

ROTONET Primer

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TABLE OF CONTENTS

TABLE OF CONTENTS		i
1	INTRODUCTION	1-1
2	ACOUSTICS REVIEW	2-1
2.1	Concepts	2-1
2.2	Units	2-4
2.3	Frequency-Domain Representation	2-5
2.4	Typical Noise Levels	2-8
2.5	Air Properties	2-9
3	HELICOPTER NOISE	3-1
3.1	Overview	3-1
3.2	Tone Noise Sources	3-2
3.3	Broadband Noise Sources	3-5
3.4	Propagation	3-6
3.5	Noise Metrics	3-7
4	ROTONET EXECUTION	4-1
4.1	Basic Concepts	4-1
4.2	Functional Module Groups	4-2
4.3	Input Deck Structure	4-6
4.4	Inputs and Outputs	4-6

4.5	ANOPP Control Statements	4-7
4.6	Sample Input Deck	4-9
4.7	Notes on ROTONET Use	4-10
5	FUNCTIONAL MODULES	5-1
5.1	Coordinate Systems	5-1
5.2	Harmonic Representations	5-2
6	INPUTS	6-1
6.1	Parameters	6-1
6.1.1	Notes on certain parameters	6-2
6.2	Members	6-2
6.2.1	Notes on certain members	6-3
7	EXAMPLE CASE	7-1
7.1	Blade Properties Deck	7-2
7.2	Source Modeling	7-3
7.3	Flight Trajectory & Propagation	7-4
	References	8-1
A	Global Parameter List	A-1
B	Global Member List	B-1
C	Example Deck 1	C-1
D	Example Deck 2	D-1
E	Example Deck 3	E-1
F	Glossary	F-1

ROTONET Primer

iii

G Symbols

G-1

Chapter 1

INTRODUCTION

Rotorcraft noise has become a subject of considerable interest to the aerospace community. Manufacturers of civil rotorcraft are facing increasingly stringent federal and local noise regulations, and military aircraft makers are being required to reduce noise signatures in the interests of battlefield survivability.

A computer program called ANOPP has been developed at the NASA Langley Research Center for prediction of the noise received at the ground due to aircraft. The ANOPP program has evolved into a system with three subsystems; a system for CTOL aircraft, the Propeller Analysis System (PAS), and ROTONET. The ROTONET subsystem was developed to predict the external noise generated by a given helicopter flying in a specified flight condition. This program calculates several noise sources on the helicopter, predicts the propagation of the noise to farfield observers, sums the various noise components, and computes various noise metrics for use in certification studies.

This document provides introductory information for novice users of the ROTONET code. Brief reviews are presented on; acoustics theory, rotorcraft noise phenomena, ROTONET concepts, input data creation, code execution, and interpretation of results. In addition, ROTONET users will also need the following documents; “Aircraft Noise Prediction Program Theoretical Manual” [1], “Aircraft Noise Prediction Program User’s Manual” [2], “The NASA Aircraft Noise Prediction Program Improved Propeller Analysis System” [3], and “Aircraft Noise Prediction Program Theoretical Manual” [4]. An additional reference

which can prove helpful for developing non-level flight trajectory predictions is “An Introduction to High Speed Aircraft Noise Prediction” [5]. These documents provide detailed and comprehensive information on the theoretical methods used, the input and output quantities, and the ANOPP Control Language syntax.

Since theoretical and programmatic quantities are discussed in this work, several type fonts are used to distinguish between forms. All ANOPP input and output quantities are printed in Courier font, for example the `SFIELD(PHI)` unit member. All filenames are printed in a slanted font, *rotonet.exe* for example. Analytical symbols are printed with a math italic font, \vec{x} for example.

Chapter 2

ACOUSTICS REVIEW

This chapter gives a brief discussion of acoustics concepts, to provide the non-acoustician with a quick reference for ROTONET work. Additional references for general acoustics include Pierce [6] and Kinsler et al [7]. Various noise metrics used in rotorcraft acoustics are discussed by Pearsons & Bennett [8]. Signal processing considerations are presented by Hardin [9] and Bendat and Piersol [10]. An overview of rotor noise is presented by Hubbard [11] and Brentner and Farassat [12]. The theoretical methods actually employed in ROTONET are discussed in references [1], [2], [3], [4], and [5]. Discussions of rotorcraft-specific noise phenomena and issues are given in Chapter 3.

2.1 Concepts

For practical purposes, unsteady pressure disturbances in a compressible fluid is a definition of sound. For aeroacoustics, the fluid is air. Noise may be defined as annoying or undesirable sound. Sound waves traveling through a fluid cause fluctuations in pressure, density, and particle velocity. The field of aeroacoustics is that subset of acoustics which has aerodynamic phenomena as the noise sources. Some examples of aeroacoustic noise sources are; jet engines, propellers, helicopter rotors, and sonic booms. The noise of concern may be exterior to the aircraft, such as community response to airport noise, or internal to the aircraft, such as propeller noise experienced by a passenger in a turboprop commuter airliner.

Acoustic problems are typically described in terms of the “source”, the “path”, and the “observer.” The source is defined as the aerodynamic body or fluid parcel which originates the outgoing pressure waves. Because the speed of sound is finite, a pressure wave received at an observer location at time t must have originated at the source at an earlier time τ . This earlier time τ is commonly denoted the “emission” or “retarded” time, while the time t is commonly called the “reception” time. The path is the trajectory of the part of a pressure wave which reaches the observer. A differential surface element of the pressure wave arriving at an observer has an incident direction, which in a two-dimensional problem is described by a reception angle. Likewise, that differential surface element of the pressure wave has an emission angle at the source. Observer may mean an actual person, a pressure transducer which is part of a data acquisition system, or a hypothetical transducer in an analytical representation of the pressure field. In any case, the observer is considered to exist at a single point.

The behavior of sound waves in a fluid can be modeled using the mass, momentum, and energy conservation equations for a compressible continuous fluid. For low intensity sound, which is usually the case far from the noise source, the disturbances can be considered mathematically small and allow assumptions leading to a linear governing equation. The acoustic farfield is defined to be the region where the acoustic pressure gradient and the acoustic velocity are parallel and in phase. One form of the linear wave equation is

$$\nabla^2 p = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} \quad (2.1)$$

where p is the acoustic pressure, t is time, c is the sound speed, and ∇^2 is the Laplacian operator. The time variation of the pressure field of an aircraft as measured on the ground is due to motion of constant-strength sources relative to the fixed ground observer, as well as time variation of the sources on the aircraft. For rotorcraft, the relative source/observer motion has two components; the relative velocity between the aircraft and a ground observer, and the relative velocity between a pressure source on a rotor blade and an observer in a nonrotating frame.

Various forms of the linear governing equation for sound have been studied analytically for quite a long time. Since the behavior of the linear equation produces ideal mathematical wave phenomena, most acoustics work is couched in the mathematics and terminology of wave mechanics. There are three common types of waves considered in linear acoustics. Plane waves have flat wave fronts; a classic plane wave field occurs in front of a flat piston moving in a cylindrical tube. Cylindrical waves are caused by phenomena like an infinite-length cylinder expanding and contracting radially. Two-dimensional analytical problems such as oscillating airfoil flows involve cylindrical waves. Spherical waves are three-dimensional and are caused by sources like expanding and contracting spheres, infinitesimal point pressure sources and the like. Phenomena involved in rotorcraft system noise studies are predominantly three-dimensional in nature.

Acoustics problems may also be classified into free-field and reverberant cases. A free-field case is one in which waves emanating from a source propagate away from the source into the surrounding space without striking any solid object. Reverberant fields are those in which sound waves reflect off other solid bodies in the field. Examples of reverberant field problems are aircraft interiors, noise reflection off the ground, and reflection from buildings. Solid surfaces which reflect sound waves may have either finite impedance (they absorb some acoustic energy from the incident wave) or infinite impedance (all acoustic energy is reflected). In a reverberant problem, the sound waves can reflect off of a solid surface, or diffract around an obstacle.

Waves traveling in a fluid can also be subject to refraction (a “bending” of the waves due to local changes in the fluid properties such as sound speed), scattering (a disorganization of the waves due to irregular fluid motions or suspended solid particles), and attenuation due to viscosity and other factors. In aircraft noise problems, refraction is frequently present due to vertical gradients in air properties (i.e. temperature or wind velocity) across the altitudes between the aircraft and the ground. Since the Earth’s atmosphere usually has some turbulence present, scattering can be appreciable for aircraft flyover noise. Attenuation

is always present, since air is a viscous fluid. All three of these phenomena (refraction, turbulent scattering, and attenuation) tend to become important for wave propagation over long distances, particularly high altitude flyovers.

One of the difficulties of aeroacoustics is that the sound source, usually an aircraft, is moving relative to a fixed observer. Most acoustic theory and technique is oriented to “stationary” problems, for which the descriptive statistics of the acoustic pressure (i.e. mean and variance) do not vary with time. For situations with relative motion between the source and observer, the problem is usually nonstationary. An additional difficulty in aeroacoustics is that real-world problems have observers fixed to the ground, an aircraft flying on some flight profile, and some amount of mean and turbulent ambient wind. Thus, there are three coordinate systems involved rather than the usual single system, which complicates the formulation of modeling equations, and limits our ability to use physical intuition to understand the behavior of sound waves. Fortunately, many flyover situations consist of an aircraft flying at constant speed and altitude, in little or no wind, allowing a simpler formulation of the problem.

The usual intention of acoustics work is slanted towards the end effect on humans. Undesirable sound is studied to determine the physiological and psychological effect caused by a given source. There are non-human effects of sound, as well. Acoustic fatigue of structures is one such effect, as well as acoustic modification of aerodynamic boundary layers. Though aircraft vary tremendously in size (thus their acoustic signatures vary substantially in magnitude and frequency), humans have relatively fixed length and frequency scales, so the end result of acoustic work is usually phrased in a dimensional or quasi-dimensional form.

