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The effect of flow-permeable material on the flow field and the aerodynamic noise of cylinders

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Abstract

The flow around circular cylinders is one of the major aeroacoustic noise source mechanisms. Such a cylinder represents a simple model for technical applications like parts of the landing gear of airplanes, train pantographs, antennas or other protruding parts of vehicles. A reduction of the flow noise is especially desirable since it contains both a broadband component and tonal components due to the regular vortex shedding. One approach to reduce this noise is to cover the cylinder with flow-permeable materials, such as foams or porous rubbers. In a recent experimental study in the aeroacoustic wind tunnel at the Brandenburg University of Technology, both the aerodynamic noise radiation as well as the flow field around a set of porous covered cylinders were investigated. The acoustic measurements were performed at Reynolds numbers (based on cylinder diameter) between 16,000 and 100,000 using single microphones, while the detailed flow measurements were done using hot-wire anemometry. The results show the influence of the material properties and of the thickness of the porous layer on the aeroacoustic noise and on the turbulence in the wake of the cylinders.

Keywords: Porous Cylinder, Vortex Shedding, Aeroacoustic Noise

INTRODUCTION

The noise generated by a two-dimensional cylinder in a cross flow is a fundamental problem in aeroacoustics. It is composed of both broadband noise and a strong tonal noise contribution generated by the regular shedding of vortices (the so-called aeolian tone). Thus, much research is done to study the effects of passive porous coatings on the flow field and the associated generation of aeroacoustic noise [1–16].

The present paper is a continuation of a previous study [8] on the reduction of vortex shedding noise from two-dimensional cylinders through the use of porous covers. However, the current paper focuses on the measurement of the flow in the vicinity of the porous covered cylinders. Only selected results of the acoustic measurements will be shown to correlate the flow field results.

MEASUREMENT SETUP

2.1 Wind Tunnel

All experiments took place in the small aeroacoustic open jet wind tunnel at the Brandenburg University of Technology in Cottbus [17], using a nozzle with a rectangular exit area of 0.23 m × 0.28 m. With this nozzle, the maximum flow speed is in the order of 60 m/s, with a low turbulence intensity in the order of 0.2 %. The circular cylinders were fixed between two side plates, with a distance of 0.15 m from the nozzle exit area.

2.2 Porous Cylinders

As in [8], the cylinders examined in the present study consist of non-porous core cylinders made of polyurethane, which are covered by different flow permeable materials. The resulting outer diameter D of these cylinders is 30 mm, with a length l of 0.28 m. This results in an aspect ratio l/D of 9.3. In most cases, the diameter of the core cylinder, d, was 10 mm, while for one porous cover this parameter was varied, taking values of 6 mm, 10 mm, 15 mm and 20 mm. This was done in order to examine the influence of the thickness of the porous layer on the noise generation and the flow field. The porous materials are characterized by their airflow

Table 1. Overview of cylinders used for the present study (for the cases with the outer cylinder diameter printed bold, only acoustic measurements were performed)

Name	**Material**	**Description**	l (mm)	D (mm)	d (mm)	r (Pa s/m^2)
Reference	-	(non-porous) polyurethane	280	30	-	∞
Porous 1	Regufoam Vibration 190 plus	rubber-polyurethane-composite	280	30	10	314,800
Porous 2	Getzner CM GR 0525	polyurethane	280	30	10	141,300
Porous 3	Damtec Black Rubber	rubber granulate	280	30	**6**, 10, **15**, 20	9,400
Porous 4	Packing Foam	polyurethane	280	30	10	4,100

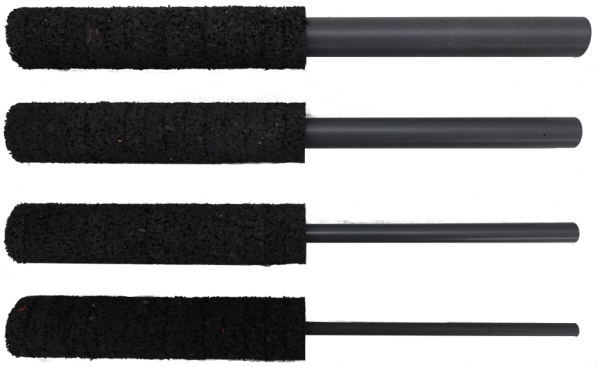


Figure 1. Photograph of the four cylinders (half-)covered by Damtec Black Rubber (from top to bottom: d = 20 mm, 15 mm, 10 mm and 6 mm)

