ACTIVE NOISE CONTROL AT A MOVING VIRTUAL SENSOR IN THREE-DIMENSIONS

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ABSTRACT: A common problem in local active noise control is that the zone of quiet generated at the physical error sensor is limited in size. This requires that the physical error sensor (the microphone) is placed at the desired location of attenuation (the ear), which is often inconvenient. Virtual acoustic sensors overcome this by estimating the pressure at a location that is remote from the physical sensor and therefore, when combined with an active noise control system, generate a zone of quiet at the desired location of attenuation. 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 attenuation is not spatially fixed. A method for generating a virtual sensor that tracks a three-dimensional trajectory in a three-dimensional sound field is summarised in this paper. The performance of an active noise control system in generating a zone of quiet at the ear of a rotating head in a three-dimensional cavity has been experimentally investigated and the results included here demonstrate that moving virtual sensors provide improved attenuation compared to fixed virtual sensors or fixed physical sensors.

1. INTRODUCTION

Active noise control involves the use of secondary sound sources to cancel the primary noise disturbance, based on the principle of superposition, in which antinoise of equal amplitude but opposite phase is combined with the primary noise to cancel both disturbances. Active noise control systems generally consist of three major components; a sensor component, an actuator component and a controller. The sensor component is usually a number of microphones that measure the sound pressure at a number of locations within the acoustic field and monitor the performance of the active noise control system. The actuator component is often a number of loudspeakers that generate the antinoise which destructively interferes with the primary noise disturbance. These loudspeakers are referred to as secondary sources and are driven by a control signal generated by the controller [1].

Local active noise control systems generate a localised zone of quiet at the physical error sensor using secondary sources to cancel the acoustic pressure produced by the primary noise source at the physical sensor location. While significant attenuation may be achieved at the physical sensor location, the zone of quiet is generally small and impractically sized. Also, the sound pressure levels outside the zone of quiet are likely to be higher than the original disturbance alone with the active noise control system present.

This is illustrated in Fig. 1 (a), where the zone of quiet located at the physical error sensor is too small to extend to the observer's ear and the observer in fact experiences an increase in the sound pressure level with the active noise control system operating. Virtual acoustic sensors overcome this by shifting the zone of quiet to a desired location that is remote from the physical sensor. This is shown in Fig. 1 (b) where the zone of quiet is projected from the physical sensor to a virtual sensor located at the observer's ear. Using the

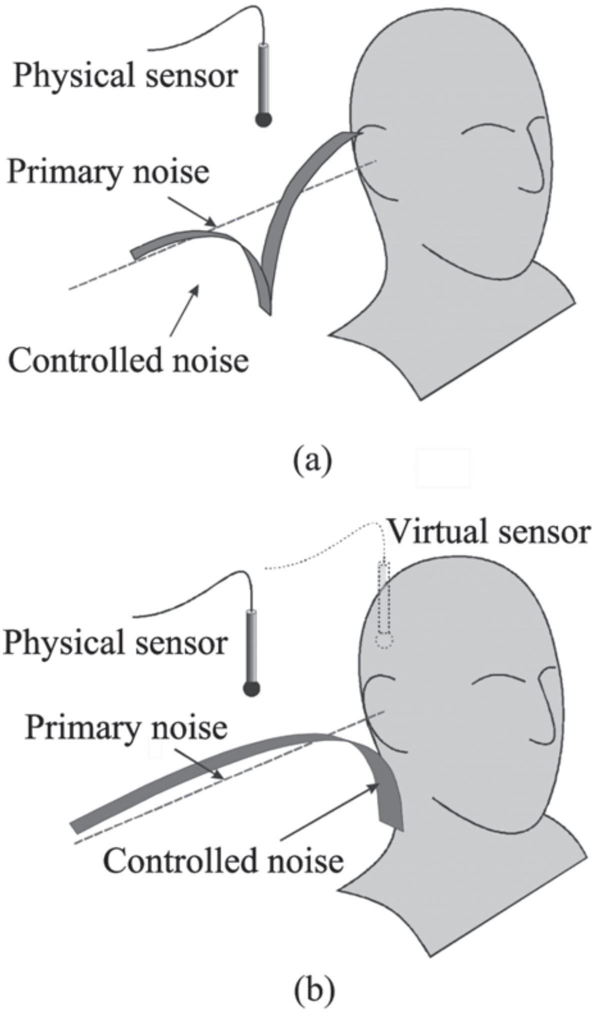


Figure 1: Comparison of local active noise control (a) at a physical sensor and (b) at a virtual sensor.