2.2 Units

Sound, being a pressure disturbance, has the units of force per unit area. Some units and conversions common in acoustics are;

1 μbar	= 0.1 N/m ²
1 psi	= 6894 N/m ²
1 dyne/cm ²	= 10 ⁻¹ N/m ²
1 Pa	= 1 N/m ²

Because the dimensional magnitude of sound waves varies dramatically, acoustic pressure is often logarithmically scaled using the decibel (dB). Sound Pressure Level (SPL) is defined as

$$\text{SPL} = 20 \log_{10} \left(\frac{p}{p_{ref}} \right) \quad \text{dB} \quad (2.2)$$

$$= 20 \log_{10} p + 94 \quad (2.3)$$

where p_{ref} is set to the commonly used reference pressure 20 μPa . Often, the acoustician is only interested in magnitudes, so the mean square pressure, $\langle p^2 \rangle$, is used; then

$$\text{SPL} = 10 \log_{10} \left(\frac{\langle p^2 \rangle}{p_{ref}^2} \right) \quad \text{dB} \quad (2.4)$$

2.3 Frequency-Domain Representation

Due to the wave nature of sound and the many analytical and experimental tools applicable to signals expressed in sine series representations, pressure time histories are typically Fourier transformed to obtain amplitude and phase as functions of frequency. Plots of these functions are called spectra, with the amplitude vs. frequency spectrum used frequently in aeroacoustics. Since the acoustic pressure time series are analyzed on digital computers, the analog signal from a microphone is digitized, converted from units of voltage to units of pressure, then stored for subsequent Fourier analysis. Note that in the present work, “band” is used to describe the width of the span of frequencies corresponding to a single Fourier coefficient. The term “bandwidth” is often used to describe the width of the total spectrum, which can lead to confusion. The frequency resolution of a spectrum is measured by

the width of the frequency bands which is dependent on the digitization rate. Narrowband spectra are spectra which have bands that are constant in width (i.e. range of frequencies) and narrower than 1/3 octave bands. Frequency resolution for most rotorcraft narrowband spectral analysis of full-scale acoustic data ranges from 1 to 10 Hz. Broadband analysis typically uses 1/3-octave bands, for which the center frequencies (and thus the width of individual bands) are logarithmically spaced. The advent of high-speed analog/digital converters and Fast Fourier Transforms (FFTs) has made narrowband analysis a common tool.

One analytic form for the Fourier transforms are

$$p(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \mathcal{P}(\omega) e^{-i\omega t} d\omega \quad (2.5)$$

$$\mathcal{P}(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} p(t) e^{i\omega t} dt \quad (2.6)$$

though the reader will frequently find different ways of handling the 2π factor in the literature. As long as the Fourier integral identity holds,

$$p(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-i\omega t} \left[\int_{-\infty}^{\infty} p(t') e^{i\omega t'} dt' \right] d\omega \quad (2.7)$$

the form is correct, but care must be taken when comparing Fourier coefficients from two separate analyses. Since the $p(t)$ time series is usually in digital form, for both predictions and measurements, the Fourier analysis must be done in a discrete form. The general Discrete Fourier Transform (DFT) has the form

$$\mathcal{P}(\omega) = \frac{\Delta t}{2\pi} \sum_{n=-\infty}^{\infty} p(n\Delta t) e^{-i\omega n\Delta t} \quad (2.8)$$

However, since we are limited to analysing a finite length time series, the DFT is restated as

$$\mathcal{P}(\omega) = \frac{\Delta t}{2\pi} \sum_{n=1}^N p(n\Delta t) e^{-i\omega n\Delta t} \quad (2.9)$$

which can be applied to a finite time series of arbitrary length $N\Delta t$. Since this transform is computationally intensive when applied to many time series with large N , various Fast

Fourier Transform (FFT) algorithms have been developed for use in computer programs. These FFT methods are very efficient, but most require that N be a power of 2. There are many issues requiring treatment when performing Fourier analysis, such as aliasing, leakage, and windowing; the reader is referred to Hardin [9] or Bendat and Piersol [10].

When rotorcraft noise is measured and plotted in an amplitude spectrum, certain individual frequencies have magnitudes well above the rest of the spectrum. These frequencies, called tones, are generally considered to originate from deterministic, discrete phenomena. Other regions in the frequency spectrum have relatively equal magnitude across a short range of frequencies. The content of the acoustic signal creating these flat spectral regions is called broadband noise. Broadband noise tends to come from non-deterministic sources, usually turbulence in some form; the viscous boundary layer on the blade, aerodynamic response to atmospheric turbulence, turbulence in the rotor wake, and turbulence in the engine plume are all causes of broadband noise. Broadband noise can be adequately described in the frequency domain with $\frac{1}{3}$ -octave bands, while tone noise requires narrowband analysis to properly capture the height and shape of the tone in the amplitude spectrum.

Human hearing is generally considered to span frequencies from 2 Hz to 20 kHz. However, for most aeroacoustic applications, the upper limit is reduced to 10 kHz. Since much signal processing is performed with $\frac{1}{3}$ -octave band analysis, the upper limit is extended to 11.2 kHz, which is the upper limit of the 10 kHz $\frac{1}{3}$ -octave band. For jet noise, the lower limit is generally set to 50 Hz, but rotorcraft often have dominant tonal content below 50 Hz which should not be overlooked. Note that, since the end result is human perception of the noise, scaling effects become important. If one is interested in estimating the noise of a full-scale rotorcraft by measuring the noise from a sub-scale model, the frequencies of interest must be shifted. For example, if a one-fourth scale model operates at constant tip Mach number, then the rotor rpm would increase by a factor of four, and likewise the characteristic noise frequencies. Then if the noise of the full-scale aircraft is required up to 10 kHz, then the $\frac{1}{4}$ scale model noise must be measured to 40 kHz.

To look at a frequency-integrated sound level, the Overall Sound Pressure Level (OASPL) is defined by

$$\text{OASPL} = 10 \log_{10} \sum_n \left(\frac{\langle p^2 \rangle_n}{p_{ref}^2} \right) \quad \text{dB} \quad (2.10)$$

where $\langle p^2 \rangle_n$ is the mean square pressure of the n -th frequency band. In an attempt to quantify the frequency response of the human ear, particularly increased sensitivity to high (1-2 kHz) frequencies, various frequency weighting schemes have been developed. Two common ones in use for aeroacoustics are A-weighting and PNL weighting. These schemes multiply the magnitude of each frequency band by some weighting factor, then sum the products as for OASPL. An additional correction to the PNL scheme is the PNLT (Perceived Noise Level, Tone-corrected). This metric weights distinct tones and adds their contribution to the PNL-weighted broadband content of the spectra. This additional step is performed to quantitatively model the additional annoyance that is associated with tonal sources. For aircraft flyover noise, the Effective Perceived Noise Level (EPNL) is used as a certification metric [13] as well for estimation of community response to noise levels. EPNL is obtained by a time integration of PNLT during a flyover.

2.4 Typical Noise Levels

The following table presents some typical noise levels in decibels and pounds per square inch to illustrate the effect of log scaling and give a reference for aircraft noise relative to other noise sources;

<u>noise</u>	<u>dBA</u>
hearing threshold	0
whisper	20
quiet neighborhood	40
normal speech	60
busy office	80

heavy traffic	100
discotheque	120

where dBA means the sound pressure levels are A-weighted. Note that a helicopter flying overhead at 500 feet altitude may have a noise level of 80-100 dBA. Even at noise levels of 140 dBA, which is a rough estimate of the pain threshold, the root-mean-square acoustic pressure is only 200 Pa, which is a very small variation about the 101,325 Pa static pressure. Noise levels of 100 dB, which is loud enough to make conversation difficult, have a root-mean-square acoustic pressure of only 2 Pa. This difference in magnitude between the mean and acoustic pressure has severe ramifications when trying to directly compute acoustics from governing fluid dynamics equations, since numerical errors can be larger than the acoustic content of the calculations.

2.5 Air Properties

Some properties of air at sea level, standard conditions are listed below. Properties of the U. S. standard atmosphere for different conditions have been tabulated in English and metric units for a series of altitudes [14].

pressure	101325 Pa
density	1.225 kg/m ³
sound speed	340.29 m/s

Using $\lambda = \frac{c}{f}$ to relate wavelength λ to sound speed c and frequency f , the following list illustrates wavelengths in the frequencies of interest for a sound speed for air of 340 meters per second;

<u>f (Hz)</u>	<u>λ (meters)</u>
20	17
200	1.7
2000	0.17
20000	0.017

since helicopter tone noise occurs roughly between 15 and 1500 Hz, the lowest frequencies have a wavelength larger than most helicopters, while the highest are smaller than the rotor blade thickness.

Chapter 3

HELICOPTER NOISE

Helicopter aeroacoustics has become a distinct field in recent years, due to the increased interest in FAA certification and military survivability issues. The aims of the workers in this field are to understand the physical mechanisms which cause noise, to measure and/or predict the noise level of a particular aircraft for comparison purposes, and to reduce the noise level of future designs. The tremendous expense and difficulty in getting detailed, accurate experimental data has hampered efforts on all three fronts. Recent experimental programs have sparked substantial progress in understanding the aeroacoustic processes, and have illustrated the need for improved analysis and design tools. This chapter discusses the various noise sources on rotorcraft and the current methods for predicting them.

3.1 Overview

The noise signature generated by rotorcraft is quite complex, and has many difficult-to-model sources. Aerodynamic noise is generated from main rotors, tail rotors, fuselage boundary layers, and engines. While aeroacoustics may be thought of conceptually as fine resolution of unsteady pressures in an aerodynamic flowfield, it is pragmatically difficult to model the entire flow region, which includes the helicopter, ground plane, and observers. Thus, prediction efforts to date have identified the more important noise mechanisms and applied focused approaches on more tractable models.

Some aerodynamic phenomena on rotorcraft are; unsteady self-interacting vortical rotor wakes, transonic flow around the blade tips in high-speed forward flight, rotor/fuselage interaction, rotor/rotor interaction, blade boundary layer separation, continually varying blade pitch due to pilot-commanded control inputs, rotor wake/engine plume interaction, and atmospheric turbulence. Likewise, computing propagation of the relatively weak acoustic waves using nonlinear computational methods has been very difficult. The solution of some form of the governing equations for unsteady compressible fluid dynamics for the region enclosing the vehicle and observers is a task which will not become practical for some time, due to limitations of current algorithms for solving the governing equations as well as limitations of available computer hardware.

The Lighthill acoustic analogy is used to separate the aerodynamics from the acoustics [15, 16]. In this way, the aerodynamics can be solved using existing methods without requiring the resolution needed to capture acoustic waves. The aerodynamic modeling typically used reduces the problem to that of an isolated rotor, since the interaction with other bodies and rotors is an extremely difficult problem, and the isolated rotor problem is the primary contributor to the total noise signature. Using the aerodynamic loading on the rotor, the generation and propagation of sound is then predicted with several acoustic theories [12]. The noise has contributions from both rotor tone noise and rotor broadband noise models. A recent state-of-the-art review article on helicopter rotor noise is given by Brentner and Farassat [12]. Another overview of rotor noise is presented by Hubbard [11].

