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# ACTIVE NOISE CONTROL AT A MOVING LOCATION USING VIRTUAL SENSING

Cornelis D. Petersen, Ben S. Cazzolato, Anthony C. Zander, Colin H. Hansen

Active Noise and Vibration Control Group, School of Mechanical Engineering
The University of Adelaide, 5005 SA Australia
cornelis.petersen@adelaide.edu.au

## Abstract

A problem limiting the scope of practical local active noise control applications is that the zone of quiet created at the error sensor tends to be very small. This means that the error sensor generally needs to be positioned close to the location where control is desired, which might not always be a convenient or feasible solution. A number of virtual sensing algorithms have been suggested previously that can effectively move the zone of quiet away from the physical error sensor to a desired location that is spatially fixed. It is, however, very likely that the observer will move their head, which means that the desired location of maximum attenuation will not be spatially fixed. A local active noise control system incorporating a virtual sensing method thus has to be able to create a moving zone of quiet that tracks the observer's ear. This paper presents a method for creating a moving zone of quiet that tracks a desired location based on a virtual sensing method called the remote microphone technique. The developed algorithm is implemented in an acoustic duct and experimental results are presented.

## INTRODUCTION

A local active noise control system aims to create a zone of quiet at a specific location, for instance at the passenger's ear inside a vehicle cabin. The created zone of quiet generally tends to be very small, and is usually centered at the location of the error sensor [1]. This means that the error sensor usually has to be placed close to an observer's ear, which might not always be a convenient or feasible solution. Virtual sensing is a method that has been developed in order to overcome these problems often encountered in local active noise control systems [2–5]. This method uses a non-intrusive physical sensor, which is placed remotely from the desired location of maximum attenuation, to provide an estimate of the pressure at this location. The estimated pressure can then be minimised by a local active noise control system such that the zone of quiet is moved away from the physical sensor to the spatially fixed desired location of maximum attenuation, such as a person's ear. The concept of virtual sensing has shown potential to improve the performance of a local active noise control system [2–8]. It is, however, very likely that the desired location of maximum attenuation is not spatially fixed. As an example, a passenger inside an aircraft cabin will move their head, thereby changing the desired location of the zone of quiet. This means that an active noise control system incorporating a virtual sensing method has to be able to create a moving zone of quiet that tracks the passenger's head. A method for creating a moving zone of quiet inside an acoustic duct using the adaptive LMS virtual microphone technique [5] has been presented previously by the authors in [9]. In this paper, an alternative virtual sensing method called the remote microphone technique [4, 8] is used to create a moving zone of quiet.

## PROBLEM DESCRIPTION

Figure 1 shows a schematic diagram of the rigid-walled acoustic duct arrangement considered here. The duct has a length $L = 4.83\,\mathrm{m}$, a primary source located at $x_p = 4.73\,\mathrm{m}$, a control source located at $x_s = 0.5\,\mathrm{m}$, a physical microphone located at $x_{ph} = 1.475\,\mathrm{m}$, and is rigidly terminated at both ends. The aim of the active noise control

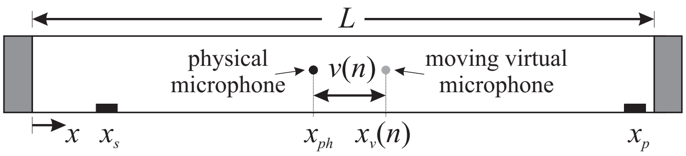



*Figure 1 – Schematic diagram of a the acoustic duct arrangement under consideration.*

system is to minimise the virtual error signal $e_v(n)$ at a moving virtual microphone located inside the acoustic duct. This moving virtual microphone tracks the desired location of the zone of quiet, which is denoted by the moving virtual location $x_v(n) = x_{ph} + v(n)$, with $v(n)$ the moving virtual distance as shown in Figure 1. Also located inside the duct is a traversing microphone, which can be position controlled to track the moving virtual location. The virtual error signal at the moving virtual location is defined as

