The Effect of Porosity on the Porous Coated Cylinder Diameter

Elias Arcondoulis and Yu Liu

Department of Mechanics and Aerospace Engineering, Southern University of Science and Technology, Shenzhen, China.

ABSTRACT
Cylinders placed in uniform flow produce a vortex shedding tone that can be observed in many commercial and industrial applications, such as chimney stacks, high-speed train pantographs, power lines and aircraft landing gear. Porous coating treatments have been effective at weakening this vortex shedding tone. The true outer diameter of a porous coated cylinder is uncertain, as the outer surface area decreases with increasing porosity, thus making the Strouhal number estimation of the cylinder difficult. An experimental investigation is presented in this paper. The investigated cylinders are three polyurethane coated cylinders with outer diameters of 60 mm and varying porosity coating thicknesses of 10 mm, and two bare cylinders with outer diameters of 40 mm and 60 mm. Far-field acoustic measurements conducted in an anechoic wind tunnel were obtained at four flow speeds, between 20 m/s and 40 m/s. From these data, a relationship between an effective porous coated cylinder diameter and porosity is presented.

1 INTRODUCTION
Passive flow control methods have become increasingly important and popular in commercial and industrial applications that display bluff body aeroacoustic noise. Porous coatings of bluff bodies is a relatively new passive method of flow control. The investigation of porous coated cylinders is of specific interest, as the cylinder can pose as a simplistic representation of typical noisy engineering components due to fluid-structure interaction, such as aircraft landing gear (Boorsma et al., 2009) and parts of high speed train pantographs (Sueki et al., 2009). Vortex shedding control of a cylinder was investigated by Zradkovich (1981) who applied a metal foam coating to a cylinder surface to minimise the effects of vortex shedding. Sueki et al. (2009) experimentally showed that the material type (i.e., comparing metal foam to polyurethane) had little or no impact on the measured noise reduction. The typical experimentally investigated pore density range (Pores Per Inch: PPI) using metal foam and polyurethane is from 10 PPI to 30 PPI (Sueki et al., 2009; Sueki et al., 2010; Ruck et al., 2011; Aguiar et. al., 2016; Yuan et al., 2016) with significant vortex shedding tone reduction observed using 10 PPI materials (Sueki et al., 2010; Aguiar et. al, 2016; Arcondoulis et al., 2018). These PPI ranges correspond to porosities of 80% to 95%, where the porosity here is the ratio of the porous media volume to its solid equivalent.

Uncertainty exists regarding the Strouhal number (*St*) related to the tone(s) recorded from a porous coated cylinder in uniform flow. The Strouhal number is defined as

$$St = \frac{fD}{U} \tag{1}$$

where *f* is the vortex shedding frequency (Hz), *D* is the characteristic length that causes the vortex shedding, (m) (corresponding to the cylinder diameter in this paper) and *U* is the freestream velocity (m/s).

There exists controversy regarding the porous cylinder outer diameter, i.e., the diameter that is responsible for the vortex shedding behaviour and the Strouhal number evaluation as presented in Equation 1. The inner diameter and outer cylinder diameter have been used in order to understand the porous coated cylinder vortex shedding tone behaviour in the aforementioned studies yet there is no consensus on which diameter is responsible for the vortex shedding behaviour. In order to accurately predict the shedding tone(s) of a porous coated cylinder, the effect of the porous coating on the cylinder outer diameter needs to be understood and whether the recorded tone(s) are due to the typical cylinder vortex shedding processes. A preliminary investigation of the effective cylinder diameter with respect to the vortex shedding Strouhal number is presented here.

2 EXPERIMENTAL FACILITY AND PROCEDURES

2.1 Cylinder Models

Five (5) cylinders were investigated in this study; two bare cylinders with 40 mm and 60 mm outer diameters and three porous coated cylinders each with 60 mm outer diameters. A basic polyurethane foam material was selected for the porous coated cylinders used in this study. Each of the porous coated cylinders possessed different PPI and thus porosity, ϕ, as presented in Figure 1. The range of PPI was restricted by the availability of materials by local suppliers. The polyurethane porous covers were cut directly from solid polyurethane blocks in tubular sections. This ensured that no distinct seam regions would be present that could potentially affect the porous structure. The polyurethane material possesses open cell randomised pores.

