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Active noise cancellation: air conditioner and transformer case study

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Two cases of active noise cancellation technique are discussed in the paper. A feedforward control systems for both cases were used. FxLMS (Filtered Least Mean Square) algorithm for noise reduction of air conditioner is implemented whilst sub band LMS utilized in transformer case. To provide a good quality of the reference signal the special method of flow isolation for reference and error microphones is proposed. The noise reduction efficiency of 15 and 10 decibels at frequencies 90 and 240 Hz is provided using proposed configuration of the system. Three tonal components 120, 240 and 360 Hz are dominated in transformer noise spectrum. Implementation of sub band FxLMS algorithm for transformer case has shown the high efficiency of proposed technique within local area for tonal component 120 and 340 Hz. The most wide silent zone at frequency 240 Hz is revealed during study.

INTRODUCTION

Last decade Active Noise Control (ANC) became a hot topic between researcher and developers involved in the noise control engineering. Nevertheless despite the huge number of theoretical and practical efforts, a real implementation and commercial applications are still very small. The product lines of ANC solutions are limited to active anti noise headsets and active duct silencers.

Active noise control means that noise reduction happens due to introducing into the primary acoustic field a sort of opposite disturbance creating so-called destructive interference, which leads to reduction the energy of the primary noise field. Therefore in order to obtain the noise reduction with high effect an exact copy of primary field has to be reproduced. Theoretical basis of active noise control was developed by Nelson and Elliott and can be found in the reference [1]. Further practical development of active noise control technique was made by Colin H. Hansen [2] and Scott D. Snyder [3]. Details about DSP algorithms for active noise control are described in the [4] by Sen M. Kuo, Dennis R. Morgan.

The aim of the paper is to point out the physical and commercial constraints for the two cases study of ANC application and to estimate theirs potential and real efficiency *in situ*.

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1. FxLMS AND SUB BAND FxLMS ALGORITHM

The block diagram of FxLMS (Filtered Least Means Square) algorithm is depicted in Fig. 1. FxLMS means that reference signal is filtered using transfer function of secondary path therefore abbreviation denotes the fact that signal is filtered. This technique allows compensating the delay caused by secondary electro acoustic path. Thus FxLMS algorithm has advantage because it takes into account the secondary transfer electro acoustic path that simple LMS algorithm does not. The data about secondary transfer path can be acquired during so-called "off-line modeling" [4].

Fig. 1. Block diagram of FxLMS

$x(n)$ — reference signal from the reference microphone, $e(n)$ — error signal from error microphone, $d(n)$ — primary noise disturbance, $x'(n)$ — filtered reference signal, $y(n)$ — cancellation signal, $y'(n)$ — filtered cancellation signal, $P(z)$ — primary acoustic path from reference microphone to error microphone, $S(z)$ — secondary path from controller output to summation point, $S'(z)$ — estimated secondary path obtained during off-line modeling, $W(z)$ — Weiner filter response

The filter quotients are adapted according to equation (1)

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \mu\, \mathbf{x}'(n) \cdot e(n), \tag{1}$$

where μ is so-called convergence factor, $\mathbf{w}$ — quotients of adaptive filter, n — discrete time.

Method how to set the μ value can be found in [4]. The role of reference sensor is getting the "pure" signal referred to the noise source spectrum feedback to controller in order to monitor the residual acoustic pressure and adjusting controller for optimal results.

To minimize the influence of the airflow to reference and error signals in the air conditioner case two methods can be implemented: the usage the reference signal from tacho sensor or isolation of the reference microphone from flow noise. The optimal frequency response function of the adaptive filter can be expressed in the form:

$$W^o(z) = \frac{P(z)}{S(z)},\ W^o(f) = \frac{S_{dx'}(f)}{S_{x'x'}(f)}, \tag{2}$$

where f — frequency, $S_{dx'}(f)$ — cross spectrum between filtered reference signal and disturbance signal, $S_{x'x'}(f)$ — auto spectrum of filtered reference signal.

The equation (2) expresses the frequency response of the optimal controller in least mean square sense.

Sub band FxLMS algorithm for implementation in transformer active noise control case was chosen. The block diagram of sub band FxLMS algorithm is shown in Fig. 2.

Fig. 2. Block diagram of sub band FxLMS algorithm

2. AIR CONDITIONER CASE STUDY

To determine the frequency component of the interest the narrow band FFT measurement of air borne noise levels for conditioner were made. The measurement setup is shown in Fig. 3.

It can be seen from Fig. 3 that there is dominant tonal component in air conditioner noise spectrum at 90 Hz. This frequency component is due to blade passing of impeller and has its sound pressure level 15 dB higher than others.

Fig. 3. Measurement setup for measurement of air conditioner noise and background noise

Fig. 4. Air conditioner noise spectrum, solid line – aircon noise levels (reference microphone),dashed line – background noise level (error microphone)

It can be seen from Fig. 4 that there is dominant tonal component in air conditioner noise spectrum at 90 Hz. This frequency component is due to blade passing of impeller and has its sound pressure level 15 dB higher than others.

The signal-to-noise ratio obtained during the testing of ANC system efficiency was quite high and achieved value of 30 dB. The high level of signal-to-background noise shows the reliability of the testing results of ANC system efficiency.

The other factor which can substantially impact the efficiency of ANC system is so-called "causality problem". In our case this is due to influence of the airflow noise. The model of airflow noise influence is depicted in Fig. 5.

In the case of existing the flow noise with spectrum $N(f)$ the efficiency of the system can be deteriorated due to reduction of coherence function between input and output (reference and error microphones) signal.

