Applied Acoustics 79 (2014) 58–68

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Improvement of noise reduction performance for a high-speed elevator using modified active noise control

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ARTICLE INFO

Article history:
Received 21 July 2013
Received in revised form 27 October 2013
Accepted 31 October 2013

Keywords:
Active noise control
High-speed elevator
Modified Filtered X-LMS (Modified FXLMS) algorithm
Correlation Filtered X-LMS (Co-FXLMS) algorithm
Moving Band Pass Filter (MBPF)

ABSTRACT

A high rise building demands a high-speed elevator. Since a high-speed elevator has various transfer paths of noise transmitted from motor and rope to cabin interior, it is very difficult to solve the noise problem. Most research for noise reduction has been performed regarding passive noise control by using mainly absorption material and insulation material. In this study, while it is modeling as multiple-input and single-output with respect to transfer paths of high-speed elevator on conditions of stationary and driving states, the characterized frequency in the cabin is discovered through a contribution technique. It is able to replace by 1-dimensional model to control noise at a major contributed frequency. Also, a new active noise control technique has been proposed to control the cabin noise effectively at unpleasant area that is required to make quite zone for passenger. The Correlation Filtered X-LMS (Co-FXLMS) algorithm has been applied to control the dominant frequency noise that it has a high contribution. Simultaneously, this study has a proposed Moving Band Pass Filter (MBPF) to improve the performance of active noise control in the cabin which is able to apply a dynamic system with time variant states. Finally, we obtained the 8 dB noise reduction in the cabin at ear level and it has been proved that the modified active noise control using Co-FXLMS algorithm and MBPF is available to improve the performance of noise reduction.

1. Introduction

As buildings are progressively higher, the demands for high-speed elevators increase. Elevators driving over 500 m/min are by definition ‘high-speed elevators’. Specifically, when the elevator is driving at high speed, wind noise in the hoistway, vibration of the guide rail and the rope cause the cabin noise in the elevator. The significant noise problem is occurred by high speed elevator and the noise causes passenger discomfort. The passive control method has been performed for noise reduction inside the cabin using sound absorbing materials, insulation materials or changing the design parameters of the elevator system through optimal design. However, the passive control methods are not effective for low-frequency noise of less than 500 Hz. As the elevators are getting faster, passengers feel more discomfort by low-frequency noise. Active noise control (ANC) methods are therefore appropriate for cancelling a major contributing frequency to passengers. When sound absorbing materials are installed to reduce the noise passively, it has disadvantages at low frequencies especially below 500 Hz. To solve this problem, ANC methodology was introduced and developed during last 30 years [1–3,15–18]. ANC is based on electronic cancellation in order to control undesired disturbances. To achieve this, control and data acquisition system or sensors such as loudspeakers, for sound cancellation, or accelerometers or microphones, for the cancellation of sound or vibrations must be used. Commercial applications are needed to decrease cost and real time control. Therefore, an effective method for the noise reduction inside the cabin of high speed elevator is necessary. Many algorithms based on the Filtered X-LMS (FXLMS) algorithm for active noise control have been modified to solve the problems mentioned above for practical considerations, but the convergence performance of the LMS algorithm decreases rapidly when the FXLMS algorithm is applied to the active control of elevator noise under rapidly driving condition.

Therefore, in this study, the Correlation FXLMS (Co-FXLMS) algorithm is realized by using an estimate of the cross correlation between a transfer path, such as the adaptation error, and filtered input signal to control the step size. Also introduced are modified active noise control methods such as the Co-FXLMS algorithm using Moving Band Pass Filter (MBPF) that is appropriate to frequency characteristic changing system with time. The modified FXLMS algorithm has been developed and applied to the elevator

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0003-682X/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apacoust.2013.10.016

system in order to improve the performance of active noise control under a rapid driving state [4].

Furthermore, we have modeled the elevator system (3-dimensional enclosure) as one-dimensional system for commercialization and effectiveness at a major contributing frequency and characterized zone. To apply modified active noise control method for a one-dimensional model, it was performed to identify a major degree of contribution by using a transfer path analysis of elevator with rapid driving speed.

2. Theory

2.1. Transfer path analysis for multiple-input/single-output system [5–9]

In any mechanical system, noise and vibration sources exist and these sources are correlated to each other. Therefore, to remove the pure contribution of each source to output, the correlation among the sources should be considered. Fig. 1 shows the multiple-input single-output (MISO) model that is represented by the optimum frequency function. The coherence method is able to determine the contribution of an input for an output by eliminating the correlation among the inputs. Eq. (1) represents the residual spectrum after the correlation is removed among the inputs. L_{rj} is the optimum transfer function after the correlation is removed among the inputs.

$$S_{jj\cdot r!} = S_{jj\cdot(r-1)!} - |L_{rj}|^2 S_{rr\cdot(r-1)!} \quad (j > r) \tag{1}$$

The residual spectrum expressed by the optimum transfer function, where, L_{2y} is the optimum transfer function between x_2 and an output. The Ordinary Coherence Functions (OCF) between each input and the output are as follows:

$$\gamma^2_{ij}(f) = \frac{|S_{ij}(f)|^2}{S_{ii}(f)S_{jj}(f)} \tag{2}$$

$$\gamma^2_{iy}(f) = \frac{|S_{iy}(f)|^2}{S_{ii}(f)S_{yy}(f)} \quad (i = 1,2,3,4,\ldots,q;\ j = 1,2,3,4,\ldots,q;\quad i \neq j) \tag{3}$$