resistivity r, which was measured according to ISO 9053 [18]. In total, acoustic measurements were performed on cylinders covered with 19 different materials, while flow measurements were only performed on a subset of these cylinders. For brevity, results will only be shown in the present paper for seven different cylinders (four porous covers plus different thicknesses) and a non-porous reference cylinder with the same outer diameter D that serves as a baseline. Table 1 lists these cylinders, while Figure 1 shows a photograph of the cylinders half covered by Damtec Black Rubber.

2.3 Acoustic Measurement Setup

For acoustic measurements, the wind tunnel test section is surrounded by absorbing side walls, leading to a quasi anechoic measurements environment for frequencies approximately above 125 Hz. The cylinders were mounted vertically (along the z-direction). The measurements were conducted with 16 1/4th inch free field measurement microphones, located on a horizontal arc centered at the cylinder axis approximately at mid span (see Figure 2). The exact microphone positions are at azimuthal angles of 30° to 130° in 10°-steps on one side and -30° to -110° in 20°-steps on the other side of the cylinder, with a distance of 0.66 m to the cylinder axis. For brevity, only results obtained with the microphone located at +90° to the flow will be shown in the present paper.

The data were recorded with a sampling frequency of 51.2 kHz and a duration of 90 s using a National Instruments 24 Bit multichannel measurement system. In post processing, the time data were converted to the frequency domain by a Fast Fourier Transformation (FFT) on Hanning-windowed blocks of 16,384 samples with an overlap of 75 % using Welchs method [19]. This lead to sound pressure level spectra with a frequency step size of 3.125 Hz.

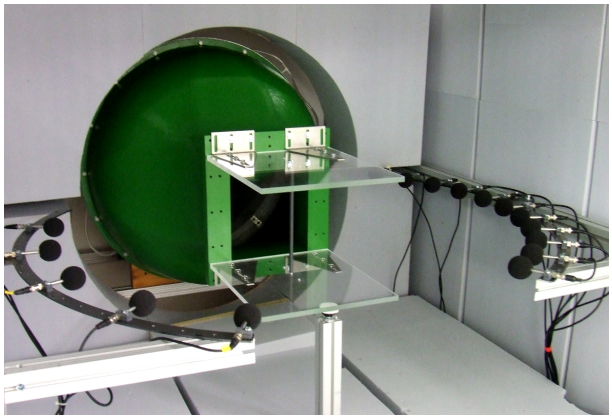


Figure 2. Photograph of the setup for the acoustic measurements

2.4 Flow Measurement Setup

In order to quantify the flow field around the cylinders, Constant Temperature Anemometry (CTA) was utilized. For these experiments, the cylinders were mounted horizontally (along the y-direction). The measurements were performed using a Dantec single wire P11 probe, which was positioned using a 3D traverse system with a minimum step size of 0.1 mm, and a Dantec 8-channel CTA hardware system. The sampling frequency was set to 25.6 kHz. A photograph of the measurement setup is shown in Figure 3(a).

In total, three different kinds of measurements were performed. First, profiles of the mean velocity and the turbulence intensity were obtained along the vertical direction at four downstream distances of $0.5D$, $1D$, $5D$ and $10D$ in the wake of the cylinders, approximately at mid span. Thereby, the turbulence intensity was calculated as the ratio of the root-mean-square value of the turbulent velocity fluctuations to the "outer" flow speed U_0. Figure 3(b) shows a schematic of the setup used for these measurements. Second, power spectral densities of the turbulent velocity fluctuations were measured at a point one outer diameter downstream and one half outer diameter off center, approximately at mid span. This was done for ten flow speeds approximately between 8 m/s and 52 m/s. Finally, the coherence γ^2 was measured along a spanwise line one outer diameter downstream from the cylinders. This was done using two identical probes. One probe was fixed, with a distance of one outer diameter from the side plate, while the other was traversed along the span in steps of 2.5 mm ($D/12$) away from the first probe.

