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Investigation of a jet-noise-shielding methodology

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Ongoing research toward the reduction of environmental noise from aircraft is investigating the possible shielding of engine-noise sources by novel airframe configurations. To assess the noise-reduction benefits attainable from such configurations, it is necessary to develop appropriate acoustic evaluation tools. In this paper, a jet-noise-shielding-prediction methodology is described. The Tam-Auriault ("Jet Mixing Noise from Fine-Scale Turbulence," AIAA Journal, Vol. 37, No. 2, 1999, pp. 145–153) jet-noise model with a Reynolds-averaged Navier-Stokes solution input, together with a Fresnel-Kirchhoff diffraction method (Fundamentals of Physical Acoustics, Wiley-Interscience, New York, 2000, pp. 472–494), is used to make isolated and shielded far-field jet-noise predictions. This methodology is employed as a sensitivity-analysis tool to establish the relative importance of the source location, spatial extent, and directivity in jet-noise-shielding predictions. Predictions have been made for a shielded single-stream Mach 0.9 jet, and compared with experimental data. Good qualitative agreement is observed, and the disagreement in the shielding levels is most likely due to underestimation of the source axial extent by the jet-noise model.

Nomenclature

c_A	= model amplitude constant
c_l	= model length-scale constant
c_τ	= model time-scale constant
D_j	= jet nozzle exit diameter
d	= number density
f	= frequency
G	= Green's function
k	= wave number
l_t	= turbulence characteristic length-scale
l_X	= shield chord length
l_Z	= shield span length
M_j	= jet exit Mach number
m	= molecular mass
$\mathbf{n}$	= inward-pointing unit vector normal to the integration surface
p	= acoustic pressure
p_{turb}	= fine-scale turbulence pressure
q_t	= kinetic energy root-mean-square value
$\mathbf{r}$	= source to receiver location vector
r_s	= source location radial component
S	= spectral density
$\mathbf{s}$	= slot location vector
t	= receiver time
t_s	= source time

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$\mathbf{U}$ = velocity vector
 U_c = convection velocity
 U_j = jet exit velocity
 $\mathbf{u}$ = random molecular velocity vector
 V = jet volume
 $\mathbf{x}$ = receiver position vector
 $\mathbf{x}_s$ = source position vector
 x_s = source location axial component
 δ = Dirac delta function
 ϵ = turbulence dissipation
 $\boldsymbol{\eta}$ = spatial separation vector
 θ = polar angle between the receiver and the downstream jet axis
 κ = turbulence kinetic energy
 κ_t = fine-scale turbulence kinetic energy
 ρ = density
 τ = time separation
 τ_t = turbulence characteristic time-scale
 ϕ_s = source location azimuthal component
 ω = angular frequency

I. Introduction

Over the past twenty years air travel has grown by an average of approximately 5% annually, and recent long-term predictions [1, 2] forecast that this trend will continue for the period between 2012 and 2031. This means that the number of aircraft will double over the next fifteen years. It is accepted that future industry growth is likely to depend on further reductions in the environmental impact of airline operations [3]. Reducing the environmental noise from aircraft on takeoff and approach is an essential consideration in the design of new commercial aircraft [4, 5]. One of the main sources of aircraft noise is the engine.

Measures to reduce the noise from future aero-engines must be balanced against other aircraft design requirements. With growing pressures on fuel usage, future noise reduction techniques must avoid weight increases, which lead to higher fuel consumption. Novel low-noise aircraft configurations must be considered if the ACARE Vision 2020 [6] target of a reduction in perceived noise to 50% of the 2001 average levels is to be met.

A novel approach to reduce the engine noise that propagates towards the ground is to position the engines such that the airframe would potentially act as a noise shield or barrier. Such configurations are already the subject of investigation in a number of research projects [7–11]. Their acoustic benefit is typically quantified by the far-field shielding factor, which is the decibel difference between the installed and isolated jet sound pressure level (SPL) at a far-field receiver. The necessary computational capabilities to evaluate the shielding factor for novel airframe shielding concepts, with attendant computational resource constraints, must be developed.

In this paper a jet noise shielding prediction methodology is investigated. An acoustic-analogy-based jet noise model – the Tam-Auriault model [12] – with a Reynolds-averaged Navier-Stokes (RANS) solution input is used to distribute point sources representative of the jet noise source, and together with a Fresnel-Kirchhoff diffraction method (FKM) [13] is used to make isolated and shielded far-field jet noise predictions. This methodology is beneficial in that it is computationally light. Directly solving the governing Navier-Stokes equations, by direct numerical simulation (DNS) or large-eddy simulation (LES) [14], is for the foreseeable future too expensive for use as a design tool. Also, the FKM shielding prediction technique is much less demanding than the alternative boundary element method (BEM), which tends to limit investigations to quite low frequencies [15, 16].

The methodology also builds on established jet noise acoustic analogy based models. Predicting the far-field acoustics from an isolated jet using a RANS solution of the flow and some form of acoustic analogy is well established [17–20]. However, as the majority of jet noise research conducted over the past sixty years has focused on isolated jets [21], it is unclear how traditional jet models can be used to efficiently represent a turbulent jet flow in shielding computations. This paper explores the sensitivity of the far-field shielding factor to variation in a number of relevant jet noise source parameters, with the aim of guiding future investigations in this area.

This paper is structured as follows. In Section II the jet noise shielding prediction methodology is

presented. In Section III, predictions for the isolated and shielded sound levels from a single stream jet are presented and compared with experimental data. The results are discussed in Section IV, with conclusions drawn in Section V.

II. Acoustic Prediction Methodology

Using an acoustic analogy implies that in jet noise shielding problems the domain is separated into two regions – inside, and outside the turbulent jet region – and it is assumed that the sound only radiates outwards from the jet region. This decoupling of the source and propagation means that the jet shielding problem is separated into two steps: firstly, source definition where the complex turbulent jet flow from an isolated jet is represented as an acoustic source; and secondly, source propagation where the propagation of the sound from these sources to the far-field is determined using an appropriate method, which should account for the scattering of the sound by an acoustic shield.

