Development of a technique to minimise the wind-induced noise in shielded microphones

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ABSTRACT

Environmental noise measurements are usually performed in atmospheric conditions where wind and thus turbulent flow over the microphone is present. In such conditions the measured noise is highly affected by the wind-induced noise generated by turbulence structures present in the flow and microphone generated wakes. A novel approach has been employed to distinguish the contribution of wind-induced noise from the acoustic signal using Incoherent Output Power analysis between two microphone signals. Various experimental arrangements were investigated to examine the influence of the experimental parameters on the results obtained. The technique was successfully tested and validated in a series of indoor experiments in a small anechoic wind tunnel. Finally, a new approach for minimising wind-induced noise using the Coherent Output Power between two shielded microphones is proposed and tested.

INTRODUCTION

Wind-induced noise due to the presence of turbulent flow passing over the microphone surface contaminates the desired acoustic signal and thus reduces the accuracy of measurements. A common practice to reduce the unwanted effects of wind-induced noise on measurements is to use microphone windshields. However, their performance is limited to a maximum wind speed in which valid measurements can be performed. An example where high speed airflows may cause difficulties in noise measurement is wind farm noise assessment. Field measurement in such environments may sometimes require noise measurement at wind speeds of up to 12 m/s (King, Mahon, Pilla and Rice 2009). However, most environmental noise guidelines require that noise measurements be conducted at wind speeds of less than 5 m/s.

Significant efforts have been devoted to overcome these restrictions with the aim of increasing the reliability of noise measurements in turbulent airflows. However there have been insufficient investigations directed towards methods enabling reliable separation of the wind-induced noise contribution from the desired acoustic signal.

This paper utilises a novel approach first introduced by Wang, Zander and Lenchine (2012) to estimate the wind-induced noise using the Incoherent Output Power obtained from cross spectral analysis between two microphones positioned within and outside of an air flow. The effect of various experimental arrangements on the results obtained using this technique has been investigated in the current study to validate the feasibility of utilising this technique for outdoor noise measurements. Finally, a new approach for minimising wind-induced noise using the Coherent Output Power between two shielded microphones is proposed and tested.

WIND-INDUCED NOISE

Wind-induced noise is caused by non-acoustic pressure fluctuations imposed on a microphone diaphragm and comprises two major mechanisms: pressure fluctuations due to the interaction of flow over the microphone surface; and, pressure disturbances due to existing eddy structures in the flow impinging on the microphone surface (Leclercq, Cooper & Stead 2008; Morgan & Raspet 1992; Van den Berg 2006; Zheng & Tan 2003).

In low Mach number flows, noise due to the interaction of flow over bluff bodies is generated by the fluctuating aerodynamic forces, causing eddy structures (Lida, Mizuno & Brown 2004). The resulting pressure fluctuations on the microphone diaphragm contaminate the acoustic pressure measurement. This phenomenon is known in the literature as self-generated noise (Strasberg 1988) or self-noise (Leclercq, Cooper & Stead 2008) or "pseudo-noise" (Pearse & Kingan 2006).

The contribution of these two sources may vary based on the level of pressure disturbances in the flow. For instance, in a turbulence-free flow, the dominant noise may be due to the interaction of flow over the surface of the microphone (Morgan & Raspet 1992; Zheng & Tan 2003). However, in a highly turbulent flow the dominant pressure fluctuations on the microphone diaphragm may be mainly due to the eddy structures impinging on the microphone surface (Morgan & Raspet 1992). The interaction of turbulence structures impinging on the surface of the microphone has been claimed as the dominant contributor to the wind-induced noise in shielded microphones in atmospheric conditions (Morgan & Raspet 1992; Van den Berg 2006).

Strasberg (1988) has provided a dimensional analysis of airborne noise due to turbulence-free flow interaction on microphone windshields. The dimensional analysis of Strasberg (1988) summarises the effects of self-generated noise as a function of the windshield diameter, frequency and flow velocity. The analysis shows a linear relationship between the logarithms of dimensionless one-third octave sound pressure level and Strouhal number, defined as the product of frequency and windshield diameter divided by the flow velocity. However, the extent of this analysis is limited to Strouhal numbers below five. Above this value, linear approximation is no longer valid. Strasberg (1988) suggests that for Strouhal numbers higher than five, the effects of other parameters such as porosity may impair the linear dependency. Further, Strasberg's (1988) analysis is based on a uniform flow simulation, where no initial turbulence is considered. However, in outdoor flow conditions, the interaction of flow turbulence on the windshield is considered to be responsible for the majority of the wind-induced noise measured by the microphone (Morgan & Raspet 1992; Van den Berg 2006).

Morgan and Raspet (1992) also performed an empirical study of wind noise for bare and shielded microphones in outdoor environments. They used different windshields with various diameters and porosity to investigate the wind-induced noise in windy environments. The research found that the major contributor to wind noise in outdoor environments is the pressure disturbances existing in the flow. One of their conclusions is that pressure fluctuations caused by flow velocity variations are the dominant source in outdoor wind noise generation. However, they also indicate that in flow conditions where low levels of pressure fluctuations exist, this dominance shifts to the interaction of flow over the windshield surface and it's associated wake generation (the mechanism which may contribute less in a highly turbulent flow).

