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An Adaptive System for Active Noise Reduction

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An adaptive system for active noise reduction in an acoustic duct is presented. The system is based on a modification of a least mean square (LMS) algorithm called filtered-U with on-line error path modelling. The system was assembled and examined on a laboratory test stand in the Laboratory of Active Noise Reduction Methods of the Central Institute for Labour Protection (Warsaw, Poland). The structure of the stand, the block structure of the active noise reduction system, the basic assumption concerning the applied adaptive algorithm, and examples of measured effectiveness of the system for various kinds of noise are presented.

noise reduction active cancellation adaptive system low frequency noise

1. INTRODUCTION

A very high degree of pollution of the working environment with noise, connected with increasing requirements concerning safety at work are a reason for developing increasingly more effective and technologically advanced methods of noise reduction (Engel, 1993). Those methods certainly include methods of active noise reduction, which consist in

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applying an additional controlled source of vibroacoustic energy. These additional sources have to be specially controlled in order to guarantee conditions of destructive interference of acoustic waves. A reduced noise level is a result of destructive interference. Active methods of noise reduction are highly effective for low frequency noise (less then 500 Hz). In this range of frequency, active reduction methods are an alternative for traditional passive methods of noise reduction. The reduction of noise propagated along acoustic ducts is one of the main applications of active methods. HVAC (heating, ventilating, and air conditioning) systems are examples of those noise sources. Investigations on active methods of noise reduction have been carried out in the Central Institute for Labour Protection (Warsaw, Poland) for a few years. They focus on an active reduction of noise propagated along ducts. As a result of those investigations a test stand was built. It combines features of a laboratory stand and a real ventilating system with wide possibilities of configuration. This stand is used to carry out investigations on digital controllers, which constitute the basic element of each modern active noise reduction system.

2. TEST STAND

The test stand (Figure 1) consists of the following parts:

- a measurement duct,
- a ventilating system,
- instrumentation, which includes elements of the active noise reduction system.

The acoustic measurement duct consists of three elements:

- two extending segments (17),
- one extending segment, which includes additional, replaceable elements in the form of barriers that introduce disturbance of a medium flow inside the duct (18).

The ventilating system consists of a ventilating duct and a set of replaceable ventilators. The ventilating duct is based on standard available metal segments with a 20×20 cm square cross-section. In the present form, the whole ventilating duct consists of 30 elements, including

- 15 segments of the total length of 1,176 cm (2, 4, 5, 6, 8, 9, 10, 11, 12);
- 4 pipe tees (3);

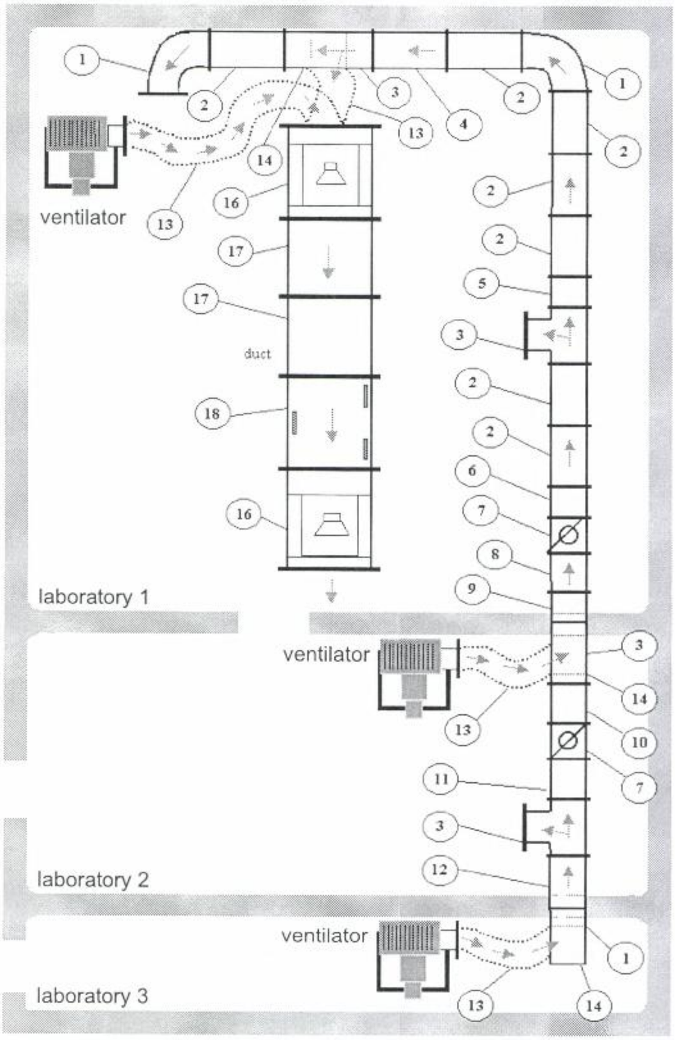

Figure 1. Diagram of the test stand. *Notes.* 1—elbows; 2, 4, 5, 6, 8, 9, 10, 11, 12—segments; 3—pipe tees; 7—valves; 13—elastic ducts; 14—angular reducers; 16—loud-speaker boxes; 17—extending segments; 18—extending segment.