This approximation may have implications for cases where the back-scatter is significant. The inclusion of back-scatter would necessitate the use of coupled simulations, which would require considerable computational resource – probably too much for a design analysis tool. For this reason, the methodology has been applied for the moment to a case where the influence of backscatter is expected to be small.

In this section a propagation or shielding prediction technique is presented firstly followed by a jet noise source model.

A. Shielding Prediction

A variety of computational methods are available to compute the scattering of an acoustic field by a shielding object [22–25]. When selecting an appropriate shielding prediction method, an inevitable trade-off between accuracy and computational demand must be made. The selected method should give an acceptable level of accuracy for the configuration at hand using available (and ideally small) computational resources. It should also be remembered that the shielding effect becomes greater with increased frequency – as the wavelength decreases relative to the shield dimension – and so it may be important to select a shielding method that does not require excessive computational resources at high frequencies.

If the shield geometry may be approximated by a flat rigid plate, which is the case for a wing profile, then the scattering of sound by that plate may be determined efficiently using the Fresnel-Kirchhoff shielding prediction method (FKM). This method is considerably lighter in computational demand than alternatives – most likely a boundary element method (BEM) or finite element method (FEM).

The scattering of sound by a flat rigid plate may be determined by applying Fresnel-Kirchhoff diffraction theory [13] to its geometric complement, i.e. a source and receiver separated by a slot in an infinitely long rigid plate (see Fig. 1). The acoustic pressure at the receiver point may be obtained using the Helmholtz-Kirchhoff integral equation,

$$\hat{p}(\mathbf{x}, \mathbf{x}_s, \omega) = \frac{1}{4\pi} \int_s \left(\hat{p}(\mathbf{s}, \mathbf{x}_s, \omega) \frac{\partial G_\lambda(\mathbf{s}, \mathbf{x}, \omega)}{\partial \mathbf{n}} - G_\lambda(\mathbf{s}, \mathbf{x}, \omega) \frac{\partial \hat{p}(\mathbf{s}, \mathbf{x}_s, \omega)}{\partial \mathbf{n}} \right) ds, \quad (1)$$

where $\mathbf{x}$ is the receiver position, $\mathbf{x}_s$ is the source position, $\mathbf{s}$ is a point on the slot surface s , $\mathbf{n}$ is an inward-pointing unit vector normal to the integration surface, $G_\lambda = \exp(ik|\mathbf{r}_\lambda|)/|\mathbf{r}_\lambda|$, $\mathbf{r}_\lambda = \mathbf{r} - \mathbf{s}$, $\mathbf{r} = \mathbf{x} - \mathbf{x}_s$, ω is the angular frequency, and k is the wave number.

Assuming that the acoustic pressure on the shielded side of the infinitely long plate is zero, and that the acoustic pressure field in the slot is the same as it would be in a completely free-field, the computation only requires integration over the area of the slot. Although these assumptions may not hold entirely at lower frequencies, it is shown in Section III A that they are acceptable for the configuration investigated in this study.

Applying Babinet’s principle, that complementary diffracting objects have complementary diffraction patterns, reverts the analysis back to the original shielding problem of interest, and so the shielded pressure at a receiver separated by a plate (with the dimensions of the slot) is given by

$$\hat{p}_{\text{shield}}(\mathbf{x}, \mathbf{x}_s, \omega) = \hat{p}_{\text{iso}}(\mathbf{x}, \mathbf{x}_s, \omega) - \hat{p}_{\text{slot}}(\mathbf{x}, \mathbf{x}_s, \omega), \quad (2)$$

where $\hat{p}_{\text{iso}} = \exp(ik|\mathbf{r}|)/|\mathbf{r}|$ is the free-space isolated pressure and $\hat{p}_{\text{slot}}$ is given by Eqn. (1). The shielding level for a single source is therefore given by

$$\begin{aligned} \text{SPL}_{\text{shield}} - \text{SPL}_{\text{iso}} &= 20 \log_{10} \left(\frac{\hat{p}_{\text{shield}}}{\hat{p}_{\text{iso}}} \right) \\ &= 20 \log_{10} \left(1 - \frac{\hat{p}_{\text{slot}}}{\hat{p}_{\text{iso}}} \right). \end{aligned} \quad (3)$$

B. Jet Noise Source Model

The jet noise source has been modelled in this work using the Tam and Auriault [12] model for fine-scale turbulence with a κ - ϵ RANS solution. The acoustic shield is positioned in the sideline of the jet, where the acoustic field is dominated by sound from fine-scale turbulence. Attention in this paper focused on the shielding of jet noise at angles in the sideline and upstream of the jet. The shield is also assumed to be at a distance where it is believed to not effect the jet flow or scatter large-scale sources towards the sideline and upstream receivers.

For jet noise shielding predictions the Tam and Auriault approach has the advantage over traditional Lighthill [26]-based formulations [17] that an explicit Green's function term is retained in the expression for the far-field acoustics. This Green's function may be evaluated to include a scattering object either using the FKM outlined in the previous section or alternative propagation methods. It should be noted that a solution to Lighthill's equation, which also retains an explicit Green's function, may be derived [27]. However, as the Tam-Auriault jet noise model has been shown to agree well with a wide set of far-field isolated jet noise data [12, 18] it is selected here.

Although the position, spatial extent and directivity of the acoustic sources would differ with the selection of alternative semi-empirical jet models, it is the sensitivity of shielding predictions to variation in precisely these parameters that is investigated in this paper. As such the trends established are largely independent of the selected jet noise model, and more general conclusions can be drawn.