The Partial Coherence Function (PCF) is as follows,

$$\gamma^2_{iy\cdot(i-1)!}(f) = \frac{|S_{iy\cdot(i-1)!}(f)|^2}{S_{ii\cdot(i-1)!}(f)S_{yy\cdot(i-1)!}(f)} \tag{4}$$

The Multiple Coherence Function (MCF) is a direct extension of the concept of ordinary coherence, which provides a measure of the linear dependence between a collection of q and output. The MCF is represented as follows,

$$\gamma^2_{y:q!} = 1 - (1-\gamma^2_{1y})(1-\gamma^2_{2y\cdot 1})\cdots(1-\gamma^2_{qy\cdot(q-1)!}) \tag{5}$$

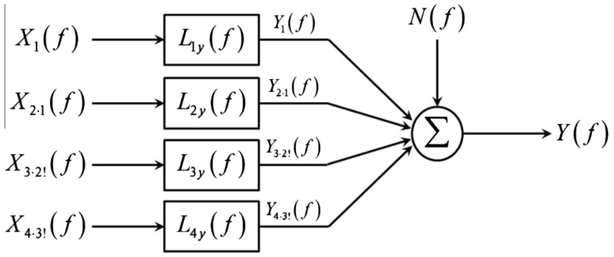

Fig. 1. Multiple-input (4 input)/single-output model for conditioned inputs.

2.2. The Co-FXLMS algorithm based on contributed frequency [10,11]

As shown in Fig. 2, the active noise control system using the FXLMS algorithm requires a reference signal $x(n)$ for generating the control signal $y(n)$. To drive the control signal, the reference signal $x(n)$ has to pass through the adaptive filter $W(z)$ in order to minimize the error sensor signal $e(n)$.

$$e(n) = d(n) - y'(n) \tag{6}$$

$$= d(n) - s(n) * y(n) \tag{7}$$

$$= d(n) - s(n) * [\mathbf{w}^T(n)\mathbf{x}(n)] \tag{8}$$

$s(n)$ is the impulse response of the secondary path transfer function $S(z)$ at time n, and $*$ is the convolution. $y(n)$ is generated after the reference signal $x(n)$ has passed through the adaptive filter $W(z)$. L is the filter order. FXLMS algorithm is

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \mu\mathbf{x}'(n)e(n) \tag{9}$$

μ is the step size that must satisfy

$$0 < \mu < \frac{2}{LP_x} \tag{10}$$

where P_x is the power of the reference signal.

As shown in Eq. (9), the stability, convergence time, and fluctuation of the FXLMS algorithm is governed by the step size μ and the filtered input signal $x'(n)$. In Eq. (10), the FXLMS algorithm uses the constant, μ and the upper bound on μ is made inversely proportional to the input signal power. Thus, weaker signals can use a larger μ, and stronger signals have to use a smaller μ. Therefore, the power of input signal changes excessively according to time, the FXLMS algorithm cannot converge. One useful approach is to normalize μ with respect to the power of the filtered input signal $x'(n)$. δ is a small positive value.

$$\mu(n) = \frac{\alpha}{\delta + \mathbf{x}'^T(n)\mathbf{x}'(n)} \quad (0 < \alpha < 2) \tag{11}$$

The Co-FXLMS algorithm is realized using Eq. (11), an estimate of the correlation between the filtered input signal $x'(n)$, and the error signal $e(n)$ to adjust the step size of the adaptive algorithm. After $\mathbf{w}(n)$ has converged to the optimum weight $\mathbf{w}^0$, the correlation between the filtered input signal $x'(n)$ and the error signal $e(n)$ would be zero [4,10].

$$R(n) = E[e(n)x'(n)] = 0 \tag{12}$$

In Eq. (12), the estimated correlation $R(n)$ is an expected value of $e(n)x'(n)$, and $R(n)$ at time n is represented as follows:

$$\begin{aligned} R(n) &= E[e(n)x'(n)] = E[(d(n) - y'(n))x'(n)] \\ &= E[(d(n) - \mathbf{w}^T(n)\mathbf{x}'(n))x'(n)] \\ &= E[\{d(n) - \mathbf{w}^T(n)(\hat{s}(n) * \mathbf{x}(n))\}x'(n)] \end{aligned} \tag{13}$$

where $\hat{s}(n)$ is the estimated impulse response of the secondary-path filter $\widehat{S}(z)$. When the current weight vector $\mathbf{w}(n)$ is far away from $\mathbf{w}^0$, the correlation is high and the adaptive algorithm is in an active

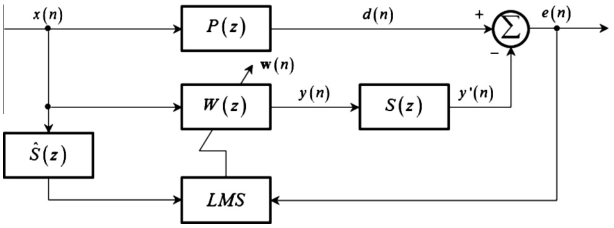

Fig. 2. Block diagram of FXLMS algorithm.