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SCALING OF NOISE FROM HEATED SUBSONIC JETS WITH PROPERTIES FROM RANS CFD

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Abstract. *Scaling laws traditionally use global information about the jet such as exit velocity and temperature; in this paper a scaling law that takes input from a numerical RANS solution is presented. By using Lighthill acoustic analogy the sources of jet mixing noise are split in two components related to (i) momentum and (ii) entropy fluctuations. The contribution of each component to the overall sound pressure level (OASPL) is computed for subsonic single-stream jets at different exit velocities and temperatures and results are compared with experimental data. OASPL results are used to compute the noise spectrum by shifting two experimental spectra assigned to each source component. Results agree well with experiments for observer angles near 90 degrees, confirming that jet noise consists of the two aforementioned source components and showing how the entropy component scales with the logarithm of the local temperature gradient. This study is a step towards the development of a RANS-based model to predict the contribution of the entropy source component to the total jet mixing noise.*
Keywords: *jet noise, Lighthill equation, RANS CFD, scaling law*

1. INTRODUCTION

Despite significant technological advances in noise mitigation since the introduction of the jet aircraft, engine noise is still a critical aspect of aircraft design. In particular, jet noise is dominant at take off when the engine is at full power. So to achieve the needed reductions of noise emitted by civil aicraft to comply with ever stricter regulations a reduction of jet noise is envisaged by the aircraft industry.

Approaches to study jet noise range from fundamental theories to describe the mechanics of noise generation (Lighthill, 1952, 1954; Lilley, 1972; Goldstein, 2003) to experimental works focused on empirical understanding of the phenomena while bringing aspects of the theory (Rollin, 1958; Davies *et al.*, 1963; Fisher *et al.*, 1973; Lush, 1971; Fisher *et al.*, 1973; Cocking, 1975; Tanna *et al.*, 1975; Tanna, 1977). More recently numerical solutions of the flow are used together with a theory of sound generation to predict jet noise. The numerical solution of the mean flow from a Reynolds-Averaged Navier–Stokes (RANS) simulation can be used together with a model for the sources of sound (Khavaran *et al.*, 1992; Bailly *et al.*, 1993; Khavaran and Krejsa, 1999; Tam and Auriault, 1999; Self, 2004; Self and Azarpeyvand, 2008; Ilário *et al.*, 2011), or the sound can be computed directly from transient solutions of the flow using methods such Lattice-Boltzmann Methods (Lew *et al.*, 2014), Large Eddy Simulations (Bogey *et al.*, 2007, 2009) or Direct Numerical Simulation (Freund, 2003).

Although numerical methods are getting more efficient and computational power getting cheaper, methods based on a transient solution of the flow are still too computationally expensive in an industrial time frime. The use of a RANS solution is then justified by the need of a fast numerical method to predict jet noise to help the design of quieter jet engines. In this paper a RANS-based scaling law is presented as part of a study to extend the model of Ilário *et al.* (2011) to account for the additional entropy-related source in heated jets. The scaling law is an extenstion of the work by Fisher *et al.* (1973) to use local properties from the flow from a RANS solution thus making the scaling law more general.

In the next section the derivation of the scaling law is presented, followed by a model to account for mean-flow interaction effects in Section 3.. Results from the scaling law are compared with experimental data for 14 different operation conditions in Section 4. The paper ends with conclusions about this study and the nexts steps in this research.

2. RANS-BASED SCALING LAW

Lighthill (1952, 1954) showed that the sources of jet noise can be described by three components related to fluctuations of momentum, entropy and viscous stresses. The model by Ilário *et al.* (2011) follows the theory by Lighthill however discarding the entropy and viscous components. Predictions agree well with experiments for unheated jets, however empirically adjusted coefficients are needed to maintain the same level of accuracy for heated jets. To develop a model for the entropy component the scaling law presented in this paper is used to assess the magnitude of this component and its relation with a RANS $k-\varepsilon$ solution.

