Investigating the Aeroacoustic Properties of Porous Fabrics

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https://doi.org/10.2514/1.J061385

The aeroacoustic properties of porous fabrics are investigated experimentally with the goal of finding a fabric that serves as an improved interface between wind tunnel flow and quiescent conditions. A total number of eight porous fabrics were investigated, namely, four glass fiber fabrics, two plain-weave Kevlar fabrics, and two modified plain Kevlar fabrics with their pores irregularly clogged. Two custom-made rigs were used to quantify the transmission loss (TL) and self-noise of all fabrics. The pores were found to serve as a low-resistance gateway for sound to pass through, hence enabling a low TL. The TL was found to increase with decreasing open area ratio (OAR), whereas other fabric properties had a minor impact on TL. The thread density was found to be a primary factor in determining the frequency range of porous fabrics' self-noise, with the OAR potentially playing a secondary role in the self-noise levels. Fabrics with irregular pore distribution showed a more broadband self-noise signature associated with lower frequencies compared to fabrics with periodic pore patterns. Overall, fabrics with an irregular pore distribution or fabrics with increased thread density were identified as two potential ways to obtain superior aeroacoustic behavior compared to commonly used Kevlar fabrics.

Nomenclature

f	=	frequency, Hz
G	=	cross spectrum, dB
l	=	Mylar thickness, m
M	=	Mach number
m	=	fabric mass per unit area, $\mathrm{g/m^2}$
r	=	separation distance, m
T	=	transmission loss, dB
u_∞	=	freestream velocity, m/s
Δ_r	=	distance correction factor, dB
ρ	=	air density, $\mathrm{kg/m^3}$

Subscripts

1,2	=	microphone numbers
p	=	microphone signal
u	=	white noise signal

Presented as Paper 2021-2255 at the 27th AIAA/CEAS Aeroacoustics Conference, Virtual, August 2–6, 2021; received 19 October 2021; revision received 17 December 2021; accepted for publication 21 December 2021; published online 31 January 2022.

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I. Introduction

AEROACOUSTIC investigations have long been seeking an ideal interface that could separate the flowfield from quiescent conditions or anechoic chambers. In hybrid anechoic wind tunnels (HAWT), tensioned ballistic Kevlar is often placed as an interface between the flow inside the test section and the surrounding anechoic chambers [1–4]. Similarly, Kevlar and wire meshes have been used for covering inflow phased (or beamforming) microphone arrays to separate flow noise from microphones [5–10]. More recently, Kevlar has also been used as an interface between boundary layer flow and acoustic metamaterials [11,12]. Overall, porous fabrics (such as Kevlar, or wire mesh) may be seen as an acoustic window (or interface) efficiently separating the acoustic field from the flowfield, and they may be used as a tool to improve aeroacoustic measurements.

The benefits of Kevlar walls (or windows) are relatively well understood, as Kevlar has been in use in HAWTs for more than a decade. Most often, the lightest available Kevlar weave is used in HAWTs (Kevlar type 120, 60 $\mathrm{g/m^2}$) [4,13–17]. This fabric was found to be acoustically transparent, that is, having a low transmission loss, on the order of a few decibels below 20 kHz [1,2], whereas it is almost impervious to flow. The underlying reason for both of these properties is associated with its porosity, often measured using open area ratio (OAR), which is the ratio of the area of the pores to the overall area of the fabric. The typical OAR of Kevlar type 120 fabrics usually ranges between 2% and 8%. When comparing the transmission loss of Kevlar to a sheet of solid material with matching thickness and mass per unit area, it can be seen that the transmission loss of Kevlar is significantly lower, confirming the importance of pores in its acoustic transparency.

There are a series of benefits of HAWTs compared to open-jet aeroacoustic facilities. The Kevlar walls greatly reduce lift-induced aerodynamic interference and eliminate the presence of a jet, and also the need for a jet catcher [1,4,18]. The parasitic facility noise sources are therefore located farther from the test section and acoustic instrumentation, hence the Kevlar wall configuration reduces facility background noise. Kevlar windows also allow for a much larger test section length-to-width ratio [3]. The combination of these advantages enables phased microphone arrays to be positioned over a wider range of observer angles and closer to the noise source of interest compared to an open jet wind tunnel with identical nozzle geometry.

In turn, these properties of HAWTs greatly increase the signal-to-noise ratio of acoustic measurements made with phased microphone arrays [19]. The aerodynamic response of Kevlar to the flow stems from its membranelike behavior [1,18]; in other words, Kevlar lacks bending stiffness, hence it can efficiently follow the aerodynamic pressure field. Kevlar also has a rather high tensile strength, on the order of 30 GPa [20]. In addition, it has a low creep strain. The combination of these mechanical properties makes Kevlar rather rugged and resistant to all of the loads it experiences in a wind tunnel environment.

In a recent development, using the Quiet Flow Facility at NASA Langley, Bahr et al. [13,21] showed that there are many benefits to using a Kevlar acoustic window configuration. One particular benefit is that Kevlar greatly reduces the thickness of the shear layers that form the boundaries of the flow. From this, we can infer that the sound rays propagating through the turbulence over the Kevlar windows undergo a lower interaction with the turbulence-related hydrodynamic pressure field than in an open-jet configuration with identical nozzle cross section. In fact, Bahr et al. [13,21] showed that at a given flow speed the coherence calculated between a reference microphone located 90 deg to the flow and other microphones at downstream observer angles showed higher coherence levels for HAWT configuration than for open-jet configuration. Whereas this effect is likely caused by the weaker hydrodynamic pressure field over the Kevlar window, the exact effect of the Kevlar itself on sound de-correlation as a function of flow speed is yet to be studied. Overall, the Kevlar walled configuration showed a favorable behavior compared to the open-jet configuration [4,13,21]. A compensating problem was also uncovered, however. At high frequencies (above 10 kHz) Kevlar can be a source of “scrubbing” noise. Studies of Kevlar fabric backed with a solid surface or with a cavity [22,23] indicated that this is not roughness noise, but noise generated by the pumping of air through the pores in the fabric, which is an efficient noise generation mechanism. Although Kevlar has a low transmission loss (a few decibels) at low frequencies (below 20 kHz), its acoustic losses may become significant at high frequencies (above 20 kHz) and may reach 10 dB [1,2,14], however, this assumption has yet to be quantified. From a HAWT or phased array application perspective, the combined effects of self-noise and high transmission loss at high frequencies (above 20 kHz) may compromise the aeroacoustic capabilities of HAWT facilities [24]. Namely, these effects may restrict aeroacoustic measurements performed from behind the Kevlar windows in the anechoic chambers or could contaminate the measurements at high frequencies.