Tam and Auriault [12] developed a jet noise prediction method for small-scale turbulence in which the sound sources are modelled explicitly. The method is based on the heuristic argument that the small-scale turbulence generates local pressure fluctuations that are proportional to the local turbulent kinetic energy per unit volume. From the kinetic theory of gases, the pressure is given by

$$p = \frac{1}{3}md \langle \mathbf{u} \cdot \mathbf{u} \rangle = \frac{1}{3}\rho \langle \mathbf{u}^2 \rangle, \quad (4)$$

where m is the mass of a molecule, d is the number density, $\mathbf{u}$ is the random molecular velocity, ρ is the density of the gas, and $\langle \rangle$ is the ensemble average. Considering the small-scale turbulence as small blobs of fluid moving randomly with the flow, a direct analogy is made with the gas molecules, such that the fine-scale turbulence effectively exerts a pressure, p_{turb} , on its surroundings given by

$$p_{\text{turb}} = q_t \equiv \frac{1}{3}\rho \langle \mathbf{u}^2 \rangle = \frac{2}{3}\rho\kappa_t, \quad (5)$$

where $\kappa_t = \langle \mathbf{u}^2 \rangle / 2$ is the kinetic energy of the fine-scale turbulence per unit mass. The fluctuation of this pressure in time is reasoned to be the cause of acoustic disturbances, and so the source of fine-scale turbulence noise is equal to the time rate of change of q_t or Dq_t/Dt , where D/Dt is the convective derivative moving with the source.

Tam and Auriault used the linearised Euler equations to describe the propagation of the sound generated by these pressure fluctuations. However, if the flow effects on the acoustic propagation are neglected, the propagation is described by the wave equation. The acoustic fluctuations in the far-field at $\mathbf{x}$ from a source at $\mathbf{x}_s$ are given by the convolution of the source with a Green's function $\hat{G}$

$$\begin{aligned} p'(\mathbf{x}, t) &= \int \int \left[\int_{-\infty}^{\infty} \hat{G}(\mathbf{x}, \mathbf{x}_s, \omega) \exp(-i\omega(t - t_s)) d\omega \right] \\ &\quad \times \frac{Dq_t(\mathbf{x}_s, t_s)}{Dt_s} dt_s d\mathbf{x}_s, \end{aligned} \quad (6)$$

where $D/Dt_s = \partial/\partial t_s + U_c \partial/\partial x_s$ is the convective derivative following the source, t and t_s are the receiver and source times respectively, and $i = \sqrt{-1}$.

The spectral density of the radiated sound (i.e. the Fourier transform of the autocorrelation function) is

$$S(\mathbf{x}, \omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \langle p'(\mathbf{x}, t) p'(\mathbf{x}, t + \tau) \rangle \exp(i\omega\tau) d\tau, \quad (7)$$

which using Eqn. (6) leads to

$$\begin{aligned} S(\mathbf{x}, \omega) &= \int \dots \int \hat{G}(\mathbf{x}, \mathbf{x}_1, \omega_1) \hat{G}(\mathbf{x}, \mathbf{x}_2, \omega_2) \\ &\quad \times \left\langle \frac{Dq_t(\mathbf{x}_1, t_1)}{Dt_1} \frac{Dq_t(\mathbf{x}_2, t_2)}{Dt_2} \right\rangle \\ &\quad \times \exp(-i(\omega_1 + \omega_2)t + i\omega_1 t_1 + i\omega_2 t_2) \\ &\quad \times \delta(\omega - \omega_2) d\omega_1 d\omega_2 dt_1 dt_2 d\mathbf{x}_1 d\mathbf{x}_2. \end{aligned} \quad (8)$$

The two-point cross-correlation of the source fluctuations is modelled, in a fixed reference frame, as

$$\begin{aligned} &\left\langle \frac{Dq_t(\mathbf{x}_1, t_1)}{Dt_1} \frac{Dq_t(\mathbf{x}_2, t_2)}{Dt_2} \right\rangle \\ &= \frac{\hat{q}_t^2}{\tau_t^2} \exp\left(-\frac{|\boldsymbol{\eta}_1|}{U_c \tau_t} - \frac{\ln 2}{l_t^2} \left((\eta_1 - U_c \tau)^2 + \eta_2^2 + \eta_3^2\right)\right), \end{aligned} \quad (9)$$

where $\boldsymbol{\eta} = \mathbf{x}_1 - \mathbf{x}_2$; $\tau = t_1 - t_2$; l_t is the characteristic length-scale of the turbulence, τ_t is the characteristic time-scale and $\hat{q}_t$ is the root-mean-square value of the fluctuating kinetic energy of the small-scale turbulence.

Upon inserting Eqn. (9) into Eqn. (8), and evaluating the integrals (following the manipulation described in Ref. [12]), the spectral density of the sound radiated from an elemental volume dV is given by

$$\begin{aligned} dS(\mathbf{x}, \mathbf{x}_s, \omega) &= 4\pi \left(\frac{\pi}{\ln 2}\right)^{3/2} \frac{\hat{q}_t^2 l_t^3}{\tau_t} |\hat{G}(\mathbf{x}, \mathbf{x}_s, \omega)|^2 \\ &\quad \times \frac{\exp\left(\frac{-\omega^2 l_t^2}{U_c^2 (4 \ln 2)}\right)}{1 + \omega^2 \tau_t^2 \left(1 - \frac{U_c}{c_0} \cos \theta\right)^2} dV, \end{aligned} \quad (10)$$

where θ is the polar angle between the receiver and the downstream jet axis and c_0 is the speed of sound.