Van den Berg (2006) also studied wind-induced noise in shielded microphones in outdoor measurements and provided analytical expressions for wind noise corresponding to atmospheric conditions. Van den Berg (2006) showed that atmospheric turbulence is the major contributor to outdoor microphone wind noise. Therefore he concluded that outdoor wind noise in a shielded microphone is dependent not only on the average wind speed and windshield diameter, but also depends on atmospheric turbulence which is defined by thermal and frictional turbulence. Consequently, two other parameters associated with wind-induced noise were introduced by Van den Berg (2006), which are defined by atmospheric conditions (i.e. atmospheric stability) and terrain properties (i.e. terrain roughness height).

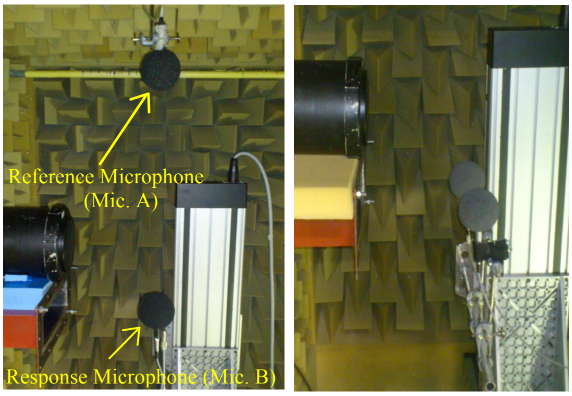
Leclercq, Cooper and Stead (2008) have investigated wind-induced self-noise in shielded microphones using a series of indoor experiments conducted in a small anechoic wind tunnel. They have utilised a single shielded microphone positioned within a free jet to characterise the wind-induced noise in the velocity range from 4 to 10 m/s. They found a 6th power law dependence between self-noise and flow speed where an increase in flow speed will result in higher self-noise. Good agreement was found between their 6th power law model and Strasberg's (1988) model. It is noteworthy to mention that Leclercq, Cooper and Stead (2008) clearly state that the microphones were positioned outside the potential core of the jet where the turbulence intensity was significant. This means that there would have been turbulence structures in the flow impinging on the surface of the windshield. Therefore, the classification of the measured wind noise as self-noise may not be completely accurate.

A technique has been developed by Wang, Zander and Lenchine (2012) to estimate and characterise the wind-induced noise generation using Incoherent Output Power (IOP) analysis between two shielded microphones. Different shaped windshields were tested in a small anechoic wind tunnel in an initially uniform flow with relatively low turbulence intensity in the velocity range of 2 to 12 m/s. The findings of Wang, Zander and Lenchine (2012) indicate that Incoherent Output Power between two shielded microphones, one positioned inside the jet and another positioned outside the jet, is a reliable representation of the wind-induced noise. Therefore, they have successfully characterised the wind-induced noise in various commercial windshields in the velocity range of 2 to 12 m/s. The significance of the findings lies in the fact that the wind-induced noise contribution has been successfully extracted from the total noise signal, indicating the potential of this technique for environmental noise measurements in the presence of flow over the microphone windshield.

EXPERIMENTAL ARRANGEMENT

Windshields of different shapes and dimensions were tested in this study in various flow conditions in a small anechoic wind tunnel (AWT) in the School of Mechanical Engineering, University of Adelaide. The test chamber of the anechoic wind tunnel has walls that are acoustically treated with foam wedges and has a cut-off frequency of 200 Hz (Leclercq, Doolan & Reichl 2007). The outlet of the anechoic wind tunnel is an open diffuser which allows for external noise to propagate to the chamber and contribute to the background noise. The wind tunnel outlet is equipped with a collector made of standard mild steel sheet which causes some reflections in the chamber.

Two different experimental arrangements used in this study are shown in Figure 1. Arrangement 1 consisted of a microphone equipped with a windshield (microphone A) located outside the flow in order to provide a reference signal and another microphone equipped with the same type of windshield (microphone B) mounted within the potential core of the jet to capture the contribution of wind-induced noise. In Arrangement 1, the position of the response microphone was kept constant while the position of the reference microphone was varied with respect to the loudspeaker axis.



(a) (b)

Figure 1. Experimental arrangements, (a) Arrangement 1, both microphones equipped with a 90 mm windshield and (b) Arrangement 2, both microphones equipped with a 75 mm windshield

Arrangement 2, shown in Figure 1, consisted of two microphones equipped with the same windshields positioned side by side within the flow having spacing of 80 and 50 millimetres. The microphones were positioned symmetrically with respect to the loudspeaker axis in the lateral direction. For both arrangements the leading edges of the windshields were positioned at 200 mm downstream of the jet exit plane. The same windshield was used on each microphone to provide the identical windshield transmission loss and frequency response characteristics for the two microphones.

The loudspeaker generated a white noise signal with overall sound pressure level (SPL) of approximately 106 dB in the audio frequency span for all acoustic measurements, except a number of measurements which were intended to investigate the effect of acoustic excitation level on the estimated wind-induced noise. In these measurements the effect of different levels of acoustic excitation was investigated utilising various overall loudspeaker levels of 96, 86 and 78 dB in the audio frequency span. The 106 dB loudspeaker level was chosen to ensure minimal interference of background noise on the measured wind-induced noise. Figure 2 shows autospectra of the background noise and the loudspeaker signal without the jet present, indicating that the loudspeaker has provided sufficient excitation above the background noise level (except for some frequencies below 32 Hz) which ensures the non-interference of the background noise on further acoustic measurements.

