Comprehensive Review of Virtual Sensing Algorithms for Enhancing Active Noise Control Systems

Mamadou Diallo[1], Souleymane Camara[2], and Mariama Kaba[3]
[1]Department of Electrical Engineering, University of Conakry, Conakry, Guinea
[2]Department of Computer Science, University of Conakry, Conakry, Guinea
[3]Department of Civil Engineering, University of Conakry, Conakry, Guinea

Abstract:
Traditional local active noise control (ANC) systems aim to minimize the measured acoustic pressure in order to create a zone of quiet at the physical error sensor location. However, the effectiveness of these systems is often limited by the relatively small size of the quiet zone, which requires the physical error sensor to be placed precisely at the location where noise reduction is desired. This positioning can be inconvenient and impractical in many applications, particularly when the sensor cannot be placed directly in the desired zone of attenuation. To address these limitations, virtual sensing algorithms have been developed as an innovative solution for active noise control. Virtual sensing algorithms leverage the physical error signal, the control signal, and the system's knowledge to estimate the error signal at a remote location, referred to as the virtual location. Rather than focusing on minimizing the error at the physical sensor location, the system is designed to minimize the estimated error at the virtual location, thus generating a more effective and flexible zone of quiet at the target location, even if it is not directly accessible for sensor placement. This paper provides a comprehensive review of various virtual sensing algorithms that have been proposed for active noise control. The performance of these algorithms is evaluated through both numerical simulations and real-world experimental results. In addition to comparing the effectiveness of these algorithms, the challenges and opportunities associated with their implementation in practical ANC systems are also discussed, highlighting the potential benefits and limitations of virtual sensing in achieving broader and more dynamic noise attenuation zones.

Keywords: Virtual sensing; Active noise control; Active headrest; Acoustic noise reduction; Error signal estimation; Zone of quiet; Noise attenuation; Remote sensor; Control signal; Noise cancellation; ANC algorithms; Sensor placement optimization; Acoustic feedback; Virtual location; Noise control systems1.

1. Introduction

Local active noise control systems aim to create a localised zone of quiet at the physical error sensor (typically a microphone) by minimising the acoustic pressure at the physical error sensor location with secondary sound sources (typically loudspeakers). While significant attenuation may be achieved at the physical sensor location, the zone of quiet tends to be very small. 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. Elliott et al. [**1**] investigated the spatial extent of the zone of quiet when controlling pressure with a remote secondary source in a pure-tone diffuse sound field. The zone of quiet generated at the microphone was found to be defined by a *sinc* function, with the primary sound pressure level reduced by 10 dB over a sphere of diameter one tenth of the excitation wavelength, $\lambda/10\lambda/10$. The zone of quiet generated at the sensor location may be enlarged by minimising the acoustic energy density instead of the acoustic pressure. As the control of acoustic pressure and pressure gradient at a point is equivalent to minimising the acoustic energy density at that point [**2**], Elliott and Garcia-Bonito [**3**] investigated the control of both pressure and pressure gradient in a diffuse sound field with two secondary sources. Minimising both the pressure and pressure gradient along a single axis produced a 10 dB zone of quiet over a distance of $\lambda/2\lambda/2$, in the direction of pressure gradient measurement. This is considerably larger than the zone of quiet obtained by minimising pressure alone. As the zone of quiet generated at the physical error sensor is limited in size for active noise control, virtual acoustic sensors were developed to shift 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 shifted from the physical sensor to a virtual sensor located at the observer's ear. Using the physical error signal, a virtual sensing algorithm is used to estimate the pressure at a fixed virtual location. Instead of minimising the physical error signal, the estimated pressure is minimised with the active noise control system to generate a zone of quiet at the virtual location. A number of virtual sensing algorithms have been developed to estimate the pressure at a fixed virtual location including *the virtual microphone arrangement* [**4**], *the remote microphone technique* [**5**], *the forward difference* *prediction technique* [**6**], *the adaptive LMS virtual microphone technique* [**7**], *the Kalman filtering virtual sensing method* [**8**] and *the stochastically optimal tonal diffuse field virtual sensing technique* [**9**].

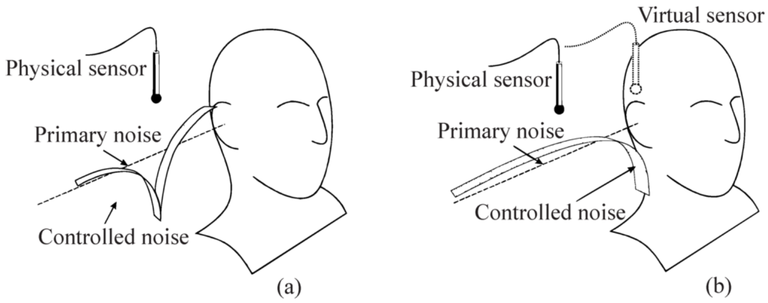


Figure 1. Comparison of local active noise control (a) at a physical sensor; and (b) at a virtual sensor.

