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Prediction of Helicopter Rotor Discrete Frequency Noise

A Computer Program Incorporating Realistic Blade Motions and Advanced Acoustic Formulation

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CONTENTS

SUMMARY

A computer program has been developed at the Langley Research Center to predict the discrete frequency noise of conventional and advanced helicopter rotors. The program, called WOPWOP, uses the most advanced subsonic formulation of Farassat that is less sensitive to errors and is valid for nearly all helicopter rotor geometries and flight conditions. A brief derivation of the acoustic formulation is presented along with a discussion of the numerical implementation of the formulation. The computer program uses realistic helicopter blade motion and aerodynamic loadings, input by the user, for noise calculation in the time domain. The structure of the program and the subroutines describing the input functions are described in this report. A detailed definition of all the input variables, default values, and output data is included. A comparison with experimental data shows good agreement between prediction and experiment; however, accurate aerodynamic loading is needed.

A second program, which is used to provide graphic output, is described briefly in an appendix. Four realistic example cases are presented. Complete input data, printed output, and graphical output are included in the appendixes for each of the example cases. These examples can be reproduced by users to check the program on their system.

INTRODUCTION

Helicopters have proven to be a very versatile means of transportation and fulfill a unique roll in civil and military aviation. In the past, controllability and performance completely dominated the design requirements. As the helicopter became more mature and its use was expanded, a great deal of importance was then placed on the vibrational and acoustical properties of the helicopter design. This interest has resulted in helicopters that are quieter and vibrate less; however, large gains can still be made in this effort.

Since model and full-scale testing of helicopter rotors can be time-consuming and expensive, a computer program, called WOPWOP, has been developed at the Langley Research Center to predict the discrete frequency noise for helicopter rotors. This paper is intended as a description of the WOPWOP program. WOPWOP is actually an updated version of an earlier computer program developed at Langley by Paul A. Nystrom and F. Farassat, but WOPWOP uses a more advanced acoustic formulation and all realistic blade motions. References 1 and 2 refer to a version of the Nystrom-Farassat program that was developed for advanced propellers. The original helicopter program was not documented and used a considerably different computation strategy; therefore, only the present version of WOPWOP will be discussed.

The program WOPWOP uses acoustic formulation 1A of Farassat (ref. 3). This time-domain formulation is valid in both the near-field and far-field and is appropriate for arbitrary blade motions with loading given on either the actual blade surface or the mean camber surface. In WOPWOP, the flapping, feathering, and lead-lag motion of a helicopter rotor in hover, vertical flight, and forward flight are described using coefficients of a Fourier series. Coefficients up to the second harmonic can be specified. WOPWOP can also be used to simulate propellers correctly in asymmetric flight conditions, rather than to change the loading distribution to account for asymmetry in an axisymmetric flow, as is normally done. The formulation used in WOPWOP does not require a numerical time differentiation found in Farassat's earlier formulation and, for this reason, is better suited to study impulsive blade loadings such as blade-vortex interaction. A brief derivation of Farassat's formulation 1A is included for completeness as well as a discussion of how the formulation is implemented numerically. Special effort has been taken to minimize the mathematical and numerical approximations used.

The program WOPWOP uses input in the form of blade geometry, realistic blade motion, and aerodynamic blade loading that are input through a FORTRAN namelist and three input subroutines. Using this combination for input ensures great flexibility when the program is applied to different engineering applications. The namelist input and input subroutines are described in detail, and the program output is explained as well. In appendix A, a sample procedure to execute WOPWOP on a VAX with the VMS operating system is shown. Appendix B contains four example cases with printed output from the program WOPWOP. An interactive postprocessing program, called WOPPLT, is described in appendix C, and the graphical output for the four example cases is shown in appendix D.

SYMBOLS AND ABBREVIATIONS

BPF blade passage frequency

c_o speed of sound in undisturbed medium

E distance from rotor hub center to lead-lag hinge

E2 radial distance from center of rotor hub

ER nondimensional radial distance, E2/R

$f(\vec{x},t) = 0$ equation of blade surface

ℓ_i local force per unit area on fluid in direction i

M Mach number

M_r Mach number in radiation direction

$\hat{n}$ unit outward normal vector to surface $f = 0$

OASPL overall sound pressure level, dB (re 20 μPa)