Only a limited amount of efforts have been made [22,23] to understand the underlying physical problem associated with these drawbacks, which would be at the basis to overcome them. This paper, therefore, makes one of the first attempts to understand the underlying physical mechanisms of how Kevlar generates self-noise, while also quantifying its self-noise and transmission loss (TL). The goal of the work presented here is to identify the properties of porous fabrics that are in close relation to the generated self-noise and to find ways to mitigate this self-noise while keeping the transmission loss of the fabric low. Ultimately, our aim is to find an ideal fabric associated with low self-noise and low transmission loss even at high frequencies (above 20 kHz), while maintaining the mechanical properties of Kevlar. To reach these goals, this paper presents a detailed aeroacoustic characterization of various porous fabrics. First, the aeroacoustic properties, namely, self-noise and transmission loss, of a commonly used Kevlar type 120 fabric are investigated at high frequencies (between 1 kHz and 100 kHz). Then, a parametric study is presented by studying the aeroacoustic properties of carefully selected porous fabrics. A detailed analysis of the results is then presented, where links are found between the aeroacoustic properties of the fabrics and their properties.

II. Experimental Approach

Two sets of experiments were performed. First, the self-noise and transmission loss of a commonly used Kevlar type 120 fabric were quantified at high frequencies, namely, between 1 kHz and 100 kHz, within the Stability Wind Tunnel (SWT) of Virginia Tech [1]. This experiment was then followed by a parametric study focusing on the transmission loss and self-noise of various porous fabrics, and this part of the work was performed in the Wall Jet Wind Tunnel of Virginia Tech [25]. The following sections describe in detail the experimental approaches used in the two facilities.

A. Characterizing the Aeroacoustic Properties of Commonly Used Kevlar Fabrics at High Frequencies

A Kevlar type 120 fabric, produced by EAS Fiberglass, was used to assess the properties of commonly used Kevlar fabrics above the audible frequency range. The fabric is labeled as K120-EAS in the following, with its properties listed in Table 1. The schematic representation of the aeroacoustic tests performed in the Stability Wind Tunnel is shown in Fig. 1. The self-noise of the K120-EAS fabric was measured by placing a Brüel and Kjaer type 4138 1/8-in. pressure-field microphone into the port-side anechoic chamber of the SWT. The microphone was positioned at 1, 2, 3, and 4 ft separation distance from the center of the acoustic window to enable the assessment of the high-frequency noise source, while the wind tunnel was operated at freestream flow speeds of $u_\infty = 50$, 60, and 70 m/s under an empty test section configuration. As the microphone was used in a free-field configuration, the data were corrected using the free-field correction as provided by the manufacturer [26]. The time-series data was recorded for a time span of 32 s using a Brüel and Kjaer LAN-XI module at a sampling rate of 131 kSamples/s. The power spectral density of the signal was then calculated using Hamming window and 50% overlapping so that the resulting frequency resolution was 64 Hz.

To obtain transmission loss information of the fabric in the SWT, two separate experiments were performed. Both of these experiments were performed in the absence of flow. The first experiment, which was tailored to assess the acoustic loss of K120-EAS between 100 Hz and 10 kHz, was performed in an identical manner, as described by Devenport et al. [1]. From this procedure, a curve fit was found that describes the transmission loss of the fabric between 100 and 20 kHz.

To quantify the transmission loss of the K120-EAS fabric at high frequencies (20–100 kHz), a high-frequency acoustic source was used that was generated using laser-induced plasma (LIP). For a

Table 1 The properties of the tested porous fabrics

Fabric ID	Fabric type	OAR, %		Air permeability	Thread density	Mass, g/m^2
		Calculated	Measured	(CFM)	Warp/Weft (TPI)	
K120-CST	Plain Kevlar	4.2	3.9	79.7 ± 3.6	34/34	60
K120-EAS	Plain Kevlar	2.2	1.8	57.0 ± 2.0	34/34	60
GF108	Glass fiber	24.1	20.5	587.2 ± 32.3	60/47	48
GF1078	Glass fiber	19.8	13.1	392.0 ± 34.4	54/54	48
GF1080	Glass fiber	21.5	18.9	545.6 ± 24.5	60/47	48
GF1280	Glass fiber	13.1	14.1	304.0 ± 17.2	60/60	56
K120-13	Coated Kevlar	N/A	0.53	21.8 ± 5.9	34/34	68
K120-14	Coated Kevlar	N/A	0.95	15.1 ± 5.6	34/34	74

CFM = Cubic Feet per Minute.

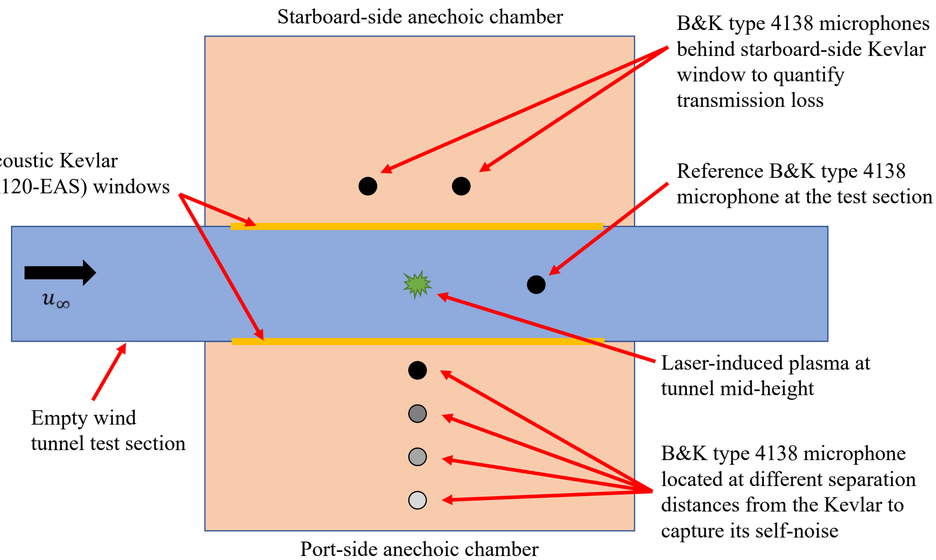


Fig. 1 The schematic representation of the aeroacoustic tests performed in the Stability Wind Tunnel of Virginia Tech. The schematic shows the cross-sectional view of the wind tunnel at the test section midheight.

detailed description of the laser-optical setup, we refer to Szőke and Devenport [27]. The LIP was positioned at the center of the wind-tunnel test section and three microphones were used to quantify the transmission loss of the fabric. A reference microphone was placed inside the test section of the SWT, hence directly observing the sound signature of the LIP. Two microphones were positioned behind the starboard-side Kevlar window of the SWT, that is, these microphones observed the sound signature of the LIP after it was attenuated by the Kevlar fabric. All three microphones were identical in type, namely, Brüel and Kjaer type 4138 1/8-in. pressure-field microphones. Data was acquired using a Tektronix DPO 2012B digital oscilloscope at a sampling rate of 10 MSamples/s for a time span of 100 ms. The impulse pressure signature of the LIP was gated, windowed, and Fourier transformed in an identical manner, as described in Ref. [27], but in this study, a gate length of 0.1 ms was used. This step ensured that the analysis was limited to direct acoustic ray propagation only. The ratio between the Fourier transformed data of a microphone signal obtained from behind the Kevlar window (i.e., in the anechoic chamber) and the microphone data from inside the test section then provided the transmission loss of the Kevlar fabric. This data, due to the short life-span of the LIP (approximately 0.05 ms), provides significant signal content above the audible frequency range and can be used to determine the transmission loss of the Kevlar fabric for frequencies approximately between 30 and 100 kHz. The transmission loss results were one-third Octave-band averaged and then corrected for losses caused by atmospheric acoustic absorption and propagation distance differences between the microphones [28].

