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INVESTIGATION ON AEROACOUSTIC EFFECTS INDUCED BY VORTEX SHEDDING FROM CIRCULAR CYLINDER

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ABSTRACT

Aerodynamic noise embraces the disciplines of acoustics and aerodynamics. For the flow around bluff bodies, the primary source of aerodynamic noise generation is vortex shedding. The alternately separating vortices, which constitute the cause of lift forces on the upstream bluff body act as pressure dipole and induce pressure differences in the surrounding fluid. These pressure differences propagate at sound velocity and cause Aeolian tones, in accordance with Strouhal law at the vortex shedding frequency. The objective of this study was to investigate the effect of vortex shedding on the aerodynamic noise level emitted by a circular cylinder. In this paper, the results of an aeroacoustic wind tunnel study in determining the overall sound pressure level (OASPL) are presented. The OASPL is determined by analyzing a circular cylinder with and without spirally wrapped wire (scruton wire) along the cylindrical surface. It is confirmed through this study that adding passive aerodynamic devices such as helical strakes can play a significant role in reducing the coherence of vortex shedding along the bluff body span and hence, can lead to a significant reduction in aerodynamic noise emissions.

Keywords: Aeolian tone, Vortex shedding, Sound pressure level (SPL)

Introduction

Apart from classical acoustics, aerodynamic noise is self-generated rather than being the response to an externally imposed source. The investigation of the flow induced noise has always been of high interest to researchers, as it is closely related to the environmental noise induced by wind streams. Examples of such flow noise can be found in wind turbines, automobiles, cables, transmission lines etc. The aerodynamic noise radiated from the bluff body normal to the air stream is predominantly periodic (tonal character) and is commonly known as vortex noise or Aeolian tones. A practical application of this phenomenon is an Aeolian harp, which is a musical instrument that is played solely by the wind. This traditional instrument consists of strings stretched lengthwise across two bridges. If it is placed, where the wind can blow across the strings then it would produce pleasant sounds. Scientifically, the harp is driven by the von Kármán vortex street. The motion of wind across the string causes periodic vortex shedding and these alternating vortices excite the string, leading to vibrations, i.e. flow induced vibrations. Similarly, when a cylinder is placed normal to air stream, fluctuating lift and drag forces occur and, if the vortex shedding frequency is of an appropriate value, noise is radiated as a result of the fluctuating fluid pressures acting on the cylindrical surface.

Lighthill (1951) did the fundamental study in relating fluid flow and sound generation. He transformed the Navier-Stokes and continuity equations to form an exact inhomogeneous sound wave equation, which is known as Lighthill’s equation. Keefe (1961) experimentally investigated the fluctuating forces on circular cylinders as well as the associated sound field and derived an empirical relation between lift forces and the associated sound pressures. The rapid advancement in numerous transportation systems during recent decades leads to increase in noise pollution and studies revealed that considerable amount of vehicle noise are air borne. Mostly, these systems comprise of bluff bodies such as cylinder and their interaction with the flow often results in undesired noise. This triggered the attention of researchers recently to carry out more studies in order to address this problem. Li et.al (2000) investigated the tonal noise source on aircraft's landing gear and found that in modern aircrafts, undercarriage noise during landing is more dominant than the total airframe noise. Dobrzynski (2010) also presented a detailed study on airframe noise research. Ono et.al (1999) studied the wind noise radiated from high-speed trains and revealed that pantograph systems are the primary source of aerodynamic noise.

Thus it has since long been a topic of interest to study the aeroacoustic effects of cylindrical geometries. The aim of this paper is to determine the Aeolian tone and to investigate the effect of vortex shedding on overall sound pressure level (OASPL) radiated form a circular cylinder, with a case study

Methodology

The study cases are based on a slender circular cylinder of diameter 3 mm and having an aspect ratio (length/diameter) of 15. To investigate the influence of vortex shedding on acoustic pressure, a thin wire of 1 mm thickness is spirally wrapped along the cylinder surface and was spaced uniformly at 8 mm along the cylinder. The dimension details are shown in Figure 1.