The equation presented by Lighthill (1952) is an exact rearrangement of the equations of motion with the wave operator in the LHS and a distribution of equivalent sound sources in the RHS:

$$\frac{\partial^2 \rho}{\partial t^2} - a_\infty^2 \nabla^2 \rho = \frac{\partial^2 \mathcal{T}_{ij}}{\partial x_i \partial x_j}, \tag{1}$$

where ρ is the fluid density, a is the speed of sound, the subscript ∞ denotes the property at the far field and $\mathcal{T}_{ij}$ is the Lighthill stress tensor. The tensor is given by

$$\mathcal{T}_{ij} = \rho U_i U_j + \delta_{ij}\left(p - a^2\rho\right) + \epsilon_{ij}, \tag{2}$$

where U_i is the velocity vector, p is the pressure, and ϵ_{ij} the viscous stress tensor. The term $\rho U_i U_j$ is the momentum component, $\delta_{ij}\left(p - a^2\rho\right)$ is the entropy component and the third component is readily discarded because viscous stresses are negligible in turbulent flows.

The solution of Eq. 1 by the free-field Green's function yields (Goldstein, 1976)

$$\overline{p^2\left(\mathbf{x}\right)} \propto \frac{1}{a_\infty^4 r^2} \iint \frac{\partial^4 \overline{\mathcal{T}_{xx}\mathcal{T}'_{xx}}}{\partial t^4} d\boldsymbol{\xi} d\mathbf{y}, \tag{3}$$

where $\overline{p^2\left(\mathbf{x}\right)}$ is the mean square acoustic pressure at the far field, $\mathbf{x}$ is the observer position, r is the distance between the observer and the nozzle exit, $\overline{\mathcal{T}_{xx}\mathcal{T}'_{xx}}$ is the two-point correlation of $\mathcal{T}_{ij}$ in the direction of the observer, $\mathbf{y}$ is the source coordinate and $\boldsymbol{\xi}$ is the separaction vector of the correlation.

To proceed with the derivation of the scaling law, it is assumed that the correlation scales with the magnitude of the tensor in the form

$$\overline{\mathcal{T}_{xx}\mathcal{T}'_{xx}} \propto \mathcal{T}^2. \tag{4}$$

where $\mathcal{T}$ is the magnitude of $\mathcal{T}_{ij}$ in the direction of the observer. As the viscous stresses component is neglected, $\mathcal{T}$ is split in two components so that

$$\mathcal{T}^2 = \mathcal{T}_\mathrm{m}^2 + \mathcal{T}_\mathrm{e}^2, \tag{5}$$

with $\mathcal{T}_\mathrm{m}$ and $\mathcal{T}_\mathrm{e}$ the momentum and entropy components, respectively (shown in the exact form in Eq. 2). Note that Eq. 5 is akin to assuming both components are completely uncorrelated (as done by Harper Bourne (2007)).

It is assumed that the momentum component takes the form

$$\mathcal{T}_\mathrm{m} = c_\mathrm{m}\bar{\rho}k, \tag{6}$$

where c_m is an empirical coefficient, the overbar denotes the mean of the property, and k is the mean turbulent kinetic energy per unit mass. This model can be traced back to the theory on two point velocity correlations by Batchelor (1953).

To model the entropy component the form proposed by Fisher *et al.* (1973) is considered so that

$$\mathcal{T}_\mathrm{e} \propto \frac{\bar{\rho}\,\bar{a}^2}{C_p} s', \tag{7}$$

where C_p is the specific heat at constant pressure, s is the entropy and $'$ denotes turbulent fluctuations. Fisher *et al.* (1973) followed by proposing that the entropy fluctuations are related to global properties of the jet as

$$s' \sim s_j - s_\infty = C_p \ln\left(\frac{T_j}{T_\infty}\right). \tag{8}$$

In order to make the scaling law more general by using local flow information the relation is modified to

$$s' = s - \overline{s} = C_p \ln\left(\frac{T}{\overline{T}}\right), \tag{9}$$

$$= C_p \ln\left(\frac{T' + \overline{T}}{\overline{T}}\right), \tag{10}$$

$$= C_p \ln\left(\frac{T'}{\overline{T}} + 1\right). \tag{11}$$

Unfortunately the available RANS solution does not provide information about temperature fluctuations. As in Eq. 8 for the entropy, it could be assumed that the temperature fluctuation is related to a global temperature difference such as $T_j - T_\infty$. But following with the use of local information instead of global properties, a *local temperature difference* is envisaged. The natural choice is to compute the local gradient and multiply it by a relevant length scale in the form

$$T' \sim |\nabla T| \, \ell, \tag{12}$$

where ℓ is length scale representing the mixing process that leads to temperature fluctuations. However somewhat arbitrary, this assumption is physically and dimensionally coherent and leads to good prediction as shown in Section 4.
.