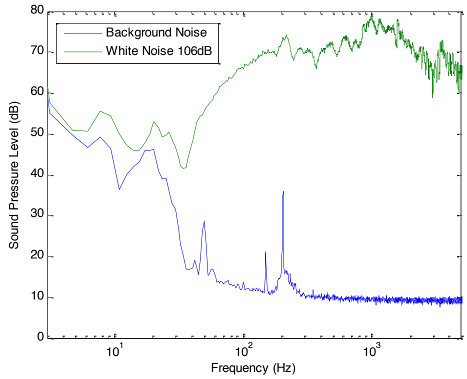


Figure 2. Sound pressure level of the response microphone for background and 106 dB white noise without the jet present and with microphones covered with a 90 mm windshield

Two B&K 4190 free field microphones equipped with windshields were utilised to perform the acoustic measurements. A multi-channel data acquisition system was used to record the microphone signals at each airflow velocity and for each type of windshield. Instantaneous time-dependent pressure levels were recorded for 60 seconds with a sampling frequency of 50 kHz and then transferred to the frequency domain using the Fast Fourier Transform (FFT). The FFT was done over 12801 lines with a frequency resolution of 1.5625 Hz and 50% overlap. The Hanning window was used for the FFT analysis. No filtering was utilised for the microphone signals. Four different shaped and sized windshields with different arrangements were examined in this study, as listed in Table 1 and shown in Figure 3. One ellipsoidal and three spherical windshields with similar porosity were tested in this study.

Table 1. Windshields used in this study

No.	Diameter [mm]	Type
1	45	Ellipsoidal
2	60	Spherical
3	75	Spherical
4	90	Spherical

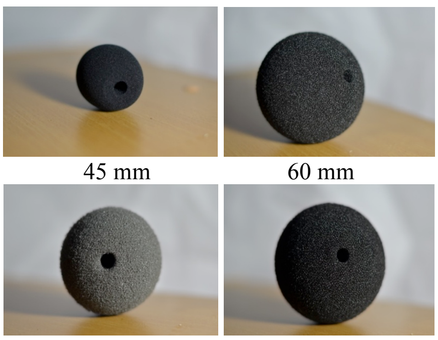


Figure 3. Different windshields used in experiments

The free jet stream was characterised by turbulence intensity not exceeding 2 % at the centreline of the jet. It was measured by hotwire constant temperature anemometry for all velocities at 200 mm downstream of the jet exit plane where the leading edge of each of the windshields was positioned. Mean velocity and turbulence intensity profiles measured at 200 mm downstream of the contraction within the potential core of the jet for an airflow velocity of 6 m/s, are shown in Figures 4 and 5 respectively. The mean velocity profile indicates that the flow is highly uniform in the central area. In addition, the turbulence intensity profile shows that the turbulence intensity increases as a function of vertical distance from the centreline of the jet. Therefore, the central area of the windshields was subjected to relatively low levels of turbulence while the upper and lower areas were subjected to higher levels of turbulence.

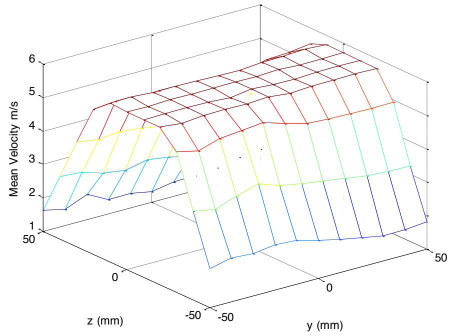


Figure 4. Mean airflow velocity profile 200 mm downstream from the jet exit plane for free stream velocity of 6 m/s. Graph origin corresponds to the jet centreline.

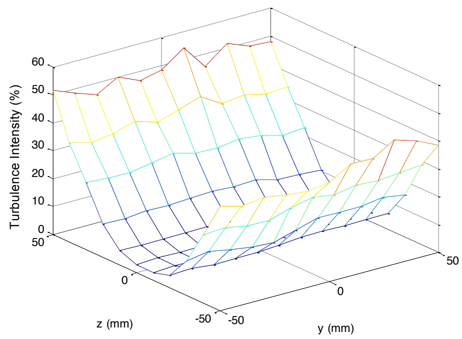


Figure 5. Turbulence intensity profile 200 mm downstream from the jet exit plane for free stream velocity of 6 m/s. Graph origin corresponds to the jet centreline.

SIGNAL PROCESSING

The concept behind this technique first introduced by Wang, Zander and Lenchine (2012) is that the loudspeaker signal can be thought of as the desired acoustic signal to be measured in outdoor conditions. The acoustic signal is contaminated with the wind-induced noise due to the unwanted pressure fluctuations caused by flow interaction over the windshield. This technique can then be utilised to extract the wind-induced noise from the total contaminated signal.

In this technique the background noise, fan noise, jet noise and aerodynamic noise radiated from flow disturbances are assumed to be sensed by both microphones and therefore assumed to be coherent between the two microphones. Aerodynamic sources contributing to the wind-induced noise are supposed to be localised around the airflow and windshield interface. The output of microphone A is not affected by the jet, since it is positioned outside the airflow, while the output of microphone B which is located in the air stream includes the contribution of wind noise due to flow interaction over the windshield surface.