PCA pitch change axis

$p'(\vec{x},t)$ acoustic pressure

Q chordwise position expressed as fraction of chord

R radius of rotor blade

r length of radiation vector, $|\vec{x} - \vec{y}|$

$\vec{r}$ radiation vector, $\vec{x} - \vec{y}$

$\hat{r}$ unit radiation vector, $\vec{r}/r$

S surface area of blade

SPL sound pressure level

t observer time

$\hat{t}$ unit tangent vector to surface $f = 0$

v_n local normal velocity of blade surface

$\vec{v}$ local velocity of blade surface

$\vec{x}$ observer position in frame fixed with respect to undisturbed medium

$\vec{x}_{obs}$ observer location

$\vec{y}$ source position in frame fixed with respect to undisturbed medium

$\vec{y}_o(t)$ position vector from origin of ground-fixed frame (GF) to moving frame (MF)

α_f rotor-shaft tilt angle

β blade flapping angle

$\delta(f)$ Dirac delta function

ζ blade lead-lag angle

$\vec{\eta}$ blade-fixed frame coordinates

θ blade feathering angle

ρ_o density of undisturbed medium

τ source time

ψ azimuthal angle

∇^2 Laplacian operator

Subscripts:

B blade-fixed frame (BF)

F flapping frame (FF)

i,j indices of summation, i and j = 1, 2, or 3

L lagging frame (LF)

M moving frame (MF)

R rotating frame (RF)

r radiation direction

ret evaluated at retarded or emission time

1,2,3 coordinate directions

THEORETICAL FORMULATION

The problem of noise prediction can be represented as the solution of the wave equation if the distribution of sources on the moving boundary (the rotor blade surface) and in the flow field is known. The noise prediction should not be limited to a particular blade geometry or blade motion, and observer positions in both the near-field and far-field should be included. Ffowcs Williams and Hawkings (ref. 4) derived the governing differential equation by applying the acoustic analogy of Lighthill (ref. 5) to bodies in motion. Farassat has developed several integral representations of the Ffowcs Williams-Hawkings (FW-H) equation that are valid for general motions in both subsonic and supersonic flow. These integral representations become solutions to the acoustic problem when the body geometry, motion, and surface loadings are given. Farassat neglects the volume source term, or "quadrupole" term, in the FW-H equation on the basis that the term becomes important only for strongly transonic flow and the source strength is generally not available in practice. However, Hanson and Fink (ref. 6), as well as Schmitz and Yu (ref. 7), have shown that this quadrupole term can be important for high-speed rotating machinery, particularly those with thick blades. This shortcoming of the formulation should be addressed in the future. Formulation 1A of Farassat, which is used in WOPWOP, will be briefly derived in the following section by using the original method. A more complete discussion of this derivation is found in references 3, 8, and 9.

DERIVATION OF FORMULATION 1

The governing differential equation used here is the Ffowcs Williams-Hawkings (FW-H) equation. Let $f(\vec{y},t) = 0$ describe the surface of the blade where $f > 0$ outside the blade. The FW-H equation is

$$\square^2 p'(\vec{x},t) = \frac{1}{c_o^2}\frac{\partial^2 p'}{\partial t^2} - \nabla^2 p'$$

$$= \frac{\partial}{\partial t}[\rho_o v_n |\nabla f| \ \delta(f)] - \frac{\partial}{\partial x_i}[\ell_i |\nabla f| \ \delta(f)]$$

$$- \frac{\partial^2}{\partial x_i \ \partial x_j}[T_{ij} \ H(f)] \tag{1}$$

where p' is the acoustic pressure, ρ_o and c_o are the density and speed of sound of the undisturbed medium, respectively, v_n is the local normal velocity of the blade surface, ℓ_i is the force per unit area on the fluid, T_{ij} is the Lighthill stress tensor, and $\square^2$ denotes the wave operator. The quantity ℓ_i is equal to $P_{ij}\hat{n}_j$, where P_{ij} is the compressive stress tensor that includes the surface pressure and viscous stress and $\hat{n}_j$ is the unit outward normal vector to the surface $f = 0$. The Dirac delta function and the Heaviside function are denoted by $\delta(f)$ and $H(f)$, respectively. This notation is consistent with that of Farassat (ref. 3). The source terms on the right-hand side of the FW-H equation are known as the thickness, loading, and quadrupole terms, respectively.

