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# Flow noise generation of cylinders with soft porous cover

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**The use of porous materials is one of several approaches to control or minimize the generation of flow noise. As a simple model for struts and other protruding parts (for example components of the landing gear or pantographs from high speed trains), the noise generated by circular cylinders with a soft porous cover was measured in a small aeroacoustic wind tunnel at Reynolds numbers between approximately 16,000 and 103,000. The porous materials were characterized by their air flow resistivity, a parameter describing the permeability of an open-porous material. The aim of this study is to identify those materials that result in the best noise reduction, which refers to both tonal noise and broadband noise. To this end, measurements with single microphones were performed on a set of cylinders whose porous materials cover a large range of air flow resistivities.**

**The results show that materials with low air flow resistivities lead to a noticeable flow noise reduction. Thereby, the main effect of the porous cylinder covers is that the spectral peak due to the aeolian tone is much narrower, but is not suppressed completely. Additionally, a reduction of broadband noise can be observed, especially at higher Reynolds numbers. The noise reduction increases with decreasing air flow resistivity of the porous covers, which means that materials that are highly permeable to air result in the best noise reduction.**



## List of symbols

| | | |
|---|---|---|
| $B$ | [Hz] | width of the spectral peak |
| $b$ | [m] | thickness of a sample of porous material |
| $D$ | [m] | outer diameter of the cylinders with porous cover |
| $d$ | [m] | diameter of the rigid core cylinder |
| $f$ | [Hz] | frequency |
| $G_{\mathrm{mic1,mic2}}(f)$ | [Pa$^2$/Hz] | cross-spectral density between signals from microphone 1 and 2 |
| $Ma$ | [-] | Mach number |
| $L$ | [m] | length of the cylinders |
| $L_p$ | [dB] | sound pressure level |
| $\Delta p$ | [Pa] | static pressure difference |
| $r$ | [Pa s/m$^2$] | air flow resistivity of a porous material |
| $Re$ | [-] | Reynolds number based on cylinder diameter |
| $S_{\mathrm{auto,mic1}}(f)$ | [Pa$^2$/Hz] | auto-spectral density of the signal from microphone 1 |
| $S_{\mathrm{COP,mic1}}(f)$ | [Pa$^2$/Hz] | coherent noise spectral density from microphone 1 according to Equation (6) |
| $Sr$ | [-] | Strouhal number based on cylinder diameter |
| $Tu$ | [%] | turbulence intensity |
| $u$ | [m/s] | turbulent velocity fluctuations |
| $U$ | [m/s] | mean (time-averaged) flow velocity |
| $U_0$ | [m/s] | free stream velocity (flow speed) |
| $x$, $y$, $z$ | [m] | cartesian coordinates |
| $\gamma^2_{\mathrm{mic1,mic2}}(f)$ | [1] | coherence between signals from microphone 1 and 2 |
| $\sigma$ | [1] | volume porosity |
| $\tau$ | [1] | tortuosity |

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# I. Introduction

The use of flow-permeable materials is a very promising approach to control or minimize the generation of flow-induced noise. Since many different components of the landing gear, such as struts, axles and cables, but also different parts of the pantograph of high speed trains can be modeled as cylinders, the potential effect of porous materials on the reduction of noise generated by a cylinder in a fluid flow are of great interest. Due to the fact that cylinder flow noise in general contains both narrowband (tonal) contributions due to vortex shedding as well as broadband noise, a potential noise reduction seems even more promising.

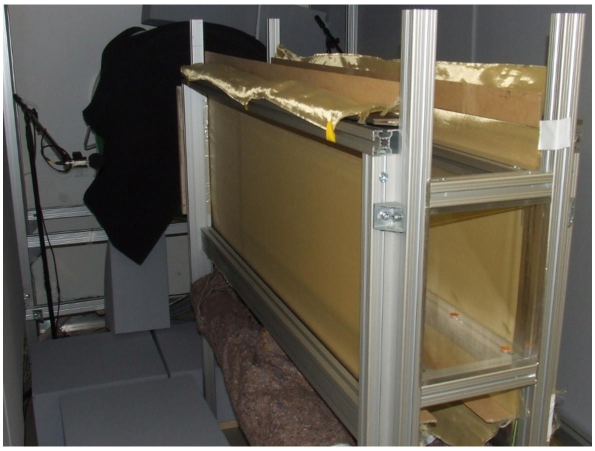
Only few published studies exist on the use of porous materials to reduce the aerodynamic noise from cylinders. Nishimura et al. [1] measured the noise generated by two cylinders made of different pile fabrics, which are cloth materials with fine fibers of high density, such as fur or down. The experiments were conducted at a single flow speed of 50 m/s in an open jet wind tunnel with a rectangular exit area of 0.2 m $\times$ 0.24 m. The cylinders had a diameter of 38 mm and were positioned 1 m from the nozzle exit. Measurements were performed using a single microphone positioned at 1 m distance at an angle of 90° to the flow direction and the cylinder axis. Due to the pile-fabric cloth, the vortex shedding noise of the cylinders was suppressed almost completely. Compared to the noise of a smooth, untreated cylinder, they also observed a broadband noise reduction of 4 dB for the cylinder with 3 mm long fibers and 10 dB for the cylinder with 10 mm long fibers.

Yahathugoda and Akishita [2] experimentally investigated the effect of the surface impedance on the noise generated by cylinders with a length of 0.2 m. Measurements took place in an open jet wind tunnel using side plates. The surface impedance of the cylinders, which consisted of a rigid inner cylinder and a co-axial hollow cylinder with an outer diameter of 10 mm, was varied through different micro perforations of the outer surface. Between the inner cylinder and the outer surface was a thin layer of air. Acoustic measurements were performed at flow speeds between 10 m/s and 20 m/s using several microphones positioned at distances of 1 m and 1.5 m on an arc with angles from 15° to 90° to the flow. For an optimized distribution of holes they measured noise reductions of up to 6 dB at the vortex shedding frequency, but it was not possible to completely suppress the tonal peak. A Large Eddy Simulation was performed by the same authors [3] to examine the effect of the different impedances on the surface pressure and the flow field, which, overall, yielded comparable trends.

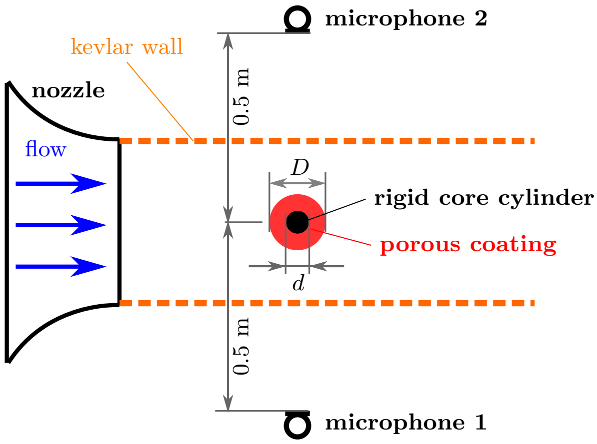
Several investigations aim at the reduction of noise generated by pantographs of high-speed trains, as for example the work by Sueki et al. [4, 5]. They performed measurements on cylinders that consisted of a non-porous inner cylinder with a diameter of 25 mm, which were covered by different open-porous materials including porous urethane and porous metal. The materials, which were characterized by their number of cells, all had porosities above 95 %. The outer diameter of the models was 45 mm and the length was 0.6 m. They were attached to the wind tunnel wall at one side only, which implies that noise was generated both along the cylinder and at the tip. The acoustic measurements were performed at a single flow speed of 83 m/s using a single omnidirectional microphone, positioned outside of the flow at a distance of 5 m from the cylinder. With the porous coatings it was possible to completely reduce the tonal noise due to the vortex shedding and additionally enable a reduction of the broadband noise. A numerical study by the same group of authors was conducted to examine the suppression of vortex shedding by the porous material [6]. Good agreement with the experimental results was found and it was concluded that flow through the porous material leads to an upstream shift of the flow separation and to a reduction of the vortex strengths.

A more recent and very detailed numerical study on cylinders with a porous cover, again with the aim to reduce the aerodynamic noise from the pantograph, was performed by Liu et al. [7] using Computational Fluid Dynamics (CFD). It was found that the porous material can effectively reduce the aerodynamic noise and also has an influence on the frequency of the tonal peak by adjusting the peak frequency towards a lower frequency and by narrowing the bandwidth "near the peak". However, the porous layer did not lead to a total reduction of the spectral peak. Regarding the porous material the results showed that the noise level decreases with increasing porosity, pore density and porous layer thickness, although the porosity was found to have the biggest influence.