To determine the radiated sound requires evaluating the Green's function, which is defined as the solution of the Helmholtz equation

$$\nabla^2 \hat{G} + \frac{\omega^2}{c_0^2} \hat{G} = \frac{i\omega}{2\pi c_0^2} \delta(\mathbf{x} - \mathbf{x}_s). \quad (11)$$

The amplitude selected here is for consistency with the original derivation of Tam and Auriault [18]. This solution may take into account the scattering of the sound field by an acoustic shield. However, in the free-space case, the solution is

$$|\hat{G}(\mathbf{x}, \mathbf{x}_s, \omega)|^2 = \frac{\omega^2}{64\pi^4 c_0^4 |\mathbf{x} - \mathbf{x}_s|^2}, \quad (12)$$

and so the spectral density from an elemental volume is

$$\begin{aligned} dS(\mathbf{x}, \mathbf{x}_s, \omega) &= \frac{\omega^2}{16\pi^3 c_0^4 |\mathbf{x} - \mathbf{x}_s|^2} \left(\frac{\pi}{\ln 2}\right)^{3/2} \\ &\quad \times \frac{\hat{q}_t^2 l_t^3}{\tau_t} \frac{\exp\left(\frac{-\omega^2 l_t^2}{U_c^2 (4 \ln 2)}\right)}{1 + \omega^2 \tau_t^2 \left(1 - \frac{U_c}{c_0} \cos \theta\right)^2} dV. \end{aligned} \quad (13)$$

It is necessary to evaluate model parameters $\hat{q}_t^2$, l_t and τ_t , which may be done using a RANS solution of the jet flow. The spectral density from the total jet source volume, V , is $S(\mathbf{x}, \omega) = \int_V dS$

A RANS solution with κ - ϵ turbulence statistics model provides two pieces of information about the turbulence of the jet flow. These are the averaged turbulence kinetic energy κ and the dissipation rate ϵ . From these quantities it is possible to form a length l , characterising the size of the turbulence, and a time τ , characterising the decay time of the turbulence [12, 18]. The model parameters l_t and τ_t are proportional to these values and may be given as

$$l_t = c_l \left(\kappa^{3/2} / \epsilon \right); \quad \tau_t = c_\tau (\kappa / \epsilon) , \quad (14)$$

where c_l and c_τ are model constant. The source strength is taken to be

$$\hat{q}_t^2 = c_A^2 (2 \rho \kappa / 3)^2 , \quad (15)$$

with c_A as an amplitude constant.

C. Point Source Distribution

To evaluate the scattering of jet noise by a shielding object, it is often necessary to replace the jet source region with an equivalent distribution of point sources. The amplitude and directivity of each source should lead to the far-field spectral density given in Eqn. (10). If, for example, each element in the RANS mesh acts as a single source located at the centroid of the element, $\mathbf{x}_s$, then

$$\hat{p}(\mathbf{x}, \mathbf{x}_s, \omega) = \hat{A}(\mathbf{x}, \mathbf{x}_s, \omega) \hat{G}(\mathbf{x}, \mathbf{x}_s, \omega) , \quad (16)$$

where

$$\begin{aligned} \hat{A}^2(\mathbf{x}, \mathbf{x}_s, \omega) = & 4\pi \left(\frac{\pi}{\ln 2} \right)^{3/2} \frac{\hat{q}_t^2 l_t^3}{\tau_t} \\ & \times \frac{\exp \left(\frac{-\omega^2 l_t^2}{U_c^2 (4 \ln 2)} \right)}{1 + \omega^2 \tau_t^2 \left(1 - \frac{U_c}{c_0} \cos \theta \right)^2} dV , \end{aligned} \quad (17)$$

is a local directional amplitude term. As all interaction effects between the source and surrounding elements in the jet have been included in the amplitude, the sound fields produced by a discrete distribution of such sources are incoherent, and will sum as

$$|\hat{p}(\mathbf{x}, \omega)|^2 = \sum_{i=1}^{N_S} |\hat{p}_i(\mathbf{x}, \mathbf{x}_s, \omega)|^2 , \quad (18)$$

where N_S is the elements that comprise the total jet source volume. As the phase relationship between the sources is not important, any phase may be assumed for the purposes of computing the propagation about a shielding object from an individual source.

The RANS domain most likely includes nozzle ducts and numerical buffer-zones and other flow regions, which do not contribute to the jet noise and should be removed. The jet source volume may be defined through a cut-off criteria

$$\mathbf{x}_s \in V \quad \text{if} \quad W(\mathbf{x}_s) \geq \alpha (W(\mathbf{x}_s))_{\max} , \quad (19)$$

where W is a weight distribution across the domain and $0 \leq \alpha \leq 1$ is an appropriately selected cut-off factor. Only elements which meet the criteria value are included in the jet source volume V .

A useful initial weighting function is the turbulent kinetic energy. This will ensure that regions beyond the cone of the expanding jet flow are removed as sources. The shield should be located outside of this volume. As the source region (within this jet source volume) changes with frequency, there will still be a considerable number of redundant sources, particularly at higher frequencies.

A more effective filter may be applied by using the frequency dependent amplitude of Eqn. (17). As the amplitude term is also dependent on the angle between the receiver and the jet axis, direct use of this term would result in a set of sources for each receiver position. To avoid this the amplitude may be averaged over a sphere of receiver positions to give

$$\hat{A}(\mathbf{x}_s, \omega) = \frac{1}{2} \int_0^\pi \hat{A}(\mathbf{x}, \mathbf{x}_s, \omega) \sin \theta d\theta , \quad (20)$$

which is independent of the receiver and along with Eqn. (19) may be used to define a frequency dependent jet source volume.

III. Jet Noise Predictions

Using the methodology that has been described in the previous section, isolated and shielded predictions for a single-stream circular unheated jet have been made, and are presented in this section. The configuration chosen is the same as that examined experimentally by Young *et al.* [28] so as to enable a direct comparison. This dataset was chosen as it is believed that the shield is sufficiently far removed from the jet so that its introduction has not significantly changed the jet noise source or introduced new shield sources. This enables the use of an isolated RANS solution to evaluate the source model for different shield positions.

Young *et al.* used a jet with a diameter of $D_j = 0.0381$ m and a two-dimensional cross-section aerofoil based on the NACA0012 profile (see Fig. 2) with a chord of $l_X/D_j = 5.333$ and a span of $l_Z/D_j = 40$ as a shield. Far-field isolated and shielded jet measurements were made at a radius of $r/D_j = 80$. A jet exit Mach number of $M_j = 0.9$ with no external flow and a number of shield positions were examined as illustrated in Fig. 3.

