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INEXPENSIVE IMPLEMENTATION OF ACTIVE NOISE CONTROL SYSTEMS FOR ONE-DIMENSIONAL DUCT WITH APPLICATION TO A VENTILATING SYSTEM

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Abstract

In this paper we examine inexpensive implementation of active noise control (ANC) systems for one-dimensional duct based on experiments carried out on the ventilating system installed in a real house. Two types of time-invariant low-order controllers are compared: One is based on the conventional adaptive filter (the filtered-U recursive LMS algorithm) but the coefficients are fixed by the stationary values. Another is obtained by a robust control method (sampled-data $\mathcal{H}_\infty$ control). The experimental results show the advantage of the robust control method.

INTRODUCTION

The aim of this study is to develop inexpensive active noise control (ANC) systems for small buildings. The ANC technique, in which noise is attenuated by the same sound but opposite phase, has been practically used in air conditioning systems in large scale buildings, aircraft cabins, and so on [1]. However, there are many fields e.g. ventilation systems for small buildings where ANC is desired but has not been applied yet because the conventional adaptive algorithms for ANC require expensive implementation.

One way to reduce the cost of ANC systems is to implement time-invariant low-order controllers which allows to use cheaper hardwares for implementation. In addition, it is expected that sufficient performance can be achieved by fixed controllers for recent energy-efficient houses since variation of room temperature is not significant throughout the year.

We employ two ways to obtain fixed controller: the adaptive control based method and the robust (non-adaptive) control method. In the adaptive control based method, controller is at first obtained by the conventional LMS based algorithm, then the resultant controller at stationary is implemented as a fixed controller. This controller design is applied to ANC systems for automobiles [2]. On the other hand, the robust control method is also applicable to design fixed controllers for ANC. Indeed desired performance have been shown by experimental results for simple experimental apparatus [3, 4]. However, as authors knowledge, both design methods have not been compared by experiments with ventilation systems. Note that in the ventilation systems driving signal of noise speaker is not available to identify plant model as opposed to applications in the literatures which deal the robust control approach to ANC.

In this paper, both adaptive control based and robust control methods are applied to obtain fixed low-order active noise controllers for a ventilation system. Firstly, as conventional adaptive control method, the filtered-U recursive LMS (RLMS) algorithm is used and possibility of obtaining low-order controller is examined. Secondly, as a robust control method, sampled-data $\mathcal{H}_\infty$ control is applied, where the generalized plant in the design problem is derived without using the driving signal of noise speaker. The experimental results show the advantage of the robust control method.

EXPERIMENTAL APPARATUS

Fig. 1 and Table 1 show the block diagram and the outline of the experimental apparatus respectively. The apparatus is the same as in [4] except the flexible duct for connecting to a ventilation system, while an alternative loudspeaker (SPK1) is attached only for verification for the modelling process as described later.

Fig. 2 shows the configuration of the ventilation system installed to a two-storied real house. The grilles are attached on the ceiling of each floor, and the ANC system is connected between fresh-air grilles and the ventilation fan.

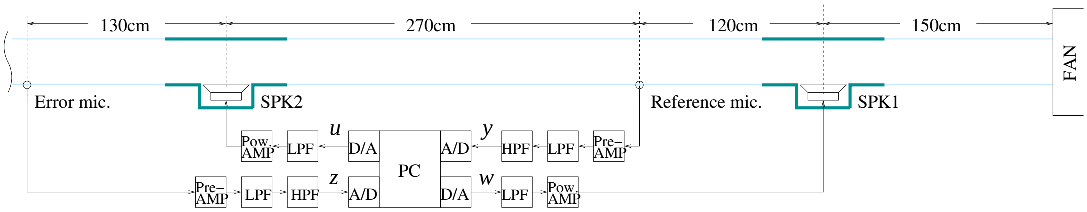


Figure 1: Active noise control system

Table 1: Experimental instruments

Ventilation fan	Kaneka corp. SV-200U (250 m^3/h, energy-recovery ventilation)
loudspeakers (SPK1,2)	FOSTEX FW208N woofer speaker with PVC pipe enclosure
Microphones	electlet condenser type
Sound level meter	RION NL-20
Power amplifier	TOSHIBA TA8213K
High Pass Filter	NF ELECTRONIC INSTRUMENTS FV-664 (2ch, 40 Hz, 24dB/oct)
Low Pass Filter	500 Hz 4th order Butterworth
PC	SONY VAIO PCG-SR9/K (RT-Linux 3.1, kernel 2.4.18)
A/D,D/A	CONTEC AD12-8(PM) (2ch, 12bit, 10μ sec)