- 3 elbows (1);
- 3 elastic ducts (13);
- 3 angular reducers (14);
- 2 valves (7).

The ventilating duct was mounted in three adjacent laboratories. To connect it with ventilators, the end segments were fitted with angular reducers adapted for connecting with elastic ducts. Ventilators can be placed in each of the three laboratories (1, 2, and 3).

Owing to its wide possibilities of configuration, the test stand allows measuring active noise reduction systems under laboratory and real conditions.

3. AN ADAPTIVE SYSTEM OF ACTIVE NOISE REDUCTION WITH ERROR PATH MODELLING

A large number of contemporary active noise reduction systems are based on various kinds of modifications of the least mean square (LMS) algorithm (Rutkowski, 1994). One of the more advanced versions of the LMS algorithm is the filtered-U algorithm. Mathematical fundamentals of this algorithm were formulated in 1991 (Eriksson, 1991). Since then, controllers of high efficiency active noise reduction systems based on this algorithm have been developed in many research laboratories. An adaptive system of active noise reduction utilising the filtered-U LMS algorithm has been developed in the Laboratory of Active Noise Reduction Methods of the Central Institute for Labour Protection (Makarewicz, Zawieska, Matuszewski, & Morzyński, 1998). A block diagram of this system is presented in Figure 2.

In agreement with theoretical assumptions (Eriksson, 1991) a combined vector of filter's coefficients $\mathbf{w}_n$ and a combined vector of input samples $\mathbf{u}_n$ have been introduced in the description of the algorithm controlling the operation of the system. Those vectors are defined as follows:

$$\begin{aligned} \mathbf{w}_n &= [f_n^A(0),\, f_n^A(1), \dots,\, f_n^A(N),\, f_n^B(0),\, f_n^B(1), \dots,\, f_n^B(M)]^T \\ \mathbf{u}_n &= [x(n), x(n-1), \dots, x(n-N), y(n-1), \dots, y(n-M)]^T \end{aligned} \tag{1}$$

where

$f_n^A(0), \dots, f_n^A(N)$ — filter A coefficients for discrete time n;
$f_n^B(0), \dots, f_n^B(M)$ — filter B coefficients for discrete time n.

The output signal used in the process of active noise reduction is calculated from the equation:

$$\begin{aligned} y(n) &= \mathbf{w}_n^T \times \mathbf{u}_n \\ e(n) &= d(n) + y(n) \end{aligned} \tag{2}$$

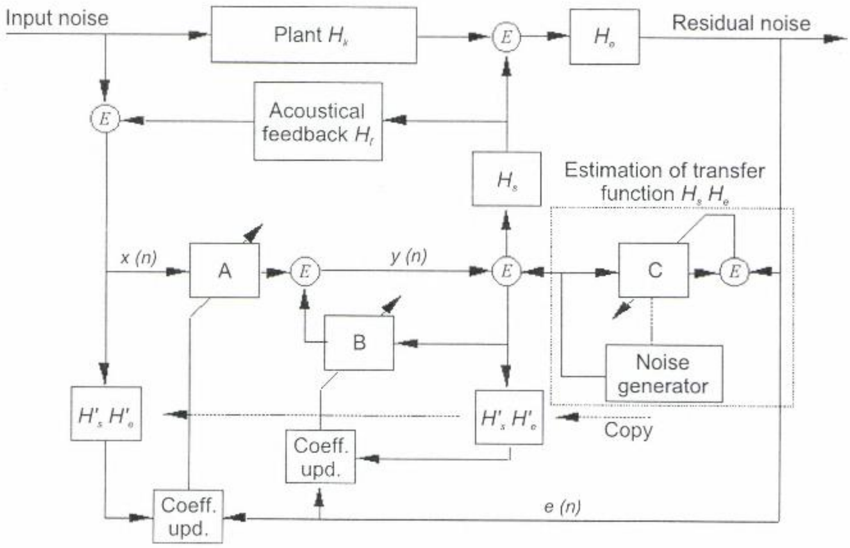

Figure 2. Diagram of an active noise reduction system based on the filtered-U least mean square (LMS) algorithm with on-line error path modelling and on-line error path transfer function estimation. *Notes.* *A, B, C*—filters; H_e, H_f, H_k, H_s—transfer functions; $H_s' H_e'$—combined transfer function; Σ—summation node; Coeff. upd.—coefficients update block.

