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Prediction of near-field and far-field harmonic noise from subsonic propellers with non-axial inflow

**Associated software: ESDUpac A1105
ESDUpac B1105
VIEWpac M1105
VIEWpac MG1105**



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PREDICTION OF NEAR-FIELD AND FAR-FIELD HARMONIC NOISE FROM SUBSONIC PROPELLERS WITH NON-AXIAL INFLOW

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PREDICTION OF NEAR-FIELD AND FAR-FIELD HARMONIC NOISE FROM SUBSONIC PROPELLERS WITH NON-AXIAL INFLOW

1. NOTATION

		<i>Units</i>	
		<i>SI</i>	<i>British</i>
B	number of blades		
$b(r_0)$	local chord	m	ft
C_D	drag coefficient		
C_L	lift coefficient		
c_0	ambient speed of sound at propeller location	m/s	ft/s
c_{ij}	elements of transformation matrix		
D	diameter of propeller	m	ft
d_f	Doppler factor ($= 1 - M \cos \theta$)		
$F_{i\mu, \nu}$	time dependent discrete loading element in coordinate direction i		
$F_{ik\mu, \nu}$	discrete loading element in coordinate direction i , k th complex harmonic		
$F_{\phi k\mu, \nu}$	discrete tangential loading element, k th complex harmonic		
$F_{xk\mu, \nu}$	discrete axial loading element, k th complex harmonic		
f_{obs}	observer frequency	Hz	Hz
f_s	source frequency	Hz	Hz
G_m	harmonic Green's function		
H	height of propeller hub above observer plane (see Sketch 3.1)	m	ft
h	blade thickness, normalized by r_t		
$J_n(x)$	Bessel function of order n and argument x		

For footnotes refer to end of Notation Section

k	load harmonic		
k_m	wave number in harmonic Green's function ($= mBM_t$)		
M	flight Mach number		
M_t	tip rotational Mach number ($= \Omega r_t / c_0$)		
M_r	section relative induced Mach number		
m	harmonic of blade passing frequency		
N_v	number of elements in chordwise direction		
P	sound harmonic levels, with subscripts L signifying loading noise, T signifying thickness noise and m signifying harmonic		
R	sideline distance to observer in flight coordinates	m	ft
R'	sideline distance to observer in propeller coordinates	m	ft
r	radiation distance from propeller centre	m	ft
r_t	radius of propeller	m	ft
r_0	radial coordinate normalized by r_t		
r, θ, ϕ	emission-flight observer spherical coordinates		
r, θ', ϕ'	emission-propeller observer spherical coordinates		
S	amplitude radius, given by Equation (3.7)	m	ft
S_c	term used in Equations (3.3) and (3.4) [$= \cos \theta' / (1 - M \cos \theta)$]	m	ft
S_o	amplitude radius used in far-field case [$= \{x^2 + \beta^2(y^2 + z^2)\}^{1/2}$]		
S_s	term used in Equations (3.3) and (3.4) [$= \sin \theta' / (1 - M \cos \theta)$]		
$V_{\mu, \nu}$	discrete form of thickness source term		
$V_{0\mu, \nu}$	steady part of $V_{\mu, \nu}$		
$V_{c\mu, \nu}$	part of $V_{\mu, \nu}$ that varies with $\cos \phi_0$		
$V_{s\mu, \nu}$	part of $V_{\mu, \nu}$ that varies with $\sin \phi_0$		
x, y, z	reception-flight observer Cartesian coordinates		