3.2 Tone Noise Sources

A substantial understanding of rotor tone noise has been developed using the Ffowcs Williams-Hawkings (FW-H) equation [17]. One form of the FW-H is

$$\frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} - \nabla^2 p = \frac{\partial}{\partial t} [\rho_\infty v_n | \nabla \mathcal{F} | \delta(\mathcal{F})] - \frac{\partial}{\partial x_j} [l_j | \nabla \mathcal{F} | \delta(\mathcal{F})] - \frac{\partial^2}{\partial x_m \partial x_n} [T_{mn} H(\mathcal{F})] \quad (3.1)$$

There are several forms of the FW-H equation to be found in the literature [18, 19, 20, 21]. This equation, which is a rearrangement of the fluid dynamic conservation equations, can be reduced to a linear three-dimensional wave equation. The left hand side is a wave operator, and the right hand side has forcing functions due to the kinematics and aerodynamics of the problem. The kinematic forcing term can be construed to be the effect of a finite-thickness blade displacing fluid as it passes through the air, thus it is called the “thickness term.” Likewise, the aerodynamic term is called the “loading term” since it is due to the aerodynamic force (or load) on the fluid by the blade. This nomenclature can be misleading, insofar as a nonlifting case still has loading noise, due to the surface pressure and shear distributions on a blade section at its angle of zero lift.

A Green’s function solution to the FW-H equation has been developed by F. Farasat [18]. The solution is known as “formulation 1A” and is given here,

$$p(\vec{x}, t) = p_L(\vec{x}, t) + p_T(\vec{x}, t) \quad (3.2)$$

where the thickness noise $p_T(\vec{x}, t)$ is

$$4\pi p_T(\vec{x}, t) = \int_{\mathcal{F}=0} \left[\frac{\rho_\infty v_n (r\dot{M}_j \hat{r}_j + cM_r - cM^2)}{r^2 (1 - M_r)^3} \right]_{ret} dS \quad (3.3)$$

and the loading noise is

$$\begin{aligned} 4\pi p_L(\vec{x}, t) &= \frac{1}{c} \int_{\mathcal{F}=0} \left[\frac{\dot{l}_j \hat{r}_j}{r (1 - M_r)^2} \right]_{ret} dS + \int_{\mathcal{F}=0} \left[\frac{l_r - l_j M_j}{r^2 (1 - M_r)^2} \right]_{ret} dS \\ &+ \frac{1}{c} \int_{\mathcal{F}=0} \left[\frac{l_r (r\dot{M}_j \hat{r}_j + cM_r - cM^2)}{r^2 (1 - M_r)^3} \right]_{ret} dS \end{aligned} \quad (3.4)$$

The thickness noise, i.e. noise predicted by the thickness term, of a rotor is predominantly in-plane with the rotor and is highly directional. It is affected by the rotor tip speed, advance ratio, number of blades, and airfoil shape. Since it is based only on kinematics and geometry of the blade, prediction methods have been successful for this contributor to tone noise.

Loading noise effects are strongest out of plane with the rotor, i.e. above and below the rotor disk. Loading noise is affected by thrust coefficient, advance ratio, number of blades, blade twist, blade camber, tip speed and rotor trim. The aerodynamic forcing to the FW-H equation is typically obtained for an isolated rotor encountering level steady flight conditions. Even for this ideal situation, only recently have the rotor aerodynamicist's tools been adequate for use in predicting tone noise. Some preliminary work has been done on rotor/airframe and rotor/rotor interactions, but these techniques are still exploratory in nature.

The effects of compressibility on the acoustic field of a rotor are twofold; the noise due to shocks, and the alteration of wave propagation due to varying air density near the blade. They may be lumped into the High-Speed Impulsive noise (HSI) category. Both of these phenomena are modeled by the quadrupole terms of the FW-H equation and are not commonly modeled. Research is underway to determine how to incorporate their effects into FW-H equation solvers. Additionally, a technique called the Kirchhoff method is being used to predict farfield rotor noise by direct computation of the pressure field around a rotor blade using Computational Fluid Dynamics (CFD) codes for a small region surrounding the blade, and a linear wave equation method for wave travel beyond the the CFD solution region. In this way, nonlinear methods (i.e. the inherent nonlinearity of the CFD governing equations) are used to directly compute the pressure wave behavior in regions with nonlinearity, and an efficient linear wave equation where the problem is predominantly linear [22, 23].

Blade-Vortex Interaction (BVI) is an impulsive aerodynamic phenomenon where a well-defined tip vortex passes near a rotor blade, and induces sharp spatial and temporal gradients in the blade surface pressure distribution. These surface pressure fluctuations generate highly directional acoustic impulses which can greatly increase the peak-to-peak pressure experienced in the farfield. A main rotor can have BVIs with its own wake in high speed level steady flight, and also in forward flight descents at intermediate speeds. In high speed forward flight, the noise problem can be magnified by the presence of shock waves on the

blade tip during the advancing quarter of each revolution. The vortex interaction with the transonic flow around the blade tip can generate very strong impulses. Tail rotors encountering main rotor vortices also have BVIs. The propagated noise for both causes is highly directional and extremely unpleasant.

The tones generated by a helicopter rotor occur at frequencies which are integer multiples of the “Blade Passage Frequency” or BPF, which equals the number of blades multiplied by the rotor angular speed in Hz. The BPF for a McDonnell Douglas MD-500 helicopter is about 41 Hz, which is the vehicle used for the example cases discussed later in this document. For flight conditions in which there is no BVI or shock noise, the tonal part of the spectrum is appreciable for the first 5-10 harmonics of the BPF. Impulsive phenomena such as BVI and HSI increase the tonal content beyond 30 harmonics [24].

3.3 Broadband Noise Sources

There are many mechanisms which contribute broadband noise to rotorcraft acoustic signatures. Turbulence ingestion noise is generated by the fluctuation on rotor blade loading caused by ingestion of atmospheric turbulence and the resulting azimuthal change in blade effective angles-of-attack. Engine broadband noise arises from the turbulent mixing of the exhaust stream with the freestream air, the combustion noise inside the engine, and compressor noise. Another broadband noise source is Blade-Wake Interaction (BWI) [25]. This is caused by turbulence in the blade’s shed wake interacting with the blade aerodynamics. Very little research has been done on this topic. Turbulent boundary layer trailing edge noise is caused by the passage of turbulent eddies in the boundary layer passing by the blade trailing edge. Laminar boundary layer trailing edge noise is due to vortex shedding at the trailing edge from the laminar boundary layer. Separation-stall noise can be caused by both mild trailing edge separation regions as well as massively separated regions. Very little is known about this noise source. Vortex formation noise is due to the rapid creation of turbulent flow in the formation region of a rotor tip vortex. Trailing edge bluntness noise

is caused by vortex shedding from a blunt trailing edge. These noise sources are discussed in more detail by Brooks *et al* [25, 26].

While current technology rotors have amplitude spectra dominated by low frequency tones, frequency-integrated noise metrics show that broadband noise is as important as tone noise. In fact, broadband noise tends to dominate the total levels computed using frequency-weighting (dBA, for example). However, prediction of broadband noise is a difficult task, since turbulence and/or chaotic phenomenon; thus, current technology for the prediction of broadband noise is limited to combinations of semi-empirical and analytical methods.

3.4 Propagation

As sound waves pass through the atmosphere, there are losses in signal strength due to several causes. The dominant effect is “spherical spreading”, which is due to the increase in area of a spherical wave as the wave front travels away from the source. Note that there is no loss of total acoustic energy, just a reduction in energy per unit area per unit time. Another effect is the loss of acoustic energy by heating the fluid and other internal energy loss mechanisms. These losses are generally denoted “atmospheric absorption.” The effect of a wave striking the ground can be large. The wave is partly absorbed and partly reflected, with a reflected signal arriving at an observer some time after the original wave. Atmospheric turbulence can also scatter sound waves. Lastly, temperature, humidity, and wind velocity gradients can refract the sound waves. All of these effects attenuate the original noise generated by the aircraft.

In the human-audible range, the attenuation is frequency-dependent, with greater attenuation at higher frequencies for most problems. Note that the presence of the ground vastly alters the propagation due to diffraction and thermal gradients. Propagation in free air is a much simpler problem. Generally, 100 meters is a typical distance beyond which atmospheric effects are considerable.

Some means of combining propagation models and source models is needed for rotorcraft flyover noise prediction. The method used in ROTONET is to use the noise source models to predict the noise in the moving aircraft frame, with the only propagation effect being the spherical spreading behavior implicit in the governing equations, and use separate propagation models to predict the attenuation, scattering, and ground reflection. The transfer of information between the source models and atmospheric propagation models occurs at a hypothetical “sound bubble”, a spherical surface some 5-10 rotor radii away from the rotor hub.

3.5 Noise Metrics

Major drivers for developing rotorcraft noise prediction capability are the community noise and certification problems. Two metrics are commonly used to quantify the relative human response to aircraft flyovers. The EPNL metric is a PNL-based quantity for a single flight event, while the Day-Night Level, DNL (sometimes denoted by L_{DN}) is an A-weighting based metric for an assumed series of flights during both daylight and nighttime hours of a 24-hour day [8]. Neither of these seem to properly assess the annoyance of a low-frequency dominated vehicle such as the UH-1. Research is ongoing in the psychoacoustics field to develop better models for the relative human response to tone noise and particularly, highly impulsive noise.

Chapter 4

ROTONET EXECUTION

ROTONET is a large Fortran program which reads in the flight conditions and a user-created helicopter database, and executes a user-specified sequence of subroutines to predict the noise received at ground observer locations. This computer program, developed by the Acoustics Division of the NASA Langley Research Center during the 1980's, can be installed on several computer types and operating systems. The complexity of the problem and the diversity of models involved in utilizing ROTONET for prediction and design work requires a substantial commitment of time to learning the ANOPP executive and the mechanics of the various ROTONET modules. This and other publications [1, 2, 3, 4] provide the user with information needed to run ROTONET. This chapter discusses the way execution paths are configured in order to make various kinds of noise prediction with ROTONET.

4.1 Basic Concepts

ROTONET actually consists of a subset of the ANOPP Aircraft NOise Prediction Program. Certain user-invoked modules are helicopter-specific, and, when given the proper inputs and execution sequence, produce the desired outputs. Depending on the computer it resides on, ANOPP may be run either interactive- or batch-mode. For either, a procedure or script file is required to assign the input and output files to logical I/O units, as well as run the executable file.

