PROCEEDINGS

People versus Noise

Volume II

editors :
Pierre Chapelle
Gerrit Vermeir

LEUVEN, BELGIUM ■ 1993 August 24 - 26

ACTIVE VIBRATION CONTROL
Session A3

inter•noise 93
Leuven - Belgium, August 24-26

NOISE CONTROL ON AIR DUCTS: EVOLUTION OF ACTIVE SYSTEMS AND PERSPECTIVES

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Abstract: An active noise control system on air ducts was recently proposed [1]. In this paper, two new systems are presented which being the evolution of the former, have higher performances. The first one is physically identical to the previously proposed system, but it employs another electronic control procedure, so that the noise reduction is considerably increased. The second system shows a really new shape, as it consists of a single loudspeaker which acts both as sensor and actuator. This second one would be less expensive and easier to install but, at the moment, its performances are less efficient than the two loudspeaker system. A maximum reduction of about 1.5 dBlin on the total noise level has been measured. However, a theoretical reduction of about 3 dBlin has been proven, so that improvements of the system are expected which would make it considerably attractive.

AIM OF THE WORK

Studies on active noise control in air ducts have been going on for two years in the acoustic laboratory of the University of Perugia [1],[2], following up several researches which are reported in Literature [3],[4],[5]. A first control system was proposed in 1992 [1], which succeeded in controlling a fixed sinusoidal signal. A reduction of about 14dB was obtained, but it was limited to single wave generating sources, while no global effect could be measured when the source was noise. In the present paper, some evolutions of the system are described. The first one implies a modification of the electronic circuit used in [1] and the fan rotating speed, which is held under similiar conditions with the commonly employed Air Conditioning Ducts. The second one implies a modification of the physical configuration used in the control: a single loudspeaker is used both as sensor and as actuator.

EVOLUTION OF THE CONTROL SYSTEM BASED ON TWO LOUDSPEAKERS (D.L.S.)

The experimental facility and the control system are constituted by the following elements:
*a)*an air duct, section 150 x 250 mm, length 4m: a grill outlet is set on one end of the duct, while a variable speed centrifugal fan is set on the other end;
*b)*two electrodynamical loudspeakers are employed: woofer type, frequency range 50-1000 Hz, diameter 160 mm;
*c)*a control system purposely built and supplied by 12 Volts battery. The circuit amplifies and regulates the signal up to an output power of 20 W;
*d)*a variable speed centrifugal fan with the following features: maximum flow-rate 800 m^3/h; power of the electric driving motor 0.2 KW; continuously variable speed in the range 300-900 r.p.m..

The elements c) and d) are the real innovations in the system described in [1] . The air velocity inside the duct is maintained in the range of 0.75-3.0 m/s, which is the usually used range in air conditioning ducts. The experimental results are reported in table 1. It may be observed that an important reduction of the fan noise is obtained which varies in the range of 4-7 dBlin and depends on the speed of the fan.

THEORY OF THE SINGLE LOUDSPEAKER SYSTEM (S.L.S.)

Statement of the problem. The two loudspeaker systems may cause instability problems because the control noise generated by the actuator, influences the sensor and auto-oscillating phenomena might arise. So a new system has been studied which utilizes only one loudspeaker, both as sensor and actuator. A woofer type loudspeaker is used, which can reduce noise in the 50-300 Hz range, where porous absorbent materials have no practical effect.

