ACTIVE NOISE CONTROL EXPERIMENTS IN A FORK-LIFT TRUCK CABIN

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Abstract

High comfort for the driver in working vehicles is an important feature as well as a demand from the drivers. Low noise level is an essential factor for the manufacturer to maintain a high standard and comfort of vehicles. In many cases the noise inside the cabin can be related to the engine orders. Hydraulic pumps and fans are also related to the engine but not necessarily integers of the engine order. Passive absorbers are not suitable for the lowest frequencies and one approach is to use an active noise control system to solve the noise problem at low frequencies. In the present experiment loudspeakers were mounted inside the cabin of a fork lift-truck to produce the secondary noise field. To sense the residual noise, microphones were installed close to the driver's head. The aim is to create a zone of reduced noise around the head. Since a large portion of the noise inside the cabin can be related to the engine, an active control system based on a feedforward solution is possible. Experimental results from a feedforward solution of active noise control in a fork-lift truck cabin show that the noise level in the low frequency region can be reduced significantly.

INTRODUCTION

Low noise level in the cabins is a comfort parameter of high importance. Since almost all places of work are subjected to regulations in the noise area, defining the maximum noise level a worker is allowed to be exposed to, the topic has become more interesting. The classical remedy for noise is by passive means e.g. sound absorbing materials and different kinds of dampers. The passive methods have however in many circumstances little impact on the low frequency part of the noise [1, 2]. A method that has been proven able to tackle low frequency noise problems in various situations is active noise control. This technique has started to become an attractive method for the industry when passive techniques are not suitable. Active noise control is not a universal cure for noisy environments but since it is best suited for low frequencies and passive techniques are usually best suited at higher frequencies, a combination is often an attractive solution.

The cabin of a fork-lift truck can be viewed as box. The driver needs to have free sight in all directions, thus most of the cabin surface is transparent. Inside a closed space such as a fork-lift truck cabin, the sound field is not propagating freely but reflected off the enclosure boundaries, causing internal standing waves at certain frequencies [2]. The standing waves are the acoustic modes of the enclosure. The acoustic pressure at low frequencies is the sum of the contributions from each of these modes. When the size of the enclosure is smaller than the wavelength at the frequencies of interest, the sound field is dominated by a few modes [1], such as in the fork-lift truck cabin.

To control the sound field in an enclosure such as a fork-lift truck cabin the secondary noise must be able to couple into as many modes of the sound field as possible. This usually requires more than a single secondary source generating the secondary noise, and several error sensors to enable active noise control over a large portion of the low frequency region [2]. The active noise control system is illustrated in Fig. 1.

To be able to adjust the active control system a control algorithm is needed. The least squares approach provides a powerful approach to digital filtering in situations where a fixed, finite length filter is applicable. This approach has achieved widespread application in many areas [3]. It is an important member of the family of stochastic gradient algorithms [4]. In active control a complication arises when the signal is altered between the output of the adaptive filter and the error sensor, due to the acoustic path between the loudspeaker and microphone. The path between the controller output and the error sensor output is denoted the control path. When the adaptive filter is followed by a control path the conventional LMS algorithm must be modified in order to ensure convergence. In active control applications there is always a control path present [5], which should be compensated for. In 1985 Elliott et. al. presented an algorithm in [6] that is able to handle a multiple input multiple output environment. The algorithm is based on the filtered-x lms algorithm with the extension of being able to minimize the sum of squared errors at several error sensors. Since most components in the noise spectrum in the fork-lift truck cabin can be derived to the speed of the engine, one or several reference signals can be constructed with the aid of a engine tacho signal.

This paper discusses active noise control in a fork-lift truck using a MIMO filtered x-lms algorithm to reduce the noise level at several error microphones and develop control signals for the two loudspeakers.