$$e_v(n) = d_v(n) + y_v(n) = d_v(n) + G_{vu}u(n), \tag{1}$$

where $d_v(n)$ is the *non-stationary* virtual primary disturbance signal, $y_v(n)$ is the virtual secondary disturbance signal, $u(n)$ is the control signal, and $G_{vu}$ is the linear *time-varying* virtual secondary transfer path. The signal $d_v(n)$ and the transfer path $G_{vu}$ are non-stationary and time-varying, respectively, because the virtual microphone is moving through the spatially varying sound field inside the acoustic duct. To minimise the virtual error signal at the moving virtual location, an adaptive controller is generally used [10], which requires feedback information contained in a virtual error signal $e_v(n)$. This information would normally be provided by a physical microphone positioned at the moving virtual location. In the problem considered here, however, there is actually no physical microphone at the moving virtual location, and the virtual error signal $e_v(n)$ thus needs to be estimated using a *moving virtual sensing* method. The estimated virtual error signal can then be used as feedback information to an adaptive controller that aims to minimise this signal, thereby creating a moving zone of quiet inside the acoustic duct.

## ALGORITHMS

In this section, the active noise control algorithm that is used to create a moving zone of quiet inside the acoustic duct arrangement is introduced.

### Moving virtual sensing algorithm

The remote microphone technique [4, 8] has been introduced for estimating the virtual error signal $e_v(n)$ at a spatially fixed virtual location $x_v$. This technique is now used to obtain an estimate of the virtual error signal at the moving virtual location $x_v(n)$, where it is assumed that the moving virtual location stays within a certain region inside the duct called the *target zone* located between $x_{v1}$ and $x_{M_v}$. Using the remote microphone technique, estimates $\hat{\mathbf{e}}_v(n)$ of the virtual error signals at a number of spatially fixed virtual locations $\mathbf{x}_v \in \mathbb{R}^{M_v}$ throughout the target zone can be obtained, with $\mathbf{x}_v$ given by

$$\mathbf{x}_v = \begin{bmatrix} x_{v1} & x_{v2} & \dots & x_{vM_v} \end{bmatrix}. \tag{2}$$

This is illustrated in Figure 2, where a block diagram of the suggested moving virtual sensing algorithm is depicted. The input signals to the algorithm are the control sig-