For footnotes refer to end of Notation Section

x, R, ϕ	reception-flight observer cylindrical coordinates		
x_0, y_0, z_0, ϕ_0	noise source coordinates		
x_{mc}, ϕ_{mc}	blade mid-chord coordinates		
x_e, y, z	emission-flight observer Cartesian coordinates		
x_e, R, ϕ	emission-flight observer cylindrical coordinates		
x', y', z'	emission-propeller observer Cartesian coordinates		
x', R', ϕ'	emission-propeller observer cylindrical coordinates		
$x_{\mu, \nu}$	x coordinate of source element μ, ν		
$x_{444}, y_{444}, z_{444}$	blade mid-chord coordinates		
α_p	angle of pitch of propeller axis with respect to flight coordinate system (see Sketch 5.2)	deg	deg
α_r	angle of roll of propeller axis with respect to flight coordinate system (see Sketch 5.2)	deg	deg
α_y	angle of yaw of propeller axis with respect to flight coordinate system (see Sketch 5.2)	deg	deg
β	given by $(1 - M^2)^{1/2}$		
γ	ratio of specific heat capacities, 1.4 for air		
η	propeller efficiency		
μ	index for counting source elements in radial direction		
ν	index for counting source elements in chordwise direction		
θ_b	blade angle <i>i.e.</i> angle from plane of rotation to chord line	deg	deg
Φ	air angle, which is sum of advance and induced angles	deg	deg
$\phi_{\mu, \nu}$	cylindrical coordinate to source element μ, ν	deg	deg
ϕ_{ref}	reference angle that serves as starting point for loading waveform	deg	deg
σ	phase radius	m	ft
Ω	rotational speed of propeller	rad/s*	rad/s**

* For convenience, the rotational speed of the propeller is input to the program in rev/min.

2. INTRODUCTION

This Item permits the user to predict near-field and far-field harmonic noise from propellers, with subsonic relative Mach numbers at the blade tip, which may be either stationary or in flight. The airflow into the propeller need not be parallel to the propeller axis. The Item can be used to predict harmonic noise in both the near-field and the far-field of the propeller using the same physical input parameters. The near-field is considered to extend approximately as far as one propeller diameter from the propeller tip.

A description of the propeller blade section data at several radial stations is required and, if the full calculation capacity of the program is to be exploited, both steady and unsteady lift coefficient distributions are required.

Two computer programs, known as ESDUpac A1105* and VIEWpac M1105, for estimating far-field and near-field harmonic noise of propellers in non-axial inflow are provided. The implementation of the programs is described in Section 5 of this Item.

Sound pressure levels and the relative phase in degrees are calculated for loss-less free-field ambient conditions with no temperature gradients or wind. The observer can either be stationary or positioned on the aircraft. Aircraft climb and descent are handled by defining an appropriate coordinate system. The results can be corrected for the effects of a real atmosphere and for ground reflection using other ESDU Items (References 2, 3 and 6).

3. THEORETICAL BACKGROUND

Aerodynamically induced propeller noise may be separated into two components: broadband and discrete frequency. The broadband component arises from turbulent flow and is only likely to assume significance at high angles of attack of propeller blades and is not predicted by this Item. The discrete component is produced as a result of the rotational motion of the propeller blades. The main sources of noise that generate the discrete component are listed.

- (i) Air volume displacement effects as each blade passes through the air, referred to as thickness noise. When the propeller axis is at an angle of incidence to the airflow, thickness noise contains unsteady components that vary sinusoidally due to varying relative blade section velocity within a single revolution of the propeller. Thickness noise is represented by a monopole distribution.
- (ii) Loading noise is represented by a dipole distribution. It is generated by steady aerodynamic loading which, because of blade rotation has a phase velocity relative to the observer and, periodic unsteady loading when the propeller axis is at an angle of incidence to the airflow. Loading can be broken up into radial, tangential and axial components of which the tangential and axial components are calculated here, but the insignificant radial component is not. The maximum contribution of this component is only about 0.6 dB (Derivation 1).

Non-linear effects generate quadrupole noise which though important at transonic/supersonic tip speeds, can be neglected at helical tip Mach numbers lower than 0.9 (Reference 4).