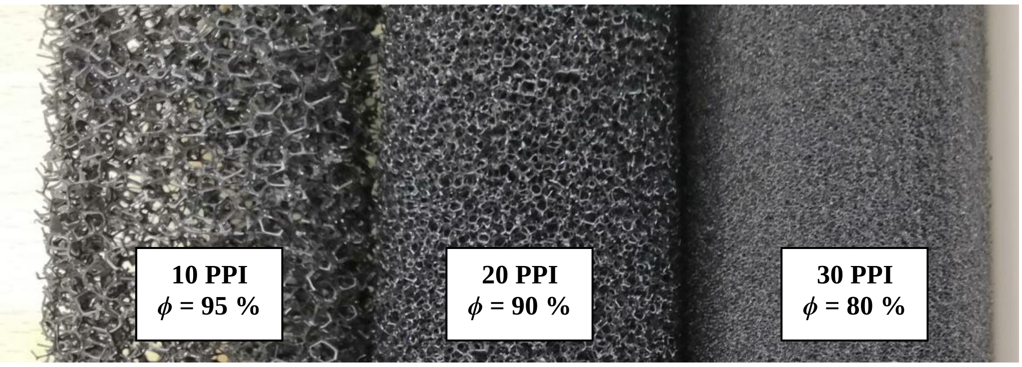

Figure 1: The polyurethane cylindrical coatings used in this study.

In this study ϕ (%) is defined as

$$\phi = 100 \times \left(1 - \frac{V_{PCC}}{V_S}\right) \tag{2}$$

where V_{PCC} is the volume of the polyurethane porous coating and V_S is the volume of a solid annular cylinder with inner diameter 40 mm and outer diameter 60 mm. Each of the polyurethane coatings were weighed and divided by their material density to determine V_{PCC}.

2.2 Anechoic Wind Tunnel Facility

Acoustic measurements were obtained at the Key Laboratory of Aerodynamic Noise Control, China Aerodynamics Research and Development Center (CARDC) in Mianyang, China, as shown in Figure 2. The closed-circuit aeroacoustic wind tunnel used in this study has a test section area of 550 mm (wide) × 400 mm (high), shown in Figure 2a. The turbulence intensity is ≤ 0.08% when using an open test section configuration and the blockage ratio using a 60 mm diameter cylinder is less than 11%. The chamber is acoustically treated using perforated wedges attached to the chamber walls and the flow collector is covered in acoustic foam that can be seen in Figure 2b.

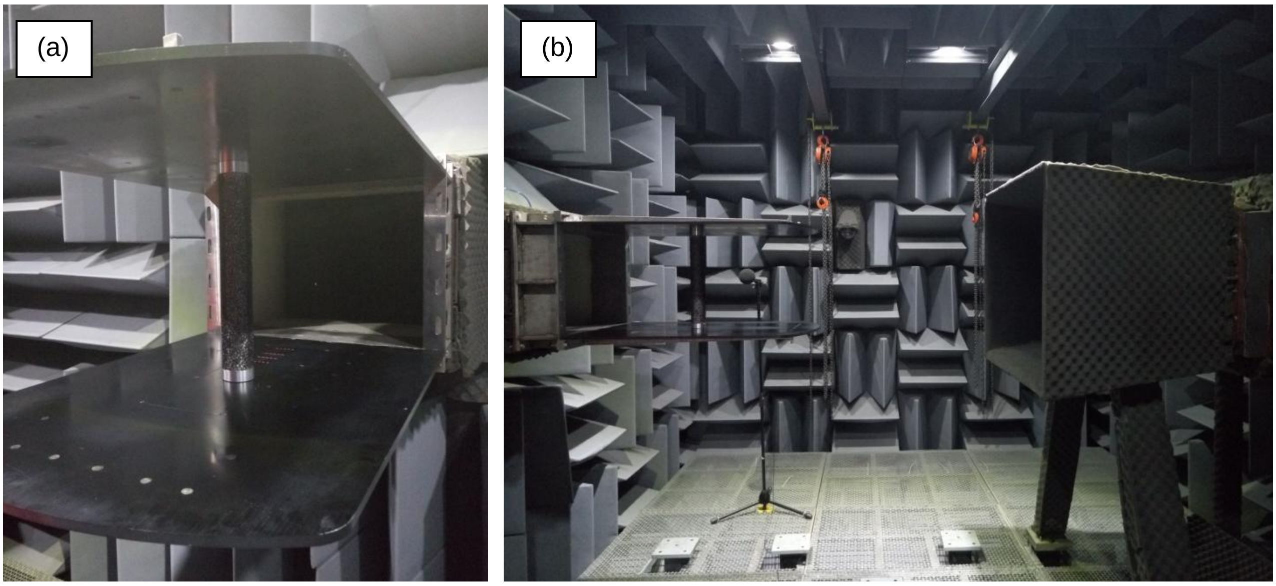

Figure 2: The 550 mm × 400 mm Aeroacoustic Wind Tunnel in CARDC, Mianyang
(a) The 10 PPI cylinder installed between the test section plates (b) The test facility side-view, where flow is from left to right.

