

Evaluation of an Additive-Manufactured Acoustic Metamaterial as a Nacelle Liner using the Advanced Noise Control Fan

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This paper examines the performance of a 3D printed acoustic metamaterial as an acoustic treatment for aircraft engine nacelles in the Advanced Noise Control Fan. As the level of air travel continues to increase, so too does the demand for better noise-reduction technologies for aircraft. Engines are one of the two main sources of noise generated by aircraft, with fan noise, in particular, being of concern due to its broadband and tonal contributions. Small and lightweight methods of addressing both broadband and tonal noise are necessary due to the limits presented by the current engine design. Presented in this paper is a novel acoustic metamaterial which has undergone design optimisation for broadband noise reduction. The final design was produced using 3D printing and tested using the Advanced Noise Control Fan at the University of Notre Dame. It is seen that the material is capable of reducing the first harmonic of the blade passing frequency by up to 18.5 dB, with an overall noise reduction of 3.7 dB.

I. Nomenclature

α	Absorption coefficient
τ	Transmission coefficient
c_0	Speed of sound in air (ms^{-1})
p_0	Incident pressure wave (Pa)
p_t	Total pressure wave (Pa)
r	Reflection coefficient
ANCF	Advanced Noise Control Fan
B	Number of Blades
PWL	Sound power level
SPL	Sound pressure level (dB)
RPM	Revolutions-per-minute
TL	Transmission loss (dB)

II. Introduction

As air travel continues to become more frequent, the demand on the industry to improve the efficiency of aircraft increases. While the aviation industry was greatly impacted by restrictions implemented during the pandemic, as discussed by [1], it is expected that annual numbers of air passengers will return to 88% of the 2019 levels by the end of

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2022, and will exceed the 2019 levels by 2024 [2]. For those living in close proximity to airports and aviation centres, the return to normal air traffic levels and the anticipated increases will see a return of high levels of noise pollution. These levels of noise pollution have been seen to have a significant impact on the environment and populations in the surrounding areas. In recent years aircraft noise has been the subject of a number of studies which have linked noise to numerous health problems including cardiovascular diseases, Non-Hodgkin lymphoma and hypertension, as well as learning and developmental problems in young children [3–7]. The European Union introduced a number of regulations to reduce the impact of aviation on surrounding communities. Vision 2020, for example, required that by 2020 the perceived noise level from aircraft must be reduced by 50% compared to standard levels in 2000. Flightpath 2050 continues on from Vision 2020, and seeks to reduce the perceived noise emissions from aircraft by 65% compared to 2000 standard levels by 2050 [8].

Approaches to reducing aircraft noise are typically split into two categories: air-frame noise reduction and engine noise reduction. The introduction of the turbofan brought a significant reduction to the noise produced by the conventional jet engines of the time. However, the turbofan also introduced a new source of noise from the compressor fan. While the overall noise profile is significantly reduced, the fan noise is predominately in the broadband, low-frequency range and produces tonal noise which is more noticeable and irritating than non-tonal noise at the same frequency [9]. At the same time, higher bypass ratios are currently being used when designing engines in order to improve fuel efficiency and reduce emissions. The increase in the size of the nacelle means that the technologies employed must be small and lightweight.

The current industry standard for nacelle liners is a perforated panel over honeycomb liner. The design is lightweight and strong due to the structural strength of the honeycomb core. This single-degree-of-freedom design acts as a quarter-wavelength resonator, a Helmholtz resonator, or a combination of both, and is limited in its ability to target the broad range of noise generated by the engine. The characteristic absorption curve of the liner is dependent on the depth of the resonator [10]. In order to achieve low-frequency attenuation, the depth of the liner must be increased. However, as the depth of the liner is increased the frequency response of the liner narrows. Combined with the growing constraints on the size of the liners, an alternative approach to engine liner development must be explored.

Acoustic metamaterials (AMMs) hold significant promise as the next generation of engine nacelle liners. Artificially designed and engineered, AMMs typically exhibit effective properties different to those expected from their physical properties. A variety of different approaches are used when designing AMMs including space coiling, lattice structures such as Kelvin cells, decorated membranes, acoustic plates and hybrid technologies. These different approaches each have a focus that allows a specific property to be obtained by manipulating the effective properties of the material. Many of these approaches have been investigated in the case of normal incidence, in which the incident acoustic wave is normal to the active surface of the metamaterial [11–15]. However, for use as a nacelle liner, the performance of the material in grazing incidence is of greater interest as the liner must not interfere with the airflow through the engine. The application of multi-degree of freedom liners and similar technologies in grazing incidence has been investigated in NASA Langley using the Grazing Flow Impedance Tube, as well as a number of other laboratories including KTH, DLR and JAXA [16–19]. However, to the author's best knowledge, testing of such technologies in an engine nacelle has yet to be published.

The current study, reports the design, optimisation and manufacture of an AMM liner which is tested in the Advanced Noise Control Fan (ANCF) rig. The ANCF rig [20] is well known to aeroacoustics researchers having been involved in many research campaigns while located in NASA Glenn. It now resides in the University of Notre Dame and continues to be used as a research and development tool. The current AMM has been 3D printed into 237 blocks of 50 mm depth (2 inch) which were inserted into the inlet casing of the ANCF rig to form an inlet sound-absorbing liner targeting low frequency (approx. 1kHz) fan noise.

III. Experimental Set-Up

The experimental approach consists of two stages. The first was conducted in the Grazing Incidence Impedance Tube (GIIT) at Trinity College Dublin in order to optimise its design using a small-scale impedance rig. The second test campaign took place in the ANCF rig at the University of Notre Dame to assess its capacity to perform as an aeroengine acoustic liner. The AMM is considered to have a low Test Readiness Level (TRL) as the 3D printed parts are made of plastic suiting the cold-flow operation of the ANCF rig. The primary objective was to evaluate the design which if successful could lead to further research into more suitable materials for aeroengines.

A. GIIT TCD

The Grazing Incidence Impedance Tube (GIIT) in Trinity College Dublin is designed for transmission loss testing in accordance with ASTM E2611-09 [21]. It is additionally capable of measuring reflection and absorption coefficients of samples mounted in normal incidence in accordance with ISO 10534-2:1998 [22].

The GIIT is designed for high SPL testing of up to 130 dB. The walls of the tube are aluminium measuring 0.015 m. The tube has an internal rectangular cross-section of 0.05 m x 0.08 m to allow for easier design and mounting of test samples. The tube measures 1.75 m from the acoustic source to the termination. The acoustic source is two loudspeakers mount opposite each other in the top and bottom walls of the tube. There are twenty-two microphone mounts in the upper wall of the tube; twenty microphone mounts are for grazing incidence tests and the final two located near the termination are for normal incidence tests. Of the twenty grazing incidence microphone mounts, sixteen are located directly above the test section and four are offset from the test section. The central sixteen microphones have a spacing of 0.03 m and the four offset microphones have a spacing of 0.12 m. The normal incidence microphone mounts are located 0.13 m and 0.05 m from the termination. In normal incidence testing, the acoustic samples are mounted in the place of the acoustic termination. The design of the GIIT including all microphone locations can be seen in Fig. 1 in the grazing incidence configuration.

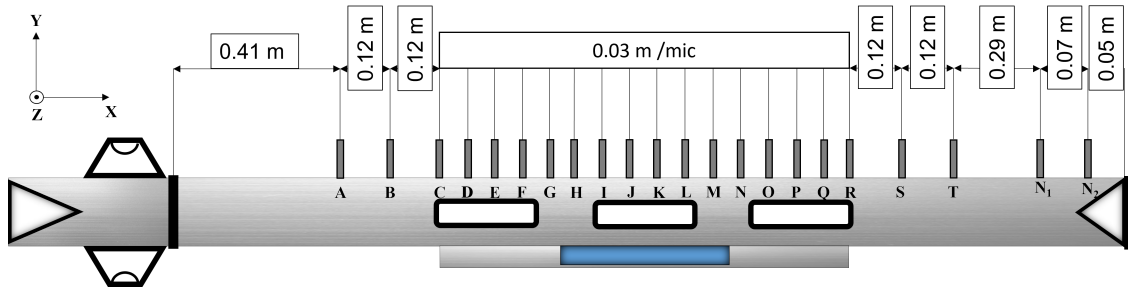


Fig. 1 Design of the GIIT in grazing acoustic incidence configuration.

In normal incidence testing, samples are installed in the place of the downstream anechoic termination as seen in Fig. 2a. Samples can have a surface area that is the same size as the cross-section of the GIIT. Samples are installed in a holder which attaches to an external flange on both side walls. An example of a sample attached to the GIIT can be seen in Fig. 2b.

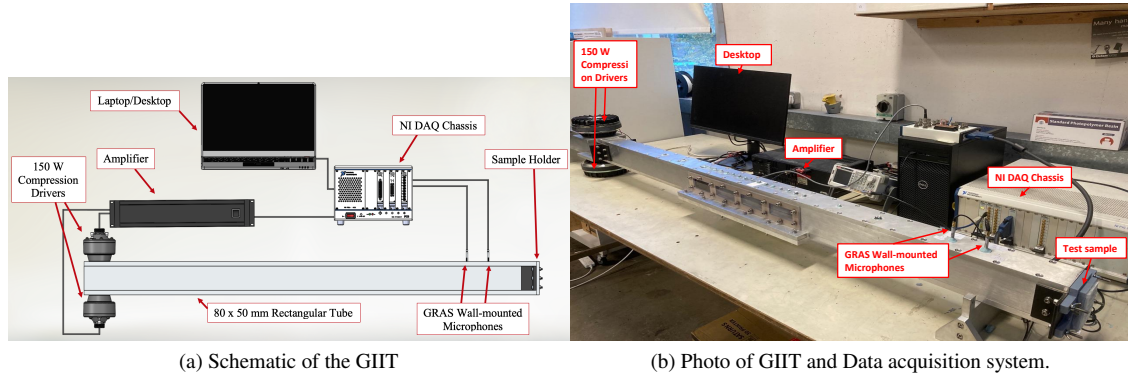


Fig. 2 GIIT set-up for normal incidence testing.

There is a 0.45 m x 0.05 m cut-out centred in the lower panel of the tube to facilitate grazing acoustic incidence testing. Samples are installed in an aluminium holder that is attached to an external flange. This external flange is part of the lower panel. The holder has an internal depth of 0.035 m, so samples with a height of 0.05 m will be flush with the internal wall when attached. If the sample installed is not 0.45 m in length, blanking inserts can be used to fill the empty space. For samples that have a depth greater than 50 mm, a spacer can be added to the upper surface of the sample holder. A solid aluminium insert is also available, which can be installed to facilitate calibration and hardwall

testing. Additionally, poly-carbonate windows are present in both side walls along the length of the test section to allow PIV measurements to be performed. The windows are separated into four sections, separated by aluminium columns.

The loudspeakers which function as the acoustic source are two BMS 4591 2" compression drivers. The frequency range of the drivers is between 200 Hz and 9 kHz. The loudspeakers are mounted vertically opposite each other in the upper and lower panels of the GIIT. The loudspeakers are connected to an external amplifier which can be fed input from a signal generator or through the data acquisition system. The anechoic terminations at both the upstream and downstream locations are made from Basotect G+ melamine resin foam. The foam is cut into a wedge to target a wide range of frequencies.

The microphones used in the measurements were G.R.A.S 40PH microphones. The 40PH has a flat frequency response from 20 Hz to 20 kHz, in excess of the frequency range of the acoustic drivers and the GIIT.

1. Reflection and Absorption Coefficients

In normal incidence, the reflection coefficient is determined using the transfer function method as outlined in British Standards ISO 10534-2:1998 [22]. The sound pressure at the two microphones locations N_1 and N_2 are recorded as p_1 and p_2 respectively. The transfer function, H_{12} , can be expressed as the ratio between these two pressures. As these pressures are composed of the incident and reflected waves, the transfer function can be written in terms of the reflection coefficient using the wave's exponential form

$$H_{12} = \frac{e^{jkx_2} - re^{-jkx_2}}{e^{jkx_1} - re^{-jkx_1}} \quad (1)$$

where x_1 is the spacing between N_1 and the sample location, x_2 is the spacing between N_2 and the sample location, and r is the reflection coefficient. It is possible to rewrite Eq. 1 to give the reflection coefficient in terms of the transfer function

$$r = \frac{H_{12}e^{jkx_1} - e^{jkx_2}}{e^{-jkx_2} - H_{12}e^{-jkx_1}} \quad (2)$$

In normal incidence testing, the component of the wave that is not reflected must be absorbed by the material. The absorption coefficient is therefore determined by

$$\alpha = 1 - abs(r)^2 \quad (3)$$

where α is the absorption coefficient. Similarly, the normal surface impedance of the material may be expressed in terms of the reflection coefficient:

$$Z = \frac{1 + r}{1 - r} \quad (4)$$

2. Transmission Loss

The transmission coefficient τ of a material is the ratio of the incident sound pressure to the transmitted sound pressure on the opposite end of the acoustic sample. This requires four measurement points to be used, two upstream of the sample and two downstream. Additionally, the measurement as outlined in ASTM E2611-09 [21] requires the wave to be measured with two termination conditions; anechoic and non-anechoic.

Four acoustic waves are recorded to determine the transmission coefficient: (A) the incident wave, (B) the reflected wave, (C) the transmitted wave and (D) the reflected transmitted wave. These four waves can be seen in Fig. 3. As the measurement is performed twice, there are two sets of each of these four waves. The waves measured in the anechoic configuration are denoted with the subscript o and the waves in the non-anechoic configuration are denoted with the subscript h . The transmission coefficient is given by

$$\tau = \frac{A_o D_h - A_h D_o}{C_o D_h - C_h D_o} \quad (5)$$

where each of A, C, and D refer to the transfer function for each wave of the same label. Using the transmission coefficient, it is possible to determine the transmission loss

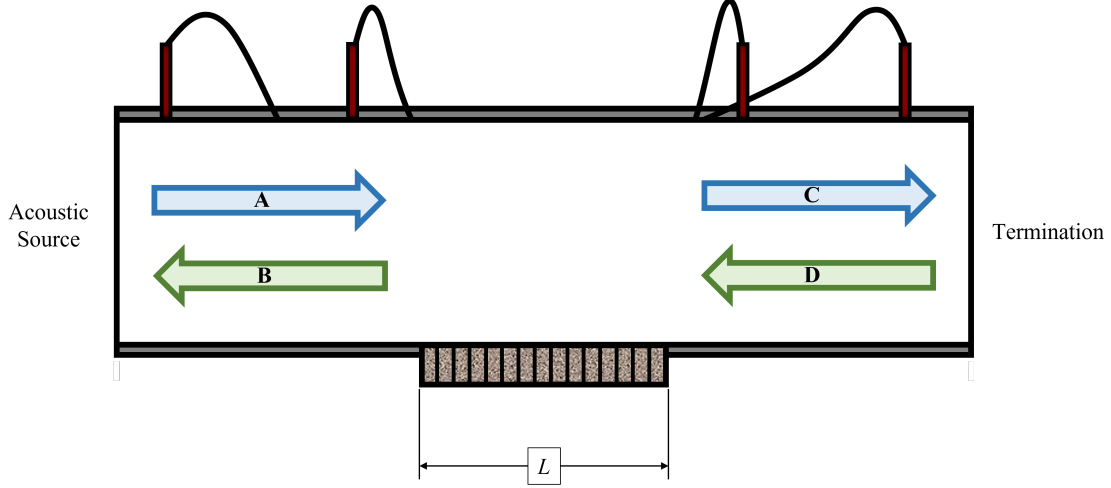


Fig. 3 The transmission coefficient is determined using the four waves superimposed upstream and downstream of the acoustic sample as shown.

$$TL = -20 \log_{10} \left(\frac{1}{\tau} \right) \quad (6)$$

in which TL is the transmission loss, given in decibels.

