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ESDU 14014

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

Associated software: ESDUpac A1414
ESDUpac B1414
VIEWpac M1414
VIEWpac MG1414

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A THEORETICALLY-BASED METHOD FOR PREDICTING STATIC-TO-FLIGHT EFFECTS ON COAXIAL JET NOISE

CONTENTS

		Page
1.	NOTATION	1
2.	INTRODUCTION	3
3.	VISUALIZATION OF THE COAXIAL JET	4
4.	THE STRUCTURE OF THE PREDICTION METHOD	5
5.	THE THREE-SOURCE MODEL COMPONENTS	5
5.1	Secondary Jet	5
5.2	Mixed Jet	6
5.3	Interaction Jet	7
6.	PREDICTING THE COMPONENT SPECTRA	10
6.1	Static	10
6.2	Flight	10
7.	VALIDATION	10
7.1	Database	10
7.2	Accuracy	11
8.	COMPUTER PROGRAMS	13
8.1	Input and Output Data	13
9.	DERIVATION AND REFERENCES	17
10.	EXAMPLE	18
10.1	Computer Runs	18
APPENDIX A –	ESDU DATA FILE	28
A.1	ADDITONAL NOTATION	28
A.2	DATA FILE STRUCTURE STANDARD	30
A.3	USING THE DATA FILE	30

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Full document details: ESDU 14014-R2 2018

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1. NOTATION

		Units	
		SI	*British*
A_j	area of jet component	m^2	ft^2
A_p	geometric area of primary stream	m^2	ft^2
A_s	geometric area of secondary stream	m^2	ft^2
AR	area ratio, A_s/A_p		
AR'	area ratio based on flow areas [see Equation (5.7)]		
a_0	ambient speed of sound'	m/s	ft/s
C_d	nozzle discharge coefficient		
D_j	nozzle diameter of jet component	m	ft
D_p	equivalent primary jet nozzle diameter $\left(= \sqrt{\frac{4\,A_p}{\pi}}\right)$	m	ft
D_s	equivalent secondary jet nozzle diameter $= \left(\sqrt{\frac{4(A_p + A_s)}{\pi}}\right)$	m	ft
F_D	spectral weighting for secondary jet	dB	dB
F_U	spectral weighting for mixed and interaction jets	dB	dB
f	frequency	Hz	Hz
f_m	cut-off frequency for mixed jet	Hz	Hz
f_s	cut-off frequency for secondary jet	Hz	Hz
h'	modified ratio of secondary annulus height to the primary radius (see Equation (5.21))		
k	ratio of dipole to quadrupole source strengths	–	–
$OASPL$	overall sound pressure level	dB†	dB†
p_{ISA}	ambient pressure under ISA conditions	kPa	lbf/ft^2
p_0	ambient pressure	kPa	lbf/ft^2
r	sound propagation distance (see Sketch 1.1)	m	ft

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r'	ratio of turbulence levels		
S	Strouhal number, $S = fD_j/V_j$		
SPL	one-third octave band sound pressure level	dB	dB
T_j	static temperature of jet component	K	K
T_p	primary jet static temperature	K	K
T_s	secondary jet static temperature	K	K
T_0	ambient temperature	K	K
V_a	flight velocity	m/s	ft/s
V_j	fully-expanded velocity of jet component	m/s	ft/s
V_p	fully-expanded primary jet velocity	m/s	ft/s
V_s	fully-expanded secondary jet velocity	m/s	ft/s
VR	velocity ratio, V_s/V_p		
Δ	correction for difference in turbulence levels	dB	dB
ρ_p	density of primary jet flow	kg/m^3	‡
θ_e	flight emission angle (see Sketch 1.1)	degree	degree
θ_j	angle between line to observer and engine exhaust axis for static jet	degree	degree

Subscripts

i	interaction jet
m	mixed jet
p	primary jet
s	secondary jet

† The reference pressure for all decibel levels is 20 μPa (*i.e.* 2×10^{-5} N/m^2) or 0.42×10^{-6} lbf/in^2.

‡ A density value expressed in British units as lb per cubic foot has to be divided by 32.2 before the calculation for A_p shown in Equation (5.2) is carried out. (A force of 1 lbf acting on a mass of 1 lb produces an acceleration of 32.2 ft/s^2.)

