Setup for experimental study of porous plate acoustics and local flow features

John R. Kershner[1,2], Thomas F. Geyer[3], Justin W. Jaworski[4]
[1] *Brandenburg University of Technology, 03046 Cottbus, Germany*
[2] *Lehigh University, 18015 Bethlehem, USA, Email: jrk520@lehigh.edu*
[3] *formerly: Brandenburg University of Technology , 03046 Cottbus, Germany,*
now with: Deutsches Zentrum für Luft- und Raumfahrt , 03046 Cottbus, Germany, Email: thomas.geyer@dlr.de
[4] *Lehigh University, 18015 Bethlehem, USA, Email: jaworski@lehigh.edu*

Introduction

Porous plates are investigated as an engineering approach to reduce trailing-edge noise in the greater effort to reduce aircraft noise pollution. Inspired by nature's silent flier, the owl, porosity has been shown to be effective for noise reduction in previous theoretical and experimental works, where a single dimensionless parameter controls the effects of porosity on the sound field. Prior vortex-sound experiments using a vortex ring [1] have validated predictions of the sound scaling on flight speed and associated changes in directivity [2]. The acoustics and flow features of porous plates characterized by this same dimensionless porosity parameter are tested in a wind tunnel.

In this work, a phased microphone array and subsequent beamforming analysis enable the collection of detailed source maps near the porous edge, and radially-spaced microphones measure the directivity changes of the generated noise. In addition to acoustic measurements, flow measurements are taken with a hot-wire probe. This approach enables the investigation of how local flow changes due to geometric details of the plate porosity might affect the overall flow about the plate and the aerodynamic sound field. Since bluntness noise is a large source of trailing-edge noise for flat plates, special attention is made to the experiment setup to reduce bluntness noise so that turbulent boundary-layer noise is the dominant source at the trailing edge (TE). Notable acoustic results will be presented and compared for the nonporous reference case with various trailing edge thickness modifications, and a highly porous plate.

Theory

Noise measurements of live animals indicate that owls fly quieter than other birds [3], especially at high frequencies [4]. This quiet flight is caused in part by the tattered fringe at the trailing edge of their wings. This edge feature has been idealized by wing porosity [4], which has been shown to reduce flow noise in a laboratory setting using guidance from theoretical analyses [2, 5].

The early theoretical and numerical work of Howe [6] on porous plate acoustics modeled a point vortex passing over a trailing edge to show that the presence of perforations could reduce trailing-edge noise significantly. Computational simulations by Khorrami & Choudhary [7] indicated that the presence of porosity on a flat plate can reduce sound by reducing the strength of the edge scattering and by modifying the hydrodynamic noise source itself. Flow-noise experiments using porous SD 7003 airfoils composed of various foams have shown that porosity can reduce noise up to 10 dB, which depends strongly on the flow resistivity of the porous medium. However, these porous airfoils generated excess noise at higher frequencies, which may be due to flow interactions with surface roughness [8, 9]. Flat plates with blunt trailing edges can produce a specific type of trailing-edge noise, called bluntness-noise. In Ali et al. [10], porous treatments are investigated to reduce bluntness noise, which they found to be prevalent at Strouhal number $St = 0.20$, a fundamental vortex shedding frequency. In the best case, they found that highly permeable materials could reduce the peak tonal noise by 35 dB [10].

The acoustic power scaling of the radiated sound on flow speed, U^γ, is also affected, where values of γ, the scaling exponent, vary from 5 to 6 for porous airfoils [4, 8], which is to be compared against the $\gamma = 5$ result for impermeable edges [11]. In Chen et al. [2], a time-domain Green's function approach is used to solve the problem of a vortex ring passing over a semi-infinite porous edge to predict the acoustic power scalings, directivity patterns, and acoustic pressure waveforms. Their theoretical model uses a dimensionless porosity parameter,

$$\delta = \frac{2\alpha_h c}{\pi^2 f R}, \tag{1}$$

which was identified by Ffowcs Williams [12] in his analysis of infinite porous surfaces and was later used by Jaworski & Peake [4] to show that the acoustic scaling of porous edge noise on flight speed becomes U^6 for large values of δ, which results in an effective decrease of noise. In this equation, α_h is the open-area fraction, c is the speed of sound, f is the frequency, and R is the pore radius.

The effect of this parameter on trailing edge noise created by single vortices was tested in the Applied Research Laboratory's anechoic chamber. In Yoas [1], a vortex ring generator was used to pass vortices over semi-infinite porous plates characterized by δ.

