INVESTIGATION OF A NEW SHIELDING MATERIAL FOR SLOTTED TUBES REGARDING SOUND POWER MEASUREMENTS OF DUCTED FANS

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SUMMARY

Slotted tube probes are the preferred measurement methodology for the acoustic characterization of axial fans in duct flows at high flow velocities. This paper investigates the suitability of aramid fabric, marketed under the trade name Kevlar®, as a porous covering material for slotted tube probes. For this purpose, two identical slotted-tube probes were fabricated that have a socket for a ½-inch microphone. One of the two probes was covered with a previously selected aramid fabric, while the other was left uncovered along the slot. During subsequent measurements in a pipe segment of an axial fan test rig, the probe covered with Kevlar® showed major advantages in detecting the acoustic phenomena of the fans being studied.

INTRODUCTION

In recent years, Kevlar® fabrics have been increasingly used for acoustic measurements in wind tunnels [1, 2, 3]. In this case, the actual measurement section is surrounded by large-area Kevlar®-covered walls after the nozzle outlet. The aim of this procedure is to keep fluid mechanical pressures away from the measuring microphones and to allow acoustic pressures, which are characteristic for the particular flow problem, to pass through. Among other things, this promises to allow the measurement microphones to be moved closer to the measurement section and the free jet, which would enable more compact measurement setups and smaller acoustic chambers. Another advantage of these materials is that they can be stretched very tightly to suppress flow-induced excitation of a membrane vibration here.

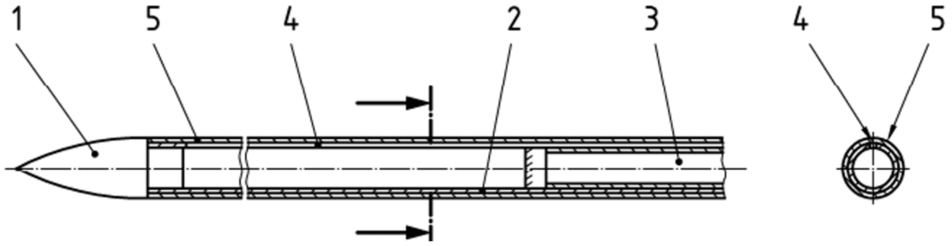
The problem of shielding from fluidic pressures while maintaining acoustic sensitivity arises in many situations in everyday life. Examples include annoying wind noise to which hearing aid users are exposed during outdoor activities, or unpleasant "popping" noises that occur in sound and event technology when recording speakers and singers.

Another application is the in situ characterization of fans and aggregates in duct flows. The sound radiation of fans is known to be highly dependent on the installation situation. The sound pressure spectrum of a free-blowing fan differs fundamentally from that of a fan installed in a duct. For the described measurement situation, DIN EN ISO 5136:2009-11 [4] proposes different measurement configurations depending on the prevailing flow velocity:

- < 15 m/s: Foam wind ball
- < 20 m/s: Nose cone
- < 40 m/s: Slotted tube probe

DESIGN AND FUNCTION OF A SLOTTED TUBE PROBE

As the preferred measuring instrument for all three cases, the DIN EN ISO 5136:2009-11 standard recommends the slotted-tube probe. The disadvantage of the slotted tube probe is the increased space requirement and the increased calibration effort compared to the other two measurement configurations.



Legend

1 Nose cone
2 Slotted Tube
3 Microphone
4 Slot
5 Porous Material

Figure 1: Technical Sketch of a slotted tube probe according to [4].

As shown in Figure 1, the standard suggests covering the slotted area of the probe with a porous material. The problem in this context is that the standard does not specify the material in more detail. Nevertheless, several materials, such as Mylar® [5], felt-wool [5], a stainless steel membrane [5], cloth [6], or a simple metal grid [6, 7], have already been investigated in the literature in the past. So far, no material is considered to be generally best suited. Since there is, to the author’s knowledge, no commercially available slotted tube at the time when this document is written but still ongoing research in the field of ducted fan acoustics, research institutes have to build self-constructed slotted tube probes. The objective of this research project it therefore to verify to what extent Kevlar® fabric is suitable as a slot cover material to prevent hydrodynamic pressure fluctuations from entering the probe and masking useful acoustic signals due to the disparity of scales. The disparity of the scales is referred to in this case as the 1000 to 10000 times higher hydrodynamical pressures compared to the acoustic pressures in the flow field.