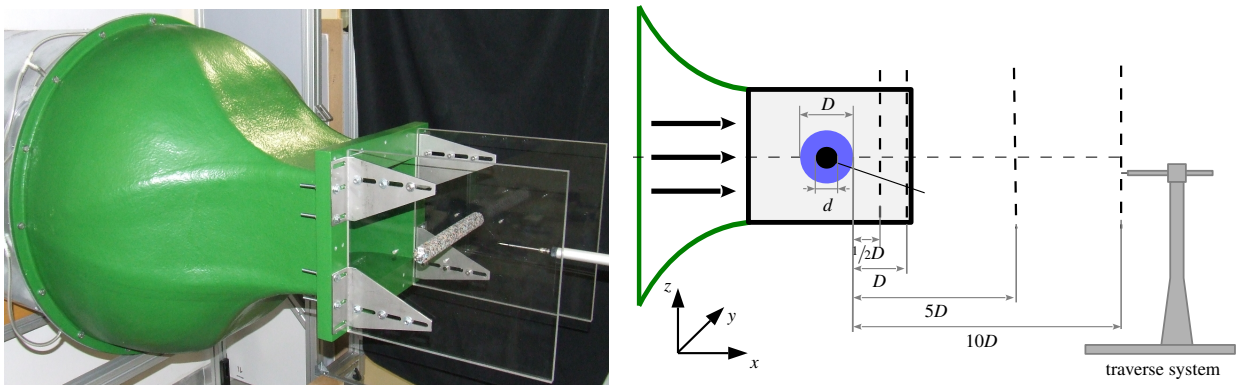
RESULTS

3.1 Acoustic Results

Figure 4 exemplarily shows sound pressure level spectra obtained for the different cylinders at a single flow speed of 40.7 m/s. In agreement with previous results shown in [8], it is visible that the porous covers do not lead to a complete suppression of the vortex shedding tone, but to a notable narrowing of the peak. At the same time, the peak level may even increase compared to the reference cylinder. The noise reducing effect is better for porous covers with low air flow resistivities (Figure 4(a)). Although the effect is rather small, in increase of the thickness of the cover (or a decrease of the inner diameter d) is also beneficial, as visible in Figure 4(b).

3.2 Flow Field Results

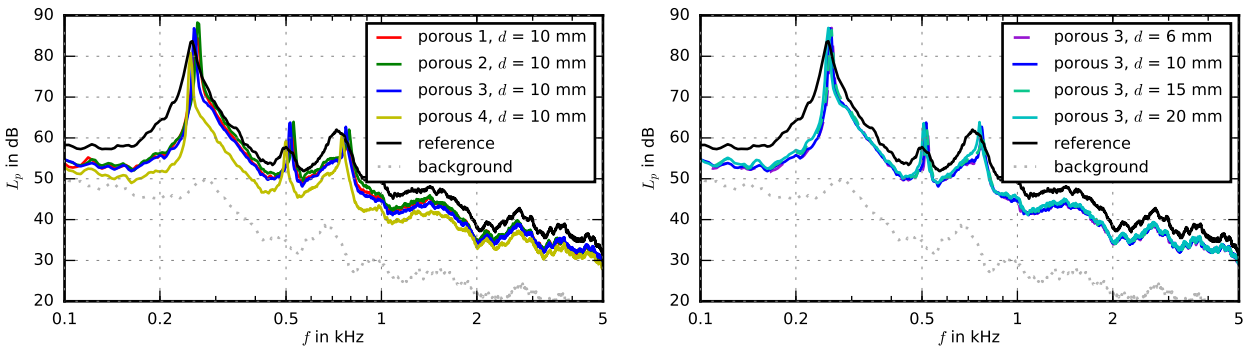
The effect of the porous covers on the wake profiles of the mean velocity and the turbulence intensity is shown for two different distances in Figures 5(a) and 5(b). It can be seen that the porous covers lead to a reduced mean velocity and a reduced turbulence intensity directly downstream of the cylinder in its shadow zone. For



(a) Photograph

(b) Schematic of the wake measurements (not to scale)