When reviewing those publications it becomes apparent that, despite the fact that the use of a porous coating to reduce the generation of aerodynamic noise from cylinders in a flow has been investigated to some extent, these studies are very sparse and only a few materials were examined. Further questions arise, for



(a) Photograph of the aerodynamically closed, acoustically open test section




(b) Schematic (top view)

**Figure 1. Experimental setup in the aeroacoustic wind tunnel**

example regarding the underlying mechanisms responsible for the noise reduction or the influence of the flow speed and the material parameters. Additionally, some of the results from numerical studies still lack experimental validation.

Besides the effect of porous or permeable materials on the generation of flow noise, they are expected to have an effect on the aerodynamic properties as well. For example, Noymer et al. [8] measured an increase in drag for a cylinder made from an open-porous aluminum foam compared to a non-porous aluminum cylinder.

In the present study, wind tunnel experiments were conducted on circular cylinders covered by a homogeneous, soft, open-porous material at Mach numbers below 0.18 and Reynolds numbers below 110,000. The main focus thereby is to investigate the influence of the properties of the porous materials on the reduction of both tonal noise, which is due to the periodical shedding of vortices, and broadband noise. The influence of other parameters, like the thickness of the porous cover, on the noise generation was not examined in this study.

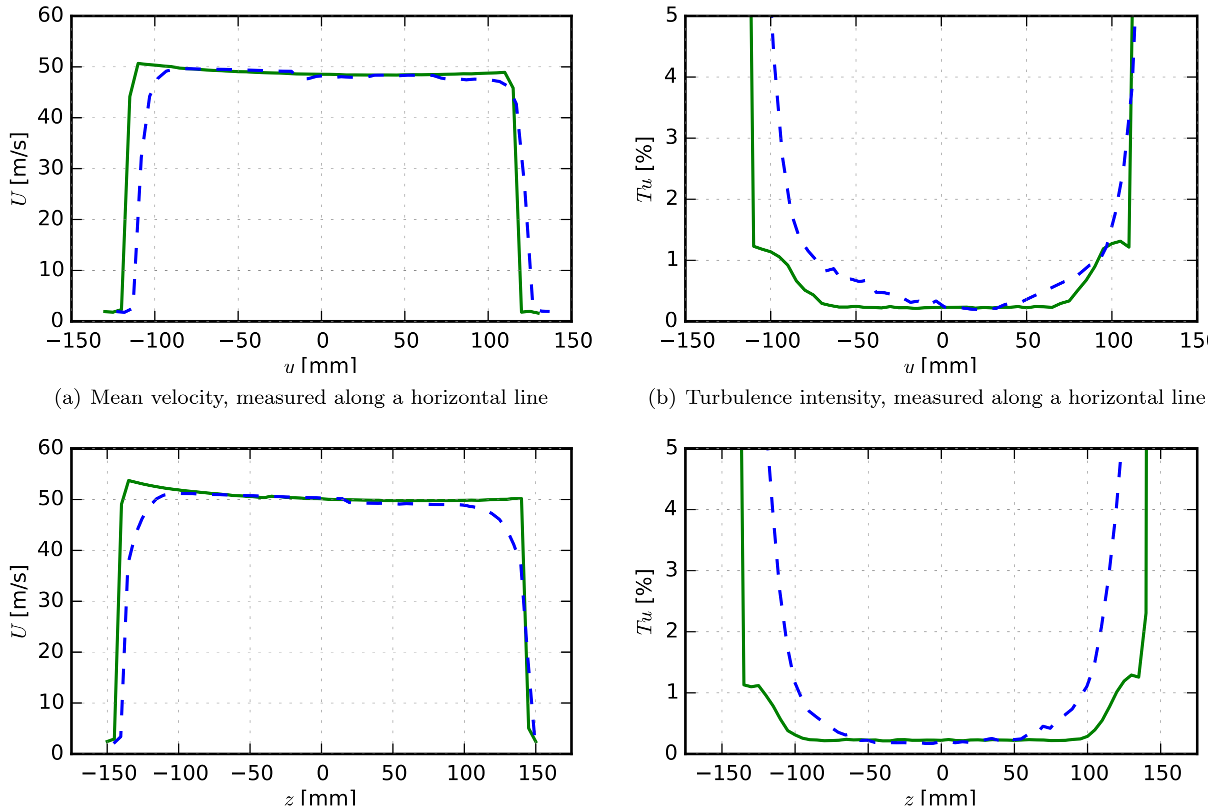
## II. Materials and methods

### II.A. Aeroacoustic wind tunnel

All measurements were performed in a small aeroacoustic open jet wind tunnel [9] using a nozzle with a rectangular exit area of 0.23 m $\times$ 0.28 m. With this nozzle, the maximum flow speed is about 60 m/s. Prior measurements on a set of non-porous cylinders of varying diameter showed that the cylinder aspect ratio as well as the flow quality have a great influence on the generation of tonal noise. This is in agreement with various measurements on cylinders reported in the literature (see for example [10–12]). In certain cases, for example when the aspect ratio of the cylinders is not large enough or when the assumption of a nearly two-dimensional flow is not justified (for example when the cylinders were placed too far downstream), no aeolian cylinder tones were generated.

In order to provide a quasi-two-dimensional flow, the nozzle was extended for the present study with an aerodynamically closed test section of approximately 1.5 m length. The upper and lower wall of this test section are made of thick acrylic glass while the two side walls contain windows covered by a tensioned kevlar fabric. Thus, the flow inside this test section remains quasi two-dimensional, while at the same time the kevlar is permeable for acoustic waves, which enables measurements with microphones positioned outside the flow. A photograph of the experimental setup is shown in Figure 1(a), a corresponding schematic in Figure 1(b). Similar setups are also used in other, often larger wind tunnel facilities [13–15].

To characterize the flow quality inside the test section, hot-wire measurements were performed downstream of the nozzle (without the test section attached) and downstream of the test section using a Dantec Constant-Temperature-Anemometry (CTA) measurement system and a single wire probe, with the wire




(a) Mean velocity, measured along a horizontal line

(b) Turbulence intensity, measured along a horizontal line

(c) Mean velocity, measured along a vertical line

(d) Turbulence intensity, measured along a vertical line

**Figure 2. Mean velocity and turbulence intensity in the test section at an adjusted flow speed $U_0$ of 50 m/s (▬ at the entrance of the test section, directly behind the nozzle and ‒ ‒ at the exit of the test section)**

perpendicular to the $y$-axis (see Figure 1(b)). Figure 2 shows the mean flow speed $U$ and the turbulence intensity

$$Tu = \frac{\sqrt{u^2}}{U} \cdot 100\ \% \tag{1}$$

measured across a horizontal and a vertical line. The results prove that the influence of the kevlar walls, which are to a certain degree also permeable to the flow, on the mean flow profile is negligible. The turbulence intensity inside the test section is in the order of 0.2 %, characterizing the flow as virtually non-turbulent.

Surrounding the acoustically open, but aerodynamically closed test section is a chamber with absorbing side walls, which provide a virtually anechoic environment for frequencies above 100 Hz (the absorber is the light gray material visible in Figure 1(a)).

### II.B. Porous covered cylinders

The circular cylinders that were subject to the experiments have a length $L$ of 280 mm and an outer diameter $D$ of 30 mm. The outer diameter was chosen in order to obtain an aspect ratio $L/D$ close to 10. In the experiments, Reynolds numbers $Re$ (based on the outer diameter) approximately between 16,000 and 103,000 were obtained. According to Schlichting and Gersten [16], this subcritical Reynolds number range is characterized by a laminar near-wake with vortex street instability. A pure Karman vortex street would appear in a lower Reynolds number range ($90 < Re < 300$). The performance of measurements in this regime would require either lower wind speeds or thinner cylinders. Both means were not feasible with the current setup, since the lowest wind speed with the selected nozzle is about 7 m/s and it is rather difficult to assemble cylinders with a noticeably thinner porous cover.