FLUID MECHANICAL AND ACOUSTICAL CHARACTERISATION
OF DIFFERENT SHIELDING MATERIALS

There is a wide range of different aramid fabrics available on the market. The differentiating criteria for the various fabrics are, on the one hand, the weave - a distinction is made here between linen and twill weave - and, on the other hand, the surface weight. Three aramide fabrics with surface weights of 61 g/m², 110 g/m² and 170 g/m² were used in the present investigations. Figure 2 shows the three different fabrics stretched and glued onto a metal frame and the corresponding microscope images. The images are intended to provide an impression of the different coarse and fine structure of the fabrics.

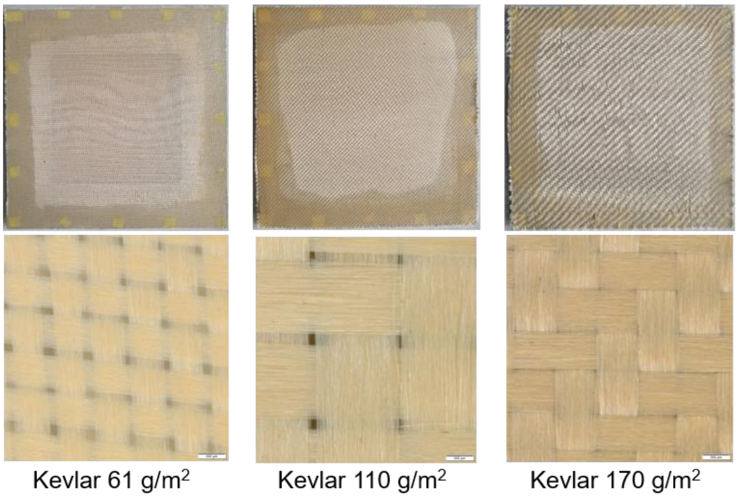


Figure 2: Kevlar®- fabrics with different surface weights, stretched on the sample carrier (top) and as microscope image (bottom).

Before the slotted tube probes were fitted with the fabrics, the Kevlar® fabrics were first characterized in the aeroacoustic wind tunnel [9] both in terms of their acoustic transmissibility, referred to below as the damping measure, and in terms of their ability to keep hydrodynamic pressure fluctuations away from the microphone, referred to below as the shielding measure.

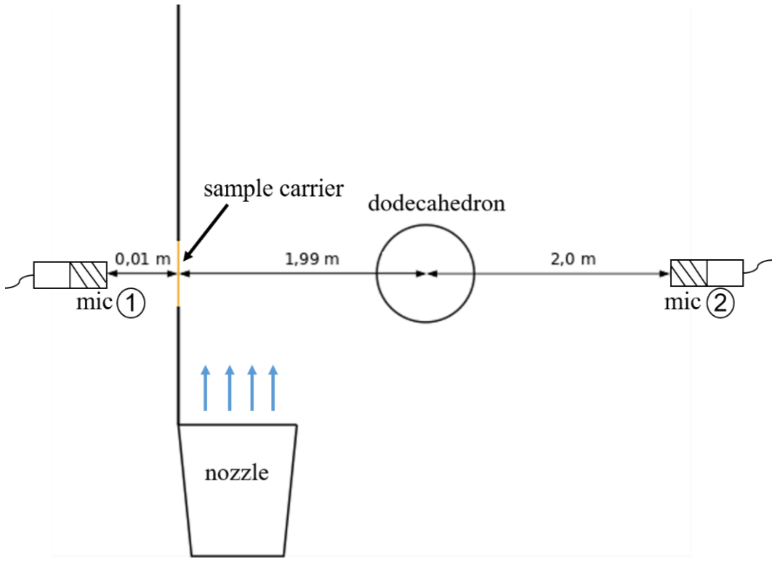


Figure 3: Schematic drawing of the experimental setup for the chacterisation of the fabrics.