Figure 3. Setup for the constant temperature anemometry measurements

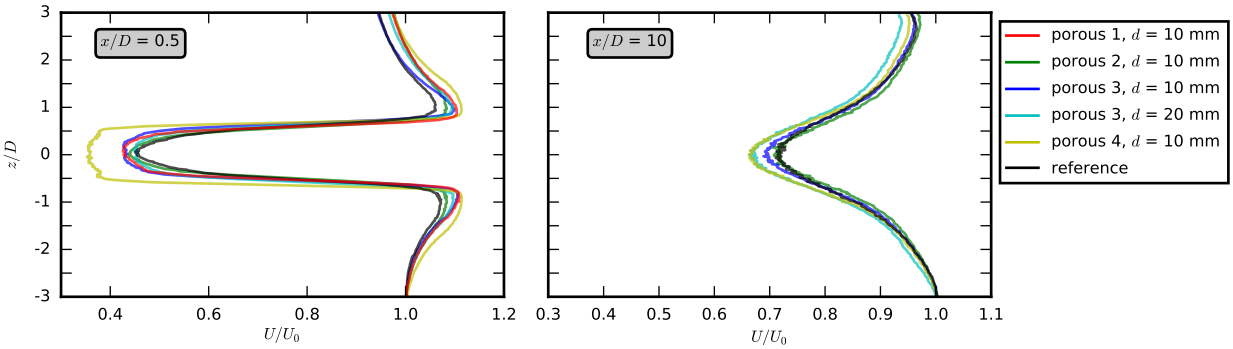


(a) Influence of porous material (d = 10 mm)

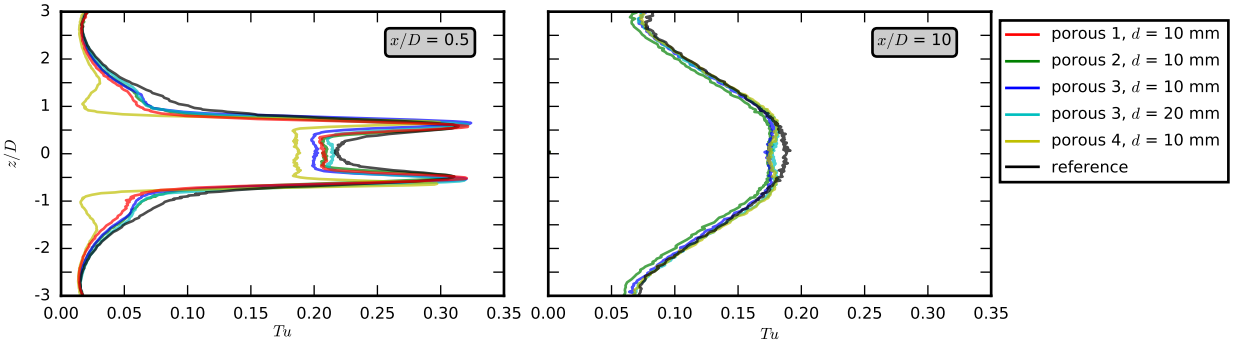
(b) Influence of thickness (Porous 3)

Figure 4. Sound pressure levels measured at a flow speed of 40.7 m/s (Re = 80,700)

x/D = 0.5, the mean velocity in the side region (the shear layer) is increased due to the porous covers, but their effect on the turbulence intensity in this region is very small only. The width of the shear layer seems to be increased for the porous cylinders, since the region of high turbulence has an increased extent in z-direction. Power spectral densities of the velocity fluctuations measured at different flow speeds in the wake of the cylinders are shown in Figure 6. Basically, the same trend is visible as for the acoustic spectra shown in Figure 4: The porous covers lead to a narrowing of the vortex shedding peaks and to an increase of the peak amplitude. The latter effect is again presented in Figure 7(a), where the magnitude of the vortex shedding peak of the turbulence spectra is shown as a function of the Reynolds number $Re = U \cdot D/\nu$ (with ν being the kinematic viscosity of the fluid). Basically, the peak magnitude of the porous covered cylinders is always higher than that of the reference cylinder. Materials having a low airflow resisitivity lead to higher peaks than materials with low air flow resistivities, while there is no clear trend regarding the influence of the thickness of the porous cover. The trend regarding the corresponding Strouhal number based on vortex shedding, $Sr = f_{\text{peak}} \cdot D/U_0$, is more complex, which is shown in Figure 7(b). At Reynolds numbers approximately below 40,000, the Strouhal numbers of the porous covered cylinders are slightly below that of the non-porous reference cylinder. At higher Reynolds numbers, the Strouhal numbers of the porous covered cylinders increase notably to values well above that of the reference cylinder. Thereby, materials with low air flow resistivities lead to a higher Strouhal number