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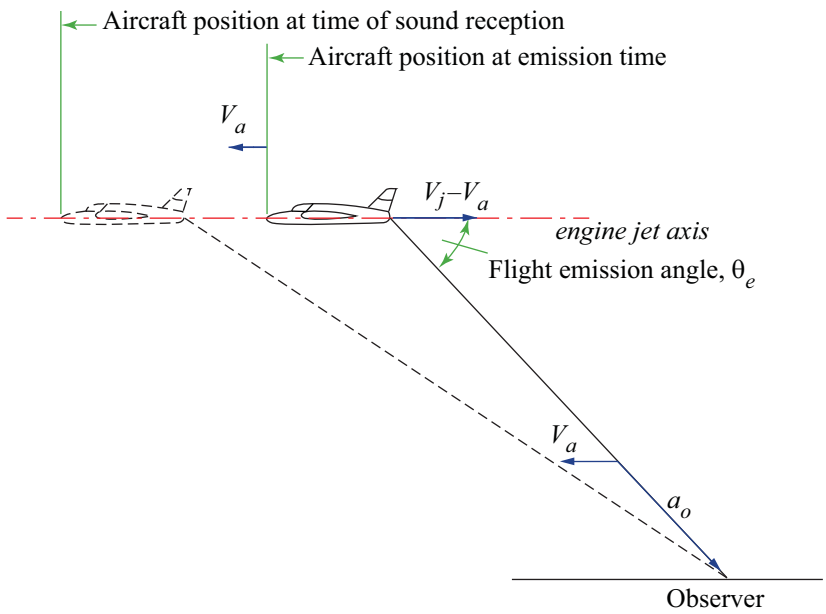

Sketch 1.1

2. INTRODUCTION

ESDU 14014 provides a computerized method for estimating static-to-flight effects on coaxial jet noise. It is intended that this method should be applicable to aircraft turbofan engines with separate core and bypass exhaust nozzles and with a hot core flow. The method is a theoretically-based one which reflects the known aerodynamic characteristics of both single-stream and coaxial jets. An account of the development of the prediction method, which is based on the coaxial jet modelling described in References 2 and 3, is given in Derivation 1 which is an internal ESDU technical memorandum available on request.

In essence, the method breaks up the coaxial jet mixing noise into three single-stream jet noise sources which can be predicted using Reference 4, modified appropriately and then summed. To each of these sources, the static-to-flight effect estimation procedure for single-stream jets described in Reference 1 is applied. The three spectra are then recombined to provide a flight spectrum. The difference between this flight spectrum and the static spectrum provides the static-to-flight effects for a coaxial jet.

It is postulated that the prediction accuracy of the changes in going from static to flight conditions should be substantially better than the prediction accuracy of the absolute spectral levels. Thus when predicting a flight spectrum:

(a) for the greatest accuracy, these calculated static-to-flight effects should be applied to a measured static spectrum,

(b) alternatively the method given in ESDU 11002 (Reference 5) may be used to predict a static spectrum,

(c) if neither of these options is available the flight spectrum generated here may be used, but the errors will be greater.

As stated above, the computer programs that accompany this Item can be used to predict flight spectra either directly or from static spectra input by the user. In the first case, flight spectra are predicted at angles

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specified by the user, whereas in the second, flight spectra are predicted at the same angles as those of the static spectra.

The prediction method has been developed for a coplanar exhaust configuration but is considered to be applicable to jets with short centre-bodies and for cases where the secondary stream emerges a little upstream of the primary nozzle exit plane, as, for example, in a "three-quarter cowl" configuration of an engine exhaust system.

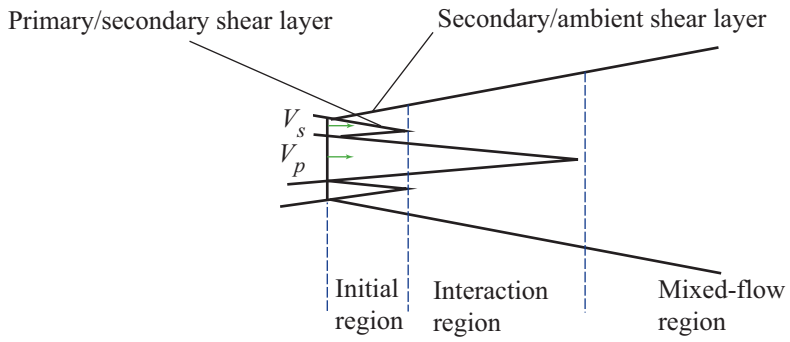
The method is not applicable to mixed exhaust configurations or non-circular nozzles and does not take into account any acoustic or aerodynamic installation effects.