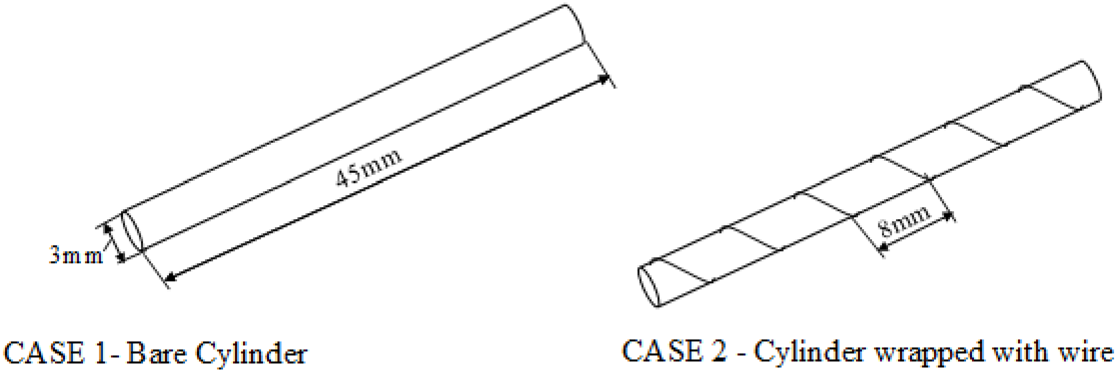

Fig. 1: Configuration of study model with measures of importance.

Wind tunnel tests were carried out to determine the magnitude of aerodynamic noise from the bare cylinder (i.e. cylinder without wire) and the cylinder with spiral arrangement of wire at free stream velocities of 19 m/s, 26 m/s and 32 m/s. The effect of vortex shedding on acoustic pressures is analyzed by comparing both studies cases.

Experimental Setup

The experimental studies were conducted in a 2.0 m x 2.0 m, anechoic wind tunnel facility at the Institute of Sound and Vibration Engineering (ISAVE) under University of Applied Sciences Düsseldorf as shown in Figure 2. The walls of the wind tunnel chamber are acoustically treated with foam wedges and can be considered anechoic at frequencies above

300 Hz. The air outlet duct is of circular cross-section of 0.11 m in diameter. The air blower is operated by a generator and volume flow rate inside the tunnel can be varied by changing the generator frequency. Experiments were conducted at free stream velocities of 19 m/s, 26 m/s and 32 m/s, which approximates to the Reynolds number between 3.5 x 10^3 and 5.8 x 10^3.

Fig. 2: Wind tunnel facility at Institute of Sound and Vibration Engineering (ISAVE).

The acoustic pressure fluctuations were recorded by two 1/4" condenser microphones of ROGA instruments (Type RG-50) having sensitivity of 50.9 mV/Pa. The microphone 1 is placed in near field, midspan of the mounted cylinder and at a vertical distance of 0.20 m top of the test specimen, whereas the microphone 2 is placed in far field at a distance of 1.70 m apart from the test specimen. Figure 3 shows a schematic representation of test setup. The measured analog signals are digitalized by using a "Plug.n.DAQ" soundboard of ROGA instruments. The instantaneous acoustic pressure fluctuations are recorded and averaged for 40 seconds at a sampling frequency of 48000 Hz in order to achieve characteristic and reliable results. The recorded signals of each test case are analyzed using PAK automotive software.

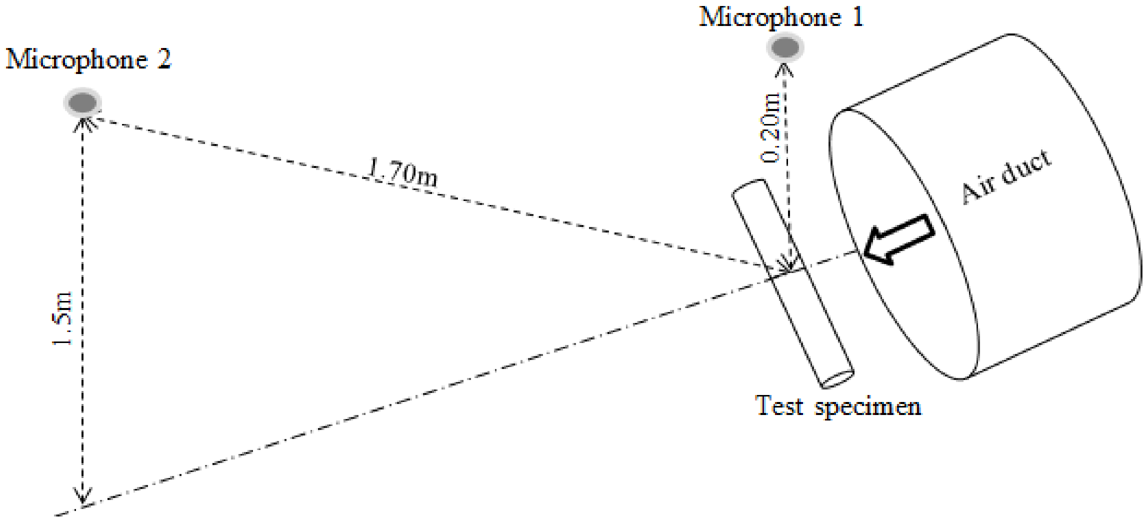

Fig. 3: Schematic representation of test setup

Results and Discussions

For each test case, frequency analysis via Fast Fourier Transform (FFT) was carried out, where the sound pressure level (SPL) can be determined according to Eq. (1).

