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Supersedes ESDU 01004
and ESDU 86019
Amendment A
April 2014

The prediction of the far-field mixing noise from coaxial subsonic jets based on a database for stationary coplanar conical nozzles

Associated software: ESDUpac A1102
B1102
C1102
M1102



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THE PREPARATION OF THIS DATA ITEM

The work on this Data Item, which supersedes ESDU 86019 and ESDU 01004, was originally monitored and guided by the Jet Noise Working Party which had the following membership:

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THE PREDICTION OF THE FAR-FIELD MIXING NOISE FROM COAXIAL SUBSONIC JETS BASED ON A DATABASE FOR STATIONARY COPLANAR CONICAL NOZZLES

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THE PREDICTION OF THE FAR-FIELD MIXING NOISE FROM COAXIAL SUBSONIC JETS BASED ON A DATABASE FOR STATIONARY COPLANAR CONICAL NOZZLES

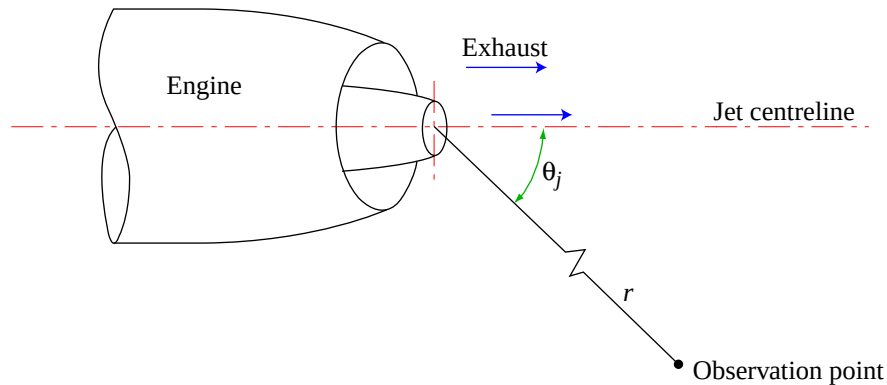
1. NOTATION

		Units	
		SI	British
A_p	flow area of primary stream [see Equation (3.2)]	m ²	ft ²
A_s	flow area of secondary stream [defined by an equation similar to Equation (3.2)]	m ²	ft ²
AR	area ratio, A_s/A_p		
a_0	ambient speed of sound	m/s	ft/s
D_j	reference jet nozzle diameter (see Section 3.2)	m	ft
f	frequency	Hz	Hz
$OASPL$	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
Q_p	primary jet mass flow	kg/s	lb/s
r	radial distance from centre of primary nozzle exit to observer	m	ft
SPL	one-third octave band sound pressure level	dB	dB
Sr	Strouhal number, $Sr = fD_j/V_p$		
T_{ps}	primary jet static temperature	K	K
T_0	ambient temperature	K	K
V_p	fully-expanded primary jet velocity	m/s	ft/s
V_s	fully-expanded secondary jet velocity	m/s	ft/s
ρ_p	density of primary jet flow	kg/m ³	†
θ_j	angle between line to observer and engine exhaust axis (see Sketch 1.1)	degree	degree

* The reference pressure for all decibel levels is 20 μ Pa (i.e. 2×10^{-5} N/m²) or 0.42×10^{-6} lbf/in².

† 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 (3.2) is carried out. (A force of 1 lbf acting on a mass of 1 lb produces an acceleration of 32.2 ft/s².)

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Sketch 1.1

2. INTRODUCTION

This Item provides a computerized method for estimating exhaust noise spectra from a given database. The procedure is an interpolation/extrapolation routine which, because of the variables considered, is applicable to estimating the noise from coaxial jets. Because the procedure is essentially one of interpolation of noise spectra, the particular form of the database need not be restricted to data for isolated coaxial jets. However, in other and more complex situations, due consideration must be given to the underlying physics of the noise generating process.

This method does not predict the shock-associated noise which can exist with supercritical jets. It can, however, be used to predict the mixing noise component of a supercritical jet by using the fully-expanded jet velocity.

In order to provide a basic prediction procedure and illustrate the use of this method, a comprehensive database is provided for the case of far-field, coaxial, static jet mixing noise.

An advantage of this method over other approaches is the ease with which the database may be replaced.