B. Parametric Study of Porous Fabrics

The experiments of the parametric study were conducted at the Wall Jet Wind Tunnel (WJT) facility of Virginia Tech [25] to quantify the self-noise and transmission loss of various porous fabrics. In addition, microscopic images of the fabrics were taken to determine their open area ratio (OAR). The following sections detail the experimental approaches for each of the measurements performed.

1. Fabrics Tested

A total number of eight fabrics were tested whose properties are listed in Table 1. Three different types of materials were tested: 1) a commercially available Kevlar (K120-CST) and a custom-made Kevlar (K120-EAS, with a reduced OAR of 2.2%), 2) different glass fibers, and 3) spray-on adhesive applied to K120-EAS, resulting in a further-reduced OAR and increased mass per unit area m without changing the thread density of the fabric. Some properties listed in Table 1 were determined experimentally, whereas others were determined either analytically or obtained from manufacturer specifications. The OAR of the fabrics were determined both analytically [29], using the weave type and yarn properties (denoted as calculated), and experimentally, using microscopic images. In addition, the air permeability (CFM, cubic foot per minute) of the fabrics was also determined experimentally, as specified in Ref. [30]. Finally, the weight of the fabrics was obtained from the manufacturer's specifications, except for K120-13 and K120-14, whose weight was determined using a high-precision scale (Intelligent Weighing Technology PM-100).

The properties of the tested fabrics listed in Table 1 determine important characteristics of the test matrix, namely, the various fabrics help us to quantify how the changes in open area ratio (OAR), thread density (TPI, thread per inch), and mass per unit area m affect self-noise and transmission loss. Table 1 reveals that the glass fiber fabrics have a significantly higher OAR than the Kevlar fabrics, and about twice the thread density but a lower mass per unit area. These fabric samples can help to quantify the effects of OAR and TPI on transmission loss and self-noise. The commercially available Kevlar, K120-CST, may be considered as a baseline case in our investigations, as it has been widely used in HAWT facilities [1,2,16]. The K120-EAS fabric has been in use in the Stability Wind Tunnel of Virginia Tech since 2015. This fabric was custom-made by EAS Fiberglass, as commercially available fabrics are generally shorter in span than 6 ft, hence a single stripe of commercial fabric could not cover the entire height of the Kevlar windows used in the SWT. This fabric has a nominal OAR of 2.2%, which is half the OAR of K120-CST, although it maintains all other properties of K120-CST. Again, a comparison between K120-EAS and K120-CST can shed light on the aeroacoustic effects of OAR. Finally, the K120-EAS fabric has been treated with Exceval RS-2117-type spray-on adhesive made by Kuraray America, Inc. to reduce its OAR and increase its mass per unit area m. Two levels of spray-on adhesive coating have been applied: a lower amount of spray has been manually applied to K120-13, whereas a higher amount of coating has been applied to K120-14. Note that the measured OAR values of these fabrics are inconsistent with the amount of coating applied. Their air permeability, on the other hand, is in agreement with the applied amount of spray-on adhesive. These observations imply that the pore distribution of these fabrics (K120-13, K120-14) is irregular compared to the regular pore pattern that can be found on other fabrics tested in this study.

2. Aeroacoustic Testing

Previous investigations have shown that the WJT is a good candidate to investigate scrubbing, and surface roughness noise sources

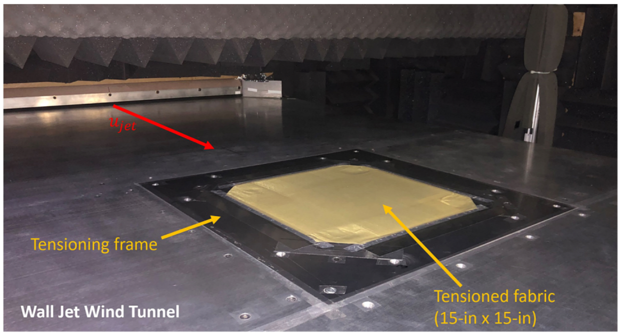


Fig. 2 The rig mounted to the wall jet plate in the wall jet wind tunnel.

[22,23]. In this tunnel, a 1/2-in.-tall nozzle blows air over a flat plate, hence its name "wall jet", which results in a self-similar flow over the plate [31,32]. The developing boundary layer over the plate has two main flow regions. The near-wall flow exhibits the properties of a canonical zero pressure gradient turbulent boundary layer until a maximum velocity is reached in the boundary layer profile. Above this point, a two-dimensional shear-layer flow dominates, which is characterized by energetic, large-scale structures.

The rig used to assess the acoustic properties of the Kevlar fabrics is depicted in Fig. 2. The fabrics were mounted on a fabric tensioner, made by Eino Diamondchase, and were brought into a tension of 1500 ± 200 N/m measured using a Newman ST1E tension meter. The tensioning frame was flush-mounted to a 2×2 ft aluminum plate. The area of the fabric exposed to the flow was 15×15 in.; see Fig. 2. A Brüle and Kjaer type 4938 1/4-in. microphone was positioned below the center of the tensioned fabrics with a separation distance of 8 in. Due to the high-frequency nature of the fabrics' self-noise tested, the microphone was in the acoustic far field. The microphone was calibrated using a pistonphone calibrator on a daily basis. The flow speed of the jet in the wind tunnel was set to the maximum reachable value, that is, $u_{\mathrm{jet}} = 70$ m/s, during the self-noise measurements. This resulted in a flow passing over the tested fabrics with a maximum speed of approximately 25 m/s, corresponding to a Mach number of $M \approx 0.08$ [25].