Each porous cylinder contained a rigid, non-porous core cylinder with a diameter $d$ of 10 mm, hence the thickness of the porous layer is 10 mm. Different open-porous materials were used in the present study, for

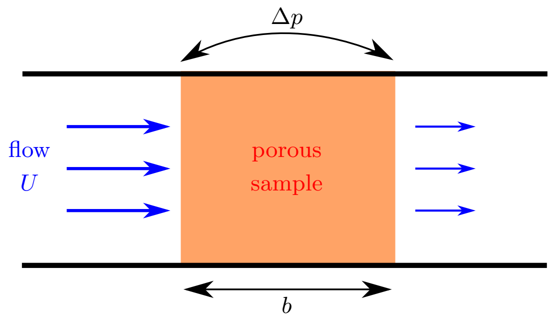



**Figure 3. Definition of the air flow resistivity $r$ of a sample of open porous material according to Equation (2)**

example foams (made of polyurethane or melamine resin), which are commonly used for sound absorption, or rubber granulates used for vibration damping. Usually, such materials are available as plates or mats, from which hollow cylinder disks were prepared either by using water jet cutting technology or simply by using an annular cutting tool. Several of these disks were then threaded on the 10 mm diameter core cylinder in order to obtain the desired porous covered cylinders of 280 mm length (see Figure 4(a)). The water jet cutting was chosen since, as opposed to other techniques such as laser cutting or simply drilling, it leaves the open pores of the material intact. In total, 12 cylinders with a porous cover were made, an overview of which is given in Table 1. Additionally, a smooth, non-porous cylinder was used as a reference.

The materials used as porous covers are assumed to be homogeneous. They are characterized in the present study by their air flow resistivity $r$, which is believed to be the parameter with the biggest influence on the desired noise reduction. It describes the resistivity of a porous material against a fluid flow through the material and is defined as the ratio of a static pressure difference $\Delta p$ across a sample of porous material to the product of the flow velocity $U$ of a static fluid flow through the sample and the sample thickness $b$ (see Figure 3):

$$r = \frac{\Delta p}{U \cdot b}. \tag{2}$$

The air flow resistivity of the porous materials used for the present experiments was measured according to ISO 9053 [17], the results are given in Table 1. The main focus of the present study was to identify the best materials regarding the highest possible noise reduction. Therefore, in order to cover a large range of air flow resistivities, it is desirable to acquire a large number of different open-porous materials. However, since it is hard to find materials with a very low air flow resistivity that can still be cut into hollow cylinders, many of the materials of the present study have a rather high air flow resistivity.

Other parameters that may affect the noise reduction potential of such porous covers, but that were not examined in the present study, are the volume porosity $\sigma$, defined as the ratio of the volume of the pores to the total volume, and the tortuosity $\tau$, defined as the ratio of the effective length of the flow path through the pores of the porous material to the minimum length between flow inlet and outlet[a]. Based on prior investigations using different porous materials [18, 19] it can be estimated that the porosity of the foams in the present study is at least well above 90 %, while the porosity of the rubbers is almost certainly lower. This assumption is plausible when the rubbers are viewed as a bulk of densely packed spheres of different sizes. Several theoretical models exist for the calculation of the porosity of such materials. With the simple assumption of identical spheres in a random packing, the porosity is known to be greater than 0.36 [20]. This gives a rough estimation and indicates that the porosity of the rubbers can be expected to be lower than that of the foams.

It has to be mentioned that the porous covers lead to a certain surface roughness of the cylinders, which has not been measured in the present study. This surface roughness will most likely affect the generation of flow noise, and it can be assumed that it may also lead to a reduction of the tonal noise generated by the cylinder. However, since rough surfaces are known to increase the generation of broadband flow noise [21, 22], especially at high frequencies, it is reasonable to presume that any potential broadband noise

[a]Sometimes the tortuosity $\tau$ is defined as the *squared* ratio of the effective length of the flow path through the pores to the minimum length between flow inlet and outlet.

Table 1. **Cylinders used in the present study (given is the air flow resistivity $r$ of the porous covers, measured according to ISO 9053 [17])**

| No. | Name | Material | Description | $r$ [Pa s/m$^2$] |
|---|---|---|---|---|
| 1 | Reference | – | non-porous polyvinyl chloride | $\infty$ |
| 2 | Rubber 1 | Damtec black uni | rubber granulate | 1,474,300 |
| 3 | Rubber 2 | Damtec standard | rubber granulate | 594,200 |
| 4 | Foam 1 | Oasis Rainbow Foam | polyurethane foam | 416,200 |
| 5 | Foam 2 | ArmaFoam Sound | elastomer foam | 112,100 |
| 6 | Rubber 3 | Damtec USM | rubber granulate | 86,100 |
| 7 | Rubber 4 | Damtec vibra ultra | rubber granulate | 75,600 |
| 8 | Rubber 5 | Conmetall Rubber Mat | rubber granulate | 53,200 |
| 9 | Rubber 6 | Damtec Estra | rubber granulate | 12,900 |
| 10 | Foam 3 | Basotect | melamine resin foam | 9,800 |
| 11 | Rubber 7 | Damtec black rubber | rubber granulate | 9,400 |
| 12 | Foam 4 | Packing Foam | polyurethane foam | 4,100 |
| 13 | Foam 5 | Panacell 90 ppi | polyurethane foam | 4,000 |

(a) Assembling of a porous covered cylinder

(b) Overview of the cylinders used for the experiments (from left to right with decreasing air flow resistivity as given in Table 1)

**Figure 4. Porous covered cylinders**



reduction observed in the present experiments is due to the permeability of the porous covers, not to their roughness.

## II.C. Acoustic measurements

The spectrum of the generated flow noise of a cylinder is characterized by a strong tonal contribution, the aeolian tone. The peak frequency of this tone can be calculated based on the flow velocity $U$, the cylinder diameter $D$ and the Strouhal number $Sr$ using

$$f = \frac{Sr \cdot U}{D}. \tag{3}$$

According to theory [16], the Strouhal number governing the flow around cylinders in the range of subcritical Reynolds numbers is 0.21. With the chosen dimensions of the cylinders and the possible range of flow velocities, the frequency of these tones can be expected to be very low in the present experiments, in some cases down to approximately 57 Hz. Spectra of the cylinder flow noise were obtained from measurements with two single microphones. These were positioned at an angle of 90° to the flow and the cylinder axis at an equal distance of 0.5 m on opposite sides of the test section (see Figure 1). The microphones are 1/4th inch electret free-field microphones with a sensitivity of 50 mV/Pa, which, although positioned outside the flow, were equipped with a windscreen to exclude potential effects from low level recirculation inside the anechoic chamber. Due to the relatively low Mach numbers, no correction was included for the refraction and scattering of sound at the boundary layer along the kevlar windows inside the test section.

Acoustic data were recorded using a 24 Bit National Instruments digital dynamic signal acquisition module (NI-USB 4431) with a sampling frequency of 51,200 Hz. The measurement duration was 60 s, leading to a total number of 3,072,000 samples per measurement and channel.

### II.D. Data processing

In most cases, the time domain data were transformed to the frequency domain using a Fast Fourier Transformation (FFT) with a Hanning window and 16,384 samples per block, resulting in a frequency spacing of 3.125 Hz. With an overlap of 75 %, this lead to 750 blocks which were then averaged to yield the desired microphone auto spectra and cross spectra. Another processing was applied for the special purpose of examining the generation of the aeolian tone, where a smaller frequency spacing was desired. For these cases, the time domain data were Fast-Fourier-transformed with the same window function and overlap, but with an increased block size of 131,072 samples, which lead to a very small frequency spacing of only about 0.39 Hz.

Two different data processing procedures were tested on the acoustic data, which can also be found in the work by Hutcheson et al. [23] for the measurement of airfoil leading edge noise. The first method to analyze the noise generated by the porous-covered cylinders simply uses the auto spectral density $G_{\mathrm{mic1,mic1}}(f)$ from microphone 1 directly:

$$S_{\mathrm{auto,mic1}}(f) = G_{\mathrm{mic1,mic1}}(f). \tag{4}$$

Thus, the use of this approach is based on the assumption that measured noise originates mainly from the cylinder in the flow and that signals from other noise sources are well below the noise source of interest. It was used in many well-known studies of aerodynamic noise from cylinders and airfoils, such as the comprehensive investigation by Schlinker et al. [24]. One possible method to improve the results is to subtract the background noise, that is the auto spectral density of a measurement at the same flow speed, but without the cylinder installed, from the auto spectral density.