2.3 Experimental Methods

Each cylinder was placed in a uniform flow of U = 20, 25, 30 and 40 m/s, corresponding to a Reynolds number, Re, of 0.8×10^5 to 1.6×10^5 for the 60 mm diameter cylinders. These flow speeds are selected to correspond with the Reynolds numbers of previous porous coated cylinder studies (Sueki et. al, 2010; Naito and Fukagata, 2012; Liu and Azarpeyvand, 2016; Arcondoulis et al., 2018). The Reynolds number terms are not further quoted in this paper due to the investigation of the porous coated cylinder outer diameter that could lead to potentially misleading and confusing Reynolds number values. A schematic diagram representing the testing configuration is presented in Figure 3 identifying the test section, cylinder and microphone location.

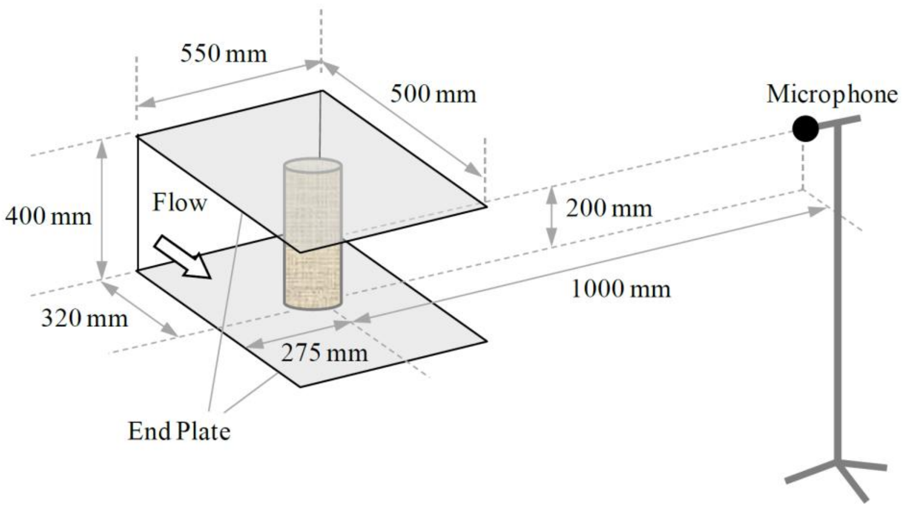

Figure 3: Schematic diagram representing the testing configuration.

Acoustic data were collected using a single Brüel & Kjær (B&K) 1/2" free-field microphone positioned in the acoustic far field to determine the Power Spectral Density (PSD) of the self-noise of the cylinders placed in uniform flow. Measurements were obtained at a sampling rate of 2^{15} = 32,678 Hz over a sampling period of 16 seconds. High and low pass filters were set at 30 Hz and 20,000 Hz respectively. The MATLAB pwelch function was used to produce estimates of the PSD. The data were segmented into eight equal lengths that were windowed using a Hanning window of equal length of each length. The PSD (Pa/Hz) are presented with 1 Hz resolution.

Figure 4 displays the background noise spectra at the flow speeds considered in this study. At the maximum considered flow speed of U = 40 m/s, the background noise is observed to be 64 dB or less at a frequency greater than 50 Hz.

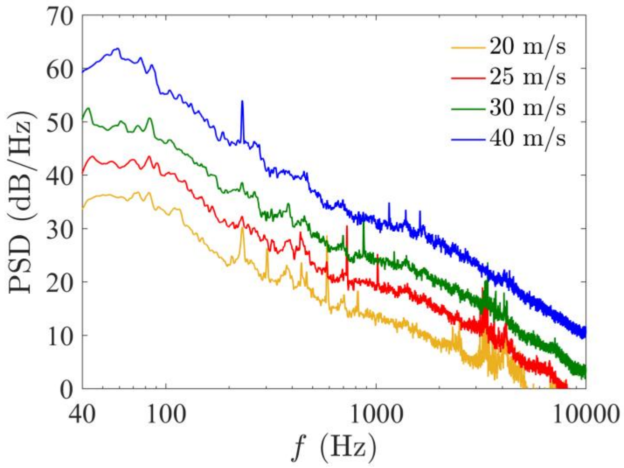

Figure 4: Recorded background noise measurements for U = 20, 25, 30 and 40 m/s.

3 RESULTS

3.1 Acoustic Spectra

The measured acoustic PSD of the 40 mm and 60 mm bare cylinders and the 60 mm polyurethane coated cylinders (PCCs) are presented in Figures 5 and 6 for U = 20, 25, 30 m/s and 40 m/s respectively. Enlargements of the figures are presented on the right-hand side to help illustrate differences in tone characteristics. It can be easily observed that applying a polyurethane porous coating causes significant reduction of the vortex shedding tone produced by the bare cylinder, for any of the porosities considered in this study. Each PCC displays two tones, which is consistent with the results of Geyer et. al (2015) and other porous coated media, such as a structured porous coating and similar porosity metal foam (Arcondoulis et al., 2018).