physical error signal, a virtual sensing method is used to estimate the pressure at the virtual sensor location. Instead of minimising the physical error signal, the estimated pressure is minimised to generate a zone of quiet at the virtual location. A number of virtual sensing methods have been developed to estimate the pressure at a fixed virtual location including *the virtual microphone arrangement [2], the remote microphone technique [3], the adaptive LMS virtual microphone technique [4] and the Kalman filtering virtual sensing technique [5].*

The virtual microphone arrangement [2] projects the zone of quiet away fromthe physicalmicrophone using the assumption of equal primary sound pressure at the physical and virtual locations. A preliminary identification stage is required in this virtual sensing method in which models of the transfer functions between the secondary source and microphones located at the physical and virtual locations are estimated. These secondary transfer functions, along with the assumption of equal sound pressure at the physical and virtual locations, are used to obtain an estimate of the error signal at the virtual location given the physical error signal. The remote microphone technique [3] is an extension to the virtual microphone arrangement that uses an additional filter to compute an estimate of the primary pressure at the virtual location using the primary pressure at the physical microphone location.

The adaptive LMS virtual microphone technique [4] employs the LMS algorithm to adapt the weights of physical microphones in an array so that the weighted sum of these signals minimises the mean square difference between the predicted pressure and that measured by a microphone placed at the virtual location. Once the weights have converged they are fixed and the microphone at the virtual location is removed.

The Kalman filtering virtual sensing technique [5] uses Kalman filtering theory to obtain an optimal estimate of the error signal at the virtual location. In this virtual sensing method, the active noise control system is modelled as a state-space system whose outputs are the physical and virtual error signals. Estimates of the plant states are first calculated using the physical error signals and then estimates of the virtual error signals are calculated using the estimated plant states.

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. Large pressure gradients in the vicinity of the virtual sensor result in significant changes in the perceived sound pressure level as the observer moves around within the zone of quiet and this could be more annoying than the original disturbance alone. Subsequently, Petersen et al. [6, 7] 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. Hence if the observer moves their head, the small zone of quiet also moves with the observer. The one-dimensional moving virtual sensing methods developed by Petersen et al. [6, 7] use the adaptive LMS virtual microphone technique and the remote microphone technique. The performance of these one-dimensional 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.

This paper reports on the development of three-dimensional moving virtual sensing methods. A method for generating a moving virtual sensor that tracks a three-dimensional trajectory in a threedimensional sound field is summarised here. The performance of an active noise control system in generating a zone of quiet at a virtual sensor located at the ear of a rotating head has been experimentally investigated and experimental results are presented.

2. THEORY

Full details of the method for generating a zone of quiet at a moving virtual microphone that tracks a three-dimensional trajectory are given in [8]. A summary of the three-dimensional moving virtual sensing algorithm is provided as follows.

To create a zone of quiet at a moving virtual location, the active noise control system must minimise the estimated virtual error signal, $\tilde{e}_v(n)$, at the moving virtual location, $x_v(n)$. It is assumed here that the desired position of the moving virtual microphone is known at every time step, n. In practice, the desired location of attenuation could be determined using a three-dimensional tracking system based on camera vision or on ultrasonic position sensing [7].

In this moving virtual sensing method, a number, N_v, of spatially fixed measurement locations are first selected. It is assumed here that the moving virtual location, $x_v(n)$, is confined to a three-dimensional region and that the N_v spatially fixed measurement locations are therefore located within this region. The vector of the N_v spatially fixed measurement locations is given by

$$\mathbf{x}_v = \left[\begin{array}{cccc} x_{v1} & x_{v2} & \ldots & x_{vN_v} \end{array} \right]. \qquad (1)$$

Next, the remote microphone technique is used to obtain estimates of the virtual error signals, $\tilde{\mathbf{e}}_v(n)$, at the N_v spatially fixed measurement locations in $\mathbf{x}_v$. 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 measurement locations, $\tilde{\mathbf{G}}_{vu}$, are measured. The vector of N_v primary transfer functions at the spatially fixed measurement locations from the physical microphone location, M, is also estimated in this preliminary identification stage.