B. ANCF

The Advanced Noise Control Fan (ANCF) was designed in the early 1990s, envisaged as a testbed for fan noise reduction technologies. It was designed to be a low-cost, low-technical readiness-level experimental rig. In addition to its role in aiding the development of fan noise reduction technologies, it has also served to further the understanding of aeroacoustic physics and code validation. In the over 20 years of its lifetime, the ANCF has been upgraded a number of times and most recently relocated from NASA Glenn Research Center to the Turbomachinery Laboratory at the University of Notre Dame [20].

The ANCF is a duct fan which has a 4-foot internal diameter. The duct is highly configurable with ring sections which are capable of being moved to obtain the desired duct geometry or have hardwall sections replaced with liner sections for testing. These sections can be seen in Fig. 4. The nominal operational speed of the ANCF is 1800 RPM, with a range of 100 RPM to 2400 RPM. At the nominal operating speed, the fan tip speed is approximately 115 ms^{-1} , the inlet Mach number is approximately 0.15, and the fundamental blade passing frequency (BPF) is approximately 500 Hz. The ANCF rotor has 16 blades with a nominal pitch angle of 28° , though it can additionally be set to 18° or 38° . It is possible to run the ANCF in a rotor-only configuration, or with a stator stage attached downstream of the rotor. The stator count is variable and they are capable of being set to any angle. An inlet control device is installed at the front of the ANCF, which is used during static ground tests in order to condition the airflow into the duct. The ICD conditions the airflow by breaking up vortices and reducing the turbulent flow which would otherwise become an additional noise source in the duct. The ICD is a layer of honeycomb sandwiched between two layers of fine mesh, installed in 22 longitudinal sections [20].

1. Farfield Acoustic Measurements

Since the transfer to the University of Notre Dame, ANCF testing has been conducted outdoors at the White Field Facility [23]. The data acquisition is performed by an array of ground-based microphones. This array typically consists of 30 microphones, split into a fore array and an aft array each containing 15 microphones. However, the primary focus of this study is the ability of the inlet liner to reduce the upstream propagating fan noise so a single fore array of all 30 microphones is used. The microphones are set up at a radius of 20 feet from the ANCF. The microphones have a 3.2° spacing, spanning from the centre line of the ANCF at 0° to just past the inlet at 93.2° . The setup can be observed in Fig. 5

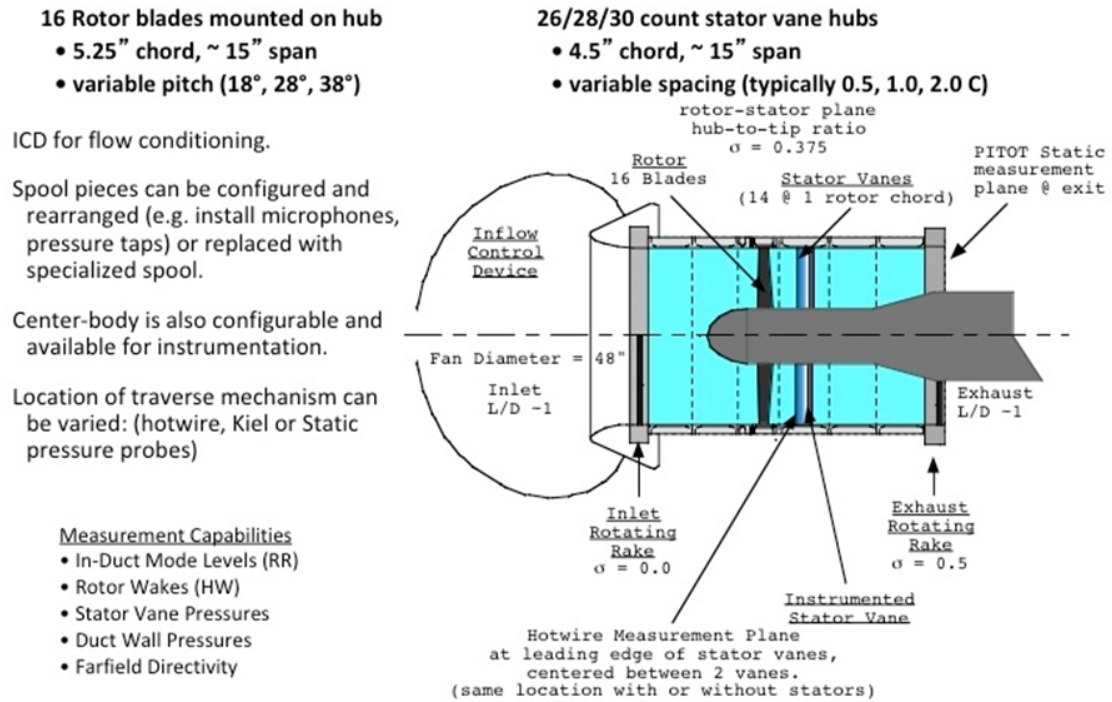


Fig. 4 Schematic of the ANCF [20]



Fig. 5 ANCF setup at the White Field facility in the University of Notre Dame

The angle of separation between the microphones is the polar angle. As the outdoor test setup uses ground microphones for the data acquisition, the microphones are not in the same plane as the ANCF. To address this, the azimuthal angle is used for any calculations relating to the directivity of the noise and the power level calculations [23]. The azimuthal angle can be found using

$$\phi = \cos^{-1} \left(\frac{R * \cos(\theta)}{\sqrt{R^2 + H^2}} \right) \quad (7)$$

in which ϕ is the azimuthal angle, θ is the polar angle, R is the radial distance from the ANCF to the microphone and H is the height of the ANCF centre line from the ground.

Data acquisition is performed using an HMB GEN2i Data Recorder which records the time series data from the 30-microphone array and the shaft rotation of the ANCF. The time histories are processed using ensemble averaging. An example of the time history can be seen in Fig. 6a. Ensemble averaging allows the tonal and broadband components to be analysed separately by extracting the tones that are generated by the fan. The data is further analysed in terms of the frequency bands centred on the fan tones and harmonics. The 1st harmonic band is defined as the integration about the 1st fan tone, which occurs between 0.5B and 1.5B where B is the number of blades. As can be seen in Fig. 6b, the 1st harmonic band is centred on 16 shaft orders and the integration is performed from 8 to 24 shaft orders. The 2nd harmonic band occurs between 1.5B and 2.5B corresponding to 24 to 40 shaft orders, with each subsequent harmonic band following the same principle to determine its band. This approach is used to analyse the overall, or original, time histories and the extracted broadband series. Using this, the fan harmonic data can be isolated from the overall time history spectra. The data can be converted into the acoustic Power Level (PWL) by squaring the pressure and multiplying by the appropriate area, and then normalising by the specific acoustic impedance. The area is determined using the corrected azimuthal angle given in Eq. (7). This can be used to obtain the farfield acoustic data in terms of the overall, broadband and tonal power components [24].

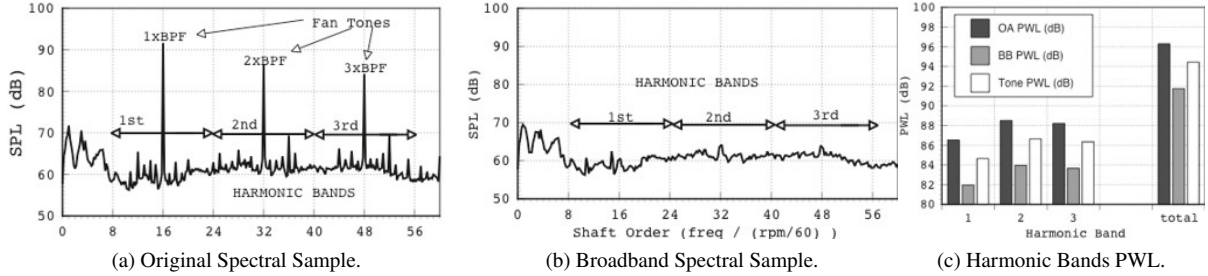


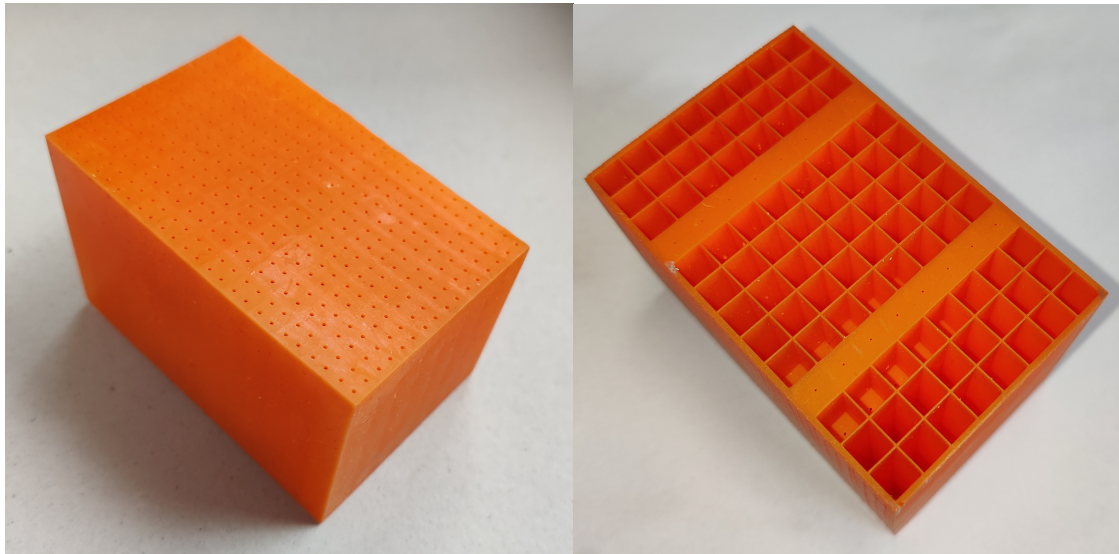
Fig. 6 Example of the Farfield data reduction into broadband and harmonic bands [24].

IV. Liner Design Concept

The material being investigated is a multi-degree-of-freedom acoustic metamaterial manufactured using additive manufacturing. The design is a modification of the traditional perforated panel over honeycomb liner, which is a conventional acoustic treatment for aircraft engine nacelles.

The initial premise for this design was proposed by Tang et al. [25]. In their initial paper, the concept of a "honeycomb core" structure with two perforated layers was introduced; the first perforated layer is a facesheet and the second perforated layer is a perforated septum which divides the core structure at various heights. The honeycomb core used has a square cross-section, so will be referred to as the core structure in this study. An example of the liner can be seen in Fig. 7 from two viewpoints.

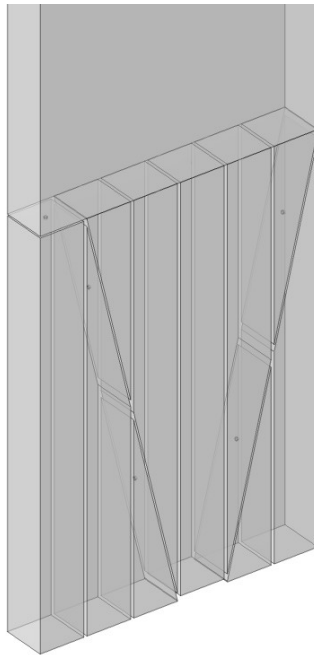
Two methods of incorporating the septum were investigated in this study. Both approaches have a periodic design which repeats every six cells. The first is a diagonal septum as seen in Fig. 8a. The second method has a horizontal septum as seen in Fig. 8b. In both models, the general structure is the same. The first cell has a perforated septum at the top of the cell, and the fourth cell has a septum at the bottom of the cell. While the diagonal and horizontal septa divide the remaining cells differently, the height of the perforation in the septum is the same. In the second and sixth cells, the perforation is at 3/4 the height of the cell; in the third and fifth cells, the perforation is at 1/4 the height of the cell.



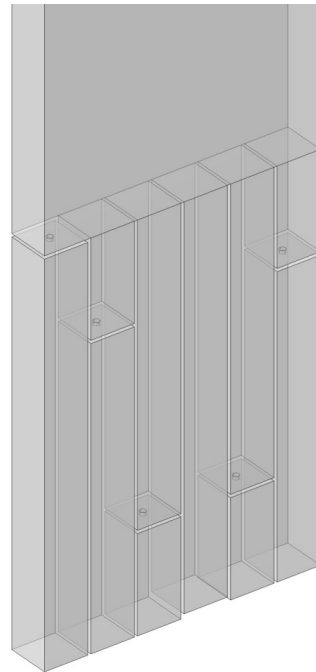
(a) Top view of the liner.

(b) Bottom view of the liner.

Fig. 7 Photo of the design of the proposed liner as viewed from (a) the top of the liner and (b) the bottom of the liner.



(a) Design featuring a diagonal septum.



(b) Design featuring a horizontal septum.

Fig. 8 Design concept for the liner options investigated.

As the material being investigated in this work is produced using additive manufacturing a number of design limitations introduced by the traditional manufacturing methods do not apply. The use of the corrugated layer to divide the honeycomb core is not necessary as the additive manufacturing process allows horizontal septums to be used instead.