It is, however, likely that the desired location of attenuation is not spatially fixed. This occurs, for example, when the desired location of attenuation is the ear of a seated observer and the observer moves their head, thereby moving the virtual location. As a result, a number of moving virtual sensing algorithms have been developed to generate a virtual microphone capable of tracking a moving virtual location including *the remote moving microphone technique* [**10**], *the adaptive LMS moving virtual microphone technique* [**11**] and *the Kalman filtering moving virtual sensing method* [**12**].

This paper will review the spatially fixed and moving virtual sensing algorithms developed for active noise control. Additionally, the performance of these virtual sensing algorithms in numerical simulations and in experiments is discussed and compared. Finally, it should be noted that the performance of the virtual sensing algorithms is generally assessed indirectly through the performance of the active noise control system in achieving control at the virtual location. Key references are provided for those who wish to obtain further details on any of the virtual sensing algorithms. As the focus of this paper is on the spatially fixed and moving virtual sensing algorithms, details of active noise control algorithms that can be used to control the sound field and generate zones of quiet at the virtual locations are not given. Details of active noise control algorithms, such as the filtered-x LMS algorithm, may be found in Kuo and Morgan [**13**], Elliott [**14**] and Nelson and Elliott [**2**].

2. Spatially Fixed Virtual Sensing Algorithms

Spatially fixed virtual sensing algorithms are used to obtain estimates of the error signals at a number of spatially fixed virtual locations using the error signals from the remotely located physical error sensors, the control signal and knowledge of the system. These virtual sensing algorithms are then combined with an active noise control algorithm to generate zones of quiet at the fixed virtual locations. A number of spatially fixed virtual sensing algorithms have been developed in the past including *the virtual microphone arrangement* [**4**], *the remote microphone technique* [**5**], *the forward difference prediction technique* [**6**], *the adaptive LMS virtual microphone technique* [**7**], *the Kalman filtering virtual sensing method* [**8**] and *the stochastically optimal tonal diffuse field virtual sensing technique* [**9**]. A discussion of these algorithms is provided as follows.

2.1. The virtual sensing problem

The virtual sensing problem and notation used throughout this paper are introduced in this section. It is assumed here that there are MpMp physical microphones, MvMv spatially fixed virtual microphones and L secondary sources. The vector of the total pressures at the MpMp physical microphones, $\mathbf{e}p(n)$ep(n), is defined as

$\mathbf{e}p(n)=[ep1(n)ep2(n)...epMp(n)]$T.ep(n)=ep1(n)ep2(n)...epMp(n)T. (1)

The total pressures at the MpMp physical microphones, $\mathbf{e}p(n)$ep(n), is the sum of the sound fields produced by the primary and secondary sound sources at the physical microphone locations, and may be written as

$\mathbf{e}p(n)=\mathbf{d}p(n)+\mathbf{y}p(n)=\mathbf{d}p(n)+\mathbf{G}pu\mathbf{u}(n)$,ep(n)=dp(n)+yp(n)=dp(n)+Gpuu(n), (2)

where $\mathbf{d}p(n)$dp(n) is a vector of the primary pressures at the MpMp physical microphones, $\mathbf{y}p(n)$yp(n) is a vector of the secondary pressures at the MpMp physical microphones, $\mathbf{G}pu$Gpu is a matrix of size $Mp\times L$Mp×L whose elements are the transfer functions between the secondary sources and the physical microphones, $\mathbf{u}(n)$u(n) is a vector of the secondary source strengths and n is the time step.

Similarly, the vector of the total pressures at the M_vMv spatially fixed virtual locations, $\mathbf{e}_v(n)$ev(n), is defined as

$\mathbf{e}_v(n)=[e_{v1}(n)\, e_{v2}(n) \ldots e_{pM_v}(n)]^T$.ev(n)=ev1(n)ev2(n)...epMv(n)T (3)

The total pressures at the M_vMv virtual microphones, $\mathbf{e}_v(n)$ev(n), is the sum of the sound fields produced by the primary and secondary sources at the M_vMv virtual locations and may be written as

$\mathbf{e}_v(n)=\mathbf{d}_v(n)+\mathbf{y}_v(n)=\mathbf{d}_v(n)+\mathbf{G}_{vu}\mathbf{u}(n)$,ev(n)=dv(n)+yv(n)=dv(n)+Gvuu(n) (4)

where $\mathbf{d}_v(n)$dv(n) is the vector of the primary pressures at the M_vMv virtual locations, $\mathbf{y}_v(n)$yv(n) is the vector of secondary pressures at the M_vMv virtual locations and $\mathbf{G}_{vu}$Gvu is a matrix of size $M_v \times L$Mv×L whose elements are the transfer functions between the secondary sources and the virtual locations.