A block diagram of the moving virtual sensing algorithm is given in Fig. 2. As shown in Fig. 2, estimates, $\tilde{\mathbf{e}}_v(n)$, of the virtual error signals at the N_v spatially fixed measurement locations in $\mathbf{x}_v$ are obtained by firstly estimating the primary disturbance at the physical microphone, $\tilde{d}_p(n)$, using

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

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 measurement locations, $\mathbf{x}_v$, are obtained using

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

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

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

As shown in Fig. 2, 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 measurement locations. This estimate, $\tilde{e}_v(n)$, of the virtual error signal at the moving virtual location is minimised with the active noise control system to generate a zone of quiet that tracks a desired three-dimensional trajectory.

As the virtual error signal at the moving virtual location, $\tilde{e}_v(n)$, is estimated by interpolating the virtual error signals, $\tilde{\mathbf{e}}_v(n)$, at the N_v spatially fixed measurement locations, $\mathbf{x}_v$, the accuracy of the estimate of the moving virtual error signal is dependent on the number and position of the spatially fixed measurement locations within the sound field. If the sound field varies significantly in magnitude and phase over a certain region then the spatially fixed measurement locations must be closely spaced within this region to ensure an accurate estimate of the moving virtual error signal is obtained.

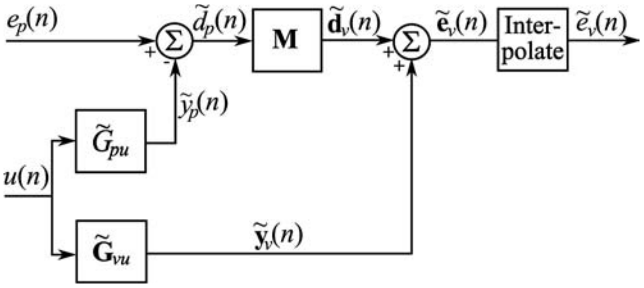


Figure 2: Block diagram of the moving virtual sensing algorithm using the remote microphone technique.

3. EXPERIMENTAL METHOD

The performance of an active noise control system in generating a zone of quiet at a moving virtual sensor located at the ear of a rotating artificial head was investigated in real-time experiments. The experiments were conducted in a three-dimensional cavity with dimensions of 1m × 0.8m × 0.89m. A HEAD acoustics HMS III.0 Artificial Head mounted on a turntable to simulate head rotation was located in the centre of the cavity, as shown in Fig. 3. The turntable was position controlled to generate triangular head rotations from −45° to +45° which is typical of the complete head rotations capable of a seated observer.

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

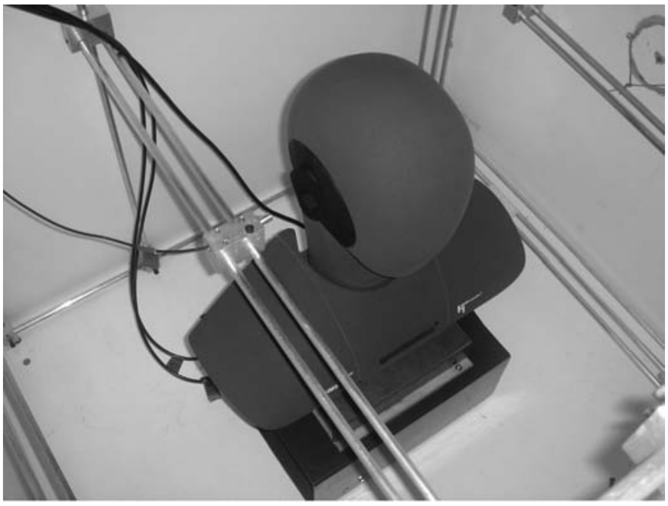


Figure 3: The HEAD acoustics HMS III.0 Artificial Head mounted on a turntable and located in them centre of the cavity. The fixed frame supports the physical microphone.

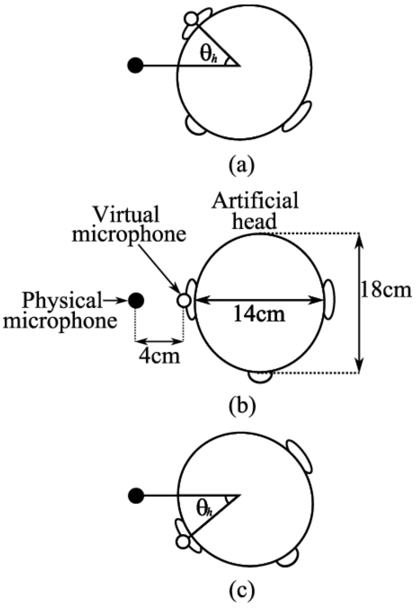


Figure 4: The physical arrangement of the artificial head and the physical and virtual microphones at (a) $\theta_h = -45^\circ$; (b) $\theta_h = 0^\circ$; and (c) $\theta_h = 45^\circ$. The physical microphone is indicated by a solid circle marker and the virtual microphone is indicated by an open circle marker.