The Green's function for the wave equation in unbounded space is $\delta(g)/4\pi r$ where

$$g = \tau - t + \frac{r}{c_o} \tag{2}$$

and $r = |\vec{x} - \vec{y}|$. Here τ and t are the source and observer times, respectively. The vectors $\vec{x}$ and $\vec{y}$ are the source and observer positions, respectively. Noting that the thickness and loading terms are source terms on the right-hand side of the FW-H equation, one can use the formal solution of the wave equation to give the integral representation

$$4\pi\, p'(\vec{x},t) = \frac{\partial}{\partial t}\int \frac{\rho_o v_n |\nabla f|\ \delta(f)\ \delta(g)}{r}\, d\vec{y}\, d\tau - \frac{\partial}{\partial x_i}\int \frac{\ell_i |\nabla f|\ \delta(f)\ \delta(g)}{r}\, d\vec{y}\, d\tau \tag{3}$$

Note that the $\vec{y}$ frame is fixed to the undisturbed medium. Let a blade-fixed frame $\vec{\eta}$ be defined and related to the $\vec{y}$ frame by

$$\vec{y} = \vec{y}_o(\tau) + A(\tau)\,\vec{\eta}$$

where $\vec{y}_o(\tau)$ is the position of the origin of the frame and $A(\tau)$ is the transformation matrix. Then the Jacobian of the transformation is unity since the determinant of $A(\tau)$ is 1. Using this result, equation (3) may now be written

$$4\pi\, p'(\vec{x},t) = \frac{\partial}{\partial t}\int \frac{\rho_o v_n |\nabla f|\ \delta(f)\ \delta(g)}{r}\, d\vec{\eta}\, d\tau - \frac{\partial}{\partial x_i}\int \frac{\ell_i |\nabla f|\ \delta(f)\ \delta(g)}{r}\, d\vec{\eta}\, d\tau \tag{4}$$

Now change the variable of integration from τ to g, keeping $\vec{\eta}$ fixed. The Jacobian of the transformation is $1/|1 - M_r|$ where $M_r = \vec{v} \cdot \hat{\vec{r}}/c_o = v_i\hat{r}_i/c_o$ is the Mach number in the radiation direction. If f is a function of $\vec{\eta}$ only and $d\vec{\eta}$ is written as $d\vec{\eta} = df\, dS/|\nabla f|$, where dS is an element of surface area on f = Constant, the result will be

$$4\pi\, p'(\vec{x},t) = \frac{\partial}{\partial t} \int_{f=0} \left[\frac{\rho_o v_n}{r(1 - M_r)}\right]_{ret} dS - \frac{\partial}{\partial x_i} \int_{f=0} \left[\frac{\ell_i}{r(1 - M_r)}\right]_{ret} dS \qquad (5)$$

where the subscript ret denotes that the integrand is evaluated at the source or retarded time. The spatial derivative of the second integral can be converted to a time derivative giving the result that Farassat has called formulation 1, which is written as

$$4\pi\, p'(\vec{x},t) = \frac{1}{c_o}\frac{\partial}{\partial t} \int_{f=0} \left[\frac{\rho_o c_o v_n + \ell_r}{r(1 - M_r)}\right]_{ret} dS + \int_{f=0} \left[\frac{\ell_r}{r^2(1 - M_r)}\right]_{ret} dS \qquad (6)$$

where $\ell_r = \ell_i\hat{r}_i$ is the force on the fluid per unit area in the radiation direction. Farassat used this formulation for his early work with the time differentiation evaluated numerically.

DERIVATION OF FORMULATION 1A

The speed and accuracy of the calculation is improved by eliminating the numerical differentiation; therefore, using equation (2) and the fact that r is a function of τ gives

$$\left.\frac{\partial}{\partial t}\right|_{\vec{x}} = \left(\frac{1}{1 - M_r}\left.\frac{\partial}{\partial \tau}\right|_{\vec{x}}\right)_{ret}$$

This relation allows the time derivatives to be taken inside the first integral. Then, from using the useful relations

$$\frac{\partial r}{\partial \tau} = -v_r$$

$$\frac{\partial \hat{r}_i}{\partial \tau} = \frac{\hat{r}_i v_r - v_i}{r}$$

$$\frac{\partial M_r}{\partial \tau} = \frac{1}{c_o r}\left(r_i \frac{\partial v_i}{\partial \tau} + v_r^2 - v^2\right)$$

$$\frac{\partial v_n}{\partial \tau} = \left(\frac{\partial v_i}{\partial \tau}\hat{n}_i + v_i \frac{\partial \hat{n}_i}{\partial \tau}\right) \equiv \dot{v}_n$$

the final result is

$$p'(\vec{x},t) = p_T'(\vec{x},t) + p_L'(\vec{x},t)$$

where

$$4\pi\, p_T'(\vec{x},t) = \int_{f=0}\left[\frac{\rho_o \dot{v}_n}{r(1 - M_r)^2}\right]_{ret} dS + \int_{f=0}\left[\frac{\rho_o v_n\left(r\dot{M}_i\hat{r}_i + c_o M_r - c_o M^2\right)}{r^2(1 - M_r)^3}\right]_{ret} dS$$

$$4\pi\, p_L'(\vec{x},t) = \frac{1}{c_o}\int_{f=0}\left[\frac{\dot{\ell}_i\hat{r}_i}{r(1 - M_r)^2}\right]_{ret} dS + \int_{f=0}\left[\frac{\ell_r - \ell_i M_i}{r^2(1 - M_r)^2}\right]_{ret} dS$$

$$+ \frac{1}{c_o}\int_{f=0}\left[\frac{\ell_r\left(r\dot{M}_i\hat{r}_i + c_o M_r - c_o M^2\right)}{r^2(1 - M_r)^3}\right]_{ret} dS$$