The design of the liner is optimised to increase the sound reduction capabilities in the 200 Hz to 2000 kHz frequency range, the frequency limits of the GIIT used in this process. To achieve this, a multi-stage optimisation procedure is used. The optimised liner is called the T-liner, or Trinity Liner. Seen in Fig. 9, the first stage of the T-Liner optimisation is a numerical parameterisation of the liner core. The numerical parameterisation includes an investigation into the performance of both a diagonal and horizontal septum. A prototype of the optimal core geometry determined by the parameterisation is printed and the impedance of the liner core is measured experimentally in normal incidence in the GIIT. The experimental value of the impedance is used in a semi-analytical optimisation routine to determine the optimal faceplate for the liner core. The optimised core and faceplate are manufactured as a single component. This performance of the T-Liner prototype is measured in normal and grazing incidence in the GIIT before accepting the design.

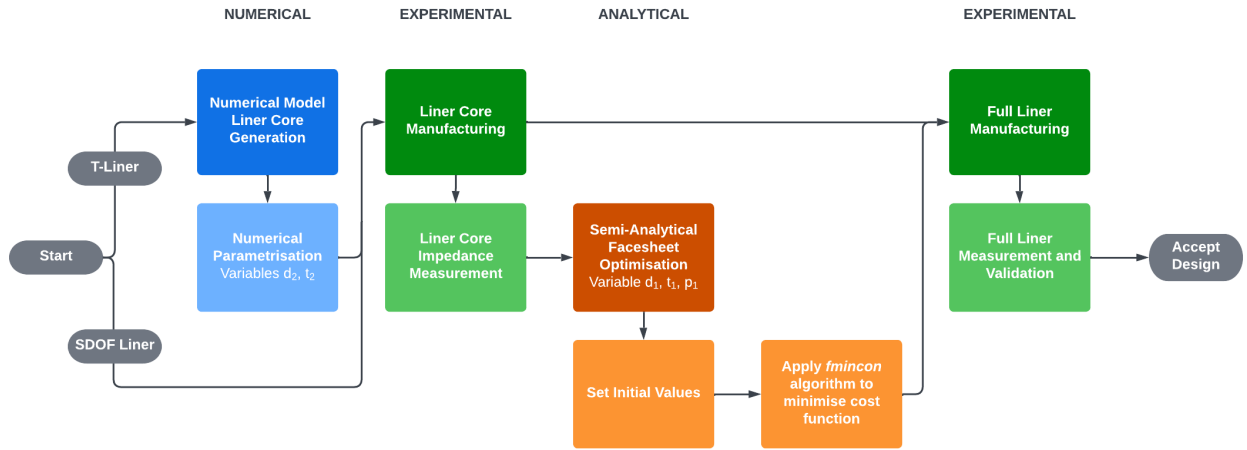


Fig. 9 Multi-stage optimisation process used to optimise the liner geometry.

A similar multi-stage optimisation procedure is used to optimise a single-degree-of-freedom (SDOF) liner which is used as a baseline comparison for the performance of the T-Liner. As can be seen in Fig. 9, the numerical parameterisation is not used to optimise the SDOF liner, as the height of the sample is fixed.

V. Numerical Simulation

A FEM numerical analysis of the experimental work conducted using the GIIT was implemented in the frequency domain. The simulations were performed using COMSOL Multiphysics® version 6.0 with the Acoustics module.

A. FEM Model

Due to the lack of axial symmetry in the material design, it was not possible to use a 2D axisymmetric representation of the model. Instead, a full 3D model was required, as can be seen in Fig. 8. The full 3D model has higher computational costs but accurately replicates the experimental setup. Preliminary work and investigations in normal incidence were conducted using a single unit cell. The single-unit cell is a one-by-six array of ducts.

Meshing

The meshing is performed with a user-controlled mesh. For acoustic meshing within COMSOL it is recommended to have at least 6 to 8 mesh elements per wavelength, so the maximum element size is set at $1/8^{th}$ of the smallest acoustic wavelength of interest, λ_0 . The minimum element size is set at $1/3^{rd}$ of the viscous boundary layer thickness,

$$d_{visc} = 220\mu m * \sqrt{\frac{100Hz}{f_0}}.$$

The model is meshed with a combination of swept mesh elements in duct sections, boundary layer meshing in the

microperforated holes, and free tetrahedral mesh elements in the duct region directly above the sample. The swept mesh extrudes the surface mesh of a boundary through the domain. If a domain has different, complex geometries at either end of a domain or a non-planar boundary a swept mesh cannot be used. When a swept mesh is required for a domain with incompatible end boundaries, a domain partition is used to create a transition zone. An example of this can be seen in Fig. 10a. By partitioning the domain, the larger section can be meshed using a swept mesh first. A free tetrahedral mesh can then be used in the smaller domain which has two different end boundaries. The boundary layer meshing used in the perforations can be seen in Fig. 10b.

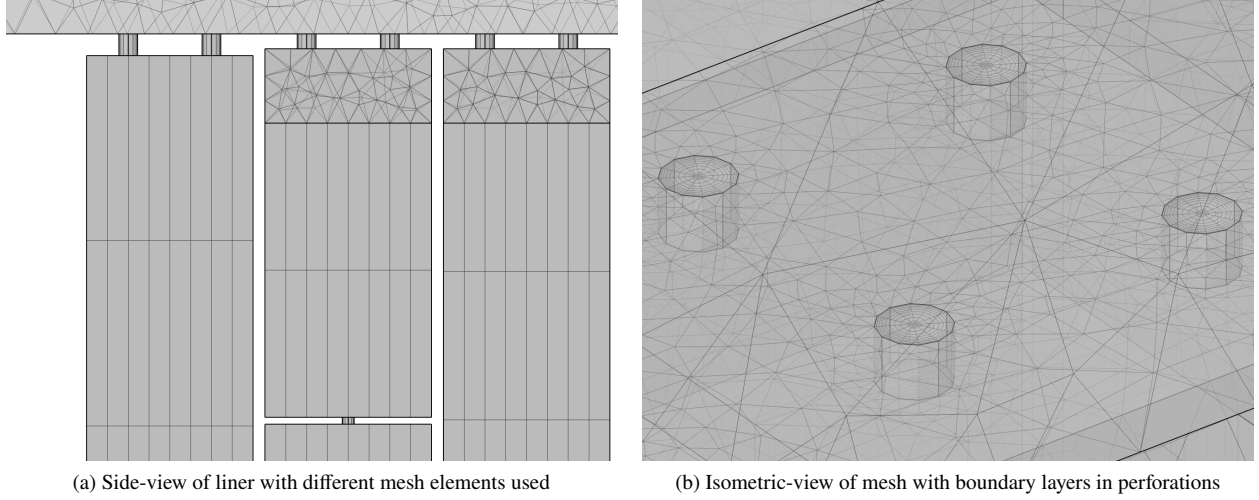


Fig. 10 Different mesh element types are used to mesh the different domains of the acoustic sample. In (a) the side view shows the different types of mesh elements that are used in the different geometric features, while (b) shows the boundary layers used to model the thermoviscous losses within the micro-perforation.

B. Governing Equations

The numerical simulations were performed using the pressure acoustic module and the thermoviscous acoustics module to simulate boundary layer loss in the small micro-perforated holes. The pressure acoustics physics and thermoviscous physics are coupled using the acoustic-thermoviscous boundary interface.

The pressure acoustics module makes the assumption that the system is lossless and isentropic. These assumptions are valid in a number of applications, including the propagation of the wave in a duct or in large volumes. The governing equation in the pressure acoustics interface is formulated using the inhomogeneous Helmholtz equation:

$$\nabla \cdot \left(-\frac{1}{\rho_c} (\nabla p_t - \mathbf{q}_d) \right) - \frac{k_{eq}^2 p_t}{\rho_c} = Q_m \quad (8)$$

where p_t is the total pressure field and is the sum of the background pressure and the scattered pressure fields; k_{eq} is the wavenumber containing the ordinary wavenumber and the out-of-plane contributions; $\mathbf{q}_d$ is the dipole domain source and Q_m is the monopole domain source.

While the pressure acoustics assumptions that the system is lossless and isentropic hold valid for the impedance tube in which the acoustic wave propagates, the same assumption is not valid in the smaller ducts of the material. This is due to the much smaller volume relative to the surface area of these ducts. The cell ducts are much larger than the boundary layer and to model them entirely using thermoviscous acoustics is computationally expensive. This is particularly of concern during parameterisation studies, where many iterations of the model must be computed. Instead, the Narrow Region Acoustics feature in the Pressure Acoustics Module is used in these regions. The Narrow Region Acoustics adds the losses that are associated with the boundary layer effects in a homogenised way. These losses are solved analytically and applied to the bulk behaviour of the fluid. To perform this accurately, a number of assumptions are applied. The geometry of the cross-section of the duct must be defined. Additionally, the acoustic wavelength must be much larger than the cross-section and the boundary layer thickness. These assumptions hold true for this duct which

has a cross-section of 5.6 mm x 5.6 mm and a boundary layer thickness of 0.22 mm at 100 Hz. The acoustic wavelength is 3.43 m at 100 Hz and decreases to 0.172 m at 2000 Hz.

In the small regions of the micro-perforations in the facesheet and the duct septum, the pressure acoustics assumptions are not accurate. The thermoviscous physics module is used to model the losses in these regions. Thermoviscous modelling assumes small harmonic oscillations in the steady background properties. To study the behaviour of these small oscillations, the variables of interest are;

$$p = p_0 + p' e^{i\omega t}, \mathbf{u} = \mathbf{u}_0 + \mathbf{u}' e^{i\omega t}, T = T_0 + T' e^{i\omega t} \quad (9)$$

in which p is the pressure, $\mathbf{u}$ is the velocity, T is the temperature, and ω is the angular frequency. In each instance, the background mean flow of the variable is represented by the subscript 0, and the acoustic variable is represented by the primed variable. Thermoviscous acoustics assumes that the background fluid is quiescent, meaning $\mathbf{u}_0 = 0$. The background values of the pressure and the temperature have to be specified, either by definition in the module set-up or as functions of the model.

The governing equations used in the thermoviscous module in the frequency domain are the linearised Navier-Stokes equations:

$$i\omega\rho = -\rho_0 (\nabla \cdot \mathbf{u}) \quad (10)$$

$$i\omega\rho_0\mathbf{u} = \nabla \cdot \left(-p\mathbf{I} + \mu (\nabla\mathbf{u} + (\nabla\mathbf{u})^T) + \left(\mu_B - \frac{2}{3}\mu \right) (\nabla \cdot \mathbf{u}) \mathbf{I} \right) \quad (11)$$

$$i\omega (\rho_0 C_p T - T_0 \alpha_0 p) = -\nabla \cdot (-k \nabla T) + Q \quad (12)$$

$$\rho = \rho_0 (\beta_T p - \alpha_0 T) \quad (13)$$

C. Estimation of the Absorption Coefficient

To calculate the reflection and absorption coefficients in COMSOL, a frequency domain study is applied to the model. The frequency range used in the study was between 200 Hz and 2 kHz to match the frequency range of the GIIT, and a step size of 5 Hz was used for the study. The incident acoustic impedance can be given as:

$$Z_{in} = \frac{\langle p_t \rangle}{\langle -v_z \rangle} \quad (14)$$

where $\langle p_t \rangle$ is the averaged total pressure at the radiation plane and $\langle v_z \rangle$ is the averaged velocity in the vertical direction. The total impedance of the system can thus be obtained using the impedance translation theorem [26] using:

$$Z_{trans} = z_0 \left(\frac{Z_{in} - iz_0 \tan(k_0 x_1)}{-iZ_{in} \tan(k_0 x_1)} \right) \quad (15)$$

where k_0 is the wavenumber, x_1 is the height of the material, and $z_0 = \rho_0 c_0$ is the specific acoustic impedance of air. From the transfer impedance of the material, it is possible to calculate the reflection coefficient

$$r = \left(\frac{Z_{trans} - z_0}{Z_{trans} + z_0} \right) \quad (16)$$

and with the reflection coefficient, it is possible to calculate the absorption coefficient using Eq. 3

VI. 3D Printed Liner Design Optimisation

As seen in Fig. 9, the design optimisation began with a numerical parameterisation to optimise the core structure of the material. The parameterisation focuses on the thickness of the septum and the diameter of the septum perforations, and the difference in performance when a diagonal or horizontal septum is used. A prototype of the liner core identified by the parameterisation was then manufactured and tested in normal incidence in the GIIT to measure the experimental impedance of the liner. The impedance was then used as an input to a semi-analytical optimisation routine to optimise the facesheet for the designed liner core. This T-Liner prototype was printed and tested, first in normal incidence and subsequently, a larger model was produced for grazing incidence testing. The final stage of the design process was the adaptation of the material for the geometry of the liner casings used in the ANCF testing.

A. Liner Core Parameterisation

The initial geometry in the parameterisation study was based on one of the designs investigated by Tang et al. [25] as it would allow verification that the model is valid. The initial parameterisation fixed the width of the honeycomb walls, the width of the honeycomb ducts and the height of the core. These values can be found in Table 1 and the geometry can be seen in Fig. 11. As previously mentioned, the design was studied using both a diagonal septum and a horizontal septum. The heights of the horizontal septums were chosen to ensure the centre point of the perforations would be in the same location for both geometries. In the second and sixth cells, this is at $3/4$ the total height of the part and in the third and fifth cells, this is at $1/4$ the total height.

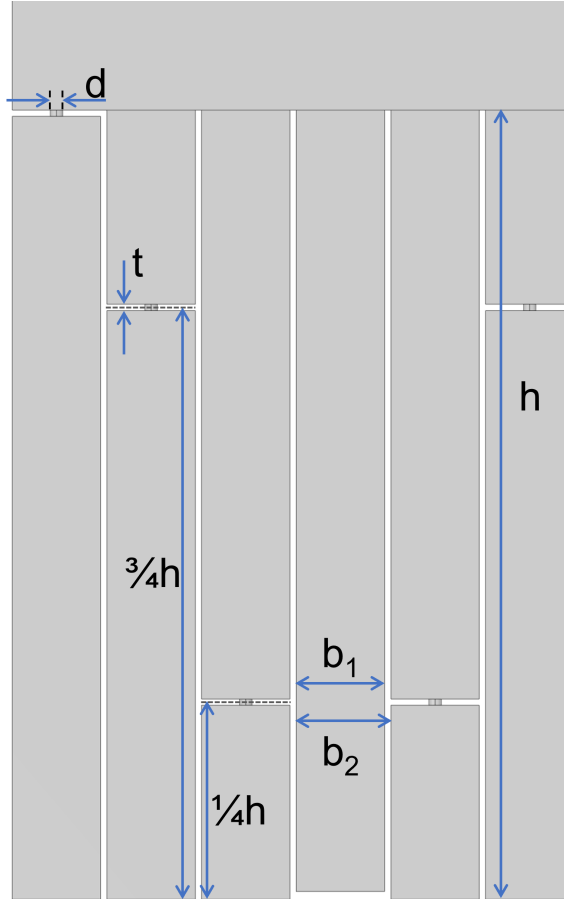


Fig. 11 Mid-plane section view of the geometry and parameters of the initial material design used in the parameterisation.