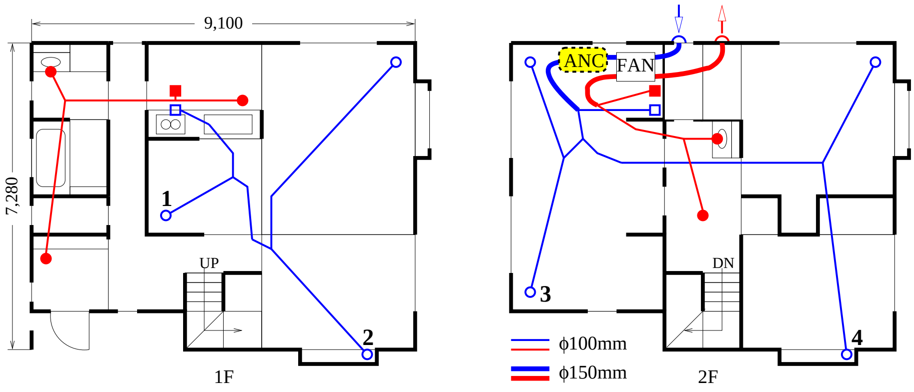


Figure 2: Ventilation system configuration

CONTROLLER DESIGN

In this section, two fixed controllers are designed by the adaptive control based and the robust control methods. The sampling period of controller is 1 msec throughout this paper.

Adaptive Control Based Design

As a conventional adaptive control method, the filtered-U RLMS algorithm [5](p.90) is utilized to obtain low-order fixed control law of IIR filter. The design procedure below is standard except the truncation of the filter order.

Step1 Identify the secondary path (from u to z) filter by driving SPK2 but turning off the ventilation fan.

Step2 Optimize the adaptive filter from y to u which, together with the identified secondary path filter, cancels out the primary path (from y to z) dynamics where the ventilation fan is turned on.

In Step1, 500th order FIR filter is chosen as the secondary path filter and is identified by the LMS algorithm. (The experimental result is omitted for the paper brevity.) In Step2, let $F(z)$ be the adaptive IIR filter represented as

$$F(z) := \frac{\sum_{i=0}^{N} a_i z^{-i}}{-1 + \sum_{i=0}^{N} b_i z^{-(i+1)}} \tag{1}$$

where a_i and b_i are coefficients to be optimized, and N is the given filter order. In this paper, both cases of $N = 500$ and $N = 100$ are compared to examine low-order controller feasibility. Fig. 3 shows the results. It can be seen that the similar performance are obtained for both cases. Fig. 4 shows the resultant coefficients of the adaptive filters. It can be seen that $N = 500$ is high enough to approximate the primary path dynamics in Step2 since a_i and b_i converge to zero as i is increased, while $N = 100$ might not be enough. Nevertheless, $F(z)$ with $N = 100$ will be adopted as a low-order fixed controller since the performance is similar to that of $N = 500$.