(a) Mean flow velocity



(b) Turbulence intensity

Figure 5. Profiles of mean velocity (top) and turbulence intensity (bottom) measured at two downstream distances at a flow speed of 34 m/s (left: close to the cylinder, right: far downstream of the cylinder)

than materials with low air flow resistivities. Such a behavior was also observed in previous acoustic measurements [8].

Finally, the spanwise coherence γ^2 between data from one hot-wire probe at a fixed position and one hot-wire probe that was traversed along a spanwise line in the wake of the cylinders is shown in Figure 8. Interestingly, the coherence measured for the porous covered cylinders is much stronger along the spanwise direction than for the reference cylinder. This means that turbulent structures, which are shed from the porous covered cylinders, have a greater spanwise length than for the baseline case. Thus, the flow noise reduction that can be achieved by the porous covers is not caused by any disturbance of the spanwise coherence. Still, it can be observed that, as is the case for the turbulence spectra measured in the wake (Figure 6), the maxima of the spanwise coherence appear narrower along the frequency axis.

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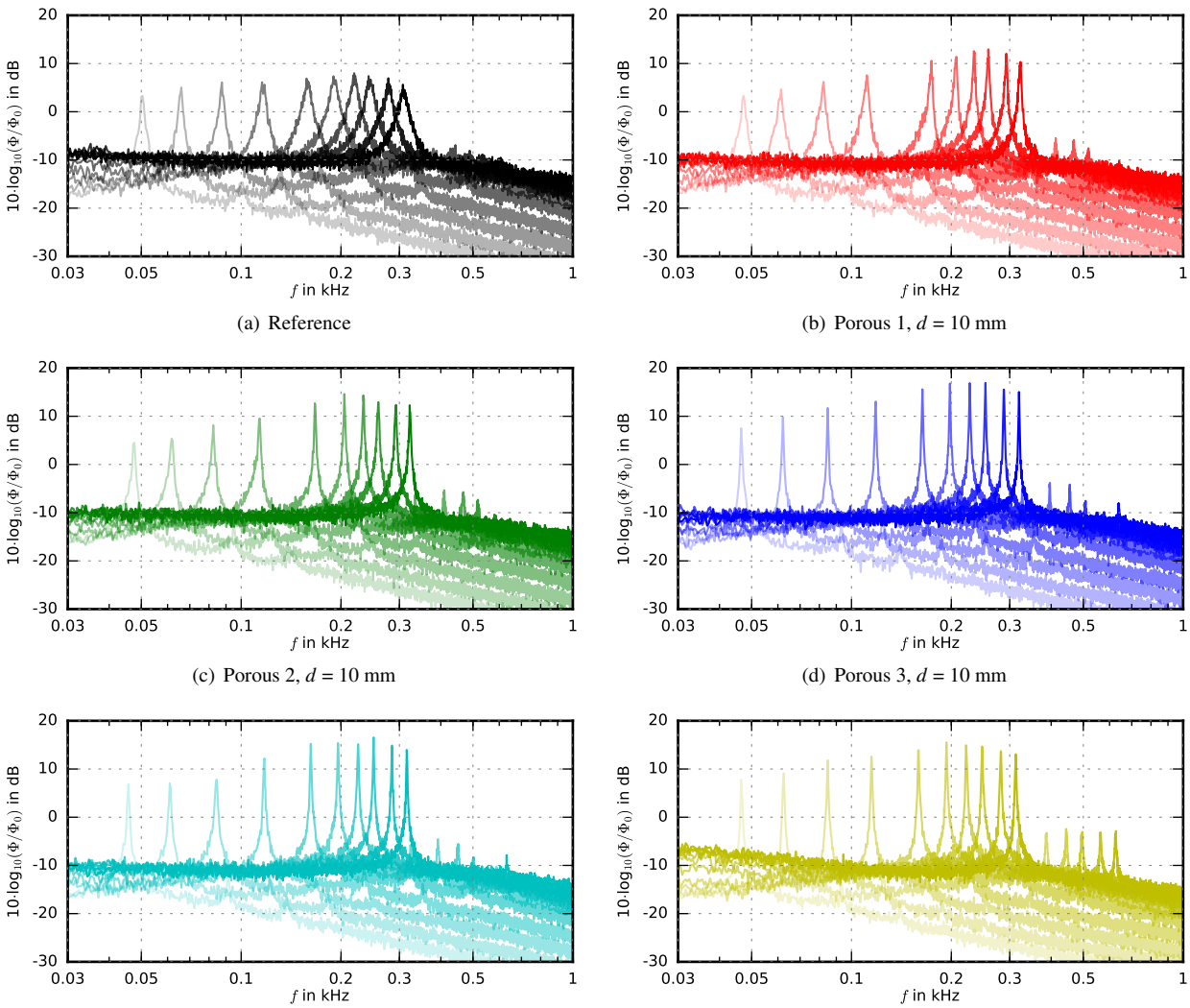