With the new relation between the entropy fluctuations and temperature fluctuations (Eq. 11), and the relation between temperature fluctuations and its gradient (Eq. 12) the proposed model for the entropy component is

$$\mathcal{T}_{\mathrm{e}} = c_{\mathrm{e}} \bar{\rho} \bar{a}^2 \ln \left(\frac{|\nabla \bar{T}|}{\bar{T}} \ell + 1 \right), \tag{13}$$

where c_{e} is an empirical coefficient.

Additionally, the following substitutions are made:

$$\frac{\partial}{\partial t} = \tau^{-1}, \tag{14}$$

$$\int d\boldsymbol{\xi} = \ell^3, \tag{15}$$

where τ is a local time scale. It is assumed that the time and length scales take the form of the standard RANS $k - \varepsilon$ scales:

$$\tau = \frac{k}{\varepsilon}, \tag{16}$$

$$\ell = \frac{k^{3/2}}{\varepsilon}, \tag{17}$$

where ε is the turbulent dissipation rate per unit mass. These scales are related to the process of turbulent momentum transfer, and thus it is coherent to apply them for the model of the momentum component. For the entropy source, however, it could be argued that a length and time scales related to heat transfer process are necessary. Nevertheless, good predictions were achieved by applying the same scales for both momentum and entropy sources, showing that this possible flaw in the model do not lead to great prediction errors.

Finally, the far-field pressure can be computed by

$$\overline{p^2(\mathbf{x})} = \frac{1}{a_\infty^4 r^2} \int \left(\mathcal{T}_{\mathrm{m}}^2 + \mathcal{T}_{\mathrm{e}}^2 \right) \tau^{-4} \ell^3 d\mathbf{y}, \tag{18}$$

with the integral in $\mathbf{y}$ being performed numerically over the RANS grid.

3. MEAN-FLOW INTERACTION

If Lighthill's equation (Eq. 1) is written in a coordinate system moving with the source at the local mean flow velocity the following *flow factor* appears in the integral of Eq. 18:

$$F = (1 - M_c \cos\theta)^{-m}, \tag{19}$$

where $M_c \equiv U_1/a_\infty$ is the convective Mach number and θ is the polar angle (between the jet axis and the observer position). Such predicts an amplification at low polar angles (downstream the jet exit) and attenuation at higher polar angles; an effect observed experimentally (Lush, 1971).

Following the theory Lighthill (1952) showed that $m = 6$, which was corrected by Ffowcs Williams (1963) to $m = 5$ to account for a limited source volume. Based on measurements Harper Bourne (2003) showed that m should vary with frequency approximately in the range between 2 and 4.

If instead the equation presented by Lilley (1972) is used, Self (2005) showed that it results in $m = 4$. As the theory by Lilley results in a better description of the effects of mean-flow interaction and the numerical value of m from its solution is closer to the empirical value by Harper Bourne (2003), $m = 4$ is the value used for the computations in this paper.

4. RESULTS

To assess the scaling law 14 single-stream jets with operating conditions in Table 1 were analysed. These cases comprise 3 different jet velocities and 5 temperatures covering the subsonic range present in commercial aircraft[1]. Although the cases are for the simple single stream axysimmetric jet, it is expected that valuable information about the sources of noise can be infered from these cases. For each case a matching RANS simulation by Ilário (2011) using the standard $k - \varepsilon$ solver in ANSYS Fluent 6.3.26 was available.

