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Quiet Zone for the patient in an Ambulance: Active Noise Control Technology for Siren Noise Reduction

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This paper proposes an active noise control (ANC) application to attenuate siren noise for the patient lying inside ambulance with no sound proofing. From the point of cost effectiveness, a local ANC system based on feedforward scheme is considered. Further, to handle the limitation of limited Zone of Silence (ZoS), the ANC based on virtual sensing is explored. The simulations are done in MATLAB for the recorded ambulance siren noise signal. The results indicate that ANC can be an effective solution for creating a silent environment for the patient.

Keywords: active noise control; virtual sensing technique; ambulance siren noise; zone of silence; feedforward ANC; virtual ANC.

1. Introduction

Ambulance is a medically equipped vehicle to shift patients to the hospital when their health condition demands immediate attention. To reach the hospital at the earliest, ambulances have loud siren to alert other vehicles to make way for their movement. Generally, it is expected that an ambulance must be well equipped and has good acoustic insulation for patient being shifted to the hospital. However, in most of the developing countries where there is dearth of health infrastructure, an ambulance means a van with an oxygen cylinder and lying facility for the patient. In such an ambulance, there is no provision of acoustic insulation and no separation between patient's cabin and driver's seat. Hence, the patient is directly exposed to the ambulance siren noise of more than 90 dB (Sharma, Vig, 2014). This noise brings in distress and anxiety for the ailing patient (especially when ambulance is stuck in traffic jam) which may further worsen his/her health condition (Weber *et al.*, 2009) and hence calls for mitigation.

Providing good acoustic insulation inside an ambulance using passive techniques is unaffordable hence there is a necessity to resort to alternate means. Active Noise Control (ANC) system can be a possible solution, provided the ambulance siren frequency is in low frequency range (Howard *et al.*, 2011). Some sample siren noise analyses have revealed that most of them have a distinct peak around 1 kHz and hence ANC can become a possible solution. However, for achieving global reduction many loudspeakers and microphones along with high speed processor are required which is not viable in terms of cost and infrastructure requirement. Therefore, local ANC system which achieves Zone of Silence (ZoS) around the area of interest is a feasible approach.

The ZoS achievable is inversely proportional to the frequency of the noise or in other words it is directly proportional to the wavelength, λ of the noise signal. In fact, it is quantified to be a sphere with $\lambda/10$ as its radius (Snyder, 2000). The ears of the listener have to fall in this zone to perceive the noise reduction. As mentioned earlier, the siren noise frequency is about

1 kHz and this results in a ZoS of about 2.5 cm radius. Thus, the noise reduction can be achieved with ANC embedded headset. However, use of headset is not feasible in some cases such as head injury, neck injury, etc. In such a scenario, virtual ANC is an apt solution wherein the ZoS is shifted from microphone location to the location of interest (Liu *et al.*, 2009), i.e. ears of the patient. This is achieved by considering the transfer function between the actual sensor position and the desired location.

1.1. Paper outline

The feedforward active noise control (ANC) system is elaborated in Sec. 2. In Sec. 3 virtual sensing technique is explained. The ANC with virtual sensing technique is explained in Sec. 4. The simulations are done and results are discussed in Sec. 5. The conclusion is presented in Sec. 6.

2. Feedforward ANC System

In feedforward ANC system, the reference noise signal is measured using reference sensor and is used for weight updation in adaptive filter. Figure 1 shows the feedforward ANC system using the FxLMS algorithm. The reference microphone picks the reference signal $x(n)$ which is processed through adaptive filter $W(z)$ to generate the cancelling signal $y(n)$ driven by a secondary loudspeaker (Kuo, Morgan, 1999, cited by Sharma, Vig, 2014). The residual signal is sensed by the error microphone and is used for the weight updation (Tsuei *et al.*, 2000).

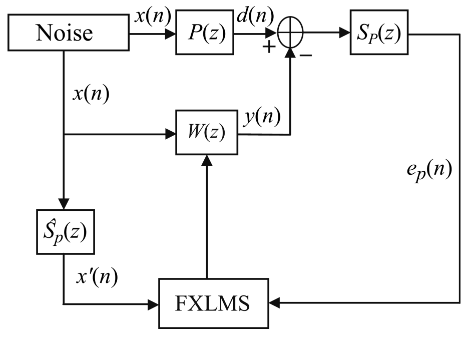


Fig. 1. Block diagram of feedforward ANC system (Kuo, Morgan, 1999).

