Reduction of vortex shedding noise from finite, wall-mounted, circular cylinders using porous material

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The aerodynamic noise generated by a circular cylinder in a cross flow is a classical problem in aeroacoustics, which can be found in various practical applications such as antennas of vehicles, train pantographs and parts of the landing gear of airplanes. The noise is especially disturbing since it contains strong tonal contributions due to the regular vortex shedding at the cylinder. If the cylinders are not two-dimensional, but finite and wall-mounted at one end and free at the other, additional flow phenomena occur at both the tip and the wall junction, which can lead to additional noise contributions. One method to reduce the aerodynamic noise from such cylinders is to cover them with a flow permeable, porous material. The present paper describes an experimental study on the effect of porous covers on the reduction of noise generated by wall mounted, finite, circular cylinders. Three different porous materials were tested. Thereby, special focus was put on the identification of both the optimum position and the optimum extent of the porous cover regarding a maximum noise reduction. The experiments were conducted in an aeroacoustic open jet wind tunnel at subsonic flow speeds, leading to low to moderate Reynolds numbers between 8,000 and 61,000 based on the outer cylinder diameter. It was found that a placement of porous material at the wall end is more efficient in reducing Kármán vortex shedding noise than a placement of porous material at the free end.

I. Introduction

The flow around wall-mounted, finite cylinders is very complex, as it may consist of various different vortex structures, which are highlighted in the schematic shown in Figure 1. This includes a horseshoe vortex and base vortices at the wall junction, classical Kármán vortices along the span and tip vortices at the free end [1, 2]. Consequently, such cylinders can also be a source of strong tonal noise [3, 4]. As shown exemplarily in Figure 2, this may include noise sources due to the classical Kármán vortex shedding (the so-called aeolian tone), noise sources due to flow phenomena at the wall junction and noise sources due to flow over the free end. Both the flow phenomena and the noise generation depend on the Reynolds number Re of the flow based on cylinder diameter and, especially, on the aspect ratio (ratio of cylinder length to cylinder diameter) l/d of the cylinder.

Basically, different approaches exist to reduce the noise generated by a cylinder in a cross flow and, especially, the tonal noise due to the classical vortex shedding (see for example [5]). However, one method that more and more gets in the focus of scientific research is the use of flow-permeable or porous media. Consequently, several publications exist that investigate the effect of cylinders modified with porous materials on the reduction of aerodynamic noise. One of the first studies is the work of Ikeda and Takaishi [6], who performed measurements on a two-dimensional perforated cylinder with the aim to reduce the tonal noise from the pantograph horn. They found that the perforation suppressed the aeolian tone, although tonal noise was generated at another frequency due to resonance effects at the holes. Similarly, Yahathugoda and Akishita [7] also performed acoustic measurements on two-dimensional circular cylinders equipped with perforations. They did not observe a complete suppression of the tonal peak due to Kármán vortex shedding, however, depending on the design of the perforations they achieved a reduction of the tonal peak sound pressure level of up to 6 dB. The effect of porous covers, consisting of porous metal, porous urethane or fur,

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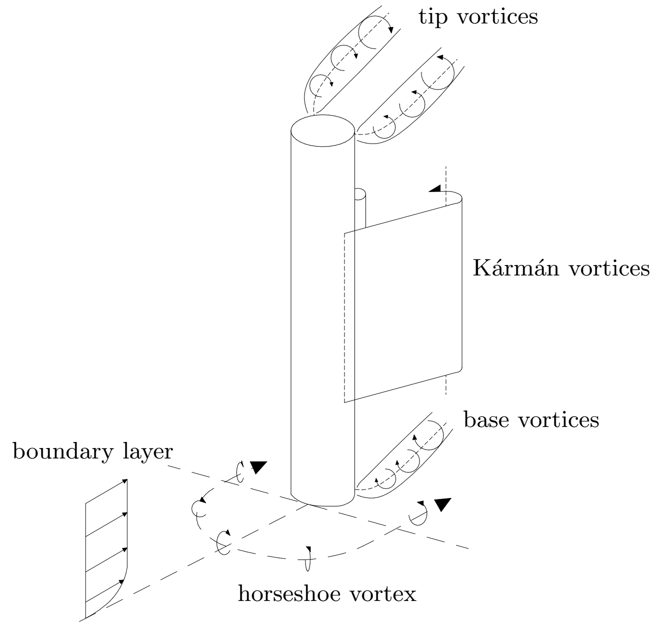


Figure 1. Schematic of the flow around a finite, circular, wall-mounted cylinder (adapted from [1])

on the flow noise generated by a finite, wall mounted cylinder was first examined experimentally by Sueki et al. [8]. They found that the tonal noise due to Kármán vortex shedding was completely suppressed by the porous materials. In a later study by the same group, the noise generated by two-dimensional cylinders covered by rigid porous materials (porous urethane and porous metal) was examined [9]. Again, it was found that the vortex shedding peak was suppressed as long as the material has open pores. A cylinder covered with a closed-cell porous material still generated a vortex shedding tone. It has to be noted that the acoustic results from Sueki et al. [8, 9] were presented in one third octave bands only. Thus, it would still be possible that the porous-covered cylinders generate a very narrow tone (as reported by other researchers) that is not visible when displayed in one third octave bands. Such a narrowing of the width of the cylinder vortex shedding peak caused by porous covers was reported by Liu et al. [10], who performed a two-dimensional Large Eddy Simulation with the Ffowcs Williams-Hawkings integration method [11] on cylinders covered with porous materials of different porosity, pore density and thickness. In addition to the narrowing of the tonal peak they observed a shift of the peak towards lower frequencies. Geyer and Sarradj [12] performed detailed acoustic measurements on two-dimensional cylinders covered with open-porous materials of varying air flow resistivity. The materials consisted of various foams and porous rubber granulates. In agreement with the numerical results by Liu et al. [10] they found that the porous covers lead to a notable narrowing of the vortex shedding tone, but not to its suppression. In a consecutive numerical study [13] this noise reducing effect was investigated using a 2D Detached Eddy Simulation, which gave some insight into the flow inside the porous material but failed to exactly reproduce the narrowing of the vortex shedding tone. Another recent experimental study on the effect of porous covers on the reduction of cylinder vortex shedding noise was performed by Arcondoulis et al. [14], who used both common metal foam and polyurethane foam covers as well as a structured, 3D-printed porous cover of equal thickness. They also observed a narrowing of the vortex shedding tone as well as a notable reduction of its peak amplitude. Interestingly, each of their porous covered cylinder generated two tones, a small one at a frequency below that of the non-porous reference cylinder and one at a frequency slightly above that of the reference cylinder.