A schematic sketch of the test setup is shown in Figure 3, and a photograph from inside is shown in Figure 4. The carrier with the aramid fabric is inserted flush with the wall in a plate over which a wind tunnel nozzle blows. A dodecahedron loudspeaker is used to play a test signal in this case a sinusoidal sweep. Behind the fabric, at a distance of 1 cm, a free-field microphone Brüel & Kjaer type 4189 is placed, which will be referred to as microphone 1 in the following. On the opposite side of the dodecahedron, a second microphone of the same type is installed for reference, that one is called microphone 2 in the following. The two microphones are therefore each 2 m away from the sound source, which radiates uniformly in all spatial directions. The orientation of the two microphones with regard to the sound source can also be seen in Figure 3.

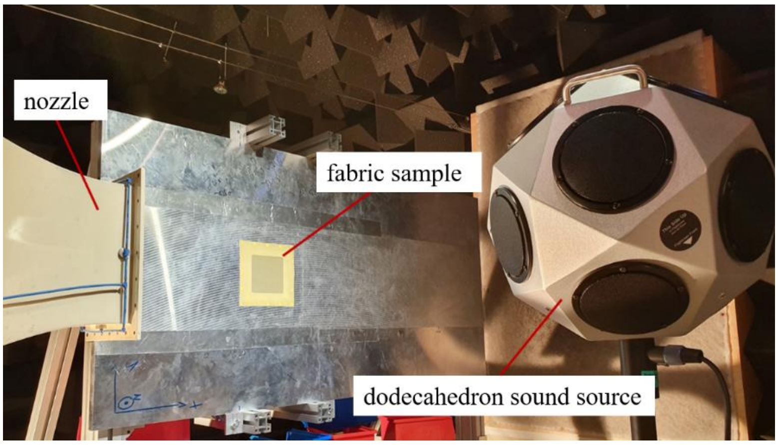


Figure 4: Photo from the interior of the aeroacoustic wind tunnel.

A characteristic quantity in technical acoustics for specifying the acoustic permeability of materials is the damping measure. In the present case, it is calculated by subtracting the sound pressure level detected at the reference microphone (microphone 2) from the sound pressure level measured at the shielded microphone 1 over the entire frequency range according to equation 1.

$$PSD(f)_{damping} = PSD(f)_{mic\,1} - PSD(f)_{mic\,2} \qquad (1)$$

The subtraction is performed for each discrete point in the frequency spectrum. A negative value of the damping measure here means that a considerable portion of the acoustic test signal at the microphone is damped behind the fabric. An ideally permeable material would result in a horizontal graph at the level of the 0 value of the ordinate.

