric motor.

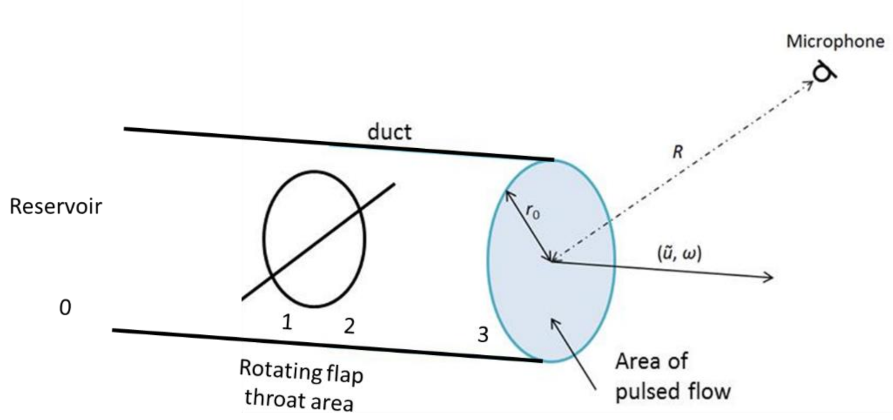

Figure 1: principle used of the pneumatic device based on a rotating flap to modulate the throat area.

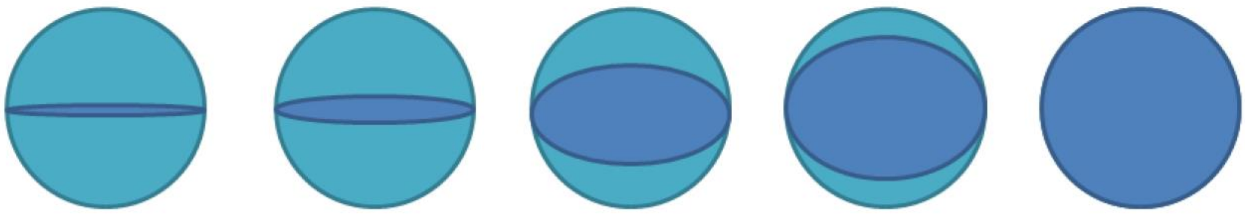

Figure 2: views of the throat area as a function of the flap angle from 0 to 90 degrees.

Based on the theoretical analysis of a compressed air loudspeaker by Chapman and Glendinning [13], the analysis of the device is based on 9 assumptions. (1) A one-dimensional flow is assumed; (2) compressed gas emerges into the atmosphere (mark 3); (3) the flow is uniform; (4) the variation of the throat area is a function of the time $A(t)$; (5) the oscillation frequency is low enough to allow a static approximation of the flow; (6) the fluid is a perfect gas; (7) in the reservoir (mark 0), the air is in stagnation conditions; (8) the Mach number at the throat is 1; (9) the transformation is adiabatic. Under these assumptions, the pressure and the particle velocity after the valve can be derived to obtain the basic operating equation of the sonic pneumatic transducer. It can be demonstrated that the pressure-velocity relation involving aperture area is specified by

$$\boldsymbol{u_3 p_3 = \beta A} \tag{1}$$

with the coefficient $\beta = \left(\frac{5}{6}\right)^3 \frac{c_0 p_0}{A_3}$ which shows that he amplitude of the right term of (1) can be controlled by the pressure in the reservoir (mark 0). By the quasi-static assumption, equation (1) continues to hold for an alternating throat area $\tilde{A} = A - \bar{A}$ which leads to velocity and pressure perturbations, respectively $\tilde{u}_3 = u_3 - \bar{u}_3$ and $\tilde{p}_3 = p_3 - \bar{p}_3$. Consequently, the valve rotation produces a throat area fluctuation $\tilde{A}$, then it generates velocity $\tilde{u}_3$ and pressure fluctuations $\tilde{p}_3$.

Based on the aerodynamic theory elaborated by Lighthill [16] and extended by Ffowcs Williams and Hawkings [17], a pulsed flow source in an open field can be considered as a monopolar source. Laumonier [18] has proposed equation (2) to determine the acoustic pressure p at the frequency ω generated by the device at a distance R from the mouth (mark 3).

$$\boldsymbol{p = \frac{\rho \omega r_0^2}{\sqrt{2} R} \tilde{u}_3} \tag{2}$$

with r_0 is the jet flow radius and ρ the air density.