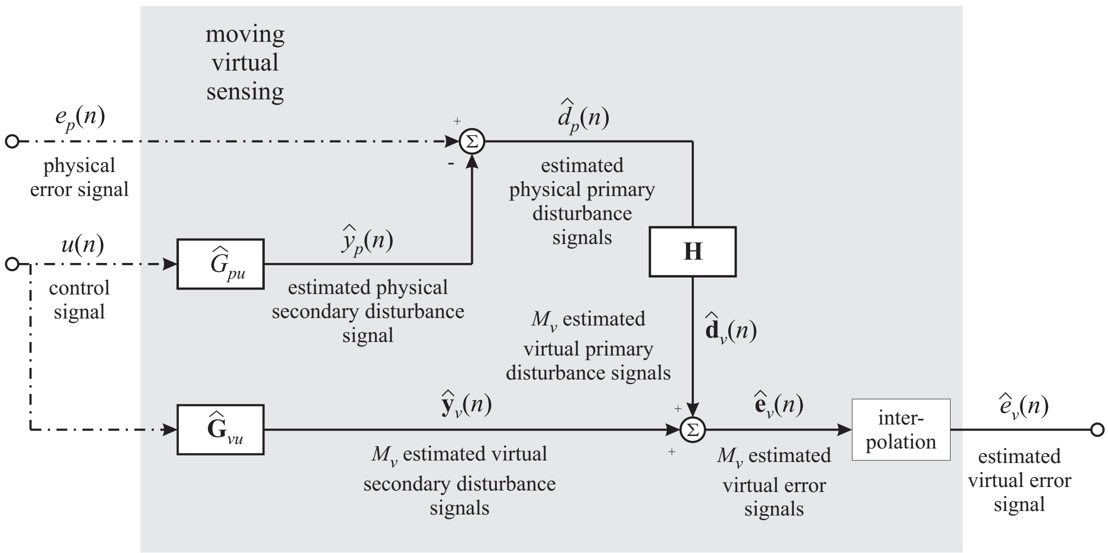



*Figure 2 – Block diagram of the moving virtual sensing algorithm.*

nal $u(n)$ and the physical error signal $e_p(n)$. First, an estimate $\hat{d}_p(n)$ of the *stationary* physical primary disturbance signal is obtained as

$$\hat{d}_p(n) = e_p(n) - \hat{y}_p(n) = e_p(n) - \hat{G}_{pu}u(n), \tag{3}$$

with $\hat{y}_p(n)$ an estimate of the physical secondary disturbance signal, and $\hat{G}_{pu}$ an estimate of the linear *time-invariant* physical secondary transfer path. Next, estimates

$\hat{\mathbf{d}}_v(n) \in \mathbb{R}^{M_v}$ of the *stationary* virtual primary disturbance signals at the spatially fixed virtual locations $\mathbf{x}_v$ are obtained as

$$\hat{\mathbf{d}}_v(n) = \mathbf{H}\hat{d}_p(n), \tag{4}$$

where $\mathbf{H}$ is an $M_v \times 1$ linear *time-invariant* transfer matrix that estimates the transfer paths between the physical primary disturbance signal $d_p(n)$ and the virtual primary disturbance signals $\mathbf{d}_v(n)$. Estimates $\hat{\mathbf{e}}_v(n)$ of the virtual error signals at the spatially fixed virtual locations $\mathbf{x}_v$ are then calculated as

$$\hat{\mathbf{e}}_v(n) = \hat{\mathbf{d}}_v(n) + \hat{\mathbf{y}}_v(n) = \mathbf{H}\hat{d}_p(n) + \hat{\mathbf{G}}_{vu}u(n), \tag{5}$$

with $\hat{\mathbf{G}}_{vu}$ an estimate of the $M_v \times 1$ linear *time-invariant* virtual secondary transfer path matrix. As illustrated in Figure 2, an estimate $\hat{e}_v(n)$ of the virtual error signal at the moving virtual location $x_v(n)$, which is assumed to be somewhere in the target zone located between $x_{v1}$ and $x_{vM_v}$, is now obtained by using an interpolation technique between the virtual error signals $\hat{\mathbf{e}}_v(n)$ belonging to the spatially fixed virtual locations $\mathbf{x}_v$.

**Filtered-x LMS algorithm**

The filtered-x LMS algorithm is used to generate a control signal $u(n)$ that aims to minimise the estimated virtual error signal $\hat{e}_v(n)$ at the moving virtual location. It is assumed that there is a reference signal $x(n)$ available that is strongly correlated to the virtual primary disturbance signal $d_v(n)$, such that a feedforward control strategy can be applied. The filtered-x LMS algorithm used here is then given by [10]

$$\mathbf{w}(n+1) = \mathbf{w}(n) - \mu\hat{\mathbf{r}}_v(n)\hat{e}_v(n), \tag{6}$$

with $\mu \in \mathbb{R}^+$ the convergence coefficient, $\mathbf{w}(n) \in \mathbb{R}^I$ a vector of filter coefficients given by

$$\mathbf{w}(n) = \begin{bmatrix} w_0 & w_1 & \dots & w_{n-I+1} \end{bmatrix}^{\mathrm{T}}, \tag{7}$$

and $\hat{\mathbf{r}}_v(n) \in \mathbb{R}^I$ a vector defined as

$$\hat{\mathbf{r}}_v(n) = \begin{bmatrix} \hat{r}_v(n) & \hat{r}_v(n-1) & \dots & \hat{r}_v(n-I+1) \end{bmatrix}^{\mathrm{T}}, \tag{8}$$