The second method, called the coherent output power (COP) method [25], is based on the assumption that the noise from a cylinder in a flow is basically dipole-shaped and hence the noise on opposite sides of the dipole axis, as measured by the two microphones shown in Figure 1(b), is coherent. Uncorrelated noise, which is measured only by one of both microphones, is thus excluded. The method makes use of the coherence function $\gamma^2_{\mathrm{mic\,1,\,mic\,2}}(f)$, which is calculated as

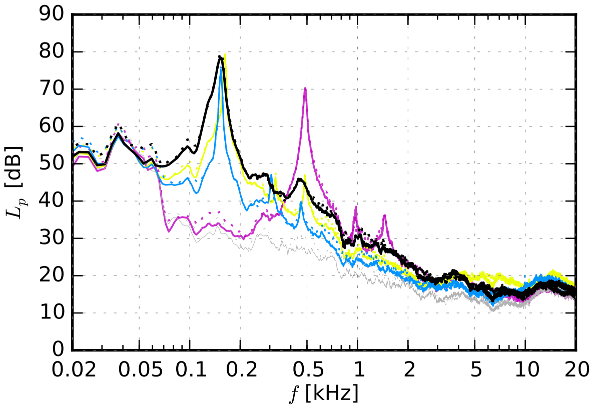
$$\gamma^2_{\mathrm{mic1,mic2}}(f) = \frac{|G_{\mathrm{mic1,mic2}}(f)|^2}{G_{\mathrm{mic1,mic1}}(f) G_{\mathrm{mic2,mic2}}(f)} \tag{5}$$

and takes values between 0 (for incoherent signals) and 1 (for fully coherent signals). The coherent noise spectral density from microphone 1 can then be obtained simply as the product of the coherence function and the auto spectral density from microphone 1:

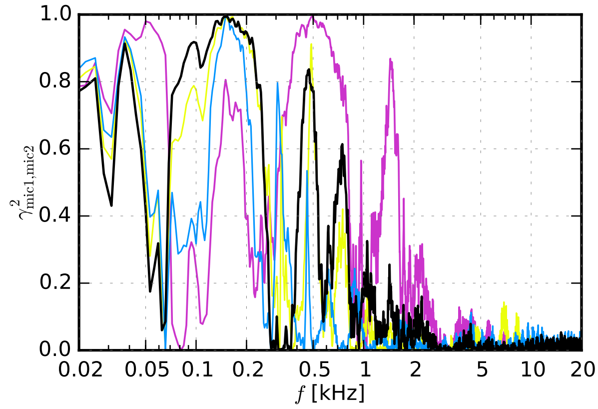
$$S_{\mathrm{COP,mic1}}(f) = \gamma^2_{\mathrm{mic1,mic2}}(f) \cdot G_{\mathrm{mic1,mic1}}(f). \tag{6}$$

Finally, for both the microphone auto spectra and the coherent output power spectra, sound pressure level spectra $re\, 2 \cdot 10^{-5}$ Pa were calculated.

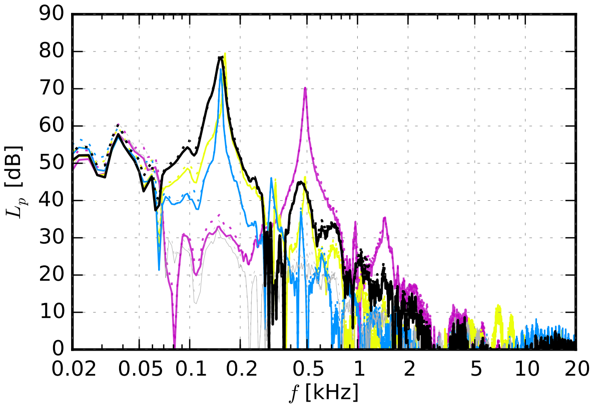
To examine the method best suited for the analysis of the present measurements, the different algorithms were tested on the measurement data obtained for four cylinders at a flow speed $U_0$ of about 26 m/s, corresponding to a Reynolds number of approximately 50,000. The results are shown in Figure 5. The diagrams contain data for a non-porous reference cylinder with a diameter of 30 mm, corresponding to the outer diameter $D$ of the porous-covered cylinders, and, additionally, for a non-porous reference cylinder with a diameter of 10 mm, corresponding to the inner diameter $d$ of the porous-covered cylinders. The porous covered cylinders used for this comparison are that made of Rubber 3 (Damtec USM, $r$ = 86,100 Pa s/m$^2$) and that made of Foam 3 (Basotect, $r$ = 9,800 Pa s/m$^2$).



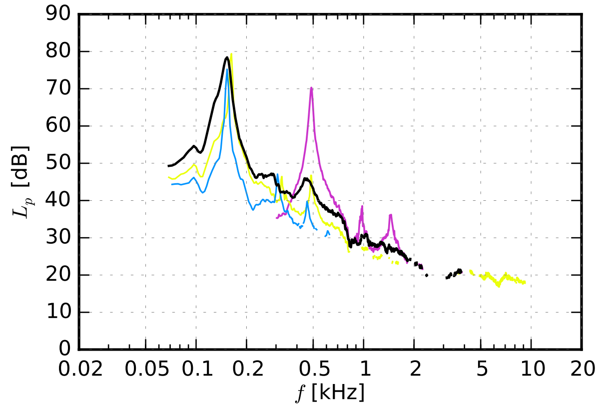

(a) Sound pressure level spectra obtained from auto spectra according to Equation (4) (solid lines: microphone 1, dotted lines: microphone 2)




(b) Coherence between microphone 1 and microphone 2, calculated according to Equation (5)




(c) Sound pressure level spectra obtained from the Coherent Output Power (COP) method according to Equation (6) (solid lines: microphone 1, dotted lines: microphone 2)




(d) Sound pressure level spectra obtained from microphone 1 auto spectra according to Equation (4), corrected for background noise

**Figure 5. Sample results for different data processing routines, *Re* = 49,500 (▬ non-porous reference cylinder, 30 mm diameter, ▬ non-porous reference cylinder, 10 mm diameter, ▬ Rubber 3, ▬ Foam 3, ▬ wind tunnel background noise)**

The sound pressure level spectra, derived from the auto spectra of a single microphone according to Equation (4), are shown in Figure 5(a), for data from both microphone 1 and microphone 2. The peak of the noise from the 30 mm reference cylinder is located at approximately 150 Hz, a smaller hump can be found around 450 Hz. The spectral peak belonging to the smaller, 10 mm diameter reference cylinder is located at a noticeably higher frequency of approximately 490 Hz. Again, a smaller hump can be found, in this case at a frequency of approximately 1,460 Hz. The spectra obtained for both porous covered cylinders show a strong spectral peak at approximately the same frequency as the thick reference cylinder with a diameter of 30 mm, although it appears that the peak frequency of the porous cylinders is a little bit higher. Again, a smaller maximum can be seen between 450 Hz and 500 Hz. The spectral peaks generated by the porous covered cylinders have about the same maximum level as that of the 30 mm reference cylinder, but are much narrower. At frequencies approximately above 3 kHz, the differences in sound pressure level are very small only. It is visible that, depending on the frequency, the porous covers (especially Foam 3) may generate less noise than the reference cylinder with 30 mm diameter, while in other frequency ranges more noise is generated.

It can also be concluded from Figure 5(a) that the outer diameter $D$ of the porous cylinders, not the diameter $d$ of the rigid core cylinder, seems to be the main parameter regarding the generation of tonal noise, at least for the two porous materials used for this comparison. However, it is reasonable to assume that for porous covers with very low air flow resistivities (especially when approaching the special case when $r \to 0$)

the core cylinder might be more important, and spectral peaks could be related to the smaller diameter $d$ rather than to the outer diameter. Included in Figure 5(a) is the background noise level, obtained from a measurement without a cylinder installed in the test section. It is visible that at frequencies below the spectral peak the measured level is basically that of the background noise. At frequencies above approximately 2 kHz, the measured broadband noise still exceeds the background noise, although the sound pressure level difference is very small only and decreases with increasing frequency. Another important fact that can be concluded from Figure 5(a) is that the spectra obtained from both microphones are essentially similar.

Figure 5(b) shows the corresponding coherence $\gamma^2_{\mathrm{mic\,1,\,mic\,2}}(f)$, obtained by using Equation (5). It is visible that the signals from microphone 1 and microphone 2 show a good coherence only in the range of frequencies where tonal noise is generated by the cylinders. At high frequencies, again approximately above 3 kHz, the signals are practically not coherent.