The Incoherent Output Power (IOP), which indicates the part of a given signal (i.e. Microphone A) that is incoherent with another signal (i.e. Microphone B), is defined as

$$IOP(f) = [1 - \gamma^2(f)]\, G_{BB}(f), \qquad (1)$$

where G_{BB} is the response auto spectrum of signal B and γ^2 is the coherence which is a measure of the linear dependency between two signals as a function of frequency (Randall 1987). A perfectly linear dependence between two signals gives a coherence value of unity, while a coherence value of zero may indicate that two signals are linearly uncorrelated (Randall 1987). The coherence is calculated from the auto spectra and cross spectrum of two given signals (Randall 1987):

$$\gamma^2(f) = \frac{|G_{AB}(f)|^2}{G_{AA}(f)\, G_{BB}(f)} \qquad (2)$$

where G_{AA} is the reference auto spectrum of Signal A, and G_{BB} is the response auto spectrum of signal B, and G_{AB} is the cross spectrum between the two signals. The Coherent Output Power (COP) gives the part of the measured auto spectrum $G_{BB}(f)$ that is coherent with a particular signal with auto spectrum $G_{AA}(f)$,

$$COP(f) = \gamma^2(f).\, G_{BB}(f). \qquad (3)$$

Without the wind tunnel operating and the loudspeaker signal present, both microphone signals represent the contribution of background noise and the loudspeaker signal. In this case the microphone signals are fully coherent. When the wind tunnel is operating, the interaction of the flow structures over the windshield surface will cause some extraneous noise added to the response microphone signal. This will cause the coherence between the two microphones to deviate from unity. Since the background, jet noise and loudspeaker noise are sensed by both microphones and are fully coherent, the only incoherent part between the signals with the wind tunnel operating is the wind-induced noise in the response microphone signal. By estimating the Incoherent Output Power between two microphone signals in the presence of the flow on the response microphone, the portion of the total power which is contaminated by the wind-induced noise can be obtained. In addition, the coherent part between the two microphone signals measured in the presence of the flow represents the combined contribution of the background, jet noise and loudspeaker signals, which is the desired acoustic signal to be measured.

RESULTS

The coherence between the two microphones positioned in Arrangement 1 and 2 with only the loudspeaker operating (and no flow) shown in Figures 6 and 7 indicate that the loudspeaker noise is highly coherent for both of the channels. Figure 6 shows that the effect of the airflow over the windshield significantly reduces the coherence between the two microphones at low to mid frequencies. This indicates that with the wind tunnel operating, an extraneous source is affecting the response microphone positioned within the flow, causing a level of incoherence between the two microphone signals. As discussed before, the background noise, fan noise, jet noise and aerodynamic noise radiated from flow disturbances are assumed to be sensed by both microphones and therefore assumed to be coherent between the two microphones. Therefore, the only extraneous source between the two microphones is the wind-induced noise. Hence the Incoherent Output Power (IOP), which represents the portion of the total power of the response microphone that is incoherent with the reference microphone, corresponds to the wind-induced noise due to the flow interaction over the surface of the windshield.

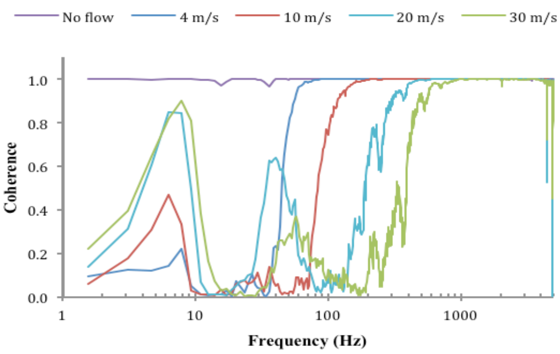


Figure 6. Coherence between microphones positioned in Arrangement 1 equipped with 90 mm windshield at selected airflow velocities of 4, 10, 20 and 30 m/s as well as with no flow

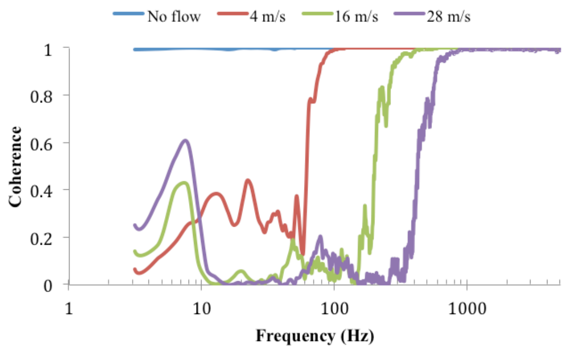


Figure 7. Coherence between microphones positioned in Arrangement 2 equipped with 45 mm windshield at selected airflow velocities of 4, 16 and 28 m/s as well as with no flow

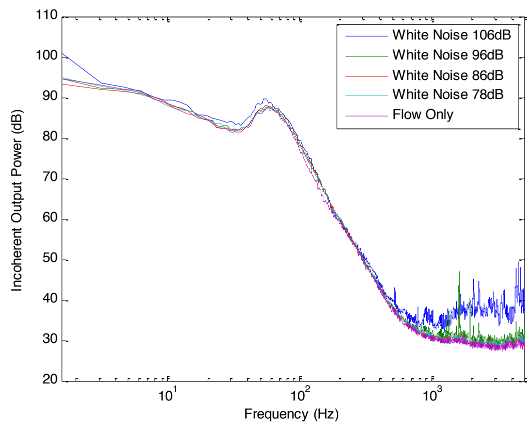


Figure 8. IOP between microphones positioned in Arrangement 1 and equipped with 60 mm windshields at airflow velocity of 16 m/s and different loudspeaker levels

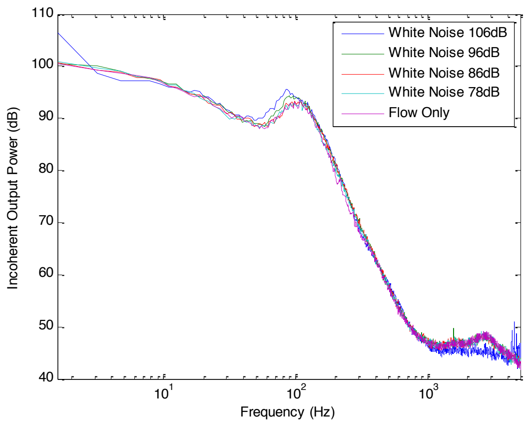


Figure 9. IOP between microphones positioned in Arrangement 1 and equipped with 60 mm windshields at airflow velocity of 28 m/s and different loudspeaker levels