Upon initial inspection the lower frequency tone of the two appears to correspond to the vortex shedding tone of the outer diameter, D = 60 mm, due to its corresponding Strouhal number laying within the range of 0.16 to 0.18 (these Strouhal number data are further discussed and presented in Figure 8). The higher frequency tone, in all flow cases and for all PCC cylinder types, is twice the lower tone frequency. Typically such a tone would be recognised as a primary harmonic of the shedding tone; however, its magnitude in most cases exceeds the shedding tone magnitude, significantly so at the higher Reynolds numbers investigated here. Consideration was given to any resonances within the test section and other non-anechoic facility effects that may cause strong reflections and thus amplifications of specific frequencies, yet if they were to exist, such strong secondary tone behaviour would also be observed with the bare cylinder shedding frequency, yet this data very closely matches theory and extensive published data (Norberg, 2003).

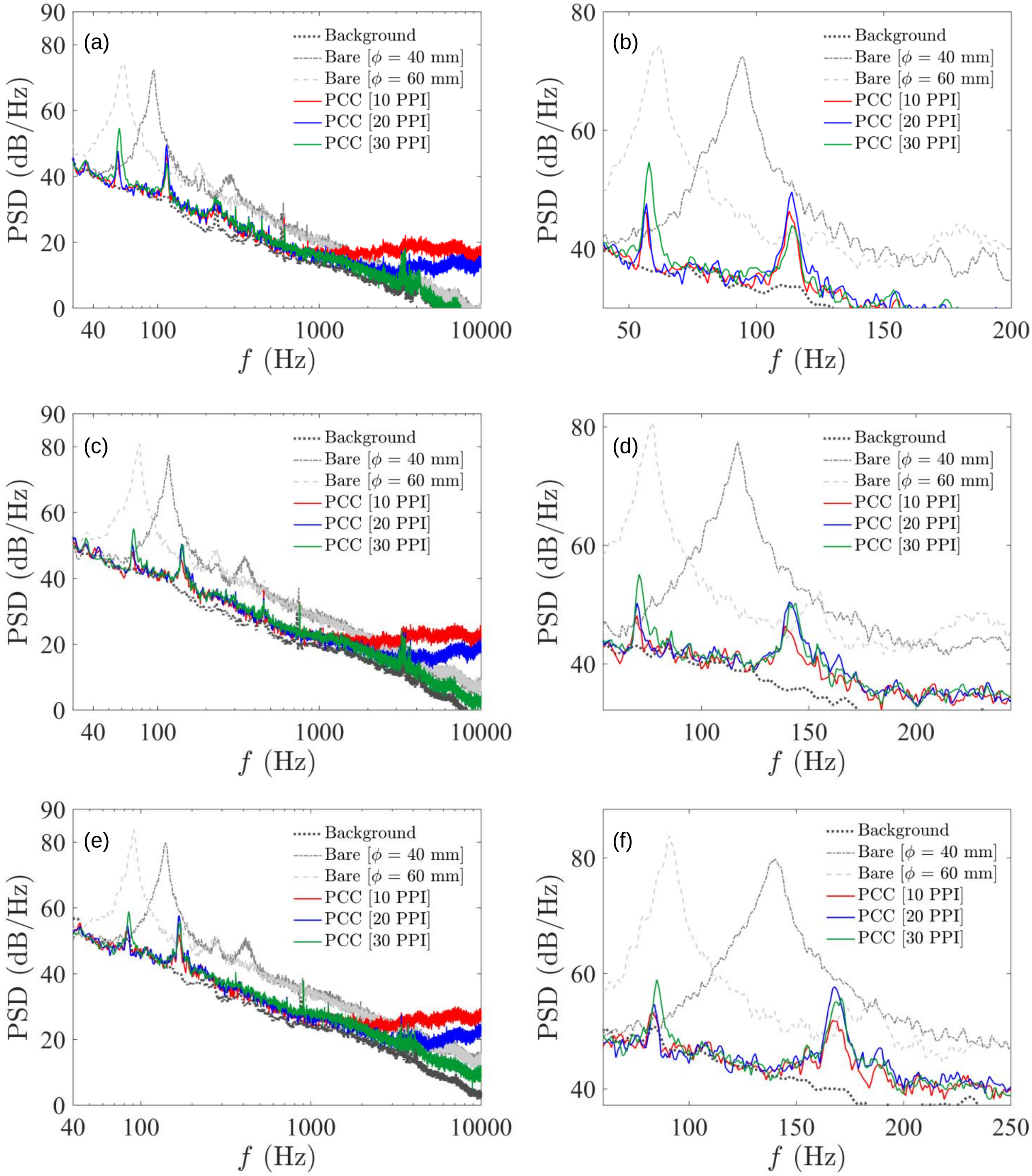

Figure 5: Polyurethane porous coated cylinder acoustic spectra (left) and enlargements of the spectra (right) at (a)(b) U = 20 m/s, (c)(d) U = 25 m/s and (e)(f) U = 30 m/s.