By using fully-expanded jet velocities, the method can be applied to the mixing noise of supercritical jets although this has not been validated with experimental data. The noise arising from shock-associated sources is not included.

3. VISUALIZATION OF THE COAXIAL JET

The representation of the noise creating mechanism of a coaxial jet is extremely complex. The three-source model (References 2 and 3) is an attempt to simplify matters by representing the noise from a coaxial jet by the sum of three separate single-stream jets, each with specific operating conditions and dimensions.

The noise-producing regions of a coaxial jet for an aero-engine are illustrated in Sketch 3.1.



Sketch 3.1 Noise-producing regions

An overview of the noise characteristics of each of these regions is given here before the governing equations for the different parameters are presented.

In the outer part of the initial region, the mixing of the secondary jet with the ambient air can be represented as the high-frequency part of a single-stream jet with the secondary jet velocity, temperature and nozzle diameter. This region is subjectively important because it generates high-frequency noise and because it contributes substantially to the total jet noise at other than low secondary-to-primary velocity ratios. This jet is referred to as the secondary jet.

In the far downstream region, where the primary and secondary flows become well mixed, the noise generated is at low frequencies and characterized by the low-frequency part of a single-stream jet at the mixed-flow jet velocity, temperature and diameter. This jet is referred to as the mixed jet.

A third region is the interaction zone where the primary jet generates noise by its interaction with the secondary jet shear layer. This is the most difficult region to characterize. Its noise is deemed to depend on

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the primary jet velocity but at a level lower than that of an isolated single-stream jet. This jet is referred to as the interaction jet.

In addition to the noise sources from these three regions, there is a fourth noise source arising from the shear layer between the primary and secondary flows in the initial region of the jet. However, this source has been found to be of little significance in the context of aero-engines and has been neglected in the modelling.

4. THE STRUCTURE OF THE PREDICTION METHOD

The three main components of the prediction method are:

(i) the specification of the single-stream jet parameters describing the individual components of the coaxial jet as three single-stream jets, together with the spectral cut-off and other modifications required to each,

(ii) the prediction of the static noise spectra for each of the three sources and

(iii) the calculation and application of the static-to-flight effects for each of the three sources.

Each of these stages is detailed in the following Sections. There are several complex issues involved in the modelling which, for the sake of brevity, are specified below without explanation. The reader is referred to Derivation 1 for elucidation.

5. THE THREE-SOURCE MODEL COMPONENTS

The three-source model represents the coaxial jet by three single-stream jets, each with its own characteristics, viz.

(i) the secondary jet,

(ii) the mixed jet and

(iii) the interaction jet.

The specific parameters of each single-stream jet required for predicting its noise spectra are the fully-expanded jet velocity, V_j, the jet static temperature T_j, the jet nozzle diameter D_j and the area A_j.

It is then necessary to specify what spectral or other modifications should be applied to the predicted spectra.

Such details for each of the three jet components are given in the sections below.

5.1 Secondary Jet

The mixing of the secondary jet with the ambient air can be represented by a single-stream jet at the secondary jet flow conditions and nozzle diameter. This jet is cut off at low frequencies. Somewhat arbitrarily, the cut-off frequency is taken to be that at a Strouhal number of unity, which corresponds roughly to the end of the potential core of the jet.

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Jet Parameters

$$V_j = V_s \tag{5.1}$$
$$T_j = T_s \tag{5.2}$$
$$D_j = D_s \tag{5.3}$$
$$A_j = A_s \tag{5.4}$$

Spectral Modification

To cut off the single-stream jet spectrum calculated with the above parameters, the predicted sound pressure levels, $SPL_s(f)$, are modified by the addition of a frequency weighting to give

$$SPL_s(f) + 10\log F_u(f)$$

where

$SPL_s(f)$ is the estimated noise spectrum of the secondary jet,

$$F_u(f) = 1 - e^{-4f/f_s} \cdot \left[1 + \frac{4f}{f_s} + \frac{1}{2}\left(\frac{4f}{f_s}\right)^2 + \frac{1}{6}\left(\frac{4f}{f_s}\right)^3\right] \tag{5.5}$$

and where the cut-off frequency corresponding to a Strouhal number of unity is given by

$$f_s = \frac{V_s}{D_s}. \tag{5.6}$$

5.2 Mixed Jet

Downstream of the potential core of the primary jet, where the flows from the primary and the secondary jets are deemed to have combined, the noise generated is at low frequencies and is characterized by the mixed-flow jet conditions. This jet is cut off at high frequencies.