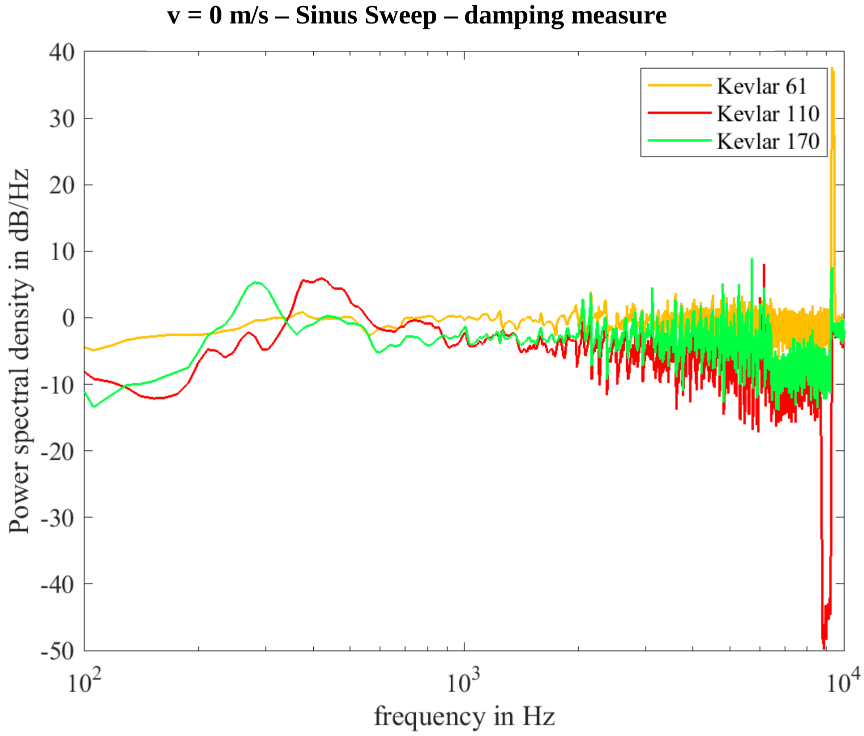


Figure 5: Calculated narrow band damping measure for the three different fabrics.

Figure 5 illustrates the results for the fabrics investigated here. It can be clearly seen that Kevlar®-61 comes closest to the horizontal ideal line over the entire frequency range from 100 Hz to 10000 Hz. This indicates that the least amount of sound information is lost when Kevlar®-61 is used as shielding material.

In a second step, it was investigated to what extent the selected materials are suitable for shielding hydrodynamic pressure fluctuations from the microphone 1 located behind the fabric. For this purpose, the particular fabric carriers are overflowed at a velocity of 20 m/s, so that a turbulent boundary layer has already formed along the flat plate in the area of the frame insert. No additional acoustic signal from the dodecahedron is used for these investigations. As a reference, a measurement is used in this case in which the sample carrier is not equipped with any fabric, i.e. the microphone 1 is directly overflowed. The orientation of microphone 1 towards the flow can be seen in figure 3. A characteristic measure, which is referred to here as the shielding measure, can also be calculated in this test case according to equation 2.

$$\mathrm{PSD(f)}_{\mathrm{shielding}} = \mathrm{PSD(f)}_{\mathrm{open}} - \mathrm{PSD(f)}_{\mathrm{fabric}} \quad (2)$$

For this purpose, the corresponding spectrum over the entire frequency range is subtracted from the variant with open frame, which serves as a reference here, for each fabric sample. This results in the illustration shown in Figure 6.

