Active noise control at a moving location in a modally dense three-dimensional sound field using virtual sensing

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Local active noise control systems generate a zone of quiet at the physical error sensor using secondary sources to cancel the acoustic pressure at the sensor location. The resulting zone of quiet is generally limited in size and as such, placement of the physical error sensor at the location of desired attenuation is required, which is often inconvenient. Virtual acoustic sensors overcome this by projecting the zone of quiet away from the physical error sensor to a remote location. While virtual acoustic sensors have shown potential to improve the performance of local active noise control systems, it is, however, likely that the desired location of maximum attenuation is not spatially fixed. The work described here presents a virtual sensing method capable of tracking a desired location in a modally dense three-dimensional sound field. The developed algorithm has been experimentally verified in a three-dimensional enclosure and the experimental results demonstrate that moving virtual sensors provide improved attenuation compared to fixed virtual sensors or fixed physical sensors.

1 Introduction

Local active noise control systems reduce the sound field at a number of points within the acoustic domain to create localised zones of quiet at the error sensors. While significant attenuation may be achieved at the error sensor locations, the zone of quiet is generally small and impractically sized. Virtual acoustic sensors overcome this by shifting the zone of quiet to a desired location that is remote from the physical sensor. A number of virtual sensing methods have been developed to project the zone of quiet away from the physical microphone to a virtual location including *the virtual microphone arrangement* [1], *the remote microphone technique* [2], *the adaptive LMS virtual microphone technique* [3] and *the Kalman filtering virtual sensing technique* [4]. Even though the sound is significantly attenuated at the virtual location, the spatial extent of the zone of quiet generated with these virtual sensing algorithms is still impractically small. A human observer with a virtual sensor located at their ear would experience dramatic changes in sound pressure level with only minor head movements. Subsequently, Petersen et al. [5, 6] developed a number of one-dimensional moving virtual sensing methods that create a zone of quiet capable of tracking a moving virtual location in a one-dimensional sound field. The one-dimensional moving virtual sensing methods developed by Petersen et al. [5, 6] employ the adaptive LMS virtual microphone technique and the remote microphone technique. The performance of these moving virtual sensors has been investigated in an acoustic duct, and experimental results demonstrated that minimising the moving virtual error signal achieved greater attenuation at the moving virtual location than minimising the error signal at either a fixed physical or virtual microphone.

In this paper, a method for creating a moving zone of quiet inside a modally dense three-dimensional cavity is developed. This three-dimensional moving virtual sensing algorithm employs the remote microphone technique to estimate the virtual error signal at the moving virtual location. To determine the level of attenuation that can be expected at the ear of a human observer, the performance of the moving virtual sensing algorithm in generating a moving zone of quiet at a single ear of an artificial head is experimentally investigated in a modally dense three-dimensional cavity.

2 Theoretical Background

The aim of this paper is to create a zone of quiet at a moving virtual microphone located at the ear of an artificial head in a modally dense three-dimensional cavity. The active noise control system must therefore minimise the estimated virtual error signal, $\tilde{e}_v(n)$, at the moving virtual location, $x_v(n)$, which tracks the ear of the rotating artificial head. The moving virtual sensing algorithm described here uses the remote microphone technique [2] to obtain an estimate of the moving virtual error signal and is an extension to that described by Petersen et al. [5].

A block diagram of the moving virtual sensing algorithm is given in Fig. 1. In this moving virtual sensing algorithm, the remote microphone technique is first used to obtain estimates of the virtual error signals, $\tilde{\mathbf{e}}_v(n)$, at N_v spatially fixed virtual microphone locations, $\mathbf{x}_v$. It is assumed here that the moving virtual location, $x_v(n)$, is confined to a three-dimensional region within the cavity and that the N_v spatially fixed virtual microphone locations, $\mathbf{x}_v$, are therefore located within this region. The vector of the N_v spatially fixed virtual microphone locations is given by

$$\mathbf{x}_v = \left[\begin{array}{cccc} x_{v1} & x_{v2} & \dots & x_{vN_v} \end{array} \right]. \tag{1}$$

The remote microphone technique requires a preliminary identification stage in which the transfer function between the control source and the physical microphone, $\tilde{G}_{pu}$, and the vector of N_v transfer functions between the control source and the N_v spatially fixed virtual microphone locations, $\tilde{\mathbf{G}}_{vu}$, are measured. The vector of N_v primary transfer functions at the spatially fixed virtual locations from the physical microphone location, $\mathbf{M}$, is also estimated in this preliminary identification stage.