The weights are updated using Normalized Filtered Input LMS algorithm and adaptation is as per Eq. (1)

$$w_i(n+1) = w_i(n) + \frac{\alpha}{(N+M)P_{x'}(n)} x'(n-1)e_p(n),$$

$$i = 0, 1, ..., N-1, \tag{1}$$

where $x'(n) = \widehat{S}_p(z) \cdot x(n)$, $\widehat{S}_p(z)$ is the secondary path estimation filter of length M, α is the step size, $P_{x'}(n)$ is the power of the filtered input signal computed recursively as

$$P_{x'}(n+1) = \beta P_{x'}(n) + (1-\beta)x'^2(n), \quad 0 < \beta < 1, \tag{2}$$

where β is forgetting factor.

3. Virtual Sensing Technique

Virtual sensing technique is applied to estimate the information at desired location (virtual location, say 'A') by accessing the information obtained at other (physical location, say 'B'). Therefore, information at one place ('A') can be retrieved by the information at other place ('B'). In this technique, zone of silence created at the desired location is detected without actually placing the error microphone at that location (Garcia-Bonito *et al.*, 1997; Pawelczyk, 2009; Liu *et al.*, 2009; Kestell *et al.*, 2001). In some ANC applications, it is not feasible to place an error microphone at the desired location like in case of neonatal ICU around baby's ears, around patient's ears in ambulance, etc. In such a situation virtual sensing technique is used with ANC. Virtual sensing technique is the solution to the problem in which an adequate zone of silence (ZoS) or reduction of noise is difficult to achieve at the locations where error microphone cannot be placed (Miyazaki, Kajikawa, 2015).

The schematic diagram of virtual sensing technique with ANC for a patient lying inside an ambulance is shown in Fig. 2. The physical microphone can be placed in the pillow. This technique has been implemented with ANC system in neo-natal ICU 'NICU' for pre-term babies (Veena *et al.*, 2013).

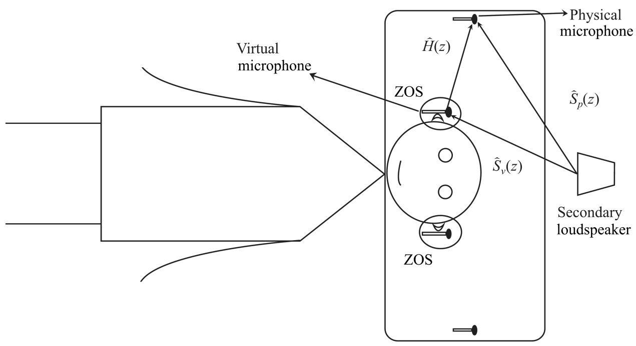


Fig. 2. Acoustic ANC system with virtual sensing technique for reducing ambulance siren noise inside ambulance system.

4. Implementation of Feedforward ANC System with Virtual Sensing Technique

Virtual sensing technique is used in the case where it is not feasible to place the error sensor at desired location. In this paper, it is proposed to use the virtual sensing technique with ANC system for patients lying inside the ambulance. Figure 3 shows the block diagram of feedforward active noise control system using virtual sensing technique, where $P(z)$ is the primary path, $W(z)$ is the control filter to generate anti-noise signal $y(n)$, and $S_p(z)$ is the secondary path transfer function between the loudspeaker and the physical microphone location.

In this technique, estimation of virtual error $\widehat{e}_v(z)$ requires estimation of $\widehat{S}_p(z)$ and $\widehat{S}_v(z)$, the path between secondary speaker and virtual microphone and $\widehat{H}(z)$, the path between physical and virtual microphone. The first two paths are estimated by passing a white noise signal through the loudspeaker, where $\widehat{H}(z)$ is estimated using the actual ambulance noise.