The ROTONET program is modular. To execute certain functions, *Functional Modules* are invoked in the input deck. Each of these modules is a set of subroutines which do the various calculations. Required data are fetched, operated on by a specific algorithm, and results stored in ROTONET's run-time database as well as printed out to the standard output file.

For any given ROTONET run, an input file (also called an input deck) is needed to provide the code with input data and an execution sequence for the chosen modules. Example decks are illustrated in later sections of this chapter.

The many modules in the ROTONET group can be grouped in the following manner;

- atmospheric conditions & source/observer geometry
- blade properties
- rotor performance
- rotor tone noise
- tone noise propagation
- rotor broadband noise
- engine broadband noise
- broadband noise propagation
- noise metric calculation

4.2 Functional Module Groups

Table 4-1 lists the modules used in typical ROTONET analysis, as well as a brief description of their functions; the modules are grouped by similar and/or related functions, and are listed in order of execution for most analyses. Figure 4.1 presents a flowchart of the entire ROTONET system.

Module	Purpose
ABS SFO GEO APM ATM	atmospheric absorption coefficients steady level flight trajectory source/observer geometry atmospheric property parameters atmospheric properties
IBS IBA IBL	reads and interpolates blade shape inviscid aero forces and moments viscous forces
LRP RWG RIN RRD RLD	rotor trim and aerodynamics rigid wake geometry wake-induced velocity rigid-blade flapping response rotor airloads
LRN RBN RTN ABL STL TIN MSN	compact-chordwise rotor tone noise rotor broadband noise full-surface rotor tone noise atmospheric turbulence properties streamline distortion tensor turbulence ingestion noise combines source noise for two rotors
PRO PRT	propagates rotor broadband noise propagates rotor tone noise
LEV EFF	frequency-integrated noise metrics EPNL for each ground observer

Table 4.1: ROTONET Modules listed by function

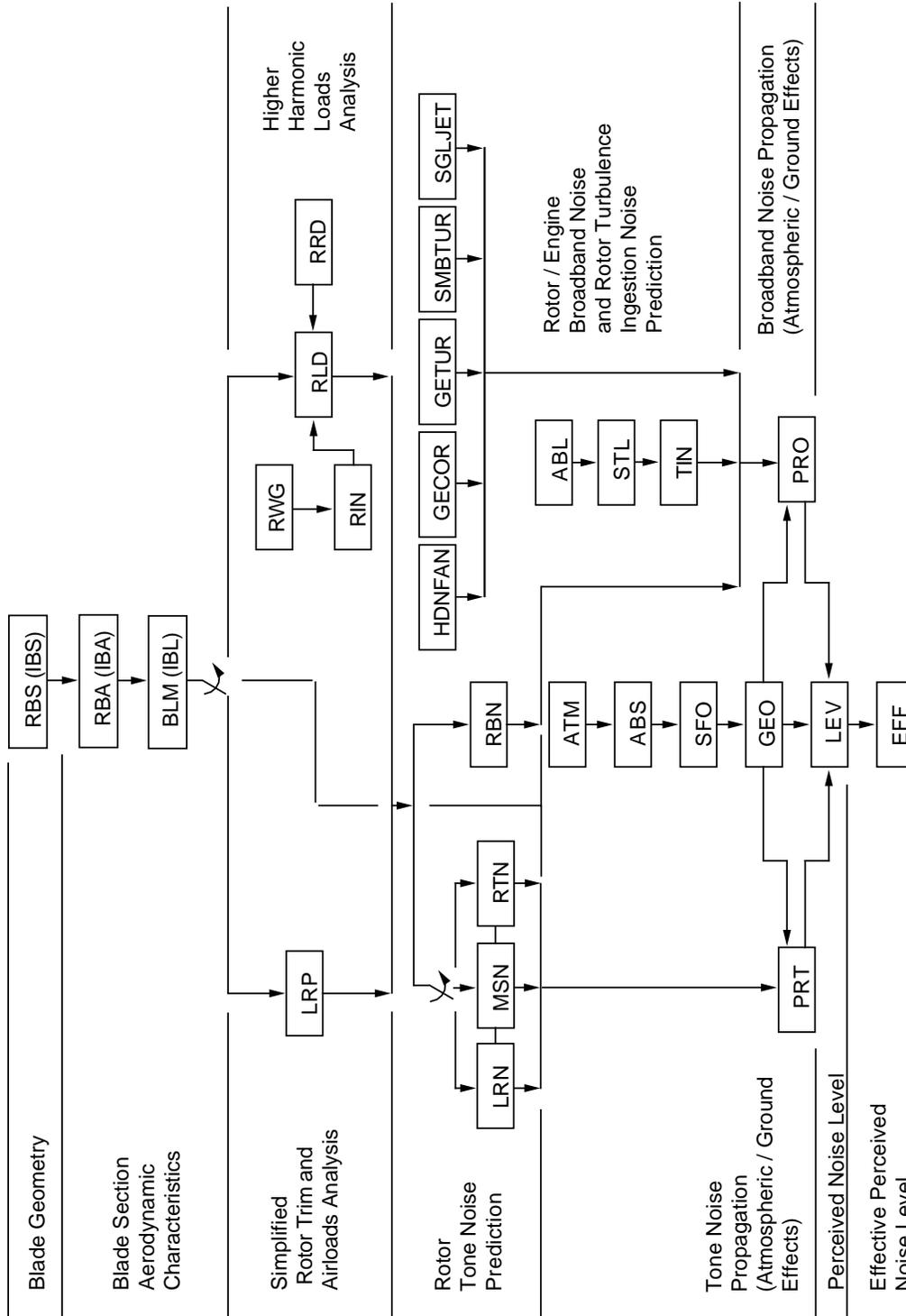


Figure 4.1: ROTONET System Flowchart

The acoustic properties and source/observer geometry generate inputs to the propagation and metric calculation modules. The sequence of executed modules is ATM-ABS-SFO-GEO.

The blade properties modules generate inputs for the rotor performance and rotor broadband noise modules. There are two sets of modules which can be used; either RBS-RBA-BLM, or IBS-IBA-IBL. The former are the original modules, and the latter are more recently developed modules. The improved modules should be used whenever possible, and the original modules will not be discussed further in this document.

The rotor performance modules create airloads tables for the rotor tone noise and broadband noise modules. For simple blade element/momentum theory calculations, the LRP module is executed. For higher harmonic loads, the RLD module is executed, in conjunction with RRD, RIN, and RWG in an iteration loop. The rotor tone noise prediction generates pressure time histories or spectra for direct use or for input to propagation modules. If the LRP module has been used, the LRN module must be exercised; if rotor loads were generated with the RLD system, the RTN module must be used. The rotor broadband module RBN likewise generates spectra. These may be used directly or as input to the broadband propagation module. Rotor tone noise propagation is computed with PRT. Its calculations may be used directly (narrowband spectra) or input to the noise metrics modules. Broadband noise propagation is calculated with the PRO module. As with PRT, PRO's calculations may be used directly ($\frac{1}{3}$ -octave band spectra) or input to the noise metrics modules. The noise metric modules are called with the sequence LEV-EFF. Various integrated noise metrics at a ground observer are produced from the propagated noise generated by the modules PRT and PRO.

The various Functional Modules are discussed in detail in Chapter 5. Their inputs and outputs are discussed in Chapter 6.

4.3 Input Deck Structure

When creating a ROTONET input deck, the following choices must be made;

- what observer locations and reference frame are desired
- what noise outputs are needed (EPNL, $\frac{1}{3}$ -octave band spectra, narrowband spectra, time-histories)
- what noise sources are to be modeled (main rotor tone noise, main rotor broadband noise, engine broadband noise, etc.)
- how rotor aerodynamic loading is to be predicted (simple momentum, generalized wake + rigid rotor dynamics, experiment)

By working backward, the required modules are found, which then determines the order of execution via the needed output-to-input relationships of the modules. Also, the external user inputs are defined at this point.

There are several input deck templates which illustrate workable ROTONET models. Often, the fastest way to create a new input deck is to reconfigure one of the templates for the problem at hand. However, the flexibility of the executive structure is such that a great many more possible configurations may be used to accomplish a new task.

4.4 Inputs and Outputs

There are two basic types of inputs and outputs; parameters and user database members. Both may be used as input, output, or both. Parameters are single valued or one-dimensional arrays, while members are arrays, frequently two- and three-dimensional. Note that parameters and members are global during the run; the information is in a common memory area and all functional modules and data manipulation commands have access to the value of a database element.

Parameters are integer, real, logical, or character data arrays of one or more elements. Most parameters are single element real numbers. Some are one-dimensional arrays. Most

parameters have default values as well as upper and lower limits.

Database members may be unit members, table members or procedure members. They can be either “run-life” or part of a database stored on disk. Note that ANOPP has a permanent database containing all data ANOPP provides for itself. A database can consist of several members, each of which is composed of records. Each record can consist of one or more elements. Elements can be character strings, integer, real, or logical data.

Unit members are database members for data which are used as-is, and not interpolated from. An example is the `GRID(XI1)` member which represents a spanwise blade grid distribution. Table members are database members which are designed to be interpolated from. When a table is created, the user specifies the type of interpolation used. An example is the `EMP(PRES)` table, which consists of a blade surface pressure distribution on a given grid. The pressures are interpolated to obtain the pressure at the desired computational blade grid. Procedure members are portions of ANOPP input decks which may be executed during part of an ANOPP run. One may think of them as a “macro”, or set of commands which are frequently used in the same sequence.

A thorough discussion of the ANOPP input syntax is given in reference [2]. Definitions of input and output variables are given in “The NASA Aircraft Noise Prediction Program Improved Propeller Analysis System” [3], “Aircraft Noise Prediction Program Theoretical Manual” volume 4 [4], “An Introduction to High Speed Aircraft Noise Prediction” [5], and “Aircraft Noise Prediction Program User’s Manual” [2]. Another excellent reference for input and output variables can be formed by making a printout in alphabetical order of the “help files” (Vax versions) or “man pages” (Unix versions) for all of the modules used in typical ROTONET predictions.