As shown in Fig. 1, an estimate of the primary disturbance at the physical microphone, $\tilde{d}_p(n)$, is first obtained using

$$\tilde{d}_p(n) = e_p(n) - \tilde{y}_p(n) = e_p(n) - \tilde{G}_{pu}u(n), \tag{2}$$

where $e_p(n)$ is the total error signal measured at the physical microphone, $\tilde{y}_p(n)$ is an estimate of the secondary disturbance at the physical microphone and $u(n)$ is the control signal. Next, estimates of the primary disturbances at the N_v spatially fixed virtual microphone locations, $\mathbf{x}_v$, are obtained by

$$\tilde{\mathbf{d}}_v(n) = \mathbf{M}\tilde{d}_p(n). \tag{3}$$

Estimates, $\tilde{\mathbf{e}}_v(n)$, of the total virtual error signals at the N_v spatially fixed virtual microphone locations, $\mathbf{x}_v$, are

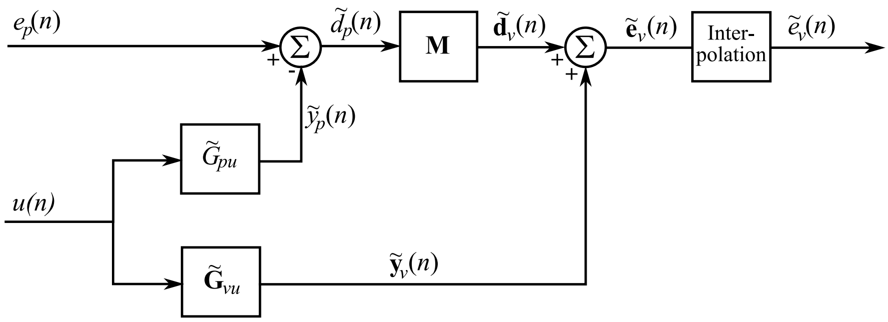


Figure 1: Block diagram of the moving virtual sensing algorithm using the remote microphone technique.

now calculated as

$$\tilde{\mathbf{e}}_v(n) = \tilde{\mathbf{d}}_v(n) + \tilde{\mathbf{y}}_v(n) = \mathbf{M}\tilde{d}_p + \tilde{\mathbf{G}}_{vu}u(n). \quad (4)$$

As shown in Fig. 1, an estimate, $\tilde{e}_v(n)$, of the virtual error signal at the moving virtual location, $x_v(n)$, is now obtained by interpolating the virtual error signals, $\tilde{\mathbf{e}}_v(n)$, at the N_v spatially fixed virtual microphone locations in $\mathbf{x}_v$.

To create a zone of quiet at the moving virtual location, $x_v(n)$, the moving virtual sensing algorithm just described is now combined with the filtered-x LMS algorithm [7]. The filtered-x LMS algorithm is used to generate the control signal $u(n)$ using the estimated moving virtual error signal, $\tilde{e}_v(n)$. The filtered-x LMS algorithm is given by [7]

$$\mathbf{w}(n+1) = \mathbf{w}(n) - \mu\tilde{\mathbf{r}}_{x_v}(n)\tilde{e}_v(n), \quad (5)$$

where $\mathbf{w}(n)$ is a vector of I filter coefficients given by

$$\mathbf{w}(n) = \begin{bmatrix} w_0 & w_1 & \dots & w_{n-I+1} \end{bmatrix}^{\mathrm{T}}, \quad (6)$$