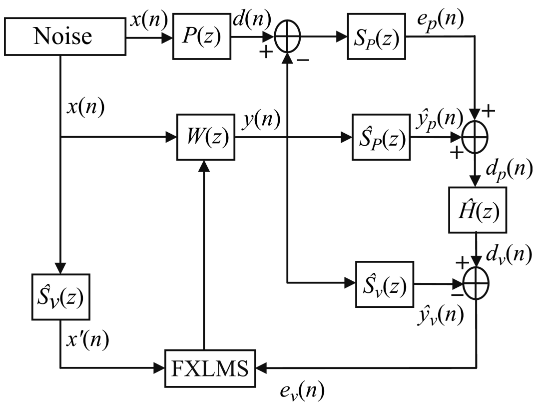


Fig. 3. Scheme of feedforward ANC system using virtual sensing technique.

Using the path information, the virtual error $e_v(n)$ is estimated as follows:

1) Estimate of the primary disturbance $d_p(n)$, at the physical microphone $\widehat{d}_p(n)$ is calculated using

$$\widehat{d}_p(n) = e_p(n) + \widehat{y}_p(n) = e_p(n) + \widehat{S}_p(z) \cdot y(n), \quad (3)$$

where, $\widehat{y}_p(n)$ is an estimate of secondary disturbance at the physical microphone, $y(n)$ is the control signal, $e_p(n)$ is the error signal picked up at the physical microphone.

2) Primary disturbance at the virtual location $\widehat{d}_v(n)$ is

$$\widehat{d}_v(n) = \widehat{H}(z) \cdot \widehat{d}_p(n). \quad (4)$$

3) Virtual error $e_v(n)$ is calculated using

$$e_v(n) = \widehat{d}_v(n) - \widehat{y}_v(n) = \widehat{d}_v(n) - \widehat{S}_v(z) \cdot y(n), \quad (5)$$

where $\widehat{y}_v(n)$ is an estimate of secondary disturbance at the virtual microphone and $\widehat{S}_v(z)$ is an estimate of the virtual secondary path. This error is used for adaptation of adaptive filter coefficients and thus, the ZoS is achieved at the virtual location.

In this approach, weights are updated using Eq. (6)

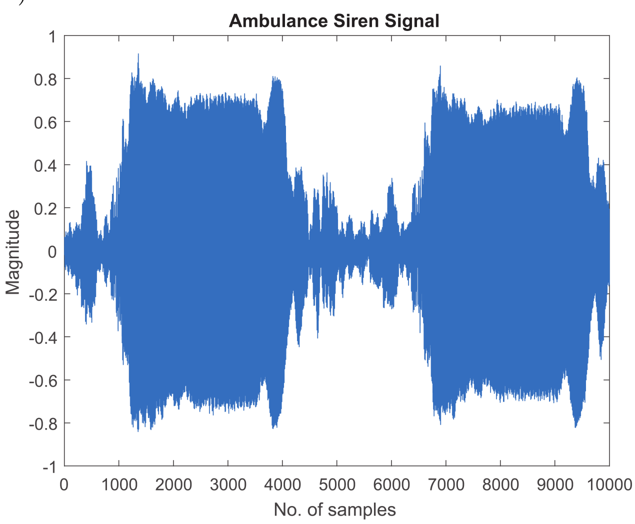
$$w_i(n+1) = w_i(n) + \frac{\alpha}{(N+M)P_{x'}(n)} \cdot x'(n-i) \cdot e_v(n). \quad (6)$$

5. Simulations

Howard *et al.* (2011) discussed different characteristics of siren. There are two main siren types: ‘wail’ and ‘yelp’ sirens. In this paper, the ambulance siren noise considered is recorded using a sound recorder from the ambulance of university health centre at 8 kHz sampling frequency. The signal obtained is ‘wail’ type siren noise which is periodic in nature. The simulations are done in MATLAB.

Figure 4 show the time plot and the corresponding STFT plot of the ambulance signal. The STFT plot indicates that the maximum signal energy is concentrated around centre frequencies at 850 Hz peak and it harmonics at 1700 Hz, 2550 Hz. This is typical of a wail type of signal which sweeps non-linearly between 800–1700 Hz with a period of 4.92 s (Sherratt, 2000, cited by Howard *et al.*, 2011). The frequencies oscillate with a bandwidth of about 800 Hz. From ANC

a)



b)