Table 1 Fixed parameters of the liner core geometry

Cell Width (mm)	Wall Thickness (mm)	Total Height of Core (mm)
b_1	$b_2 - b_1$	h
5.6	0.4	50

The parameterisation study determined the ideal value of the thickness of the septum in the ducts, t , and the diameter of the perforations in the, d . The parameter ranges for the values of the septum thickness and perforation diameter used in the parametric sweep are given in Table 2; the same parameters were used for both the horizontal septum configuration and the diagonal septum configuration. The liner core configuration with the highest mean absorption was

the horizontal septum configuration with a septum thickness of $t = 0.2$ mm and a perforation diameter of $d = 0.4$ mm. The mean absorption of this liner core is $\bar{\alpha} = 0.53$ in the 200 Hz - 2kHz frequency range.

Table 2 Ranges for the parametric sweep

	Septum Thickness, t (mm)	Perforation Diameter, d (mm)
Minimum	0.2	0.2
Maximum	0.4	0.8
Step size	0.025	0.02

B. Facesheet Optimisation

A prototype of the liner core was produced using the design parameters identified in the parametric study. The impedance of this liner core was experimentally measured using the GIIT and used in a semi-analytical optimisation routine. The semi-analytical optimisation is based on the analytical solution of a micro-perforated panel (MPP) as described by Maa [27] and uses the experimentally measured impedance of the cavity or core structure as an input for the reactance. The acoustic impedance of the liner is given by:

$$Z = Z_{MPP} + Z_C \quad (17)$$

in which Z_{MPP} is the acoustic impedance of the microperforated plate, Z_C is the acoustic impedance of the liner core. The acoustic impedance of a microperforated plate is given by:

$$Z_{MPP} = -Z_0 \left(\frac{i\omega_0}{c_0\phi} \frac{J_0\left(\frac{d}{2}\sqrt{\frac{-i\omega_0}{\nu_0}}\right)}{J_2\left(\frac{d}{2}\sqrt{\frac{-i\omega_0}{\nu_0}}\right)} [t + 0.85d \cdot \Psi(\phi)] \right) \quad (18)$$

where ϕ is the porosity of the microperforated plate, J_0 and J_1 are the 0^{th} and 1^{st} order Bessel functions, ν_0 is the kinematic viscosity of air. The values t and d are the plate thickness and perforation diameter respectively [28]. Finally, $\Psi(\phi)$ is the Fok function which is used to determine the hole-to-hole interactions [29] and is given by

$$\Psi(\phi) = \sum_{n=0}^a a_n \left(\sqrt{\phi}\right)^n \quad (19)$$

where the first nine coefficient a_n that are used in this study are given in McKay et al. [28].

This semi-analytical solution was used to determine the ideal thickness, perforation diameter and number of perforations in the facesheet. Due to the design of the liner core, a fixed number of holes per duct was used as opposed to having the total number of holes be unconstrained. Three values for the number of perforations were used; 104 (1 hole per cell), 416 (4 holes per cell), and 936 (9 holes per cell). The remaining options used in the optimisation are given in Table 3.

Table 3 Ranges for the analytical optimisation

	Facesheet Thickness (mm)	Perforation Diameter (mm)
Minimum	0.2	0.3
Maximum	0.9	1.0

The final design for the facesheet had a thickness $T_2 = 0.5$ mm, a perforation diameter $D = 0.63$ mm and 416 perforations in the facesheet. This configuration for the optimised faceplate and liner core had a mean absorption $\bar{\alpha} = 0.72$. The final design configuration can be seen in Fig. 12 and the parameters are summarised in Table 4.

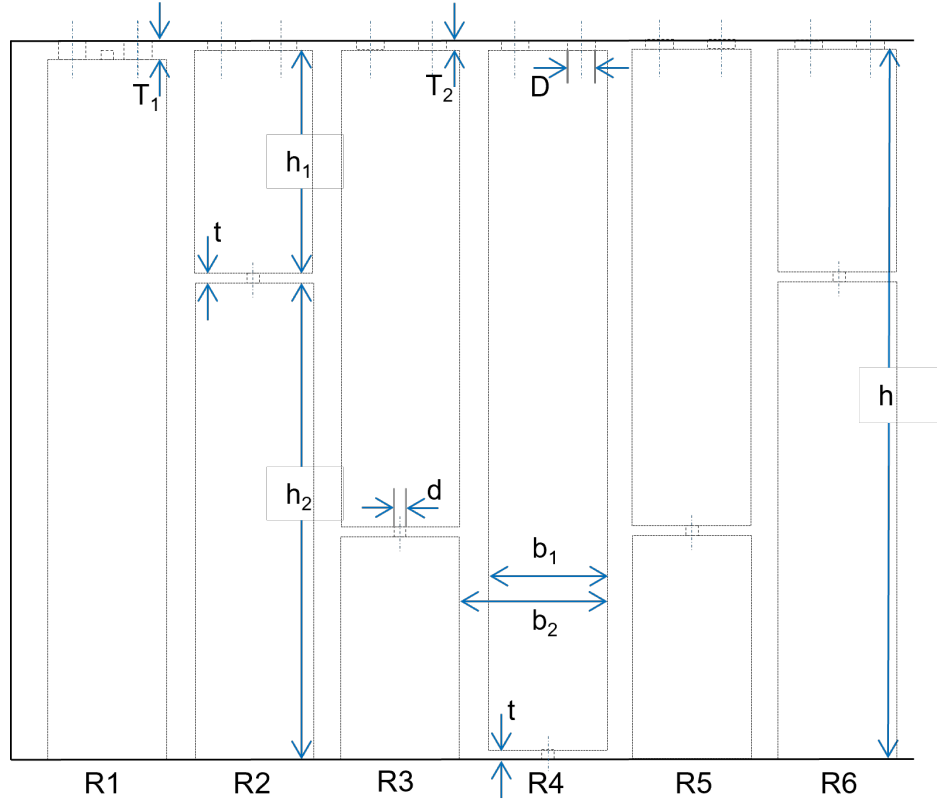


Fig. 12 Geometry of the final material design with a horizontal septum.

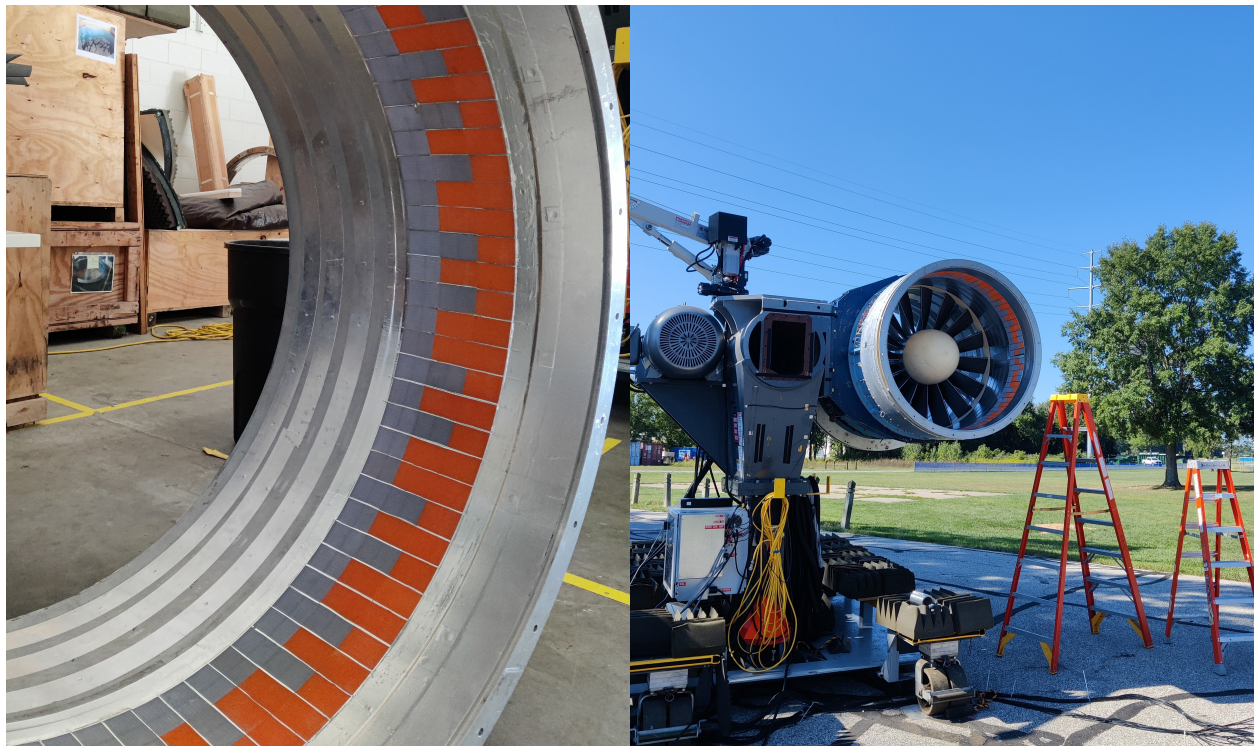
Table 4 Final parameters

Parameter		Value (mm)
Total height	h	50
Upper duct height	$h_{1,R2}$	12.35
Lower duct height	$h_{2,R2}$	37.25
Duct internal width	b_1	5.6
Duct total width	b_2	6
Facesheet thickness	T_2	0.5
Septum thickness	t	0.2
Facesheet perforation diameter	D	0.63
Facesheet perforation count	$\#N$	416
Septum perforation diameter	d	0.4

C. ANCF Adaptation

Acoustic samples were installed in a liner casing for testing on the ANCF which can be seen in Fig. 13. The casing has a rectangular cross-section in the circumferential direction with a length of 228.6 mm and a depth of 57.15 mm. The depth of the acoustic material was kept at 50.5 mm to keep the expected frequency response consistent with the testing conducted using GIIT. The remaining depth in the casing was filled using carpet padding between the casing wall and the base of the material.

The final liner design consisted of 6 full unit cells and one repetition of the R1 cell seen in Fig. 11. The additional R1 cell was included to make the design symmetric in the axial direction. To ensure reliable printing of the T-Liner, it was divided into three components or parts. The first and third parts are mirror images of each other and contained two full-unit cells. The second part contained two full unit cells plus the single R1 cell. The wall thickness at the contact between the components was 0.8 mm in total, double the wall thickness used within a unit cell. It was necessary to increase the thickness of the wall at this point as thinner walls did not print reliably. A buffer spacing of 2.9 mm was added to both the front and end of the design to make the total length 228.6 mm.



(a) T-Liner installed in the ANCF liner casing.

(b) T-Liner installed in ANCF at the White Field test facility.

Fig. 13 Photos of the 3D printed T-Liner used in ANCF testing.

Additionally, the width of the part was modified to account for the curvature of the casing. The curvature of the faceplate matches that of the ANCF inner wall, which has a diameter of 4 ft. This can be seen in Fig. 14. The width at the top of the cell was kept constant and the width at the base increased. Each part would contain eight columns of rows and the part would span 4.556° . This would be approximately 50 mm measured at the top of the part and takes into account the approximate expansion of the printed parts. 79 parts are required in the circumferential direction to fill the casing.

In total, 237 parts were required to fill the casing. Each part was printed at a rate of $80 \text{ cm}^3 \text{hr}^{-1}$ and took approximately 480 hours to manufacture the total amount.

D. Manufacturing

All printers used in this work were masked stereolithography (mSLA) printers. Stereolithography is a form of additive manufacturing often used for fast prototyping, particularly when the prototype involves small features. It uses a

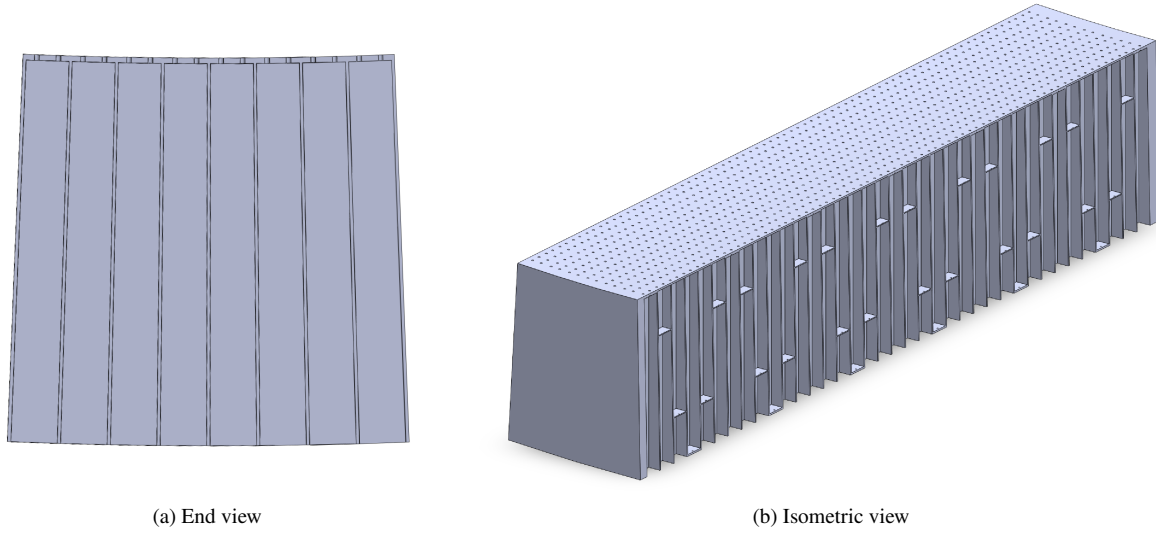


Fig. 14 Final design of T-Liner accounting for ANCF curvature.

liquid resin photo-polymer that can be cured when exposed to UV light. The cured resin forms very thin solid layers which stack to form the object. Stereolithography is often used in prototyping as it is able to achieve high levels of precision and accuracy.

Masked stereolithography uses a LED and LCD photomask to produce the pattern for each layer. The LED array is located below the LCD photomask display. The entire LED array illuminates for every layer but the LCD photomask deactivates individual pixels to produce the pattern for each layer which allows the LED light to pass through [30]. As the mSLA light source is an array, the power passed through each pixel of the LCD photomask is the same resulting in a more uniform build quality.