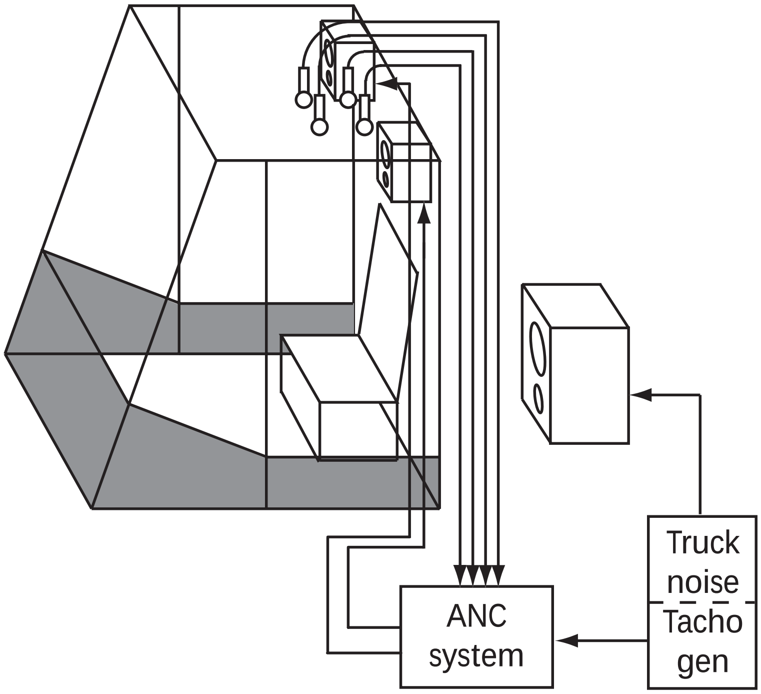

Figure 1: The active noise control system of a fork-lift truck cabin using 4 error microphones and 2 loudspeakers.

MATERIALS AND METHODS

Experimental Setup

The experiments have been conducted at Kalmar industries in Ljungby, Sweden and on a test bench at Blekinge Institute of Technolgy. The test bench is a complete fork-lift truck cabin provided by Kalmar Industries , in order to be able to perform preliminary tests on the active control system. The weight of the fork-lift truck is approximately 23660 kg, and the interior size of the cabin is approximately 1.05 m long, 1.25 m wide and 1.43 m high. The lift capacity of the truck is 16000 kg, 1.20 m from the center of gravity. The engine is a 174 kW a VOLVO TAD720VE, a straight six turbo charged engine. Fig. 2 shows a) the fork-lift truck during measurements of the truck noise and b) a practical system installation of an active noise control system inside a truck cabin.

The truck noise measurements were conducted with the cabin suspended in three different ways. First, the ordinary suspension with rubber mounts, and second, with the cabin hanging from the ceiling, and third, a rigid attachment to the fork-lift truck. The aim of this measurement was to investigate if the transfer path of the noise was structure-borne and/or airborne.

The active noise control experiments were carried out on a ”stand-alone” fork-lift truck cabin. The simulated engine sound was recorded sound from a truck engine and produced by a large loudspeaker placed behind the cabin. The controller was an EZ-ANC II system by casual systems Pty Ltd which uses a MIMO filtered-x lms algorithm

Figure 2: The experimental setup in a) the cabin of the fork-lift truck and in b) the microphones and loudspeakers mounted in the cabin.

configured for two loudspeakers and 4 error microphones. The 4 microphones were mounted above the normal location of the driver's head, illustrated in Fig. 1. The reference signal was a sine wave corresponding to the 3rd order of the engine derived from a tacho signal from the engine.

Control algorithm

An algorithm able to handle multiple reference, multiple output and multiple errors was derived by Elliot et. al. in [6]. The algorithm minimizes the sum of the squared errors of all error sensors in the mean square sense and uses the instantaneous gradient, usually referred to the MIMO filtered-x lms algorithm. A typical example of the MIMO filtered-x lms algorithm is in an active noise control application, illustrated in Fig. 3. Error microphones are deployed in the region where the driver's head is located and loudspeakers are mounted at appropriate locations in order to produce the secondary noise.