An update of the combined vector of filter coefficients has been effected in accordance with Equation 3:

$$\begin{aligned}\mathbf{w}_{n+1} = \mathbf{w}_n - \alpha \cdot e(n) \cdot [h_s^* h_e^* x(n), \ldots, h_s^* h_e^* x(n-N),\\ h_s^* h_e^* y(\mathrm{n}-1), \ldots, h_s^* h_e^* y(n-M)]^T\end{aligned} \tag{3}$$

where

h_s — impulse response corresponding with the transfer function H_s,
h_e — impulse response corresponding with the transfer function H_e,
α — convergent constant.

The most important signals in the process of active noise reduction are reference signal $d(n)$, output signal $y(n)$, and error signal $e(n)$. The error signal is a measure of the effectiveness of the active noise reduction process. Thus, for the correct calculation of the output signal, that is, to update coefficients in the filtered-U algorithm (Equation 3), one has to know impulse responses corresponding with transfer functions H_s and H_e, which are constituents of the so-called error path. In practice, those transfer functions are not known and they have to be estimated.

In practical implementation of active noise reduction systems based on the filtered-U algorithm, familiarity with the combined transfer function $H'_s H'_e$ is necessary. $H'_s H'_e$ is the closest approximation of the transfer function of the error path $H_s H_e$. This transfer function can be estimated before starting the system (off-line estimation) or during the operation of the system (on-line estimation). An additional adaptive filter and a source of uncorrelated noise are used in the developed active noise reduction system. On-line estimation allows taking into account changes of the transfer function of an error path during the operation of the system.

4. MEASUREMENTS

A device consisting of a digital signal processor, A/D (analogue/digital) and D/A (digital/analogue) converters, and an interface for communication with a personal computer was used to measure the effectiveness of the active noise reduction system. The filtered-U algorithm with on-line error path modelling was implemented on a digital signal processor. The arrangement of the test stand is presented in Figure 3.

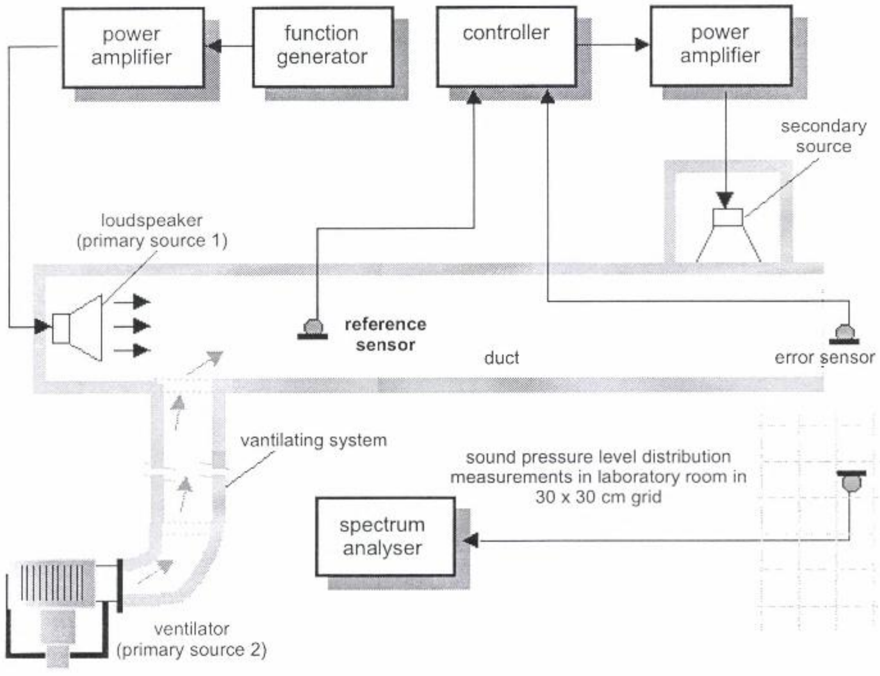

Figure 3. Block diagram of the test stand.

Low frequency noise generated by real noise sources can be more or less complex. In most cases acoustic energy is concentrated in certain relatively narrow bands around some frequencies. The effectiveness of active noise reduction was tested for noises of various degrees of complexity. Measurements were made for

- tones (frequency in 10-Hz steps),
- 10-Hz narrow band noise (centre frequency set to 10-Hz steps),
- 100-Hz narrow band noise with 150-Hz centre frequency.