The prototype manufacturing during the design optimisation was completed using a Prusa SL1S. The final manufacturing was completed using 6 printers: one Prusa SL1S, two Prusa SL1s, one Elegoo Mars 3 and two Elegoo Saturn Ss. All four models are mSLA printers.

The Prusa SL1S is the newer, speed variant of the Prusa SL1. The SL1S has a 5.96" LCD screen which has a $49 \mu\text{m}$ xy resolution. The SL1 has a 5.5" LCD screen which has a $47 \mu\text{m}$ xy resolution. Both printers can printer layers with a height of 0.025 mm up to a layer height of 0.1 mm. The Elegoo Saturn S has a 9.1" LCD screen with a $48 \mu\text{m}$ xy resolution. It can print at layer heights from 0.01 mm up to 0.15 mm, and has a z-axis resolution of $1.25 \mu\text{m}$. The Elegoo Mars 3 has a 6.6" LCD screen with a $35 \mu\text{m}$ xy resolution. It can print at layer heights from 0.01 mm up to 0.2 mm, and has a z-axis resolution of $1.25 \mu\text{m}$.

VII. Results

A. Normal Incidence

The performance of the final metamaterial design is presented in Fig. 15, which shows the absorption coefficient of the semi-analytical, experimental, and numerical data. The experimental absorption coefficient of the SDOF liner is also included as a point of comparison for the T-Liner's performance. The experimental SDOF liner absorption coefficient is shown as the solid red line; the experimental T-Liner absorption coefficient is shown as the solid light blue line; the semi-analytical prediction of the T-Liner absorption coefficient is shown as the broken (dash-dot) black line; and the numerical prediction of the T-Liner absorption coefficient is shown as the dotted green line. The absorption coefficient, α is on the vertical axis and the frequency in hertz, Hz, is on the horizontal axis. Across the frequency range, the mean absorption coefficient of the T-Liner experimental results is $\bar{\alpha} = 0.74$; the mean absorption coefficient of the semi-analytical results is $\bar{\alpha} = 0.72$; and the mean absorption coefficient of the numerical results is $\bar{\alpha} = 0.72$. The mean absorption coefficient of the SDOF Liner experimental results is $\bar{\alpha} = 0.51$. For all three sets of results of the

T-Liner, the absorption coefficient is greater than 0.8 between 800 Hz and 1.8 Hz. There is good agreement for all three results between 800 Hz and 1200 Hz, and again around the 1600 Hz peak. The semi-analytical and experimental results show more similarities in their behaviour below 800 Hz than with the numerical results, however, it is the numerical and semi-analytical results which are in closer agreement between 1200 Hz and 1600 Hz. In this frequency range, the numerical and semi-analytical show a drop in the absorption coefficient to 0.8 and 0.84 respectively. Meanwhile, the experimental absorption coefficient remains above 0.92 in this range with a peak absorption coefficient of 0.98 at 1465 Hz.

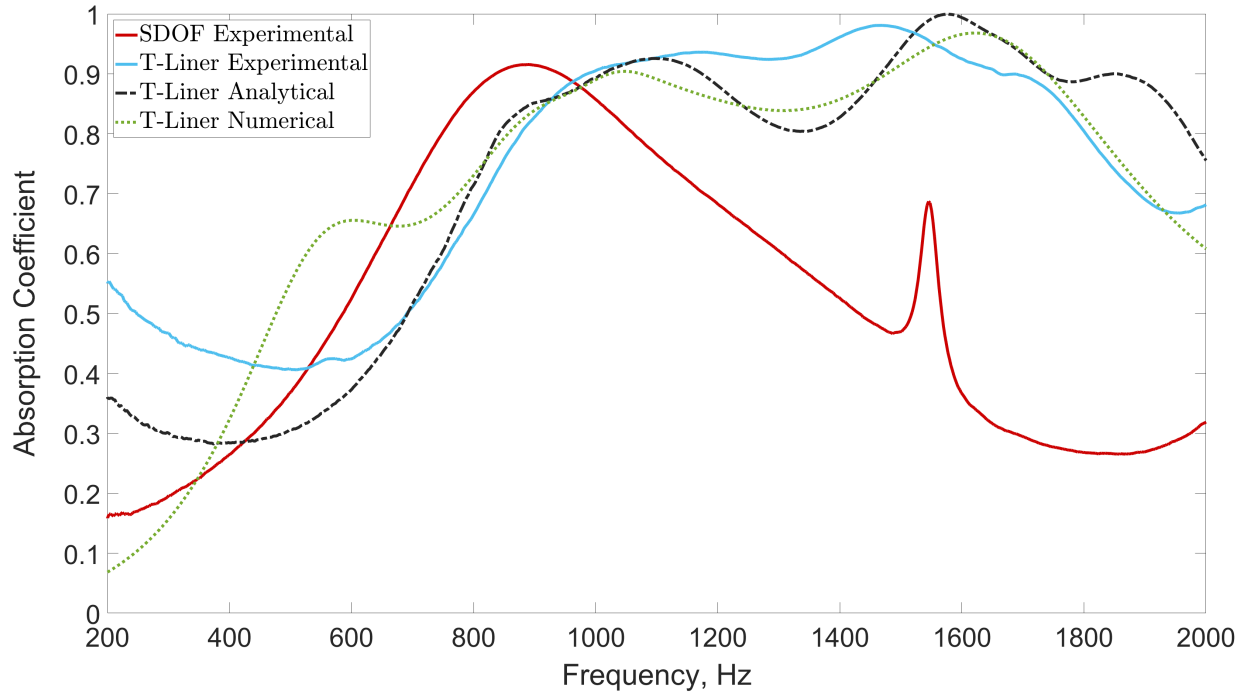


Fig. 15 Comparison of the experimentally measured absorption coefficient of the SDOF liner and T-Liner. The numerical and semi-analytical absorption coefficient of the T-Liner are also included.

B. Grazing Incidence

Figure 16 shows the comparison of the experimentally measured transmission loss of the SDOF liner and the T-Liner. The SDOF liner is shown as the solid red line; the T-Liner is the solid light blue line; and the hardwall measurement, which is the baseline transmission loss of the GIIT, is shown as the broken black line. The transmission loss in decibels is on the vertical axis and the frequency in hertz is given on the horizontal axis. The SDOF liner experimental measurement has a transmission loss peak of 6.5 dB at 640 Hz. The T-Liner experimental measurement has a transmission loss peak of 15.2 dB at 810 Hz. Above 650 Hz, the T-Liner has a consistently higher transmission loss than the SDOF liner. Between 700 Hz and 1.2 kHz the transmission loss of the T-Liner is greater than 8 dB. Above 1.2 kHz there is a gradual reduction in amplitude from approximately 10 dB at 1.2kHz to 5 dB at 1.7 kHz.

As the T-Liner has a transmission loss peak at 810 Hz, this is the approximate frequency range in which the liner is expected to perform best in the ANCF. However, the exact frequency response of the liner may be higher due magnitude of the incident acoustic wave and the flow conditions in the inlet which were not investigated using the GIIT.

C. ANCF

Measurements were taken at 100 RPM increments between 1500 RPM and 2000 RPM. Additionally, static tests were taken at 0 RPM. Measurements were performed for the full liner configuration, with the liner installed in the first spool section after the inlet section. A hardwall test was also performed at the same RPM test points. These measurements are the baseline configuration of the ANCF.

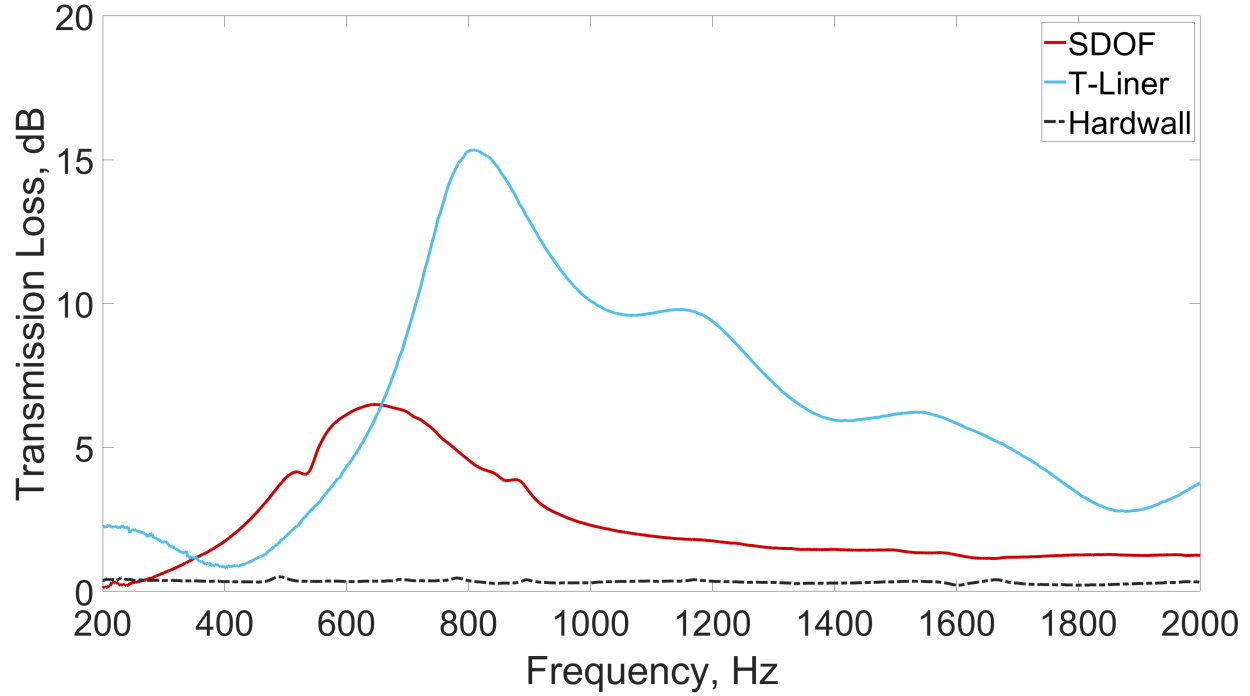


Fig. 16 Comparison of the experimental transmission loss of the SDOF liner and T-Liner, with the hardwall measurement included as a baseline.

An example of the spectra for the baseline and liner configurations of the ANCF can be seen in Fig. 17. Both spectra are for the same test speed of 1800 RPM and for the same microphone location. The recorded SPL in decibels, dB, is on the vertical axis and the frequency in hertz, Hz, is on the horizontal axis. The baseline configuration is shown in black in Fig. 17a. The liner configuration is shown in green in Fig. 17b. The fan tones can be seen by the periodic sharp increases in the SPL. As discussed previously these are a function of the number of blades in the fan, B , and occur at shaft orders which are integer multiples of B . The shaft order can be converted to frequency by multiplying by the test RPM and dividing by 60, $RPM/60$. As a result of this, the frequency at which the fan tones occur increases with increasing fan speed.

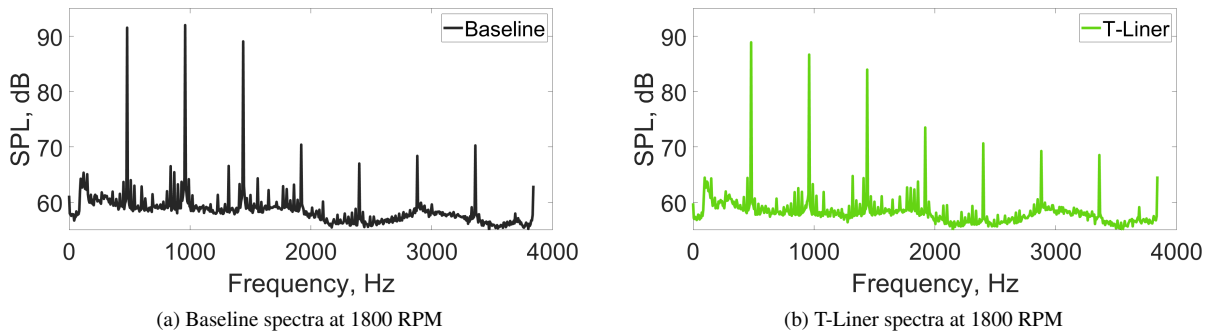


Fig. 17 Example of the (a) baseline and (b) liner spectra of the ANCF at a test speed of 1800 RPM.

While the T-Liner is designed to attenuate broadband noise, there is a frequency at which its performance is highest as indicated by the transmission loss peak seen in Fig. 16. The T-liner will perform best at a test RPM where the frequency of a fan tone corresponds to the frequency of the transmission loss peak. In the preliminary testing in the GIIT, this occurred at approximately 810 Hz. However, in the ANCF the incident acoustic pressure and flow conditions

are different to the static testing in the GIIT. Therefore a direct comparison of the liner at each of the test points was necessary. The spectra centred on the 2BFP were isolated for each test speed between 1500 RPM and 1800 RPM which is seen in Fig. 18. The recorded SPL in decibels, dB, is on the vertical axis and the frequency in hertz, Hz, is on the horizontal axis. The baseline for each test speed is shown in the solid black line for each speed. The corresponding liner is shown: in solid green for 1500 RPM; in solid blue for 1600 RPM; in solid cyan for 1700 RPM; in solid pink for 1800 RPM; in solid orange for 1900 RPM; in solid red for 2000 RPM. The most significant reduction is seen in the 1800 RPM test point, which is the nominal operating speed of the ANCF. This speed is the primary focus of the in-depth analysis of the liner's performance, for the entire microphone array.