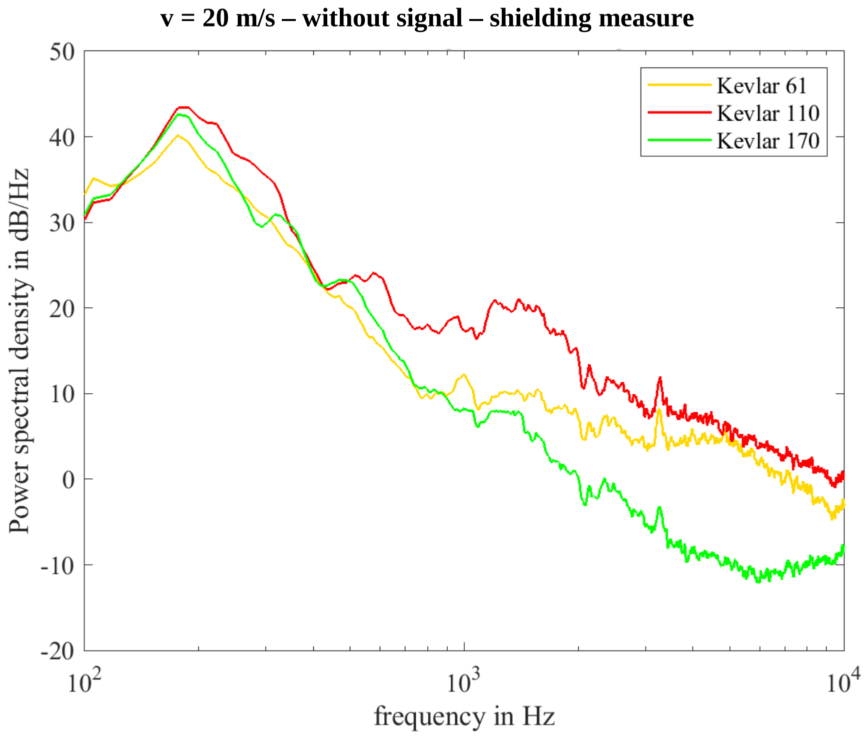


Figure 6: Calculated narrow band shielding measure for the three different fabrics.

In contrast to the damping measure, a particularly large value on the ordinate axis is desirable for the shielding measure. That means that the higher the shielding measure at a specific frequency point is, the greater is the fabric's capability to suppress hydrodynamic fluctuations. Here it is shown that Kevlar®-110 has the best shielding properties against hydrodynamically induced pressure fluctuations. Taking both evaluation criteria into account, a decision must be made between Kevlar®-110 and Kevlar®-61 as the covering material for the slotted tube probe. Since the coarse-fibered Kevlar®-110 is much more difficult to process and cut to size, Kevlar®-61 is finally selected as the porous covering material for the slotted tube probe.

ASSEMBLY AND EQUIPMENT OF THE SLOTTED TUBE

As mentioned at the beginning, two identical slotted-tube probes were manufactured in the institute's own mechanical workshop for the investigations presented. The probes consist of an aluminum inner tube, onto which the fabric is glued in the case of the covered probe, and a brass outer tube, which acts as a shell and gives the probes a smooth and streamlined surface. An aluminum tip is also attached to the front end. Figure 7 shows the dimensions of the probe used according to pre-existing research by KAMEIER [7].

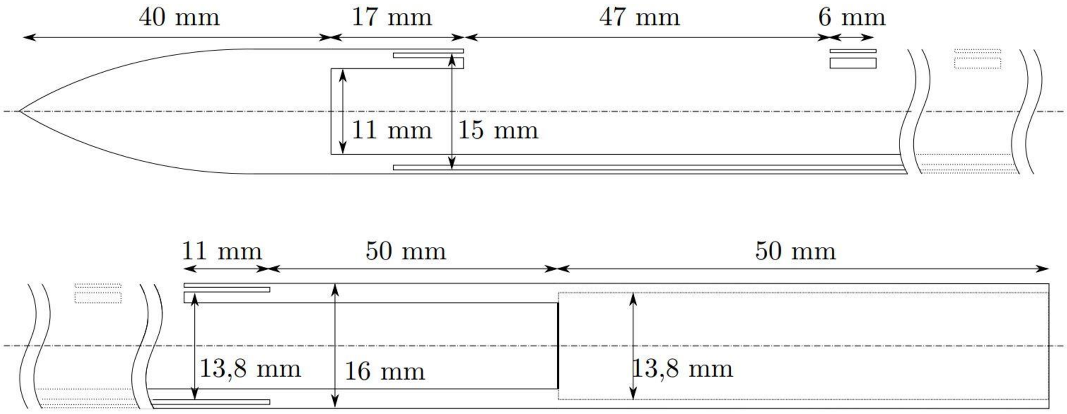


Figure 7: Dimensions of the built slotted tube probes from [10].

The total length is 450 mm. The slot along the length of the slotted tube probe is divided into seven slots of equal length, each 47 mm long, for stability reasons. In between there is a bridge of 6 mm length each. The inner tube has a diameter of 15 mm when glued. When the brass tube is slid over it, the total diameter of the probe is 16 mm. At the rear end of the probe is the shaft for holding a ½-inch Brüel & Kjaer type 4189 microphone, which has a diameter of 13.8 mm to allow the microphone with protective grille to be inserted into the probe.

Figure 8: Tensioning device for the inner tube.