Using the physical error signals, $\mathbf{e}_p(n)$ep(n), a virtual sensing algorithm is used to estimate the pressures, $\mathbf{e}_v(n)$ev(n), at the spatially fixed virtual locations. Instead of minimising the physical error signals, the estimated pressures are minimised with the active noise control system to generate zones of quiet at the virtual locations.

2.2. The virtual microphone arrangement

The virtual microphone arrangement, proposed by Elliott and David [**4**], was the first virtual sensing algorithm suggested for active noise control. This virtual sensing algorithm uses the assumption of equal primary sound pressure at the physical and virtual microphone locations. Virtual sensing algorithms similar to the virtual microphone arrangement have also been proposed by Kuo et al. [**15**] and Pawelczyk [**16**,**17**]. A block diagram of the virtual microphone arrangement is shown in **Fig. 2**. The virtual microphone arrangement is most easily implemented with equal numbers of physical and virtual sensors, so $M_v=M_p$Mv=Mp [**12**]. The microphones are located in M_vMv pairs, each consisting of one physical microphone and one virtual microphone. In this virtual sensing algorithm the primary sound pressure is assumed to be equal at the physical and virtual microphones in each pair, i.e. that $\mathbf{d}_v(n)=\mathbf{d}_p(n)$dv(n)=dp(n). This assumption holds if the primary sound field does not change significantly between the physical and virtual microphones in each pair.

A preliminary identification stage is required in this virtual sensing algorithm in which the matrices of transfer functions, $\tilde{\mathbf{G}}_{pu}$G˜pu and $\tilde{\mathbf{G}}_{vu}$G˜vu, are modelled as matrices of FIR or IIR filters. Once this preliminary identification stage is complete, the microphones temporarily placed at the virtual locations are removed. As shown in **Fig. 2**, estimates, $\tilde{\mathbf{e}}_v(n)$e˜v(n), of the total error signals at the virtual locations are calculated using

$\tilde{\mathbf{e}}_v(n)=\mathbf{e}_p(n)-(\tilde{\mathbf{G}}_{pu}-\tilde{\mathbf{G}}_{vu})\mathbf{u}(n)$.e˜v(n)=ep(n)-(G˜pu-G˜vu)u(n). (5)

The performance of the virtual microphone arrangement has been thoroughly investigated in both tonal and broadband sound fields by a number of authors [**16**,**17**,**18**,**19**,**20**,**21**,**22**,**23**,**24**,**25**,**26**,**27**,**28**,**29**,**30**,**31**,**32**]. Theoretical analysis in a pure tone diffuse sound field demonstrated that at low frequencies, the zone of quiet generated at a virtual microphone with the virtual microphone arrangement is comparable to that achieved by directly minimising the measured pressure of a physical microphone at the virtual location [**18**,**19**]. At higher frequencies however, those above 500 Hz, the 10 dB zone of quiet is substantially smaller when using a virtual microphone compared to a physical microphone at the same location. This is due to the assumption of equal primary pressure at the physical and virtual microphone locations being less valid as the wavelength decreases [**18**,**19**].

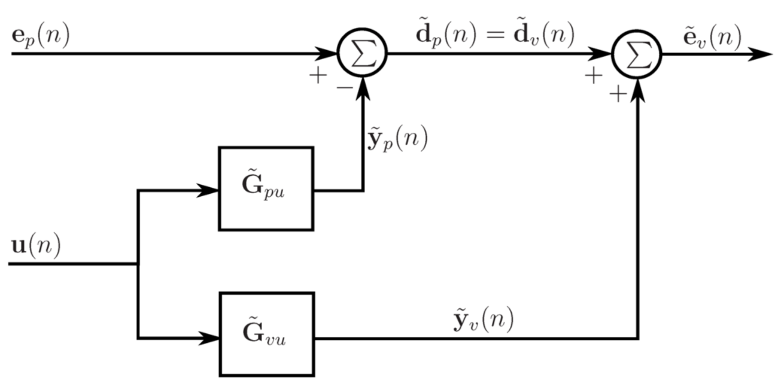
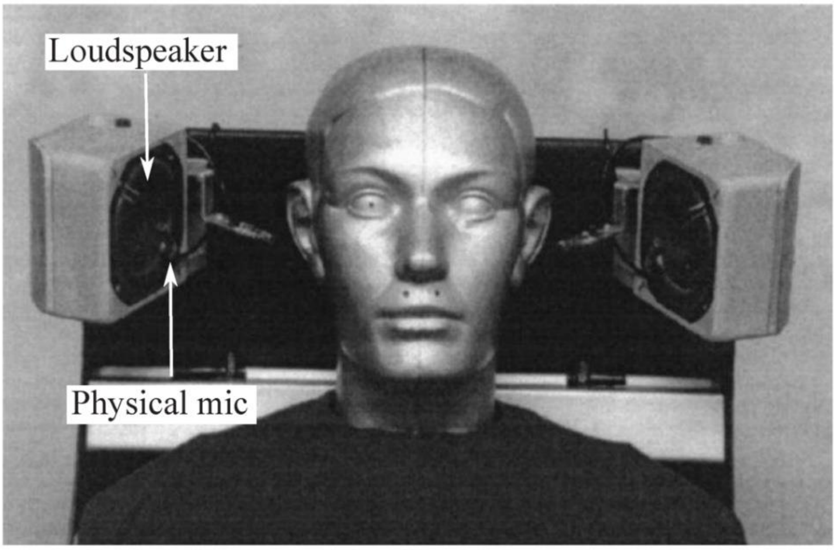


Figure 2. Block diagram of the virtual microphone arrangement.