Monopole and dipole noise are covered by the prediction method used in this Item while quadrupole noise is not. The prediction method used here is based on that described in Derivation 1 and, to facilitate cross-referencing, the same notation is used here. Before the operating equations required to calculate these components are presented, it is necessary to consider the different coordinate systems that are and may be used.

* 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 A1105 is A1105V10. The current version of the ESDUpac is given on the example program output.

3.1 Coordinate Systems

The theoretical method uses a moving medium analysis so that the coordinate system is considered fixed to the aeroplane and the air moves past it at a uniform Mach number. Standard flight dynamics conventions (Reference 5) are used to denote the location of the observer.

In flight coordinates, the x -axis is considered positive in the direction of flight, the y -axis lies in the lateral plane of the aircraft and the z -axis is positive downwards (Sketch 3.1). The y -axis will usually be in the horizontal plane for an aircraft in level flight and is defined as positive to the right of the flight path looking in the direction of flight.

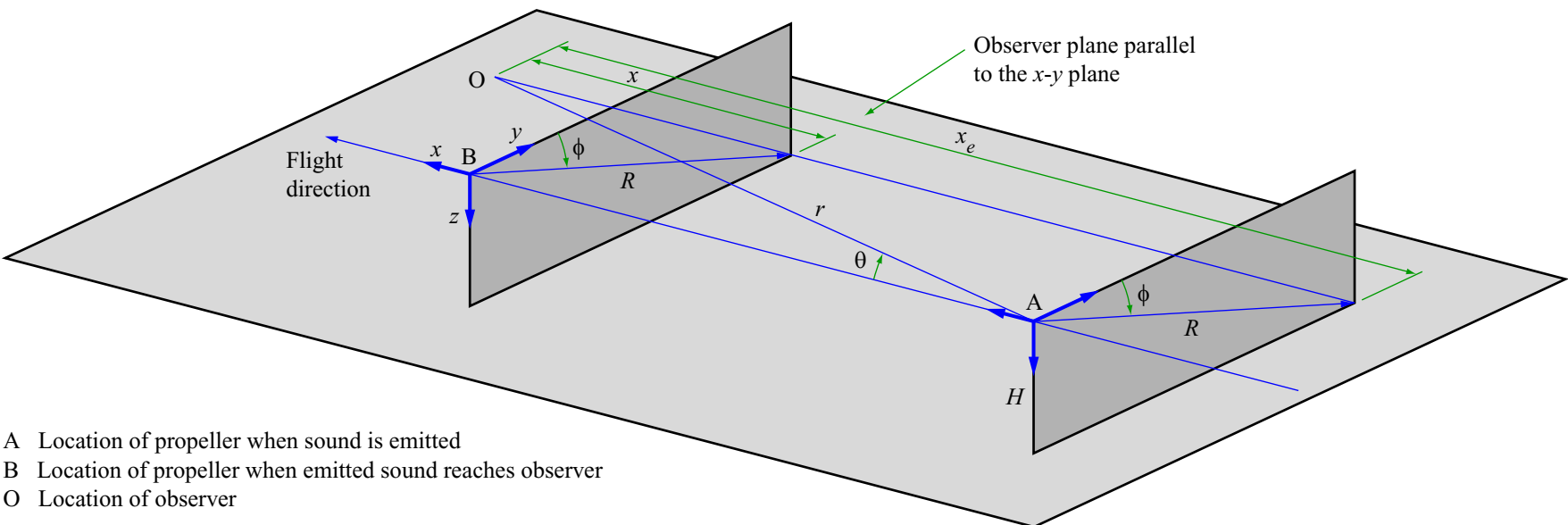
In propeller coordinates using a similar right hand system, the x -axis is considered to be coincident with the propeller axis, the y -axis to the right of this axis and the z -axis again pointing down.