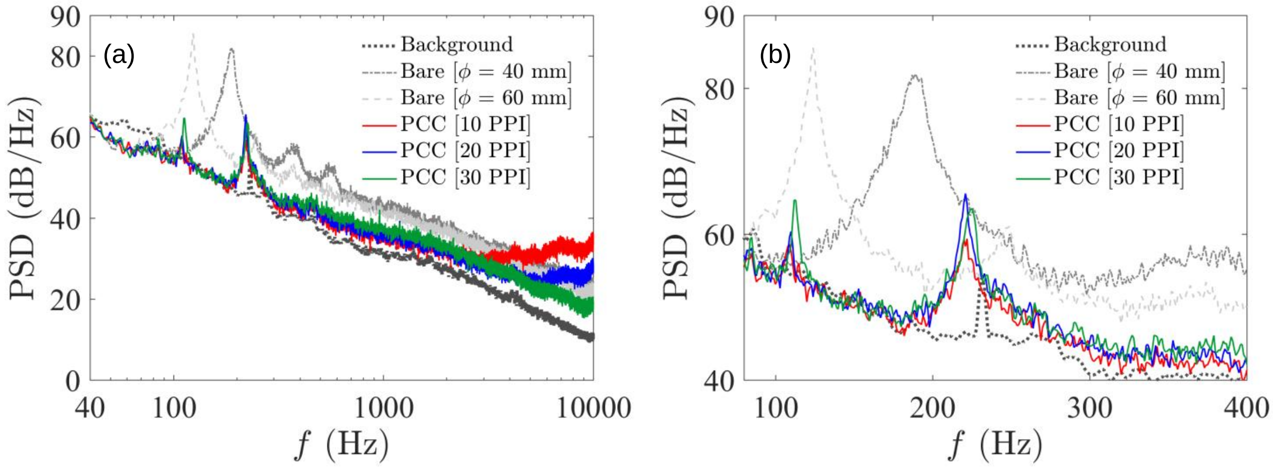

Figure 6: Polyurethane porous coated cylinder acoustic spectra (a) and enlargements of the spectra (b) at *U* = 40 m/s.

The higher-frequency content of the acoustic spectra *(f* > 1000 Hz) shows variation with respect to PPI. It can be seen that the high-frequency broadband contribution magnitude increases with decreasing PPI (increasing porosity). This is likely due to the larger pore structures producing stronger coherent cavity modes where the incoming freestream flow is capable of penetrating the porous coating, whereas at higher PPI (lower porosity) the flow is less capable of penetrating the porous coating. This theory is supported by comparing the 10 PPI and 20 PPI data, where the increase in broadband noise for the 20 PPI PPC occurs at a higher frequency than the 10 PPI PCC. Furthermore, the pore sizes are significantly smaller and if cavity modes are responsible for this higher frequency contribution, they will occur at much higher (possibly ultrasonic) frequencies.

The broadband noise level at frequencies greater than the recorded tones and less than the aforementioned broadband noise increase, is typically less than the bare cylinder spectral level. This shows that the PCCs possess some broadband noise reduction flow mechanisms in addition to tonal noise reduction mechanisms, which is also observed by Geyer et al. (2015) and Arcondoulis et al. (2018).

3.2 Tone Magnitudes

The magnitudes of the tones for all cylinders are recorded and presented in Figure 7. It can be observed that the lower and higher PCC tones follow a similar tone magnitude increase with respect to increasing velocity. The difference between the bare cylinder and PCC tones appears to decrease with increasing flow speed (i.e., the noise reduction properties of the porous coating decreases with increasing flow speed). The ratio of the lower and higher frequency tones for the PCCs does not appear to follow a noticeable trend with either porosity, PPI and / or flow speed. This leads to further uncertainty regarding the existence of this secondary higher frequency tone and its generating mechanism. In addition, if the ratio of tone magnitude between the lower and higher frequency tones were near-constant, this would provide some evidence of this higher frequency tone being a harmonic of the lower frequency tone.