μ is the convergence coefficient and $\tilde{\mathbf{r}}_{x_v}(n)$ is a vector of I filtered reference signals given by

$$\tilde{\mathbf{r}}_{x_v}(n) = \begin{bmatrix} \tilde{r}_{x_v}(n) & \tilde{r}_{x_v}(n-1) & \dots & \tilde{r}_{x_v}(n-I+1) \end{bmatrix}^{\mathrm{T}}, \quad (7)$$

where $\tilde{r}_{x_v}(n)$ is the virtual filtered reference signal at the moving virtual location $x_v(n)$. The virtual filtered reference signal, $\tilde{r}_{x_v}(n)$, is obtained by filtering a reference signal which is strongly correlated with the primary disturbance, $x(n)$, by the virtual secondary transfer matrix $\tilde{\mathbf{G}}_{vu}$. This results in a vector, $\tilde{\mathbf{r}}_{\mathbf{x}_v}(n)$, of the N_v virtual filtered reference signals at $\mathbf{x}_v$

$$\tilde{\mathbf{r}}_{\mathbf{x}_v}(n) = \begin{bmatrix} \tilde{r}_{v1}(n) & \tilde{r}_{v2}(n) & \dots & \tilde{r}_{vN_v}(n) \end{bmatrix}^{\mathrm{T}}. \quad (8)$$

An estimate of the virtual filtered reference signal, $\tilde{r}_{x_v}(n)$, at the moving virtual location $x_v(n)$ is obtained by interpolating the virtual filtered reference signals in $\tilde{\mathbf{r}}_{\mathbf{x}_v}(n)$ over three-dimensions.

3 Cavity Experiments

The performance of an active noise control system in generating a moving zone of quiet at a single ear of a rotating artificial head is investigated in real-time experiments conducted in a three-dimensional cavity. The cavity has dimensions of 1m × 0.8m × 0.89m and a volume of 0.712 m^3. A HEAD acoustics HMS III.0 Artificial Head mounted on a turntable to simulate head rotation is located in the centre of the cavity, as shown in Fig. 2. The artificial head has overall dimensions of 465mm × 400mm × 180mm to approximate the size of a human head. The turntable is position controlled to generate 90° head rotations from −45° to +45° which is typical of the complete head rotations capable of a seated observer. The desired trajectory of the artificial head and of the virtual microphone is a triangular waveform with peak amplitudes of ±45°. The expression of the triangular waveform governing the desired head rotations, in degrees, is given by

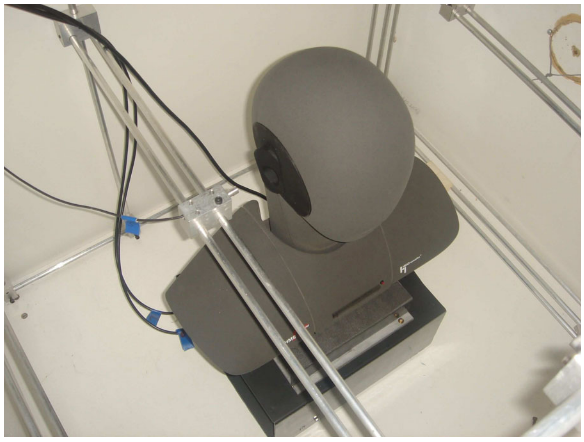


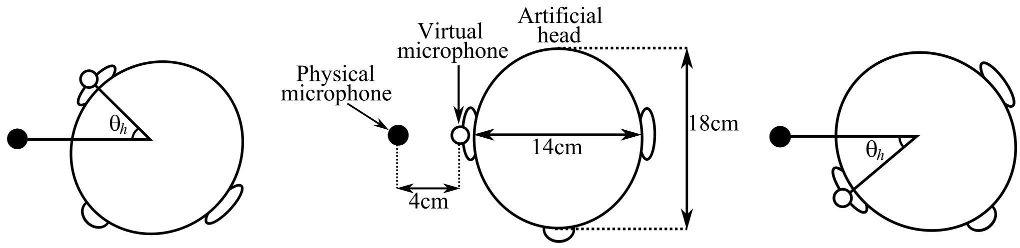
Figure 2: The HEAD acoustics HMS III.0 Artificial Head mounted on a turntable and located in the centre of the cavity.

$$\theta_h(n) = \frac{180}{\pi} arcsin\left(sin\left(\frac{2\pi n}{t_v f_s}\right)\right), \quad (9)$$

where n is the time sample, t_v is the period of the head motion and $f_s = 2.5$kHz the sampling frequency.