Two loudspeakers were 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 was investigated at the excitation frequency of 525Hz which corresponds to the 33rd acoustic resonance of the cavity. For the excitation frequency of 525Hz, the performance at the moving virtual location was measured for two different periods of 90° head rotation; $t_v = 5$s and $t_v = 10$s.

In the preliminary identification stage, the microphone at the ear of the artificial head was placed at $N_v = 31$ s spatially fixed measurement locations, $\mathbf{x}_v$, equally spaced along the 90° arc of head motion. The required primary and secondary transfer functions were modelled as 2 coefficient FIR filters during this preliminary identification stage because the primary disturbance is tonal.

4. EXPERIMENTAL RESULTS

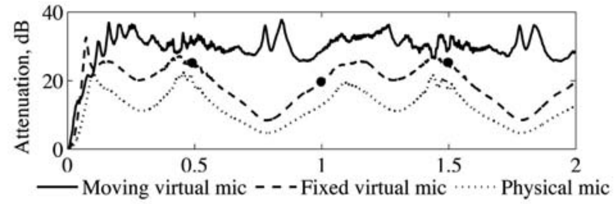
Fig. 5 shows the attenuation achieved at the moving virtual location for active noise control at the moving virtual microphone, a fixed virtual microphone located at the ear of the artificial head when $\theta_h = 0°$ and the fixed physical microphone. The control performance at the ear of the artificial head is shown for the period of head rotation being $t_v = 10$s in Fig. 5 (a) and $t_v = 5$s in Fig. 5 (b). Fig. 5 (c) shows the desired trajectory of the artificial head compared to the actual controlled head position.

The control profiles in Fig. 5 demonstrate that for both periods of head rotation, minimising the moving virtual error signal achieves the best control performance at the moving virtual location. For $t_v = 10$s, attenuation between 30dB and 40dB is achieved at the ear of the artificial head for active noise control at the moving virtual microphone, as shown in Fig. 5 (a). Minimising the fixed virtual microphone signal achieves a maximum attenuation of 30dB at the ear of the artificial head when $\theta_h = 0°$ and a minimum attenuation 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 $\theta_h = 45°$. The transient behaviour seen at time $t/t_v = 0$ is caused by the controller initialising.

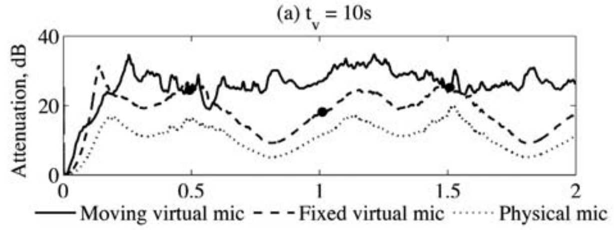
When the period of head rotation is reduced to $t_v = 5$s, Fig. 5 (b) shows that minimising the moving virtual error signal results in attenuation of between 20dB and 35dB being achieved at the ear of the artificial head. This is a significant improvement in control performance compared to active noise 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

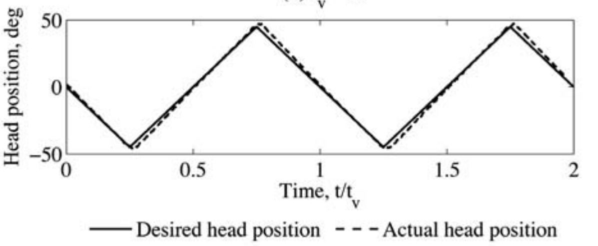
In this paper, a method for generating a moving virtual sensor that tracks a three-dimensional trajectory has been presented. The performance of an active noise control system in generating a zone of quiet at a single ear of a rotating artificial head has been experimentally investigated and real-time 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.



(a) $t_v = 10$s



(b) $t_v = 5$s



(c) Head position

Figure 5: 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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