Minimizing the error in the least squares sense at all M error sensors $e_m(n)$ yields the cost function

$$J(n) = \sum_{m=1}^{M} e_m^2(n). \tag{1}$$

At the mth error sensor, assuming that the control path can be estimated with an FIR filter with I weights, the error can be expressed as

$$e_m(n) = d_m(n) + \sum_{l=1}^{L} \sum_{i=0}^{I-1} \hat{s}_{ml}(i) y_l(n-i) \tag{2}$$

where $d_m(n)$ is the primary disturbance at the error sensor m and the other term is the secondary noise originating from all L loudspeakers, $\hat{s}_{ml}$ is the estimated control

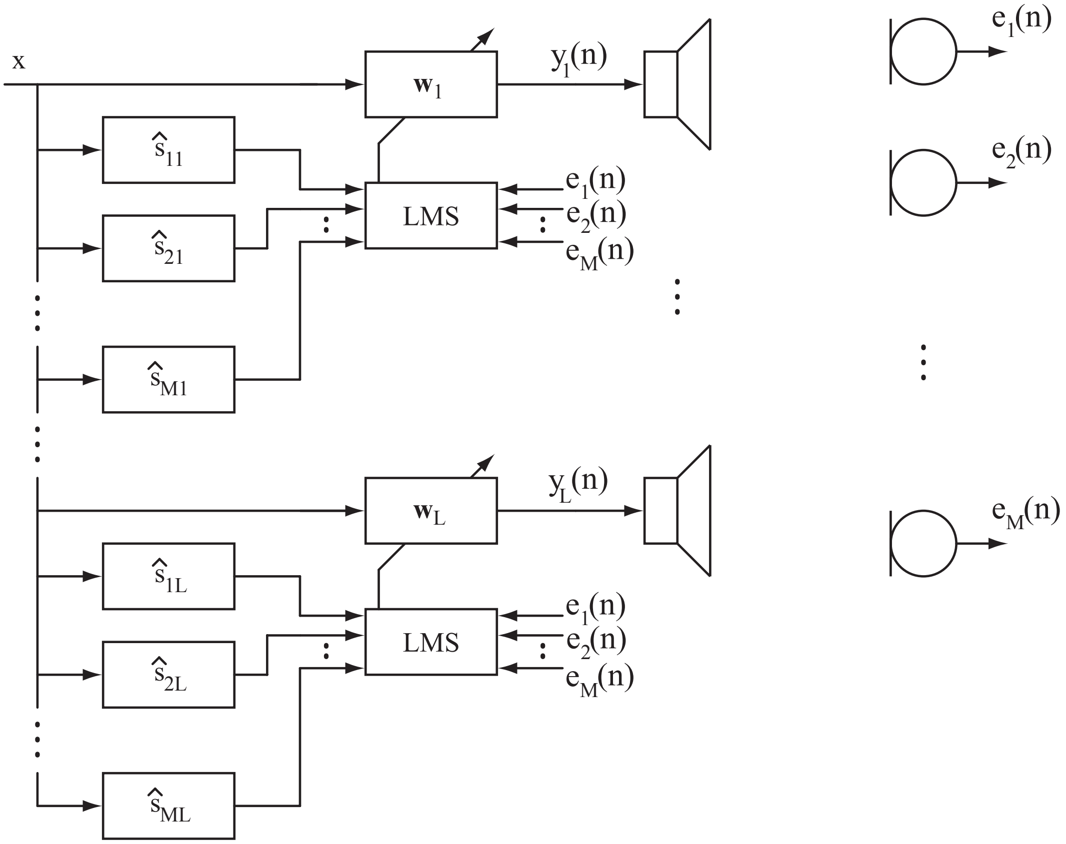

Figure 3: Multiple-input multiple-output filtered-x lms algorithm.

path from loudspeaker l to error sensor m and $y_l(n)$ is the signal to loudspeaker l. The output of the adaptive algorithm is

$$y_l(n) = \sum_{k=0}^{K-1} w_l(k)x(n-k) \quad \text{, for } l = 1, 2, \ldots, L \tag{3}$$

where K is the length of the L adaptive filters w_l.