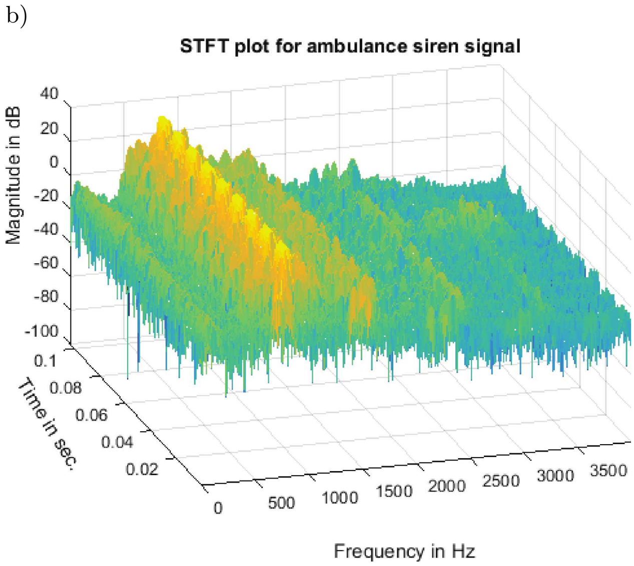


Fig. 4. a) Plot of ambulance siren noise signal and b) STFT of ambulance siren signal.

point of view, the first two peaks can be attenuated using this technique. Also, reduction in first peak results in sufficient reduction. The ZoS for the two peaks turn out to be about 4 cm, 2 cm, respectively. This is sufficient if ANC system is embedded into headphones. However, in some cases it may not be possible to use headphone configuration and some distance needs to be maintained between patient ear and the ANC microphone. In such a case, the ZoS has a very small volume and the movement of patient head may affect the attenuation perceived. To address this, virtual sensing technique is implemented.

Impulse responses considered for the primary path $P(z)$ and secondary path $S_p(z)$ are obtained from the actual ANC set up (Veena, Narasimhan, 2004). They are of having 128 taps as shown in Fig. 5. Further, the virtual path $S_v(z)$ is derived from $S_p(z)$ by incorporating phase reversal and gain change in some of the coefficients as given by

$$S_v = -S_p, \qquad S_v(8) = 0.8 \cdot S_v(8),$$
$$S_v(10) = 0.4 \cdot S_v(10), \qquad S_v(9) = 1.1 \cdot S_v(9).$$

The impulse response $H(z)$ is considered to be of 15 taps with

$$H(0), H(1), H(2) = 0, \qquad H(3) = 0.8,$$
$$H(4) = -0.6, \qquad H(5) = 0.9,$$
$$H(6) = 0.2, \qquad H(7) = -0.05,$$
$$H(8) = 0.05, \qquad H(9), \ldots, H(14) = 0.$$

All the impulse responses used for simulations are plotted in Fig. 5.

The various simulation parameters are shown in Table 1.

Table 1. The simulation parameters considered for ANC system.

Step size parameter (α)	0.05
Forgetting factor (β)	0.999
Signal length (samples)	100 000
Sampling frequency	8000 Hz