Figures 8 and 9 show the estimated wind-induced noise using Arrangement 1 at various levels of loudspeaker excitation as well as without the loudspeaker excitation at two free stream velocities of 16 m/s and 28 m/s. The IOP spectra representing the estimated wind-induced noise are approximately identical within 3 dB which indicates that the estimated wind-induced noise is almost independent of the level of acoustic excitation. This confirms that the IOP provides a reliable estimate of the wind-induced noise, as the wind-induced noise is only dependent on the airflow velocity. This highlights that the IOP technique has the capability to estimate the wind-induced noise contamination for different levels of acoustic excitation and more importantly in self-excitation where the combination of the background and jet noise acts as a replacement for the loudspeaker excitation. This further adds to the feasibility of utilising this technique as a reliable method of wind-induced noise estimation for outdoor noise measurements where the uncontrollable background/ambient noise affects the response of the microphones.

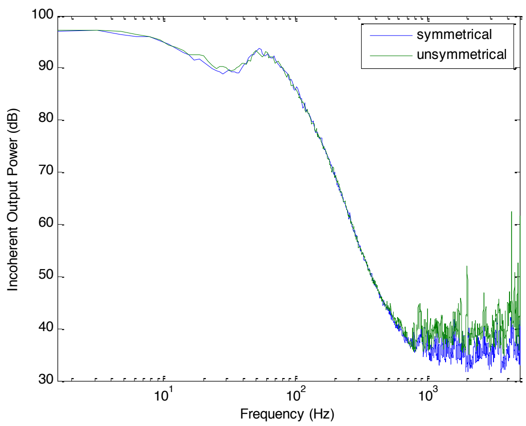


Figure 10. IOP between microphones for Arrangement 1 equipped with 45 mm windshield with airflow velocity of 16 m/s for symmetrical and asymmetrical positioning of microphones

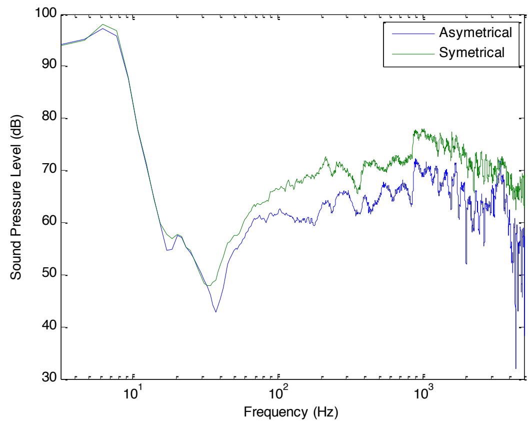


Figure 11. Autospectra of reference microphone for Arrangement 1 equipped with 45 mm windshield with airflow velocity of 16 m/s for symmetrical and asymmetrical positioning of microphones

Figure 10 shows the measured IOP for an airflow velocity of 16 m/s with symmetrical and asymmetrical positioning of the microphones with respect to the loudspeaker axis. In both symmetrical and asymmetrical arrangements, the position of the response microphone in the airflow was kept constant while the position of the reference microphone was varied. The centre-centre distance between windshields positioned symmetrically and asymmetrically was 34 cm and 57 cm respectively. Despite the notable difference between the reference microphone signals shown in Figure 11, the IOP was similar within 2 dB for a constant position of the response microphone and symmetrical and asymmetrical positioning of the microphones relative to the loudspeaker axis. The findings suggest that using this technique the estimated wind-induced noise is almost independent of the relative position of the reference microphone with respect to the loudspeaker and response microphone. This finding reveals that this method can be utilised with less concern on the effect of the location of the microphones relative to the source of sound on the estimated wind-induced noise provided that the microphones are positioned such that significant differences in autospectra levels does not exist between the two microphones.

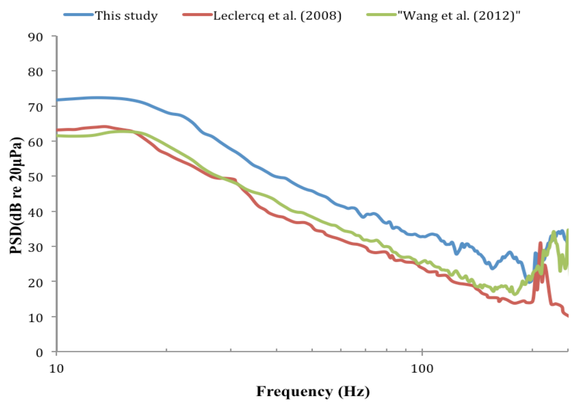


Figure 12. Comparison of estimated wind noise spectra with Wang, Zander and Lenchine (2012) and Leclercq, Cooper and Stead (2008) at airflow velocity of 4 m/s and for 90 mm windshield