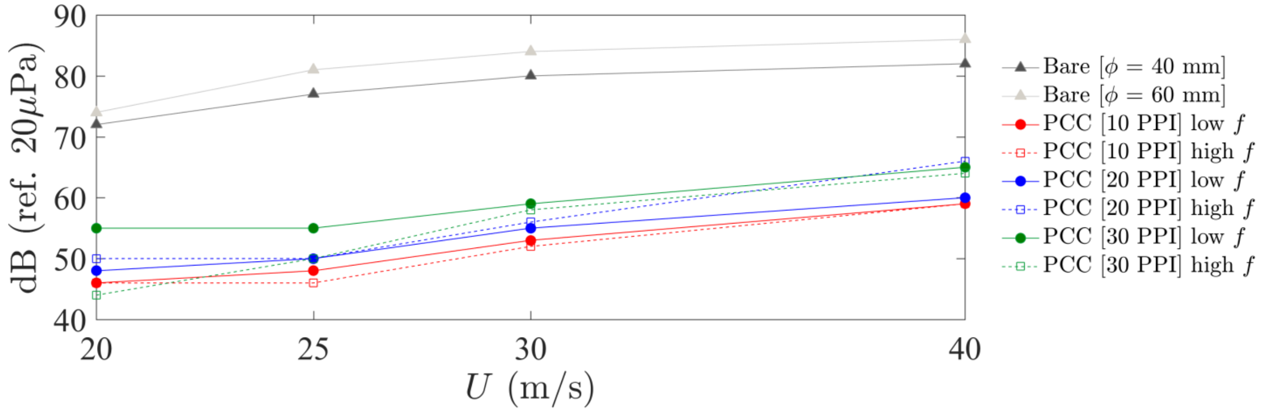

Figure 7: Cylinder tone magnitude variation with respect to varying flow speed and porous coating porosity. Low *f* and high *f* denote the lower and higher frequency tones shed by the porous coated cylinders, respectively.

3.3 Strouhal Number

The Strouhal number of the bare 60 mm cylinder and the polyurethane coated cylinders are calculated based on *D* = 60 mm, the lower-frequency tone they produce and the freestream velocity. The Strouhal numbers are presented in Figure 8. The 40 mm diameter and 60 mm diameter bare cylinders produce Strouhal numbers of *St* = 0.188 (not shown) and 0.186 respectively, which provides very good agreement with the collated experimental data and prediction envelope of Norberg (2003). It can be observed that with increasing porosity, the Strouhal number decreases, with a larger rate of decrease at higher flow speeds.

It should be noted that the 40 mm diameter bare cylinder data (i.e., theoretically corresponding to ϕ = 100%) are omitted from Figure 8 as its Strouhal number would cause a sharp discontinuous change in *St* with respect to porosity. The intention of this chart is to show the required adjustment of the PCC outer diameter, whereas the Strouhal number of the 40 mm bare cylinder is accurately obtained using its true outer diameter of 40 mm.

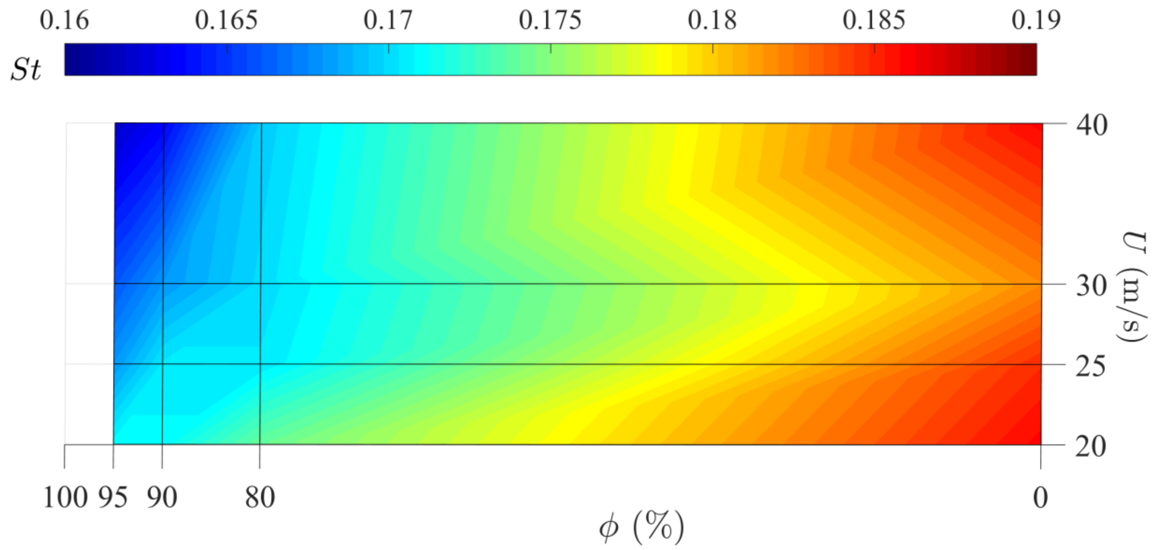

Figure 8: Strouhal number spectrogram for the polyurethane porous coated cylinders and bare 60 mm diameter cylinder, subject to various flow speeds. The shaded values (not coincident with the black lines) are interpolated between the experimentally obtained values.

4 EFFECTIVE DIAMETER ANALYSIS

Assuming that the vortex shedding behaviour of the porous coated cylinder is the same as the bare cylinders, they should possess the same Strouhal number as the bare cylinders (i.e., the spectrogram data presented in Figure 8 should have near-constant values that correspond to the 60 mm diameter bare cylinder Strouhal number calculated at ϕ = 0%).