The physical arrangement of the artificial head and the physical and virtual microphones is shown in Fig. 3. As shown in Fig. 3, the physical microphone is located 4cm from the virtual microphone when the artificial head is positioned at $\theta_h = 0°$. An electret microphone is located at the ear of the artificial head to measure the performance at the virtual microphone position.

Two loudspeakers are located in the corners of the cavity, one to generate the tonal primary sound field and the other to act as the control source. The performance of the active noise control system at the moving virtual location is investigated at the excitation frequency



(a) $\theta_h = -45°$ (b) $\theta_h = 0°$ (c) $\theta_h = 45°$

Figure 3: The physical arrangement of the artificial head and the physical and virtual microphones at (a) $\theta_h = -45°$; (b) $\theta_h = 0°$; and (c) $\theta_h = 45°$. The physical microphone is indicated by a solid circle marker and the virtual microphone is indicated by an open circle marker.

of 525Hz which corresponds to the 33rd acoustic resonance. At this frequency, the modal overlap is $M = 4$ illustrating that the sound field is modally dense, as a modal overlap of $M = 3$ defines the boundary between low and high modal density [7]. For the excitation frequency of 525Hz, the performance at the moving virtual location is measured for two different periods of 90° head rotation; $t_v = 5$s and $t_v = 10$s.

The host-target software program XPC TARGET is used to implement the moving virtual sensing technique and the modified filtered-x LMS algorithm in real-time. In the preliminary identification stage, the microphone at the ear of the rotating artificial head is placed at $N_v = 31$ fixed virtual locations, $\mathbf{x}_v$, equally spaced along the 90 degree arc of head rotation. The required primary and secondary transfer functions are modelled as 2 coefficient FIR filters because the primary disturbance is tonal. The filtered-x LMS algorithm is also implemented using an $I = 2$ coefficient control filter.

4 Experimental Results

Fig. 4 shows the attenuation achieved at the moving virtual location for active noise control at the moving virtual microphone, a fixed virtual microphone located at the ear of the artificial head when $\theta_h = 0°$ and the physical microphone. The control performance at the ear of the artificial head is shown for the period of head rotation $t_v = 10$s in Fig. 4 (a) and $t_v = 5$s in Fig. 4 (b). Fig. 4 (c) shows the desired trajectory of the artificial head and of the virtual microphone, in degrees, compared to the actual controlled head position. The control profiles in Fig. 4 demonstrate that for both periods of head rotation, minimising the moving virtual error signal generates the best control performance at the moving virtual location. The transient behaviour seen at time $t/t_v = 0$ for both $t_v = 5$s and $t_v = 10$s, is caused by the controller initialising.

For $t_v = 10$s, attenuation between 30dB and 40dB is achieved at the ear of the artificial head when minimising the moving virtual microphone signal, as shown in Fig. 4 (a). Active noise control at the fixed virtual microphone achieves a maximum attenuation of 30dB at the ear of the artificial head when $\theta_h = 0°$. This maximum level of attenuation is reduced to the minimum of 10dB when $\theta_h = 45°$. Similarly, active noise control at the physical microphone achieves 22dB of attenuation at the ear of the artificial head when $\theta_h = 0°$ and only 6dB of attenuation when $\theta_h = 45°$.

When the period of head rotation is reduced to $t_v = 5$s, Fig. 4 (b) shows that minimising the moving virtual error signal results in attenuation of between 20dB and 35dB being achieved at the ear of the artificial head. This is a significant improvement in control performance compared to active noise control at either the fixed virtual or physical microphones where attenuation levels again fall to 10dB and 6dB respectively when $\theta_h = 45°$. As expected, when the period of rotation is reduced, the control performance reduces. This is because it takes a finite time for the controlled sound field to stabilise, so once the period of rotation nears the reverberation time of the cavity the control performance is compromised.