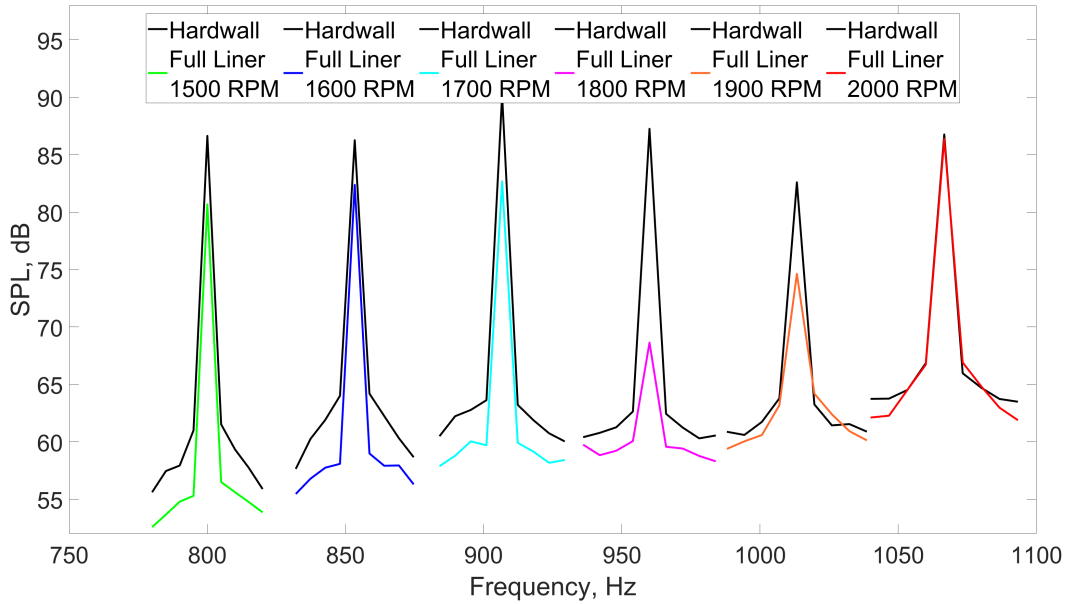


Fig. 18 Comparison of the Hardwall and Liner SPL in decibels at the 2BFP for each RPM test point.

To examine the impact of the acoustic liner on the noise generated by the ANCF fan, the difference in the SPL is obtained by subtracting the liner data from the baseline data for each microphone location. The initial analysis is performed on the data obtained at 1800 RPM, the nominal operating speed of the ANCF. The resulting data set is used to generate the directivity plot in Fig. 19. The frequency in hertz is shown in the radial direction; the azimuthal angle of the microphone location in degrees is given by the angle on the plot, and the SPL difference in decibels is given by the colour axis. A positive value for the SPL difference indicates where the liner reduced the noise and a negative value indicates an increase in SPL. The white regions at 66° and 75° are caused by dead channels in the data acquisition system. The average SPL across the full frequency range and overall microphone locations is 94.0 dB for the baseline configuration. The average SPL reduction for the full-liner configuration is 91.4 dB. The resulting average SPL reduction by the liner is 2.6 dB. While the highest broadband noise reduction is observed at higher azimuthal angles, the liner reduces the tones generated by the first and second blade passing frequency significantly at lower azimuthal angles.

The greatest tonal reductions were observed at microphone location 13 (mic13), corresponding to an azimuthal angle of 43.5° . The greatest overall broadband reduction was observed at microphone location 16 (mic16), corresponding to an azimuthal angle of 52° . The individual spectra at both locations, for both the baseline and liner configurations, are shown in Fig. 20. The spectra for mic13 are seen in Fig. 20a and the spectra for mic16 are seen in 20b. The sound pressure level in decibels is shown on the vertical axis and the frequency in hertz is on the horizontal axis. In Fig. 20a, the fundamental tone of the ANCF, located at 480 Hz, is reduced by 3.3 dB and the 1st harmonic, located at 960 Hz, is reduced by 18.6 dB. The average SPL across the entire frequency range is reduced by 2.9 dB. In Fig. 20b, the fundamental tone is reduced by 3.5 dB and the 1st harmonic is reduced by approximately 9.5 dB. The average SPL across the entire frequency range is reduced by 3.0 dB. The overall noise reduction across the frequency range, and all microphone locations, is 3.7 dB. The significant reduction of the 1st harmonic is expected as the harmonic occurs at approximately the same frequency as the peak of the transmission loss predicted in the numerical simulation in Fig. 16.

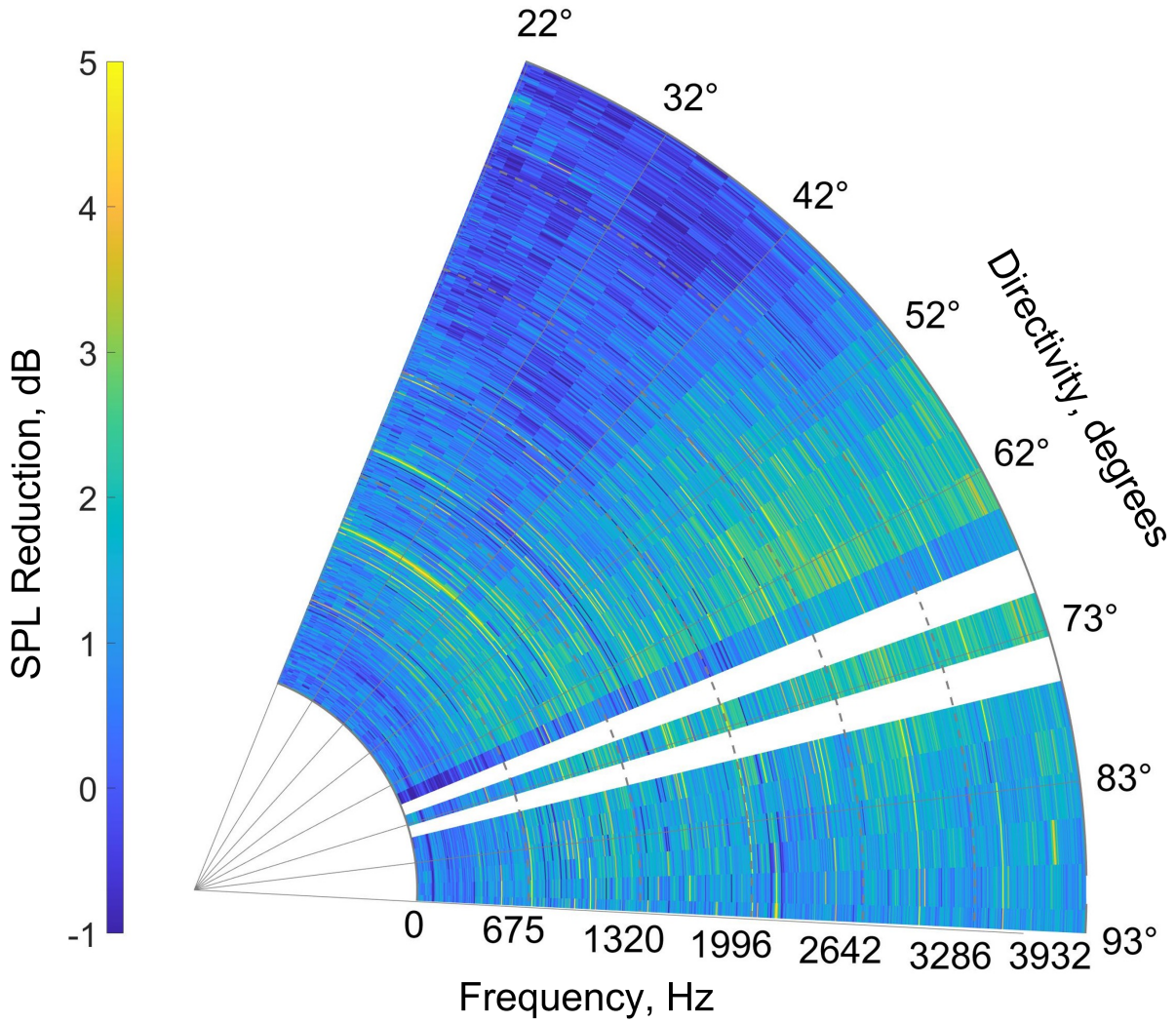


Fig. 19 Directivity plot of the difference in SPL between the baseline measurement and full liner measurement measured at 1800 RPM. Angles for microphone measurements are corrected to the azimuthal angle.

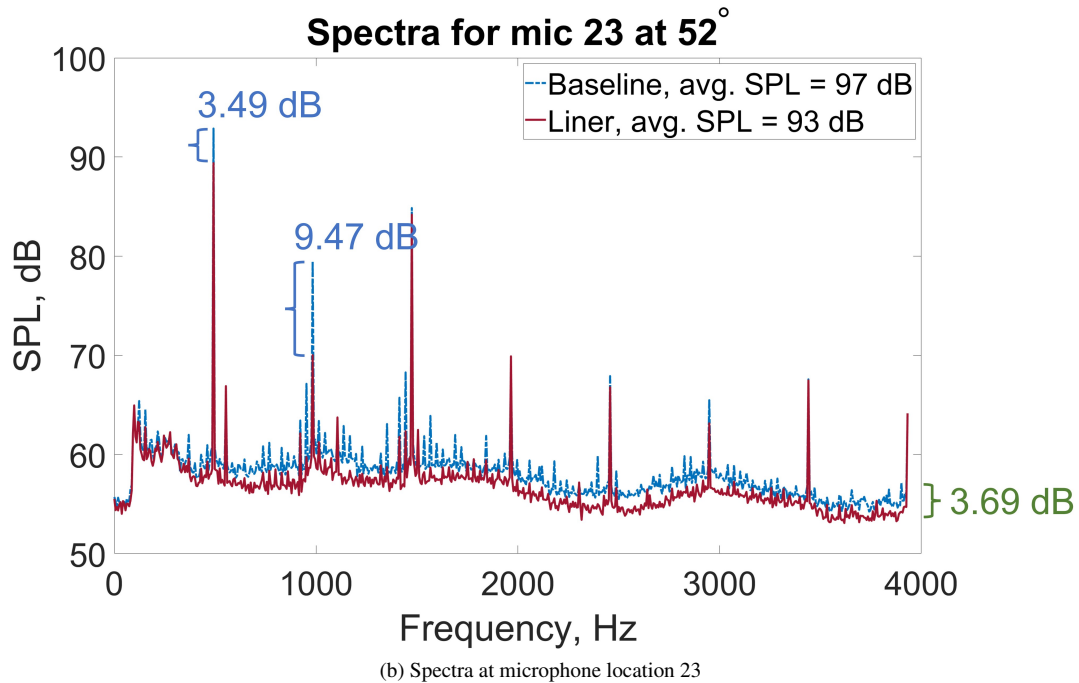
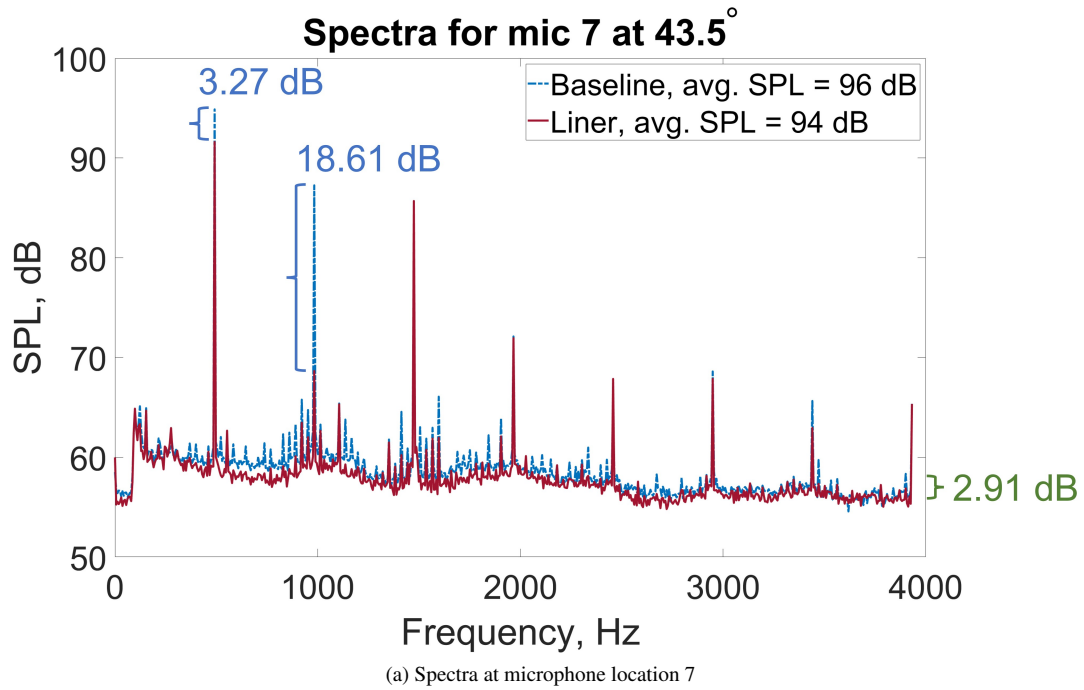


Fig. 20 Spectra for the individual microphone measurements at locations 7 and 23, at 1800 RPM. In both figures, the baseline measurement is shown in the broken blue line and the liner measurement is shown in red.

1. Sound Power Level - Harmonic Bands

The sound power levels, PWL, for each of the harmonic bands were determined by integrating the individual microphone spectra over each of the harmonic bands and multiplying by the area. The PWL calculation had to be corrected for the microphone array used, accounting for the change in the area caused by using a fore-only microphone array. The overall PWL for each of the harmonic bands are given in Fig. 21, along with the sum. The tonal and broadband harmonic bands are given by Fig. 22 and Fig. 23 respectively, which separates the overall PWL into the tonal and broadband contributions. In Fig. 21 it can be seen the greatest reductions to the Overall PWL occur in the first and second harmonic bands. However, this is largely due to the significantly higher tonal PWL reductions that are achieved in these harmonic bands. In Fig. 23 it can be seen that the T-Liner has quite a consistent reduction in the broadband PWL. The greatest contribution to the overall reduction in the PWL is by the tonal PWL reduction in the 2nd harmonic band where there is a reduction of 5.3 dB, as seen in Fig. 22. As a result of this, the overall PWL reduction for the 2nd harmonic band is 4.68 dB. Across all harmonic bands, there was a 2.72 dB reduction in the overall PWL which is indicated by the Sum data set in Fig. 21. The sum reduction in the tonal PWL across all harmonic bands is 3 dB, and the sum reduction in the broadband PWL is 1.1 dB.