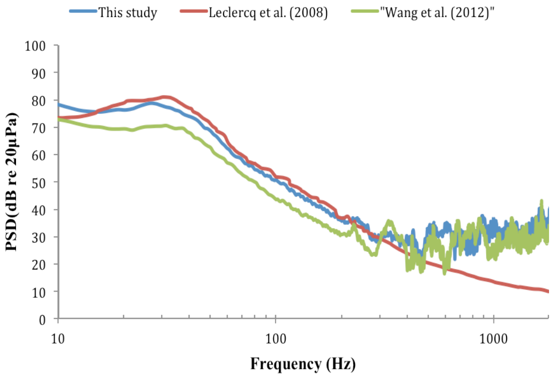


Figure 13. Comparison of estimated wind noise spectra with Wang, Zander and Lenchine (2012) and Leclercq, Cooper and Stead (2008) at airflow velocity of 8 m/s and for 90 mm windshield

The results of Leclercq, Cooper and Stead (2008) and Wang, Zander and Lenchine (2012) for a 90 mm spherical windshield have been compared with the findings of this study as shown in Figures 12 and 13. Both aforementioned investigations were done in the same wind tunnel facility as this study where the shielded microphones were positioned within a turbulent jet with approximately the same characteristics. Some minor modifications to the anechoic wind tunnel and thus the characteristics of the jet have occurred between 2008 and the current study. Wang, Zander and Lenchine (2012) utilised the same methodology while Leclercq, Cooper and Stead (2008) only measured the response of one shielded microphone positioned inside the flow. Thus the contributions of the background noise, fan noise, jet and other aerodynamic disturbances are also considered in the response of the microphone. Further, in Leclercq, Cooper and Stead's (2008) measurements the microphone was positioned immediately outside the potential core of the jet where the turbulence intensity is higher than in this study.

Generally good qualitative agreement in the estimated wind-induced noise can be seen for different velocities between the findings of this study and those of Wang, Zander and Lenchine (2012) and Leclercq, Cooper and Stead (2008). General shape of wind noise spectra, slope of the wind noise decay and the local maximum frequency agree well with both studies. However there are noticeable differences between the measured wind-induced noise levels and the results of Wang, Zander and Lenchine (2012) and Leclercq, Cooper and Stead (2008). For a flow velocity of 4 m/s the measured wind noise spectrum is around 10 dB higher than the findings of both Wang, Zander and Lenchine (2012) and Leclercq, Cooper and Stead (2008). At 8 m/s the wind noise spectra is similar with the findings of Leclercq, Cooper and Stead (2008) while up to 7 dB difference exists between the measured wind noise levels and the finding of Wang, Zander and Lenchine (2012). These differences may mainly be associated with the position of microphones in the jet. For instance, in this study the response microphone is positioned within the potential core of the jet while in Leclercq, Cooper and Stead (2008) the microphone was located downstream of the potential core of the jet where the airflow velocity would be reduced from the velocity measured in the potential core. Nevertheless good qualitative agreement was observed between the estimated wind-induced noise using the Incoherent Output Power analysis and previous data reported by Leclercq, Cooper and Stead (2008), which further demonstrates the potential of the current technique as a reliable method of wind-induced noise estimation.

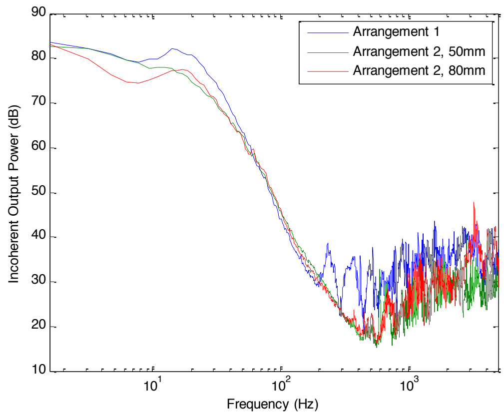


Figure 14. IOP comparison between two different microphone arrangements with a 45 mm windshield for airflow velocity of 4 m/s

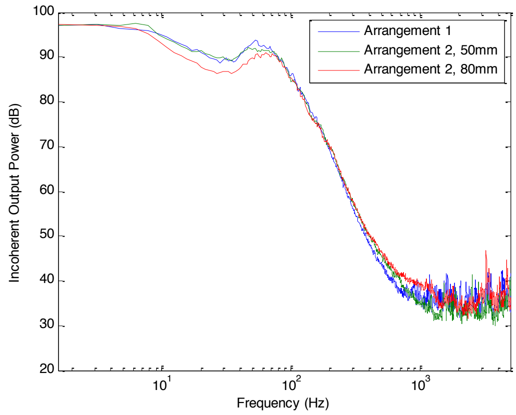


Figure 15. IOP comparison between two different microphone arrangements with a 45 mm windshield for airflow velocity of 16 m/s

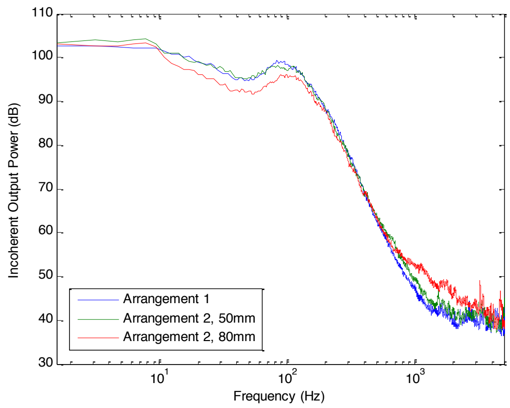


Figure 16. IOP comparison between two different microphone arrangements with a 45 mm windshield for airflow velocity of 28 m/s