One can combine the previous relations to conclude that this physical mechanism of sound production can be used as a harmonic anti-noise source because :

i) the rotation speed of the flap controls the frequency of the anti-noise
ii) the flap angle controls the phase of the first harmonic of the anti-noise
iii) the mean flow controls the amplitude of the first harmonic of the anti-noise

3. Device description

3.1 Device description

The figure 2 presents the device built. The flap is actuated by a frameless brushless motor (Bayside K032050-8Y2) and a motor drive (AMC, DPRALTE-080B020) was used to control the motor. The latter was powered by a 48VDC power supply (AMC, PS300W48) and the maximum rotational speed of the motor is 16,000 rpm at the continuous torque rating (18,700 rpm at no load speed rating). The command of the drive can be varied on a ±10V scale.

The rotor is installed directly on the flap axe, which eliminates any coupling elements and simplifies the mechanical assembly. On the axe, a 500 lines encoder is mounted (Avago HEDS-9140) and the drive used this encoder to calculate different information such as the rotor angle (i.e. the flap position) and speed. The motor speed is used internally by a speed control loop. The gains (proportional and integrator) of this loop were adjusted to obtain the desired behavior (rapid but with no overshoot). The other encoder information can be retrieved on 2 analog outputs (12 bits resolution on a ± 5 volts range).

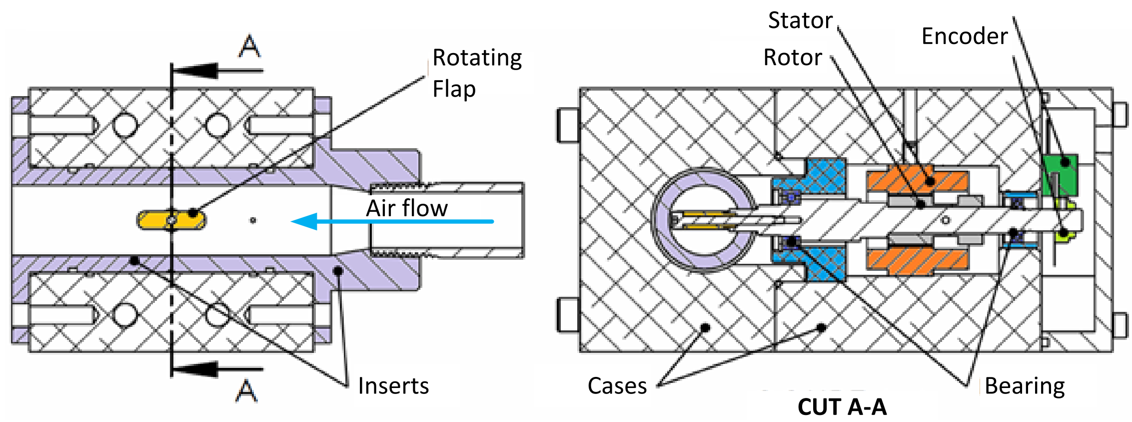

Figure 3: On the left: a side cut of the device. The flap is used to chop the airflow. On the right: the cut A-A of the device in the flap axis. The airflow is provided by a compressor.

3.2 Phase Locked Control (PLL)

The control of the motor is to ensure that the sinusoidal measured signal $y_m = A_m\sin(\omega_m t + \phi_m)$ is locked in phase with the reference complex signal $y_r = A_r\exp(j\phi_r)\,\exp(j\omega_r t)$. When the phase looked loop (PLL) ensures to keep the input and output phase in lock step ($\phi_m = \phi_r$) it also implies keeping the input and output frequencies the same ($\omega_r = \omega_m$) [19]. The PLL changes the phase and the frequency of the generated pressure by the source, since the controller modifies the frequency (i.e. the rotational speed of the motor) to correct the phase difference between the signals.

The multiplication of the reference y_r and the measured signal y_m gives a complex signal $y_m y_r^*$ where y_r^* denotes the conjugate of y_r . Once a low pass filter is applied on this product, the part of the signals which is twice the frequency of its fundamental (2 ω_0) is removed. So, only the DC component related to the phase difference between the two signals is obtained : $(\phi_r - \phi_m)$.

This phase comparison is used as an error signal by a proportional integral (PI) controller of the valve motor. If the phase error is positive, the rotation speed is increased. If the phase error is negative, the rotation speed is decreased. If the phase error is null, the rotation speed is maintained. The command of the motor will modify the rotation speed of the valve. In other words, the motor is used as a numerically controlled oscillator.

