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A method for predicting static-to-flight effects on coaxial jet noise

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ABSTRACT

Previously-published work has provided a theoretical modelling of the jet noise from coaxial nozzle configurations in the form of component sources which can each be quantified in terms of modified single-stream jets. This modelling has been refined and extended to cover a wide range of the operating conditions of aircraft turbofan engines with separate exhaust flows, encompassing area ratios from 0.8 to 4. The objective has been to establish a basis for predicting the static-to-flight changes in the coaxial jet noise by applying single-stream flight effects to each of the sources comprising the modelling of the coaxial jet noise under static conditions. Relatively few experimental test points are available for validation although these do cover the full extent of the jet conditions and area ratios considered. The experimental results are limited in their frequency range by practical considerations but the static-to-flight changes in the third-octave SPLs are predicted to within a standard deviation of 0.4 dB although the complex effects of jet refraction and convection cause the errors to increase at low flight emission angles to the jet axis. The modelling also provides useful insights into the mechanisms involved in the generation of coaxial jet noise and has facilitated the identification of inadequacies in the experimental simulation of flight effects.

1. Introduction

The prediction of the jet noise produced by aircraft jet engines is, and has been for many years, an important commercial requirement. For single-stream turbo-jet engine configurations, the number of variables involved is relatively small and noise measurements from model-scale nozzles tested in anechoic chambers provided databases covering a wide range of jet operating conditions. Following that, methods were developed for predicting the jet noise when the nozzle is static and, by using flight-simulation techniques, for the changes that take place in going from static to flight conditions. There is, for example, an ESDU method based on the interpolation of a model-scale database obtained under static conditions [1] and an ESDU method for predicting the static-to-flight effects [2] based on theoretical considerations by Bryce [3] to enable the necessarily smaller amount of model-scale experimental data in simulated flight to be utilized effectively.

The introduction of turbofan engines with separate bypass and core nozzles greatly increased the number of variables involved and this complicated the formulation of effective noise-prediction methods.

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Nomenclature

a_0	ambient speed of sound (m/s)
A	jet nozzle exit area (m^2)
AR	A_s / A_p
D	jet nozzle diameter (m)
F_d	fraction of the total jet acoustic energy generated downstream of a specified axial position in the jet (Eq. (8))
F_u	fraction of the total jet acoustic energy generated upstream of a specified axial position in the jet (Eq. (9))
f	frequency (Hz)
f_c	cut-off frequency (3 dB down point)
h	ratio of secondary nozzle annulus height to primary nozzle radius
h'	parameter defined by Eq. (17)
k	ratio of the dipole noise to the quadrupole noise (Eq. (7))
$OASPL$	overall sound pressure level (dB)
r	turbulence intensity ratio
S	Strouhal number
SPL	third-octave sound pressure level (dB)
T	jet static temperature (K)
T_0	ambient temperature (K)
V	jet exit velocity (m/s)
V_a	flight velocity (m/s)
VR	V_s/V_p
β	$A_s/A_p = AR$
δ	T_p/T_s
θ	microphone angle to jet axis (deg)
θ_e	sound emission angle to jet axis (deg)
λ	V_a / V_s
ν	$V_s/V_p = VR$
ρ	jet density (kg/m^3)
τ	T_p/T_0
ψ	logarithmic ratio of frequency to cut-off frequency (Eq. (13))

Subscripts

s	correspond to the secondary jet
p	correspond to the primary jet
m	correspond to the mixed jet
i	correspond to the interaction jet

In the late 1990s, Fisher et al. at the ISVR, Southampton University formulated a theoretically-based model for the noise from coaxial jets, initially for isothermal jets and then, more realistically, for jets with a hot primary flow [4,5]. While their model showed promise, it did not display a sufficient accuracy and its applicability was limited by the then available model-scale data which was limited to one area ratio of 2. For brevity, this work will be described henceforth as the ISVR model.

Following the availability of a substantial experimental database, ESDU extended their single-stream interpolation methodology to predict coaxial jet noise under static conditions [6]. But the prediction of static-to-flight effects for coaxial jets, with reasonable confidence, has proved elusive because of the impractically large number of variables.

The ISVR approach was based on the identification, quantification and then the addition of the separate components contributing to the overall noise. These component sources were defined by considering them as single-stream jets – with appropriate modifications. Three sources were postulated; the initial mixing of the outer, bypass or secondary jet with the ambient air, the downstream mixed-flow region and a complex interaction region where the primary or core jet flow merges into the secondary mixing region. Research on isothermal jets [7] had shown that the noise from this interaction region correlated with the primary jet velocity and this observation stimulated this approach.

The various jet velocities involved, those of the primary flow, the secondary flow and the mixed flow are not hugely different in magnitude. Hence it is argued that, if a *reasonably* accurate estimate of the balance between the various sources can be obtained under static conditions, it should be possible to predict the static-to-flight effects to a useful accuracy by applying single-stream jet flight effects to the component sources. Note that the principal objective of this work is not essentially to replace the prediction of coaxial jet noise under static conditions as can currently be done effectively by interpolation but to use coaxial jet modelling to cope with the further complexities and the lack of experimental data arising from flight conditions. On reflection, this approach can be seen to mirror the circumstances which arose decades ago with the prediction of single-stream jet noise as outlined above.

It is therefore the object of the work described herein to 1) extend the range of applicability of the ISVR model to cover the area ratios, velocity ratios and flight conditions of turbofan engines, 2) to improve the quality of the predictions of the model-scale experimental results under static conditions and then 3) to examine the extent to which the calculated static-to-flight effects reflect the experimental results obtained from the relatively few test points available. Whereas theoretical considerations are to be employed as far as possible, inevitably with complex sources, some arbitrariness is unavoidable.

In the process of seeking a practical and justifiable method for the prediction of static-to-flight effects on coaxial jet noise, many avenues have been explored in developing the formulation that is presented but it is beyond the scope of this paper to discuss the possible refinements that have been considered. Except in one or two instances.

The present study began with the application of the ISVR modelling to a substantial model-scale database for both isothermal jets and jets with heated primary flows. However, as the process of developing improvements to the modelling progressed, it became clear that significantly different formulations would be required to obtain the best modelling for the