The calculations can be performed for either static or flight conditions. With a static aircraft and observer, there is no ambiguity that arises from the use of any particular system of coordinates. Under flight conditions, the coordinate system needs to be clearly understood and the program offers two options; reception or emission coordinates. Reception coordinates refer to a snapshot of the source and receiver positions at the instant of the sound being received. Thus, these may also be described as visual coordinates. Emission coordinates are defined relative to a stationary atmosphere and refer to the geometrical relationship between the position of the source at the instant of sound emission from it and the position of the receiver at the later instant of sound reception. There is a lapse in time between these two instants and hence emission coordinates are sometimes referred to as retarded-time coordinates. The program makes the necessary transformations automatically using the formulae given in Appendix B.

ESDU 11005 can cope with both cases of an aircraft in flight with a stationary receiver (*i.e.* an aircraft flyover) or a receiver fixed to the aircraft in flight.

For an aircraft flyover, either coordinate system, reception or emission, can be used. Whichever system is selected, it will apply to both the input data and the printed results. However, for interfacing with other ESDU Data Items, the results appearing in the Common Data File will always be in emission coordinates. This is so because these reflect both the characteristics of the source (*i.e.* independent of the receiving technique) and because the propagation of the sound through the atmosphere is determined by the propagation path at the emission angle. A flyover noise prediction also requires a Doppler frequency shift to be applied to the propeller noise and this is done as described in Section 4.1.

In order to define the circumstances pertaining in flight when the receiver is fixed to the aircraft, it is necessary to use the reception coordinate system to specify the input data because this enables the fixed relationship between the propeller and the receiver positions to be input. If the receiver (observer) is on the aircraft, then no Doppler frequency correction is either required or applied.



- A Location of propeller when sound is emitted
- B Location of propeller when emitted sound reaches observer
- O Location of observer

Sketch 3.1 Reception and emission coordinates in flight system.

3.2 Method of Calculation

The noise harmonic P_{mB} is considered to be the sum of two components: P_{Lm} , associated with the lift dipole as the loading component, and P_{Tm} associated with the volume displacement or thickness source. These terms, where μ and ν refer to radial and chordwise indices respectively, are given by the following equations.

In the near-field

$$P_{Lm}(x) = B \sum_{\mu, \nu} e^{-imB\phi_{\mu, \nu}} \frac{1}{2\pi} \int_0^{2\pi} F_{i\mu, \nu}(\phi_0 - \phi_{\mu, \nu}) \frac{\partial G_m}{\partial y_i} e^{imB\phi_0} d\phi_0 \quad (3.1)$$

and

$$P_{Tm}(x) = \gamma B \sum_{\mu, \nu} e^{-imB\phi_{\mu, \nu}} \frac{1}{2\pi} \int_0^{2\pi} V_{\mu, \nu} \left[M \frac{\partial G_m}{\partial x_0} - ik_m G_m \right] e^{imB\phi_0} d\phi_0 \quad (3.2)$$

In the far-field,

$$P_{Lm} = \frac{-iBk_m e^{ik_m r}}{4\pi S_0} \sum_{\mu, \nu} \sum_k e^{i[(mB-k)(\pm\phi' - \pi/2 - \phi_{\mu, \nu}) + k\phi_{ref}]} e^{-ik_m S_c x_{\mu, \nu}} \\ \times \left[\frac{mB-k}{k_m r_0} F_{\phi k\mu, \nu} J_{mB-k}(k_m S_s r_\mu) + S_c F_{xk\mu, \nu} J_{mB-k}(k_m S_s r_\mu) \right] \quad (3.3)$$

and

$$P_{Tm} = \frac{-i\gamma B k_m e^{i[k_m r + mB(\pm\phi' - \pi/2)]}}{4\pi S_0 d_f} \\ \times \sum_{\mu} \sum_{\nu} [V_{0\mu, \nu} J_{mB}(k_m S_s r_\mu) + 1/2 (V_{c\mu, \nu} - iV_{s\mu, \nu}) e^{i(\pm\phi' - \pi/2)} J_{mB+1}(k_m S_s r_\mu) \\ + 1/2 (V_{c\mu, \nu} + iV_{s\mu, \nu}) e^{-i(\pm\phi' - \pi/2)} J_{mB-1}(k_m S_s r_\mu)] e^{-i(k_m S_c x_{\mu, \nu} + mB\phi_{\mu, \nu})} \quad (3.4)$$

In Equations (3.1) to (3.4) the source terms are given by the V and F terms. The equations which show how they are calculated are given in Appendix A.