This short overview shows that the use of flow permeable material for the reduction of cylinder-generated flow noise has already been examined in several studies. However, besides the work of Sueki et al. [8], the application of porous material to wall-mounted, finite cylinders has not been investigated properly. Therefore, based on the promising results from the past study by Geyer and Sarradj [12], the aim of the present study is to investigate how the noise generation of wall-mounted finite cylinders can be changed by applying such

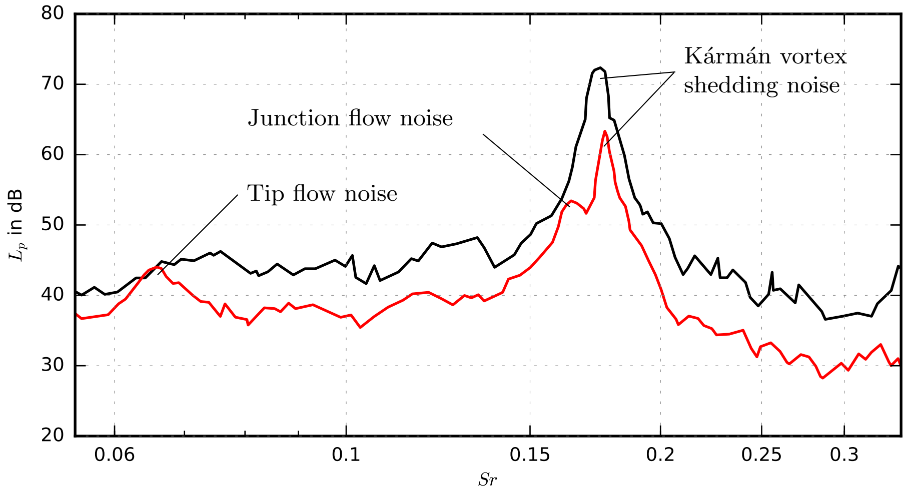


Figure 2. Overview of the noise sources occurring at a three-dimensional wall mounted cylinder (adapted from [3], ▬ 2D cylinder, ▬ 3D wall-mounted cylinder with $l/d = 22.7$)

flow-permeable materials to various parts of the cylinders. This refers especially to the strong tonal noise due to the classical Kármán vortex shedding, which is known as the aeolian tone. The chosen approach can be summarized as follows: After an effective porous material is selected, the focus is to identify both the optimum position and the optimum extent of the porous cover that lead to the maximum reduction of the aerodynamic vortex shedding noise.

II. Experimental Setup

II.A. Wind Tunnel

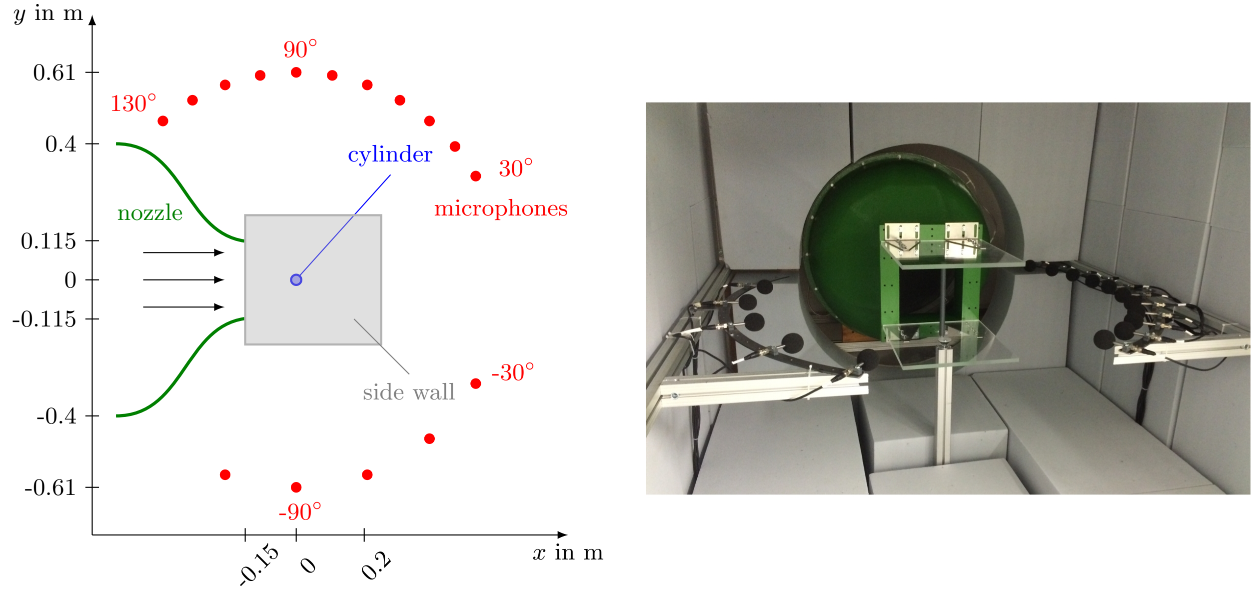
The experiments were performed in the small aeroacoustic open jet wind tunnel at the Brandenburg University of Technology in Cottbus [15] using a nozzle with a rectangular exit area of 0.23 m × 0.28 m. With this nozzle, 13 flow velocities approximately between 7 m/s and 50 m/s were adjusted in the present study, leading to Reynolds numbers (based on outer cylinder diameter d) between 8,000 and 61,000. The velocities were corrected for the blockage due to the cylinders using the approximation given by Barlow et al. [17].