(a) Reference

(b) Porous 1, d = 10 mm

(c) Porous 2, d = 10 mm

(d) Porous 3, d = 10 mm

(e) Porous 3, d = 20 mm

(f) Porous 4, d = 10 mm

Figure 6. Power spectral densities of the velocity fluctuations measured at velocities between 8 m/s and 52 m/s (the opacity of the lines decreases with increasing flow speed)

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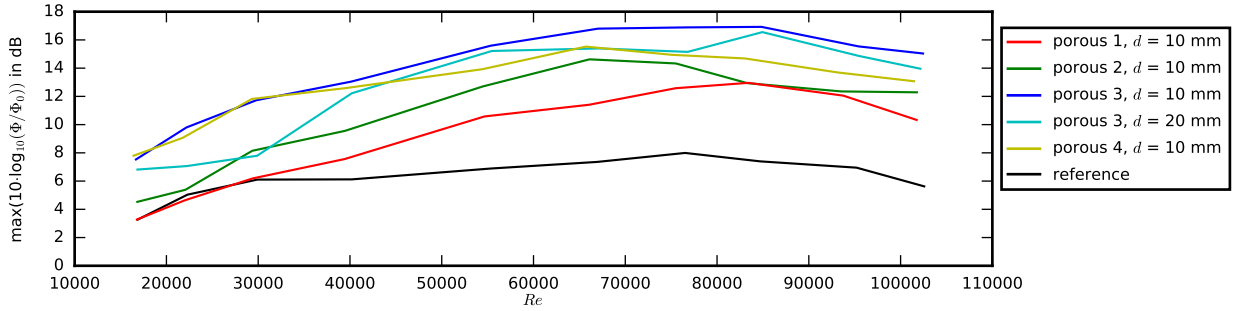
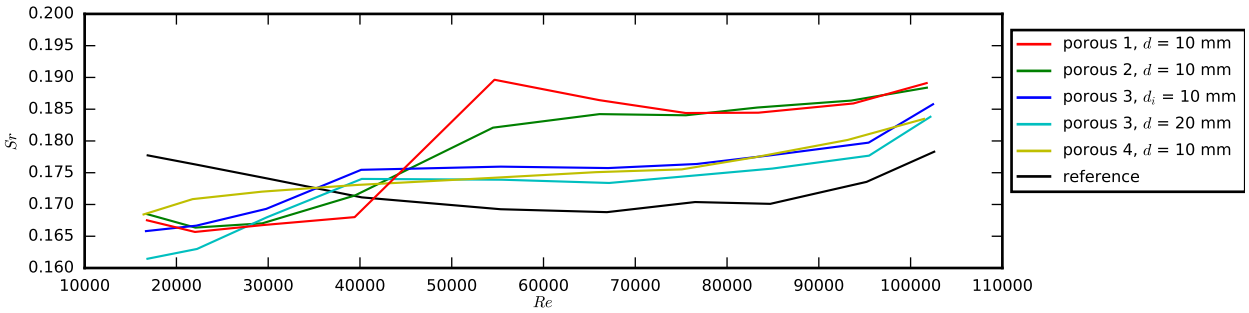