Figure 5(c) shows the sound pressure level spectra obtained using the coherent output power method according to Equation (6) as a function of frequency, and hence the spectra shown in Figure 5(c) were calculated as the product of the auto spectra shown in Figure 5(a) and the coherence functions shown in Figure 5(b). Accordingly, the coherent output power spectra are very similar to the microphone auto spectra in the range of frequencies where the coherence is close to one, which is in the region of the tones. In frequency ranges were broadband noise dominates, as for example at frequencies approximately above 3 kHz, all coherent output power spectra are very low in value. Additionally, they have a pretty similar shape in this frequency range, making it hard to differentiate between the results from the different cylinders and to make out if the use of the porous covers leads to a noise reduction.

As mentioned in the previous section, one possible method to remove the influence of wind tunnel background noise from the resulting spectra is to simply subtract the background noise from the measured signals. This approach was chosen in the detailed experimental study by Hutcheson and Brooks [26] on the noise radiation from cylinders. Another, more restrictive method is to simply remove signal components for which the auto spectral level is less than 6 dB above the background noise level, an approach that was used for example by Gerhard and Carolus [27] for the measurement of airfoil trailing edge noise. This method was applied to the auto spectra from microphone 1 to obtain the sound pressure levels given in Figure 5(d). As a result, the spectra contain gaps at frequencies where the background noise from the test section is too high, which is for example the case at the part of the spectra with frequencies below the aeolian tone. The advantage of this method is that the real differences between the spectra generated by different cylinders, especially at frequencies above the tonal peak, become distinct. Hence, the results are easier to interpret than for example the sound pressure levels obtained from the coherent output power spectra (Figure 5(c)). Additionally, the calculation is very fast and the measurement in general requires only one microphone (although both microphones were used for all measurements of the current study).

Finally, due to these advantages, for the present study it was decided to analyze only the corrected auto spectra of microphone 1 as shown in Figure 5(d) for the examination of the effect of the porous material on the cylinder noise generation.



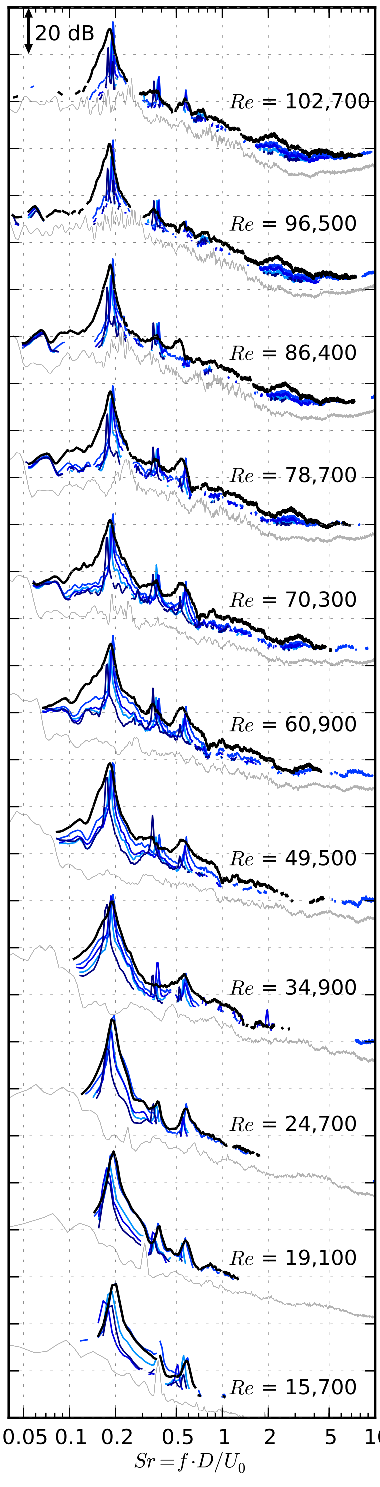
# III. Results

## III.A. Overall sound pressure level spectra

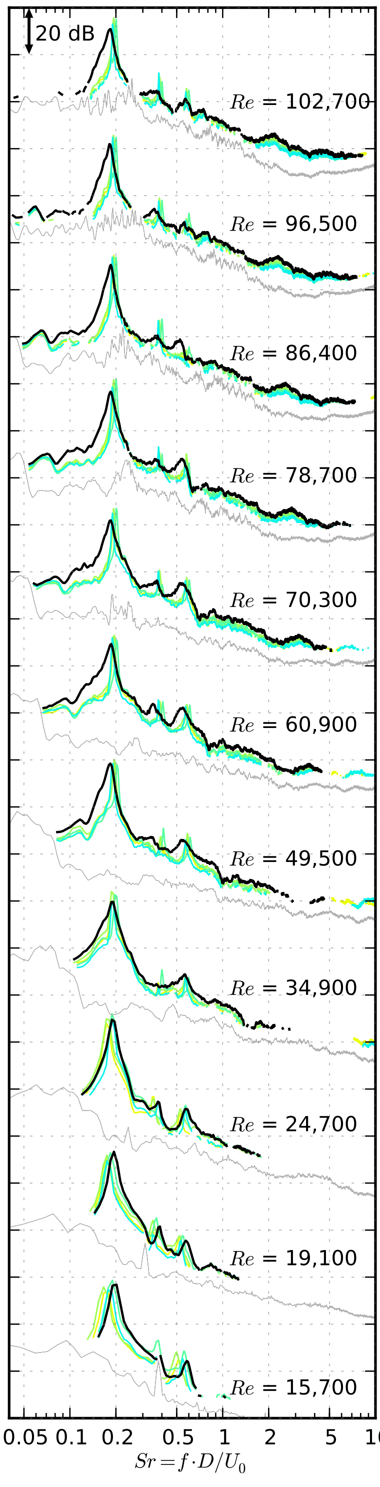
A complete overview of the noise generated by the different cylinders from Table 1 and Figure 4(b) at Reynolds numbers (based on the outer diameter $D$) between 16,000 and 103,000 is given in Figure 6. Due to the fact that it is difficult to evaluate the influence of the air flow resistivity of the porous cylinder covers on the noise reduction when all curves are plotted in one diagram, the materials are rather divided into three groups with

- low air flow resistivities ($r \leq 10$ kPa s/m$^2$),
- medium air flow resistivities (10 kPa s/m$^2$ $< r \leq 100$ kPa s/m$^2$) and
- high air flow resistivities ($r > 100$ kPa s/m$^2$),

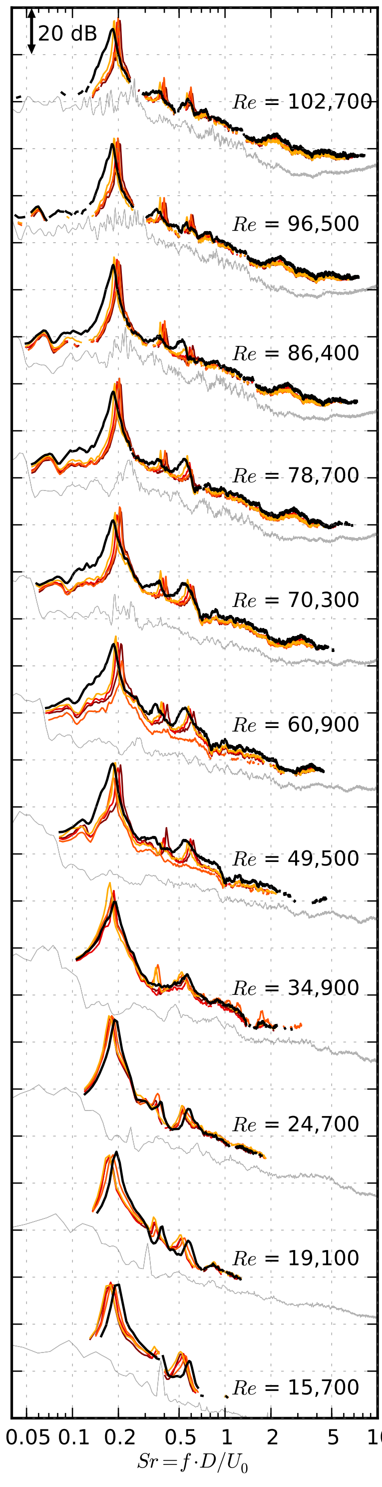
respectively. The sound pressure level spectra are given as a function of the Strouhal number $Sr$, based on the outer diameter $D$ of the cylinders. The spectral peak of all cylinders can be found at more or less the same Strouhal number. This confirms the conclusion drawn from Figure 5: Apparently, in the examined range of air flow resistivities, the generation of the aeolian tones does not dependent on the inner diameter $d$