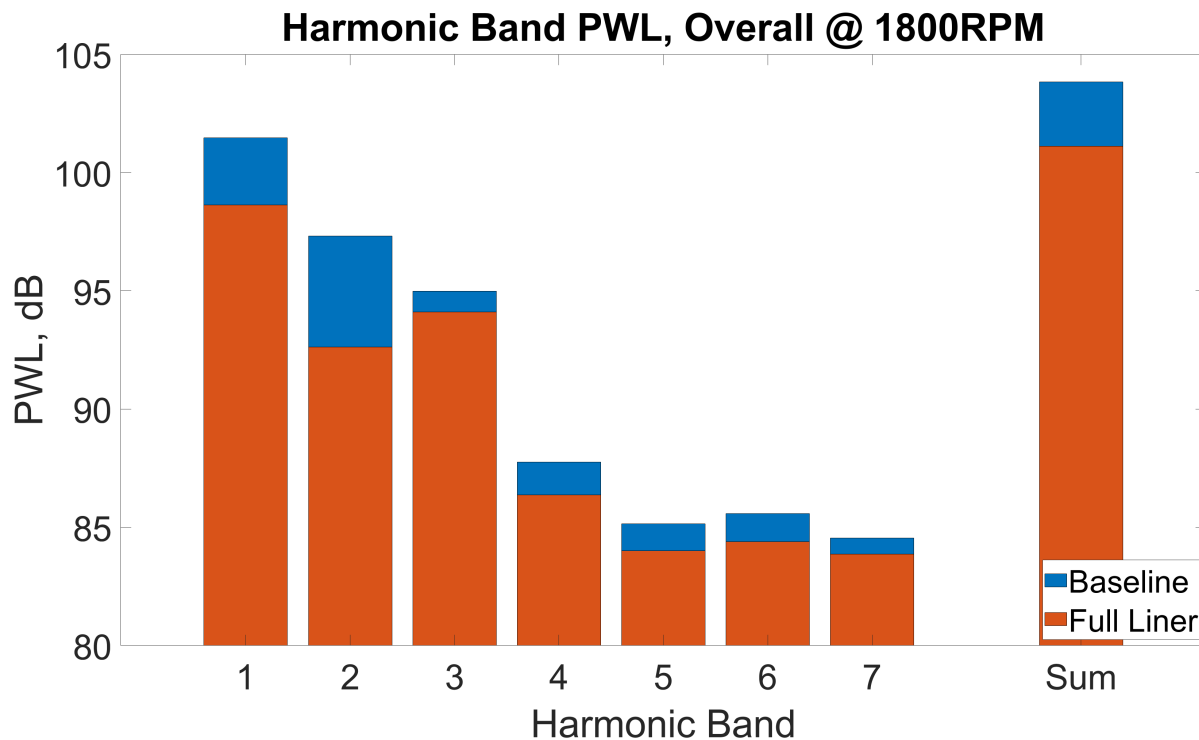


Fig. 21 Overall PWL of each of the harmonic bands for the T-Liner compared with the baseline measurements measured at 1800 RPM.

2. Repeatability

To determine the repeatability of the measurement performed on the ANCF the standard deviation across the measurements was determined. The standard deviation was determined using 4 data sets for the T-Liner measurements and 8 data sets for the baseline measurements for each of the individual microphone locations.

Figure 24 shows the standard deviation on the measurements at microphone location 7. Figure 25 shows the standard deviation on the measurements at microphone location 23. The sound pressure level in decibels, dB, is shown on the vertical axis and the frequency in hertz is on the horizontal axis. The standard deviation of the full spectra for the entire frequency range for microphone 7 is seen in Fig. 24a, and the performance of the liner at the tones corresponding to 1BPF and 2BPF can be seen in Figs. 24b and 24c respectively. Similarly, the standard deviation of the full spectra for microphone 23 is seen in Fig. 25a, and the performance of the liner at the tones corresponding to 1BPF and 2BPF can

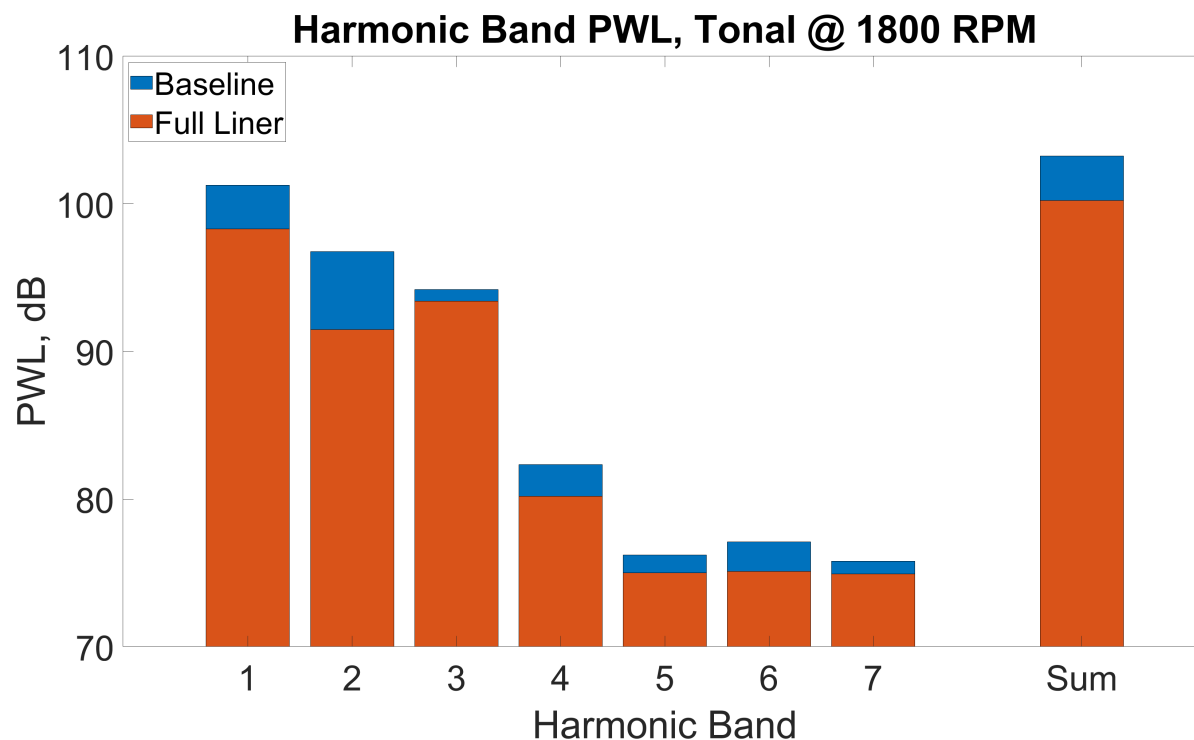


Fig. 22 Tonal PWL of each of the harmonic bands for the T-Liner compared with the baseline measurements measured at 1800 RPM.

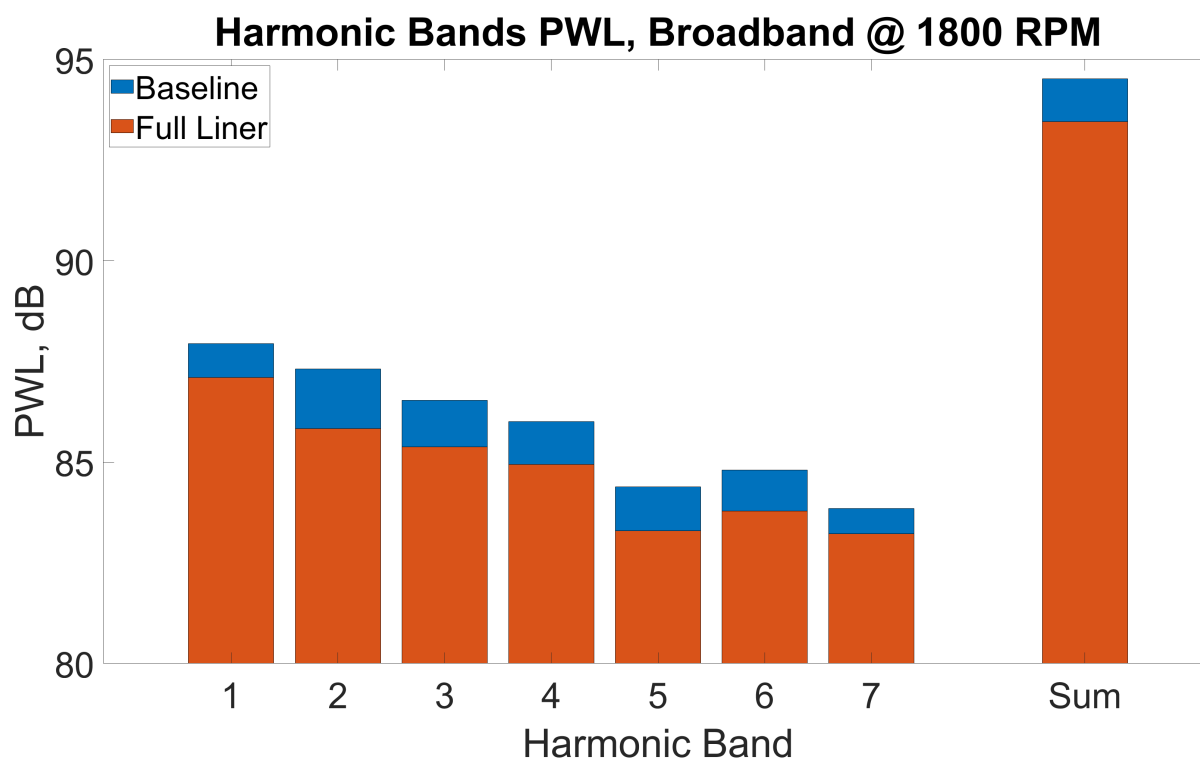


Fig. 23 Broadband PWL of each of the harmonic bands for the T-Liner compared with the baseline measurements measured at 1800 RPM.

be seen in Figs. 25b and 25c respectively.

The low standard deviation observed, particularly on the T-Liner data shows a high degree of repeatability in the liner performance. In general, there is a gap between the upper limit of the Liner standard deviation and the lower limit of the baseline standard deviation. This is not the case in the 2BPF tone observed at microphone location 23, seen in Fig. 25c, however, this is specifically seen at the tone and in the broadband behaviour seen in Fig. 25a there is a gap in the standard deviations of the liner and the baseline measurements.

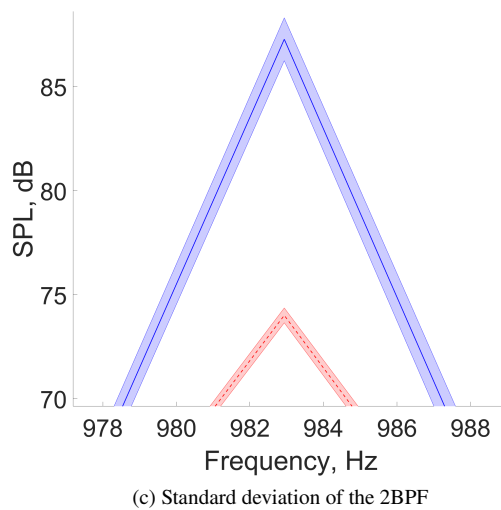
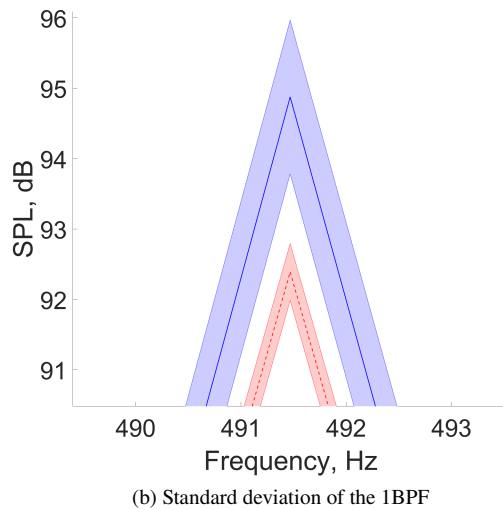
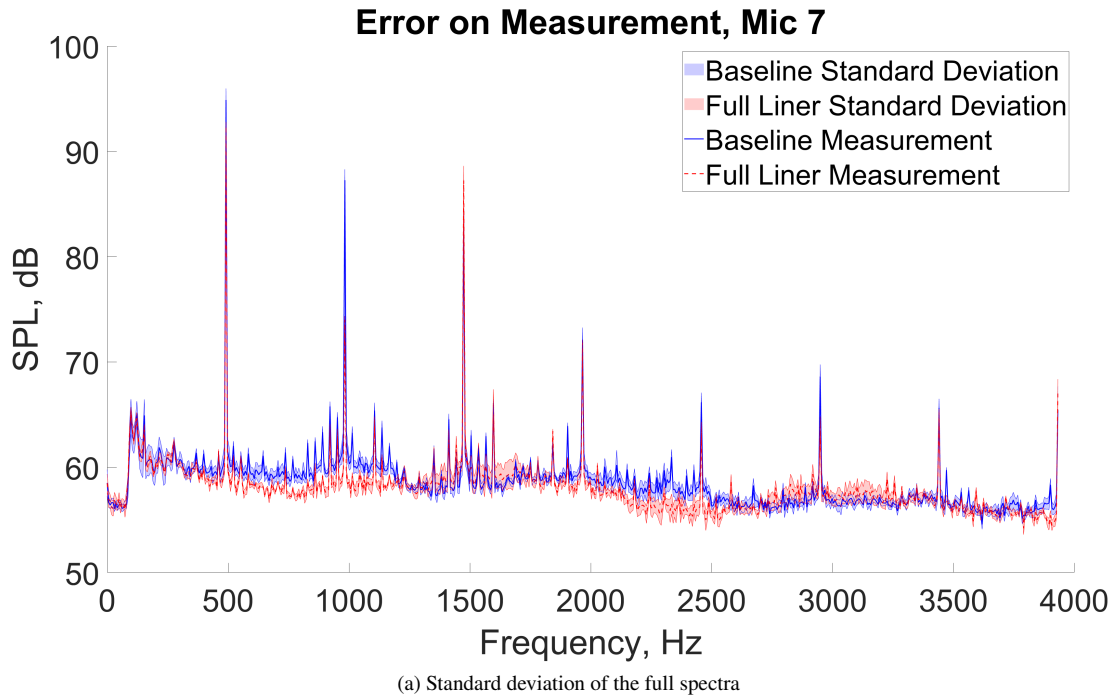


Fig. 24 Standard deviation of the baseline and liner measurements measured by mic 7.