Axisymmetric and 3D RANS solutions have been computed for a single-stream cold jet with a Reynold's number of 5×10^5 . Although a 3D solution is somewhat unnecessary for the configuration here, it will be required for cases where the source distribution is not axisymmetric (e.g. a nozzle with chevrons). The axial velocity at various cross-sections is shown in Fig. 4. It can be seen that the computed values agree well with those measured in Ref. [28]. Cross-sections of the turbulent kinetic energy are shown in Fig. 5. Both the axial velocity and turbulent kinetic energy profiles agree well with experimental results for a Mach 0.9 jet presented by Fleury *et al.* [29].

In all the following isolated and shielded predictions the maximum extent of the jet volume is defined as those elements in the RANS solution, where the turbulent kinetic energy meets the criteria $\kappa \geq 10^{-3}\kappa_{\max}$. The shield lies outside this volume.

A. Validation of the Shielding Prediction Method

The Fresnel-Kirchhoff shielding prediction method (FKM) has been benchmarked against a finite element (FEM) solution for the shielding of a single point source. Both the shielding from the NACA0012 profile shield and a flat plate have been examined in order to establish the effect of the geometry simplification assumed in the FKM.

The trailing edge of the shield was located at $(\mathbf{x}, \mathbf{y}) = (0.56 l_X, -0.94 l_X)$ and the receiver was at a radius of $r = 15 l_X$ from the source location, where l_X is the characteristic length of the shield (i.e. the chord of the aerofoil profile). This corresponds to a source at the centre of the nozzle exit for the jet shielding configuration with the shield trailing edge at $x/D_j = 3$.

Fig. 6 shows the shielding factor from the FEM solution with the NACA0012 profile. The shielded or quiet region below the profile is clearly visible. Also visible is an interference pattern due to the scattering of the sound by the shield with bands of higher and lower shielding levels. When a number of incoherent sources are present in the domain, this interference pattern is averaged out. For benchmarking purposes it is useful to look at shielding from a single source as the shielding factor is more sensitive to geometry changes without this averaging. It is therefore easier to see difference between computational approaches. This makes it more important to examine the directivity for a single source (rather than the spectrum at a point as will be done when it comes to the jet source distribution) as the spatial sensitivity will make it difficult to interpret, i.e. there is greater sensitivity to spatial changes than to frequency changes so a spatial comparison is appropriate.

A comparison of shielding levels at an arc of receiver positions on the quiet side of the shield is presented in Fig. 7, computed using both FKM and FEM at a range of frequencies. Once again the troughs and peaks of an interference pattern are visible as only one source is included here. It should be remembered that multiple incoherent sources will act to smooth these curves. As expected the level of the shielding becomes greater at higher frequencies.

Although there is some level of disagreement between the different computations, on the whole the results are comparable. Even at low frequencies, where the assumptions involved in the FKM are questionable (see Section II A), the shielding curves are quite similar. It is therefore concluded that for the present shielding configuration the FKM provides an acceptable level of accuracy. The computational effort required for a FKM prediction is considerably less than that for a FEM prediction.

B. Isolated Jet Predictions

The Tam-Auriault model constants $-c_l$, c_r and c_A - have been calibrated to best-fit the far-field isolated spectrum from Young *et al.* [28] at 90° to the jet. This is a commonly used approach to select

the model constants for isolated predictions, and resulted in $c_l = 0.1261$ and $c_t = 0.0152$. Typically the values are set to best-fit at one observation point and then the model may be used to make useful predictions at others. It has been shown that this approach leads to good agreement with a wide set of far-field isolated jet noise data [12, 18]. c_A was determined to be 0.71 but as it will cancel-out in the computation of the shielding levels, it is not discussed as a parameter in this paper.

Fig. 8 shows the far-field spectra at 90° and 100° to the jet axis for the isolated (not shielded) jet configuration. As can be seen, the spectrum fit at 90° has been quite successful. The model constants c_l and c_t can be tuned to give good agreement with the measured data. This agreement should hold at angles in the side-line of the jet as can be seen at 100° , where fine-scale turbulence noise dominates, but will weaken at angles close to the jet axis, as the sound from large-scale flow structures (which is not included in this model) becomes influential.

For shielding predictions, it is important to understand the consequences to source location of using this approach to tune c_l and c_t . Calibrating the model constants to fit far-field isolated values is (for the most-part) blind to the source location. To compute the axial source amplitude distribution, the cylindrical source amplitude, Eqn. (20), is integrated over the radial and azimuthal source axes so that

$$\hat{A}(x_s, \omega) = \int_0^{2\pi} \int_0^{r_s} \hat{A}(\mathbf{x}_s, \omega) r_s dr_s d\phi_s, \quad (21)$$

where $\mathbf{x}_s = (x_s, r_s, \phi_s)$.

Fig. 9 shows how the calibration has led to a shift downstream in the location of the sources for a given frequency. The spatial region where the model predicts sound generation at $St = 1$ has been moved downstream so that it now coincides with the most energetic region in the RANS solution. This most likely has a significant effect on the shielding predictions, which is explored in the next section.

This shift in location also highlights the influence of the RANS solution in determining source location. There could well be some degree of uncertainty in the location of the maximum kinetic energy (depending of the particularities of the RANS solver), which may not be important for far-field isolated predictions, but will influence the source location for shielding predictions. Additionally, tuning c_l and c_t will move the source location but not the underlying velocity values, which influence the directivity through the $(1 - U_c \cos \theta / c_0)$ term.

C. Shielded Jet Prediction Trends

As it can be expected that the maximum shielding effect occurs when the shield is located directly between the source and receiver, attention is focused on the spectra at 120° to the downstream jet axis. Other observation angles have been investigated in this work and the results are consistent with the trends observed 120° . For this reason, they are not included here (with the exception of the result shown in Fig. 17). These angles are also within the range where fine-scale turbulence is the dominant source.

Before comparing the model predictions with the experimental data from Ref. 28, a number of source parameters are investigated in order to establish their relative influence on far-field shielding levels, and to assist in interpreting the comparison.