A complete derivation of the algorithm is stated in [7]. The adaptive weights of the $L \times R$ adaptive filters are updated according to

$$w_l(n+1) = w_l(n) + \mu\Big(\sum_{m=1}^{M} e_m(n) \sum_{i=0}^{I-1} \hat{s}_{ml}(i)x(n-i)\Big) \tag{4}$$

where μ is the step size.

Adding a leakage factor, γ, in the adaptive weight update function limits the energy in the adaptive weights which has a stabilizing effect on the algorithm [5]. The adaptive weight update function can for the leaky MIMO filtered x lms algorithm be written as

$$w_l(n+1) = \gamma w_l(n) + \mu\Big(\sum_{m=1}^{M} e_m(n) \sum_{i=0}^{I-1} \hat{s}_{ml}(i)x(n-i)\Big). \tag{5}$$

RESULTS

Sound transmission paths

In order to determine whether the sound transmitting from the engine into the cabin is structure-borne or airborne, the sound pressure inside the cabin was measured with different suspension of the cabin. The suspension of the cabin consists of ordinary rubber mounts, freely coupled from the chassis and rigid attached to the chassis.

Fig. 4 shows the sound pressure level at the driver's head for the different mounting arrangements of the fork-lift truck cabin at different engine rpm.

Active Noise Control

The active noise control experiments were carried out on a stand alone fork-lift truck cabin with a large loudspeaker outside the cabin generating truck noise. The sound was recorded truck noise at 4 different rpm; 860 (idling), 1800, 2000 and 2220 (max). The noise spectra at different rpm were dominated by a combination of the 1st, 3rd, 6th and 11th order of the engine rpm. Fig 5 shows the sound field at head level inside the cabin in decibels. The reference signal to the feed forward controller was a sine wave corresponding the 3rd order of the engine rpm, thus the active noise control system was only reducing the 3rd order of the engine.

SUMMARY

Active noise control in a cabin is a possible solution to the reduce low frequency noise in a fork-lift truck. The transfer path of the noise from the engine to the cabin is mainly airborne according to the spectra in Fig. 4. There were no significant difference of the low frequency noise inside the cabin whether the structural transfer path was present or not.

Since the cabin noise is mainly airborne the approach was to use loudspeakers and microphones in the active noise control system. The reference signal used was a tacho based signal, since most of the noise can be derived to the engine's rpm. The generated truck sound did not completely match the true noise inside a truck cabin. The third harmonic of the engine dominated the noise spectra inside the truck cabin when the truck noise was generated with a loudspeaker. The active noise control system attenuated the truck noise with approximately 10 dB SPL at 1800, 2000 and 2220 rpm of the engine.