Mathematical model: Hypotheses. The acoustic pressure P(t) produces a force on the membrane surface "A", which is given by:

$$F_p(t) = P(t) \quad A \tag{1}$$

other forces act over the membrane, i. e. :

$$F_e\,(x) = K\,x \tag{2}$$

$$F_i\,(t) = m\,a(t) \tag{3}$$

$$F_m(t) = B\ l\ i(t) \tag{4}$$

where $i=0$, $Fm=0$ and the loudspeaker becomes a simple microphone. Then the bobine attached to the membrane moves in the magnetic field inside the louspeaker and generates a voltage proportional to the speed:

$$e(t) = B\, l\, v(t) \tag{5}$$

The loudspeaker operates alternatively both as sensor and actuator: during very short periods, the mechanical work caused by the acoustic pressure is absorbed by the electronic control system. A mathematical model has been developed according to the following hypotheses;
a) the membrane is rigid and it moves all in phase;
b) the acoustic pressure due to the noise is uniform all along the membrane surface;
c) very short periods are considered (t_2-$t_0=60\ 10^{-6}$ s), during which the acoustic pressure may be considered constant;
d) each interval is divided into two parts, (t_1-t_0) and (t_2-t_1);
e) during the time (t_1-t_0) no current flows in the coil and the membrane moves under the action of the forces F_p,F_e,F_i;
f) during the time (t_2-t_1) the force Fm arises due to the electric current in the coil, and this force reduces until it stops;
g) the elastic force F_e is directed towards the neutral position and is proportional to the distance from it.

Hypothesis a) is justified by the high rigidity of the membrane, because of its conic shape. Hypotheses *b)* and *c)* are applicable because of the low range of frequency being considered (40 - 300 Hz). Hypotheses *d)* and *f)* can be actuated by an adequate electronic circuit. Finally, hypothesis *g)* can be actuated by a finalized construction of the membrane.

<u>Development of the Mathematical Model</u>. The equation of the membrane motion is :

$$m\cdot\frac{d^2x}{dt^2} \pm K\cdot x - P\cdot A=0 \tag{6}$$

The sign + is valid when the distance x from the equilibrium position increases.
For $t=0$, $x=0$ and $dx/dt=0$, the distance s1 and the velocity v1 at the time t1 can be calculated as follows:

$$s_1 = \frac{P\cdot A}{K}\cdot[1-\cos(\ (t_1-t_0)\ \cdot\ \sqrt{\tfrac{K}{m}}\ )\ ] \tag{7}$$

$$v_1 = \frac{P\cdot A}{K}\cdot\sqrt{\tfrac{K}{m}}\cdot\ sen(\ (t_1-t_0)\ \cdot\ \sqrt{\tfrac{K}{m}}\ ) \tag{8}$$

The output loudspeaker voltage is:

$$e_1 = B\, l\, v_1 \tag{9}$$

During the period (t_2-t_1), the membrane is decelerated by a force generated by a current i_1 through the coil chosen by means of the electronic system proportional to e_1, so that :

$$i_1 = e_1\, A_v/Z_a \tag{10}$$

The force Fm_1 in the period (t_2-t_1) is given by:

$$F_{m1} = B\, l\ i_1 \tag{11}$$

Therefore the membrane motion follows the equation:

$$m\cdot\frac{d^2x}{dt^2} \pm K\cdot x + B\cdot l\cdot i_1 - P\cdot A=0 \tag{12}$$

By imposing that the membrane reaches the equilibrium position at the time t_2, from the condition $dx/dt=0$, the corresponding value of A_v can be calculated:

$$Av=\sqrt{\tfrac{K}{m}}\cdot\frac{Z_a\cdot m}{B^2\cdot l^2}\cdot\frac{1}{sen[(t_1-t_0)\cdot\sqrt{\tfrac{K}{m}}\ ]\cdot sen[(t_2-t_1)\cdot\sqrt{\tfrac{K}{m}}\ ]} \tag{13}$$

Eq. (13) shows that, if the intervals (t1-t0) and (t2-t1) are fixed, Av depends only on the loudspeaker characteristics.