A simple introduction to jet mixing noise, together with other types of gas turbine exhaust noise, is given in ESDU 02020 (Reference 6). A computer-based estimation procedure for single-stream jet noise including a database for far-field jet mixing noise from circular nozzles for a stationary source is given in ESDU 98019 (Reference 4).

3. CALCULATION METHOD

3.1 General Description

The program predicts noise levels by carrying out a series of interpolations or, if necessary, extrapolations on an experimentally-derived database. The computation procedure utilises four independent variables. The fixed independent variables are the logarithms of the normalized primary jet velocity, $\log_{10}(V_p/a_0)$, the velocity ratio of the secondary to the primary jet flow, $\log_{10}(V_s/V_p)$, an area ratio dependent term, $\log_{10}(1 + AR)$, and the normalized primary jet temperature, $\log_{10}(T_{ps}/T_0)$. The choice of these particular variables is of significance in determining the quality of the predictions and they have not been chosen arbitrarily.

Fundamental jet noise theory leads to the noise being dependent on the velocities of the two jet streams normalized by the speed of sound in the ambient air. It is intuitively acceptable to represent the ballpark noise of a coaxial jet by using the normalized primary velocity and to express the balance between the primary and secondary jet noise sources using the velocity ratio.

The effect of the area ratio of the two streams in a coaxial jet has been seen as complex and unpredictable. However, the noise from the complex interaction region between the primary and secondary flows has been observed to be related to primary jet conditions (Reference 5). The noise from the secondary jet flow and that from the mixed jet region further downstream is, however, related to the outer diameter of the jet. Whereas the basic geometry of a coaxial jet is commonly expressed in terms of the secondary-to-primary area ratio, AR , the noise modelling suggests that a ratio of total-to-primary area would be more appropriate, thus suggesting a variable dependent on $(1 + AR)$. In the course of a further detailed analysis of coaxial jet noise with the objective of defining the effects of flight, this concept has been tested and found to relate well to the trends seen in measured data.

For aircraft bypass engines, the temperature of the secondary flow is similar to that of the ambient air. As this is the application for which this Data Item is intended, this similarity is assumed throughout. Insofar as quadrupole jet noise depends on the jet density, and the noise of hot jets has been found to correlate with the jet density raised to an empirical power, the effect of the temperature of the primary jet is characterized by the jet-to-ambient temperature ratio.

The sound pressure level of the noise in decibels depends on the logarithms of the terms described and hence the variables selected.

It must be noted that all parameters that influence jet noise other than the four independent variables are assumed constant, apart from those taken account of in the normalization process [Equation (3.1)]. The interpolation process is repeated through the Strouhal number range of interest for the appropriate sound radiation angle or angles. More details about the calculation procedure are provided in the next three sections.

3.2 Database Parameters

Any data that are input into the database are defined in terms of the parameters listed in Section 4.2.

Data may be input into the database only at values of θ_j that are integer multiples of 10 degrees within the range 10 to 170 degrees. The method of analysis can cope with databases not necessarily presented in a matrix pattern of the independent variables.

The program normalizes the data for nozzle exit area, radial distance and atmospheric pressure. At the same time, normalization by a term $(80 \log_{10}(V_p/a_0))$ is also carried out to adjust the data for gross parameter variations. The normalization is performed according to the relationship

$$SPL_{normalized} = SPL - 10 \log_{10}(A_p/r^2) - 20 \log_{10}(p_0/p_{ISA}) - 80 \log_{10}(V_p/a_0), \quad (3.1)$$

where p_{ISA} is 101.325 kPa in SI units or 2116 lbf/ft² in British units.

This structure has been chosen so that the normalization exactly matches that for a single-stream jet (as in Reference 4) when the coaxial jet velocity ratio, V_s/V_p , equals zero.

The term A_p is the flow area of the primary stream and forms part of the data input by the user. It may be calculated from the relationship

$$A_p = \frac{Q_p}{\rho_p V_p}. \quad (3.2)$$

Although it is suggested that flow area is used, in most practical circumstances the nozzle discharge coefficients are high and the use of geometric areas will not lead to significant errors.

If the noise levels have already been corrected to standard atmospheric pressure as is the case with the database provided here, p_0 should be input as p_{ISA} (i.e., 101.325 kPa if using SI units, or 2116 lbf/ft² if using British units).

The noise data must lie within a specific range of Strouhal number, Sr , which in the program is expressed in terms of $\log_{10} Sr$ and this parameter must lie within the range of -3.0 to 3.0 .