In the experiments, the cylinders were mounted to one of two acrylic side walls, which have a distance of 0.28 m to each other and were mounted to the nozzle (see Figure 3). The distance between the cylinder and the nozzle exit was 0.15 m. Surrounding the wind tunnel test section on all sides but the one on the opposite side of the nozzle are absorbing walls, which lead to a quasi anechoic measurement environment for frequencies greater 100 Hz (see photograph in Figure 3(b)).

II.B. Acoustic Measurements and Data Processing

The acoustic measurements were performed using 16 1/4th inch free field microphones arranged on two arcs on opposite sides of the test section. On one arc (the upper one in the schematic shown in Figure 3(a)), 11 microphones were positioned at azimuthal angles from 30° to 130° in 10° steps. On the other arc, additional 5 microphones were positioned at azimuthal angles from -30° to -110° in 20° steps. The microphones were directed towards the cylinder axis approximately at mid span, with a radial distance of 0.61 m.

The data from the microphones were recorded with a sampling frequency of 51.2 kHz and a duration of 90 s using a 24 Bit National Instruments multichannel measurement system and stored on a RAID file system. In post processing, the time data were converted into the frequency domain by using a Fast Fourier Transformation (FFT) on 75 % overlapping, Hanning-windowed blocks of 16,384 samples with Welchs method [16]. This lead to a frequency spacing of 3.125 Hz. Finally, the data were converted to sound pressure levels L_p re 20 μPa.



(a) Schematic (top view)

(b) Photograph (taken from downstream)

Figure 3. Experimental setup inside the aeroacoustic wind tunnel

II.C. Cylinder Models

All cylinders used in the present study consist of a core cylinder with a diameter of 10 mm, over which either porous material or a non-porous hull was threaded. The resulting cylinders, which could be non-porous, fully porous or partially porous, all have the same outer diameter d of 18 mm.

It is known that noise from finite wall-mounted cylinders can be generated by varying sources at different source locations (see Figure 1), which strongly depends on the aspect ratio of the cylinder models. Therefore, in order to select an appropriate length for the cylinders, a preliminary study was performed on a set of non-porous cylinders. These cylinders had lengths of 30 mm, 60 mm, 90 mm, 120 mm, 150 mm, 180 mm, 210 mm, 240 mm and 260 mm with a diameter of 18 mm, corresponding to aspect ratios between 1.67 and 14.44. Figure 4 shows the sound pressure level spectra obtained for these cylinders with the microphone positioned at an azimuthal angle of 90° at the maximum flow speed of 50 m/s.

According to previous studies [3], no vortex shedding may occur for finite cylinders with aspect ratios below a critical value of 7. This is confirmed by the current results, as Figure 4 shows that the spectra of the short cylinders with aspect ratios of 1.67, 3.33, 5 and 6.67 do not feature a peak associated with Kármán vortex shedding. In addition, in agreement with [3] it is visible in Figure 4 that both the amplitude as well as the frequency of the vortex shedding tone decrease with decreasing aspect ratio.

Finally, it was decided to perform measurements on cylinders with two different lengths: a short cylinder with a length of 90 mm and hence an aspect ratio of 5, and a long cylinder with a length of 240 mm and an aspect ratio of 13.3 (which is the same aspect ratio that was used in the experimental studies by Sueki et al. [8, 9]). Since the aspect ratio of the short cylinders is below the critical aspect ratio of 7, and hence no vortex shedding occurs along the span, it is well possible that a modification with porous material does not result in a notable noise reduction. The majority of the experiments was performed on the long cylinder with an aspect ratio above 7, for which it was aimed to identify the optimum material, position and extent of the porous cover.

Regarding the porous cover, three flow permeable materials have initially been chosen for this study: *Basotect*, a melamine resin foam well known for being an efficient sound absorber, *Regufoam Vibration 150 plus*, a polyurethane (PU) foam commonly used for isolation of vibration and structure-borne noise, and *Damtec SBM K 20*, a mixture of PU foam and rubber granulates with a PU elastomer bonding agent used for vibration isolation in rail traffic. The thickness of the porous layer was 4 mm for each material. Parameters of these materials were either measured or taken directly from the data sheet and are summarized in Table 1. In the first part of the investigation, the most effective porous material material will be chosen. In the second

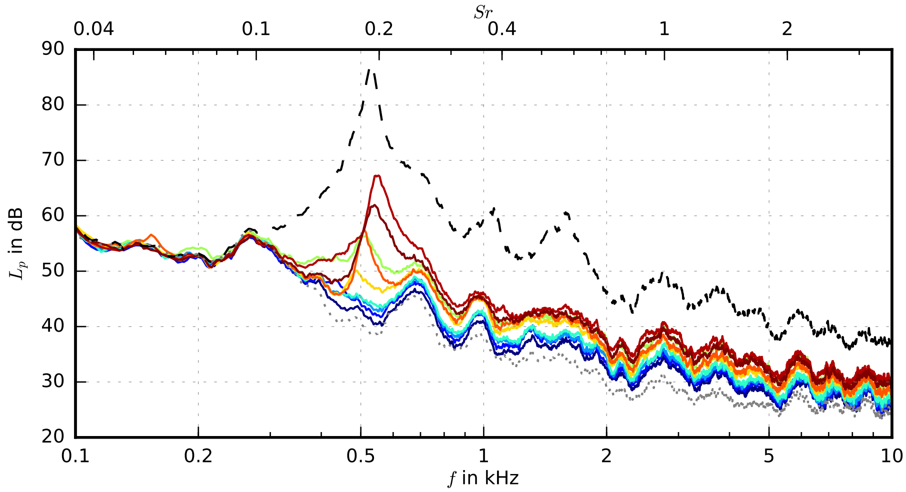


Figure 4. Sound pressure level spectra of the non-porous finite cylinders of different aspect ratio, $U \approx 50$ m/s ($l/d =$ 1.67, 3.33, 5, 6.67, 8.33, 10, 11.67, 13.33, 14.44; non-porous 2D cylinder, background noise)

