(possibly thousands) of analysis iterations are necessary. In preliminary design the accuracy of a combination of beam and laminate analyses is sufficient. Further, the superior efficiency with respect to computational time makes the combination procedure more desirable than the two-dimensional finite element procedure.

The combined beam and laminate analyses procedure requires two types of blade models: a beam model and a cross-section model. The beam model consists of a series of beam segments connected at spanwise grid points. Each segment contains equivalent beam properties such as the stiffnesses and masses. These properties are constant along a single beam segment, but may vary between segments, thus forming a step function of beam property distributions along the blade span. Displacements (translational and rotational) and beam forces (shears and moments) resulting from the applied loads are computed at the grid points.

A cross section model is a representation of the internal blade structure which is composed of several components. These components generally consist of one or more spars, a leading edge weight, an aft honeycomb or balsa core, and a skin. The cross section models serve two purposes. First, they are used to calculate the equivalent beam properties of the beam segments. Thus, there will be a different cross section model corresponding to each unique beam segment. Secondly, the cross section models are used to calculate stresses resulting from the forces associated with each beam segment. The stresses are then used in a laminate analysis to determine the margins of safety at various points in the cross section.

ACOUSTIC DESIGN CONSIDERATIONS

Ruth M. Martin

Review of Rotor Acoustic Sources

The acoustic signal from a helicopter rotor arises from several very complicated sources due to the aerodynamic loading of the blades, the interaction of the rotor with its wake, and the physical process of the blades moving through air. The various sources can be quite different in their temporal character, have different frequency spectra, occur at different flight regimes, and have differing directivity patterns. One noise source may dominate the signal at a particular measurement location and flight condition while other sources may be important at a slightly different measurement location. Due to this diversity, it is not sufficient to optimize a rotor design in terms of a single noise level calculated for a single flight condition and a single measurement location. The various noise sources, their frequency content, amplitude, and directivity as a function of operating condition must be considered.

Rotor noise is often characterized in terms of its harmonic content and its broadband content. The harmonic content typically consists of the lowest multiples of the rotor blade passage frequency (f_{bp}, typically between 10 and 30 Hz). The low frequencies (the first 5 to 10 harmonics) are generally the highest in amplitude and have the greatest importance to military detection work. Some acoustic sources also create higher frequency harmonics of the f_{bp}. The broadband part typically occurs in the middle and higher frequency regions of the spectrum. The higher frequency content can be deterministic or random depending on flight conditions, and is the most important for community noise problems and aircraft noise certification, since aircraft certification measurements emphasize the middle frequencies.

The following paragraphs present a summary of the frequency ranges, directivity patterns and the most important operational and design parameters for each major rotor noise source. Figure 7 shows the frequency ranges of these noise sources, and figure 8 shows their general directivity patterns.

Loading noise is due to the low frequency time varying lift on the blades and is a strong function of the local lift distribution (C_ℓ) and rotor thrust coefficient (C_t). This source may be predicted from the measured or predicted blade surface pressure distribution. It is the predominant contributor to the low frequency content (1 to 10 f_{bp}) at moderate advance ratios (μ up to 0.3). Analysis has shown that the strongest radiation direction is down from the rotor plane.

Thickness noise is due to the motion of the blades through air and is a strong function of blade thickness and local Mach number. This source may be predicted from a definition of the blade geometry and the rotor motion. It is a dominant contributor to the low frequency content (1 to 10 f_{bp}) at the higher advance ratios (μ above 0.3). Analysis and experimental data have shown that its strongest radiation direction is in the plane of the rotor.

High speed impulsive noise (HSI) occurs when high transonic local Mach numbers occur on the advancing-side tip region. The result is a strong increase in the low frequency harmonics (1 to 20 f_{bp}) and a steepening negative pulse in the noise signal. This source is very sensitive to tip Mach number and blade shape, particularly in the tip region. The directivity pattern of HSI is similar to that of thickness noise, strongest in the rotor plane. Although observed experimentally, due to nonlinear transonic effects, this source is not as well predicted as the subsonic loading and thickness noise.

Blade-vortex interaction noise (BVI) is attributed to the aerodynamic interaction of the trailing tip-vortices with the following blades, and is essentially a higher frequency loading noise. The BVI impulsive signal consists of higher harmonics and subharmonics of the f_{bp}, typically in the range of 5 to 30 f_{bp} harmonics, and occurs mostly at low advance ratios (0.1 to 0.2) in descent. When this source is generated it dominates the midfrequencies of the acoustic spectrum. The directivity is generally out-of-plane as is low frequency loading noise, but is more focused in its primary radiation direction. This acoustic source can be calculated in the same manner as low frequency loading noise but the results depend heavily on the accuracy and resolution of the aerodynamic prediction.