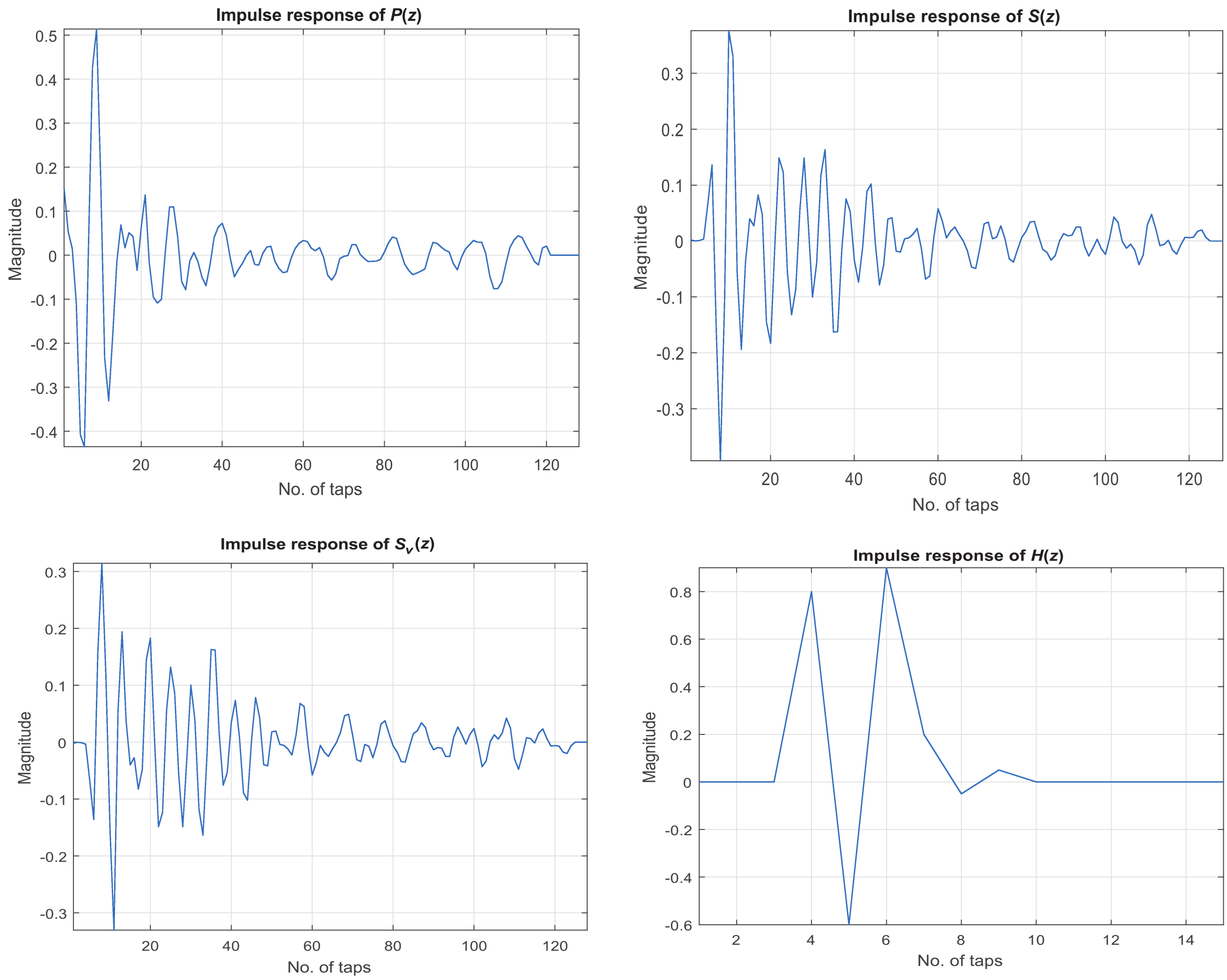


Fig. 5. Impulse responses considered for simulation.