$$SPL = 20\log_{10}\frac{p_{rms}}{p_0} \qquad (1)$$

Where p_{rms} is the root mean square value of recorded sound pressure and p_0 represents the reference sound pressure, equivalent to 2×10^{-5} Pa. Figure 4 shows the narrow band spectrum of the background noise level determined from the microphone signal. The sound pressure level of the air flow inside the acoustic tunnel, without subjecting the test specimen in the fluid flow, specifies the background noise condition for the studied scenario.

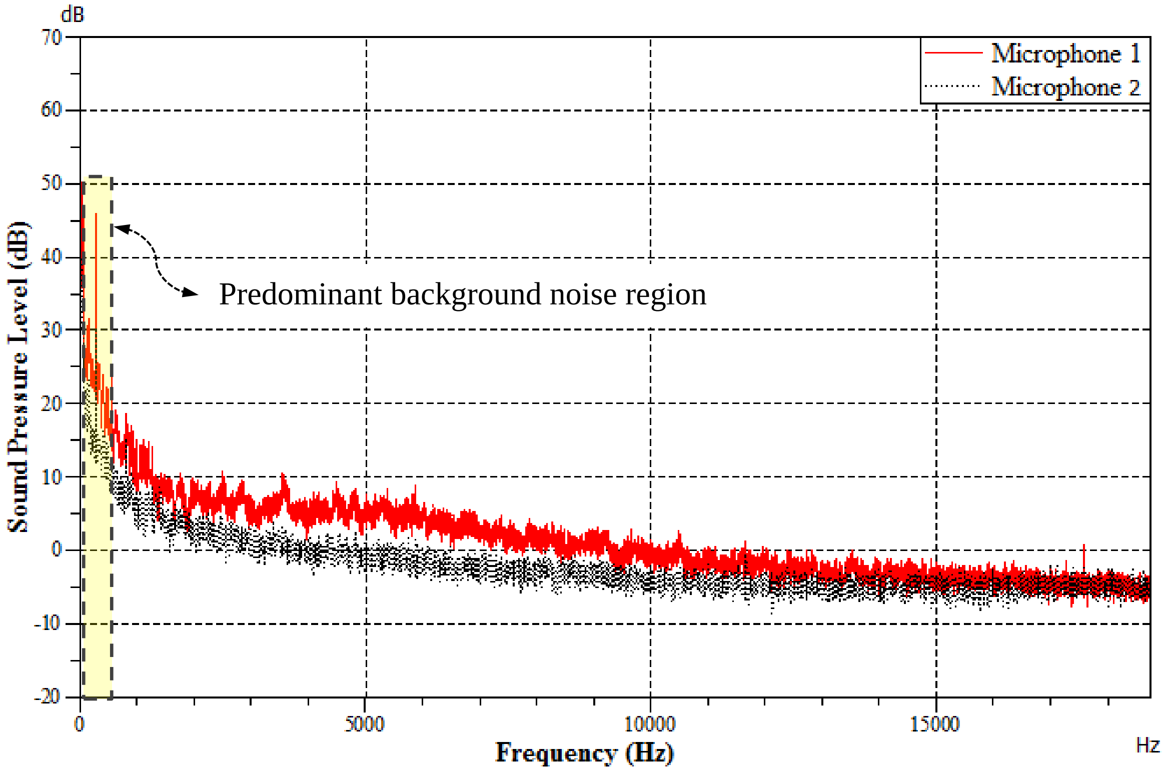

Fig. 4: Comparison of background noise level at near field (Mic 1) and far field (Mic 2).

The plotted sound pressure levels indicate that microphone 1 (near field) captures a significant part of the air flow broadband noise compared to microphone 2 (far field) which shows to have lower peaks in a frequency range of 1 kHz ≤ f ≤ 10 kHz. It indicates that the broadband free jet noise is predominantly located in this frequency band. This seems sensible in accordance with the locations of microphones, as the microphone 1 is close to the air exhaust duct. It is also noticed that the background noise condition is predominant in the lower frequency band, especially around less than 300 Hz. This reveals that the anechoic efficiency of the wind tunnel is above 300 Hz. Hence, the very low frequency signals are subjected to more amplification due to reflection from the tunnel walls. However, the combined effect of reflective nature of the wind tunnel and electrical noises at the very low frequencies imparted the microphone responses to show greater amplitude at the very low frequency bands.