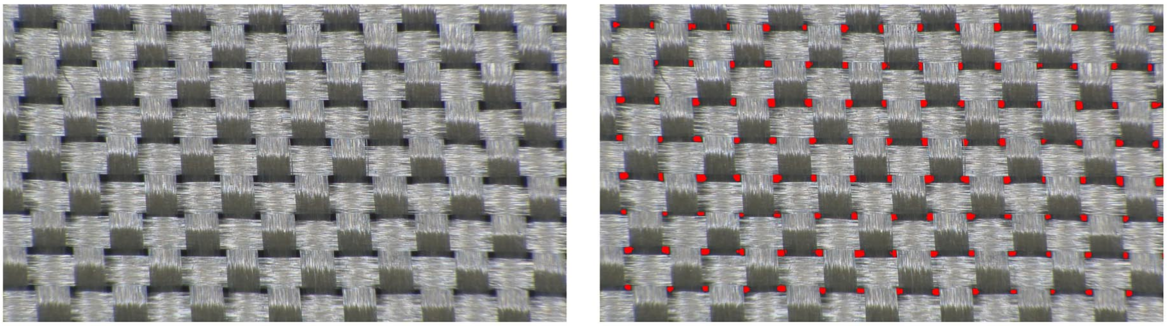


Fig. 3 Sample microscopic image of K120-EAS fabric (left) with the pores marked in red (right).

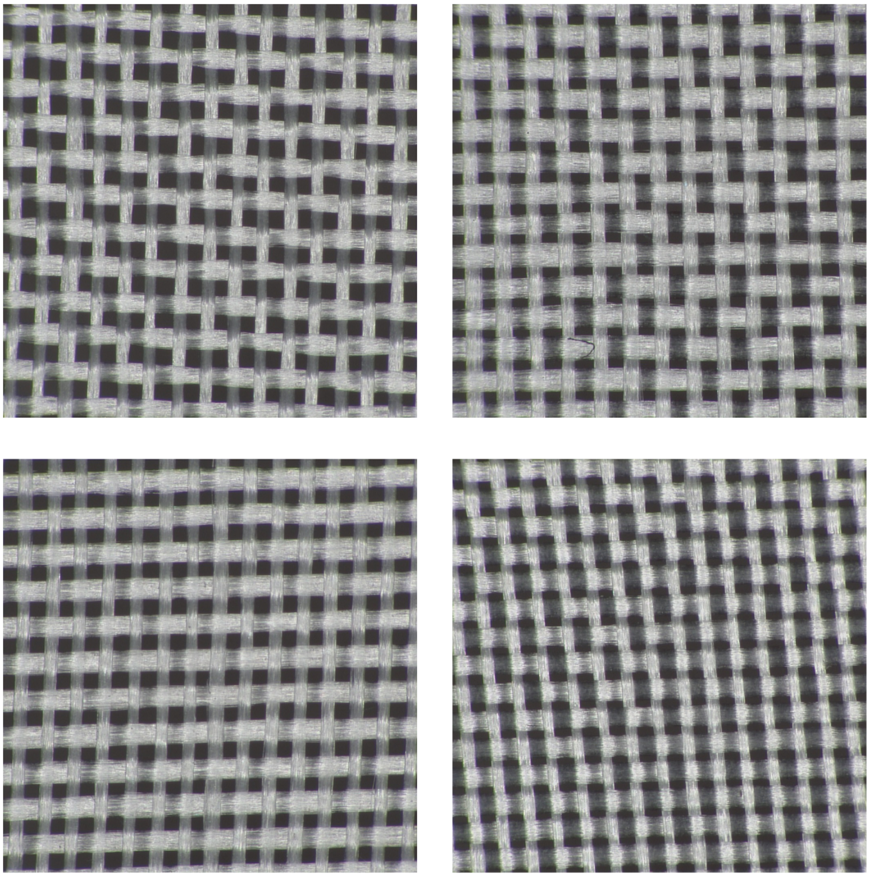


Fig. 4 Microscopic images of glass fiber fabrics: G108 (top left), G1078 (top right), G1080 (bottom left), and G1280 (bottom right).

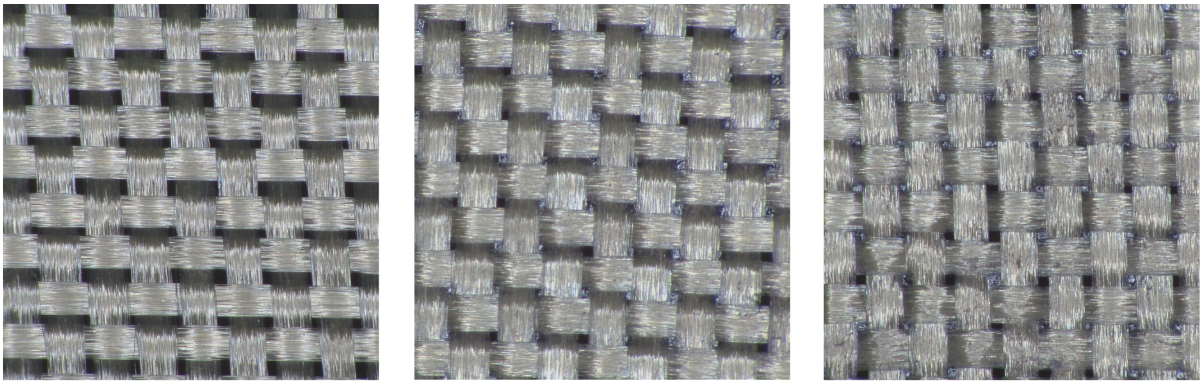


Fig. 5 Microscopic images of Kevlar fabrics: K120-CST (left), K120-13 (middle), and K120-14 (right).

To obtain transmission loss data, a small, acoustically lined box was built of medium-density fiber board with overall dimensions of $19 \times 19 \times 24$ in. The interior of the box was lined with an acoustically absorbent 1-in. thick melamine foam. The estimated cutoff frequency of the acoustic box is approximately 2 kHz. During the transmission loss measurements, the box was placed inside the anechoic chamber of the wall jet wind tunnel with acoustically absorbing foam placed over the wall jet plate. During the transmission loss tests, a Visaton FRS-8 speaker was mounted 36-in. above the center of the box opening and the speaker was supplied with a white-noise signal. The Brüel and Kajer type 4938 1/4-in. microphone was mounted inside the small acoustically lined box. Two measurements were performed. First, the opening of the box was left open, and second, the opening was covered with a fabric sample. To quantify the efficacy of the instrumentation in determining the transmission loss, the acoustic loss of a Mylar sheet was also measured. For this configuration, a closed-form solution is available for the transmission loss, which is given in Sec. III.

3. Optical Measurements

To quantify the open area ratio of the fabrics experimentally, a YSC Technologies HD807 digital microscope was used to capture images of the fabrics. After placing a dark background (black cardboard) behind the fabrics, the pores (i.e., open area) were observed in the microscopic images as pixels with low intensity, whereas the majority of the yarns were observed in the images as high-intensity pixels. Through digital image processing, it was possible to identify and count the number of pixels representing the open areas, that is, pores. The ratio between the number of these identified (masked) pixels and the overall number of pixels then defined the measured OAR, which is listed in Table 1. A sample microscopic image of the K120-EAS fabric with the pores masked in red is shown in Fig. 3, whereas the microscopic images of the glass fiber fabrics are shown in Fig. 4 and the Kevlar fabrics are shown in Fig. 5.