1. Source Axial Location

Fig. 10 shows the effect of the tuning of c_l and c_t , which has already be examined in the isolated results. As can be seen, moving the source location (see Fig. 9) has a large impact on the predicted shielding. Tuning c_l and c_t to values less than unity results in the sources being moved downstream for all frequencies. Therefore, the frequency at which the sources are shielded from the receiver is now higher than for the unity values. As expected, a shift to higher frequencies for the peak shielding is observed. Notably, the increased frequency has not lead to a significantly increased shielding level as the axial extent of the source when it being shielded remains unchanged, and this more influential than frequency in this case.

This result illustrates the sensitivity of the shielding factor to the axial position of the sources, and that care must be taken when selecting c_l and c_t . All the following results use the values for c_l and c_t that have been calibrated with the far-field isolated spectrum.

Looking at the shielding level with $c_l = 0.1261$ and $c_t = 0.0152$, it can be observed that at the lowest frequencies there is no shielding effect due to the fact that the sources are located far downstream and have a clear view of the receiver. As the frequency increases, the location of the source shifts upstream (as smaller scale turbulence is located closer to the nozzle exit) over the shield. The shielding increases

until it peaks (is most negative) before dropping-off again, as the source is once again exposed on the upstream side of the shield.

2. Source Radial Extent

Fig. 11 shows the difference between the shielding values when the jet sources are distributed about the jet axis (evaluated from a 3D RANS solution), and when the sources are distributed on the jet axis (evaluated from an axisymmetric RANS solution and moved to the jet axis). As can be seen there is almost no difference in the shielding levels (the lines are almost indistinguishable). This means that once the amplitude has been integrated about the azimuthal axis, by

$$A(\mathbf{x}, x_s, r_s, \omega) = \int_0^{2\pi} A(\mathbf{x}, \mathbf{x}_s, \omega) r_s d\phi_s, \quad (22)$$

the sources can be considered to lie along the jet axis by letting $r_s = 0$ and $r \approx |\mathbf{x} - x_s \hat{\mathbf{i}}|$. For an axisymmetric flow, this is a more natural approach (than perhaps generating a 3D distribution from an axisymmetric RANS solution), but it is important to establish that this approximation has little influence on the shielding factor.

The results also show that by moving the shield upstream, the frequency at which the peak shielding level (most negative) occurs is moved higher. This is because the shield blocks higher frequency sources nearer the jet exit. The shield is more effective at higher frequencies as demonstrated in Fig. 7.

It can also be seen that the level of the peak shielding is greater (more negative) when the shield is blocking these sources nearer the jet exit. It will be shown that this is mostly due to the axial extent of the source region decreasing, therefore, making the shield more effective. This is in contrast to the unchanged level of the peak shielding observed in Fig. 10, where it was the frequency of the source at a given location that changed, and not the location and extent of the source.

3. Source Axial Extent

Although the radial extent of the source has been shown to be unimportant, the axial extent of the source is. It has been shown in Fig. 10 how the axial position of the highest amplitude sources influences the frequency at which peak shielding occurs. Here, the axial extent of the source is examined. So far, the source region has been defined as elements where $\kappa \geq 1 \times 10^{-3} \kappa_{\max}$. This is quite a low threshold so many elements are included as sources. Using Eqns. (19) and (20) the jet source volume is trimmed by changing the value of α . With $\alpha = 0$ the source region is all the volume defined by $\kappa \geq 1 \times 10^{-3} \kappa_{\max}$.

Fig. 12 shows that there is no significant difference between $\alpha = 0$ and values up to $\alpha = 0.1$, but that the prediction does deviate when $\alpha = 0.5$. The peak shielding level increases, and at lower frequencies, the shield level is decreased. This is an important trend. The reason behind it, is that the source is more compact (as a result of neglecting lower amplitude sources in this case) as can be seen in Fig. 13. Due to geometric reasons, a more compact source will result in greater shielding when it is hidden in the shadow of the shield, and less shielding when it is at the edges of the shadow zone.

4. Source Directivity

The simplest way to examine the effect of the directivity of the source on shielding predictions is to set the source convection term $C = (1 - U_c \cos \theta / c_0) \rightarrow 1$. This makes the jet noise source omnidirectional. At the angles which are of interest here in the sideline of the jet, the directivity should be relatively unimportant. Fig. 14 shows that this is the case. This is significant as it allows the jet to be modelled by a distribution of omnidirectional sources. This would simplify the methodology that has been outlined in this paper, and the introduction of these sources into propagation codes.

It may also be concluded that the assumption that the acoustic propagation is through a quiescent medium has little effect on the shielding for the configuration examined here. The assumption amounts to ignoring the refraction of the propagating sound caused by the jet flow. However, in the sideline of the jet where the shield is located this effect does not significantly influence the shielding.

D. Comparison with Experimental Shielding Levels

The jet shielding methodology predictions (with $c_l = 0.1261$, $c_t = 0.0152$ and $\alpha = 0$) are now compared with the limited shielding data presented by Young *et al.* [28], which are shown in Fig. 15. From comparing Fig. 15 with either Fig. 11 or 14, it may be observed that there is good qualitative

agreement between the predictions and the data. As expected, moving the shield upstream moves the frequency at which the peak shielding level occurs, as higher frequency sources are blocked (see the discussions of Fig. 11).

Fig. 16 shows the direct comparison between the model predicted values and their respective experimental values at 120° to the downstream jet axis for three shield positions. The difference in levels is more apparent in these graphs with only modest quantitative agreement shown. However, in all cases there is little or no shielding at the lowest frequencies, and increasing shielding as the frequency increases until a maximum shielding level is reached. The frequency at which the maximum shielding is reached also shows good agreement, and a shift in this maximum to lower frequencies, as the shield is moved downstream from the $x/D_j = 1$ position to $x/D_j = 5$, may also be seen in the predicted and measured values. This means that the Tam-Auriault model is predicting the correct axial position of the strongest amplitude sources, despite the fact that c_l and c_t were calibrated blind to source position.

A reasonably good qualitative agreement between the predictions and data may also be observed in Fig. 17 where the receiver is at 100° . Comparing the values at the two different receiver locations and the same shield position (so Fig. 16(c) and Fig. 17) shows that as expected when the shield is blocking more compact higher frequency sources nearer the nozzle exit, the peak shielding level is greater.