4.5 ANOPP Control Statements

ANOPP control statements are available to specify or modify input data, execute modules, manipulate data arrays (either in “unit member” or “table member” form), and perform

general-purpose logic functions such as iteration loops and value tests. The following is a list of the more commonly used control statements for the ANOPP executive [2];

General Executive

ANOPP	starts ANOPP executive and sets some parameters
STARTCS	initial executable control statement
TITLE	sets title string for standard output file (appears on printouts, can change during run)
ENDCS	stops processing input deck and closes files

Parameter Controls

PARAM	used to assign a parameter to a fixed value
EVALUATE	computes the value to be assigned to a parameter
UPLIST	causes printout of all existing parameters & values

Library Controls

LOAD	read in library from disk
UNLOAD	copy active library to a disk or tape file
DROP	remove a library from the current job memory

Database Member Controls

TABLE	add a table member to the database
UPDATE	add or modify a unit member in the database
PURGE	remove a specified unit from the database

Database List Controls

CATALOG	produce summary list of current database units, or contents of a specific data unit
MEMLIST	give detailed information about a specific unit member
TABLIST	give detailed info about a specific table

Functional Module Controls

EXECUTE	run the specified module
---------	--------------------------

The following section provides an example of actual deck structure and ANOPP Control Language syntax. The reader is directed to the Aircraft Noise Prediction Program User's Manual [2] for thorough details on control statement syntax.

4.6 Sample Input Deck

The following input deck is used to illustrate the form of a "typical" ROTONET deck. Note that it is a basic text file (ASCII on most computers). Two library files, containing various unit and table members, are being read in. Thus, there must have been one or more ROTONET jobs previously run to create the library files. This feature is used to avoid running modules over and over for different flight conditions, but with the same blade geometry and properties information. Note that the library files are binary, and cannot be read from a terminal. The functional modules used here are described in the following chapter.

```

ANOPP JECHO=.TRUE. JLOG=.TRUE. NLPPM=48 $
STARTCS $
SETSYS JECHO=.FALSE. $
$
$ example input deck for ROTONET Primer.
$
$ note that on each input line, text after the dollar sign is ignored
$ and is used for comments. note all caps for actual ANOPP commands.
$ the dollar sign can be put in any column desired; Fortran style
$ commenting is being used in this input deck.
$
LOAD /BLADE/           $ a library file from a previous ROTONET run,
                       $ with IBS/IBA/IBL results, is read into the
                       $ database. BLADE.WRK is the file name on
                       $ most machines. note all caps.
                       $
LOAD /ATMSP/          $ a library file from a previous ROTONET run,
                       $ with atmospheric and flight dynamics
                       $ information.
                       $
                       $ now define some parameters; let the rest
                       $ default. note the spaces before and after
                       $ the = signs.

```

```

PARAMETER  R = 10.0          $
PARAMETER  IMPROV = .TRUE.  $ blade radius, meters.
PARAMETER  MACHRF = 0.5     $ use the IBS/IBA/IBL blade tables.
PARAMETER  MZ = 0.1         $ hover tip Mach number.
PARAMETER  NBLADE = 4       $ flight Mach number.
PARAMETER  WT = 0.006       $ number of blades.
PARAMETER  $ aircraft weight coefficient.
EXECUTE LRP                  $
                             $ compute the rotor airloads.
EVALUATE   BETA(1) = AOL     $
EVALUATE   BETA(2) = A1L     $ convert LRP output parameters to LRN input
EVALUATE   BETA(3) = B1L     $ parameters.
EXECUTE LRN                  $
                             $ compute the rotor tone noise in the a/c
                             $ reference frame.
EXECUTE PRT                  $
                             $ propagate the tone noise to the ground
                             $ observer.
UNLOAD /NOISE/              $
                             $ this writes a library file called NOISE.WRK
                             $ for future use.
ENDCS                        $
                             $ this finishes the run, and closes the files.

```

Any text following the **ENDCS** control statement is ignored. This feature allows stopping a job stream in the middle, by inserting an **ENDCS** statement in the middle of the input deck. This can be used to save CPU time, which is useful during debugging.

4.7 Notes on ROTONET Use

ROTONET is currently available on VAX/VMS and some Unix workstations. Included on the distribution tape are; an executable, help files (VAX/VMS) or man pages (Unix), certain input decks called “templates” along with matching output files (to verify the numbers generated on a user’s particular machine), and an interactive command file (VAX/VMS) or *cs*h shell script (Unix) to run ROTONET. This command file/shell script prompts the user for file names, creates a temporary working subdirectory, and runs the ROTONET executable with the specified input files.

The standard filename extensions on VAX/VMS systems are; “*.INP” for the standard input deck (containing the ANOPP control statements), “*.DAT” for the standard output

file (containing printer-formatted stuff), **.OUT* for the file containing array data in ASCII tabular form (from LRN when *IPRINT=4*, for example), and **.WRK* for library files and temporary work files used by ANOPP for data management. In Unix, the filename extensions are lower case except for library files, which must be completely upper case.

Creation of new input decks is a tedious process. The many “templates” and other demo decks provided with the ROTONET distribution tape provide sufficient examples for handling most predictions. The process for creating new decks can be broken down into five steps; determining the “end result” required, finding the sequence of Functional Module executes which will result in that end result, managing the data flow between modules, collecting and assembling the raw input data needed to start the various input decks, and debugging the decks. The first three steps are done with the help of this document, the ROTONET theoretical manual [4], and the help code/man pages. Putting together the raw data needed for modules such as IBS can be quite difficult. Predictions are quite sensitive to quantities including the geometry of the leading edge region of the blade, the geometric twist rate of the blade, the vehicle equivalent flat plate drag area, and so forth.

There are several steps to debugging ROTONET input decks. The first step is getting the decks to run through completely. If the decks finish successfully, that is with no run-time errors, the last two lines of the standard output file will be

```
ENTERING ANOPP NORMAL TERMINATION PHASE  
ANOPP IS TERMINATING NORMALLY
```

this only means that the ANOPP program finished without run-time errors. However, ANOPP may have had errors in reading the inputs or executing modules, in which case there will be error messages in the output file which can be found by string-searching in a text editor for **ERROR**. Since the standard output files can become very large, it is much quicker to use a text editor (in 132 column mode) to find error messages. To cut down on the run time while debugging a particular stretch of inputs, a new **ENDCS \$** line can be inserted in the deck just after the problematic control statements. Thus, the rest of

the deck can remain intact and when the problem is resolved the temporary `ENDCS $` line can be removed so that the rest of the deck is executed. ROTONET outputs can be very sensitive to several input quantities, including; the distribution of grid points on the blade (`GRID(XI1)` and `GRID(XI2)`), the number of time steps per rotor revolution (`NTIME`), the distribution of observers on the “sound bubble” (`SFIELD(PHI)` and `SFIELD(THETA)`), and the number of ground observers (`OBSERV(COORD)`). It is highly recommended that the user perform a study determining the necessary resolution by using increasingly fine grids until the noise predictions stabilize. There will be some variation with grid changes, but noise levels probably should not change more than 1 dB. If highly directional noise phenomena like thickness noise, high-speed impulsive noise, or Blade-Vortex Interaction become important, the observer arrays on the sound bubble and ground plane should be reviewed. If the observer distributions are inadequate, the prediction accuracy will vary substantially with changing flight conditions.

Due to ANOPP’s origins in prediction for CTOL aircraft, the LEV module expects the `SFIELD(FREQ)` array to contain the 24 standard $\frac{1}{3}$ -octave band center frequencies. The standard center frequencies start at 50 Hz and end with 10,000 Hz. If the array does not match the standard 24 bands, an error message is printed in the output file; ANOPP continues executing, however. For rotorcraft prediction, the noise usually extends below the first standard $\frac{1}{3}$ -octave band centered at 50 Hz. Depending on the main rotor’s blade passage frequency (rotation rate in Hertz multiplied by the number of blades), the `SFIELD(FREQ)` array may need to extend down several more bands. LEV will continue on with the nonstandard array of band center frequencies, so users can ignore the error message. For EPNL purposes the 24 standard bands (with center frequencies starting at 50 Hz and ending at 10 KHz) should be used. However, to correctly account for the low frequency content of main rotor noise, the set of bands should be extended down to the 12.5 Hz center frequency.

The interpolation of the blade shape is a frequent source of problems. If the distribution of airfoil ordinates is too course or too fine, or if the `GRID(XI2)` array has excessively fine

spacing around the leading edge ($XI2 = 0.5$), the IBS module has difficulty interpolating the blade shape. Also, if the trailing edge has substantial camber, the transform to the complex plane (discussed in section 10.2 of Zorumski & Weir [1]) may cause the angular coordinate to become non-monotonic, thus making interpolation impossible. The simplest fix to this problem is to remove the camber from the trailing edge.

One final comment pertains to deck maintenance and modification. Due to the large amount of input data, and the difficulty in obtaining accurate inputs, it is recommended that text be added to each deck in ANOPP control statement “comment” form (see decks in Appendices C, D, and E). Information to provide should include; vehicle type, source of input data, temporary modifications for debugging or parametric studies, local point-of-contact, file name, ROTONET system level, and purpose of the deck with list of modules called and libraries loaded. Archival versions of validated decks should be kept in a safe place so that they are not overwritten in the course of a new project.

Chapter 5

FUNCTIONAL MODULES

The following pages contain a description of the functional modules in ROTONET and the various coordinate systems involved. Commonly used ANOPP modules are also briefly discussed. Detailed discussion of the input/output variables are presented in Chapters 6 and 7. Theory for modules PRO, EFF, and LEV are discussed in Part 1 of the ANOPP Theoretical Manual [1]. Theory for RBS, RBA, BLM, and PRT are discussed in Part 3 of that report. Theory for the ROTONET modules is discussed in Part 4. Usage of the PRO, EFF, and LEV modules is discussed in the “Aircraft Noise Prediction Program User’s Manual” [2]. The IBS, IBA, and IBL modules are discussed by Nguyen [3].

5.1 Coordinate Systems

There are a variety of coordinate systems involved in a ROTONET analysis. Tracing from source to observer, there are the; blade, shaft, tip-path, and aircraft reference frames, and finally the ground-fixed reference frame. There is a certain amount of flexibility in defining the vehicle relative to a given reference frame. For instance, the definition of the blade shape in the blade reference frame may be based on zero sectional twist angle at the root, the tip, or 75% blade radius. Of course, the rotor collective pitch angle must then be adjusted appropriately.