Table 1. Parameters of the porous materials (measured or taken from data sheet)

Material	Description	Air flow resistivity (Pa s/m^2)	Porosity (-)	Density (kg/m^3)
Basotect	melamine resin foam	9,800	>0.99	9 ±1.5
Damtec SBM K 20	rubber granulate	12,900	0.29…0.32	650
Regufoam Vibration 150 plus	polyurethane foam	64,500	0.85…0.88	150

part, the most effective position and extent of said material will be determined. Basically, possible positions for a porous cover are

1. at the free end,
2. at the wall junction,
3. both at the free end and the wall junction or
4. along the span (but neither at the free end nor at the wall junction).

Figure 5 shows a schematic of these four options. Thereby, s_t denotes the extent of the porous cover at the free end ("tip"), s_w denotes the extent of the porous cover at the wall junction ("wall") and s_s denotes the extent of the porous cover along the center span ("span"). As an example, a photograph of a cylinder with a length l of 240 mm and a porous cover made of Basotect with a length s_t of 60 mm is shown in Figure 6.

III. Results

III.A. Fully covered cylinders

A comparison of the sound pressure level spectra obtained by the microphone located at an azimuthal angle of 90° for the fully covered cylinders is shown in Figures 7 and 8, exemplarily for two flow speeds of 23 m/s and 50 m/s. Thereby, Figure 7 contains the spectra for the cylinders with an aspect ratio of 5, which is below the critical aspect ratio of 7 given in [3]. In agreement with the literature, neither of the wall-mounted cylinders generates a vortex shedding peak. It appears, however, that the porous covers lead to a slight reduction of broadband noise, which agrees with the findings from [12].

The spectra measured at the same flow speeds for the fully covered cylinders with an aspect ratio of 13.3 are given in Figure 8. The Kármán vortex shedding peak of the non-porous reference cylinder of the same aspect ratio is noticeably lower than that of the 2D (full span) cylinder at both flow speeds, which is again in agreement with previous studies [3]. In addition, a clear effect of the porous covers is visible: Both Damtec

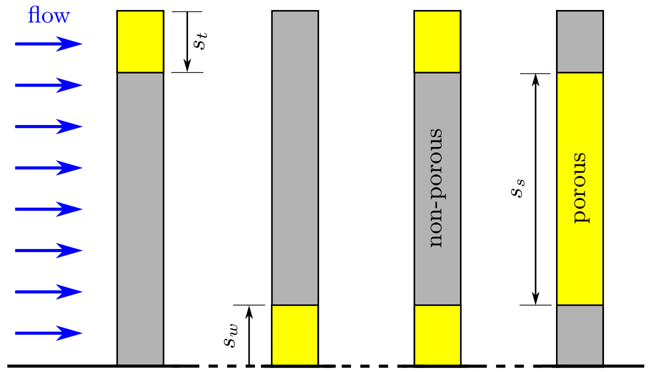


Figure 5. Possible positions for a porous cover, from left to right: at the free end, at the wall junction, at the free end and the wall junction, along the span

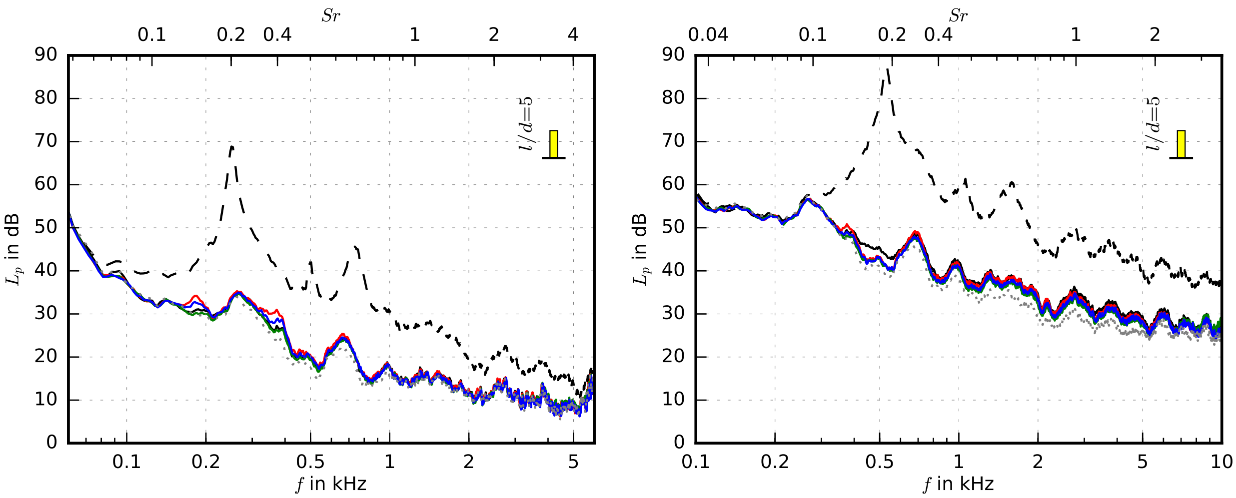
Figure 6. Left: photograph of a cylinder with l = 240 mm and a porous cover made of Basotect with s_t = 60 mm, right: porous covers made of Damtec SBM K 20, Regufoam Vibration 150 plus and Basotect

and Regufoam only lead to a decrease in peak amplitude without removing the peak completely. However, the peak as a whole appears narrower, which is especially visible at the higher flow speed (Figure 8(b)). This effect was also observed in past findings on 2D porous covered cylinders [10, 12]. For the cylinder covered by Basotect, the material with the lowest air flow resisitivity of the present study, the vortex shedding peak is completely suppressed for both flow speeds. Furthermore, this material also appears to result in the best broadband noise reduction. It is interesting to note that in the previous study performed on two-dimensional porous-covered cylinders [12], none of the porous covers led to a complete suppression of the vortex shedding peak. It can be assumed that the difference is due to the increased ratio of the thickness of the porous cover to the outer cylinder diameter in the present case.