(a) Porous covered cylinders with low air flow resistivities (Foam 3, Rubber 7, Foam 4, Foam 5)




(b) Porous covered cylinders with medium air flow resistivities (Rubber 3, Rubber 4, Rubber 5, Rubber 6)




(c) Porous covered cylinders with high air flow resistivities (Rubber 1, Rubber 2, Foam 1, Foam 2)

**Figure 6. Resulting sound pressure levels $L_p$ as a function of Strouhal number (spectra belonging to one Reynolds number were shifted in the vertical direction to improve readability, black line represents non-porous reference cylinder, gray line represents background noise)**

of the porous covered cylinders, but on the outer diameter $D$. The sound pressure level spectra measured by Hutcheson and Brooks [26] for a single circular cylinder spectra showed a large tone at the vortex shedding frequency and two smaller tones, the harmonics, that were about 25 dB lower in level. A similar observation can also be made for the data of the reference cylinder from the present study. Regarding the influence of the porous covers, two basic conclusions can be drawn from Figure 6:

First, the use of the porous covers does not lead to a complete suppression of the aeolian tone. This is in agreement with the experimental study by Yahathugoda and Akishita [2] and the numerical work by Liu et al. [7]. It also agrees, to some extent, with the study from Nishimura et al. [1], whose results still show a weak contribution of tonal noise (although a large part of it is suppressed). However, the present result does not agree well with the work from Sueki et al. [4, 5], where it was shown that the tonal noise could be completely reduced by porous covers. One possible reason for this difference may be that their experimental investigation was performed in a three-dimensional flow. It is known that, besides parameters such as the aspect ratio of the cylinders, the two-dimensionality of the flow has a large influence on the spanwise correlation of the vortices [11] and hence on the aeolian tone. Furthermore, the cylinder was attached to one wall of the wind tunnel only, while the other end protruded into the flow, and thus flow noise was most likely generated at the tip. Past experiments on cylinders with different types of end plates already showed that the shape of the tips noticeably affect the noise generation [28].

Another possible explanation for the fact that the vortex shedding noise was not suppressed in the present investigation are the chosen porous materials: It may eventually be possible to suppress the tonal noise contribution when materials with even lower air flow resistivities $r < 4$ kPa s/m$^2$ are used, which were not available for the present study. Further experiments with such materials would be needed to explore this hypothesis.

The second basic conclusion that can be drawn from the spectra in Figure 6 is that, in general, the aeolian tone of the porous covered cylinders appears much narrower than the aeolian tone of the reference cylinder with 30 mm diameter. This is in agreement with the results from the numerical study by Liu et al. [7].

In the remainder of this section, the broadband noise generated by the examined cylinders will be analyzed. A more detailed analysis of the tonal noise generation will be given in the next section. It can be seen from Figure 6 that with increasing Reynolds number the broadband noise at high frequencies (that, due to the correction, is at least 6 dB above the background noise) increases as well. Of course, the fact that the broadband noise reduction appears smaller at low Reynolds numbers is also due to the chosen correction method, since at low flow speeds the noise from the porous covered cylinders is in the order of or just above the noise from the empty wind tunnel. A trend is visible that, on average, materials with low air flow resistivities lead to a higher noise reduction than materials with medium or high air flow resistivities. As can be seen in Figure 6(a), at low Reynolds numbers (for example at $Re$ = 19,100) this noise reduction is more or less limited to the narrow frequency range in which the aeolian tone and its harmonics can be found. The maximum noise reduction in this frequency range reaches values of well over 10 dB. With increasing Reynolds number, a noticeable broadband noise reduction can additionally be observed at higher Strouhal numbers (which is especially visible for $Re$ = 60,900). Compared to the noise reduction in the frequency range around the aeolian tones, this reduction is relatively small only with values in a range below 5 dB. Basically, a similar trend can be observed for the dependence of the broadband noise reduction on the Reynolds number for porous materials with medium and high air flow resistivities (Figures 6(b) and 6(c)), although the noise generation is generally much smaller. For materials with high air flow resistivities, there is practically no noise reduction at all at low Reynolds numbers. This, however, indicates that the surface roughness of the porous covers does not contribute noticeably to the noise reduction. This is due to the fact that those materials with very high air flow resistivities (especially Rubbers 1 and 2 with $r$ = 1,474,300 Pa s/m$^2$ and $r$ = 594,200 Pa s/m$^2$, respectively) are hardly permeable to flow, while their surface does indeed have a certain roughness.

It is also visible from Figure 6 that the noise from some of the porous covered cylinders exceeds the noise from the non-porous reference cylinder. This can be observed, for example, at the small spectral peak that is positioned at a frequency approximately twice the center frequency of the aeolian tone.

In addition to the sound pressure levels derived from the corrected auto spectra of microphone 1, the single figures also contain the background noise measured without a cylinder in the test section. As was already observed from Figure 5(a), at frequencies below the aeolian tone, the wind tunnel background noise is practically the dominant noise source. It is further visible from Figure 6 that the influence of background noise

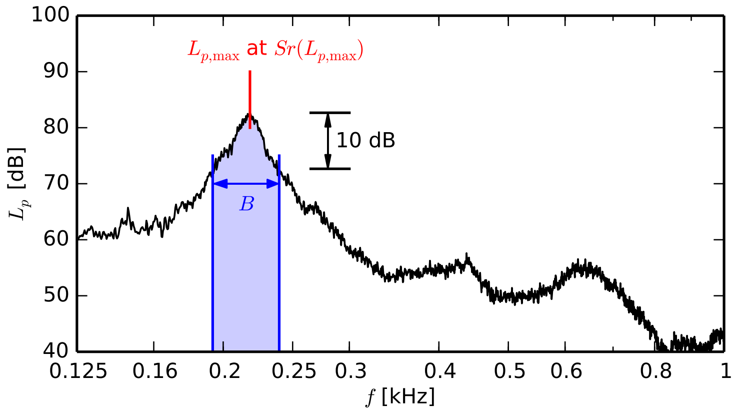



**Figure 7. Properties used to characterize the aeolian tone of the measured cylinder noise: maximum sound pressure level $L_{p,\max}$, peak Strouhal number $Sr(L_{p,\max})$, width $B$ of the peak and integral of the peak (light blue region)**

on the measured cylinder noise increases strongly with increasing Reynolds number, resulting in noticeable gaps even in close proximity to the aeolian tone. This is especially true for the two highest Reynolds numbers of 96,500 and 102,700, where it can be seen that in a Strouhal number range approximately between 0.15 and 0.3 the background noise is characterized by several small spectral peaks, showing something like a ladder type frequency structure. The reason for this increase of the sound pressure level spectrum is assumed to be a contribution of trailing edge noise from the exit of the test section, where the boundary layer that develops along the two kevlar windows interacts with the aft edge of the test section walls.

### III.B. Tonal noise

In this section, the influence of the porous materials on the aeolian tone is examined in more detail. To this end, different parameters describing such a narrow spectral peak were derived from the sound pressure level spectra. In this case, the spectra were calculated with the smaller frequency step size of 0.39 Hz.

The parameters that were selected for the description of the tonal noise are:

- the maximum sound pressure level $L_{p,\max}$ of the tone,
- the peak Strouhal number $Sr(L_{p,\max})$, at which the tone occurs,
- the width $B$ of the peak, defined as the frequency difference between the two spectral values which are 10 dB below the maximum (vertical lines in Figure 7), and
- the integral of the corresponding sound power below the peak from the first value where the level is 10 dB below the maximum to the second (given by the light blue region in Figure 7).

A visualization of these metrics is given in Figure 7. The last two parameters contain the same information. However, the integral of the sound power below the peak may be more meaningful since it is kind of an overall sound pressure level of the tone.