Figure 1 shows the directivity of the trailing edge noise from a nonporous sheet measured by radially spaced microphones. The shape matches the cardiod, U^5 scaling, very well. The acoustic scaling of porous edge noise on velocity at high parameter values very closely matches the theoretical U^6 dipole shown in Figure 2.

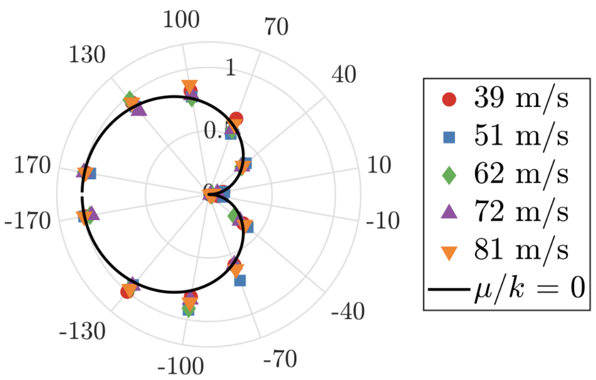

Figure 1: Directivity of trailing edge noise for impermeable sheet from [1]

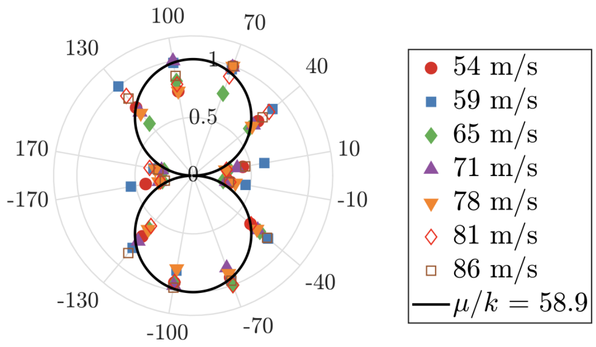

Figure 2: Directivity of trailing edge noise for highly porous sheet from [1]

The purpose of this paper is to investigate setup techniques to reduce bluntness noise using porous edges, and to enable experimental examination of the sound field from porous plates over a range of dimensionless porosity parameter values. Changes in the sound pressure levels will be measured in complement to the central focus on the reduction of edge bluntness noise engendered by porous edges.

Methods

The experimental apparatus uses 0.17 m × 0.30 m × 0.003 m acrylic plates that are designed with various hole shapes and spacings to span the range of δ. The parametric range of δ is informed from the theoretical analysis of Chen et al. [2] to span from the impermeable to the highly-porous limiting behaviors of porous edge noise. The f component of δ is estimated using the Reynolds number Re and the boundary layer thickness, H, at the trailing edge:

$$f = \frac{U_0}{H}. \tag{2}$$

Plates modified with circular and square holes with both aligned and offset pore patterns are investigated. The hydraulic radius is taken for the R term in δ in the case of square holes. For this paper, a highly porous plate is used with holes that are $R = 0.9$ mm and a spacing of $s = 4.0$ mm. The holes are cut in the plate using a Universal Systems 75 W laser cutter. This hole geometry enables a δ in the highly porous zone which should lead to a velocity sound scaling exponent of $\gamma = 6$, or U^6.

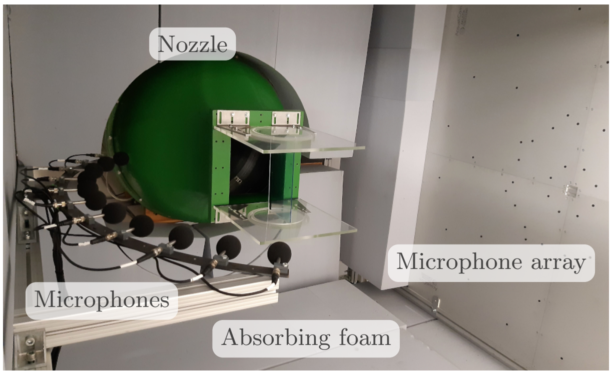

Figure 3: Photograph of the experimental setup inside the aeroacoustic wind tunnel.

The measurements were conducted in the small open jet aeroacoustic wind tunnel at the Brandenburg University of Technology (BTU) in Cottbus [13]. Figure 3 shows a photograph of the experimental setup. The nozzle in the experiments has a rectangular exit area with dimensions of 0.23 m × 0.28 m and enables a maximum flow speed of approximately 50 m/s. Attached to the upper and lower edge of the nozzle were rectangular side plates made of acrylic glass. Similar to the setup used in [14], circular rotatable discs were set into these side plates. The flat plates under examination were mounted at both end to these circular discs, allowing to adjust the angle of attack.