The sound pressure level spectra obtained for the finite wall-mounted cylinders with $l/d = 13.3$ at the lower flow speed (Figure 8(a)) also show a small hump at a frequency just below 100 Hz. A comparison with the results presented in [3], as shown in Figure 2, reveals that this peak is most likely due to tip flow noise. In addition, the main peak obtained for the cylinder covered with Damtec shows a secondary peak. Thus, the tonal characteristics look similar to that shown in Figure 2 for the three-dimensional wall-mounted cylinder. This would hint at the fact that this secondary peak is due to noise generated at the wall junction. However, it is not clear why such a secondary peak is not visible for the other cylinders of this aspect ratio.

The results obtained at the two flow speeds are confirmed by the measurements at the remaining flow speeds, as can be seen in the contour plots shown in Figure 9. The non-porous reference cylinder (Figure 9(a)) as well as the cylinders covered with Damtec (Figure 9(c)) and Regufoam (Figure 9(d)) show a noticeable vortex shedding peak for Reynolds numbers above approximately 25,000. Only the spectra for the cylinder fully covered with Basotect (Figure 9(b)) do not feature this peak.

In addition to the results obtained for the fully covered cylinders with the single microphone positioned at



(a) $U = 22.5$ m/s (Re = 26,700)

(b) $U = 50.2$ m/s (Re = 59,700)

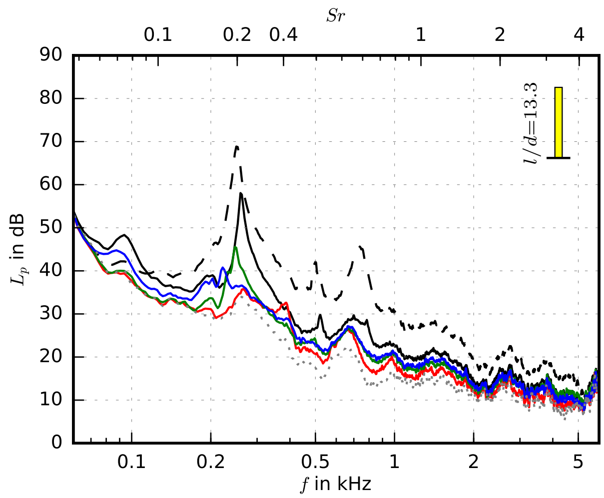
Figure 7. Comparison of the sound pressure level spectra of the fully covered cylinders with $l/d = 5$ at two different flow speeds (Basotect, Damtec, Regufoam, non-porous reference cylinder, non-porous 2D cylinder, background noise)

an angle of 90°, Figure 10 shows the resulting peak levels of the vortex shedding tone from all 16 microphones in a polar plot, thus highlighting the directivity of the aeolian tone. Thereby, the peak level was defined as the maximum sound pressure level value detected within a Strouhal number range of $0.16 < Sr < 0.21$. This range was taken from [12] for the vortex shedding noise of porous covered cylinders. It has to be noted that for cases where no vortex shedding peak exists (for the cylinder covered with Basotect as well as for the background noise measurement), this method will just yield the maximum of the broadband noise within this range, which may not even be generated by the cylinder. Hence, it is not necessarily physically meaningful and has to be understood as an approximate value to characterize the low noise generation in these cases. It can be seen from Figure 10 that the directivity for all cases is slightly increased in a range of angles between approximately $|45°|$ to $|80°|$. Since that increase is also visible for the background noise, it is likely due to an amplification of the noise caused by the flow. The main conclusion, however, is that the effect of the porous covers is independent of the direction, and hence the modification of the cylinders with porous materials does not change the directivity of the source.

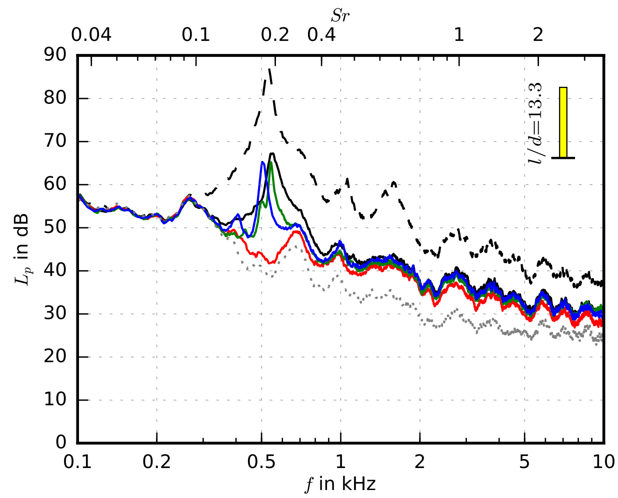
Finally, based on the results from this first part of the study, it was decided to use only the porous material Basotect for the subsequent investigation of the optimum extent and position of the porous covers. In addition, due to the fact that no classical Kármán vortex shedding occurs at cylinders with small aspect ratio (as shown in Figure 7), the following analyses are restricted to the larger cylinder models with a length of 240 mm, corresponding to an aspect ratio of $l/d = 13.3$.