The performance of a local active headrest system implementing the virtual microphone arrangement has been experimentally investigated by a number of authors [**18**,**19**,**22**,**23**,**25**,**27**,**32**]. An example of a local active headrest system is shown in **Fig. 3**. Garcia-Bonito et al. [**18**,**19**] investigated the performance of a local active headrest system in minimising a tonal primary disturbance at virtual microphones located 2 cm from the ears of a manikin and 10 cm from the physical microphones. Below 500 Hz, the 10 dB zone of quiet generated at the virtual microphone extends approximately 8 cm forward and 10 cm side to side. At higher frequencies however, the assumption relating to the similarity of the primary field at the physical and virtual microphones is no longer valid and limited attenuation is achieved at the virtual location.



The performance of a local active headrest system in attenuating a broadband disturbance with a 100 - 400 Hz frequency range was investigated by Rafaely et al. [**22**,**23**] using feedback control. An overall attenuation of 9.5 dB was obtained at a virtual microphone located at the ear of a manikin with the virtual microphone arrangement. This is compared to 19 dB being obtained at the physical microphone by directly minimising the measured pressure signal. Differences in the attenuation achieved by minimising the physical and virtual microphone signals were partly attributed to the physical microphone being significantly closer to the secondary loudspeaker than the virtual microphone. This results in a longer delay in the virtual plant, which has a negative effect on the performance of the feedback control system.

As the performance of the active headrest will be affected by the presence of the passenger's head, Garcia-Bonito and Elliott [**20**] and Garcia-Bonito et al. [**19**,**21**] theoretically investigated the performance of the virtual microphone in generating a zone of quiet near the surface of a reflecting sphere. The presence of the reflecting sphere was seen to increase the size of the zone of quiet when using the virtual microphone arrangement, especially at high frequencies. This is due to the imposed zero pressure gradient on the reflecting surfaces.

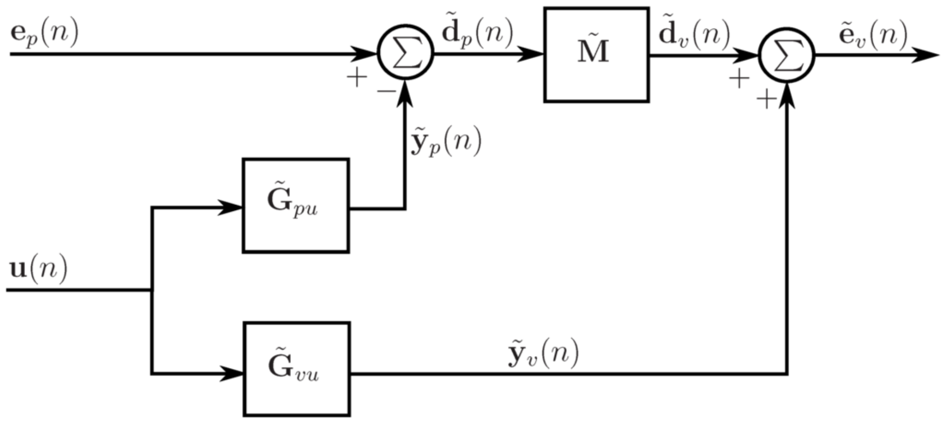
2.3. The remote microphone technique

The remote microphone technique developed by Roure and Albarrazin [**5**] is an extension to the virtual microphone arrangement [**4**] which uses an additional matrix of filters to compute estimates of the primary disturbances at the virtual sensors from the primary disturbances at the physical sensors. An active acoustic attenuation system designed to attenuate noise at a location that is remote from the physical error sensor using the remote microphone technique was independently patented by Popovich [**33**]. Versions of the remote microphone technique have also been suggested by Hashimoto et al. [**34**], Friot et al. [**35**] and Yuan [**36**].