Acoustic measurements were performed using eleven free-field microphones located on an arc at a distance of 0.61 m from the plate trailing edge. The data were recorded with a sampling frequency of 51.2 kHz and a duration of 40 s using a Multichannel Frontend. In post processing, they were transferred to the frequency domain using a Fast Fourier Transform on blocks of 4096 samples with an overlap of 50 % and the Hanning window function.

Constant Temperature Anemometry (CTA) measurements were performed at a distance of 0.09 m from the nozzle exit to analyze the flow field its supplies. This distance corresponds to the location of the flat plate leading edges in the acoustic measurements. The velocity profile at this location was found to be uniform, with a very low turbulence intensity of approximately 0.3 % at the center.

Results

Figure 4 shows the sound pressure level, SPL, for the impermeable plate with a blunt edge. The peaks are at approximately $St = 0.2$, which is due to the bluntness of the TE and matches the results of [10]. In an effort to reduce this trailing-edge bluntness noise, 3 different trailing-edge treatments are proposed, as shown in Figure 5. T1 consists of a 0.5 mm thick edge created by folded aluminum tape, T2 is a 0.8 mm thick edge created by a thicker tape, and T3 is a modification of T2 with 2 cm x 2 cm serrations cut into it. The goal of these modifications is to reduce the thickness of the trailing

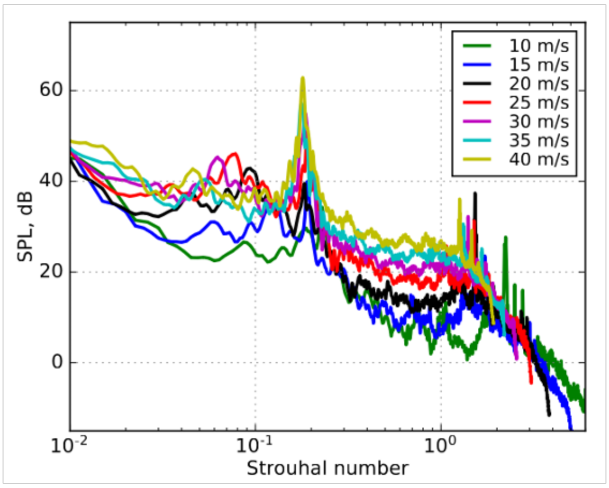

Figure 4: SPL vs. St for impermeable plate with blunt edge

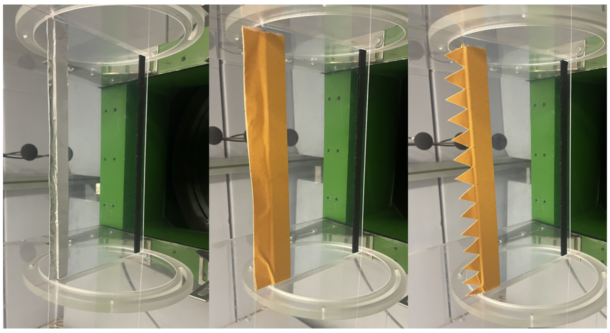

Figure 5: Edge treatment 1, T1 (left), edge treatment 2, T2 (middle), and edge treatment 3, T3 (right)

edge to make it less blunt. The results shown in Figures 6 to 8 compare the spectrum for the impermeable plate with no modifications, the highly porous plate, and edge treatments T1, T2, and T3.

Figure 6 shows that the modifications to the trailing edge for the impermeable plate are able to reduce the tonal bluntness noise at approximately 900 Hz successfully. The porous plate, indicated by the blue line, reduces the peak of the bluntness noise slightly more so than the trailing-edge modifications. The ability for the porous plate with a blunt trailing edge to reduce bluntness noise at a greater magnitude than T1, T2, and T3 shows promise for overall noise reduction. This trend continues in Figures 7 and 8, where the highly-porous plate becomes less effective in reducing the bluntness noise peak at higher flow speeds.

At lower flow speeds, the porous plate is able to not only reduce the bluntness noise, but also to reduce all noise in the 300-1,000 Hz range. The porous plates do not come without their downsides, however. In all the cases, the porous plates increase noise at frequencies greater than approximately 2,000 Hz. This phenomenon is known to be due to roughness noise, or the holes themselves acting as sound sources, also mentioned in [15, 16].