To compute the results in this section the coefficients in Eqs. 6 and 13 are computed by a best fit of numerical OASPL with experimental data, taking following values

$$c_{\mathrm{m}} = 0.6010, \tag{20}$$

$$c_{\mathrm{e}} = 0.0135. \tag{21}$$

The direct result of the scaling law is the pressure magnitude in the far field as computed from Eq. 18. The results are written in dB and compared with experimental OASPL results in Fig. 1. It is shown how the scaling law capture well the effect of velocity and temperature in the subsonic range. Results for the low speed jet $(Ma \equiv {}^{U_j}/_{a_\infty})$ are optimum and there is gradual loss of accuracy for the higher speed jets. Harper Bourne (2007) shows that the dependency of the scaling law with density should vary with the velocity, which is not considered in this paper. But before assuming this is so, it could also be argued that the way both sources are correlated changes with velocity or that an additional source—related to large scales of turbulence, for instance—is more significant for higher speed jets. This loss of accuracy is, however, sacrificed to keep the generality of the scaling law presented in this paper.

Propagation effects for moderated polar angles are also presented in Fig. 1. It is shown that the model for the convective amplification captures well the experimental trends for the two lower speeds in the 60^o–120^o range. For the higher speed jet the results are degraded, notably at 60^o. At this higher velocity the angle defining the cone of silence gets closer to 90^{o}is higher, so it is not so clear anymore that convective amplification dominates at 60^o. Moreover, a third source component might also start to play a role at higher speed and lower polar angle.

To analyse each component individually Fig. 2 shows OASPL results at 90° with the contribution of both the momentum component, $\mathcal{T}_{\mathrm{m}}^2$, and the entropy component $\mathcal{T}_{\mathrm{e}}^2$. It is shown how the entropy component is negligible for cold jets (the right most result for a given jet velocity) but significant for all heated jets, even at high speed.

An indirect computation of sound pressure level (SPL) is possible by following the idea of a *master spectrum* by Tanna *et al.* (1975). The experimental spectrum at 90° for case 10 is associated with the momentum component and the spectrum of case 5 with the entropy component. Figure 3 shows these two experimental spectra shifted so their peak-SPL are at 0 to highlight their different decay with frequency. It is clear that the momentum spectrum is flatter, whereas both present a similar peak-Strouhal-number.

To compute the numerical shifted spectrum for any of the 14 cases the contribution of the momentum and entropy components to the OASPL are computed following the same procedure as for the results in Fig. 2. Each master spectra is then shifted iteratively until its integral in frequency matches the contribution to the OASPL from the respective component. Finally, for each 1/3 octave band both spectra are summed as in $\left(\mathcal{T}_m^2 + \mathcal{T}_e^2\right)$.

Results in Fig 4 (for cases 1, 5, 6, 9, 10 and 14) show that this procedure results in good agreement with experimental data. It is expected that the level of the spectra would be close to the experimental levels as the OASPL results also agree well with experimentals. But more surprisingly the overall shape of the spectra (peak-SPL and decay with frequency) is well described by the squared sum of the two aforementioned master spectra.

[1]Experimental data from SYMPHONY project, part of the UK Technology Strategy Board contract TP11/HVM/6/I/AB201K.

Table 1. Cases information, single-stream jet with $D_j = 0.1016\mathrm{m}$.

Case	1	2	3	4	5	6	7	8	9	10	11	12	13	14
U_j/a_∞			0.50				0.75					1.00		
T_j/T_∞	1.00	1.25	1.50	2.00	2.50	1.00	1.50	2.00	2.50	1.00	1.25	1.50	2.00	2.50

The subscript j denotes the property is computed at the nozzle exit.