Figure 5 indicates the acoustic spectra of the radiated aerodynamic noise by mounting the bare cylinder (i.e. cylinder without wire) in the free jet of the wind tunnel outlet section. The effect of different air speeds of 19 m/s, 26 m/s and 32 m/s on the sound pressure level was analyzed by use of data, recorded by the near field microphone 1.

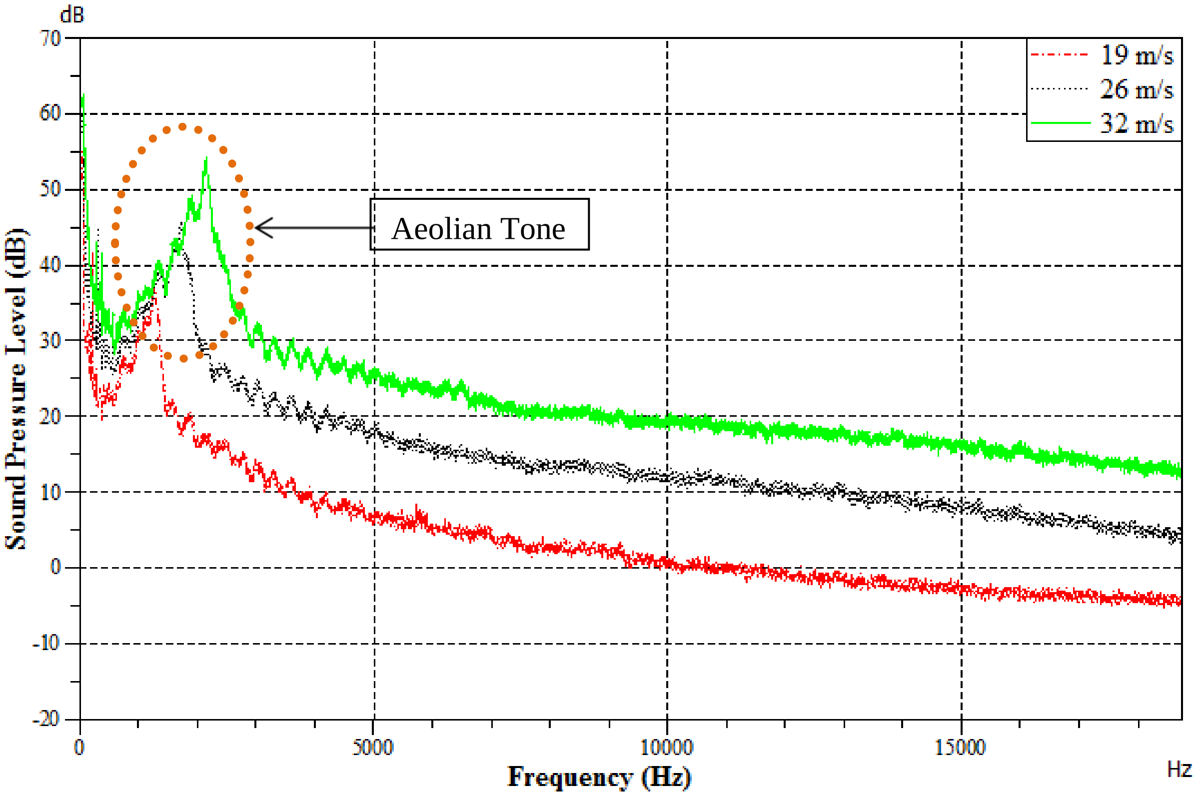

Fig. 5: Comparison of acoustic spectra of bare cylinder at different air speeds - Microphone 1

In the frequency range (~1 kHz to 2.5 kHz), a peak was observed at all measured air speeds and also noticed that the intensity of this peak increases, as the flow speed increases from 19 m/s to 32 m/s. These peaks represent the Aeolian tones generated by the circular cylinder. The rise in flow velocity increases the vortex shedding frequency, which enhances more pressure difference per unit time in the surrounding fluid, consequently the Aeolian tone magnitude increases.

Table 1 lists the predicted vortex shedding frequencies and the corresponding Aeolian tone levels radiated by the bare cylinder at different air speeds, analyzed from microphone 1 measurement.

Table 1: Vortex shedding frequency and Aeolian tone

Flow Speed (m/s)	Vortex shedding frequency (Hz)	Aeolian tone (dB)
19	1272	38
26	1726	46
32	2140	54

Figure 6 illustrates the acoustic spectra of aerodynamic noise from bare cylinder, analyzed from microphone 2 (far field) recordings.