III.B. Partially covered cylinders

The aim of the second part of the study was to determine the effect of the placement and the extent of the porous cover. In a first step, the porous material was applied only to the tip region of the cylinder. As an example result, Figure 11 shows the sound pressure level spectra from the microphone at an azimuthal angle of 90° for the cylinders with an aspect ratio of 13.3 at a single flow speed of approximately 50 m/s. The cylinders are equipped with porous covers made of Basotect of various extents s_t at the free end. Thereby, the extent was subsequently increased from 30 mm ($s_t/l = 0.125$) to 240 mm ($s_t/l = 1$) in 30 mm steps. It can be seen that the vortex shedding peak is only suppressed completely for the cases when the extent of the porous cover is 75 % of the cylinder length and greater, a behavior that was observed for all flow speeds of the present study. In addition, it is visible from Figure 11 that for the cases where $s_t/l = 0.125$ and $s_t/l = 0.25$, the vortex shedding peak is even higher than that of the finite non-porous reference cylinder of the same aspect ratio, and hence even closer to the spectrum shown for the 2D cylinder. It seems plausible to assume that such short covers at the free end of the cylinder only suppress tip vortex structures which otherwise limit mid span Kármán vortex shedding due to the downwash at the free end [3]. Thus, a small



(a) $U = 22.7$ m/s ($Re = 26{,}700$)



(b) $U = 50.7$ m/s ($Re = 60{,}400$)

Figure 8. Comparison of the sound pressure level spectra of the fully covered cylinders with $l/d = 13.3$ at two different flow speeds (Basotect, Damtec, Regufoam, non-porous reference cylinder, non-porous 2D cylinder, background noise)

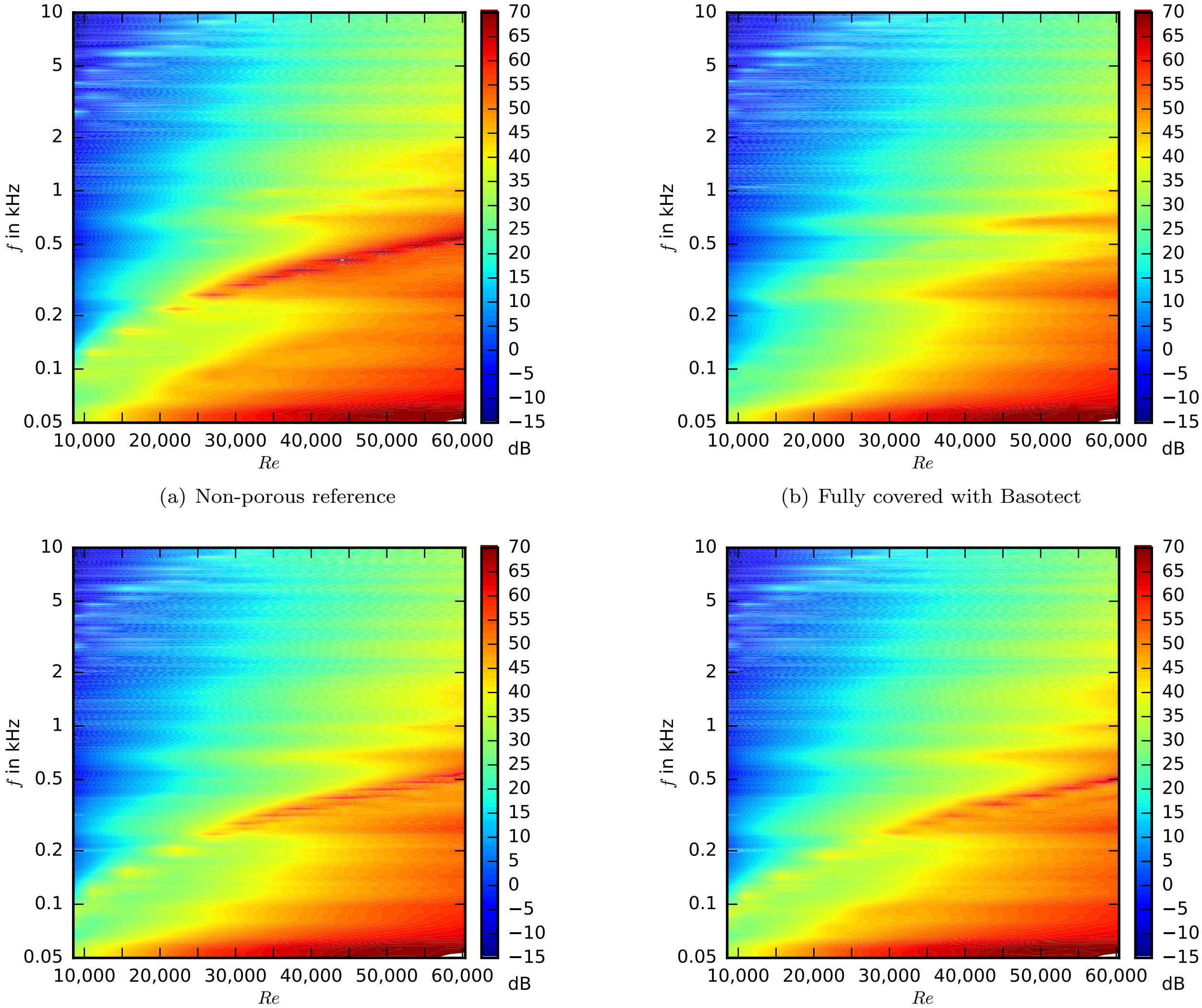
local modification with porous material at the free end will therefore only have a negative effect on the noise reduction by increasing the radiated noise. However, this effect depends on the flow speed U in a more complex manner. It is very pronounced at flow speeds below 25 m/s and above 38 m/s, but is less distinct (although still present) at the range of flow speeds between 25 m/s and 38 m/s.