The results of the analysis of the aeolian tones are given in Figure 8 through 11. As can be seen in Figure 8, the peak sound pressure level constantly increases with increasing Reynolds number. At lower Reynolds number, the data appears to roughly scale with the sixth power of the flow speed. This dependence corresponds to the theoretical behaviour of a pure acoustic dipole and is often used to scale experimental data, as for example in the work of Schlinker et al. [24] and Hutcheson and Brooks [26]. At higher Reynolds number, the velocity scaling exponent decreases a little bit and rather converges towards a $U^4$ scaling. In general, there exist various theories of varying complexity for the scaling of the vortex shedding noise from cylinders, most of them requiring the knowledge not only of the flow speed, but of parameters like the cylinder length, the fluctuating forces acting on the cylinder or a spanwise correlation length of surface pressure fluctuations as well [11, 26]. Additionally, an increase in Reynolds number also results in an increasing width of the boundary layer along the tensioned kevlar walls. This affects the noise propagation, which, eventually, leads to a slight decrease in peak amplitude as well. No clear trend can be observed regarding the influence of the porous materials on the peak level. Although it seems that most of the porous covered cylinders generate a

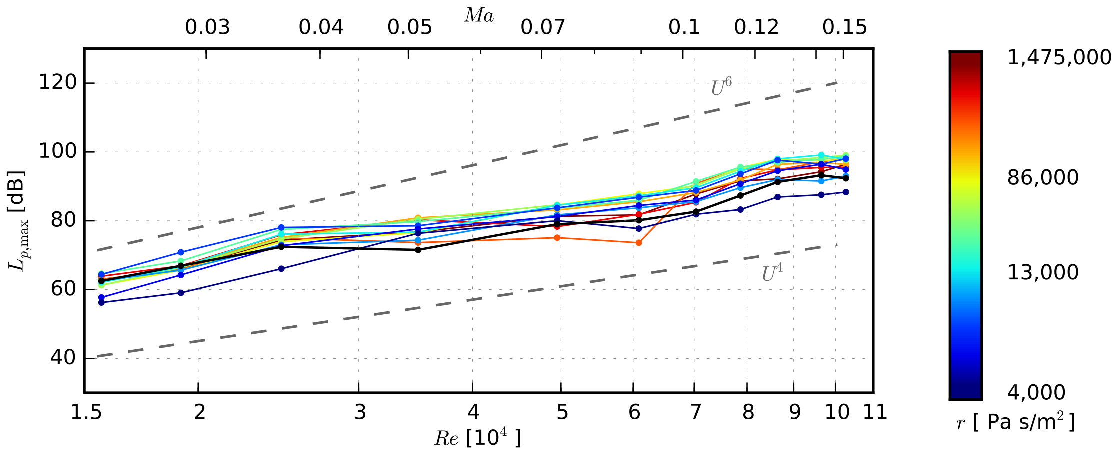



**Figure 8. Dependence of the peak sound pressure level on the Reynolds number for the different cylinders (black: reference cylinder, colored: porous covered cylinders)**



tonal level $L_{p,\max}$ that is slightly above that of the reference cylinder, there appears to be no clear dependence on the air flow resistivity.

The peak Strouhal numbers of the cylinder noise in general take values approximately between 0.17 and 0.21 (see Figure 9). The Strouhal number of the aeolian tone generated by the non-porous reference cylinder slightly decreases with increasing Reynolds number, from approximately 0.195 at $Re$ = 15,700 to 0.185 at $Re$ = 102,700. This is in agreement with basic theory: According to the summary of different studies on cylinders shown in the publication from Blake [10], the Strouhal number of a circular cylinder in this Reynolds number regime is within a range approximately between 0.18 and 0.2. Furthermore, a slight decrease of the peak Strouhal number with increasing Mach number was also reported by Hutcheson and Brooks [26] for cylinders with diameters between 2.4 mm and 25.4 mm in a uniform flow. Again, there is no absolute trend visible for the influence of the porous cylinder covers on the peak Strouhal number. Still, it seems that for materials with low air flow resistivities $r$ (blue colors in Figure 9) the Strouhal number does not vary as much with varying Reynolds number as it does for materials with medium and high air flow resistivities. For materials with high air flow resistivities, a relatively large and, in some cases, sudden increase of the Strouhal number with increasing Reynolds number can be observed. However, it is also known that the surface roughness of a cylinder affects the peak Strouhal number of the flow noise in a quite complex way [12]. Thus, in the present study both the air flow resistivity and the surface roughness of the porous covers have an influence on the Strouhal number, making it hard to determine the individual dependencies. Furthermore, according to Hutcheson and Brooks [26] the effect of the surface roughness on the peak Strouhal number depends on the cylinder diameter and the Mach number.

Figure 10 and 11 give information regarding the fact that the spectral peaks from the porous covered cylinders appear much narrower in Figure 6 than the peaks of the non-porous reference cylinder. This is in agreement with the numerical results given in [7]. The width $B$ of the peak, defined as the frequency difference between the two spectral values that are 10 dB below the maximum, is shown in Figure 10, while the peak integral is given in Figure 11. The figures show the clear trend that both the peak width and the peak integral of the aeolian tones increase with increasing air flow resistivity of the materials as well as with increasing Reynolds number. When the peak integral is interpreted as a measure for the total sound pressure level of the aeolian tone, it can be concluded that, depending on the porous material and the Reynolds number, reductions in the order of 10 dB to 15 dB are possible.

Additionally, a very interesting effect can be seen in Figure 10: Between the Reynolds number of 86,400 and 96,500, the peak width of the porous covered cylinder with the lowest air flow resistivity (Foam 5, $r$ = 4,000 Pa s/m$^2$) suddenly increases from about 2.3 Hz to 26.2 Hz. The reason for this increase is that the generated noise at higher Reynolds number gradually develops a second peak at a frequency slightly above that of the first peak, which can be seen in Figure 12. At Reynolds numbers below 96,500, the level of this second tone is more than 10 dB below the (main) aeolian tone, which is why the calculated peak width is that of the latter only. Then, at $Re$ = 96,500 and $Re$ = 102,700, this second peak is much higher in level and the corresponding peak width includes both tones. Since both the first and the second peak themselves are

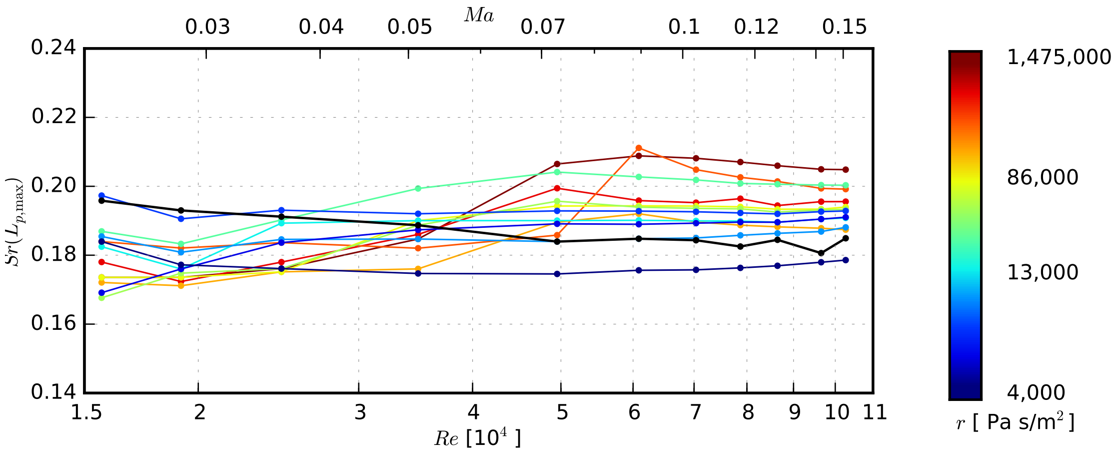



**Figure 9. Dependence of the peak Strouhal number on the Reynolds number for the different cylinders (black: reference cylinder, colored: porous covered cylinders)**