THE S.L.S. SYSTEM: ENERGETIC ANALYSIS

When the membrane is moving away from the equilibrium position, the energy balance is given by:

$$dEa - dEe = dEc \qquad \text{for } t_0<t<t_2 \tag{14}$$

$$dEc = dEm \qquad \text{for } t_1<t<t_2 \tag{15}$$

on the other hand, when the membrane is approaching the equilibrium position, the energy balance expressed by the equation (14) may be rewritten as follows:

$$dEa + dEe = dEc \qquad \text{for } t_0<t<t_2 \tag{16}$$

In the first case, only a limited fraction of the inciding energy is absorbed, because an important quantity is accumulated in the form of elastic position energy of the membrane. On the contrary, while the membrane is approaching the equilibrium position, the electronic system absorbs the kinetic energy relative to the membrane motion, which also includes the energy accumulated in the elastic form during the precedent phase. The absorbed energy is dissipated within the devices of the electronic control system. The inciding energy is partially reflected by the membrane, depending on the wave length, the loudspeaker properties and the inciding angle[6]. In the present event, the reflected energy has been estimated in the range of 15-30% of the inciding energy. Calculations are omitted for brevity.

THE S.L.S. ELECTRONIC CONTROL SYSTEM

The block diagram of the electronic control system is reported in fig.1, made up of the following components: *a)* First Stage Amplifier A1. It amplifies the electric signal from the loudspeaker, so that it may be furtherly converted. *b)* Sample and Hold. This picks up the electric signal from the loudspeaker at the time t_1 and stores it during the entire following interval (t_2-t_1). *c)* Timing Circuit. It is made up of one oscillator and two monostables and it achieves the desired timings. Besides it generates the impulses which control the length of the intervals t_1-t_0, t_2-t_1, t_2-t_0 and the sample at the instant t_1. *d)* Second Stage Amplifier A2. This is a power amplifier to elevate the control signal up to the values high enough to drive the loudspeaker; the total amplification is equal to Av, given by Eq. (13).
e) FET Switch. An electronic switch which connects A2 with the loudspeaker used as actuator during (t_2-t_1); whereas, during (t_1-t_0) it insulates the amplifier output from the loudspeaker, which then acts as sensor and generates the voltage e(t) to the preamplifier inlet. *f)* Filter PB. It cuts off a great part of the high frequency electrical signals which are generated by the master electronic system. The oscillator frequency is set equal to 16,666 KHz, so that the electrical commutation does not produce audible noise and hypothesis 3.2.c) is verified.

THE S.L. S. SYSTEM: EXPERIMENTAL RESULTS

The experimental facility is described in Chapter 2; this time only one loudspeaker is present, instead of two. The noise source is a variable speed centrifugal fan: in fig.2 the noise wave shape is reported along with the control signal. The experimental results are reported in tab.1 and tab.2 . They include data on total noise reduction at different operating conditions. The maximum theoretical noise reduction is attained when the absorption coefficient of the loudspeaker surface is equal to unity. This has been measured in the following way: the loudspeaker is moved away and the resulting window opened in the ducts, is connected with a space acoustically independent from the room where the measurements are performed. The results are shown in column 7 of table 1. The maximum reduction is variable with the noise level and it varies in the range 2.6-3 dBlin. The actual reduction is variable as well as varying in the range 0.5-1.5 dBlin

CONCLUDING REMARKS

Two new active control systems have been proposed for noise reduction inside air conditioning ducts. The first one, which utilizes two loudspeakers, one as sensor and the other as actuator, is a true evolution of a previous system set up in our laboratory [2]. By applying some modifications an improvement of performances has been obtained on electronic control system. The total noise reduction reaches 7 dBlin. A second arrangement of the noise control system is also proposed for the first time which utilizes only one loudspeaker used both as sensor and actuator: this would be cheaper and easier to install. A theoretical outline of the system is proposed and a set of experimental results is shown. The total noise reduction reaches 1.5 dBlin. The obtained results encourage us to go ahead in the research: the theoretically attainable noise reduction is considerably higher, so we think that by improving the electronic control system, it will be possible to increase the present performances of the system.