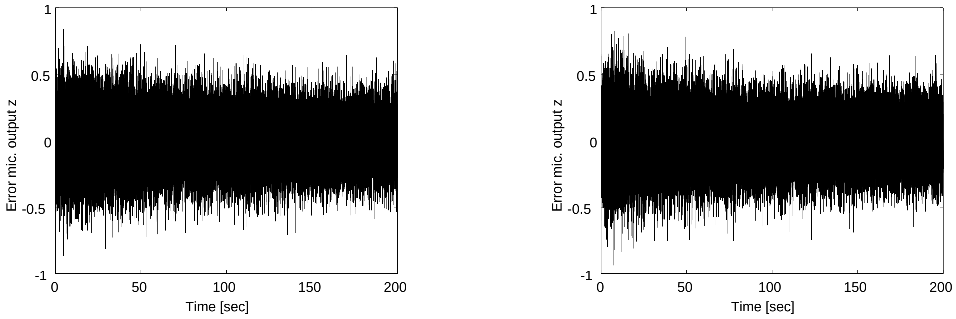


Figure 3: Optimization of $F(z)$

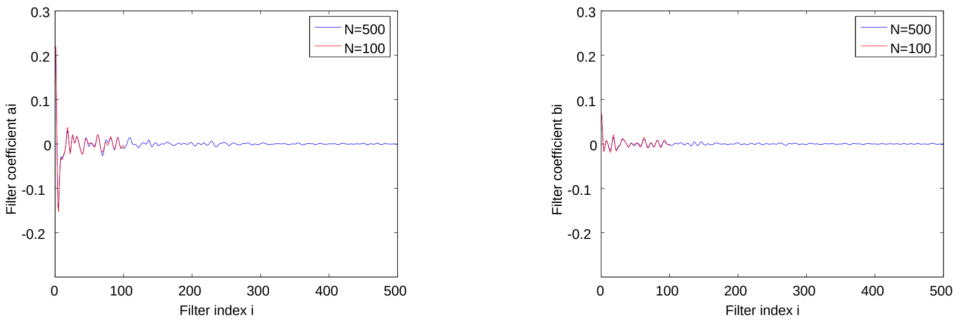


Figure 4: Resultant coefficients of $F(z)$

Robust Control Design

The design procedure in this section is similar to that of [4] except that the plant model is identified without using the driving signal of the noise speaker: Firstly, the plant model is identified based on frequency and time response experiments; Secondly, the generalized plant is composed with the plant model, and sampled-data $\mathcal{H}_\infty$ control synthesis is applied to obtain a digital controller.

Modelling

We consider the system from $\begin{bmatrix} y & u \end{bmatrix}^T$ to $\begin{bmatrix} z & y \end{bmatrix}^T$ as the plant transfer function $G(s)$ i.e.

$$G(s) := \begin{bmatrix} G_{zy}(s) & G_{zu}(s) \\ 1 & G_{yu}(s) \end{bmatrix}, \tag{2}$$

where $G_{ab}(s)$ means the transfer function from the signal b to the signal a. $G(s)$ is determined by the following steps:

Step1 Obtain frequency response of $G(s)$ at test frequencies, say ω_i $(i = 1, 2, \cdots)$:

(1) Calculate $G_{zy}(j\omega_i)$ by the measured time response of y and z excited by real fan noise: Concretely speaking, firstly, 50 seconds of time response is measured

with sampling period $h = 0.1$ msec. Secondary, a discrete-time transfer function $G_{d_{zy}}(z)$ of $h = 0.1$ msec is identified off-line by the recursive LMS algorithm [1](p.97) as 500th order IIR filter. Finally, $G_{zy}(j\omega_i)$ is approximated by $G_{d_{zy}}(e^{j\omega_i h})$.

(2) Obtain $G_{zu}(j\omega_i)$ and $G_{yu}(j\omega_i)$ by frequency response experiment with SPK2.

Step2 Set the nominal plant $\bar{G}(s)$

$$\bar{G}(s) := \begin{bmatrix} \bar{G}_{zy}(s) & \bar{G}_{zu}(s) \\ \bar{G}_{yy}(s) & \bar{G}_{yu}(s) \end{bmatrix} \tag{3}$$

which approximates the frequency response $G(j\omega_i)$ by subspace-based method (Matlab *n4sid* is used) so that $\bar{G}(s)$ is stable and $\bar{G}_{zu}(s)$ and $\bar{G}_{yu}(s)$ are strictly proper.

Step3 Choose additive uncertainty weight $W(s)$ to consider robust stability against the modeling error of $\bar{G}_{yu}(s)$ where

$$G_{yu}(s) = \bar{G}_{yu}(s) + W(s)\delta(s), \tag{4}$$

and $\delta(s)$ is any stable transfer function whose gain is less than or equal to 1.

Fig. 5 shows the frequency response of $G(s)$ and $\bar{G}(s)$. In (a), frequency response of $G_{zy}(s)$ directly obtained by the frequency response experiment with SPK1 is also shown for comparison. It can be confirmed that both frequency responses obtained with and without SPK1 show similar characteristic in the middle frequency range. In addition, it can be seen that $\bar{G}(s)$ approximates $G(s)$ well in the middle frequency range where the order of $\bar{G}(s)$ is 85. Note that the closed-loop stability is guaranteed by the robust control even if accuracy of $\bar{G}_{zy}(s)$ is not sufficient.

Fig. 6 shows the gain characteristic of the additive uncertainty and $W(s)$. It can be confirmed that the weight covers the additive uncertainty appropriately, where $W(s)$ is chosen as 4th order.