In the second step, the porous material was applied only to the wall-mounted end (the root) of the cylinder. Spectra for these cases are shown in Figure 12, again for the maximum flow speed of approximately 50 m/s. Now, the Kármán vortex shedding peak is already completely suppressed when the extent of the porous material covers more than 25 % of the cylinder span. When the flow speed is decreased approximately below 45 m/s, Kármán vortex shedding does also occur at the cylinder with $s_w/l = 0.375$. Interestingly, the spectra of the cylinders that do no generate an aeolian tone feature a small broad hump at a frequency slightly below the vortex shedding frequency of the other cylinders. According to the review in [3] and the corresponding representation in Figure 2 it can be assumed that this noise is due to junction flow.

In general, when comparing the spectra shown in Figure 12 with those obtained for the cylinders with porous material at the tip as shown in Figure 11, it becomes clear that less porous material is needed to suppress the vortex shedding tonal noise when it is applied to the wall end than when it is applied to the free end. If it is assumed that porous material at the wall junction reduces the influence of the horseshoe vortex and the base vortices (see Figure 1), it can be concluded from the comparison of Figure 11 and Figure 12 that the tip vortices at a finite cylinder have a stronger effect on the suppression of the mid span Kármán vortex shedding than the vortices at the base/wall junction.

Finally, it was investigated exemplarily if (a) the simultaneous application of porous material both to the free end and to the wall region as well as (b) the application of porous material only to the mid span region of the wall-mounted finite cylinder also result in a reduction of the vortex shedding tonal noise. However, this was only done for one extent of the porous material. For case (a), the extent of the material at the tip and at the free end was identical with $s_t = s_w = 60$ mm ($s_t/l = s_w/l = 0.25$). For case (b), the porous extent at the mid span region was $s_s = 120$ mm ($s_s/l = 0.5$).

The resulting sound pressure level spectra are shown in Figure 13, again for the maximum flow speed of 50 m/s. It is visible that for the case with porous material both at the wall region and at the free end, the vortex shedding peak is not completely suppressed. However, the peak level is lower than for the cases with the same porous extent either at the wall or at the free end. Thus, the simultaneous application of porous materials to both ends of the cylinder still results in a further noise reduction. As would be expected, if the whole mid span region is covered by porous material, the vortex shedding peak is completely suppressed. The results are then similar to the case when 0.75 % of the cylinder span are covered from the tip and only a small part close to the wall is non-porous. The results shown in Figure 13 are representative for the results



(a) Non-porous reference

(b) Fully covered with Basotect

(c) Fully covered with Damtec

(d) Fully covered with Regufoam

Figure 9. Contour plots of the sound generated by the finite cylinders with an aspect ratio of $l/d = 13.3$

obtained at the remaining flow speeds of the present study.

IV. Summary

The flow around finite, wall-mounted cylinders is a main source of aerodynamic noise, which contains both broadband noise as well as strong tonal components due to the regular shedding of vortices. In the present paper, an experimental study on the possible reduction of this noise by a modification of the cylinders with flow permeable material is described. Measurements were performed at Reynolds numbers (based on cylinder diameter) between approximately 8,000 and 61,000 in a small aeroacoustic wind tunnel on wall mounted circular cylinders of different aspect ratio. In a first step, a suitable porous material was chosen by measuring the noise generated by wall-mounted cylinders fully covered with one of three flow permeable materials of different parameters. In a second step, the optimum position (at the free end, at the wall end, both at the free end and at the wall end or only along the center part of the span) and the optimum extent of the porous cover were determined experimentally. It was found that a placement at the wall end is more efficient in reducing classical Kármán vortex shedding noise than a placement of porous material at the free end. Of course, it is also very effective to cover the cylinder along the span and to leave both the free end and the wall end uncovered.

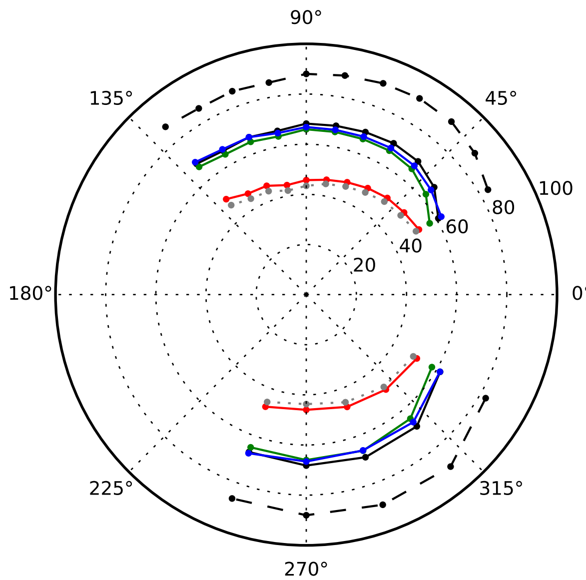


Figure 10. Directivity of the vortex shedding peak measured for the fully covered cylinders with l/d = 13.3 at the maximum flow speed U = 50.7 m/s (Re = 60,400, Basotect, Damtec, Regufoam, non-porous reference cylinder, non-porous 2D cylinder, background noise, flow from left to right)