Figures 14 to 16 show that the IOP between the microphones positioned as Arrangement 2, agrees well with the measured IOP using Arrangement 1 at various free stream velocities. Arrangement 2 with a higher spacing between the windshields (i.e. 80 mm) has somewhat underestimated the wind induced noise in low frequencies at different velocities. At low velocities a difference of up to 5 dB can be seen at low frequencies while at higher velocities the difference is about 3 to 4 dB. Arrangement 2 with a smaller spacing between windshields (i.e. 50 mm) has shown very good agreement with Arrangement 1 results in the frequency range of interest for higher airflow velocities (i.e. 16 m/s and 28 m/s) while for airflow velocity of 4 m/s it shows a difference of up to 5 dB. The difference may be explained by the fact that the arrangement with the larger spacing between microphones presumes that the windshields are placed closer to the boundary of the jet and that the aerodynamic parameters there differ from the more central location. On the contrary, the local maximum frequency and the slope of the wind noise decay obtained using Arrangement 2 with different relative microphone spacings agree very well with Arrangement 1. This indicates that the Incoherent Output Power analysis of two microphones positioned side by side within the flow at the same distance from the jet exit plane and a specific relative distance to each other has successfully estimated the wind-induced noise with 3 to 5 dB uncertainty at low frequencies.

The effect of removing the loudspeaker signal was also found to not have a significant impact on the estimated wind-induced noise using Arrangement 2. The results corresponding to both microphones positioned within the flow show the further potential of the Incoherent Output Power technique for outdoor noise measurement as an effective tool to distinguish the contribution of wind-induced noise from the acoustic signal. From a practical point of view, employing Arrangement 1 in outdoor noise measurement will be challenging, as it is hard to achieve no airflow on one of the microphones without significantly attenuating the desired acoustic signal. Therefore this arrangement incorporating both microphones within the flow removes the limitation of Arrangement 1 while providing a good estimate of the wind-induced noise relative to Arrangement 1.

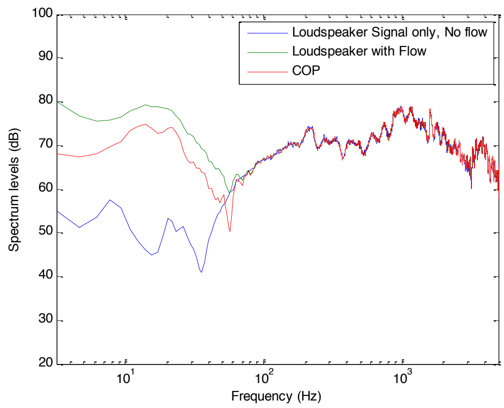


Figure 17. Auto spectra of a microphone in Arrangement 2 located in the jet with loudspeaker signal, with and without flow, as well as the COP spectrum between the microphones in Arrangement 2 for a 45 mm windshield and airflow velocity of 4 m/s

The loudspeaker signal can be thought of as the desired acoustic signal to be measured in the outdoor noise measurements. The auto-spectrum of a microphone in Arrangement 2 located in the jet with loudspeaker signal only and for no flow, which represents the desired acoustic signal, is shown in Figures 17 to 19. The auto-spectrum of a microphone in Arrangement 2 located in the jet, for loudspeaker and airflow velocities of 4, 16 and 28 m/s is also plotted in Figures 17 to 19. These represent the desired acoustic signal contaminated by the wind-induced noise. The COP with both shielded microphones in the flow with the presence of the loudspeaker excitation and flow for various free stream velocities is also shown in Figures 17 to 19. This demonstrates the use of COP to extract the desired acoustic signal from microphones within the flow. Significant correction for wind noise contribution has been achieved using this approach, where in some frequencies, the signal of interest is 20 dB lower than the total measured noise. The findings indicate that this technique can be successfully used to extract the desired acoustic signal from the total contaminated signal and therefore minimise the effects of the wind-induced noise using a simple arrangement and more importantly without velocity or air wind speed limitations for which this technique can be used.

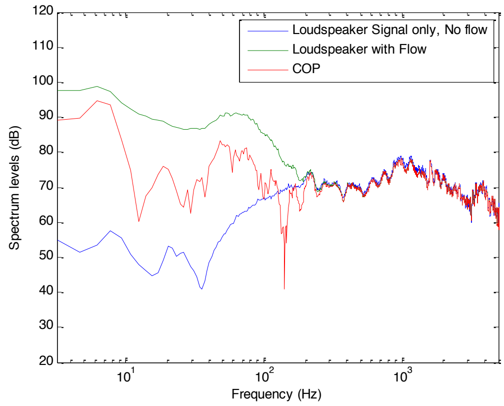


Figure 18. Auto spectra of a microphone in Arrangement 2 located in the jet with loudspeaker signal, with and without flow, as well as the COP spectrum between microphones in Arrangement 2 for a 45 mm windshield and airflow velocity of 16 m/s

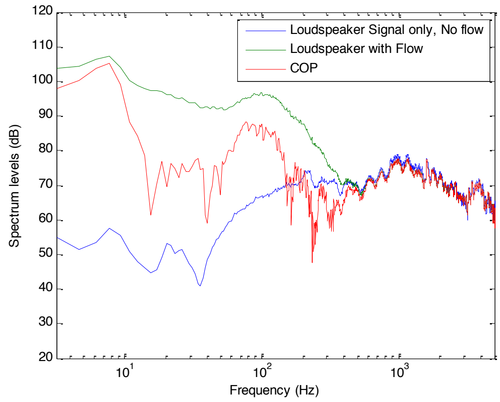


Figure 19. Auto spectra of a microphone in Arrangement 2 located in the jet with loudspeaker signal, with and without flow, as well as the COP between microphones in Arrangement 2 for a 45 mm windshield and airflow velocity of 28 m/s

The auto spectra of a microphone in Arrangement 2 in the jet at different airflow velocities (with and without the flow) are almost identical at mid to high frequencies. This shows that the flow structures impinging on the surface of the windshield are mainly generating low to mid frequency noise. Higher frequencies are not notably influenced by the effect of wind-induced noise. The frequency where the effect of wind-induced noise becomes insignificant seems to shift to a higher value as the airflow velocity increases for a specific windshield diameter. This indicates that at higher airflow velocities a wider frequency span would be affected by wind-induced noise. This is in agreement with Van den Berg's (2006) results indicating direct proportionality of this frequency with airflow velocity.