5.2 Harmonic Representations

Since most of ROTONET is written with the assumption that the airloads, and thus the noise, is periodic, it is convenient to carry the aerodynamic response information in a Fourier series. To relate the Fourier sine/cosine series coefficients to the array form used by ROTONET, the following table is given for the translation of analytical Fourier coefficients to array elements for an arbitrary quantity $A(t)$;

<i>ROTONET form</i>	<i>Fourier series</i>
$A(1)$	a_0
$A(2)$	a_1
$A(3)$	a_2
.	.
.	.
.	.
$A(N/2)$	$a_{N/2-1}$
$A(N/2 + 1)$	$a_{N/2}$
$A(N/2 + 2)$	$a_{-N/2+1}$
.	.
.	.
.	.
$A(N - 2)$	a_{-3}
$A(N - 1)$	a_{-2}
$A(N)$	a_{-1}

Table 5.1: ROTONET Harmonic Array Format

where

$$A(t) = \sum_{n=-N}^N a_n \cdot e^{in\omega t} \tag{5.1}$$

is the time history in question. Note the explicit use of the negative Fourier coefficients, though the information is already present in the positive coefficients. These harmonic tables occur frequently in the higher harmonic airloads modules such as RIN, RRD, and RLD.

The following table briefly lists the commonly used modules for ROTONET analyses, the input/output flows, and a short description;

Module	Inputs From Modules	Outputs to Modules	Purpose
ABL	none	TIN	atmospheric turbulence properties
ABS	ATM	SFO	atmospheric absorption coefficients
APM	ATM	various	atmospheric properties in parameter form
ATM	none	ABS, SFO, PRO	atmospheric properties
EFF	LEV	none	EPNL for each ground observer
GEO	SFO	PRO, PRT	source/observer geometry
IBA	IBS	IBL, ...	inviscid aero forces and moments
IBL	IBS, IBA	...	viscous forces
IBS	none	IBA, IBL	reads and interpolates blade shape
LEV	PRO, PRT	EFF	frequency-integrated noise metrics
LRN	IBS, IBA, LRP	MSN, PRT	compact-chordwise rotor tone noise
LRP	IBS, IBA, IBL	LRN, RBN, RLD	rotor trim and aerodynamics
MSN	LRN, RTN, RBN	PRT, PRO	combines source noise for two rotors
PRO	RBN, TIN, MSN	LEV	propagates rotor broadband noise
PRT	LRN, RTN, MSN	LEV	propagates rotor tone noise
RBN	LRP	PRO, MSN	rotor broadband noise
RIN	RLD, RWG	RLD	wake-induced velocity
RLD	RIN, RRD	RIN, RRD, RTN	rotor airloads
RRD	RLD, RRD	RLD, RRD	rigid-blade flapping response
RTN	RLD, RRD	MSN, PRT	full-surface rotor tone noise
RWG	none	RIN	rigid wake geometry
SFO	ATM	GEO, PRO, PRT	steady level flight trajectory
STL	none	TIN	streamline distortion tensor
TIN	ABL, STL	PRO	turbulence ingestion noise

Table 5.2: ROTONET Modules

note that the IBS/IBA/IBL results are also used by LRP, LRN, RBN, RIN, RRD, RLD, and RTN. The following figure illustrates the basic flow of information between modules;

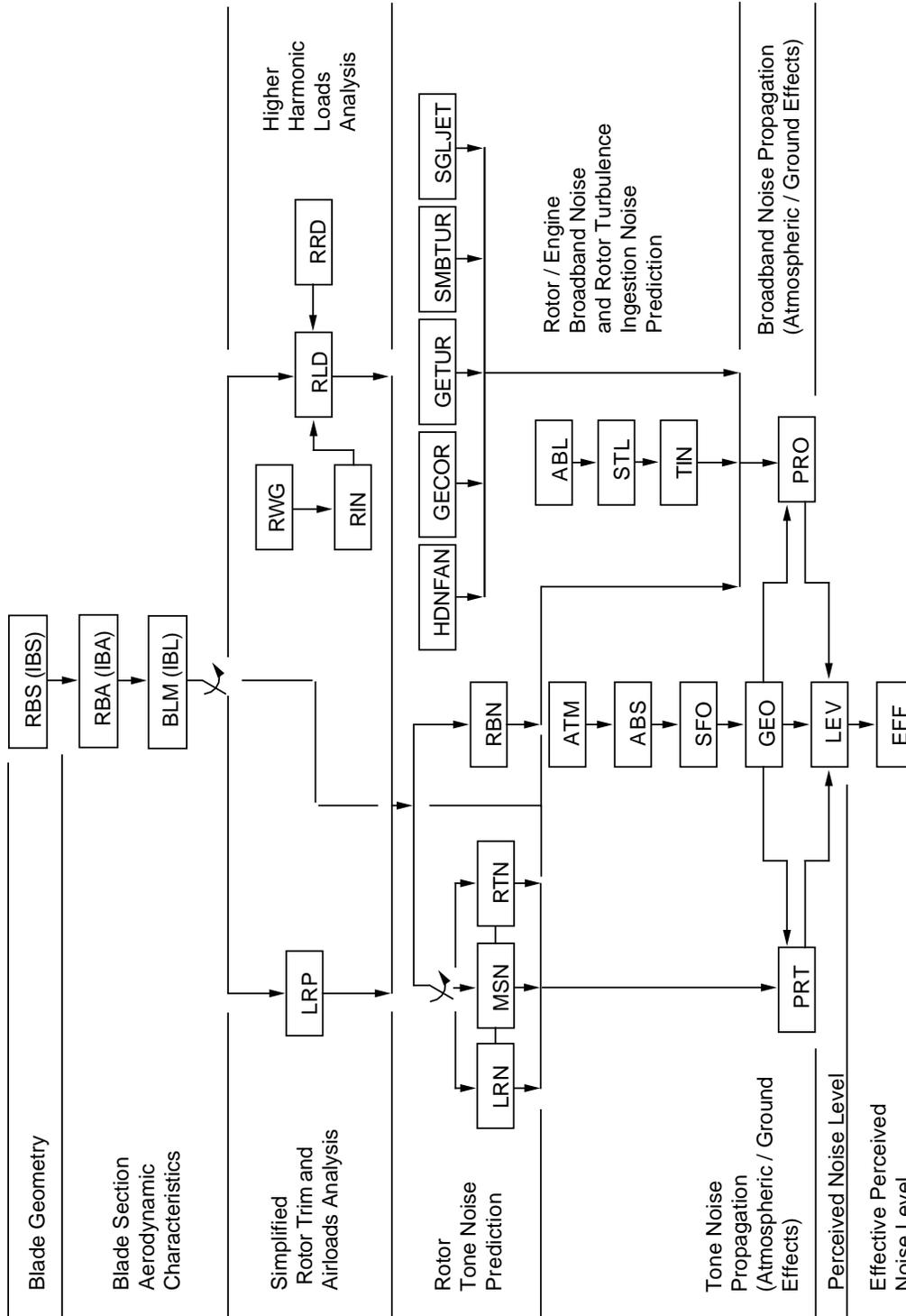


Figure 5.1: ROTONET System Flowchart

Chapter 6

INPUTS

6.1 Parameters

Parameters are variables of integer, real, logical, or string content, and can either be single element or arrays. Their value(s) can be changed with the `PARAM` or `EVALUATE` control statements. `PARAM` statements assign the value of a constant into the parameter. `EVALUATE` statements assign the evaluated value of an algebraic expression to the parameter. Parameters exist in run-time only; i.e. they can not be stored in a database for use in a later ROTONET run. Some parameters are changed by functional modules; for example, the parameter `A0`, collective pitch, is set as an initial guess going into module `LRP`, and contains the final predicted value after `LRP` finishes execution. Other parameters, such as `IOUT` and `IPRINT`, are not changed by functional modules. Examples of syntax can be found in Chapter 4 and Appendices C, D, and E, and detailed discussion of syntax is found in the “Aircraft Noise Prediction Program User’s Manual” [2].

Note also that the ANOPP Control Language has a rename feature. This allows you to use a custom parameter name which is equivalenced to the default parameter name (as found in the module’s documentation). A typical situation for this feature is for a helicopter with a main and tail rotor configuration. Since separate `LRP` runs for each rotor will create name conflicts for parameters such as `A0` (rotor collective pitch angle in radians), the rename

feature allows new parameter names such as `MRA0` and `TRA0` to represent main rotor and tail rotor collective.

Appendix A contains a global list of default names for parameters commonly used in ROTONET analyses. This list expedites development of new input decks, and speeds trace-back of a parameter's value history. During modification or creation of an input deck, the proposed name of a new parameter should be checked against the global default name list to avoid inadvertent choice of a parameter name already in use. Also, if a parameter value is different than that defined by the user, the list allows determination of which modules may have overwritten its value.

6.1.1 Notes on certain parameters

The initial guess for rotor collective pitch angle, `A0`, is used by the LRP module in its iterative determination of simplified rotor trim. If `A0` is too far away from the trimmed value, LRP will not converge and an error message will be printed to the standard output file. The IBL module allows use of boundary layer analysis using flat-plate or curved-wall methods. If the drag force table generated by IBL is unrealistic, set the `FLAT` input parameter to `.TRUE.` and rerun the module. The `GLIM` parameter used by LRN determines the relative error tolerance of the retarded time equation iteration; when in doubt, set it very small to avoid inducing phase errors in the predicted time series. In general, the `TETCAL` and `TVFCAL` models in RBN should be used for typical rotor problems; the trailing-edge bluntness noise and laminar vortex shedding noise models usually contribute little to overall noise levels.

6.2 Members

Unit members are data arrays which are fixed and not interpolated, observer locations for example. Unit members are created with the `UPDATE` command. Tables, also called table members, are data base members which are intended to be interpolated, blade shape for example. Their format is known as "Type 1" in the ANOPP literature. When a table is

created, the user specifies the kind of interpolation to be used. Tables are created with the `TABLE` control statement. Examples of syntax can be found in Chapter 4 and Appendices C, D, and E.

Note also that the ANOPP Control Language has a rename feature. This allows you to use a custom unit, table, or member name which is equivalenced to the default member name (as found in the module's documentation). A typical situation for this feature is for a helicopter with a main and tail rotor configuration. Since separate LRP runs for each rotor will create name conflicts for members such as `IBS(SHAPE)`, the rename feature allows new data unit names such as `MRIBS(SHAPE)` and `TRIBS(SHAPE)`. These two members could also be renamed `IBS(MRSHAPE)` and `IBS(TRSHAPE)`; however, since there are many more member names than unit and table names, the former scheme requires fewer renames and thus is easier and less prone to errors.

Appendix B contains a global list of default names for members commonly used in ROTONET analyses. This list expedites development of new input decks, and speeds traceback of a member's run-time history. During modification or creation of an input deck, the proposed run-time name of a member should be checked against the global default name list to avoid inadvertent choice of a member name already in use. Also, if a member state is different than that defined by the user, the list allows determination of which modules may have overwritten its values.