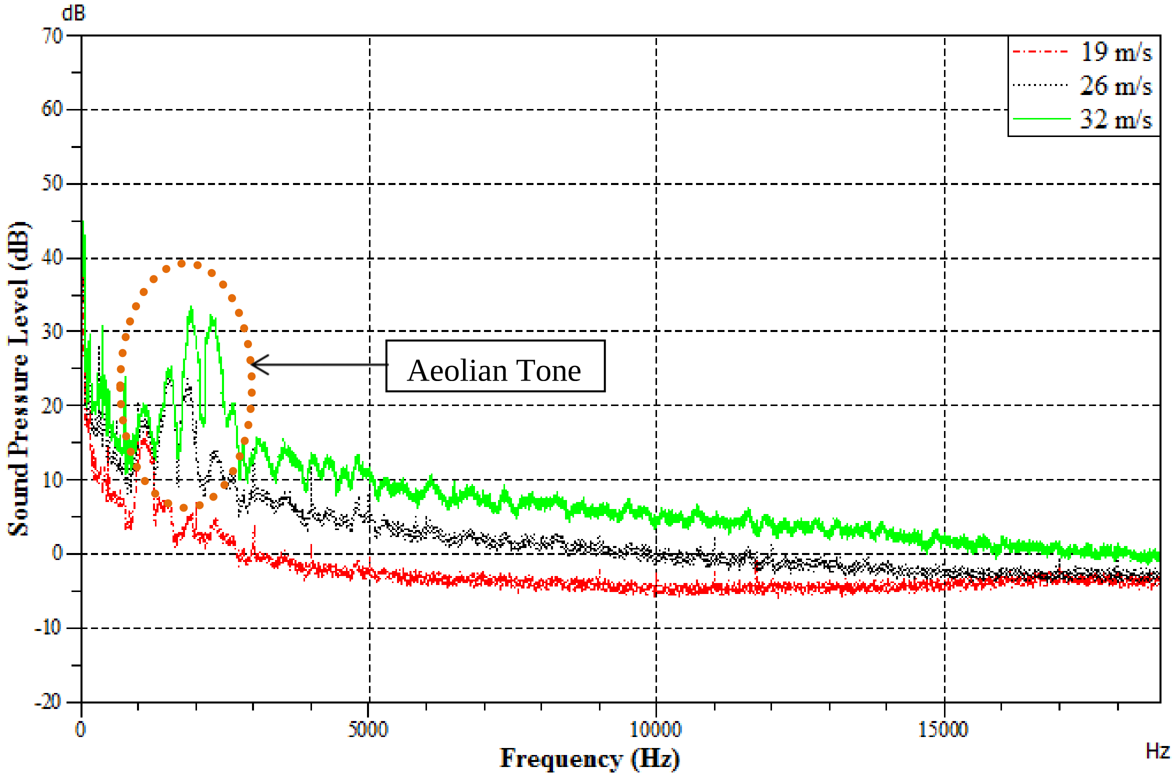

Fig. 6: Comparison of acoustic spectra of bare cylinder at different air speeds - Microphone 2

From figure 6, it is revealed that the microphone 2 is subjected to more fluctuating signal condition. The Aeolian tone levels predicted from microphone 2 measurements undergone about 40-60% reduction compared to microphone 1. This is mainly due to its location at far field and the disturbances created by the recirculation of air flow hitting the end walls of the tunnel.

To verify the correlation in response characteristics of two microphone channels, the coherence function was calculated. Mathematically, the coherence, γ^2 (f) is given by Eq. (2).

$$\gamma^2(\mathrm{f}) = \frac{|G_{12}(f)|^2}{|G_{11}(f) \times G_{22}(f)|} \qquad (2)$$

Where, G_{11}(f) and G_{22}(f) are the auto power spectra of microphone channels 1 and 2, respectively and G_{12}(f) is the cross power spectra of two microphone channels.

Figures 7 shows the coherence function analyzed from the two microphone responses at free stream velocity of 32 m/s. From the coherence plot, it can be inferred that the overall response characteristics at two channels are in good agreement in the vortex shedding frequency region (~1 kHz to 2.5 kHz). However, the far field position and the recirculation of airflow hitting the end walls of the wind tunnel contribute more disturbances in the performance of microphone 2.