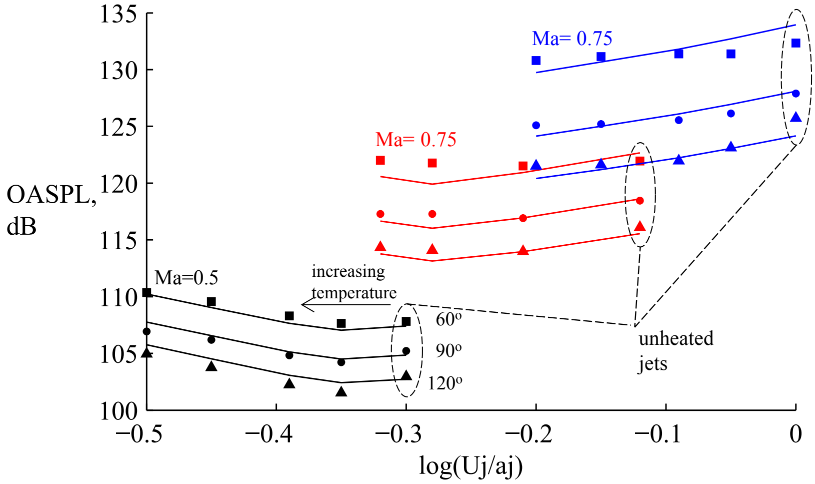

Figure 1. Comparison of scaling law results and experimental data of OASPL at different observer angles. Black lines and symbols for $M_a \equiv U_j/a_\infty = 0.5$, red for $M_a = 0.75$, and blue for $M_a = 1.00$. Solid lines are predictions with the scaling law and symbols are experimental results for polar angles: ▲, 120°; ●, 90°; ■, 60°.

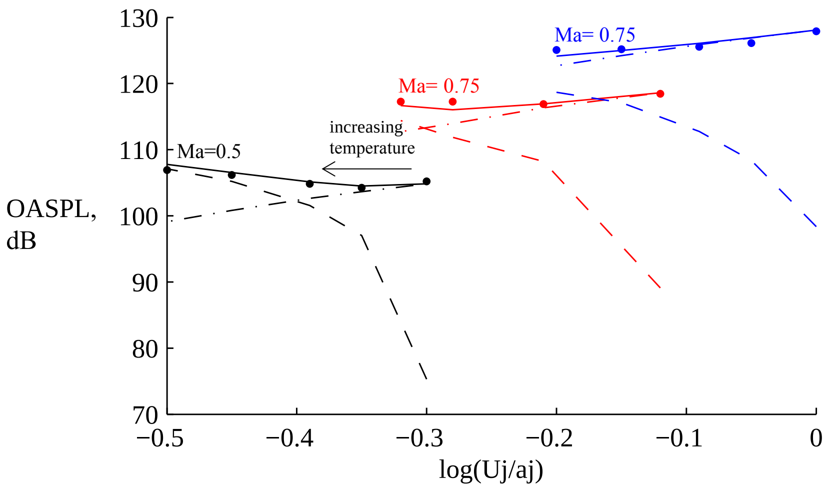

Figure 2. Numerical results from the scaling law for the different source components at 90° (same colour code as in Fig. 1): —, complete source term $\left(\mathcal{T}_\mathrm{m}^2 + \mathcal{T}_\mathrm{e}^2\right)$; $-\cdot$, momentum component $\mathcal{T}_\mathrm{m}^2$; $---$, entropy component $\mathcal{T}_\mathrm{e}^2$.

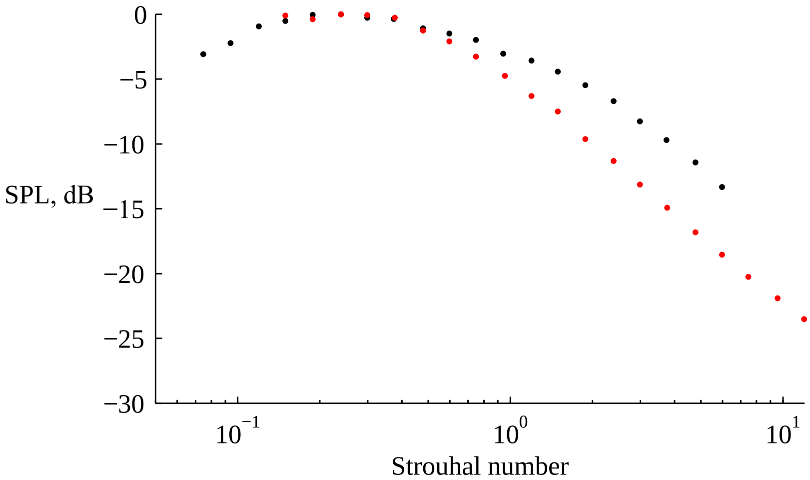

Figure 3. Master spectra in 1/3 octave bands for momentum (black dots) and entropy (red dots) source components.