Controller design

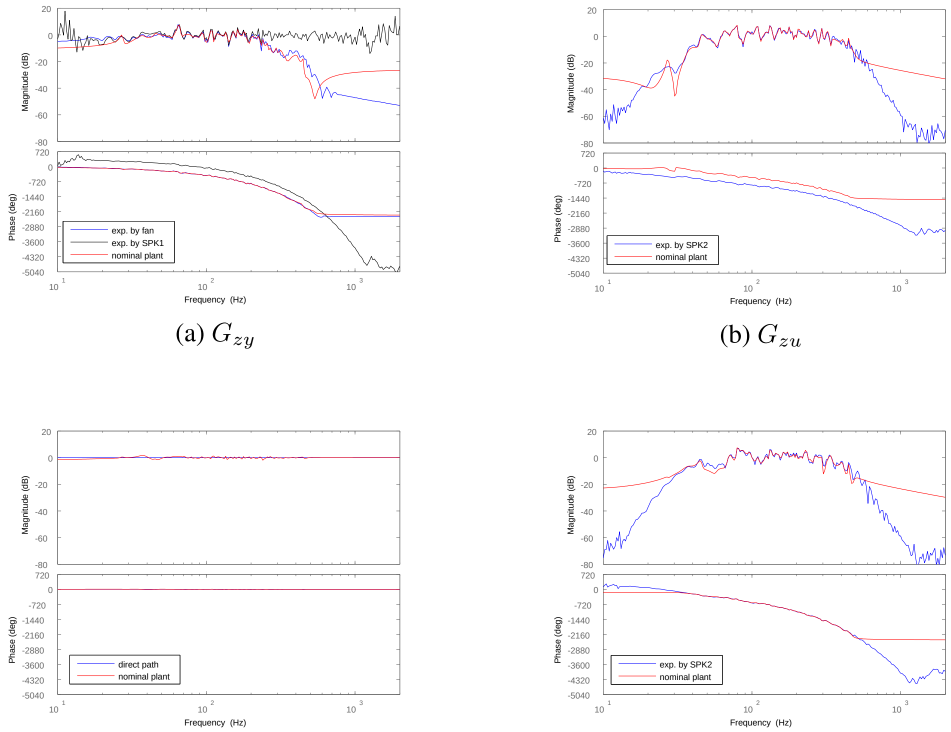
According to the preparation above, sampled-data $\mathcal{H}_\infty$ control synthesis is applied to the following digital controller design problem: find a discrete-time controller $K_d(z)$ which maximizes positive scalar α so that the following conditions hold:

- the closed-loop system of Fig. 7 is internally stable;
- there exists positive scaler d such that $\mathcal{L}_2$ induced norm of the closed-loop system is less than 1,

where S is the sampler with sampling period $h = 1$ msec, H is the zeroth-order hold, and $W_p(s)$ is a bandpass filter given by

$$W_p(s) = \left(\frac{s}{s+\omega_{p_1}}\right)^2 \left(\frac{\omega_{p_2}}{s+\omega_{p_2}}\right)^2, \quad \omega_{p_1} = 2\pi \times 40, \quad \omega_{p_2} = 2\pi \times 300. \tag{5}$$

As a result, the maximal $\alpha = 1.2$ is achived for $d = 1.1$. The order of $K_d(z)$ is 93. Moreover, because of the very structure of the generalized plant, the designed controller realization is



(a) G_{zy} (b) G_{zu}

(c) G_{yy} (d) G_{yu}

Figure 5: Frequency response of plant

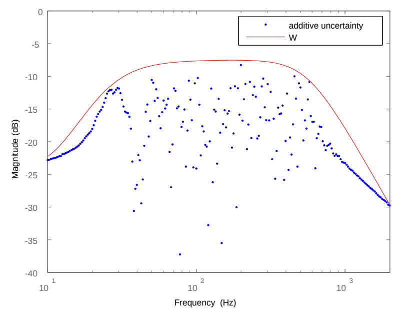


Figure 6: Additive uncertainty and weight

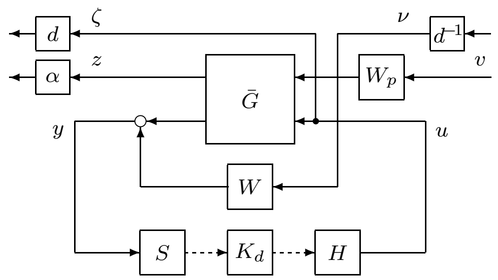
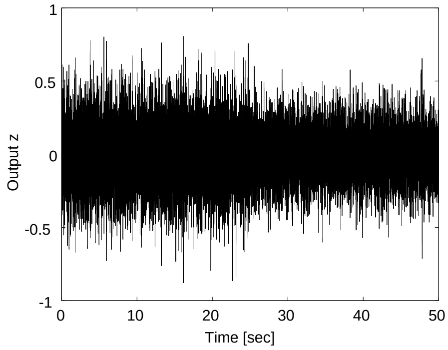
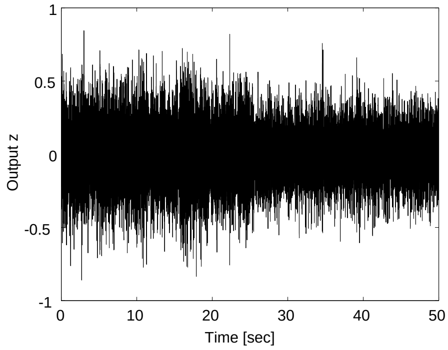


Figure 7: Robust performance problem with scalings

transformed into low-complexity one whose A matrix is in block diagonal with either 1×1 or 2×2 blocks and B is composed of $0s$ and $1s$, so that the computational time of the control law corresponds to that of the adaptive controller.