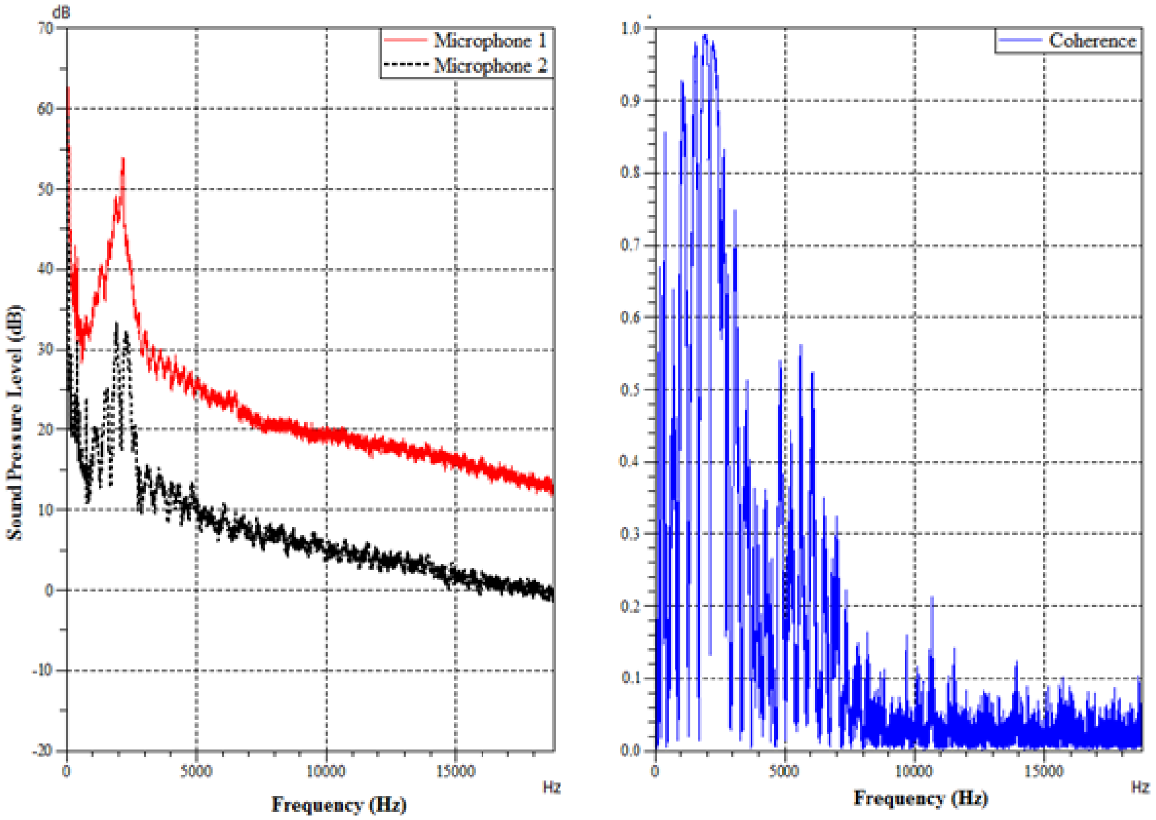

Fig. 7: Narrow band spectrum (left) and Coherence (right) of far field and near field signal.

Considering the specific aim of the study, which is to investigate the Aeolian tone and for the sake of simplicity, the results presented in detail for the comparison between different test cases are from microphone 1 measurements only.

Figure 8 shows the comparison of Aeolian tones generated by the cylinder with and without the spiral arrangement of thin wire on its surface. The spiral arrangement of wires around the cylinder surface increases the surface roughness and thereby altered the flow separation around the cylinder. Although, it affected the shedding of alternate pairs of vortices around the cylinder, changing the turbulence length scales and hence the aerodynamic change in flow pattern, results in a significant reduction in Aeolian tone. The Aeolian tones predicted for the tested configuration noticed about 30% reduction compared to the test case of the bare cylinder.

The net aerodynamic noise level in each test case was calculated in terms of overall sound pressure level (OASPL) by energetic summation of the sound pressure level (SPL) along the frequencies. Mathematically, OASPL is given by Eq. (3).

$$OASPL = 10\log_{10}\left(\sum_i 10^{SPL_i/10}\right) \qquad (3)$$

Where, SPL_i is sound pressure level of ith frequency for the corresponding air velocity.

Figure 9 shows the comparison of overall sound pressure level calculated for each test case - with and without spiral arrangement of wire around the cylinder surface at different free stream velocity.