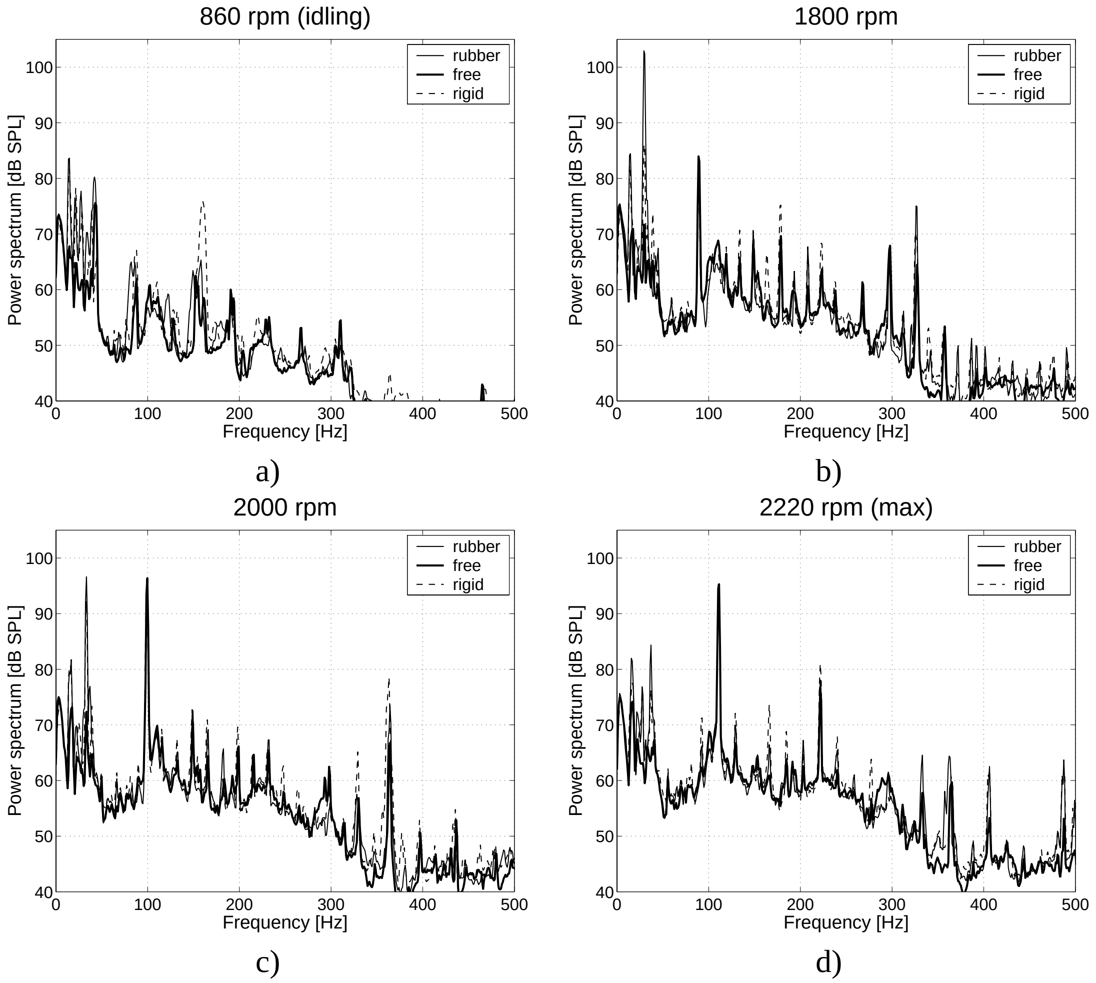

Figure 4: Power Spectrum of the sound pressure inside the fork-lift truck cabin at different rpm in a) 860 (idling), in b) 1800, in c) 2000 and in d) 2220 (max) and different mounting arrangement.