The difference between the results obtained with the white noise signal without any flow and the estimated COP between microphones positioned within the flow is associated with the fact that with the wind tunnel operating other noise sources including fan noise, jet noise and aerodynamic noise (due to existing flow disturbances and wake generation downstream of the windshields) will also contaminate the loudspeaker signal. These sources are found to affect the loudspeaker signal at low to mid frequencies. Similar noise sources also exist in outdoor measurements. For example, the wind blowing over trees and aerodynamic noise generation due to existing disturbances in the incoming flow will also affect the desired acoustic signal. Nevertheless the COP represents the desired acoustic signal which is not contaminated by the wind-induced noise due to impinging turbulence structures and wake-generation over the surface of the windshield. In addition, further inspection of Figures 17 to 19 shows that in some frequencies the COP is smaller than the loudspeaker only signal. This is due to a drop in coherence between the two microphones in Arrangement 2 to values close to zero at the corresponding frequencies (see Figure 7). While in theory the COP should be able to extract only the coherent component of the microphone signal, assumed to be the loudspeaker only signal, it can be seen that both coherent and incoherent contributions from other sources are present at some frequencies where the wind noise dominates. This may be an indication of extraneous noise mechanisms associated with flow-induced noise due to interaction of the boundary layer turbulence of the two windshields or operation of the anechoic wind tunnel causing significant incoherence at these frequencies. Although it is admitted that further investigations are necessary to address such limitations, this technique can be potentially employed in outdoor noise measurements to extract the desired acoustic signal from the total contaminated signal and thus minimise the effects of the self-generated noise on acoustic measurements.

CONCLUSION

A newly introduced technique utilising the Incoherent Output Power between two microphone signals to estimate the wind-induced noise was further developed and successfully tested in a series of indoor experiments in a small anechoic wind tunnel. The findings showed that the Incoherent Output Power technique has the capability of successfully estimating the wind-induced noise for different background excitation levels as well as different locations of the microphones relative to the source of sound. The results gathered using the Incoherent Output Power were compared with previous data obtained from the literature. Good qualitative agreement was observed between previous research and the wind-induced noise spectra estimated using this technique, indicating the validity of this technique for noise measurements in windy environments.

A new arrangement has been introduced to estimate the wind-induced noise utilising the Incoherent Output Power between two microphones positioned within the flow. The findings reveal that this arrangement can successfully estimate the wind-induced noise with 3 to 5 dB uncertainty. Further, this arrangement can be potentially employed to extract the desired acoustic signal from the total contaminated signal using Coherent Output Power between the two microphones and consequently minimise the effects of wind-induced noise.

The significant potential of this technique for wind noise estimation and more accurate noise measurements in windy environments has been depicted in this study. However, further development is deemed necessary to extend this technique to practical outdoor noise measurement, and is the subject of future work.

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REFERENCES

King, E, Mahon, J, Pilla, F & Rice, H 2009, 'Measuring noise in high wind speeds: evaluating the performance of wind shields', *Inter-Noise* 2009, Ottawa, Canada.

Leclercq, D, Cooper, J & Stead, M 2008, 'The use of microphone windshields for outdoor noise measurements', *Acoustics* 2008, Geelong, Victoria, Australia.

Leclercq, D, Doolan, CJ & Reichl, J 2007, 'Development and Validation of a Small-Scale Anechoic Wind Tunnel', *14th International Congress on Sound and Vibration*, Cairns, Australia.

Lida, A, Mizuno, A & Brown, RJ 2004, 'Identification of aerodynamic sound source in the wake of a rotating circular cylinder', *15th Australasian Fluid Mechanics Conference*, Sydney, Australia.

Morgan, S & Raspet, R 1992, 'Investigation of the mechanisms of low-frequency wind noise generation outdoors', *Journal of the Acoustical Society of America*, vol. 92, no. 2, pp. 1180-1183.

Pearse, JR & Kingan, MJ 2006, 'Measurement of Sound in Airflow', *13th International Congress of Sound and Vibration*, Vienna, Austria.

Randall, RB 1987, *Frequency analysis*, Bruel & Kjaer, Denmark.

Strasberg, M 1988, 'Dimensional analysis of windscreen noise', *Journal of the Acoustical Society of America*, vol. 83, no. 2, pp. 544-548.

Van den Berg, G 2006, 'Wind-induced noise in a screened microphone', *Journal of the Acoustical Society of America*, vol. 119, no. 2, pp. 824-833.

Wang, L, Zander, AC & Lenchine, VV 2012, 'Measurement of the Self-Noise of Microphone Wind Shields', *18th Australasian Fluid Mechanics Conference*, Launceston, Australia.

Zheng, ZC & Tan, BK 2003, 'Reynolds number effects on flow/acoustic mechanisms in spherical windscreens', *Journal of the Acoustical Society of America*, vol. 113, no. 1, pp. 161-166.