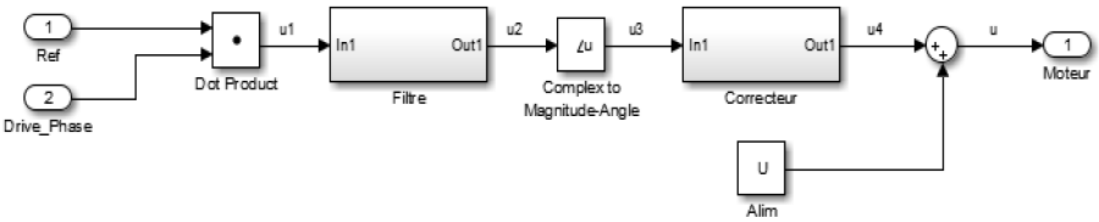

Figure 4: Phase control of the motor.

4. Experimental results

4.1 Experimental set-up

The device control was implemented on a real-time rapid prototyping controller Speed Goat PC. It used has one IO110 (16 analog outputs, 16 bit resolutions) and one IO112 (16 analog inputs, 18 bit resolution) boards in order to control the prototype. The sampling frequency was 40 kHz and the Simulink real-time code was compiled for this specific real time platform.

On the analog input board, the rotor position measured (provided by the motor drive) was compared to the complex reference signal. After the dot product, low pass filters removed the high frequency components of this dot product and the angle is calculated from the complex signal. The low pass filters used during the experimental tests were Butterworth filters (4^{th} order) with a cut-off frequency at half the frequency of the reference generated. The resulting angle is the phase difference between the reference and the measured signals. The PI controller (Kp=1, Ki=0.7) modifies the initial motor command in order to reach the required phase. The command is sent to the analog output, which modifies the analog signal at the motor drive.

Fig. 5 presents the phase difference variation during an experiment with the device. The target frequency was 500Hz (or 15,000 rpm). The initial motor speed was near the reference generated, so the controller has only a small correction to apply in order to reach the required phase. In this case, the phase difference reaches 0 after 3 seconds and oscillates between -0.1 and 0.05 rad (or -5.7 to 2.9 degrees). With this precision, it could nearly be possible to reach a 20 dB of noise attenuation.

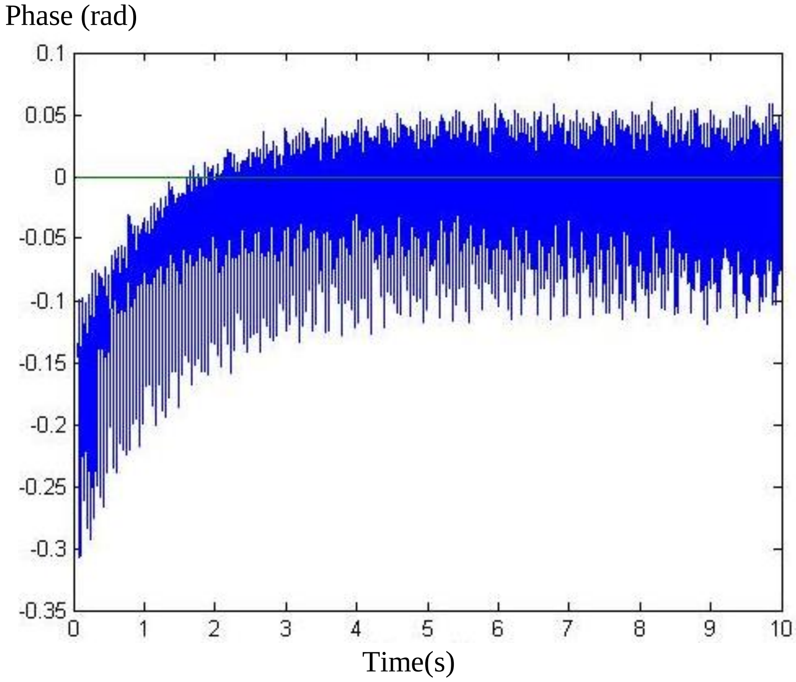

Figure 5 : Phase difference versus time obtained during an experiment (15,000 rpm).