Like the virtual microphone arrangement, the remote microphone technique requires a preliminary identification stage in which the secondary transfer matrices $\tilde{\mathbf{G}}_{pu}$ and $\tilde{\mathbf{G}}_{vu}$ are modelled as matrices of FIR or IIR filters. The $M_v \times M_p$ sized matrix of primary transfer functions between the virtual locations and the physical locations, $\tilde{\mathbf{M}}$, is also estimated as a matrix of FIR or IIR filters during this preliminary identification stage. The secondary transfer function matrix $\tilde{\mathbf{G}}_{pu}$ is identified using the secondary sources and the physical microphones while microphones temporarily placed at the virtual locations are used to obtain matrices $\tilde{\mathbf{G}}_{vu}$ and $\tilde{\mathbf{M}}$.

A block diagram of the remote microphone technique is given in **Fig. 4**. As shown in **Fig. 4**, estimates of the primary disturbances, **d**˜$p(n)$d˜p(n), at the physical error sensors are first calculated using

Radcliffe and Gogate [**37**] demonstrated that theoretically, a perfect estimate of the tonal disturbance at the virtual location can be achieved with this virtual sensing algorithm provided accurate models of the tonal transfer functions are obtained in the preliminary identification stage. Using a three-dimensional finite element model of a car cabin, the tonal control achieved at a number of virtual microphones generated with the remote microphone technique was equivalent to that achieved by directly minimising the measured signals at the virtual locations.



Roure and Albarrazin [**5**] experimentally investigated the performance of the remote microphone technique in a room simulating an aircraft cabin with periodic noise at 170 Hz. Using twelve virtual microphones, six physical microphones and nine secondary sources, the remote microphone technique achieved an average attenuation of 20 dB at the twelve virtual locations with a feedforward control approach. However, 27 dB of attenuation was obtained by directly minimising the measured pressure at the virtual locations. This disparity was attributed to the sensitivity of the remote microphone technique to errors in the measured transfer functions. The performance of the remote microphone technique has also been investigated in the control of broadband noise in an acoustic enclosure [**34**], road traffic noise [**38**] and broadband acoustic duct noise [**36**].

The performance of the remote microphone technique has been experimentally compared to that of the virtual microphone arrangement in a broadband primary sound field with 50 - 300 Hz frequency range [**39**]. Using a feedforward control approach, the two virtual sensing algorithms were used to generate a zone of quiet at a virtual location inside a three-dimensional enclosure using a physical microphone located on the enclosure wall 25 cm from the virtual location. The results demonstrated that greater attenuation is achieved at the virtual location with the remote microphone technique. The inferior performance of the virtual microphone arrangement was again attributed to the invalid assumption of equal primary sound pressure at the physical and virtual microphone locations.

2.4. The forward difference prediction technique

The forward difference prediction technique, as proposed by Cazzolato [**6**], fits a polynomial to the signals from a number of physical microphones in an array. The pressure at the virtual location is estimated by extrapolating this polynomial to the virtual location. This virtual sensing algorithm is suitable for use in low frequency sound fields, when the virtual distance and the spacing between the physical microphones is much less than a wavelength. At low frequencies, the spatial rate of change of the sound pressure between the microphones is small and extrapolation can therefore be applied [**6**].

Fig. 5 (a) shows the pressure at a virtual location, *x*, estimated by a first-order finite difference estimate. Using Mp=2Mp=2 physical microphones, separated by a distance of 2h2h, the equation for the estimate of the pressure at the virtual location using two microphone linear forward difference extrapolation is given by [**6**]

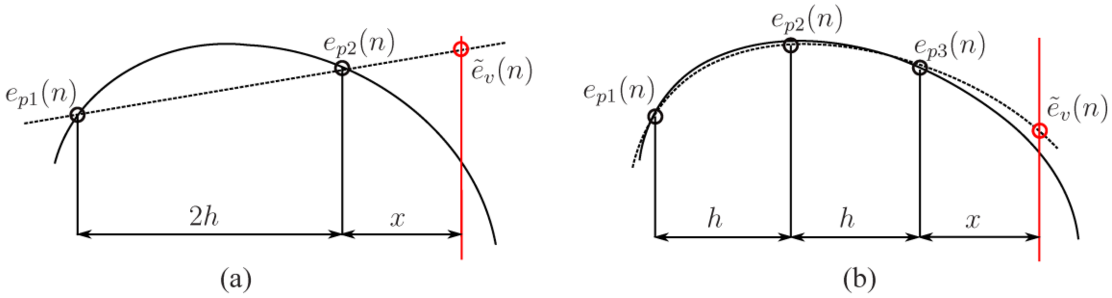


Figure 5. Diagram of (a) two microphone linear forward difference extrapolation; and (b) three microphone quadratic forward difference extrapolation. The black curved line represents the actual pressure field and the dashed line represents the pressure estimate.

The forward difference prediction technique has several advantages over other virtual sensing algorithms. Firstly, the assumption of equal primary sound pressure at the physical and virtual locations does not have to be made, but also preliminary identification is not required, nor are FIR filters or similar to model the complex transfer functions between the sensors and the sources. Furthermore, this is a fixed gain prediction technique that is robust to physical system changes that may alter the complex transfer functions between the error sensors and the control sources.