Consider the following: at U = 20 m/s, the 40 mm and 60 mm bare cylinders have St = 0.188 and 0.186 respectively. By investigating the PCCs, and assuming a 60 mm outer diameter, St = 0.174, 0.171 and 0.171 for the 30, 20 and 10 PPI cases respectively for the lower frequency tone. Therefore in order for the porous coated cylinders to possess the same Strouhal number as the bare 60 mm cylinder, their effective diameter must increase to 64.1 mm, 65.3 mm and 65.3 mm respectively, as calculated using Equation 1. This analysis can be repeated using the 40 mm bare cylinder diameter as a reference, such that the effective diameter increases to the similar values (the Strouhal numbers of the 40 mm and 60 mm bare cylinders differ slightly). A summary of the effective diameters for the flow speeds considered in this study is presented in Figure 9.

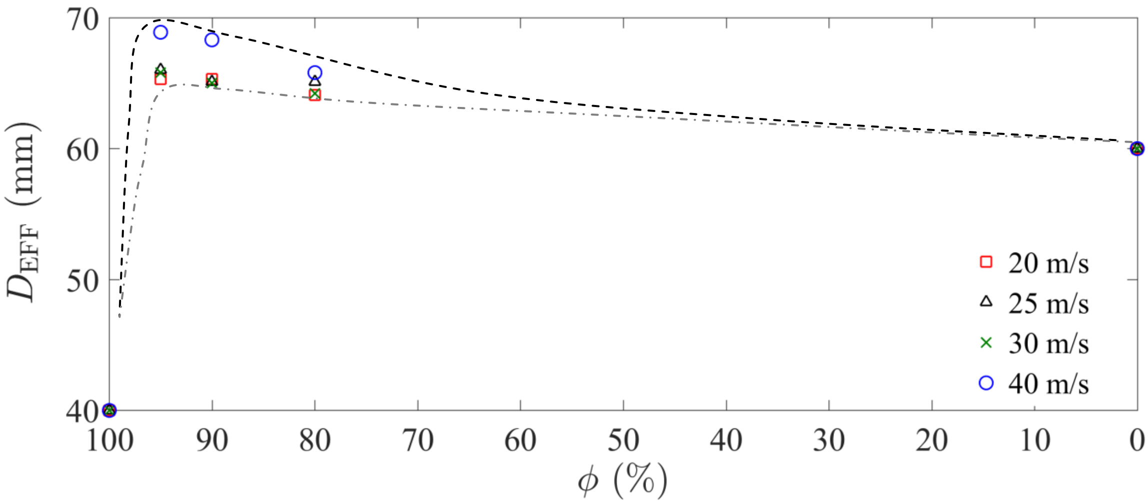

Figure 9: Calculated effective porous coated cylinder outer diameters (D_{EFF}), in order to match the Strouhal number of the bare 60 mm diameter cylinder. Dashed lines are drawn to show a predicted envelope that encases the effective diameter relationship with porosity.

Upon initial inspection, an increase of cylinder diameter may appear counterintuitive, in that one may expect the effective cylinder diameter to lie somewhere between the 40 mm and 60 mm cylinder diameters, as the increased porosity can be viewed as a reduction of material from a solid 60 mm cylinder to a solid 40 mm cylinder. However, the fluid-structure interaction of the porous media on the cylinder outer surface cannot be assumed to be smooth like the bare cylinders. The coarse fibre-like structure of the polyurethane porous media can be viewed as an extremely rough surface. For cylinders with sufficient surface roughness, the boundary layer transitions to turbulence earlier than a bare cylinder (Achenbach and Heinecke, 1981). Thus the PCCs considered here are likely to produce a very thick boundary layer around the porous coating, such that vortices are shed from a disproportionately thicker cylinder than a bare cylinder of the same outer diameter. This would generate vortex shedding of increased length scales and thus decreased shedding tone frequencies. Using smoke wire visualisation significant increases in boundary layer thickness and an expanded wake region were observed by Yuan et al. (2016), who investigated polyurethane porous coated cylinders (ranging from 10 PPI to 30 PPI) relative to bare cylinder observations of the same diameter.

Due to the highly porous nature of the polyurethane coatings, the data are clustered at high porosities and thus no data is available at lower porosities. Nonetheless, a trend can be observed between porosity and effective diameter that is consistent at each flow speed considered. A predicted envelope is shown in Figure 9 that encompasses the effective cylinder diameters. It can be observed that with increasing porosity from 0% to 90% the effective cylinder diameter increases slightly. Between porosities of 95% to near-100% it is anticipated that there is a sudden transitional behaviour in the vortex shedding mechanism that causes the effective diameter to decrease abruptly with respect to porosity. The authors suggest this could be due to a transition at which the porosity of the material is so high that the individual fibres of the material could produce their own specific flow phenomena and that the approximation of the material being a bulk porous medium is no longer valid and thus so is the concept of the effective diameter.