The data, which are input as a function of frequency, are then converted and stored as a function of $\log_{10} Sr$. This transformation is carried out using the relationship

$$Sr = \frac{f D_j}{V_p}. \quad (3.3)$$

The choice of D_j is left to the user. Normally, D_j will be given by

$$D_j = (4A_p/\pi)^{1/2}. \quad (3.4)$$

Any characteristic dimension may be used to define this reference jet diameter but it is necessary for the diameter used for the predictions to be consistent with that used in normalizing the database frequency.

The secondary flow area only arises in the context of the area ratio which is defined as

$$AR = \frac{A_s}{A_p}. \quad (3.5)$$

It should be noted that the normalization process represented by Equation (3.1) has implications that must be considered carefully with some types of data. For example, if input data have been corrected to lossless atmospheric conditions, then the normalization process will be valid.

When data are input to the database an optional procedure in the program may be used to remove spectral irregularities resulting from experimental error. This procedure is specified in Appendix A. Note that the use of this smoothing option may affect extrapolation at either end of the spectrum.

3.3 Interpolation Procedure

For each value of $\log_{10} Sr$, a least-squares fit on the selected database is performed and the resulting regression equation is solved for the jet operating conditions at which the SPL is to be estimated. The optimum combination of terms from the least-squares regression equation, i.e. that which produces the lowest standard error, is automatically selected for the final regression equation.

When a fit using four independent variables is performed, an absolute minimum of fifteen data points is required in the database for quadratic interpolation. It may sometimes be the case that data are such that it is not possible to perform a fit. In this case the program advises accordingly.

The interpolation procedure is repeated throughout the Strouhal number range of interest for the appropriate angle, θ_j . For values of θ_j that are not integer multiples of 10 degrees, quadratic interpolation using the nearest database angles is carried out. If there are insufficient data for quadratic interpolation, linear interpolation is carried out.

If sufficient data are not available to estimate spectrum values at the edges of the frequency range using the surface-fitting routine, linear extrapolation based on the slope from the two nearest spectral points is carried out and a warning is printed.

The program incorporates a weighting method by which data in the database nearer the point at which spectrum levels are to be estimated are weighted more heavily than data further away. Details of this weighting procedure are given in Appendix B.

3.4 Output Computations

The noise predictions are 'de-normalized' to the required conditions after the interpolation has been completed.

The option to specify the frequency range within which one-third octave band noise levels are output is provided. Additionally, the option of computing the *OASPL* over the frequency range specified by the user is provided.

The option is offered to provide output data corrected for atmospheric attenuation according to the procedure in Reference 3. The database provided with this Item has been corrected (see Section 5) to lossless atmospheric conditions using this procedure.

The standard error (see Appendix C) for each one-third octave band level is also printed out.

4. COMPUTER PROGRAMS

There are four programs associated with this Item, programs A1102, B1102, C1102 and M1102*.

Program A1102 estimates jet noise levels using a database, in the frequency range set by the user. A database (described in Section 5) is provided for the estimation of far-field subsonic jet mixing noise from stationary, coplanar, conical nozzles.

The program when run requires the user to enter the name of the file containing the input data. The structure of this input file is shown in Section 4.3. Program B1102 can be run to create such input files conveniently.

The two programs described above follow the standard and familiar ESDU Aircraft Noise Series means of providing software. However, for users with MATLAB^{®†} installed on their systems an additional program, M1102, is included. When this program is run, a graphical user interface is launched through which input data may be entered. These data are stored in a file named by the user. The option to load the interface

* The full ESDUpac number has an appended V followed by two digits. These digits indicate the ESDUpac version number. For example, the full ESDUpac number for version 1.0 of ESDUpac A1102 is A1102V10. See Introduction to ESDUpacs for a full description of the ESDUpac numbering system. The current version of the ESDUpac is given on the example program output.

† MATLAB is a registered trademark of The Math Works, Inc.

with data from an existing file is available. Clicking on the 'RUN' push-button starts program execution, with results output in the standard way to a text file named by the user. In addition, spectral plots of the results are generated, displayed and written to Tagged Image File Format (TIFF or TIF) files. The files containing spectral plots for the case in the Example of Section 7 are displayed in that Section.

Program C1102 can be run to create a new database using the user's data, which can then be used by program A1102 to estimate coaxial far-field jet noise.