The performance of forward difference prediction virtual sensors has been evaluated in a long narrow duct and in a free field, both numerically and experimentally, by a number of authors [**40**,**41**,**42**,**43**,**44**,**45**,**46**,**47**]. Using either linear or quadratic prediction techniques, these virtual sensors outperform the physical microphones in terms of the level of attenuation achieved at the virtual location. While the second-order estimate is theoretically more accurate than the first-order estimate, real-time feedforward experiments in a narrow duct demonstrated that quadratic prediction techniques are adversely affected by short wavelength extraneous noise. It was also shown by Petersen [**12**], that the estimation problem is ill-conditioned for the three sensor arrangement, explaining the difference between numerical and experimental results.

In an attempt to improve the prediction accuracy of the forward difference algorithm, higher-order forward difference prediction virtual sensors which act to spatially filter out the extraneous noise were developed [**45**,**48**]. Additional physical microphones were added to the array resulting in a greater number of microphones than system order. The microphone weights for this over constrained system were then calculated using a least squares approximation.

4. Conclusion

This paper has reviewed virtual sensing algorithms for active noise control. A summary of the spatially fixed and moving virtual sensing algorithms, including their characteristics, advantages and disadvantages, is given in **Table 1**.

Spatially fixed virtual sensing algorithms estimate the error signal at a spatially fixed location that is remote from the physical error sensor. The virtual microphone arrangement [**4**] projects the zone of quiet away from the physical microphone 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 often invalid 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. The remote microphone technique [**5**] 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. In theory, a perfect estimate of the tonal sound pressure may be achieved at the virtual location with the remote microphone technique provided accurate models of the tonal transfer functions are obtained in the preliminary identification stage.

The forward difference prediction technique [**6**] is a fixed gain virtual sensing algorithm that fits a polynomial to the signals from a number of physical microphones in an array. The pressure at the virtual location is estimated by extrapolating this polynomial to the virtual location. This virtual sensing method does not require a preliminary identification stage, nor are FIR filters or similar to model the complex transfer functions between the sensors and the sources. The forward difference prediction virtual sensors are, however, sensitive to phase and sensitivity mismatches and relative position errors between the physical microphones in the array.

The adaptive LMS virtual microphone technique [**7**] 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. The adaptive LMS virtual microphone technique can compensate for relative position errors and sensitivity mismatches adversely affecting the forward difference prediction technique.

The Kalman filtering virtual sensing method [**8**] 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. The Kalman filtering virtual sensing method does not require a number of FIR or IIR filter matrices to compute an estimate of the virtual error signals, instead a compact state space model is used. Also, this virtual sensing algorithm is derived with measurement noise included on the sensors.

The stochastically optimal tonal diffuse field virtual sensing method generates stochastically optimal virtual microphones and virtual energy density sensors specifically for use in pure tone diffuse sound fields [**9**,**55**]. Although a perfect estimate of the pressure at the virtual location may be obtained with the remote microphone technique [**5**], the stochastically optimal tonal diffuse field virtual sensing technique is much simpler to implement being a fixed scalar weighting method requiring only sensor position information. This virtual sensing method is independent of the source or sensor locations within the sound field and can compensate for changes in the sound field that may alter the transfer functions between the sensors and the sources.

Moving virtual sensing algorithms generate a virtual microphone capable of tracking a virtual location that is moving through the sound field. Three moving virtual sensing algorithms have been developed; the remote moving virtual microphone technique [**10**], the adaptive LMS moving virtual microphone technique [**11**] and the Kalman filtering moving virtual sensing method [**12**]. When combined with an active noise control algorithm, these three moving virtual sensing algorithms were shown to achieve greater attenuation at the moving virtual location than control at a fixed physical or virtual sensor.

References and Notes

1. Elliott, S.; Joseph, P.; Bullmore, A.; Nelson, P. Active cancellation at a point in a pure tone diffuse sound field. *Journal of Sound and Vibration* **1988**, *120(1)*, 183–189
2. Nelson, P.; Elliott, S. *Active Control of Sound*, 1st edition; Academic Press: London, 1992.
3. Elliott, S.; Garcia-Bonito, J. Active cancellation of pressure and pressure gradient in a diffuse sound field. *Journal of Sound and Vibration* **1995**, *186(4)*, 696–704.
4. Elliott, S.; David, A. A virtual microphone arrangement for local active sound control. In Proceedings of the 1st International Conference on Motion and Vibration Control, Yokohama, 1992; pp. 1027–1031.
5. Roure, A.; Albarrazin, A. The remote microphone technique for active noise control. *Proceedings of Active 99* **1999**, 1233–1244.
6. Cazzolato, B. Sensing systems for active control of sound transmission into cavities. PhD thesis, School of Mechanical Engineering, The University of Adelaide, SA, 5005, 1999.
7. Cazzolato, B. An adaptive LMS virtual microphone. In Proceedings of Active 02, Southampton, UK, 2002; pp. 105–116.
8. Petersen, C.; Fraanje, R.; Cazzolato, B.; Zander, A.; Hansen, C. A Kalman filter approach to virtual sensing for active noise control. *Mechanical Systems and Signal Processing* **2008**, *22(2)*, 490–508
9. Moreau, D.; Ghan, J.; Cazzolato, B.; Zander, A. Active noise control with a virtual acoustic sensor in a pure-tone diffuse sound field. In Proceedings of the 14th International Congress on Sound and Vibration, Cairns, Australia, 2007.
10. Petersen, C.; Cazzolato, B.; Zander, A.; Hansen, C. Active noise control at a moving location using virtual sensing. In Proceedings of the 13th International Congress on Sound and Vibration, Vienna, 2006.
11. Petersen, C.; Zander, A.; Cazzolato, B.; Hansen, C. A moving zone of quiet for narrowband noise in a one-dimensional duct using virtual sensing. *Journal of the Acoustical Society of America* **2007**, *121(3)*, 1459–1470.