5 CONCLUSIONS

The effective cylinder diameter of a porous coated cylinder has been investigated by testing three porous polyurethane coated cylinders with differing PPI and porosities. The porous coated cylinders presented two tones: one near the typical vortex shedding frequency associated with the outer diameter and the other at twice that frequency. The higher frequency tone is unlikely to be a primary harmonic of the lower frequency tone due to its amplitude. To explain the lower frequency tone in terms of typical vortex shedding, its Strouhal number was equated to that of the bare cylinders tested in this study. The effective diameter required to achieve this Strouhal number matching was greater than the physical outer diameter, most likely due to the significant boundary layer growth due to the very rough polyurethane porous coating surface resulting in vortex shedding of increased length scales and thus decreased shedding tone frequencies. This relationship can be related with the porosity of the polyurethane cylinder coating which appears to show up to 8% variation in effective cylinder diameter for porosities between 0% to 95%. At porosities higher than this, it is postulated that the porous medium can no longer be modelled using an effective cylinder diameter.

To verify the relationship between porosity and effective cylinder outer diameter, more tests are needed with porous coated cylinders of varying PPI as well as differing coating thickness to cylinder inner diameter ratios. Particle Image Velocimetry and hot-wire anemometry will be used to obtain flow field measurements in the wake of this cylinder for each PPI. Based on this preliminary study, it seems promising that an empirical relationship between porous coating porosity and the cylinder effective diameter can be determined for a range of Reynolds numbers and porous coating material and structure types.

ACKNOWLEDGEMENTS

This research was supported by the National Natural Science Foundation of China (Grant No. 11772146).

REFERENCES

Achenbach, E., and E. Heinecke, 1981, "On vortex shedding from smooth and rough cylinders in the range of Reynolds numbers 6×10^3 to 5×10^6." *Journal of fluid mechanics* Vol. 109 (1981), pp. 239-251.

Aguiar, J., Yao, H., and Liu, Y., 2016, “Passive flow/noise control of a cylinder using metal foam,” *Proceedings of the 23rd International Congress on Sound and Vibration*, 2016, Paper No. 317, pp. 1–8.

Arcondoulis, E., Liu, Y., Li, Z., Yang, Y., Wang, Y., and Li, W., 2018, "An experimental investigation of the flow and noise characteristics of structured porous coated cylinders." *Proceedings of the 24th AIAA/CEAS Aeroacoustics Conference,* AIAA Paper 2018-2963 (2018).

Boorsma, K., Zhang, X., Molin, N., and Chow, L. C., 2009, “Bluff body noise control using perforated fairings,” *AIAA Journal*, Vol. 47, No. 1, 2009, pp. 33–43.

Geyer, T. F., Sarradj, E., and Herold, G., 2015, “Flow noise generation of cylinders with soft porous cover,” *Proceedings of the 21st AIAA/CEAS Aeroacoustics Conference*, AIAA Paper 2015-3147 (2015).

Liu, H., and Azarpeyvand, M., 2016, "Passive control of tandem cylinders flow and noise using porous coating." *Proceedings of the 22nd AIAA/CEAS Aeroacoustics Conference*, AIAA Paper 2016-2905 (2016).

Naito, H., and Fukagata, K., 2012, "Numerical simulation of flow around a circular cylinder having porous surface." *Physics of Fluids* 24, Vol. 11, 2012, p.117102.

Norberg, C., 2003, “Fluctuating lift on a circular cylinder: review and new measurements,” *Journal of Fluids and Structures,* Vol. 17, No. 1, 2003, pp. 57–96.

Ruck, B., Klausmann, K., and Wacker, T., 2011, “The flow around circular cylinders partially coated with porous media,” *AIP Conference Proceedings*, Vol. 1453, No. 1, 2011, pp. 49–54.

Sueki, T., Ikeda, M., and Takaishi, T., 2009, “Aerodynamic noise reduction using porous materials and their application to high-speed pantographs,” *Quarterly Report of RTRI*, Vol. 50, No. 1, 2009, pp. 26–31.

Sueki, T., Takaishi, T., Ikeda, M., and Arai, N., 2010, “Application of porous material to reduce aerodynamic sound from bluff bodies,” *Fluid dynamics research*, Vol. 42, No. 1, 2010, p. 015004.

Yuan, H., Chao, X., Yu C., and Yang, Z., 2016, "Flow around a finite circular cylinder coated with porous media." In *Proceedings of the 8th International Colloquium on Bluff Body Aerodynamics and Applications*. 2016, Paper No. 573.

Zdravkovich, M., 1981, “Review and classification of various aerodynamic and hydrodynamic means for suppressing vortex shedding,” *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 7, No. 2, 1981, pp. 145–189.