In this region, it is required on theoretical grounds to take into account the discharge coefficients of both the primary and the secondary nozzle flows. Consequently an area ratio based on the nozzle flow areas, viz.

$$AR' = AR.\ \frac{C_{ds}}{C_{dp}} \tag{5.7}$$

has been used in determining the jet parameters. This is not a factor which is of significance in the aero-engine context and, if the discharge coefficients are not known, a value of unity should be entered.

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Jet Parameters

$$V_j = V_m = V_p \cdot \frac{1 + VR^2 \cdot AR' \cdot TR}{1 + VR \cdot AR' \cdot TR} \tag{5.8}$$

$$T_j = T_m = T_p \cdot \frac{1 + VR \cdot AR'}{1 + VR \cdot AR' \cdot TR} \tag{5.9}$$

$$D_j = D_m = D_p \sqrt{\frac{(1 + VR \cdot AR') \cdot (1 + VR \cdot AR' \cdot TR)}{(1 + VR^2 \cdot AR' \cdot TR)}} \tag{5.10}$$

$$A_j = A_m = \pi D_j^2/4 \tag{5.11}$$

Spectral Modification

The spectral correction to the mixed jet is applied in a similar manner to that of the secondary jet, the predicted spectral levels, $(SPL_m(f))$, being modified to

$$SPL_m(f) + 10\log F_D(f)$$

where

$SPL_m(f)$ is the estimated noise spectrum of the mixed jet,

$$F_D(f) = e^{-4f/f_m} \cdot \left[1 + \frac{4f}{f_m} + \frac{1}{2}\left(\frac{4f}{f_m}\right)^2 + \frac{1}{6}\left(\frac{4f}{f_m}\right)^3\right] \tag{5.12}$$

and where the cut-off frequency is given by

$$f_m = \frac{V_m}{D_m} \quad . \tag{5.13}$$

5.3 Interaction Jet

The region in which the primary jet flow interacts with the secondary shear layer is complex both aerodynamically and acoustically. However, two key observations have enabled the noise from this region to be modelled. Firstly, experimental data from isothermal coaxial jet tests showed that (after making allowances for the noise from the secondary and the mixed jet components) the interaction noise correlated well with the eighth power of the primary velocity at 90° to the jet axis – as would be expected for an isolated jet at the primary velocity. But, secondly, turbulence measurements in this region of coaxial jets have shown a lower level than would be expected for an isolated jet. Hence the interaction noise is modelled by a jet at the primary flow conditions but with the predicted noise levels reduced as a consequence of the reduced turbulence intensity.

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Jet Parameters

$$V_j = V_i = V_p, \tag{5.14}$$

$$T_j = T_i = T_p, \tag{5.15}$$

$$D_j = D_i = D_p\sqrt{1 + VR^2 \cdot AR} \qquad \text{when} \quad D_i < D_s$$

and

$$D_j = D_i = D_s \qquad \text{when} \quad D_i \geq D_s \tag{5.16}$$

$$A_j = A_i = \pi D_j^2/4 \tag{5.17}$$

Spectral Modifications

In addition to the correction for the reduced turbulence levels, the method in this Item includes both low and high frequency modifications and convective corrections to the spectral levels predicted for the interaction jet.

(a) The reduced-turbulence modification

For a hot jet, the correction for the reduced turbulence level of the interaction jet requires taking into account the balance between the dipole and the quadrupole noise sources. If the turbulence is reduced by a factor, r', then the noise reduction is given by

$$\Delta = 10\log r'^2\left[\frac{k + r'^2}{k + 1}\right]\text{dB}, \tag{5.18}$$

where

$$k = 7 \,.\, \frac{\left\{\dfrac{T_p/T_0 - 1}{V_p/a_0}\right\}^2}{1 + 0.65\left(\dfrac{T_p}{T_0 - 1}\right)} \tag{5.19}$$

The turbulence factor r' has been found to depend on the ratio of the secondary annulus height to the primary diameter modified to take account of the change in the secondary spreading rate in flight in the form

$$r' = 0.6[\exp(-0.7h')] + 0.4 \tag{5.20}$$

where

$$h' = \left(\frac{1 + V_a/V_s}{1 - V_a/V_s}\right) \,.\, (D_s/D_p - 1)\,. \tag{5.21}$$

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