12. Petersen, C. Optimal spatially fixed and moving virtual sensing algorithms for local active noise control. PhD thesis, School of Mechanical Engineering, The University of Adelaide, SA, 5005, 2007

13. Kuo, S.; Morgan, D. *Active Noise Control Systems, Algorithms and DSP Implementation*; John Wiley and Sons Inc: New York, 1996

14. Elliott, S. *Signal Processing for Active Control*; Academic Press: London, 2001.

15. Kuo, S.; Gan, W.; Kalluri, S. Virtual sensor algorithms for active noise control systems. In Proceedings of the 2003 International Symposium on Intelligent Signal Processing and Communication Systems (ISPACS 2003), Awaji Island, Japan, 2003; pp. 714–719.

16. Pawelczyk, M. Adaptive noise control algorithms for active headrest system. *Control Engineering Practice* **2004**, *12(9)*, 1101–1112.

17. Pawelczyk, M. Design and analysis of a virtual-microphone active noise control system. In Proceedings of the 12th International Congress on Sound and Vibration, Lisbon, Portugal, 2005; pp. 1–8.

18. Garcia-Bonito, J.; Elliott, S.; Boucher, C. A virtual microphone arrangement in a practical active headrest. *Proceedings of Inter-noise 96* **1996**, 1115–1120]

19. Garcia-Bonito, J.; Elliott, S.; Boucher, C. Generation of zones of quiet using a virtual microphone arrangement. *Journal of the Acoustical Society of America* **1997**, *101(6)*, 3498–3516.

20. Garcia-Bonito, J.; Elliott, S. Strategies for local active control in diffuse sound fields. In Proceedings of Active 95, Newport Beach, CA, USA, 1995; pp. 561–572.

21. Garcia-Bonito, J.; Elliott, S.; Boucher, C. A novel secondary source for a local active noise control system. In Proceedings of Active 97, Budapest, Hungary, 1997; pp. 405–418.

22. Rafaely, B.; Garcia-Bonito, J.; Elliott, S. Feedback control of sound in headrest. In Proceedings of Active 97, Budapest, 1997; pp. 445–456.

23. Rafaely, B.; Elliott, S.; Garcia-Bonito, J. Broadband performance of an active headrest. *Journal of the Acoustical Society of America* **1999**, *106(2)*, 787–793. [

24. Horihata, S.; Matsuoka, S.; Kitagawa, H.; Ishimitsu, S. Active noise control by means of virtual error microphone system. In Proceedings of Inter-Noise 97, Budapest, 1997; pp. 529–532.

25. Pawelczyk, M. Noise control in the active headrest based on estimated residual signals at virtual microphones. In Proceedings of the 10th International Congress on Sound and Vibration, Stockholm, Sweeden, 2003; pp. 251–258.

26. Pawelczyk, M. A double input-quadruple output adaptive controller for the active headrest system. In Proceedings of the Active Noise and Vibration Control Methods Conference, Cracow, Poland, 2003.

27. Pawelczyk, M. Multiple input-multiple output adaptive feedback control strategies for the active headrest system: design and real-time implementation. *International Journal of Adaptive Control and Signal Processing* **2003**, *17(10)*, 785–800.

28. Pawelczyk, M. Active noise control in a phone. In Proceedings of the 11th International Congress on Sound and Vibration, St Petersburg, Russia, 2004; pp. 523–530.

29. Pawelczyk, M. Polynomial approach to design of feedback virtual-microphone active noise control system. In Proceedings of the 13th International Congress on Sound and Vibration, Vienna, Austria, 2006.

30. Diaz, J.; Egana, J.; Vinolas, J. A local active noise control system based on a virtual-microphone technique for railway sleeping vehicle applications. *Mechanical Systems and Signal Processing* **2006**, *20*, 2259–2276.