Figure 8 shows the tensioning device that was necessary to evenly tension the aramid fabric around the inner tube of the probe. The inner tube was glued with a 2-component adhesive. The adhesive strength was increased by heating the adhesive mixture with a hot air blower. Finally, Figure 9 shows the inner tube of the slotted tube probe completely sheathed with aramide fabric.

Figure 9: Inner tube covered with Kevlar® ready to use.

INVESTIGATION OF THE SLOTTED TUBE PROBES WITHIN AN AXIAL FAN TEST-RIG

The investigations comparing Kevlar® coated and non-coated slotted tube probes were carried out on the institute's axial fan test rig, which is shown schematically in figure 10 an described explicitly in [11]. Since the slotted tube probe is used in duct flows, an additional duct segment with a diameter of 500 mm was attached to the pressure side of the original test rig. An auxiliary fan and a butterfly damper allow the complete characteristic curve of the test fans, which have a diameter of 495 mm, to be run. In the anechoic chamber inside the test rig, seven ½-inch free-field microphones of type 4189 from Brüel & Kjaer are installed in a semicircle and a quarter circle, respectively. These microphones characterize the fans under investigation on the suction side. Since the flow velocities inside the chamber are low, a foam ball is sufficient as a wind shield in this case.

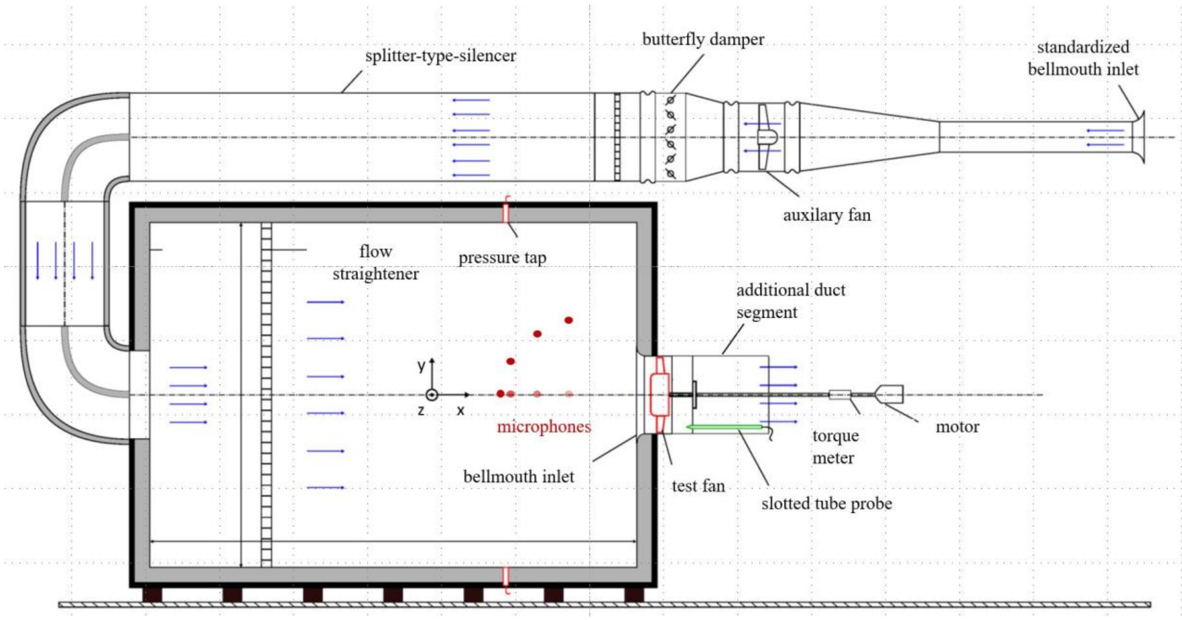


Figure 10: Schematic Sketch of the used test rig according to [11].

Figure 11 shows a photo from the interior of the test rig on the left-hand side, which is intended to illustrate the arrangement of the microphones in 3 dimensions. For the measurement results on the suction side of the fans shown later, the sound pressure levels of the seven single microphones were averaged. The right side of Figure 11 illustrates the mounting of the slotted tube probe within the tube segment. This is mounted at a relative radial distance of 0.8 from the center axis.