6.2.1 Notes on certain members

The `SFIELD(PHI)` member, used to input the lateral distribution of observers on the sound bubble, has a unique feature. If the flight trajectory is parallel to the X axis in the ground coordinates, the ground observer array is rectangular with longitudinal (along the flight path) rows of observers parallel to the X axis, and the flight path is level over a flat ground plane, then there are constant values of `PHI` which will correspond to emission angles of acoustic "rays" which will reach the longitudinal observer rows precisely. By calculating

these emission angles, the number of PHI values can be limited to the number of longitudinal observer rows, thus eliminating the need to interpolate the source noise on the bubble in the lateral (perpendicular to the flight path) direction. By minimizing the number of observers on the sound bubble, the run times will be reduced and accuracy increased for both the source noise deck and the propagation deck.

Chapter 7

EXAMPLE CASE

This chapter presents three input decks which, when executed in sequence, predict the EPNL for a level flyover of a McDonnell Douglas MD-500E helicopter, at 95 knots airspeed, 3000 pounds gross weight, and 250 feet altitude. Observe that the sequence of deck execution is such that the blade aerodynamic properties, rotor trim & airloads calculations, and source noise are all calculated *before* the third deck determines the atmospheric properties as a function of altitude. This is allowable because the flyover altitude is only 250 feet, and the ground plane is assumed to be at sea level. This is an acceptable procedure for most ROTONET calculations. However, for flyovers with high altitude above ground level and/or altitude above sea level, the decks would have to be reconfigured to compute air properties (such as density, sound speed, and kinematic viscosity) at the flight altitude of the aircraft.

The process of building input decks can be done in several ways. The beginning ROTONET user is probably best off using existing decks as “templates” for the new decks. The danger in this approach is that re-using various input parameters, unit members, and table members blindly can result in incorrect predictions; some thought should be given to all inputs. The code has defaults for almost all input parameters. For many parameters, these can be relied on to give good results, but there are many parameters that really should be customized to the particular input deck. The best source of information for building new input decks are the help files (also called “pseudocode”). It is recommended that when a

new version of ROTONET is received, the documentation for all modules pertinent to ROTONET be extracted and printed out. That printout is the most frequently used document when advanced users run ROTONET.

7.1 Blade Properties Deck

The input deck listed in Appendix C executes the IBS, IBA, and IBL modules, creating a library file which contains the blade geometry and aerodynamic characteristics for the main rotor.

The IBA(LIFT), IBA(MOMENT), and IBL(DRAG) tables should be plotted out to check for “flyer” points and to make sure the lift and drag curve slopes are reasonable. Most airfoils used on helicopter rotors behave like traditional NACA sections. For instance, the lift curve slope should be somewhat less than 2π . A good place to check the curves is in Abbott & von Doenhoff [27]. Note that the ROTONET blade properties modules do not have sophisticated stall modeling, so comparisons beyond the actual stall angle will not make sense. A stall cutoff parameter is available to limit the ROTONET-predicted lift to a known stall value. The interpolation capabilities of the blade shape modules are limited. Thus, if the user wants a fine grid at the leading edge, plenty of airfoil leading edge points should be used in GEOM(BLADE). While increasing resolution also increases run time for blade properties decks, it is generally wise to have fine resolution, since these decks are only run once per rotor. One can always use a coarser grid in the actual noise calculations. The GRID(XI2) member represents the chordwise angular coordinate in the Joukowski transform plane. The values run from 0.0 at the upper trailing edge, to 0.5 at the leading edge, to 1.0 at the lower trailing edge. The grid shown in this demonstration deck is one developed from experience for full-surface modeling with RTN. It is recommended as a standard grid for most calculations. Note that the spanwise distribution used in GEOM(BLADE) will be the one output into GRID(XI1). If the blade has unusual features such as nonlinear twist, rapidly changing airfoils, breaks in planform etc., then the spanwise stations used in GEOM(BLADE) must be enough to adequately

describe the blade. Note that if the `GRID(XI1)` member desired for the noise computations is not the same as that produced by IBS (which is quite likely), the user should rename `GRID(XI1)` on the “EXECUTE IBS” command or put the command `PURGE GRID $` after the “EXECUTE IBS” statement. Also, if the user gets a “zero determinant” error from IBS or a “laminar separation” message from IBL, the solution is to get a finer blade shape definition in `GEOM(BLADE)` and a finer `GRID(XI2)` distribution.

7.2 Source Modeling

The deck listed in Appendix D calculates the main rotor aerodynamic performance, tone noise, and blade broadband self-noise, using the modules LRP, LRN, and RBN.

Like any helicopter trim program, there are certain things to look for in a rotor airloads prediction. For the given flight condition, the gross behavior like collective pitch and tip-path-plane angle should be compared with other trim codes or experimental data. The cyclic pitch inputs and flapping response is the next level to check, again with comparison to other predictions or empirical data. Finally, the Mach number and angle-of-attack distributions should be looked at to ensure there are no nonsensical aerodynamic conditions being output (eg. a overly large angle-of-attack at the blade tip in forward flight). The `GRID(XI1)` member used in the above deck has been developed from experience with various aircraft cases. Note that, if the collective pitch and/or angle-of-attack iterations fail to converge, putting a realistic initial guess in for the parameter `A0` tends to help.

The predicted tone noise at the sound bubble can be checked by plotting the pressure time histories and narrowband spectra, and comparing them with wind tunnel data for similar flight conditions and observer location. Several publications are available with measured data [28, 29, 30]. Generally speaking, the thickness noise component should be maximum in the rotor plane, and is highly directional for a conventional rotor. Loading noise should be maximum below the rotor in forward flight and is less directional (excepting BVI). It has been found that `NTIME` should be four times greater than `NHARM`. Often, a factor of two is

used due to the Nyquist criteria, but in practice, better results are obtained with a factor of four.

7.3 Flight Trajectory & Propagation

The input deck listed in Appendix E tabulates atmospheric properties, aircraft flight path, and source/observer geometries, and propagates the source noise at the “sound bubble” to the ground observers. Modules ABS, SFO, GEO, PRO, PRT, LEV, and EFF are used. The end result of this deck is time histories of metrics such as PNLT, as well as the EPNL for the entire flyover.

The user should check the results from SFO to ensure that the time step, initial, and final flight times will result in a flight history which brackets the desired initial and final observer elevation angles. If one relies on the defaults, the flyover may not include flight times which contribute substantially to EPNL. The easiest way to check this is to look at the elevation angle printout for each observer. For rotorcraft, this angle should begin at roughly 10 or 20 degrees, and end likewise. The $\frac{1}{3}$ -octave band center frequencies in SFIELD(FREQ) should be consistent with those used downstream in the propagation and integration modules. For purposes of computing PNLT and EPNL, the 24 standard bands (with center frequencies starting at 50 Hz and ending at 10 KHz) should be used. However, to correctly account for the low frequency content of main rotor noise, the set of bands should be extended down to the 12.5 Hz center frequency.

The best bet for checking the predicted noise propagated to ground observers is to compare the predicted spectra with empirical data. Unfortunately, the database of flyover measurements is limited to a few vehicles [31, 32, 33, 34]. However, these tests do allow a certain amount of trend information to be checked. The time history of PNLT should be checked to ensure that the start and end times of the flyover are large enough that the start and end PNLT values are more than 10 dB lower than the peak PNLT. This is necessary

to correctly compute EPNL. Also, ensure that the `SFIELD(FREQ)` array used is identical to that used by the GEO module as well as the LRN and RBN modules.

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APPENDIX A

Global Parameter List

Parameter	Form	Created By	Description
A0	real	user, LRP	collective pitch angle
A0L	real	LRP, RLD	coning angle
A0P	real	RLD	updated collective pitch angle
A1	real	LRP	lateral cyclic pitch angle
A1L	real	LRP, RLD	longitudinal cyclic flap angle
A1P	real	RLD	updated lateral cyclic pitch angle
AA1	real	user	rotor pitch angle relative to body
AA2	real	user	rotor pitch angle relative to body
ABSINT	integer	user	number of integration steps in atmospheric absorption calculation
ABSORP	logical	user	activates/deactivates atmospheric absorption
AERROR	real	user	error tolerance for streamline integration
AKL	real	APM	thermal conductivity
ALPDP	real	LRP	hub plane angle
ALPHA			aircraft angle-of-attack
ALPTPP	real	RLD	rotor tip-path-plane angle
AMU	real	APM	dynamic viscosity
ANGLES	real array	user	array of directivity angles
ANU	real	APM	kinematic viscosity
APPEND	logical	user	flag for SFO to create a new flight profile or append to the existing one in FLI(PATH)
AW	real	user	reference area of aircraft
B1	real	LRP	longitudinal cyclic pitch
B1L	real	LRP, RLD	lateral cyclic flap angle
B1P	real	RLD	updated longitudinal cyclic pitch
BBB	real	user	blade tip loss factor
BETA	real array	user	0-th, 1st, 2nd rigid flapping harmonics (can be assembled from AOL, A1L, B1L, see example decks)
BN	integer	user	number of blades
BTIP	logical	user	flag to choose blunt/not blunt blade tip

Parameter	Form	Created By	Description
C CA CABAR CLMAX COH CQ CT CTK	real real real real real real real real	user user, APM APM user user LRP, RLD LRP, RLD user	blade chord sound speed average sound speed maximum lift coefficient allowed incoherence coefficient torque coefficient thrust coefficient characteristic time constant
ELDB DELH DELF DELMACH DELTA DELTH DIRECT DROTOR DS DTAIL DTIME	real real real real real logical real real real real	user user user user user user LRP user user user	dB threshold below max PNLT for EPNL calculation altitude increment frequency bandwidth Mach number limit flap setting (irrelevant to ROTONET) maximum polar directivity angle limit flag to use input/computed reception times rotor drag force distance between streamlines distance between main & tail rotor hubs ground reception time increment
E EFFOPT ENGNAM EMP EPSLON	real integer Hollerith logical real	user user user user user	rotor blade flap hinge offset flag to choose EPNL or SPL output sets XXX part of FLI(FLIXXX) member name flag to use of external surface pressures convergence limit for IBA
F FF FILENAME FI1 FLAT FTZERO	real real Hollerith real logical real	user user user user user user	vehicle flat plate drag area farfield distance for TIN calculations name of file for contour data blade moment of inertia flag to choose boundary layer model fraction of eventual tip vortex strength initially rolled up into tip vortex
G GAMMA GCT GEOERR GLIM GROUND	real real real array integer real logical	user user user, RRD GEO user user	geostrophic wind speed specific heat ratio constants used in RRD calculations flag denoting success of GEO calculations error tolerance for retarded time calculation flag to enable/disable ground effects
H1 HF HL HSEP HUMID	real integer integer real real	user user user user APM	ground level altitude counter of first harmonic in TIN analysis counter of last harmonic in TIN analysis shape factor at separation point humidity (see APM)