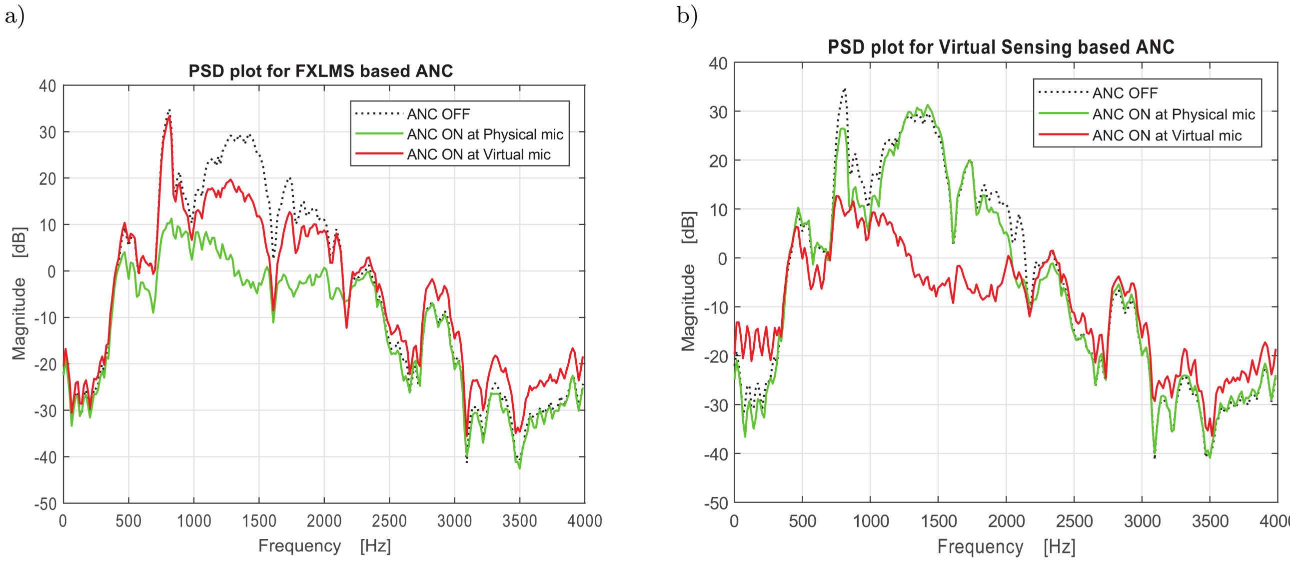


Fig. 6. Periodogram power spectral density estimate plot of ambulance siren noise (ANC OFF and ON) with (a) FXLMS and (b) virtual sensing based ANC.

ANC systems based on standard FXLMS algorithm and virtual sensing technique were implemented and their performance were compared at both physical and virtual locations. The attenuation obtained is calculated using the relation in Eq. (7)

$$\text{Attenuation} = -10\log_{10}\left[\frac{\sum e^2(n)(\text{ANC OFF})}{\sum d^2(n)(\text{ANC ON})}\right], \qquad (7)$$

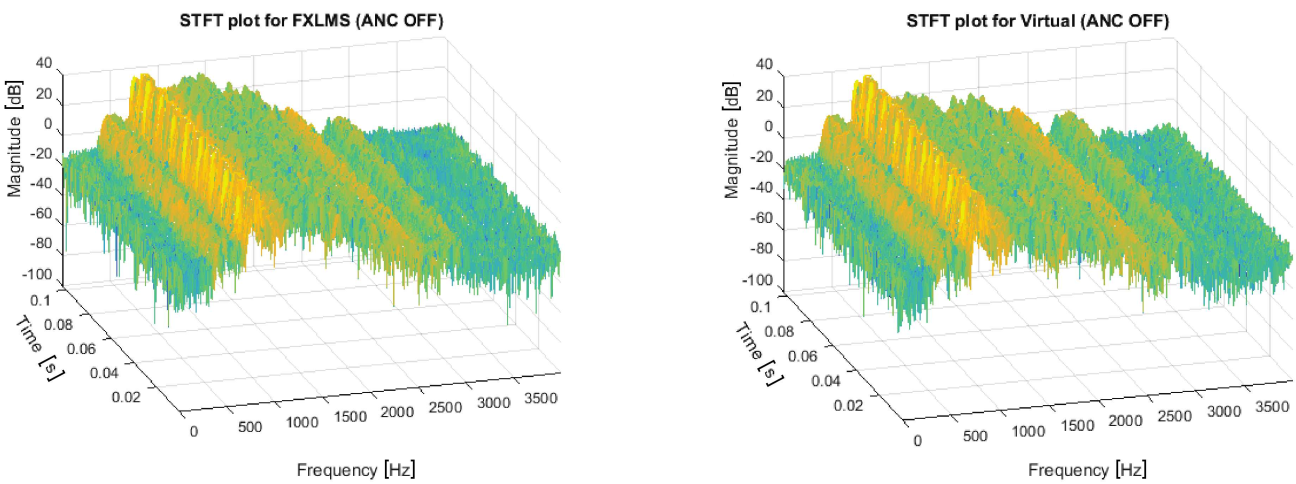
$e(n) = e_p(n)$, $d(n) = d_p(n)$, at physical microphone location, $e(n) = e_v(n)$, $d(n) = d_v(n)$, at virtual microphone location.

The standard FXLMS gave a very good reduction of about 42 dB at physical location. But hardly any reduction was observed at the virtual location. Whereas, the ANC algorithm based on virtual sensing results 26 dB at virtual location.

Table 2. Reduction in noise at physical and virtual locations for FXLMS and virtual sensing technique.

Location of microphone	FXLMS	Virtual sensing technique
Physical location	42.15 dB	2.78 dB
Virtual location	0.78 dB	26.32 dB

The STFT plots of Fig. 7 also support the above observations. The plot shows that ANC is able to attenuate the peaks in the ambulance siren signal resulting in quiet environment for the patient.



[Fig. 7.]