(a) Dependence of peak magnitude of turbulence spectral density on Reynolds number based on outer cylinder diameter



(b) Dependence of peak Strouhal number on Reynolds number based on outer cylinder diameter

Figure 7. Properties of the vortex shedding peak derived from the turbulence spectra shown in Figure 6

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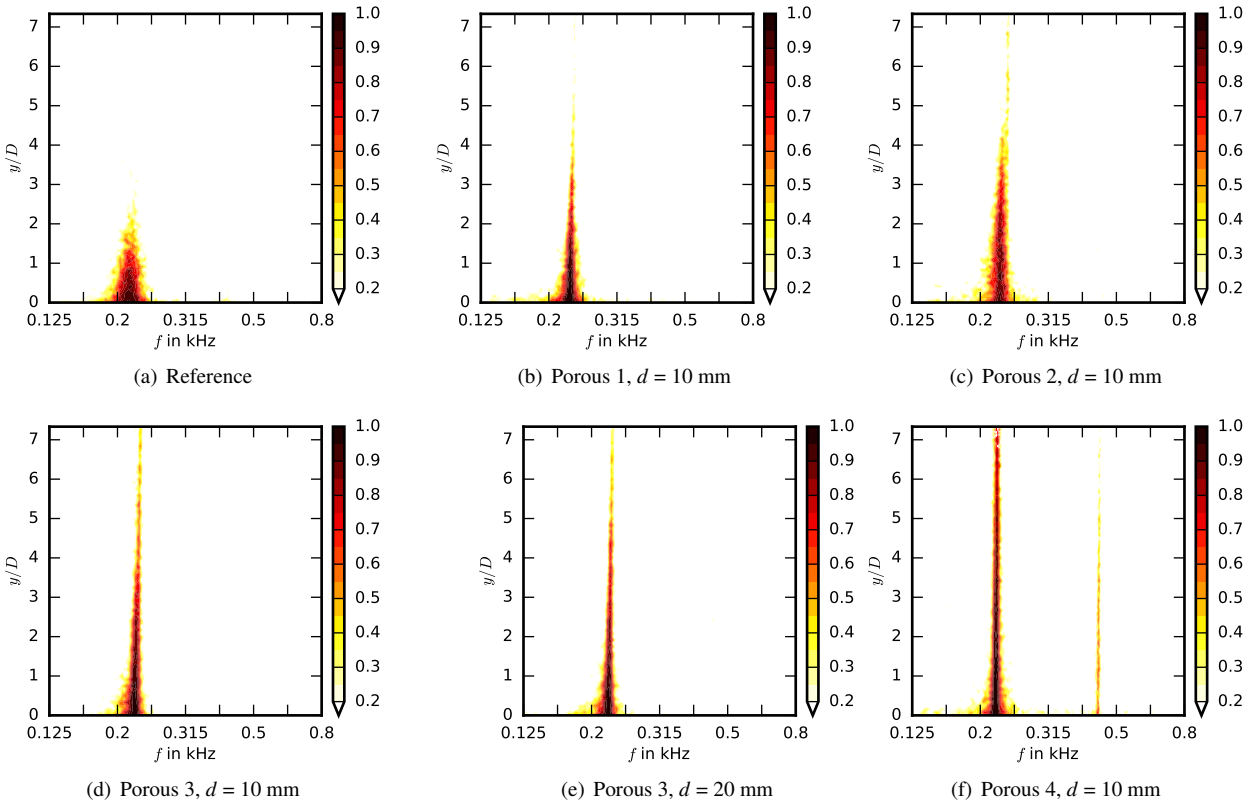

(a) Reference (b) Porous 1, d = 10 mm (c) Porous 2, d = 10 mm

(d) Porous 3, d = 10 mm (e) Porous 3, d = 20 mm (f) Porous 4, d = 10 mm

Figure 8. Spanwise coherence γ^2 measured downstream of the cylinders at a flow speed of 34 m/s

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