with $\hat{r}_v(n)$ the virtual filtered-reference signal. This signal is obtained by first filtering the reference signal $x(n)$ with the estimated virtual secondary transfer path matrix $\hat{\mathbf{G}}_{vu}$, which results in $M_v$ virtual filtered-reference signals given by

$$\hat{\mathbf{r}}_{\mathbf{x}_v}(n) = \begin{bmatrix} \hat{r}_{v1}(n) & \hat{r}_{v2}(n) & \dots & \hat{r}_{vN}(n) \end{bmatrix}, \tag{9}$$

with $\hat{r}_{vi}(n)$ the virtual filtered-reference signal belonging to the spatially fixed virtual location $x_{vi}$ in Equation (2). Next, an estimate $\hat{r}_v(n)$ of the virtual filtered-reference signal for the moving virtual location $x_v(n)$ is obtained by using an interpolation technique between the virtual filtered-reference signals $\hat{\mathbf{r}}_{\mathbf{x}_v}(n)$ in Equation (9). Since the virtual filtered-reference signal $\hat{r}_v(n)$ and the estimated virtual primary disturbance signal $\hat{d}_v(n)$ are *non-stationary*, the optimal solution for the filter coefficients $\mathbf{w}(n)$ that minimises the estimated virtual error signal $\hat{e}_v(n)$ at the moving virtual location is *time-varying* [11]. As a result, the aim of the filtered-x LMS algorithm in Equation (6) is to not only converge to, but also track the time-varying optimal solution for the filter coefficients.

## ACOUSTIC DUCT EXPERIMENTS

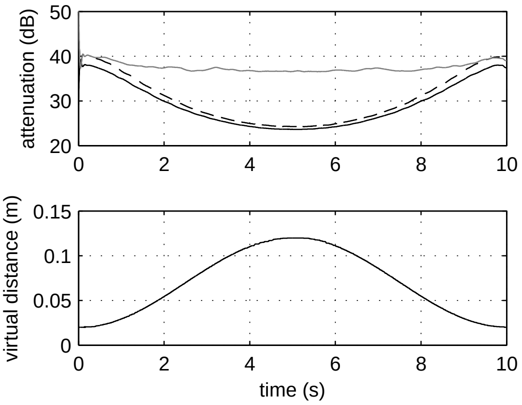
The proposed algorithm was implemented in the acoustic duct arrangement shown in Figure 1 in order to create a moving zone of quiet at a moving virtual location $x_v(n) = x_{ph} + v(n)$ that changed sinusoidally with time, with $v(n)$ the moving virtual distance. The expression governing the desired position of the virtual microphone is defined by

$$v(n) = 0.07 + 0.05 \sin\left(\frac{2\pi n}{T_v f_s}\right), \tag{10}$$

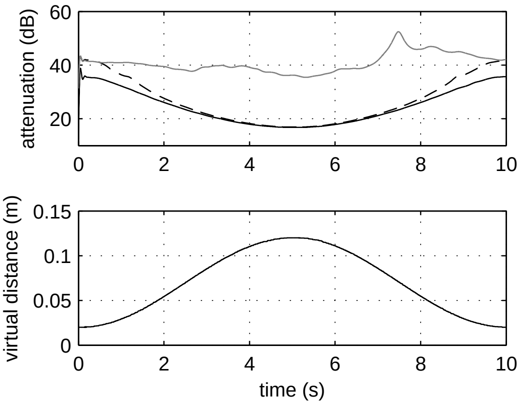
with $T_v$ the period of the sinusoidally time-varying moving virtual distance $v(n)$, and $f_s = 4\,\text{kHz}$ the sampling frequency. The virtual microphone is thus moving sinusoidally between a virtual distance of 0.02 m and 0.12 m, which is typical of the distance moved by a seated observer. The performance at the moving virtual distance was measured with the position controlled traversing microphone for two excitation frequencies $f$ of 213 Hz and 249 Hz. These frequencies correspond to the sixth and seventh resonance frequencies of the acoustic duct. For these excitation frequencies, the performance at the moving virtual distance $v(n)$ was measured for two different periods $T_v$ in Equation (10), given by $10\,\text{s}$, and $2.5\,\text{s}$. The filtered-x LMS algorithm in Equation (6) was implemented using $I = 2$ filter coefficients, since the virtual primary disturbance signal only contained a single harmonic component to be cancelled. State-space models of the required transfer paths were estimated using subspace model identification techniques [12, 13]. These models were obtained for $M_v = 16$ spatially fixed virtual locations $\mathbf{x}_v = x_{ph} + \mathbf{v}$, with $\mathbf{v}$ given by