TABLE1: Global Noise Measurements and active control noise systems comparison

V (m/s)	Q (m³/h)	Control OFF	Control ON				
			D.L.S.		S.L.S.		
		Measured noise level (dBlin)	Measured noise level (dBlin)	Measured reduction (dBlin)	Measured noise level (dBlin)	Theorical noise reductions (dBlin)	Measured reductions (dBlin)
3.0	400	86.0	79.7	6.3	85.5	3.0	0.5
2.2	300	77.5	70.4	7.1	76.6	2.9	0.9
1.85	250	75.6	70.0	5.6	74.6	2.8	1.0
1.48	200	72.4	67.0	5.4	71.0	2.8	1.4
1.10	150	69.9	65.6	4.3	68.4	2.7	1.5
0.75	100	69.6	65.4	4.2	68.5	2.6	1.1

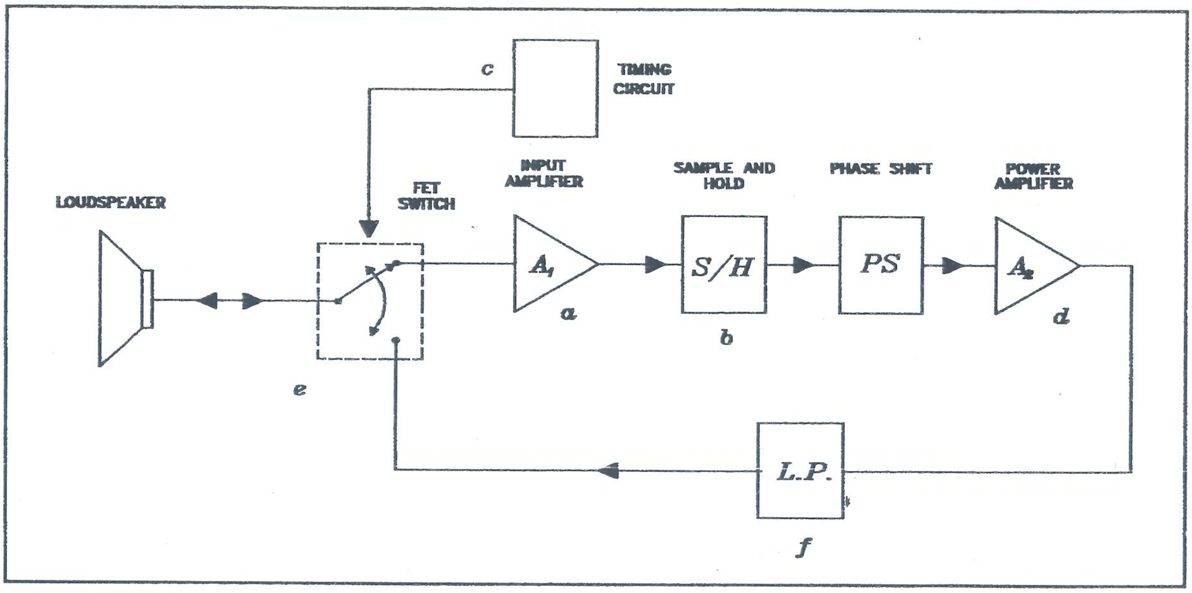

FIG. 1: Electrical block diagram of the S.L.S.

SYMBOLS

a = acceleration (m/s^2)
A = effective membrane area (m^2)
Av = voltage amplification coefficient
B = magnetic induction (Wb/m^2)
Ea = acoustic energy (J)
Ec = membrane kinematic energy (J)
Ee = elastic potential energy (J)
Em = absorbed energy (J)
e = loudspeaker output voltage (V)
F = force (N)
Fe = elastic force (N)
Fi = inertial force (N)
Fm = force due to magnetic field (N)
Fp = force relative to acoustical pressure (N)
i = current (A)
K = elastic constant (N/m)
l = loudspeaker coil length (m)
m = mobile mass: membrane and coil, (Kg)
P = acoustic pressure (Pa)
Q = flow rate (m^3/h)
t = time (s)
v = velocity (m/s)
x = displacement (m)
Za = input loudspeaker impedence (Ω)

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