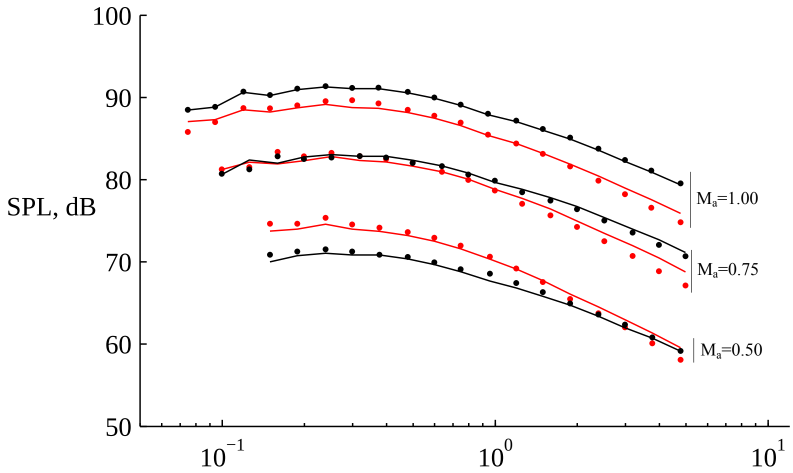

Figure 4. Comparison of experimental (dots) and shifted (solid lines) sound pressure level in 1/3 octave bands from unheated (black dots and lines) and heated (red dots and lines) jets. Results for three different acoustic Mach numbers: 0.50, 0.75 and 1.00.

5. CONCLUSIONS

There is a vast literature concerned with jet noise where the problem is approached in different ways as cited in the introduction. Among the different approaches, the use of a RANS $k-\varepsilon$ solution with an acoustic analogy results in a good trade-off between accuracy and computational cost sought by the industry. A significant drawback of such approach is that as no transient information is available so the high-order statistics present in the source term of the theory must be modelled from the available lower order mean values. Nevertheless, significant improvements on RANS-based methods has been made (Khavaran and Krejsa, 1999; Tam and Auriault, 1999; Morris and Farassat, 2002; Self and Azarpeyvand, 2008; Ilário, 2011) and this paper adds to the effort in developping a RANS-based jet noise prediction method.

The scaling law presented in this paper is used to assess the entropy source component neglected in the model of Ilário *et al.* (2011). The following remarks can be made from the analysis and results presented in the previous sections:

1. The use of local information of the flow instead of properties at the nozzle exit results in a scaling law less dependent on similarities of the flow while still keeping its simplicity. The presented scaling could be used *per se* to predict trends of jet noise reduction or—as the main objective of this study—as a means to further understand the mechanisms of noise generation and their relation with a RANS $k-\varepsilon$ solution.

2. The magnitude of the entropy source component scales with properties gathered from a RANS $k-\varepsilon$ solution as

$$\mathcal{T}_{\mathrm{e}} \propto \bar{\rho}\bar{a}^2 \ln\left(\frac{|\nabla\bar{T}|}{\bar{T}}\frac{k^{3/2}}{\varepsilon}+1\right). \tag{22}$$

This result can be used to develop a model to compute the contribution of the entropy component to the total noise spectrum by modelling correlations of the source term —as for the momentum component in Ilário *et al.* (2011).

3. The good predictions of OASPL for 60^o and 120^o show that the convective amplification effect modelled by the flow factor in Section 3. is the dominant mean flow effect for an observer near 90^o to the jet axis.

4. The assumption that the momentum and entropy components are totally uncorrelated results in optimum results for the low speed jet ($U_j/a_\infty = 0.5$) with a loss in accuracy for the higher speed jets. Additionally to a dependency of source nature with jet speed (Harper Bourne, 2007), it could be argued that the sources can become somewhat correlated for higher speed jets.

To move forwards with the development of a RANS-based entropy source model information about the correlations in Eq. 3 must be gathered from transient properties of the flow. Measurements of such properties are not pratical, so a possibility is to use numerical results of a Large Eddy Simulation for a heated jet. The strength of these correlations should be compared with the result in Eq. 22 and the shape of the correlation should be compared with functional forms such as a Gaussian used to model the momentum correlations. Moreover, a good understanding of the distribution of length and time scales of these correlations will empower its modelling by a RANS solution.

Another possibility is to assume *a priori* that the correlations of the entropy source component have the same form of the momentum-related correlation (*i.e.*, separable in space and time and modelled by a Gaussian function) and empirically adjust the parameters so to match experimental spectra. However not an ideal solution, this could be a viable way to continue the study presented in this paper.

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