Fig. 5. Model of airflow noise influence

To reduce the influence of the airflow noise the both microphones were isolated from airflow noise. The flow isolation design of the microphones is depicted in Fig. 6.

Fig. 6. Sketch of the flow isolated microphone

Table 1 gives the potential efficiency of ANC system vs. coherence function according to Nelson and Elliott [1]. The efficiency is calculated using the equation (3):

$$Eff(f) = 10\lg\left(\frac{\gamma^2_{ref.err}(f)}{1-\gamma^2_{ref.err}(f)}\right), \quad (3)$$

where $\gamma^2_{ref.err}(f)$ — ordinary coherence function between signal from error and reference microphone.

Table 1

coherence	Potential effect, dB	coherence	Potential effect, dB
0,6	2	0,95	13
0,7	4	0,96	14
0,8	6	0,97	15
0,91	10	0,98	17
0,93	11	0,99	20
0,94	12	0,999	30

Measurement of the coherence function was undertaken and results are presented in Fig. 7.

Figure 7 illustrates that the coherence function is high enough (0,98) at the frequency of 90 Hz. Hence according to estimation (see table 1) the potential effect of ANC system would be around of 17 dB. The coherence value at the frequency around of 240 Hz is also high enough. Hence the ANC efficiency at those frequencies is expected to be high. The qualification tests of ANC system were performed and testing set-up is shown in Fig. 8.

Fig. 7. Coherence function between reference and error microphone (running air conditioner)

Results are shown in Fig. 9. It can be seen from Fig. 9 that 15 dB reduction was obtained at frequency component of 90 Hz. The less reduction around 10 dB can be seen at frequency 240 Hz due to lesser signal-to-noise ratio or coherence function comparing to 90 Hz component. It should be noted here that calculated efficiency of ANC system based upon measured data of coherence function and estimated one during qualification test are in the good agreement. Therefore a measured coherence function can be utilized a priory to estimate the potential efficiency of ANC system.

Fig. 8. Qualification test set-up for aircon with ANC system

Fig. 9. ANC efficiency: solid line — ANC turned-off, dotted line — ANC turned-on

3. TRANSFORMER CASE STUDY

First analog ANC system for industrial transformer was suggested and implemented by Connover W. B. and Ringlee R. J. [5] Due to changing of environmental conditions the analog system seems to be very unstable. The digital one with DSP adaptive algorithm is more suitable for that purpose.

Small sized industrial transformer was a subject for active noise control. It was determined during transformer noise measurements that there are three dominant tonal components at frequencies 120, 240 and 360 Hz in transformer noise spectrum (see Fig. 10). Those components can be considered like critical ones or frequencies of the main interest. Coherence level between signal from reference gauge and error microphone is very high as it can be seen from Fig. 11. Thus a feedforward ANC system is expected to be very effective for implementation.

A full wave bridge rectifier as a source of reference signal was used instead of reference microphone. Here the common reference signal was filtered using three digital band pass filters with central frequencies 120, 240 and 360 Hz respectively and sent then to the DSP board. Analog Device Black Fin evaluation board is used as the core of DSP.

The view of transformer ANC system is depicted in Fig. 12 and block diagram – in Fig. 13 respectively. The noise canceling loudspeakers are essential component of ANC system. They should be capable to create high sound pressure levels with small total harmonic distortion. That type of loudspeakers were designed and tested. The loudspeakers specifications are following: THD less than 1% at SPL = 100 dB with tonal signal testing at distance of 30 cm from membrane, FRF flatness ±3 dB in the frequency range from 100 Hz to 400 Hz, electric impedance 6 Ohms.

High sensitive SiSonic microphones with embedded integrated amplifier were used as error ones. The microphone sensitivities were set to their highest values – 20 dB using external discrete electronic components. The reference level zero dB here means the reference sensitivity 1 V per Pa.

Fig. 10. Transformer noise spectrum:
solid line – transformer turned-on, dotted line – transformer turned-off

Fig. 11. Coherence function between signal from reference gauge and error microphone

Fig. 12. Set-up of transformer ANC system

Fig. 13. Block diagram of transformer ANC

The system efficiency using Praxis Audio measurement instrument over the points separated with one half of the wavelength equal to 0.3 meter was measured. This value is referred to highest critical frequency 360 Hz and speed of sound value 340 m/s. The measurements results shows (see Fig. 14) that total reduction effect exists around appropriate error microphone and becomes substantially less if observation point was moved to one half of wavelength far further from error mike. The total efficiency of the transformer system is local due to insufficiency of control channels. The number of channels was limited due to small project budget and cost effective requirements from customer.

Fig. 14. Noise reduction pattern

4. DISCUSSION

Two cases of implementation of ANC were considered in the paper. First one is the noise reduction of tonal components in air conditioner airborne sound field. It was found that two tonal components 80 and 240 Hz can be reduced by 15 and 10 dB respectively. The total efficiency is limited here due to low signal-to-noise ratio when airflow induced noise affects the microphone signals. The airflow isolation method of reference and error microphones using porous sound absorption material was proposed. Measured coherence function can be used as an input data for estimation of potential efficiency of ANC system a *priory*.

Second example of ANC implementation is given for small industrial transformer. The most wide silent zone over the space was revealed at the frequency 240 Hz. It has shown that three-channel ANC system with sub band FxLMS algorithm is not suffice to obtain the global noise reduction over transformer front plane. Another drawback of proposed ANC is a long time procedure for algorithm adjustment *in situ*.

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APPENDIX A: List of abbreviations

ANC — active noise control (cancellation)

DSP — digital signal processing

FRF — frequency response function

FxLMS — Filtered Least Mean Square algorithm

SPL — Sound pressure level

THD — total harmonic distortion