4.1 File Structure of the Database Provided

The database provided consists of ten files, each file containing spectral data for a range of jet operating conditions, at a given angle. The angular range covered is from 30 degrees to 120 degrees. File names describe the angle for which data are included in the file and the file name extension is used as a database identifier. For example, in the database provided, data at $\theta_j = 30$ degrees are contained in a file named 'ANG 30.PR'. The 'PR' is used to indicate that the file forms part of the database provided.

The first row of each file contains the run title/date input by the user when generating the database. The second row contains the name of the third independent variable, which in the database provided is area ratio. After that row, there are as many rows as there are jet operating conditions, i.e. all combinations of the independent variables for which there are data.

The column structure of a file in the database is shown in the following table.

TABLE 4.1 Structure of the database

Column number	Contents
1	Angle, θ_j (deg)
2	Normalized primary jet velocity, $\log_{10}(V_p/a_0)$
3	Logarithm of velocity ratio, $\log_{10}(V_s/V_p)$
4	Logarithm of area ratio term, $\log_{10}(1 + AR)$
5	Logarithm of normalized temperature, $\log_{10}(T_{ps}/T_0)$
6	<i>SPL</i> at $\log_{10} Sr = -3.0$
7	<i>SPL</i> at $\log_{10} Sr = -2.9$
.	.
.	.
.	.
66	<i>SPL</i> at $\log_{10} Sr = 3.0$

4.2 Creating a New Database

Program C1102 can be used to create a new database using the user's data. This program also offers the user the option to expand an existing database by adding fresh data. When the program is run, prompts similar to those shown in the following table appear on the screen.

Select whether you wish to	
i) create a new database	Enter 1
ii) add data to an existing database	Enter 2
If 1, enter a 4-character word that will identify the database you create by serving as the file name extension. The ESDU database is identified by the file name 'PRV'. Therefore, this word will not be acceptable. Neither will a full stop be acceptable.	
If 2, enter the 4-character identifier of the database you wish to expand.	
Run title and date (maximum of 275 characters)	
Units	
SI units	Enter 1
British units	Enter 2
Do you wish to smooth spectra?	
Enter Y or N	
For each set of operating conditions, enter the name of the file that contains the operating conditions and spectral data followed by RETURN. The data contained in this file must be in the format shown in the next table.	
When all file names have been entered, press RETURN at the prompt for the file name.	

The program requests the user for names of files that contain spectral data over an angular range, at a given set of jet operating conditions. Each file must contain data for one set of jet operating conditions. Therefore, there must be as many files as there are sets of operating conditions. In each file, data for a maximum of 17 angles at 10 degree intervals can be input. If data are not available at some angles, zeros must be inserted.

When all file names have been entered, the user must press the RETURN key, and the input will then be complete.

The format for each file is given in the following table. If for some frequencies there are no data, zeros must be inserted.

D_j	A_j	T_0	p_0	V_p	V_s/V_p	A_s/A_p	T_{ps}/T_0	Distance	
Angle 1		Angle 2							Angle 17
SPL at 40 Hz (dB)		SPL at 40 Hz (dB)							SPL at 40 Hz (dB)
.		.				.	.	.	.
.		.				.	.	.	.
.		.				.	.	.	.
.		.				.	.	.	.
.		.				.	.	.	.
SPL at 40 kHz (dB)		SPL at 40 kHz (dB)				.	.	.	SPL at 40 kHz (dB)

An example file is shown below.