III. Results

This section provides a detailed analysis of the results obtained from self-noise and transmission loss measurements of the various porous fabrics. First, the aeroacoustic characterization of a commonly used Kevlar fabric is presented and discussed. The discussion then continues with the evaluation of the parametric study of porous fabrics.

A. Aeroacoustic Properties of Commercially Available Kevlar Fabrics

The acoustic transmission loss of Kevlar fabrics has been quantified at various institutions thus far [1,2], however, most of these analyses are limited to the audible frequency range and an empirical formula is not yet available in the literature that could be used to correct the losses caused by the Kevlar fabric above the audible frequency range. Also, only a limited number of studies presented the self-noise of the Kevlar fabric generated when a hydrodynamic pressure field is passing over the material [13,22,23]. For this reason, the following paragraphs focus on the quantification of both of these quantities in the high-frequency range (10–100 kHz) to quantify the aeroacoustic properties of commonly used Kevlar fabrics. It is anticipated that the combination of transmission loss and self-noise would manifest into a combined acoustic penalty at high frequencies, should aeroacoustic experimentation be placed behind a Kevlar window of HAWTs.

Figure 6a presents the transmission loss results of the K120-EAS fabric in both the low- (<10 kHz) and high-frequency range (10–100 kHz). The wide-frequency transmission loss data was obtained in three steps. First, experiments identical to those described in Ref. [1] have been performed at quiescent conditions to obtain a curve-fit to the transmission loss results of the Kevlar fabric within the frequency range of 100 Hz and 10 kHz (see the blue dotted line in Fig. 6). This experiment was then followed by the use of LIP as a high-frequency sound source, and the data processing approach as described in Sec. II.A was performed to obtain transmission loss data above the audible frequency range. The results of this analysis are restricted to the high-frequency region, namely between 30 and 100 kHz due to the short time-span of the LIP; see the red dashed line in Fig. 6a. A combined curve fit using both low- and high-frequency transmission loss results were then found, which is shown as a black continuous line in Fig. 6a. The corresponding curve-fit is written in the form of

$$T = -0.053\hat{f}^2 + 1.9119\hat{f} + 0.01148 \tag{1}$$

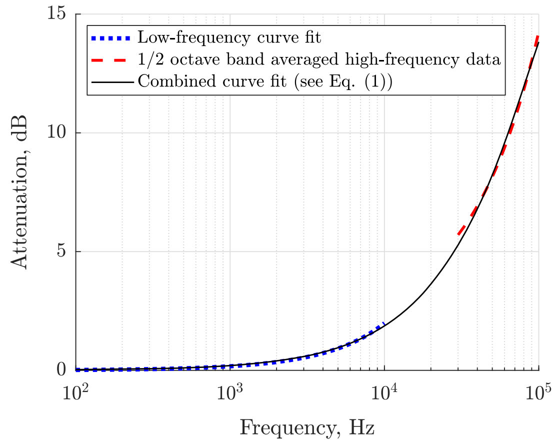
where T is the transmission loss of the Kevlar fabric in dB, $\hat{f} = f/10000$ Hz, and f is frequency in unit of Hz. The coefficients in the preceding expression have a unit of dB.

Interestingly, it can be seen in Fig. 6a that the transmission loss of Kevlar keeps increasing with frequency past the audible frequency range. Despite a gap in the results between 10 and 30 kHz, the curve fit matches the experimental data of both low- and high frequencies. In fact, the curve-fit presented here [see Eq. (1)] also relies on a second-order polynomial, similar to previous studies [1,2]. This suggests that the transmission loss of Kevlar is generated by the same mechanism in both the low- and high-frequency region.

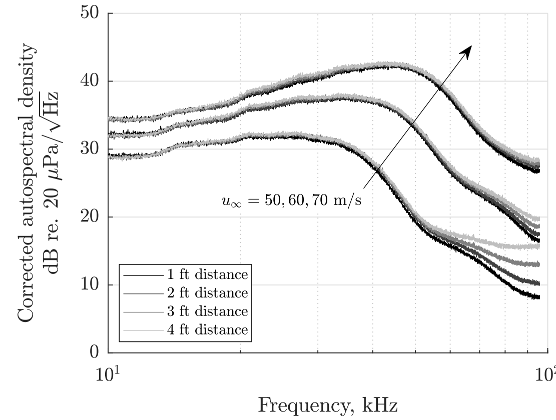
Figure 6b presents the self-noise results of the K120-EAS Kevlar fabric as measured in the SWT. The autospectral density shown in Fig. 6b has been distance-corrected using

$$\Delta_r = 20\log_{10}\left(\frac{r_1}{r_2}\right) \tag{2}$$

where Δ_r (dB) is the distance-correction factor due to different observer distances, r_1 is the separation distance between the Kevlar and the microphone (i.e., 1 ft, 2 ft, 3 ft, or 4 ft), and $r_2 = 1$ ft is the reference (or corrected) distance. We note that due to the large span of the Kevlar window (6×15 ft) and the comparably short separation distance between the Kevlar window and microphone, the results in Fig. 6b are overcorrected, hence the 4 ft separation distance results are marginally higher than the results obtained for a 1 ft separation



a) Transmission loss data of the Kevlar K120-EAS fabric. The low-frequency curve fit was obtained using the method presented in Devenport et al. [1], whereas the high-frequency data was obtained using the laser-induced plasma as a high-frequency sound source



b) The self-noise results of the Kevlar K120-EAS fabric with the observer location corrected for a 1-ft fabric-to-microphone separation distance

Fig. 6 The aeroacoustic characterization of a commonly used Kevlar fabric.

distance. Still, a good collapse is observed, which confirms that the dominant noise source between 10 and 100 kHz is indeed the self-noise of the Kevlar fabric. The self-noise levels of the Kevlar fabric are observed to increase with flow speed, which is in agreement with previous results [13], and the generated noise is broadband in nature.

Overall, the increasing transmission loss and self-noise at high frequencies result in a combined acoustic penalty when instrumentation is placed in the anechoic chambers of HAWTs. The sound source of interest is first attenuated as it passes through the Kevlar window, and the signal-to-noise ratio of the microphone signals in the anechoic chamber are weakened by the self-noise generated by the fabric. Hence, a fabric superior to the commercially available type 120 Kevlar fabrics needs to deliver a lower combined aeroacoustic penalty.

B. Parametric Study of Various Porous Fabrics

The parametric study of carefully selected porous fabrics is now considered. The experiments focused on the quantification of transmission loss and self-noise for the fabrics listed in Table 1. First, the transmission loss results are presented and discussed, followed by the analysis of the self-noise behavior of the fabrics. Based on these results, conclusions are then drawn on potentially better-performing porous fabrics as an alternative to the currently widely used Kevlar fabrics.