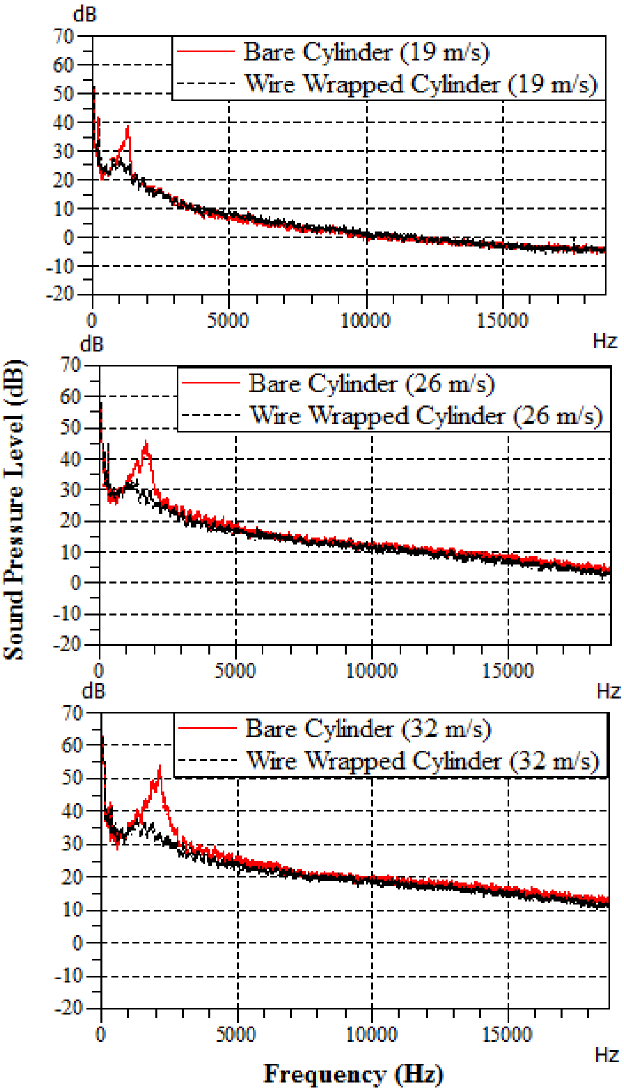

Fig. 8: Comparison of Narrow band spectrum - cylinder without and with spiral wire

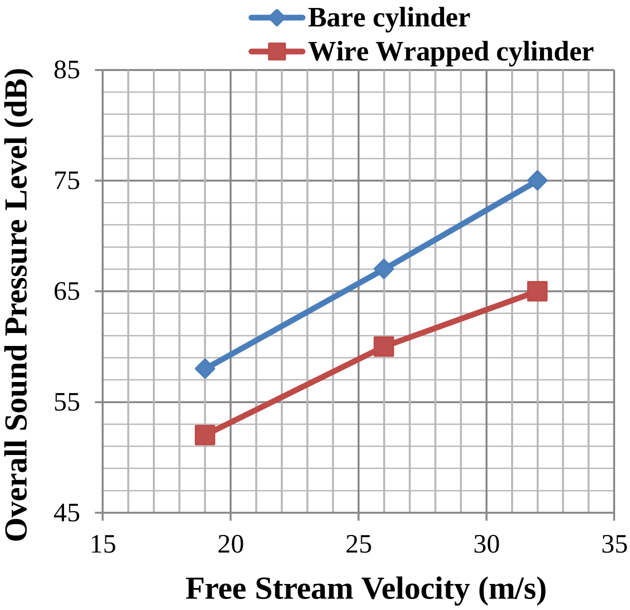

Fig. 9: Comparison of the overall sound pressure level at different free stream velocities

The overall sound pressure levels calculated was subjected to frequency weighting type A, to resemble the acoustic response of human ear. Also, for estimating the OASPL, the frequency spectra above 300 Hz were only considered, as the range below it are composed of high level of electrical noises and amplified signals due to reflection from tunnel wall. The mitigation of vortex shedding results a reduction in overall aerodynamic noise level emission, around 10-14% in the studied case type. By close comparison with the Aeolian tone and overall sound pressure level, it can be concluded that for a smooth cylindrical surface, Aeolian tone contributes about 70% of overall aerodynamic noise generation.

There had been some previous works in theoretical predication of overall sound pressure level. A remarkable one was done by Phillips (1956) and stated that the mean square acoustic pressure, $\overline{p}^2$ at points, distant r from the cylinder of length L and diameter d can be expressed by Eq. (4).

$$\bar{p}^2 = 0.037\, cos^2\,\theta \frac{\rho^2 \mathrm{Ld} St^2 U^6}{a^2\, r^2} \qquad (4)$$

Where, θ is defined as the angle between direction of observation and incoming stream, ρ is the fluid density, St is the Strouhal number, U is the free stream velocity and a is the velocity of sound in air. Figure 10, graphically depicts the comparison of overall sound pressure level from a bare cylinder by Phillips equation and the current experimental study.