Figure 11: Interior of the used test-rig with mounted microphones (left) and mounting of the slotted tube probe within the additional duct segment (right).

The two axial fans shown in Figure 12 were used in the tests. One un-skewed, as shown schematically on the left, and one forward-skewed, as shown schematically on the right.

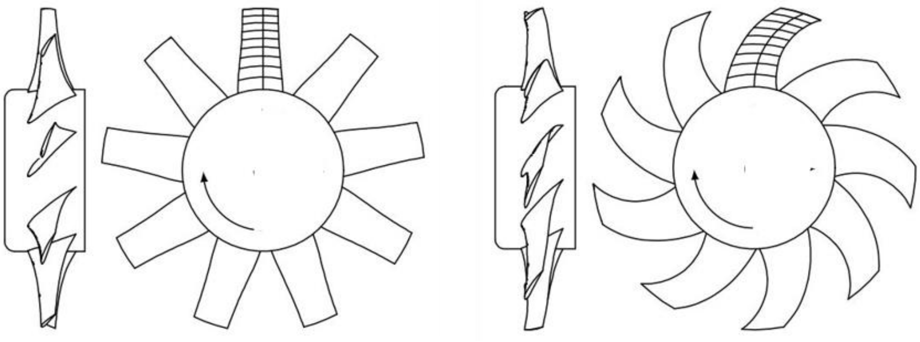


Figure 12: Schematic drawings of the axial fans used unskewed (left) forward forward-skewed (right) from [11].

RESULTS

This section compares the results of the sound pressure measurements. As this study was initially only intended to investigate the suitability of Kevlar as a covering material and the reproduction of the exact sound pressure level was not essential, the calculation of the correction factor C2 from the standard [4] was omitted. As a reference, each diagram contains the sound pressure level on the suction side of the fans, averaged over the seven single microphones, drawn in gray. The blue line shows the result of the measurement with the Kevlar® probe and the red line shows the result with the fully uncovered probe. It was not possible to insert the slotted tube probe in a duct segment on the suction side due to the spatial conditions. However, the characteristics of the fans occur both upstream and downstream of the investigated impellers. Both fans were tested at a flow rate of 1.4 m³/s and a rotational speed of 1486 rpm.

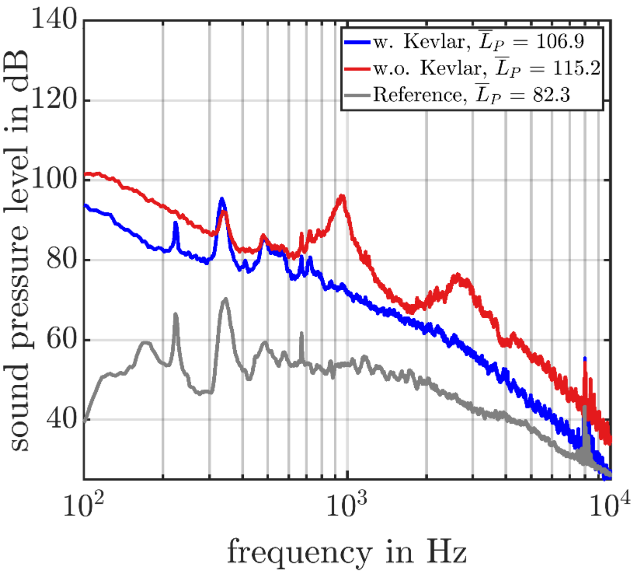


Figure 13: Measured sound pressure spectra for different probes and reference for the un-skewed fan.