$$\mathbf{v} = \begin{bmatrix} 0.00 & 0.01 & 0.02 & \dots & 0.15 \end{bmatrix} \text{ m}, \tag{11}$$

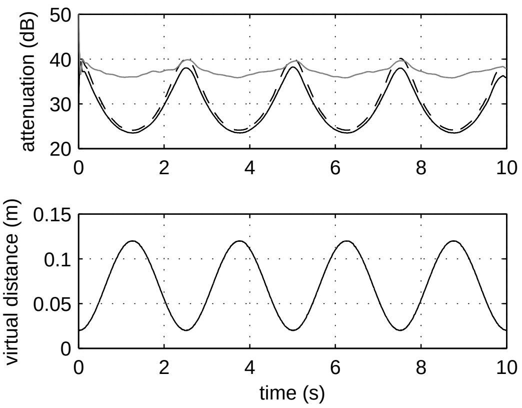
such that the target zone was located within a virtual distance range of 0–0.15 m. This distribution of spatially fixed virtual locations over the target zone was chosen after investigating the spatial distribution of the sound field over the target zone for the two considered excitation frequencies. This investigation also indicated that a linear interpolation technique between the virtual error signals $\hat{\mathbf{e}}_v(n)$ in Equation (5), and the virtual filtered reference signals $\hat{\mathbf{r}}_{\mathbf{x}_v}(n)$ in Equation (9), could be used to obtain an estimate $\hat{e}_v(n)$ of the virtual error signal at the moving virtual location, and an estimate $\hat{r}_v(n)$ of the virtual filtered-reference signal for the moving virtual location.



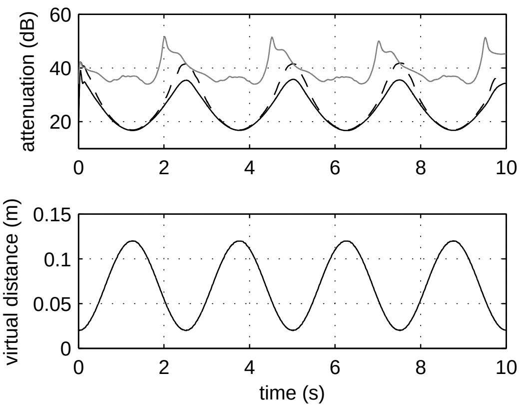

(a) $f = 213\,Hz$ and $T_v = 10\,s$




(b) $f = 249\,Hz$ and $T_v = 10\,s$




(c) $f = 213\,Hz$ and $T_v = 2.5\,s$




(d) $f = 249\,Hz$ and $T_v = 2.5\,s$

*Figure 3 – (*Bottom*) Moving virtual distance $v(n)$ plotted against time. (*Top*) Average tonal attenuation at moving virtual distance plotted against time for active noise control at:* — *physical microphone spatially fixed at $v = 0\,\mathrm{m}$;* -- *virtual microphone spatially fixed at $v = 0.02\,\mathrm{m}$;* — *moving virtual microphone at $v(n)$.*