5 Conclusion

In this paper, a three-dimensional moving virtual sensing algorithm has been presented based on the remote microphone technique. The performance of an active noise control system implementing the developed moving virtual sensing algorithm and a modified version of the filtered-x LMS algorithm has been experimentally investigated in a modally dense three-dimensional cavity at a single ear of a rotating artificial head. The real-time experimental results demonstrated that greater attenuation can be achieved at a single ear of the artificial head when a three-dimensional moving virtual sensing algorithm is employed.

References

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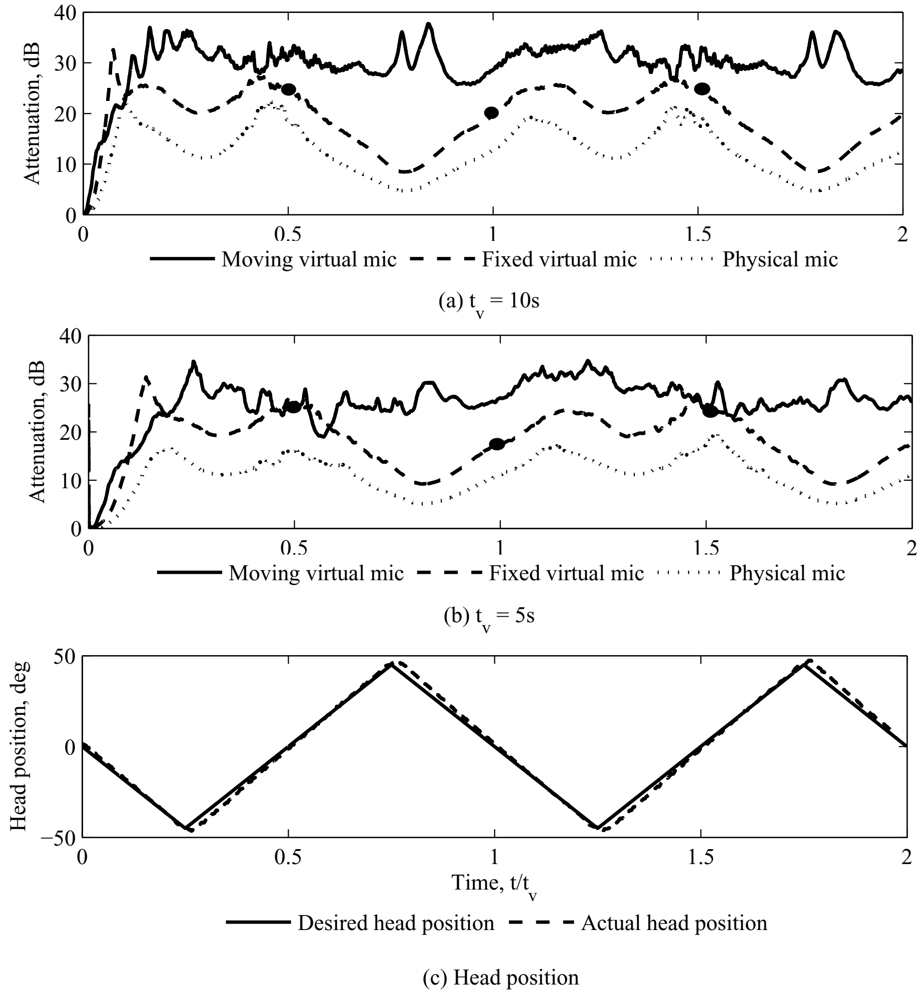

Figure 4: Tonal attenuation achieved at the moving virtual location for active noise control at the moving virtual microphone, the virtual microphone spatially fixed at the ear of the artificial head when $\theta_h = 0°$ and the physical microphone, for period of rotation (a) $t_v = 10$s; (b) $t_v = 5$s; and (c) head position. The fixed virtual microphone position at $\theta_h = 0°$ is indicated by a solid round marker.

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