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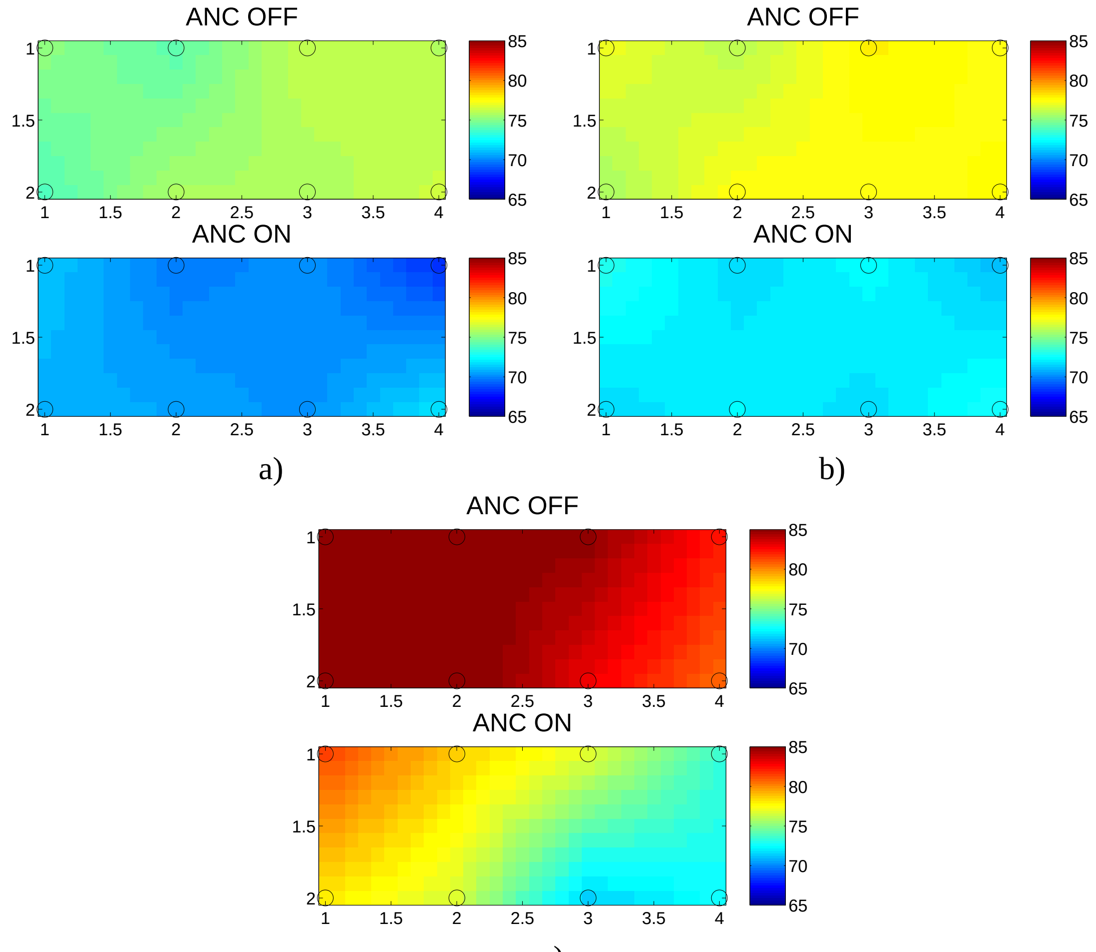
REFERENCES

[1] J. Guo, J. Pan, Active Noise Control in Rectangular Rooms, Proceedings of the International Congress on Sound and Vibration 8, Hongkong China, July 2-6, 2001.

[2] S. J. Elliott, P. A . Nelson, Active Noise Control, IEEE Signal Processing Magazine, pp 12-35, october 1993.



a)

b)

c)

Figure 5: The sound field at head level in dB SPL with and without active noise control in a) at 1800 rpm, in b) at 2000 rpm and in c) 2220 rpm.

[3] Peter M. Clarkson, Optimal and Adaptive Signal Processing, CRC Press, 1993.

[4] Simon Haykin, Adaptive Filter Theory, 4th ed, Prentice Hall, 2002

[5] Sen M. Kuo, Dennis R. Morgan, Active Noise Control Systems, Wiley Interscience, 1996

[6] S. J. Elliott and P. A. Nelson, Algorithm for Multichannel LMS Adaptive Filtering, Electronics Letters, vol 21, pp 979-981, 1985.

[7] S. J. Elliott, I. M. Stothers and P. A. Nelson, A Multiple Error LMS Algorithm and Its Application to the Active Control of Sound and Vibration, IEEE Transaction on Acoustics, Speech and Signal Processing, ASSP-35, pp 1423-1434, 1987.