Results of the measurements are presented respectively in Figures 3, 4, and 5 as a noise spectrum before and after activation of the active noise reduction system. For testing the influence of controller parameters on the effectiveness of active noise reduction, measurements were made for two orders of the estimating filter ($N = 63$ and $N = 127$) for all tested types of noise. To avoid errors connected with a finite time of adaptation, the sound pressure level was measured 5 min after the activation of the active noise reduction system.

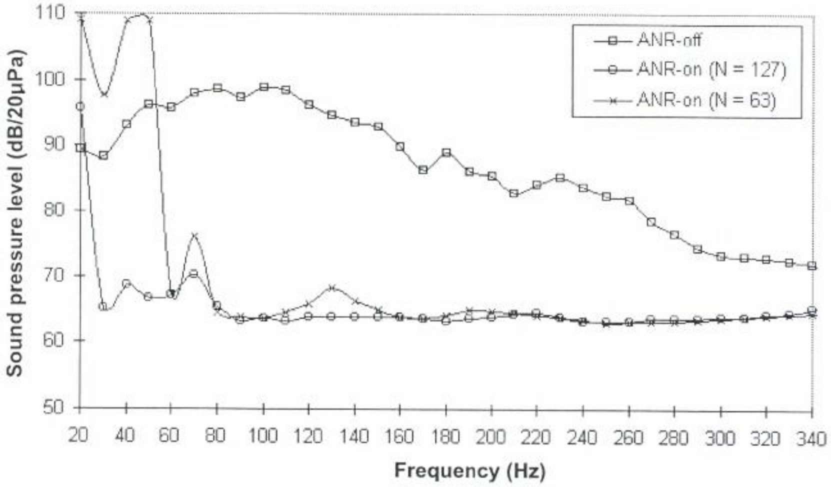

Figure 4. Efficiency of the active noise reduction system based on the filtered-U algorithm with on-line error path modelling and estimation of the H_sH_e transfer function for tonal noise. *Notes.* ANR—active noise reduction system.

Thus, for an estimating filter of the order of 63, the range of effective operation of the active noise reduction system for tonal and narrow band (10 Hz) noise oscillates between 50 and 340 Hz, and for 100-Hz narrow band noise it oscillates between 20 and 340 Hz.

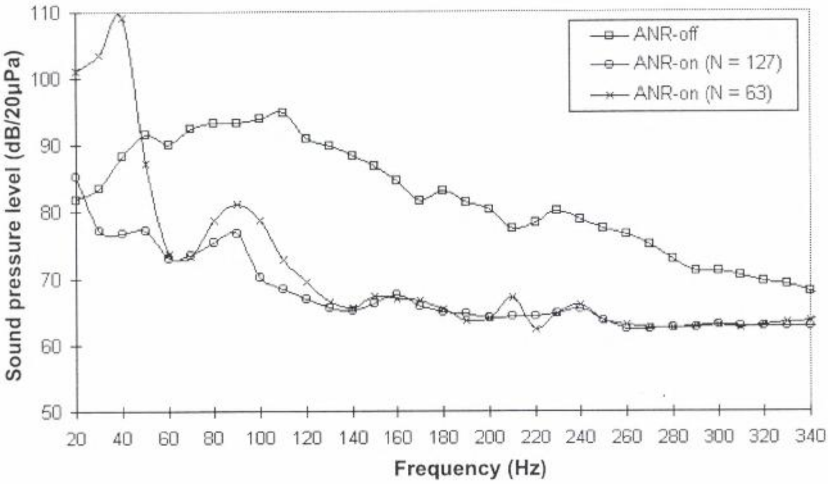

Figure 5. Efficiency of the active noise reduction system based on the filtered-U least mean square (LMS) algorithm with on-line estimation of the H_sH_e transfer function for narrow band noise (10 Hz). *Notes.* ANR—active noise reduction system.

For a higher order ($N = 127$) estimation filter, the frequency range of effective performance varies from 20 to 340 Hz for all tested types of noise. Results of measurements confirm the fundamental role of accurate modelling of the error path for good operation of an active noise reduction system. Maximum effectiveness of active noise reduction of 35 dB was achieved for tonal noise in the frequency range from 80 to 120 Hz. Results of effectiveness measurements of the active noise reduction system for narrow band noise are presented in Table 1. These measurements were made for noise bands of 31.5, 100, and 316 Hz. In all cases, the centre frequency of noise bands was equal to 150 Hz.