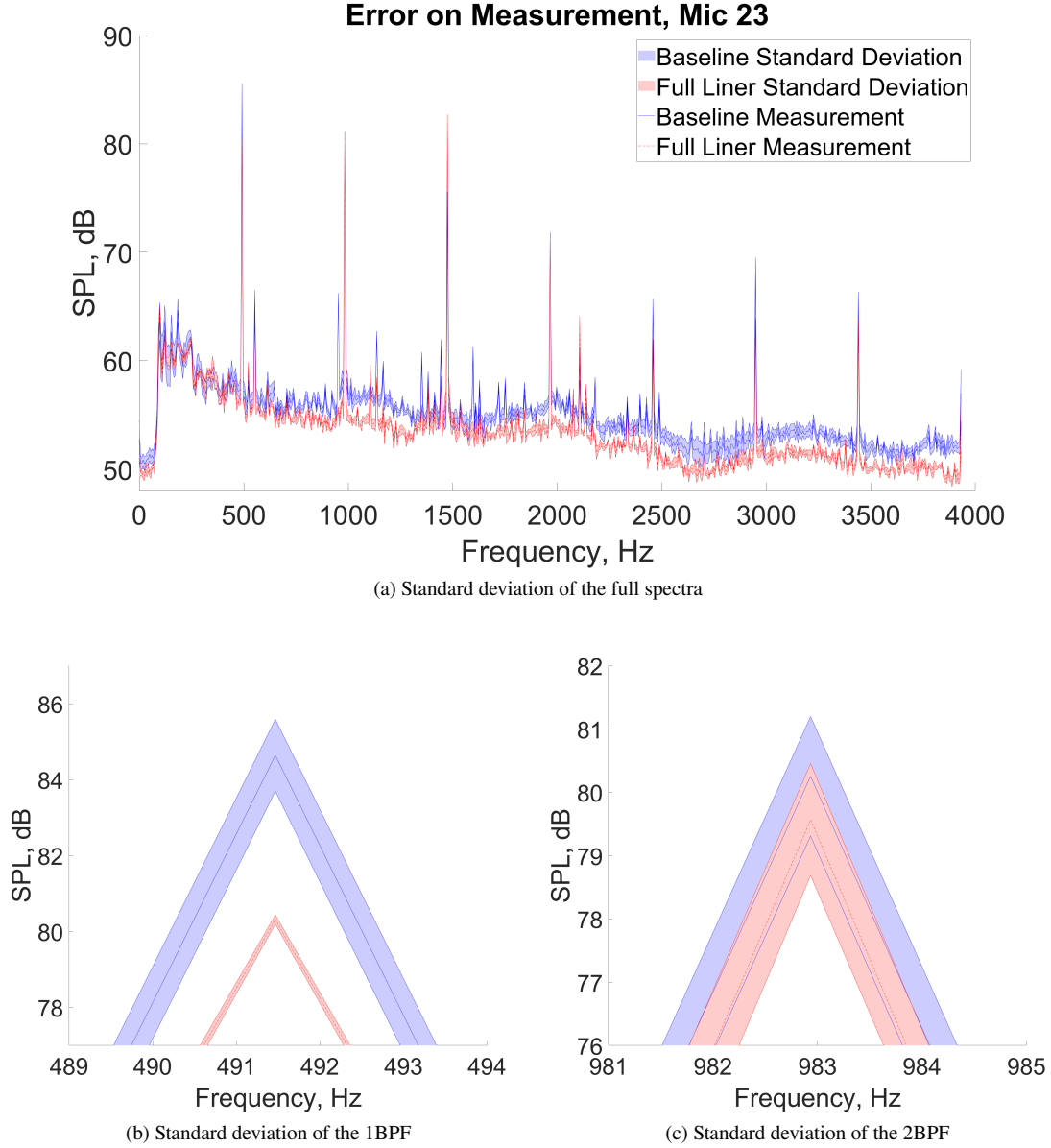


Fig. 25 Standard deviation of the baseline and liner measurements measured by mic 23.

VIII. Conclusions and Future Works

The T-liner design was optimised using a multi-stage optimisation routine. During this testing, T-Liner design was found to have an absorption coefficient of up to $\alpha = 0.97$ experimentally. It also has a very broadband response with a mean absorption coefficient value of $\bar{\alpha} = 0.73$ in the 200 Hz to 2125 Hz range. In comparison, the optimised SDOF liner with the same liner depths only achieved a mean absorption coefficient $\bar{\alpha} = 0.51$ for the same frequency range. The T-liner was subsequently tested in the ANCF at a range of fan speeds and radiation angles. The liner performed best at the nominal operating speed of the ANCF, at 1800 RPM. At this speed, a tonal reduction of 18.6 dB at a radiation angle of 43.5° was measured. Both broadband and tonal noise PWL reductions of 1.1 dB and 3 dB respectively were achieved, with an overall PWL reduction of 2.7 dB across all harmonics achieved by the liner.

While the T-Liner performed well in testing in the ANCF, the broadband performance of the device and its ability to target multiple tones could be improved with a more complicated internal structure. In the design of the T-Liner presented, the variable geometry of the cells was highly repetitive, with the periodic location and geometry of the septa remaining consistent throughout the unit cell. A more complex optimisation for multiple septa heights, and a septa

thickness and perforation diameter that is tuned to each height separately could allow for a more broadband device. Additionally, the work presented here was conducted using relatively cheap SLA printers. The performance of the liner is affected by the quality of the print, and the use of a more precise printer would allow the quality of the samples, therefore the performance to be improved. Additionally, prior to the implementation of a similar device in an aircraft engine nacelle, the performance of the device would have to be assessed at a range of temperatures that are present in aircraft nacelles. It is now achievable to 3D print in metals, and therefore as further advances to the liner technology are made, 3D printed liners which can withstand the high temperatures of aeroengines are within grasp.

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References

- [1] Hasegawa, T., "Effects of Novel Coronavirus (COVID-19) on Civil Aviation: Economic Impact Analysis," , Sep 2022. URL https://www.icao.int/sustainability/Documents/Covid-19/ICAO_coronavirus_Econ_Impact.pdf.
- [2] IATA, "Air Passenger Numbers to Recover in 2024," , Mar 2022. URL <https://www.iata.org/en/pressroom/2022-releases/2022-03-01-01/>.
- [3] Frank Theakston, "Burden of disease from environmental noise: Quantification of healthy life years lost in Europe," *World Health Organisation*, 2011.
- [4] Black, D. A., Black, J. A., Issarayangyun, T., and Samuels, S. E., "Aircraft noise exposure and resident's stress and hypertension: A public health perspective for airport environmental management," *Journal of Air Transport Management*, Vol. 13, No. 5, 2007, pp. 264–276. <https://doi.org/10.1016/j.jairtraman.2007.04.003>, URL <http://www.sciencedirect.com/science/article/pii/S0969699707000403>.
- [5] Jarup, L., Dudley, M.-L., Babisch, W., Houthuijs, D., Swart, W., Pershagen, G., Bluhm, G., Katsouyanni, K., Velonakis, M., Cadum, E., and Vigna-Taglianti, F., "Hypertension and Exposure to Noise near Airports (HYENA): Study Design and Noise Exposure Assessment," *Environmental Health Perspectives*, Vol. 113, No. 11, 2005, pp. 1473–1478. <https://doi.org/10.1289/ehp.8037>, URL <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1310905/>.
- [6] Theakston, F., "Burden of disease from environmental noise: quantification of healthy life years lost in Europe," *World Health Organisation*, 2011. OCLC: 779684347.
- [7] M. Sørensen, "Road traffic noise and risk for non-Hodgkin lymphoma among adults," *EuroNoise*, Vol. 43, 2015, pp. 99–104.
- [8] Kommission, E., and Kommission, E. (eds.), *Flightpath 2050: Europe's vision for aviation ; maintaining global leadership and serving society's needs ; report of the High-Level Group on Aviation Research*, Policy / European Commission, Publ. Off. of the Europ. Union, 2011. OCLC: 930887434.
- [9] Dowling, A. P., and Mahmoudi, Y., "Combustion noise," *Proceedings of the Combustion Institute*, Vol. 35, No. 1, 2015, pp. 65–100. <https://doi.org/10.1016/j.proci.2014.08.016>, URL <https://linkinghub.elsevier.com/retrieve/pii/S1540748914004003>.
- [10] Rie Sugimoto, J. A., and Murray, P., "Low frequency liners for turbofan engines," *International Congress on Acoustics*, 2010.
- [11] Palma, G., Mao, H., Burghignoli, L., Göransson, P., and Iemma, U., "Acoustic Metamaterials in Aeronautics," *Applied Sciences*, Vol. 8, No. 6, 2018, p. 971. <https://doi.org/10.3390/app8060971>.
- [12] Liao, G., Luan, C., Wang, Z., Liu, J., Yao, X., and Fu, J., "Acoustic Metamaterials: A Review of Theories, Structures, Fabrication Approaches, and Applications," *Advanced Materials Technologies*, Vol. 6, No. 5, 2021, p. 2000787. <https://doi.org/https://doi.org/10.1002/admt.202000787>, URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/admt.202000787>.
- [13] Gao, N., Zhang, Z., Deng, J., Guo, X., Cheng, B., and Hou, H., "Acoustic Metamaterials for Noise Reduction: A Review," *Advanced Materials Technologies*, Vol. 7, No. 6, 2022, p. 2100698. <https://doi.org/https://doi.org/10.1002/admt.202100698>, URL <https://onlinelibrary.wiley.com/doi/abs/10.1002/admt.202100698>.

- [14] Ma, G., and Sheng, P., "Acoustic metamaterials: From local resonances to broad horizons," *Science Advances*, Vol. 2, No. 2, 2016, p. e1501595. <https://doi.org/10.1126/sciadv.1501595>, URL <https://www.science.org/doi/abs/10.1126/sciadv.1501595>.
- [15] Chen, S., Fan, Y., Fu, Q., Wu, H., Jin, Y., Zheng, J., and Zhang, F., "A Review of Tunable Acoustic Metamaterials," *Applied Sciences*, Vol. 8, No. 9, 2018. <https://doi.org/10.3390/app8091480>, URL <https://www.mdpi.com/2076-3417/8/9/1480>.
- [16] Jones, M. G., Nark, D. M., and Howerton, B. M., "Overview of Liner Activities in Support of the International Forum for Aviation Research," *25th AIAA/CEAS Aeroacoustics Conference*, American Institute of Aeronautics and Astronautics, 2019, pp. –. <https://doi.org/10.2514/6.2019-2599>, URL <https://arc.aiaa.org/doi/10.2514/6.2019-2599>.
- [17] Boden, H., Sack, S., and Jacob, S., "Impedance measurements for 3-D printed liners," *25th AIAA/CEAS Aeroacoustics Conference*, American Institute of Aeronautics and Astronautics, 2019, pp. –. <https://doi.org/10.2514/6.2019-2600>, URL <https://arc.aiaa.org/doi/10.2514/6.2019-2600>.
- [18] Bake, F., Burgmayer, R., Schulz, A., and Enghardt, L., "IFAR Liner Benchmark - Challenge #1 - DLR," *25th AIAA/CEAS Aeroacoustics Conference*, American Institute of Aeronautics and Astronautics, 2019, pp. –. <https://doi.org/10.2514/6.2019-2601>, URL <https://arc.aiaa.org/doi/10.2514/6.2019-2601>.
- [19] Ishii, T., Nagai, K., Oinuma, H., and Enomoto, S., "Experimental Study of Acoustic Liner Panels Shared in IFAR Program," *25th AIAA/CEAS Aeroacoustics Conference*, American Institute of Aeronautics and Astronautics, 2019, pp. –. <https://doi.org/10.2514/6.2019-2602>, URL <https://arc.aiaa.org/doi/10.2514/6.2019-2602>.
- [20] Sutliff, D. L., *A 20 Year Retrospective of The Advanced Noise Control Fan – Contributions to Turbofan Noise Research*, American Institute of Aeronautics and Astronautics, Indianapolis, IN, 2019. <https://doi.org/10.2514/6.2019-3824>, URL <https://arc.aiaa.org/doi/10.2514/6.2019-3824>.
- [21] E2611-09, A., "Standard Test Method for Measurement of Normal Incidence Sound Transmission of Acoustical Materials Based on the Transfer Matrix Method," *ASTM International*, Vol. ASTM E2611-09, 2009.
- [22] British Standards Institution, "Acoustics: determination of sound absorption coefficient and impedance in impedance tubes - Part 2: Transfer Function Method," *British Standards Institution*, 1998. OCLC: 958821240.
- [23] Figueroa-Ibrahim, K. M., Morris, S., Ross, M., and Sutliff, D. L., *Evaluation of Radiated Sound from the Advanced Noise Control Fan facility in an Outdoor Environment Using Ground Microphones*, American Institute of Aeronautics and Astronautics, Indianapolis, IN, 2019. <https://doi.org/10.2514/6.2019-3825>, URL <https://arc.aiaa.org/doi/10.2514/6.2019-3825>.
- [24] McAllister, J., Loew, R., Lauer, J., and Sutliff, D., "The Advanced Noise Control Fan Baseline Measurements," *47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition*, American Institute of Aeronautics and Astronautics, Orlando, Florida, 2009. <https://doi.org/10.2514/6.2009-624>, URL <https://arc.aiaa.org/doi/10.2514/6.2009-624>.
- [25] Tang, Y., Ren, S., Meng, H., Xin, F., Huang, L., Chen, T., Zhang, C., and Lu, T. J., "Hybrid acoustic metamaterial as super absorber for broadband low-frequency sound," *Scientific Reports*, Vol. 7, No. 1, 2017. <https://doi.org/10.1038/srep43340>, URL <http://www.nature.com/articles/srep43340>.
- [26] Chen, W., Liu, S., Tong, L., and Li, S., "Design of multi-layered porous fibrous metals for optimal sound absorption in the low frequency range," *Theoretical and Applied Mechanics Letters*, Vol. 6, No. 1, 2016, p. 42–48. <https://doi.org/10.1016/j.taml.2015.12.002>.
- [27] Maa, D.-Y., "Potential of microperforated panel absorber," *Journal of the Acoustical Society of America*, 1998. <https://doi.org/10.1121/1.423870>.
- [28] McKay, A., Davis, I., Killeen, J., and Bennett, G. J., "SeMSA: a compact super absorber optimised for broadband, low-frequency noise attenuation," *Scientific Reports*, Vol. 10, No. 1, 2020, p. 17967.
- [29] Fok, V., "Teoreticheskoe issledovanie provodimosti kruglogo otverstiya v peregorodke, postavlennoi poperek truby (Theoretical study of the conductance of a circular hole in a partition across a tube)," *Doklady Akademii Nauk SSSR (Soviet Physics Doklady)*, Vol. 31, No. 9, 1941, pp. 875–882.
- [30] Oda, G., Miyoshi, T., Takaya, Y., Ha, T., and Kimura, K., "Microfabrication of overhanging shape using LCD microstereolithography," *SPIE Proceedings*, edited by I. Miyamoto, H. Helvajian, K. Itoh, K. F. Kobayashi, A. Ostendorf, and K. Sugioka, 2004, pp. 649–654. <https://doi.org/10.1117/12.596758>, URL <http://proceedings.spiedigitallibrary.org/proceeding.aspx?articleid=857538>.