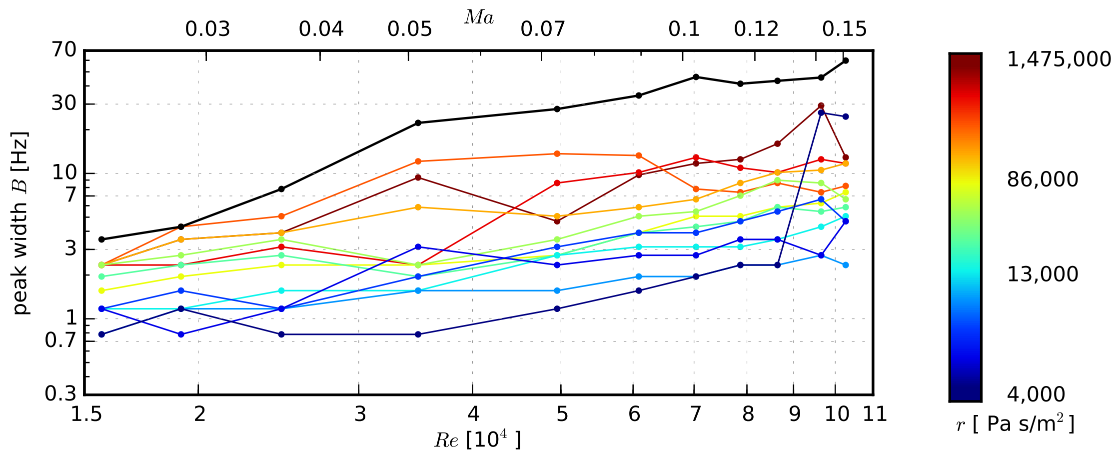



**Figure 10. Dependence of the peak width (defined as the difference of the frequencies of the sound pressure levels 10 dB below the peak level) on the Reynolds number for the different cylinders (black: reference cylinder, colored: porous covered cylinders)**

very narrow, the increase of the peak integral (Figure 11) appears not that strong. A possible reason for this bifurcation effect is that simply another vortex shedding occurs on another scale. Additional measurements in a future study using a cylinder with an even lower air flow resistivity $r < 4$ kPa s/m$^2$ would be helpful to further explore this effect.

The exact cause of the reduced flow noise generation at the cylinders with porous cover is not clear yet. It is reasonable to assume that the open pores affect the vortex generation at the cylinder surface and reduce pressure fluctuations. Similar conclusions were drawn by Nishimura et al. [1], who also state that the porous surface reduces the kinetic energy of vortices that collide with it, "without generating intense near wall vorticity". Yahathugoda and Akishita [2] also performed hot-wire measurements in the wake of their optimized porous cylinder and showed that, as would be suspected, the noise reduction is accompanied by a reduction of the intensity of the velocity fluctuations. The numerical results from Liu et al. [7] showed that "the flow adjacent to the cylinder is regularized" by the porous cover.

According to theory [11], in the Reynolds number regime of the current measurements, the boundary layers around the cylinder are still laminar and the transition occurs along the free shear layer. Based on past investigations of the trailing edge noise reduction at porous airfoils [18,19], another possible explanation for the present reduction of cylinder flow noise is that the porous material simply absorbs some of the energy contained in the laminar boundary layer. This means that the source strength of the vortices that later form along the free shear layer is already reduced. However, additional experiments, such as hot-wire

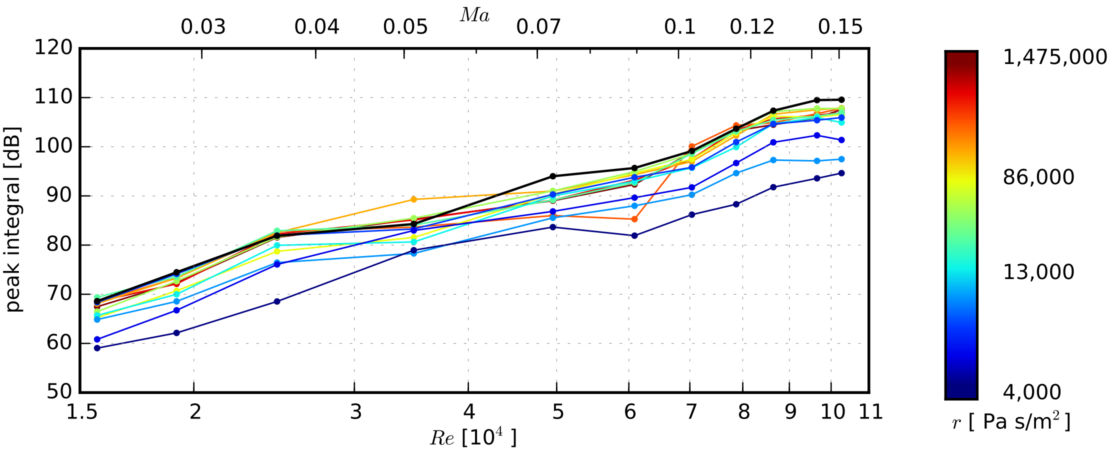



**Figure 11. Dependence of the peak integral on the Reynolds number for the different cylinders (black: reference cylinder, colored: porous covered cylinders)**

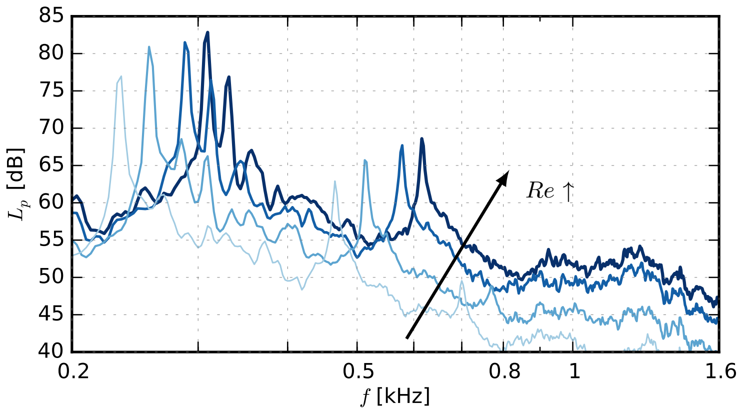



**Figure 12. Sound pressure level spectra measured for the cylinder with the porous cover made of Foam 5 ($r$ = 4,000 Pa s/m$^2$) for the four highest Reynolds numbers $Re$ = 78,700, 86,400, 96,500 and 102,700 (color intensity and line width increase with increasing Reynolds number)**



measurements in the wake, on at least some of the porous covered cylinders of the present study are required to formulate a better hypothesis regarding the cause of the noise reduction.

# IV. Conclusion

This paper presents results from acoustic measurements of the flow-generated noise from a set of cylinders that consist of a rigid core cylinder covered by different open-porous materials. These materials are characterized in the present study by their air flow resistivity, and the main focus of the investigation is to examine the influence of the porous material on the noise generation. This includes the tonal noise due to the vortex shedding (the aeolian tone) as well as the broadband noise. The cylinders were positioned in the test section of a small aeroacoustic wind tunnel, where measurements were conducted with single microphones at Reynolds numbers from approximately 16,000 to 103,000.

The results of the present study show that the porous covers have a strong influence on the tonal noise, which scales with the outer diameter of the cylinders. Although the porous covers examined do not lead to a suppression of the aeolian tone, the spectral peaks of the vortex shedding noise are noticeably smaller than that of a non-porous reference cylinder. It becomes visible that the width of the spectral peak as well as the peak integral as a simple measure for the total sound pressure level of the tonal noise increase with increasing air flow resistivity of the porous covers. This means that porous materials that are highly permeable to air result in a large reduction of the peak noise compared to a reference cylinder of the same diameter, while the noise reduction that can be achieved through the use of materials with a high air flow resistivity (and hence a very low permeability) is much lower. Both the peak Strouhal number as well as the peak level of the aeolian tone do not show a clear dependence on the air flow resistivity of the porous covers. The reduction of the total sound pressure level of the peak, determined as the peak integral, shows that reductions in the order of 10 dB to 15 dB are possible, depending on the porous material and the Reynolds number. Future measurements on materials with even lower air flow resistivities ($r < 4$ kPa s/m$^2$), which were not available for the present study, would be helpful to investigate whether a total suppression of the vortex shedding tone might eventuelly be possible after all for such materials. Besides the reduction of the tonal noise, the porous covers also lead to a reduction of broadband noise which is in a range roughly below 5 dB. Again, porous materials with low air flow resistivities result in a larger noise reduction compared to the reference cylinder than materials with high air flow resistivities.

In this paper, only the dependence of the noise generated by the porous covered cylinders on the air flow resistivity and the Reynolds number was examined. The influence of other parameters that will most likely affect the generation of flow noise, such as the surface roughness, any other parameters describing the porous materials or the thickness of the porous layer, is still not clear and remains to be examined.



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