The location of the source area elements is required and at each radial station along the blade span, the axial and tangential positions of these elements is specified by the two-dimensional arrays $x_{\mu, \nu}$ and $\phi_{\mu, \nu}$. These two arrays are calculated by the program from blade geometry input by the user (see Section 5.1.2).

The harmonic Green's function, G_m in Equations (3.1) and (3.2) is given by

$$G_m = \frac{e^{ikm\sigma}}{4\pi S}, \quad (3.5)$$

where
$$\sigma = \frac{M(x - x_0) + S}{\beta^2} \quad (3.6)$$

and
$$S = \sqrt{(x - x_0)^2 + \beta^2[(y - y_0)^2 + (z - z_0)^2]}. \quad (3.7)$$

4. APPLICATION AND ACCURACY

4.1 Application

The prediction method in this Item computes monopole and dipole noise for propellers in angular inflow. The medium in which the propeller operates is considered to be unbounded and to contain no bodies or surfaces other than the propeller. Reflections from surfaces such as wings are not considered, and neither are ground vortex effects caused by the proximity of the ground to the propeller.

Broadband noise and quadrupole noise are not computed. The former is not generally significant, and the latter is only likely to become significant for relative propeller tip Mach numbers higher than about 0.9.

Note that the noise levels are presented in terms of the source frequency, f_s , of each harmonic of blade passing frequency. If the results are calculated for a stationary reception point, the source frequency, f_s , is modified by the Doppler effect to the received frequency, f_{obs} , according to the relationship below.

$$(f_{obs} = f_s / (1 - M \cos \theta)) \quad (4.1)$$

It should be noted that the calculated values of dBA and OASPL are dependent on the number of harmonics specified by the user at which noise levels are required. If the blade passage frequency is low, an extremely high number of harmonics is necessary for a valid value of dBA to be obtained. A warning is printed out if the number of harmonics specified is not high enough*. If atmospheric attenuation is to be applied to the results, the warning might not be relevant.

ESDU 11005 is designed to cope with atmospheric conditions with zero wind and, for most practical circumstances, its use is limited to such conditions†.

If unsteady blade loadings are not to be considered in the prediction it is likely that the harmonic rate of decay predicted will be much higher than that observed in practice.

The SPL values predicted by the program are for free-field and still, loss-less atmospheric conditions. Procedures to correct for atmospheric attenuation and ground reflection in still atmospheric conditions may be found in References 2, 3 and 6. The atmospheric attenuation should be based on f_{obs} given in Equation (4.1). In order to correct for ground reflection, the height of the noise source at the time of emission is required.

* A warning is issued when the A-weighted sound pressure level of the last harmonic requested is less than 10 dB below the overall dBA level.

† Noise predictions can be made for receivers fixed to the aircraft in the presence of an atmospheric wind along the flight direction simply by increasing the aircraft flight speed (from zero in the case of static conditions) by the amount of the headwind. If the same approach is taken for flyover noise prediction, however, the predictions will be in error but only by the application of an incorrect Doppler frequency shift.

4.2 Accuracy

The results from this program have been compared with those from Derivation 1 for the case of a 6-bladed propeller at a flight Mach number of 0.46 and a propeller tip rotational Mach number of 0.677. Axial inflow and non-axial inflow cases have been compared over a range of azimuthal angles, and the agreement between the two predictions for both the near and the far-field has been within 0.2 dB.

Although both programs are based on the same theory, it is possible that variations in interpolation procedures and mesh distributions and sizes can lead to small differences. The ESDU program uses 40 radial and 40 chordwise stations.