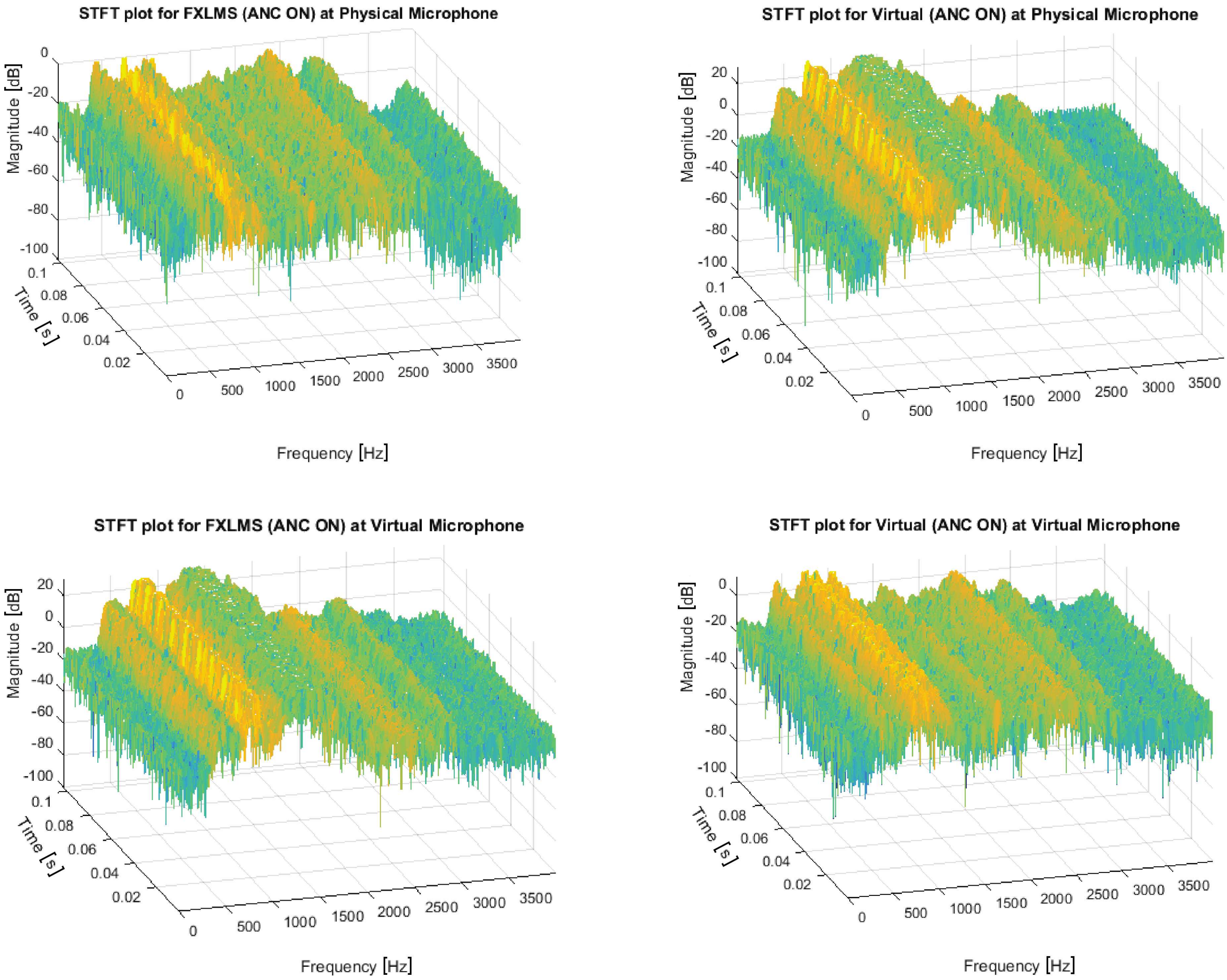


Fig. 7. The STFT plot of the error microphone signal with ANC OFF and ANC ON at physical and virtual microphone location.

6. Conclusion

In this paper, ANC with virtual sensing technique is proposed to reduce the ambulance siren noise to create a quiet environment for the patient lying inside the ambulance. The practical problem of placing the error microphone at desired location in ANC system is proposed to be overcome using virtual sensing technique. The simulations are done in MATLAB and since the typical ambulance noise is of narrowband in nature, the ANC is able to give a good attenuation. With this positive outcome, the future work is towards realizing a DSP processor based ANC system for real-time evaluation inside an ambulance.

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