1. Transmission Loss of Various Porous Fabrics

Acoustic loss measurements may be considered as a common type of acoustic testing. Such tests are most often performed for materials with higher insertion loss. There, the experimental signal-to-noise ratio, that is, drop in acoustic levels once the material is introduced, often exceeds 10 dB. Considering previous results of Kevlar transmission loss measurements [1,2,14], it was found that the acoustic loss of Kevlar does not exceed 5 dB below 20 kHz. This makes the quantification of TL rather challenging experimentally, especially at low frequencies (below 1 kHz).

Acoustic models are readily available in the literature [28], which provide a closed-form solution for estimating transmission loss of thin materials. These models are often derived for a thin sheet material (or interface) in response to one-dimensional time-harmonic acoustic waves with normal incidence. However, a limited number of models are available for the case where porous materials or fabrics are tested because the fundamentals of how sound propagates through such materials are fundamentally different from the case when the sound waves pass through a solid object [33]. In the latter case, the loss is controlled by the mechanical interaction between the sound waves and the material. In the case of porous fabrics, however, the mechanical interaction between the porous fabric and the sound waves is significantly reduced due to the presence of the pores. Namely, the sound waves can pass through the pores of the material significantly easier. This makes the direct comparison of currently available TL models with the TL results of porous fabrics presented here less relevant.

The transmission loss T was calculated from the experimental data as

$$T = -20\log_{10}\left| \frac{G_{pu}}{G_{uu}}\bigg|_{\text{open}} \frac{G_{uu}}{G_{pu}}\bigg|_{\text{covered}} \right| \tag{3}$$

where G_{ab} refers to the cross spectrum calculated between signals a and b, the microphone pressure signal is denoted as p, the white-noise signal fed to the speaker is represented by u, and the subscript "open" refers to data obtained with the cavity of the test rig being open, whereas "covered" refers to the cavity of the test rig covered with the tested materials.

First, the transmission loss of a thin Mylar sheet is investigated to assess the capabilities of the transmission loss test rig. A closed-form solution for TL is readily available from Blackstock [28], which quantifies the transmission loss of a thin sheet material in response to one-dimensional time-harmonic acoustic waves with normal incidence. In the case of Mylar, the transmission loss is mass-controlled and the expression simplifies to

$$T = -20\log_{10}\left| \frac{2}{2 + i\omega l(\rho_m/\rho_0 c_0)} \right| \tag{4}$$

where i is the imaginary unit, $\omega = 2\pi f$, f is frequency, $\rho_m = 1380\ \text{kg/m}^3$ is the density of the Mylar, $l = 0.25$ mm is the thickness of the Mylar, and ρ_0 and c_0 are the density of air and speed of sound in air, respectively.

The transmission loss results obtained for the Mylar sheet are shown in Fig. 7 along with the TL predicted using Eq. (4). The TL averaged over one-third octave bands are also shown in the figure to improve the accuracy of the TL results. The following observations can be made. First, the trend of the TL data agrees well with the theoretical prediction, which clearly indicates an increase of TL with frequency, particularly above 1 kHz. This increasing trend of TL is due to the mass-controlled nature of the interaction between the sound waves and Mylar. The narrowband TL data shows larger reflections and uncertainty at lower frequencies ($f < 10$ kHz), but above this threshold, the uncertainty of the results decreases. There

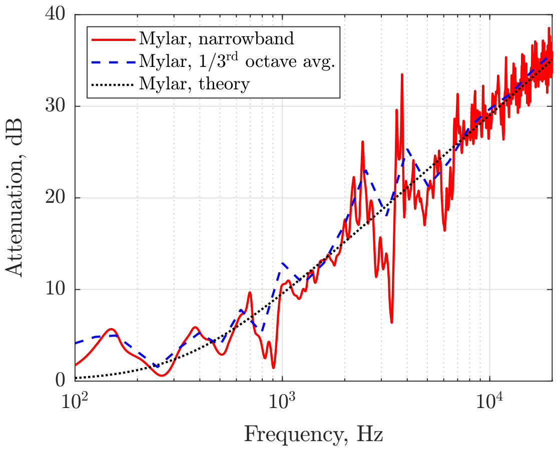


Fig. 7 Experimental and theoretical transmission loss results obtained for a thin Mylar sheet.

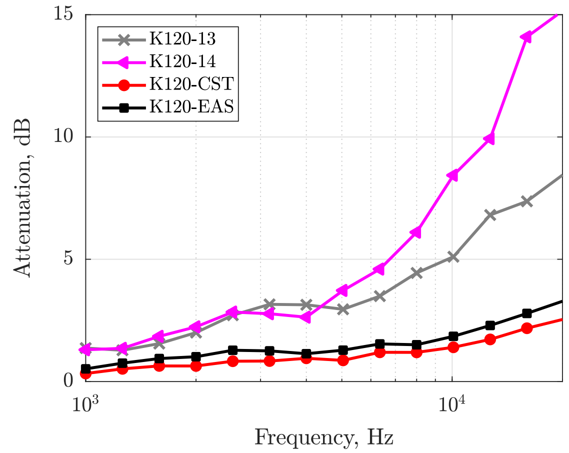


Fig. 9 One-third octave-band averaged transmission loss results obtained for the Kevlar fabrics.

are a few distinct peaks in TL in the range of 3–4 kHz. Considering the estimated cutoff frequency of the small acoustically lined box (2 kHz) and the change that the introduction of the Mylar sheet causes to the acoustic boundary conditions of the box suggests that the uncertainty of the TL data below 4 kHz increases, particularly when the amplitude of the reflected sound waves from the material tested is large. Considering the lower mechanical interaction present between the porous fabrics and sound waves compared to the interaction of sound and Mylar, it is assumed that the internal reflection-related uncertainty is lower when pores are present. In other words, the internally reflected sound levels are anticipated to be less significant for porous fabrics than for Mylar. Finally, a good agreement is found between the one-third octave-averaged data and the theoretical TL values. For these reasons, only the one-third octave-averaged TL results of the porous fabrics are shown in the following discussions.

The transmission loss results obtained for the glass fiber fabrics are shown in Fig. 8. As can be observed, the TL of these fabrics is extremely low, namely, the results remain less than 0.5 dB below 20 kHz. The uncertainty of the TL experiments was found to be approximately ±0.1 dB from repeatedly measuring the acoustic signature of the configuration where no fabric was present over the cavity of the test rig. Based on this, the signal-to-noise ratio improves at high frequencies, particularly above 10 kHz. Here, fabrics show an increasing TL in the order of GF1080, GF108, GF1280, and GF1078. Considering their measured OAR values, this corresponds to OARs of 18.9%, 20.5%, 14.1%, and 13.1%. Clearly, the identified trend suggests that a lower OAR will result in a higher transmission loss.