The fact that there is only modest quantitative agreement between all the predictions and their corresponding experimentally measured values is consistent with the modelled source regions being too compact along the jet axis. Figs. 12 demonstrated that a more compact source will produce a more pronounced peak in the shielding level of the type that is observed here. The differences between the predicted and measured shielding curves is discussed further in the following section.

IV. Discussion

In the previous two sections the Tam and Auriault [12] jet noise model has been used to weight point sources for use in a jet noise shielding computation. Predictions have been made and compared with the dataset from Ref. [28]. Although the predictions show similar qualitative trends to the experimental shielding values, there is disagreement between the two in the level of the shielding. It has been concluded that this is most likely due to an underestimation of the axial extent of the source. Given the many sources of uncertainties that exist in both the experimental data and the present methodology some further discussion is warranted. Here the focus is on the present methodology so it is assumed that the experimental data is accurate and reliable.

Fresnel-Kirchhoff theory has been used to compute the propagation of the sound around the shield. Despite the assumptions involved in the method itself, it has been shown to give good agreement with alternative acoustic propagation methods for simple sources. However, there is an additional assumption implicit in its use for jet noise shielding predictions – that in the case of a jet noise source, reflections from the nozzle and the turbulent flow are negligible. In Ref. [30] the effect on the shielding level of the inclusion of the nozzle and the fuselage (the shield in this case was a scaled aircraft) was examined using alternative propagation methods. Despite the shield being located closer to the jet axis in this case, it was concluded that reflections from these other surfaces did not significantly effect the peak shielding level. By extension it was also concluded that sound scattering back of the turbulent jet flow [31] would have even less effect on the shielding level due to its smaller amplitude.

Given the shielding configuration examined in this paper, it is, therefore, concluded that the FKM provides sufficiently accurate predictions of shielding from a jet noise source. The question is whether or not the jet noise source has been described accurately enough.

It is argued that the jet source distribution used in the predictions is too small in axial extent. This is based on the shielding trends observed in Section III, which are summarised as the following

1. As the frequency increases so does the effectiveness of an acoustic shield. This can be seen Fig. 7.
2. Peak shielding occurs when the shield is positioned directly between the source and the receiver. This is consistent with the peak shielding frequency observed in Fig. 12 and the geometry shown in Fig. 13.
3. As the frequency increases the jet noise sources are located closer to the nozzle exit. This may also mean that the source region is more compact and could contribute to the increased peak shielding levels in Fig. 11.
4. A more compact jet source region leads to a more pronounced peak in the shielding level, with less shielding when the source has a direct view of the receiver and higher shielding when source is behind the shield. This can be seen by looking at Figs. 12 and 13.

The experimental values from Ref. [28] are consistent with these trends. The difference between the predicted and measured shielding levels may be due to the jet noise model underestimating the axial extent of the jet source region. It should be noted that although the effect shown in Figs. 12 and 13 was induced by trimming the source volume, it would also occur if the jet model gives a source distribution that is too small.

As an initial investigation into this explanation, the jet noise source is modified such that the square-root and the fourth-root of the source amplitude is used to compute the shielding. This has the effect of flattening the source distribution, i.e. spreading the spatial extent and levelling the amplitude of the source. Although there is no physical basis for doing this, it is still informative about jet noise shielding. The shielding levels at 100° and at 120° with the shield trailing edge $x/D_j = 5$ are shown in Fig. 18. As can be seen the predicted shielding levels move towards the measured data as the source is spread out. The shielding level increases at lower Strouhal numbers and decreases at the peak shielding Strouhal number.

These new predictions still show some disagreement. An adverse effect has been the movement of the peak shielding to a lower Strouhal number. The model constants, c_l and c_r , perhaps need to be recalibrated to move the peak. However, further investigation would be needed before such a step, given the somewhat arbitrary nature of the additional scaling demonstrated here. This result is only intended to show how such a scaling might effect the shielding trends.

There are two possibilities as to why the source description may be too small in spatial extent – firstly, the introduction of the shield modifies the source in some way or, secondly, the jet noise model itself inherently underestimates the source extent. These causes may not be exclusive to each other as it may also be a combination of both.

In the first case, it may be that sound reflected by the shielding object acts to spread the source at a particular frequency. Cervino *et al.* [31] showed a frequency broadening when the acoustic field at a jet is forced at a single frequency. This effect was shown to be more significant at higher frequencies and could lead the source region being greater in spatial extent. However, as such a modification of the source region would be frequency dependent it does not seem highly likely that it would produce the effect on the shielding factor created in Fig. 18. It is also not clear if the sound reflected from a shield positioned five diameters away from the jet axis (as it is here) would have sufficient amplitude to cause this effect. That said this possible cause merits further investigation either experimentally or through a coupled shielding prediction, where the back-scatter is included.

An alternative source modification hypothesis is that the introduction of the shield has led to new sources, either through sound generation at the shield by entrained flow perhaps or by scattering of large-scale jet noise sources towards the upstream receiver angle investigated here. This seems unlikely as any additional source would lead to higher shielded SPLs than isolated ones, i.e. positive shielding levels would be observed, which has not been the case for this configuration. It is believed that for the configuration examined here, no additional sources are generated.

The second possible cause for the underestimation of the axial extent of the source is that jet noise model – the Tam and Auriault model with a RANS input – does not capture it. This would arise through the approximate two-point cross-correlation model used in Eqn. (9) or its inputs, i.e. the turbulent kinetic energy and dissipation rate from the RANS solution. This would appear to be the most likely explanation as it was shown in Fig. 18 that a frequency independent scaling of the source amplitude moved the predicted shielding levels towards the experimental values. Further investigation is needed into these causes either through experimental measurement of the source region perhaps using a beam-forming technique or through numerical analysis using a large-eddy simulation to determine source location.