(a) Filtered-U RLMS



(b) Sampled-data $\mathcal{H}_\infty$ control

Figure 8: Error microphone output z excited by fan noise

Table 2: Sound pressure level at each grille

	Sound pressure level ($L_{Aeq,10sec}$) [dB]		
	fan off	fan on (without control → with control (difference))	
		Filtered-U RLMS	Sampled-Data $\mathcal{H}_\infty$
grille #1	21.8	38.5 → 37.7(-0.8)	38.3 → 36.8 (-1.5)
grille #2	23.3	44.2 → 43.5(-0.7)	44.1 → 42.8 (-1.3)
grille #3	24.4	36.0 → 35.1(-0.9)	36.2 → 34.8 (-1.4)
grille #4	20.3	45.1 → 44.2(-0.9)	45.1 → 43.8 (-1.3)

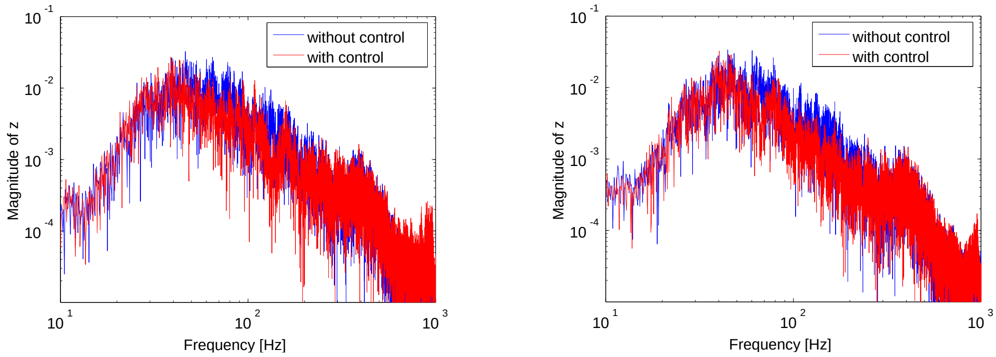
EXPERIMENTAL RESULTS

In this section, two controllers obtained in the previous section are compared by control experiment.

Fig. 8 shows the time responses of error microphone z where the first 25 second is without control and the following 25 second is with control. The smaller sampling period (0.25 msec) is used for measurement to observe inter-sample behaviour within the sampling period of the controller. It can be seen that both controllers show similar performance of noise attenuation.

Fig. 9 shows the FFT analysis result of Fig. 8 where 'without control' and 'with control' are corresponding to the first and the last 10 seconds of the time response respectively. It can be seen that the adaptive controller shows better performance than the robust controller at low frequency range about 50 Hz, while the robust controller shows better performance at higher frequency range above 100 Hz. This is caused by the selection of $W_p(s)$ whose gain is important at about 100 Hz.

Table 2 shows sound pressure level measured below each grille. It can be seen that the attenuation level of both controllers are small in this experiments, while the robust controller shows better performance than the adaptive controller. It can be considered that the better performance of the robust controller is obtained because the middle frequency range is important for the sound level meter.



(a) Filtered-U RLMS (b) Sampled-data $\mathcal{H}_\infty$ control

Figure 9: FFT analysis result of Fig.8

Note that similar advantage of robust controller has been also observed by using SPK1 as noise source when the ventilation fan is turned off, although the result is omitted due to the limitation of space.

CONCLUSIONS

In this paper, both the filtered-U RLMS algorithm and sampled-data $\mathcal{H}_\infty$ control have been applied to design fixed low-order active noise controllers for a ventilation system. It have been shown by experiments that better performance is achieved by robust controller. It might be necessary to examine the experimental results more in detail since norms for performance evaluation in design problems are different. Nevertheless, it can be concluded that robust control is available to design fixed low-order active noise controllers for one-dimensional duct as well as adaptive control. Moreover, closed-loop stability against plant perturbation due to e.g. temperature fluctuation is guaranteed by robust control if the weight function is properly chosen to cover possible perturbation, while there is no such guarantee by adaptive control.

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