Figure 3 shows the control performance obtained at the moving virtual location for three different active noise control systems. The solid black line shows the tonal attenuation measured at the moving virtual location plotted against time, for the case of minimising the physical error signal $e_p(n)$ that is directly measured by the physical microphone spatially fixed at $x_{ph} = 1.475\,\mathrm{m}$, which corresponds to $v = 0\,\mathrm{m}$. The dashed line shows the tonal attenuation measured at the moving virtual location plotted against time, for the case of minimising the estimated virtual error signal $\hat{e}_v(n)$ at a virtual microphone spatially fixed at $v = 0.02\,\mathrm{m}$. This represents the conventional implementation of the remote microphone technique. The solid grey line shows the tonal attenuation measured at the moving virtual location plotted against time, for the case of minimising the estimated virtual error signal $\hat{e}_v(n)$ at the moving virtual distance $v(n)$. Each of these lines was generated by averaging the results of 30 data-sets of 10 s measured with the traversing microphone, which was position controlled to track the moving virtual distance $v(n)$. Furthermore, the average tonal attenuations in decibels were low-pass filtered in order to prevent noisy plots in Figure 3. The results show that for each of the conducted experiments, the algorithm that uses the suggested moving virtual sensing method provides the best control performance at the moving virtual location. The average tonal attenuation at the moving virtual location does not fall below 34 dB when using a moving virtual microphone, whereas for the spatially fixed physical and virtual microphones, the average tonal attenuation at a virtual distance of $v = 0.12\,\mathrm{m}$ reduces to around 24 dB for an excitation frequency of 213 Hz, and 17 dB for an excitation frequency of 249 Hz. These results thus indicate that the filtered-x LMS algorithm is able to provide the necessary tracking of the optimal filter coefficients in the experiments, such that a moving zone of quiet is effectively created inside the acoustic duct. The tracking of the optimal filter coefficients can also be observed in Figure 4, where the filter coefficients $\mathbf{w}(n)$ have been plotted against time for $f = 249\,\mathrm{Hz}$ and $T_v = 2.5\,\mathrm{s}$. The results in Figure 3 show that the tracking ability

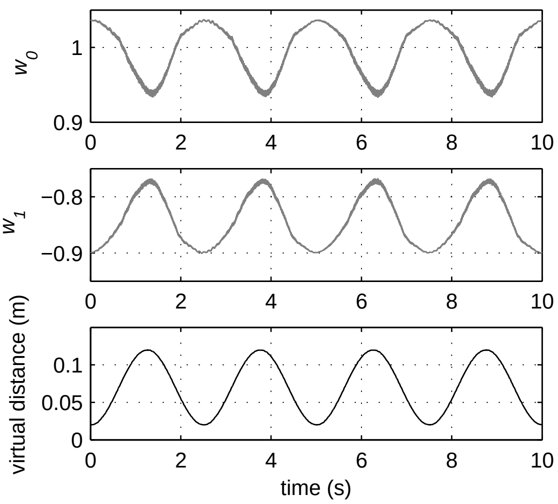



*Figure 4 – Filter coefficients $\mathbf{w}(n)$ plotted against time for $f = 249\,\mathrm{Hz}$ and $T_v = 2.5\,\mathrm{s}$.*

results in an increase in the local control performance compared to using a spatially fixed virtual sensing method or a spatially fixed physical sensing method, which cannot provide the necessary tracking of the optimal filter coefficients. This indicates that the developed algorithm has the potential to improve the scope of successful local active noise control applications.

## CONCLUSION

In this paper, an active noise control algorithm was developed for creating a moving zone of quiet inside an acoustic duct arrangement based on a virtual sensing method called the remote microphone technique. The developed algorithm used a moving virtual sensing method for estimating the virtual error signal at a moving virtual microphone located inside an acoustic duct. By minimising the estimated virtual error signal with a modified filtered-x LMS algorithm, a moving zone of quiet was effectively created inside an acoustic duct arrangement during real-time control experiments. The experimental results indicate the potential of the suggested method to improve the local control performance of an active noise control system.

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