4.2 Sound pressure

The rotating flap chops the incoming air flow provided by a reciprocating compressor that can provide a maximum of 0.1 kg/s [0.085 m^3/s] at a 410 kPa pressure. The air conduit section is 15.8 mm. The sound pressure level was measured *R*=1m from the device outlet at a 45 degrees angle (in reference to the jet axis), as to avoid having the air flow directly on the microphone. The microphone signal was recorded by the Speedgoat performance PC at a 40 kHz frequency. Fig.6 presents the experimental device installed in a semi-anechoic chamber for acoustic measurements. For that particular set-up, a non-baffled condition was considered. The compressed air supply pressure was set at 90 psi. The airflow was measured on the supply line with a volumetric flowmeter.

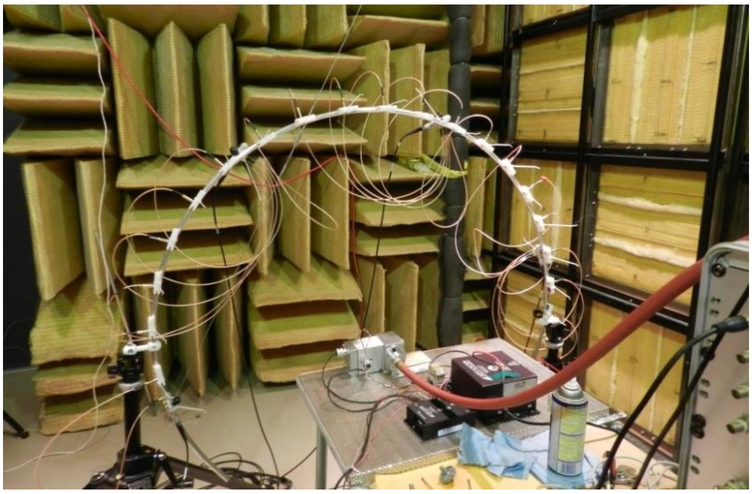

Figure 6 : experimental set-up in an anechoic room

Fig. 7 presents the sound pressure level measured for different volumetric flows. The higher SPL measured was 112 dB at a volumetric flow rate of 150 m^3/h (~88 scfm). As the theory predicts, and increased in volumetric flow rate increases the SPL measured. The sound pressure level (at 1 meter) was controlled in the range of 80-110 dB by controlling the mean flow in the range of 20-100 scfm. At low flow, the theory predicts higher SPL. However, at a higher flow rate the theory and the measured values seem to concur.

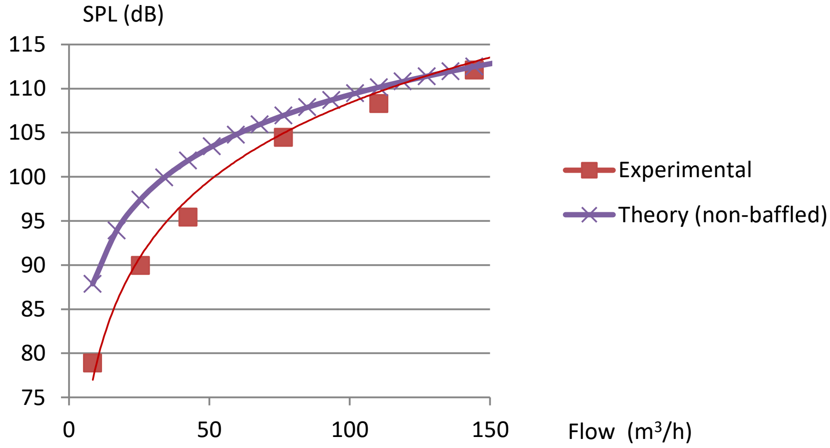

Figure 7: Sound pressure level (SPL) measured at 1 meter from the device outlet and 500 Hz (at a 45 degrees angle) in relation to the volumetric flow rate.

5. Conclusions

A fully controllable pneumatic source was designed and built to generate a pulsed flow in the low frequency range (up to 500 Hz). The device is composed of a flap put in rotation by a motor which chop an air flow, hence producing a periodic unsteady flow. A PI controller adjusts the motor speed to perfectly synchronize the angle position of the flap with a reference angle signal. Hence, the anti-noise generated by the flap rotation can be controlled both in frequency and phase.

Experimental results have shown that the device is able to generate harmonic noise at a frequency up to 500 Hz. The sound pressure level was controlled in the range of 80-110 dB by controlling the mean flow in the range of 20-100 scfm. The phase control precision is within ±6 degrees.

So, it can be concluded that such a device can be used for active noise harmonic control. Further works will be required to improve this original device and to implement it in practical applications.

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