Similar observations can be made using Fig. 9, where transmission loss results of the plain and coated Kevlar fabrics are shown. The plain Kevlar fabrics (K120-CST and K120-EAS) have an identical mass per unit area m and thread density (TPI) whereas they only differ

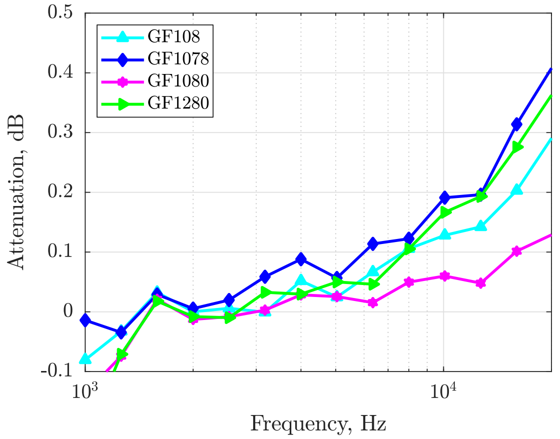


Fig. 8 One-third octave-band averaged transmission loss results obtained for the glass fiber fabrics.

in OAR. Kevlar with a lower OAR shows a higher TL, which is also in agreement with our previous findings on the TL of glass fiber fabrics. From this, we may conclude that the OAR is the major factor in determining TL, particularly at high frequencies. When considering the coated Kevlar fabrics (K120-13 and K120-14), there is a well-visible increase at high frequencies (above 10 kHz), which is in agreement with our expectations, given their lower OAR.

Based on these observations, we can conclude that the acoustic loss of the commercially available Kevlar fabrics is dictated primarily by their OAR. It was also seen that a very low OAR (see K120-13 and K120-14, in particular) results in a significant increase in TL. Therefore, when considering an acoustically ideal fabric, the OAR shall be maintained around a few percent to sustain acceptable, say, less than 5–6 dB, TL within the audible frequency range.

C. Self-Noise of Various Porous Fabrics

The acoustic self-noise results of all fabrics listed in Table 1 are now considered for discussion using Fig. 10. The results can be categorized into three sets, namely, all glass fiber fabrics, both plain Kevlar fabrics, and both coated Kevlar fabrics observe slightly different acoustic responses. This observation is also labeled in Fig. 10. All results shown were acquired at the maximum available flow speed of the wall jet wind tunnel, while the microphone was placed at an identical separation distance from the fabrics in the quiescent air. Although the maximum jet speed in the tunnel is 70 m/s, by the location where the flow reaches the fabrics, the Mach number over the fabric samples reduces to $M \approx 0.08$. The maximum jet speed was necessary to obtain a good signal-to-noise ratio (self-noise to background noise) and to keep the aeroacoustic excitation of the fabrics identical, as the hydrodynamic pressure field passing over the fabrics is responsible for the pumping of air through the pores in the fabric.

For all cases where the fabric density differs in the warp and weft directions, the higher thread count was positioned perpendicular to the mean flow. Figure 10 also presents the background noise of the facility that was obtained by replacing the test rig with a flat plate (aluminum plate) while maintaining the location of the microphone. The background noise results reveal that the electrical noise of the data acquisition chain increases toward the Nyquist frequency (65 kHz) and becomes comparable to the fabrics' self-noise at approximately 50 kHz.

Bahr et al. [21] presented the acoustic signature of a Kevlar fabric that is near-identical to K120-CST at a comparable Mach number. The results of Bahr et al. {see Fig. 12a in Ref. [21]} compare well with the self-noise results of the Kevlar fabrics shown in Fig. 10. Namely, the frequency responses of the Kevlar fabrics are broadband in nature and span between approximately 7 and 40 kHz in Fig. 10, whereas it spans between approximately 7 and 30 kHz in Fig. 12a of Ref. [21]. When comparing K120-EAS to K120-CST, a near-identical acoustic response is seen above 20 kHz, but K120-CST produces higher self-noise levels at lower frequencies (below

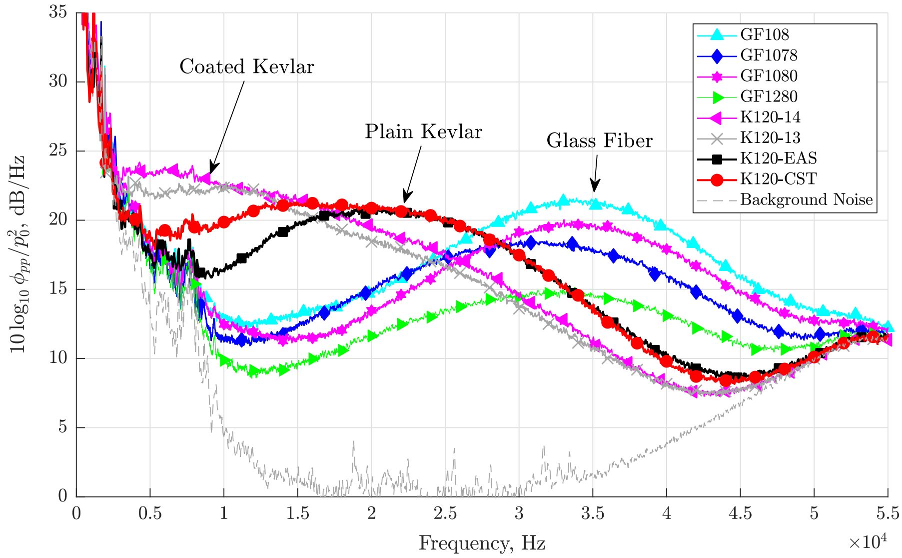


Fig. 10 Narrowband self-noise data obtained for the porous fabrics.

15 kHz) than K120-EAS. It may be assumed that the larger porosity of K120-CST is responsible for this increase, as this would imply a lower resistance to the air- pumping mechanism through the pores of the fabric, hence enabling higher self-noise levels.

The self-noise of the glass fiber fabrics is now considered; see Fig. 10. These fabrics differ from Kevlar in two main aspects; first is their significantly higher OAR (14–20%) and increased (about double) thread density (54–60 TPI). The frequency span of the glass fiber fabrics' self-noise is also broadband in nature and it is found over higher frequencies than that of Kevlar. The self-noise of the glass fiber fabrics span between 15 and 50 kHz and the peaks of their self-noise levels are approximately at the same frequency, about 35 kHz. The only exception from this observation is GF1078, whose self-noise peaks at about 30 kHz. Another important observation is that their maximum self-noise ranges from 14 to 22 dB. Unfortunately, their OAR is high enough for the mean airflow to travel across the materials at a significantly lower pressure loss, therefore, the mean flow could easily pass through these fabrics during testing. Hence, the exciting hydrodynamic pressure field passing over the top of the glass fiber fabrics was not identical to that of the Kevlar fabrics. This explains the wide range of self-noise levels and also suggests that the OAR contributes to the acoustic level of self-noise. Therefore, their very high air permeability makes glass fibers unsuitable for HAWT applications, as one of the important requirements against the porous walls is to contain the flow. In addition, the glass fibers are rather brittle, making them unsuitable to withstand the mechanical loads of wind-tunnel tests.