0.03320	0.00087	287.89999	100.40000	268.79999	1.00000	2.00924	0.90552	6.00000								
30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0	110.0	120.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
62.5	60.4	60.8	56.0	56.9	56.0	0.0	51.8	54.1	51.8	51.5	0.0	0.0	0.0	0.0	0.0	0.0
63.5	60.9	60.9	56.4	57.3	56.6	56.8	52.0	52.6	52.2	51.7	0.0	0.0	0.0	0.0	0.0	0.0
64.5	61.7	60.6	57.0	57.4	56.7	56.8	53.8	54.2	53.6	53.1	0.0	0.0	0.0	0.0	0.0	0.0
66.0	63.3	61.3	58.3	58.5	58.2	57.6	55.9	55.6	54.9	54.2	0.0	0.0	0.0	0.0	0.0	0.0
68.5	66.0	63.1	60.3	60.8	60.1	60.3	59.0	58.5	57.7	56.9	0.0	0.0	0.0	0.0	0.0	0.0
71.2	68.0	64.7	62.3	62.6	61.5	61.6	60.3	59.8	59.1	59.1	0.0	0.0	0.0	0.0	0.0	0.0
74.2	71.3	67.0	65.0	65.2	64.2	64.4	62.7	62.4	61.4	62.0	0.0	0.0	0.0	0.0	0.0	0.0
76.8	74.0	69.7	67.4	67.0	66.5	65.9	65.2	65.0	63.0	64.4	0.0	0.0	0.0	0.0	0.0	0.0
79.7	76.6	72.0	69.5	69.2	68.6	67.8	67.4	66.6	65.4	65.4	0.0	0.0	0.0	0.0	0.0	0.0
82.0	78.9	74.7	71.6	71.2	70.5	69.7	68.8	68.3	67.5	66.6	0.0	0.0	0.0	0.0	0.0	0.0
85.0	81.2	76.6	74.1	73.0	72.0	71.5	70.4	70.1	69.3	67.1	0.0	0.0	0.0	0.0	0.0	0.0
86.7	83.2	79.0	76.0	74.9	74.2	73.3	72.6	72.1	71.1	70.0	0.0	0.0	0.0	0.0	0.0	0.0
88.1	84.5	80.2	77.6	76.6	75.2	74.4	74.0	73.2	72.2	71.9	0.0	0.0	0.0	0.0	0.0	0.0
88.3	85.7	81.9	79.4	78.0	76.6	75.6	74.8	74.8	73.2	72.7	0.0	0.0	0.0	0.0	0.0	0.0
88.0	86.1	82.5	79.7	78.9	77.4	76.6	75.8	75.3	74.1	73.2	0.0	0.0	0.0	0.0	0.0	0.0
87.1	86.5	83.1	81.0	79.7	78.5	77.4	76.6	76.0	74.8	74.3	0.0	0.0	0.0	0.0	0.0	0.0
86.1	86.4	83.8	81.6	80.3	78.7	78.1	77.4	77.2	75.9	75.5	0.0	0.0	0.0	0.0	0.0	0.0
84.8	85.9	84.0	81.7	81.1	78.9	78.2	77.9	77.5	76.5	76.6	0.0	0.0	0.0	0.0	0.0	0.0
83.4	85.3	84.0	82.3	81.0	79.8	78.6	78.4	78.1	76.6	76.1	0.0	0.0	0.0	0.0	0.0	0.0
82.4	84.7	84.0	82.1	81.3	79.8	78.9	78.3	78.0	76.6	76.6	0.0	0.0	0.0	0.0	0.0	0.0
81.7	84.2	84.0	82.6	81.8	80.0	79.0	78.6	78.1	76.8	76.9	0.0	0.0	0.0	0.0	0.0	0.0
80.2	83.5	83.6	82.2	81.4	79.9	78.7	78.8	77.9	76.7	76.2	0.0	0.0	0.0	0.0	0.0	0.0
79.4	82.6	83.0	82.1	81.3	79.8	78.8	78.8	77.5	76.7	76.6	0.0	0.0	0.0	0.0	0.0	0.0
78.5	82.0	82.7	81.9	81.0	79.7	78.6	78.6	77.4	76.5	76.6	0.0	0.0	0.0	0.0	0.0	0.0
77.0	80.9	81.5	81.0	80.7	78.7	78.1	77.7	76.9	75.7	75.8	0.0	0.0	0.0	0.0	0.0	0.0
76.4	80.2	81.4	80.8	80.1	78.9	77.5	77.3	77.0	75.7	75.3	0.0	0.0	0.0	0.0	0.0	0.0
74.9	78.8	80.1	80.4	79.6	77.9	76.8	77.0	76.6	75.0	74.6	0.0	0.0	0.0	0.0	0.0	0.0
73.8	77.6	79.6	79.5	78.2	77.2	76.4	76.2	75.5	74.4	74.0	0.0	0.0	0.0	0.0	0.0	0.0
73.5	77.5	78.6	79.3	78.9	77.5	76.7	76.5	76.3	74.3	73.9	0.0	0.0	0.0	0.0	0.0	0.0
73.6	76.9	78.9	78.8	78.4	77.8	76.1	76.5	75.4	74.9	74.1	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0