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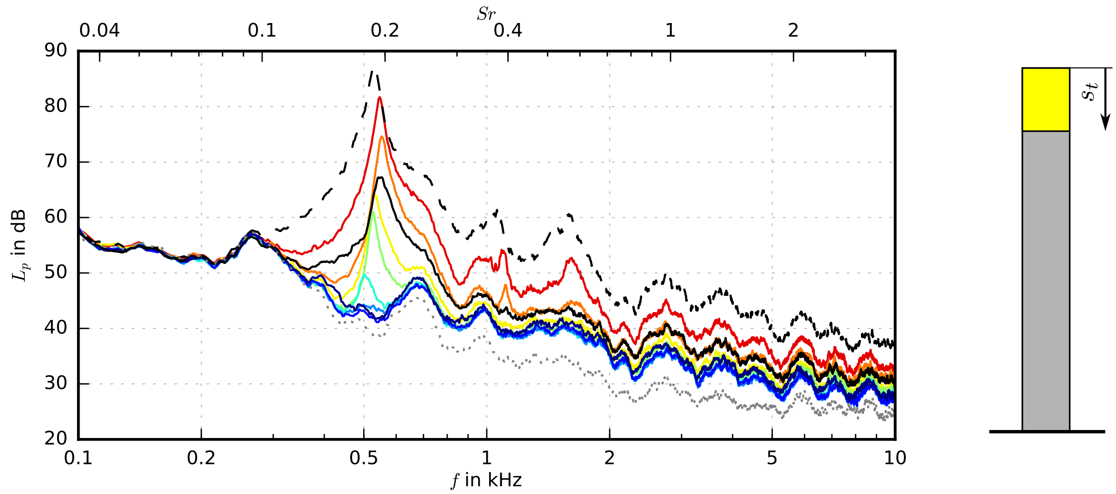

Figure 11. Sound pressure level spectra of the finite cylinders with $l/d = 13.3$ covered at the free end with Basotect, $U \approx 50$ m/s ($s_t/l =$ 0.125, 0.25, 0.375, 0.5, 0.625, 0.75, 0.875, 1; non-porous, non-porous 2D cylinder, background noise)

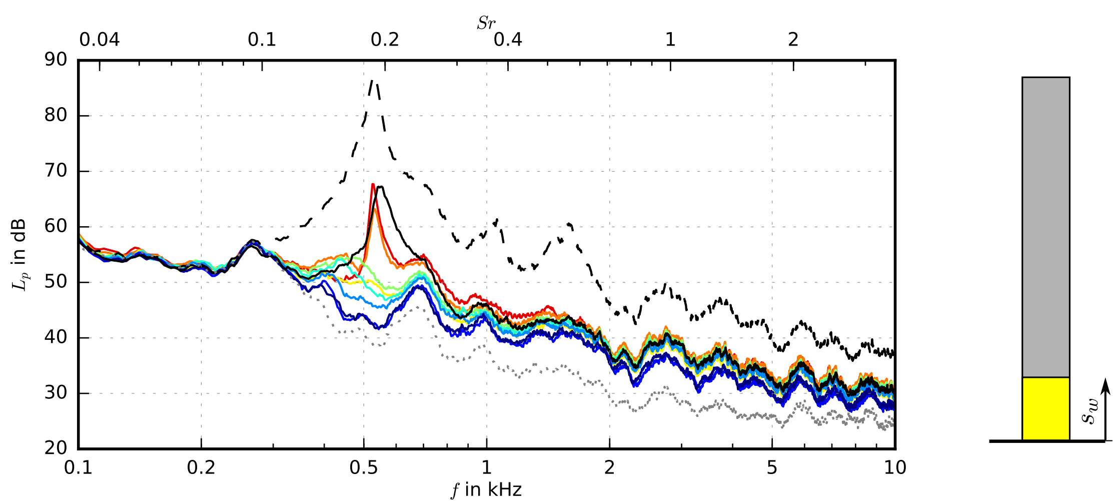

Figure 12. Sound pressure level spectra of the finite cylinders with $l/d = 13.3$ covered at the wall junction with Basotect, $U \approx 50$ m/s ($s_w/l =$ 0.125, 0.25, 0.375, 0.5, 0.625, 0.75, 0.875, 1; non-porous, non-porous 2D cylinder, background noise)

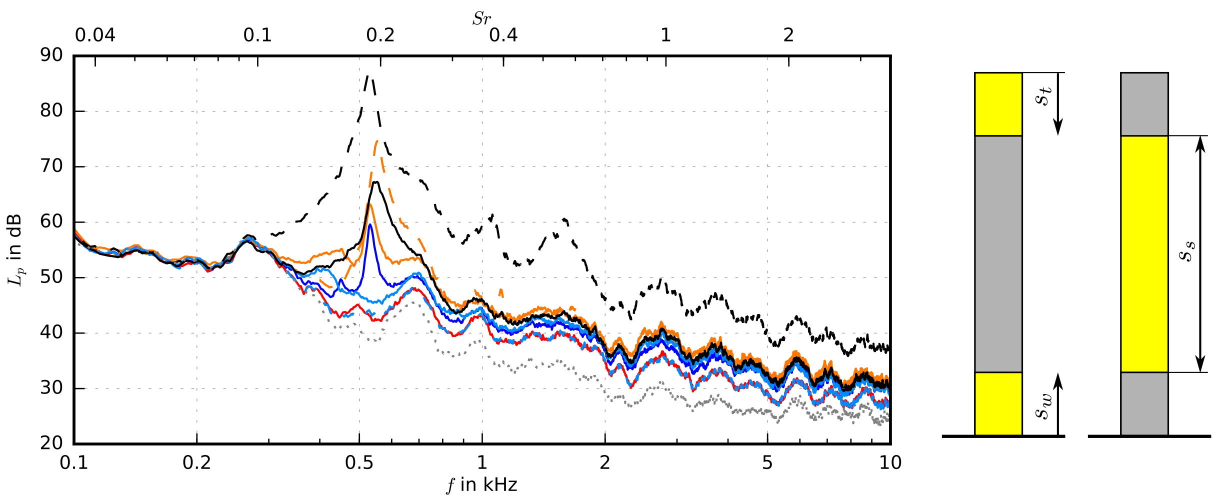

Figure 13. Sound pressure level spectra of the finite cylinders with $l/d = 13.3$ covered both at the free end and the wall junction with Basotect, ($s_t/l = s_w/l = 0.25$), at the mid span region ($s_s/l = 0.5$), with Basotect only at the wall junction $s_w/l = 0.25$ and $s_w/l = 0.75$, with Basotect only at the free end $s_t/l = 0.25$ and $s_t/l = 0.75$; non-porous, non-porous 2D cylinder, background noise, $U \approx 50$ m/s