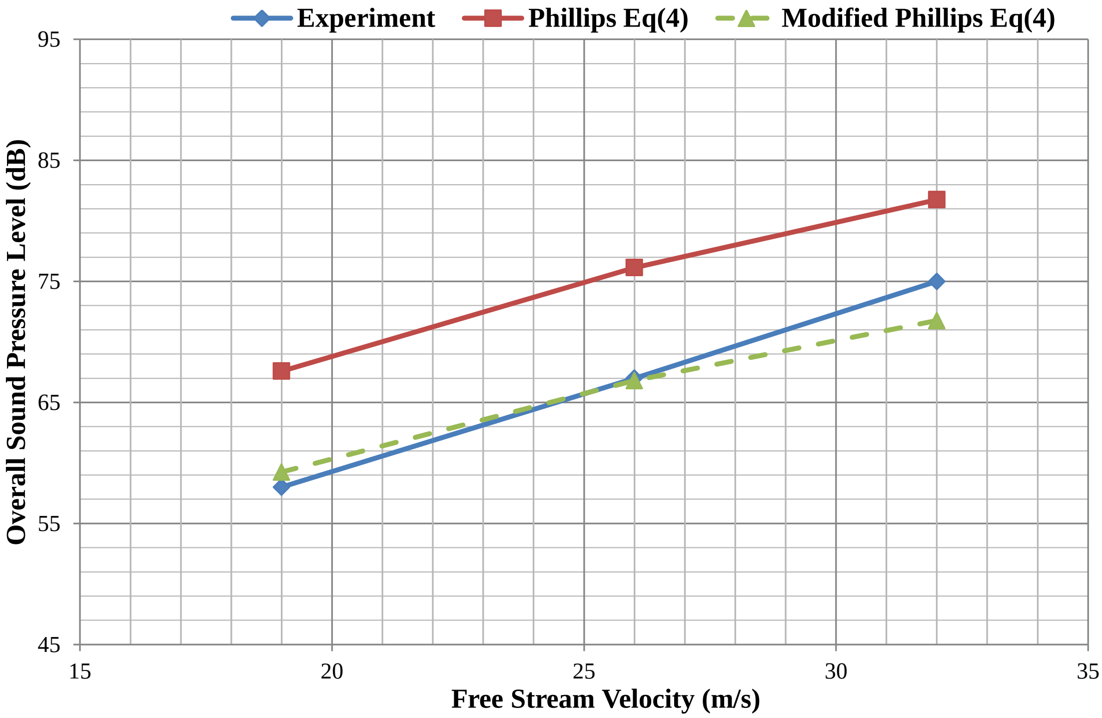

Fig. 10: Experiment vs. Theory

It can be inferred that the theoretical prediction is over conservative. The overall sound pressure levels estimated by theoretical equation are about 6 to 10 dB higher, compared to experimental results. The experimentally recorded aerodynamic noise is not perfectly proportional to the sixth power of mean airflow speed, identified as the reason for this discrepancy. The study done by Ogawa et.al (2016) on aerodynamic noise generated from the leading edge of delta wings also concluded that the characteristics of aerodynamic noise intensity radiated from the vortex system increases in proportion to 5th to 6th power of free stream velocity. For the studied case, the aerodynamic noise is proportional to about 5.3th power of free stream velocity. The squared mean sound pressure as stated in Eq. (4) is proportional to the sound power in three dimensional acoustical fields. The increase in flow speed by about 50% leads to intensify the sound power by 11 dB, in scaling with 6th power of the velocity, whereas reducing the velocity exponent to 5.3 yields an increase of solely 9 dB. From Figure 10, it is clear that the modified Phillips equation with velocity exponent 5.3 shows good agreement with the experimental results.

Concluding Remarks

It is confirmed through this study that vortex shedding is the primary source of high level of aerodynamic noise emission from bluff bodies. Passive aerodynamic devices such as helical strakes, shrouds, slats etc. on the parent body can play a significant role in altering vortex shedding characteristics and hence, reduction in noise level. So special attention need to be given for this type of elements in low noise design process. For the particular case studied, the effect of wrapping thin wires around the cylindrical surface was to reduce the Aeolian tone magnitude by about 30%. The effect of passive aerodynamic devices on aeroacoustic emissions can be varied by the inclusion of different configurations and combinations of these elements. The parameters such as the protrusion of passive aerodynamic elements from the parent body, the spacing between adjacent elements and the subjected flow conditions such as Reynolds number should be considered in detail.

It is also revealed that the theoretical predictions are over conservative, even though it can be used as a reasonable estimation to quantify the aerodynamic noise level. For accurate results, wind tunnel tests are needed. Moreover, properly designed testing conditions and well-planned layout of data acquisition is crucial in accurately measuring the aerodynamic noise levels.

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