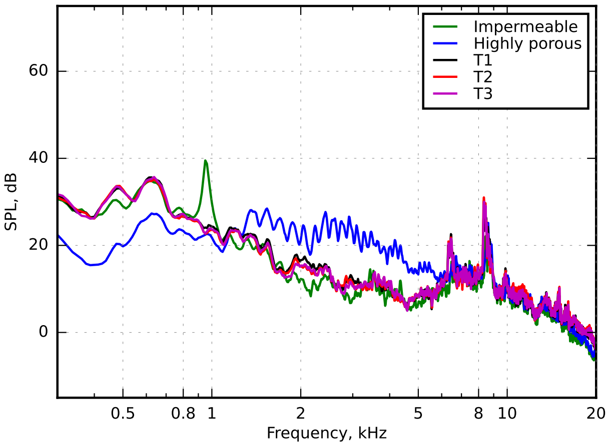

Figure 6: SPL vs. Frequency comparison at $U_0 = 15$ m/s

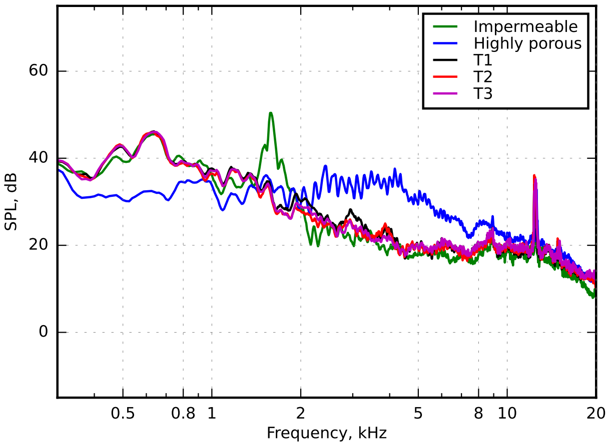

Figure 7: SPL vs. Frequency comparison at $U_0 = 25$ m/s

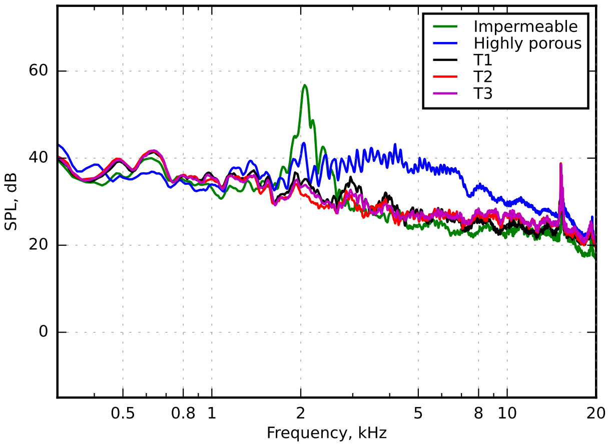

Figure 8: SPL vs. Frequency comparison at $U_0 = 35$ m/s

The plates were subsequently sharpened to have a trailing edge thickness of 1mm. The sharpening of the TE removes the tonal peak at 900 Hz for the $U_0 = 15$ m/s case in Figure 9. Results in this same figure show continued reduction of sound pressure at 300-1,500 Hz, enclosed by the red box, but increase of noise at frequencies greater than 1,500 Hz.

In summary, a setup of radially spaced microphones and a microphone array is used to measure the acoustic effects of porosity on trailing-edge boundary layer noise.

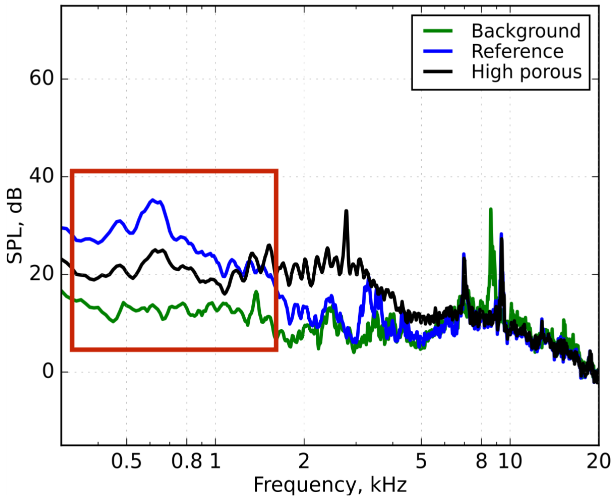

Figure 9: Direct comparison of reference and high porous plate both with sharpened TE at $U_0 = 15$ m/s

Spectra from a highly porous plate with a blunt TE is shown to have strong tonal peaks due to bluntness vortex shedding. This bluntness noise is reduced by 3 novel TE modifications and the presence of porosity. Finally, the TE are sharpened to remove the bluntness noise, and the highly porous plate is successful at reducing low frequency, 300-1,500 Hz, noise, but increase noise at high frequencies due to the holes acting like roughness elements. A hot wire measurement campaign is ongoing and further results such as changes in directivity and overall sound pressure levels and hot wire data will be presented in [17].