The rather similar acoustic response of glass fibers in terms of frequency span suggests that the frequency at which the broadband self-noise is observed is dictated by a material property that is similar across the glass fiber fabrics. Most probably, this is due to their rather similar thread density. This assumption may be supported by the fact that the hydrodynamic pressure field passes over a higher number of threads per unit length while the convection velocity of the flow can be considered nearly constant. Another supporting evidence to this observation is the slightly different acoustic response of GF1078, which has a lower thread density (54 TPI) than the rest of the glass fiber fabrics (60 TPI). With this, we may conclude that a higher thread density shifts the self-noise response of porous fabrics to higher frequencies.

Finally, we investigate the acoustic response of the coated Kevlar fabrics; see Fig. 10. Applying spray-on glue to the K120-EAS fabric resulted in an irregular blockage of pores (see Fig. 5), which means that the interaction between the hydrodynamic pressure field passing over the fabric and the pores became nonperiodic, or in other words, random (broadband) in the streamwise direction (or wave number domain). This may also mean that their thread density, which previously determined the number of pores per unit length as well, is not identical to that of K120-EAS from a pumping-excitation perspective. Also, their mass per unit area was increased due to the addition of glue. Two observations can be made regarding their self-noise. First, an increase of self-noise levels below 15 kHz is observed, and second, an approximately constant shift to lower frequencies can be seen compared to the plain Kevlar fabrics. From this, we may assume that their self-noise became more broadband in nature, which could not be captured below 5 kHz due to the facility background noise levels. These observations suggest that the periodic pore distribution is responsible for the frequency span of porous fabrics. However, nearly eliminating the pores (<1%) still results in a scrubbinglike self-noise, again confirming the responsibility of pores in the self-noise generation of porous fabrics. Finally, increasing the mass per unit area does not seem to have a significant, well-distinguishable effect on the self-noise characteristics of porous fabrics.

The following conclusions may be made by considering the joint effect of transmission loss and self-noise. When combining these properties as a penalty in signal-to-noise ratio in aeroacoustic experiments, we may identify two potential ways of improving their performances. First, introducing an irregular distribution of pores can reduce the self-noise at high frequencies and shift it to lower frequencies, but this was found to increase the transmission loss (15 dB) at high frequencies (10–20 kHz); see Fig. 9. Second, increasing the thread density while maintaining the OAR is expected to shift the self-noise of porous fabrics to higher frequencies and sustain an acceptable level of transmission loss.

IV. Conclusions

A set of porous fabrics was tested to assess their aeroacoustic properties with the aim of finding a fabric that may serve as an improved aeroacoustic interface separating the mean wind-tunnel flow and quiescent conditions in a similar manner that Kevlar is used in hybrid-anechoic wind tunnels (HAWTs). First, experiments were conducted at the Stability Wind Tunnel at Virginia Tech to quantify the transmission loss and self-noise properties of a commercially available Kevlar fabric between 1 and 100 kHz. Second, a parametric study was performed at the Wall Jet Wind Tunnel of Virginia Tech to characterize the transmission loss and self-noise of eight carefully selected porous fabrics. For the purposes of the aeroacoustic tests, two separate test rigs were built to assess transmission loss and self-noise of the various fabrics.

Results revealed that the transmission loss of Kevlar shows a continuous increase past the audible frequency range, suggesting a single mechanism responsible for the transmission loss. The self-noise of the Kevlar fabrics used in the Stability Wind Tunnel was observed to be broadband in nature and it was dominant above the audible frequency range. In addition, it was confirmed that the high-frequency noise is the self-noise emitted by the Kevlar fabric. It was concluded that the combined penalty of high transmission loss and self-noise is responsible for limiting aeroacoustic measurements at HAWTs at high frequencies.

A total number of eight porous fabrics have been tested in this study, which consisted of three major types: 1) two plain Kevlar fabrics, 2) four pieces of glass fiber fabrics, and 3) two modified Kevlar fabrics with a spray-on adhesive applied to a plain Kevlar. The effects of the following properties of the fabrics have been considered in the investigation of transmission loss and self-noise: open area ratio (OAR), defined as the porous area of the fabric to its overall area, thread density in the warp and weft direction (threads per inch, TPI), and the mass per unit area.

The transmission loss measurements confirmed that the pores serve as a low-resistance gateway to the sound waves, granting low transmission loss to porous fabrics. The pores were found to provide a different acoustic loss mechanism of porous fabrics than that of a thin solid sheet of material, such as Mylar. This suggests that a fabric superior to the commercially available Kevlar fabrics still needs to rely on porosity to sustain low levels of transmission loss. The exact level of porosity required for HAWT facilities may be determined using additional parametric studies. However, the results of glass fibers indicated that the porosity needs to be low enough to contain the flow in the wind tunnel, therefore, glass fiber fabrics were found unsuitable for HAWT use.

The self-noise measurements of commercially available Kevlar were found to be in good agreement with previous measurements. The application of spray-on adhesive to a Kevlar fabric resulted in an irregular distribution of pores. The irregular pore pattern was found to be responsible for a more broadband self-noise of the fabric. Overall, the self-noise results suggest that the thread density determines the frequency span of porous fabric self-noise, whereas the open area ratio may have an impact on the generated sound levels. The mass per unit area of the fabrics did not seem to significantly impact either transmission loss or self-noise. Additional studies of fabrics with higher mass per unit area than the range covered here (the mass ratio of the heaviest-to-lightest fabric was approximately 1.5) may shed more light on the acoustic effects of this fabric property, however, this may require the use of custom-made fabrics.

Overall, two potential ways were identified to mitigate the unwanted aeroacoustic penalties of currently used Kevlar fabrics. The following options may be considered on a case-by-case basis. First, introducing an irregular distribution of pores could reduce the self-noise at high frequencies and shift it to lower frequencies, potentially making fabric self-noise part of facility background noise, but this option also results in an increase of transmission loss at high frequencies. The second option, which may be considered a more generally applicable solution, is increasing the thread density while maintaining a few percent OAR. Although a definitive number of the desired OAR cannot be determined based on the current set of data, it can be anticipated that a limit exists for OAR where the permeability would exceed a threshold at which the transpiration flow through the fabric would negatively affect the aerodynamic performance of the wind tunnel facility. Overall, in this latter option, the fabric is expected to shift the self-noise to higher frequencies while sustaining a low level of transmission loss.

Acknowledgments

The authors would like to thank the National Science Foundation, in particular Ron Joslin, for their support of this research under grant CBET-2012443. We would like to thank Patricio Ravetta, Matthew Kuester, Nanya Intaratep, and William Oetjens for the low-frequency transmission loss measurements performed in the Stability Wind Tunnel.

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