Here p_T' and p_L' denote the acoustic pressure due to thickness and loading, respectively. The dots on $\dot{M}_i$, $\dot{\ell}_i$, and $\dot{v}_n$ denote the rate of variation with respect to source time. This integral representation of the FW-H equation is known as formulation 1A of Farassat. It is slightly more general than Farassat reported in reference 3 in that it includes the $\dot{v}_n$ term in the thickness contribution. The importance of this term has not been determined and is thought to be small, but it is included for completeness. Only the quadrupole term in the FW-H equation has been neglected. Formulation 1A is computationally more efficient since the numerical time derivative of formulation 1 has been replaced and impulsive loading can be used as well.

Formulation 1A is valid for arbitrary blade motion and geometry. The sources lie on the actual body surface and can include loading from any mechanisms that act on the blade surface. Near-field and far-field terms are seen explicitly as $1/r^2$ and $1/r$ terms in the integrals, respectively. The observer is assumed to be fixed to the undisturbed medium, but a moving observer can also be used by changing the observer position at each observer time. Formulation 1A is well-suited to helicopter rotors with subsonic tip speeds, especially if the blade does not exceed the section critical Mach number.

PROGRAM DESCRIPTION

Although the acoustic formulation 1A of Farassat allows arbitrary blade motion, geometry, and observer locations, the numerical solution is only of interest for realistic flight conditions and rotor geometries. Thus, the computer program has been written to include all realistic helicopter blade motions. The numerical implementation of formulation 1A and the corresponding approximations will be discussed in this section.

The noise calculation in WOPWOP is commenced by dividing the rotor blade surface into a number of panels. A numerical integration is carried out assuming that the integration over each panel may be approximated using the integrand value at the panel center for the entire panel area. The program WOPWOP determines the panel center and then calculates the contribution to the noise from the panel for all the desired times. This process is repeated for each blade and for all remaining panels to complete the integration over the actual blade surface. The number of panels that can be used is not limited; however, 60 chordwise panels and 40 radial panels could be considered an upper bound. The summed effect of all the panels at the observer location for all observer times desired gives the acoustic pressure time history. The time history is then Fourier decomposed to find the acoustic spectra in terms of sound pressure level (SPL) and phase for each harmonic. The overall sound pressure level (OASPL) is calculated as well.

The observer position is fixed in a ground-fixed reference frame (fig. 1). The observer location is specified in the observer reference frame (OF), where $(OF)_1$ points forward, $(OF)_2$ points to the left, and $(OF)_3$ points upward, forming a right-hand coordinate system. The actual acoustic calculations are performed in a ground-fixed reference frame (GF). The origin of the GF frame corresponds to the OF frame and $(GF)_3$ is rotated an angle α_f in the counterclockwise direction when viewing from the right side of the helicopter (for a rotation of the positive sense). Here $(GF)_2$ and $(OF)_2$ are coincident and α_f describes the angle between the rotor shaft and the vertical. The angle α_f is negative when the rotor shaft is tilted forward.

The rotor blade is described in a blade-fixed reference frame (BF). It is convenient to describe the blade surface, surface normal vector, and surface tangent vector in the BF frame since these quantities are independent of time in the BF frame. Since the acoustic calculations are performed in the GF frame, a series of intermediate reference frames are used to describe the blade-fixed vector quantities in the ground-fixed frame of reference. The transformations used in WOPWOP will be described to clarify the precise motion of the rotor blade in WOPWOP.

Four intermediate reference frames are used to relate quantities in the blade-fixed frame to the ground-fixed frame. These are necessary to include the helicopter forward motion, blade rotation, flapping, feathering, and lead-lag motions. Figure 1 shows the relationship between the ground-fixed frame (GF) and a nonrotating moving frame (MF). MF corresponds to GF at time $t = 0$, and the vector $\vec{y}_o(t)$ relates the origin of the MF frame to the origin of the GF frame. The vector $\vec{y}_o(t)$ is defined as the product of observer time t with the helicopter velocity vector $\overrightarrow{VH}$. A rotating frame (RF) is related to the moving frame (MF) by the angle ψ, which is measured from the tail of the helicopter in a counterclockwise direction when looking

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