Acknowledgements

The authors acknowledge the support of the Fulbright Program, the German-American Fulbright Commission, The Germanistic Society of America, and NSF CAREER award 1846852. The authors would also like to thank Stefan Rohark and Michael Moore for their assistance with manufacturing the experimental setup and the porous plates.

References

[1] Zachary Yoas. Passive trailing edge noise attenuation with porosity, inspired by owl plumage. Master's thesis, The Pennsylvania State University, 2021.

[2] Huansheng Chen, Zachary W Yoas, Justin W Jaworski, and Michael H Krane. Acoustic emission of a vortex ring near a porous edge. part 1: theory. *Journal of Fluid Mechanics*, 941, 2022.

[3] Ennes Sarradj, Christoph Fritzsche, and Thomas F Geyer. Silent owl flight: bird flyover noise measurements. *AIAA Journal*, 49(4):769–779, 2011.

[4] Justin W Jaworski and N Peake. Aerodynamic noise from a poroelastic edge with implications for the silent flight of owls. *Journal of Fluid Mechanics*, 723:456–479, 2013.

[5] Justin W. Jaworski and N. Peake. Aeroacoustics of silent owl flight. *Annual Review of Fluid Mechanics*, 52(1):395–420, 2020.

[6] MS Howe. On the added mass of a perforated shell, with application to the generation of aerodynamic sound by a perforated trailing edge. *Proceedings of the Royal Society of London A*, 365(1721):209–233, 1979.

[7] Mehdi R Khorrami and Meelan M Choudhari. Application of passive porous treatment to slat trailing edge noise. Technical Report NASA/TM-2003-21241, NASA, 2003.

[8] Thomas F Geyer and Ennes Sarradj. Trailing edge noise of partially porous airfoils. In *20th AIAA/CEAS Aeroacoustics Conference*, 2014. AIAA paper 2014-3093.

[9] Thomas F Geyer, Ennes Sarradj, and Christoph Fritzsche. Measurement of the noise generation at the trailing edge of porous airfoils. *Experiments in Fluids*, 48(2):291–308, 2010.

[10] Syamir Alihan Showkat Ali, Mahdi Azarpeyvand, and Carlos R Ilário da Silva. Trailing edge bluntness noise reduction using porous treatments. *Journal of Sound and Vibration*, 474, 2020. 115257.

[11] JE Ffowcs Williams and LH Hall. Aerodynamic sound generation by turbulent flow in the vicinity of a scattering half plane. *Journal of Fluid Mechanics*, 40(4):657–670, 1970.

[12] John E Ffowcs Williams. The acoustics of turbulence near sound-absorbent liners. *Journal of Fluid Mechanics*, 51(4):737–749, 1972.

[13] Ennes Sarradj, Christoph Fritzsche, Thomas F Geyer, and Jens Giesler. Acoustic and aerodynamic design and characterization of a small-scale aeroacoustic wind tunnel. *Applied Acoustics*, 70(8):1073–1080, 2009.

[14] Thomas F Geyer and Lars Enghardt. Noise generation by two staggered circular cylinders of equal diameter in cross-flow. In *28th AIAA/CEAS Aeroacoustics 2022 Conference*, 2022. AIAA paper 2022-3093.

[15] Thomas F Geyer, Ennes Sarradj, Jens Giesler, and Marcus Hobracht. Experimental assessment of the noise generated at the leading edge of porous airfoils using microphone array techniques. In *17th AIAA/CEAS Aeroacoustics Conference (32nd AIAA Aeroacoustics Conference)*, page 2713, 2011.

[16] Chaoyang Jiang. *Noise Generation by Airfoils and Rotors with Porous and Serrated Trailing Edges*. PhD thesis, University of New South Whales, 2020.

[17] John Kershner, Justin W. Jaworski, and Thomas F. Geyer. Experimental study of trailing-edge bluntness noise reduction by porous plates. *AIAA Aviation*, 2023.