31. Matuoka, S.; Kitagawa, H.; Horihata, S.; Ishimitu, S.; Tamura, F. Active noise control using a virtual error microphone system. *Transactions of the Japan Society of Mechanical Engineers* **1996**, *62(601)*, 3459–3464.

32. Holmberg, U.; Ramner, N.; Slovak, R. Low complexity robust control of a headrest system based on virtual microphones and the internal model principle. In Proceedings of Active 02, ISVR, Southampton, UK, 2002; pp. 1243–1250.

33. Popovich, S. Active acoustic control in remote regions. US Patent No 5,701,350, 1997

34. Hashimoto, H.; Terai, K.; Kiba, M.; Nakama, Y. Active noise control for seat audio system. In Proceedings of Active 95, Newport Beach, CA, USA, 1995; pp. 1279–1290.

35. Friot, E.; Roure, A.; Winninger, M. A simplified remote microphone technique for active noise control at virtual error sensors. In Proceedings of Inter-Noise 01, The Hague, The Netherlands, 2001.

36. Yuan, J. Virtual sensing for broadband noise control in a lightly damped enclosure. *Journal of the Acoustical Society of America* **2004**, *116(2)*, 934–941.

37. Radcliffe, C.; Gogate, S. A model based feedforward noise control algorithm for vehicle interiors. *Advanced Automotive Technologies ASME 52(DSC)* **1993**, 299–304.

38. Berkhoff, A. Control strategies for active noise barriers using near-field error sensing. *Journal of the Acoustical Society of America* **2005**, *118(3)*, 1469–1479

39. Renault, S.; Rymeyko, F.; Berry, A. Active noise control in enclosure with virtual microphone. *Canadian Acoustics* **2000**, *28(3)*, 72–73

40. Kestell, C. Active control of sound in a small single engine aircraft cabin with virtual error sensors. PhD thesis, School of Mechanical Engineering, The University of Adelaide, SA, 5005, 2000]

41. Kestell, C.; Hansen, C.; Cazzolato, B. Virtual sensors in active noise control. *Acoustics Australia* **2001**, *29(2)*, 57–61

42. Kestell, C.; Hansen, C.; Cazzolato, B. Active noise control in a free field with virtual error sensors. *Journal of the Acoustical Society of America* **2001**, *109(1)*, 232–243.

43. Kestell, C.; Hansen, C.; Cazzolato, B. Active noise control with virtual sensors in a long narrow duct. *International Journal of Acoustics and Vibration* **2000**, *5(2)*, 1–14.

44. Munn, J.; Cazzolato, B.; Kestell, C.; Hansen, C. Virtual error sensing for active noise control in a one-dimensional waveguide: Performance prediction versus measurement (l). *Journal of the Acoustical Society of America* **2003**, *113(1)*, 35–38.

45. Munn, J. Virtual sensors for active noise control. PhD thesis, Department of Mechanical Engineering, The University of Adelaide, SA, 5005, 2004.

46. Munn, J.; Kestell, C.; Cazzolato, B.; Hansen, C. Real-time feedforward active control using virtual sensors in a long narrow duct. In Proceedings of Acoustics 2001: Noise and Vibration Policy the Way Forward, Canberra, Australia, 2001.

47. Munn, J.; Kestell, C.; Cazzolato, B.; Hansen, C. Real-time feedforward active noise control using virtual error sensors. In Proceedings of the 2001 International Congress and Exhibition on Noise Control Engineering, The Hague, The Netherlands, 2001.

48. Munn, J.; Cazzolato, B.; Hansen, C.; Kestell, C. Higher order virtual sensing for remote active noise control. In Proceedings of Active 02, Southampton, UK, 2002.

49. Cazzolato, B.; Petersen, C.; Howard, C.; Zander, A. Active control of energy density in a 1D waveguide: A cautionary note. *Journal of the Acoustical Society of America* **2005**, *117(6)*, 3377–3380

50. Gawron, H.; Schaaf, K. Interior car noise: Active cancellation of harmonics using virtual microphones. In Proceedings of the 2nd International Conference on Vehicle Comfort: Ergonomic, Vibrational and Thermal Aspects, Bologna, Italy, 1992; pp. 739–748.

51. Munn, J.; Cazzolato, B.; Hansen, C. Virtual sensing: Open loop vs adaptive LMS. *Proceedings of the Annual Australian Acoustical Society Conference (2002)* **2002**, 24–33

52. Munn, J.; Cazzolato, B.; Hansen, C. Virtual sensing using an adaptive LMS algorithm. In Proceedings of Wespac VIII, Melbourne, Australia, 2003.
53. Skogestad, S.; Postlethwaite, I. *Multivariable feedback control: analysis and design*; John Wiley: Hoboken, NJ, 2005.
54. Haverkamp, L. State Space Identification: Theory and Practice. PhD thesis, System and Control Engineering Group, Delft University of Technology, 2001