Broadband rotor noise is a very general term for several non-periodic aerodynamic noise sources primarily due to atmospheric turbulence and blade self-generated turbulence. Broadband noise is affected by changes in boundary layer characteristics, so tip speed, blade shape and Reynolds number effects are important. Although broadband noise levels are significantly lower than the other rotor noise sources, this source is the main contributor to the high frequencies (above 25 f_{bp}). The directivity is thought to be a dipole pattern aligned with the rotor axis. The prediction of this noise source is not as mature as the more deterministic rotor noise sources and is currently under development.

Acoustic Design Requirements

Phase 1 of the optimization approach will not include an acoustic analysis coupled with the optimization process. Instead, the acoustic aspects of the problem will be accounted for in terms of effective acoustic design requirements. It is difficult to generalize design requirements for rotor noise because the acoustic output varies so widely depending on the noise source, flight condition, measurement location, and frequency range. However, assuming the rotor must lift a fixed nominal payload and operate over a wide range of flight conditions, three general design guidelines can be stated: (1) minimize tip Mach number, (2) minimize blade thickness in the tip region, and (3) minimize gradients in the spanwise lift distribution in the tip region. The first two guidelines are aimed at minimizing thickness noise and high speed impulsive noise. The third guideline is aimed at minimizing the tip vortex strength, and thus blade-vortex interaction noise.

For the phase 1 approach, constraints on blade thickness, maximum values for hover tip mach number (M_h), advancing tip Mach number ($M_{1,90}$) and spanwise lift coefficient gradient ($\partial C_\ell/\partial(r/R)$) will be specified during the aerodynamic, dynamic and structural optimization process (table 2).

Acoustic Evaluation of Rotor Designs

Once a rotor design has been optimized for the aerodynamic, dynamic, and structural constraints, including the acoustic design requirements, it will be input to an acoustic analysis for evaluation. In addition, perturbed designs will be provided, designs for which each of the design variables have been perturbed from the optimum design value. The acoustic analysis will calculate the acoustic output of the nominal and perturbed designs. Derivatives of the acoustic output with respect to the design variables will then be calculated to identify the most important acoustic parameters.

The rotor noise sources to be considered in the phase 1 analysis include the low frequency loading and thickness noise, and the higher frequency noise due to blade-vortex interactions (BVI). Broadband and high speed impulsive noise will not be addressed in phase I, but may be included in phase 2 or 3. The analyses to be employed will include the comprehensive rotor analysis and design program CAMRAD (ref. 14) and the rotor noise prediction program WOPWOP (ref. 28). The acoustic analysis will calculate three integrated sound pressure levels to quantify (1) the low frequency acoustic content, (2) the mid frequency acoustic content, and (3) the A-weighted sound pressure level, a common noise metric used in aircraft certification procedures. The acoustic signal will be predicted for several measurement locations where the different noise sources are important, for the flight conditions considered in the objective function (see eq. 1).

Basis of Acoustics Analysis

The problem of rotor noise prediction can be represented as the solution of the wave equation if the distributions of sources both on the moving surface (the rotor blade) and in the flow are known. Ffowcs Williams and Hawkings (ref. 29) derived the governing differential equation by applying the acoustic analogy of Lighthill (ref. 30) to bodies in motion. Subsequently, Farassat developed several integral representations of solution of the Ffowcs Williams-Hawkings (FW-H) equation that are valid for general motions in both subsonic and supersonic flow (refs. 31-33).

Analysis Code

The acoustics analysis (ref. 28) is based on dividing the rotor blade surface into a number of panels. Appropriate numerical integrations are carried out using the integrand value at the panel center for the entire panel area. The program determines the panel center and calculates the contribution to the noise from the panel for a specified number of times (azimuth angles). This is repeated for each blade and for all panels to complete the integration over the blade surface.

The program requires a namelist input and three input subroutines. The namelist provides the flight conditions and program control parameters. The subroutines describe the physical and aerodynamic characteristics of the rotor blade and allow great flexibility in the definition of the blade geometry and loading. One subroutine defines the blade-section geometric twist, chord, pitch change axis location, maximum thickness ratio and maximum camber ratio as a function of radial position along the rotor blade. A second subroutine defines the camber and thickness as functions of radial and chordwise locations. The third subroutine describes the aerodynamic blade loading on either the actual blade surface or the mean camber surface as a function of azimuthal position. The blade loading input will be provided by the output of the CAMRAD calculations for all flight conditions, for each of the rotor designs to be evaluated.

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AIRFRAME DESIGN CONSIDERATIONS

Raymond G. Kvaternik and T. Sreekanta Murthy

Overview

The purpose of this section of the paper is to provide a discussion of those aspects of airframe structural dynamics that have a strong influence on rotor design optimization. Primary emphasis is on vibration requirements. The constraints imposed on rotor design by airframe dynamics and included in Table 2, are discussed.