TABLE 1. Measurements of Sound Pressure Level (SPL) for the Filtered-U Least Mean Square (LMS) Algorithm With On-Line Estimation of H_sH_e Transfer Function for Various Widths of Noise Bands (Using a B&K 2236 Meter; Brüel & Kjær, Denmark)

Algorithm Parameters	$N = 63$, $\alpha = .001$ Level of Estimating Noise = –30 dB			$N = 127$, $\alpha = .0005$ Level of Estimating Noise = –30 dB		
Bandwidth (Hz)	31.6	100	316	31.6	100	316
Off – SPL (dB)	92.6	93.9	93.6	92.5	94.0	93.3
On – SPL (dB)	78.2	84.5	90.2	77.6	84.5	86.4
Attenuation – SPL (dB)	14.4	9.4	3.4	14.9	9.5	6.9

The sound pressure level in laboratory No. 1 (Figure 1) was measured with and without the active noise reduction system. These measurements were made on a 30 × 30 cm square grid, placed 1.1 m above the floor. The effectiveness of active noise reduction is defined as the difference between sound pressure levels with the active noise reduction system off and on (Figure 6).

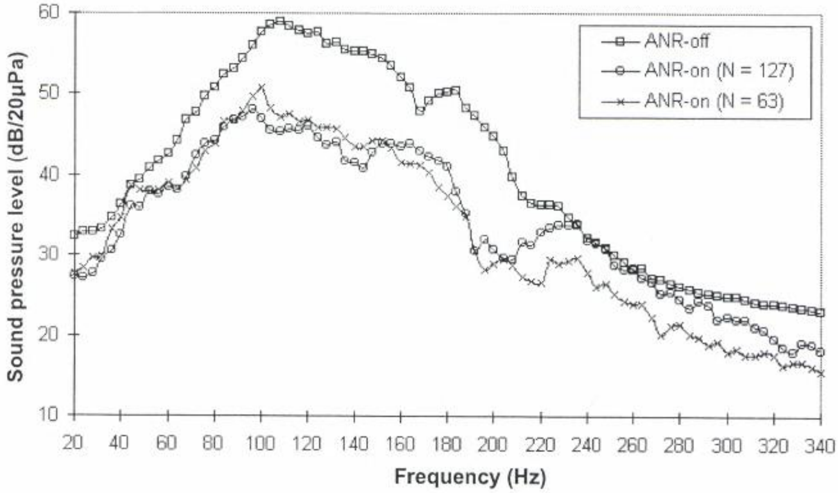

Figure 6. Efficiency of the active noise reduction system based on the filtered-U least mean square (LMS) algorithm with on-line estimation of the H_sH_e transfer function for 100-Hz noise. *Notes.* ANR—active noise reduction system.

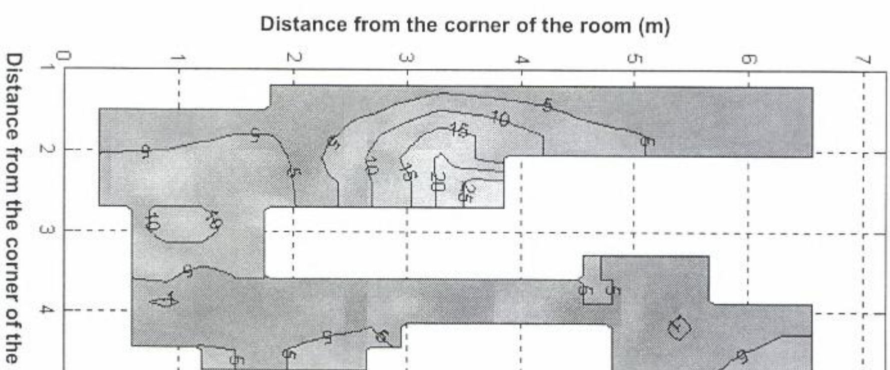

Figure 7. Efficiency of active noise reduction evaluated on the basis of sound pressure level measurements in the laboratory.

Thus, the use of the active noise reduction system reduced the noise level in the laboratory from 5 to 25 dB. Empty areas in Figure 7 are places in which measurements were impossible due to the way the laboratory was arranged.

5. CONCLUSIONS

The worked out active noise reduction system based on the filtered-U algorithm with on-line error path modelling is a good solution for reducing various kinds of low frequency tonal noise and narrow band noise, that is, noises generated by many real sources. Using the results achieved so far, investigations concerning the influence of the configuration of a ventilating system (with which the laboratory test stand is equipped) on the effectiveness of active noise reduction system are made now. Those investigations are a transient stage in applying this solution to noise reduction in a real ventilating system.

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