Although the shielding prediction methodology presented in this paper does not quantitatively match the available experimental data, it does help to understand the trends present within the jet noise shielding data. There are limitations to the applicability of this methodology given the assumptions used – the most significant being that the source and propagation may be decoupled. The configuration examined in this paper (that of Young *et al.* [28]) was chosen specifically because it is believed that the coupling effect is small and so that this assumption is valid. For more realistic geometries, where the shield is located closer to the jet or at angles further downstream of the jet nozzle (where the peak jet noise radiation is) these assumptions may no longer hold. It is however, useful to firstly develop methodologies for cases where the coupling may be neglected. These can then be used to inform more sophisticated jet noise shielding prediction methodologies.

V. Conclusions

A computationally light jet noise shielding prediction methodology has been described in this paper. This methodology has been applied to the shielding from a single stream cold jet. A number of important trends have been observed within the shielding predictions. From comparison with experimentally measured shielding levels, it has been concluded that the jet noise model correctly predicts the axial position of the jet noise sources. However it appears that the axial extent (or relative strength at a given frequency) of these sources is underestimated. Further investigation into the axial extent of model predicted jet noise sources is required as it has been shown that this is an important parameter in jet noise shielding computations.

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Fig. 1: Schematic of the Fresnel-Kirchhoff method (FKM), in which the shielded pressure at $\mathbf{x}$ from a source at $\mathbf{x}_s$ is evaluated through examining its geometric complement – a slot in an infinitely long rigid plate.

Fig. 2: Photograph of the experimental rig used by Young *et al.* taken from Ref. [28] showing the nozzle and the NACA0012 profile acoustic shield.

Fig. 3: The nozzle and shield positions investigated, with the shield moved (not scaled or extended) so that the trailing-edge is at $x/D_j = 1$ (red), $x/D_j = 3$ (green) and $x/D_j = 5$ (black). The shield was at $y/D_j = -5$ in all cases considered here.

Fig. 4: The axial velocity from the RANS solution along the jet axis $y/D_j = 0$ (a), and along cross-sections at $x/D_j = 1$ (—) and $x/D_j = 5$ (---) (b). Also in (b) are the experimental values at $x/D_j = 5$ (+) from Ref. [28]. The length of the potential core L_c is determined to be at $6.8D_j$. δ_θ is the momentum thickness and is modelled as $0.0265x + 0.114 \times 10^{-3}$ [29].

Fig. 5: The turbulent kinetic energy from the RANS solution along cross-sections at $x/D_j = 1$ (—) and $x/D_j = 5$ (---)

Fig. 6: Contour map of the shielding factor with a NACA0012 aerofoil at $kl_x = 38.75$. The point source is located at $(0,0)$.

(a)

(b)

(c)

(d)

Fig. 7: Shielding predictions for a point source: FKM (—); FEM flat plate (— —) and FEM NACA0012 aerofoil (— · —) for $kl_X = 4.84$ (a); 9.67 (b); 19.37 (c) and 38.75 (d). Note that the receiver angle is the polar angle relative to the x-axis.

(a)

(b)

Fig. 8: Far-field isolated spectrum at 90° (a) and 100° (b) to the jet axis with experimental values from Ref. [28] (+), and model predictions with the model constant set to $c_l = c_t = 1$ (---) and $c_l = 0.1261$, $c_t = 0.0152$ (—).

Fig. 9: Axial source amplitude distribution at Strouhal number 1 from the model with the constants set to $c_l = c_t = 1$ (---), and $c_l = 0.1261$, $c_t = 0.0152$ (—).

Fig. 10: Far-field shielding level at 120° from the downstream jet axis with the shield trailing edge at $x/D_j = 5$, and for $c_l = c_t = 1$ (---), and $c_l = 0.1261$, $c_t = 0.0152$ (—) .

Fig. 11: Far-field shielding level at 120° from the downstream jet axis with the shield trailing edge at $x/D_j = 1$ (red lines), $x/D_j = 3$ (green lines) and $x/D_j = 5$ (black lines), and for a 3D source distribution (—) and an axial source distribution (---).

Fig. 12: Far-field shielding level at 120° from the downstream jet axis with the shield trailing edge at $x/D_j = 5$ and with the source volume defined by $W \geq \alpha W_{\max}$ where $\alpha = 0.0$ (—), $\alpha = 0.1$ (---) and $\alpha = 0.5$ (- · -) .

Fig. 13: The jet noise source distribution at $St = 2.5$. The source region has been clipped to retain elements with $W \geq \alpha W_{\max}$ where $\alpha = 0.1$ in (a) and $\alpha = 0.5$ in (b). The nozzle and the shield with the trailing edge at $x/D_j = 5$ are also included. The dashed lines indicate the angle between the receiver at $(r, \theta) = (80D_j, 120^\circ)$ and the edges of the shield.

Fig. 14: Far-field shielding level at 120° from the downstream jet axis with the shield trailing edge at $x/D_j = 1$ (red lines), $x/D_j = 3$ (green lines) and $x/D_j = 5$ (black lines), and for $C = 1 - U_c \cos \theta / c_0$ (—) and $C = 1$ (---).

Fig. 15: Far-field shielding level at 120° from the downstream jet axis from Ref. [28] with the shield trailing edge at $x/D_j = 1$ (red +), $x/D_j = 3$ (green +) and $x/D_j = 5$ (black +).

Fig. 16: Far-field shielding level at 120° from the downstream jet axis with experimental values from Ref. [28] (+), and model predictions (—), and the shield trailing edge at $x/D_j = 1$ (a), $x/D_j = 3$ (b) and $x/D_j = 5$ (c).

Fig. 17: Far-field shielding level at 100° from the downstream jet axis with experimental values from Ref. [28] (+), and model predictions (—) with the shield trailing edge at $x/D_j = 5$.

(a)

(b)

Fig. 18: Far-field shielding levels at 100° (a) and 120° (b) from the downstream jet axis and the shield trailing edge at $x/D_j = 5$ with experimental values from Ref. [28] (+), and model predictions with the original (—), the square-root (— —) and the fourth-root source amplitude (— · —).