First, the results for the un-skewed fan from Figure 13 are discussed. The reference measurement shows a significant tonal peak at 225 Hz, which can be attributed to the fan's blade passing frequency (BPF). At 675 Hz, the second higher harmonic of the blade passing frequency is also evident. Other characteristics are the narrow-band humps in the spectrum at 350 Hz (1.55 BPF) and 485 Hz (2.15 BPF). The reason for these humps is a backflow from the pressure to the suction side in the area of the tip gap of the fan, which occurs particularly in the case of axial fans that are not skewed and are backwards skewed [11]. Finally, in the high frequency range, a tonal component occurs at 8 kHZ which is due to the frequency converter installed in the test rig. When looking at the measurement results with the probes, it is noticeable that the detected background noise is many times higher than in the reference measurement. This is due on the one hand to the generally higher flow velocity in the duct segment compared to the flow velocity in the chamber and on the other hand to the more turbulent, more vortex-rich flow behind the fan. Nevertheless, it is noticeable that the flow-related noise of the uncovered probe is additionally increased by about 10 dB over the whole frequency range compared to the Kevlar® probe. Further disturbing factors with the uncovered probe are resonance phenomena at 1000 Hz and 2500 Hz, which are due to the overflow of the open cavities inside the probe. Overall, it can be seen that the Kevlar® probe is capable of detecting all characteristic tonal components of the fan. The uncovered probe is not able to detect the blade passing frequency and cannot elaborate the further peaks as concisely as the Kevlar® probe.

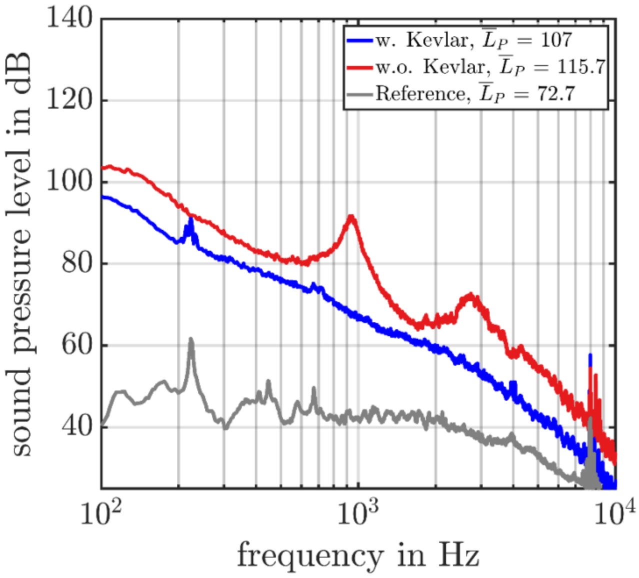


Figure 14: Measured sound pressure spectra for different probes and reference for the forward-skewed fan.

Figure 14 shows the measurement results for the forward-skewed fan. The skeweing causes an extensive suppression of the tip gap vortex, which strongly reduces the corresponding humps in the spectrum. While the covered probe detects the blade passing frequency and, to some extent, also the second higher harmonic, the uncovered probe is not able to do so.

SUMMARY AND OUTLOOK

The aim of the present investigations was to demonstrate to what extent aramide fabrics are suitable as a porous shielding material for slotted-tube probes. To accomplish this, three different fabrics were first characterized with respect to their damping and shielding measures in the aeroacoustic wind tunnel. Two slotted-tube probes were then built, one of which was left totally uncovered while the other was covered with the previously selected Kevlar®-61. The performance of the two probes was investigated during measurements in an axial fan test rig. An un-skewed fan and a forward-skewed fan were examined. The Kevlar® covered slotted tube probe was found to be capable of detecting the characteristic tonal components of the fans, such as blade passing frequency and subharmonics. On the one hand, the uncovered probe had a broadband noise floor that was about 10 dB higher than the covered one, and it also showed significant resonance peaks due to the open overflowed cavities. Aramide fabric is therefore well suited as a covering material for slotted-tube probes. However, the more difficult processing of the fabric, which requires special tools, and the complex tensioning procedure should be noted. In the future, the performance of the Kevlar® slotted-tube probe needs to be investigated at higher flow velocities. Moreover the results should be compared to measurements generated by former commercially available slotted tube probes such as the UA 0436 [8] and to measurements where the microphone is solely shielded by a foam ball.

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