It has not been possible to compare results from this program with measured data, but in Derivation 1 where this has been done an accuracy of better than ± 2.5 dB for light aircraft propellers is reported.

It must be noted that the accuracy of the method is dependent upon the accuracy of the input data and, in particular, how well the loading data are simulated.

5. COMPUTER PROGRAM

There are four computer programs associated with this Item, A1105, B1105, M1105 and MG1105*.

A1105 permits the user to predict both near-field and far-field values of the sound pressure level for a loss-less atmosphere at the blade passage frequency and its harmonics. The relative phase is also predicted.

Program B1105 facilitates the generation of input files.

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 two additional programs M1105 and MG1105 are included. When program M1105 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 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, a spectral plot of the noise harmonics is generated and written to a Tagged Image File format (TIFF or TIF) file. The file containing the spectral plot for the case in the Example of Section 7 is displayed in that Section.

Program MG1105 may be used to plot the calculated one-third octave band spectra. This program is supplied as a set of two files, mg1105v10.p and mg1105v10.fig, both of which are required.

5.1 Input Data

The structure of the input file is shown in Table 5.1. Program B1105 can be run to create an input file. The output is written to a file named by the user as part of that input data file. The facility to output three lines of descriptive text which are entered as input is provided.

The direction of rotation of the propeller is a required input parameter to the computer program. It is defined as right handed if when looking upstream the propeller rotates clockwise.

For the user's convenience, the rotational speed of the propeller, Ω , is input in revolutions per minute.

* 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 A1105 is A1105V10. See Introduction to ESDUpacs for a full description of the ESDUpac numbering system. The current version of the ESDUpac is given on the sample program output.

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

The number of harmonics of interest, with a maximum of twenty, is input by the user.

The location of the observer may be specified in Cartesian, cylindrical or spherical coordinates. Up to a maximum of 40 locations can be specified. The user can also choose instead to input H , θ and ϕ . It should be noted that H is the height of the propeller hub above the observer plane which is parallel to the xy -plane. The observer plane may not necessarily be the ground plane. It is therefore not necessary for the flight path to be level. These coordinates can be in either the flight system or the propeller system. Also, they can be in either emission coordinates or in reception coordinates as described in Section 3.1. The position of the observer may be either at a fixed point in space, such as a microphone on the ground, or at a fixed point on the aircraft, such as a microphone mounted on the fuselage. This choice determines whether a Doppler frequency shift is to be applied to the results; it being applied in the former case but not in the latter.

TABLE 5.1

Run title (maximum 75 characters)
Run title (maximum 75 characters)
Run title (maximum 75 characters)
Output file name
Enter common data output file name (enter 'NONE' if none is to be output)
Units : 0 for SI, 1 for British
Air pressure at propeller location, Pa
Air pressure at observer location, Pa
Air temperature, K
Propeller diameter, m or ft
Hub-to-tip ratio (spinner cut-off)
Number of blades
Flight Mach number
Propeller rotational speed in rev/min
1 for far-field, 2 for near-field predictions
Number of harmonics
Yaw, deg
Pitch, deg
Roll, deg
1 for right hand rotation, 0 for left hand rotation (Sketch 5.4)
1 for reception (visual), 0 for emission (retarded-time) coordinates For an observer fixed to the aircraft, reception (visual) coordinates must be used.
1 for flight, 0 for propeller coordinates
1 for Cartesian, 2 for cylindrical, 3 for spherical, 4 for flight path
0 to include Doppler effects on one-third octave band spectrum for a stationary observer 1 for an observer on the aircraft
Number of observer locations (maximum of 40)
Coordinates of observer locations: (m or ft and degrees) For each location, if coordinates are Cartesian, enter x , y and z cylindrical, enter x , R and ϕ spherical, enter r , θ and ϕ flight path, enter H , θ and ϕ