Parameter	Form	Created By	Description
IAERO IAWT IBLFRCT IBAPRES ICoord IDWT IH IMODE IMPROV IOP IOPT	integer logical Hollerith Hollerith integer logical integer integer logical integer integer	user user user user user user user user user user user	LRP/RLD airloads selector for RBN enable/disable dBA output member name prefix for IBL(YYNNNN) member name prefix for IBA(XXXNNN) source/observer coordinate selector enable/disable dBD output turbulence selector MSN mode selector flag blade properties format selector flight condition/observer format selector (RBN) contour data selector (CNT) coordinate system option flag (MSN)
IOSPL IOUT	logical integer	user user	enable/disable OASPL output printout format selector (LEV, PRO, PRT, RBN) output member format selector (LRN, RTN)
IOUTPUT IPNL IPNLT IPRES IPRINT IROLL ISAE ISTR ISYM ITAIL ITIME ITMAX IUNITS	integer logical logical integer integer integer integer integer logical integer integer integer integer Hollerith	user user user user user user user user user user user user user user	output option flag enable/disable PNL output enable/disable PNLT output plot file output selector input/output print selector tip vortex rollup extent index atmospheric absorption selector enable/disable streamline file output symmetric ground observer array flag main/tail rotor trim analysis selector enable/disable deformation tensor file output iteration limit for retarded time equation units selector
J	integer	SFO	initial flight time step counter
L LBLCAL LCSLOP	real logical real	user user user	Monin-Obukhov stability length enables/disables laminar boundary layer noise model lift curve slope
MACHC MACHRF MASSAC MEMSUM MEMSUMN MTS MU MWB MZ	real real real Hollerith Hollerith real array real real real	user user user user user user, RRD user user, LRP user	turbulence convective Mach number rotor hover tip Mach number reference mass of the aircraft unit & member names of broadband noise tables to be summed unit & member names of narrowband noise tables to be summed flapwise moment array rotor advance ratio blade flapping moment of inertia aircraft flight Mach number

Parameter	Form	Created By	Description
NAWT	logical	user	enable/disable A-weighting of narrowband data
NBAND	integer	user	number of 1/3-octave band sub-bands
NBLADE	integer	user	number of blades on rotor
NCOEFF	integer	user	number of elements in BETA and ZETA arrays
NDWT	logical	user	enable/disable D-weighting of narrowband data
NERR	logical	many modules	denotes error status of job stream
NHARM	integer	user	number of harmonics to output; acoustic pressure (LRN, RTN, MSN), azimuthal (RIN, RLD, RRD)
NHO	integer	user	number of altitudes at which to output atmospheric quantities
NISO	integer	user	number of streamlines for which trajectory is to be computed
NORDER	integer	user	order of sine series interpolation of blade shape
NOSPL	logical	user	enable/disable calculation of OASPL from narrowband noise data
NPSI	integer	user	number of azimuth angles for LRP, RWG
NR	integer	user	number of radial stations for TIN noise
NSS	integer	user	max time steps used in streamline integration
NREV	integer	user	number of wake revs used for wake inflow
NT	integer	user	number of azimuth steps for TIN noise
NTIME	integer	user	number of time steps used in acoustic analysis (LRN, RTN)
NUM	integer	user	number of frequencies in TIN noise
NX	integer	user	number of X points required for Cartesian mode calculation of streamlines
NY	integer	user	number of Y points "
NZ	integer	user	number of Z points "
OMEGA	real	user	rotor rotational speed
OMR	real	user	rotor tip speed
P1	real	user	atmospheric pressure at ground level
PARNAM	Hollerith	user	array of parameter names to be output
PLG	Hollerith	user, SFO	initial landing gear position
PLTID	Hollerith	user	file name for LRN plot file
PRES	real	APM	atmospheric pressure (see APM)
PRONUM	integer	user	noise table number (see LRN(XXXNNN))
PROSUM	Hollerith	user	names of broadband noise members to be summed before propagation
PROTIME	Hollerith	user	member name suffix of FLI(FLIXXX), also used as member name prefix of PRO output
PRTTIME	Hollerith	user	member name suffix of FLI(FLIXXX), also used as member name prefix of PRT output
PSI0	real	user	initial rotor azimuth angle

Parameter	Form	Created By	Description
R R0 R1 R2 RBAPRES RECPOL RERROR RHOA RHOACA RINF RL RNDTIP ROTFLEFT RS RX	real real real real Hollerith Hollerith real real real real real logical logical real real	user user user user user user user, APM APM user user user user user LRN user	blade radius source/observer arc radius (not used) rotor 1 radius rotor 2 radius not used polar/Cartesian streamline coordinate flag error tolerance in STL streamline integration ambient air density at aircraft characteristic impedance Reynold's number (= R*CA/ANU) rotor lag hinge offset round/square tip flag left/right-hand rotation flag sound bubble radius, dimensional sound bubble radius, nondimensional
SCRNNN SCRXXX SIDELN SIGMA SOL SRHOC SRHOF START STATIC STOP SURFACE	integer Hollerith logical real real real real real logical real Hollerith	user user user user user user user user user user user	member name suffix for XXXNNN member name prefix for XXXNNN flag to choose between observer array on ground plane or arc specific flow resistance of the ground rotor solidity ratio unburst wake core radius burst wake core radius ratio initial flight time fixed/moving noise source flag final flight time hard/soft ground surface flag
TA TAILTH TB2CAL TBLCAL TEBCAL TETCAL TF THETA THROT THW TI TLG TSTEP TVFCAL	real real logical logical logical logical real real real real real real real logical	APM LRP user user user user SFO user user user user user user user	ambient temperature (see APM) required tail rotor thrust enable/disable Brooks' TEB-VS noise model enable/disable Schlinker/Amiet TBL-TE noise model enable/disable Grosveld's TEB-VS noise model enable/disable Brooks' TBL-TE noise model final flight time geographic latitude (note name conflict with SFIELD(THETA) member) throttle setting (not relevant for ROTONET) flight climb angle initial flight time landing gear reset time time step for flight trajectory enable/disable Brooks' tip vortex formation noise model
V0 VF VI VINF	real real real real	user user, SFO user, SFO user	average wake-induced inflow velocity final flight velocity initial flight velocity vertical climb velocity

Parameter	Form	Created By	Description
W WB WEIGHT WKPRNT WT	real real logical logical real	user user user user user	aircraft weight coefficient (RLD) total blade weight weighting option for GEOM(BLADE) wake distortion/position print flag aircraft weight coefficient (LRP)
X1 X2 XARRAY XF XI XMAX XMIN	real real real array real real real real	user user user user, SFO user user user user	minimum X for streamline calculations maximum X for streamline calculations longitudinal ground observer distribution final longitudinal flight position initial longitudinal flight position streamline domain limit (see STL) streamline domain limit (see STL)
Y1 Y2 YARRAY YF YI YMAX YMIN	real real real array real real real real	user user user user, SFO user user user user	minimum Y for streamline calculations maximum Y for streamline calculations lateral ground observer distribution final lateral flight position initial lateral flight position streamline domain limit (see STL) streamline domain limit (see STL)
Z Z0 Z1 Z2 ZETA ZF ZGR ZI ZOPT ZS ZSLOPE ZMAX ZMIN	real real real real real array real real real integer real logical real real	user user user user user user, SFO user user user user user user user user	height above ground ground surface roughness height minimum Z for streamline calculations maximum Z for streamline calculations rigid blade lead/lag angle harmonics final vertical flight position altitude of ground plane above sea level initial vertical flight position flight trajectory flag source altitude (for nonmoving source) flag for blade shape interpolation streamline domain limit (see STL) streamline domain limit (see STL)

APPENDIX B

Global Member List

Member	Form	Created By	Description
ATM(AAC) ATM(IN) ATM(TMOD)	table member unit member table member	ABS user APM, ATM	atmospheric absorption coefficients temperature & humidity table air properties table also available from LIBRARY.WRK as ATMOS(STRD)
BEAM(STEER) BLADE(TRIP)	table member unit member	user user	array associated with beam steering analysis (not used) boundary layer trip location array
EFF(EPNL) EFF(SEL) EIS(VELOCITY) EMP(PRES) EMP(SHEAR) ENV(COEF)	unit member unit member table member table member table member table member	EFF EFF user user user user	EPNL at ground observer array SEL at ground observer array rotor inflow from external source blade surface pressure coefficient blade surface shear coefficient wake geometry envelope functions, available from RWGLIB.WRK
FLI(FLIXXX) FLI(PATH)	unit member unit member	SFO SFO	source time/flight condition table flight trajectory table
GEO(GEOM) GEO(BLADE) GRD(COORD) GRID(PSI) GRID(XI1) GRID(XI2)	unit member unit member unit member unit member unit member unit member	GEO user GRD user user user	GEOM = BODY, WIND, XXXX prop/rotor blade geometry ground observer array table of ψ s for LRP airloads blade radial grid points blade chordwise grid points

Parameter	Form	Created By	Description
IBA(AEROCTR) IBA(ALPHA) IBA(INCOMP) IBA(LIFT) IBA(MACH) IBA(MOMENT) IBA(STAG) IBA(YYNNN) IBA(ZERO) IBL(DRAG) IBL(THICK) IBL(YYNNN) IBS(EDGTHK) IBS(SHAPE) IBS(SLPCRD) IBS(SLPSPN) IBS(SPAN)	unit member unit member	IBA user IBA IBA user IBA IBA IBA IBA IBA IBL IBL IBL IBS IBS IBS IBS IBS	aerodynamic center distribution angles-of-attack for IBA calculation incompressible pressure coefficients section lift coefficients angles-of-attack for IBA calculation section moment coefficients stagnation point distribution blade surface pressure zero lift angle-of-attack dist'n section drag coefficients boundary layer thickness skin friction table trailing edge thickness dist'n blade shape table chordwise derivative of blade shape spanwise derivative of blade shape blade cross-sectional characteristics
LEV(AWGT) LEV(PNLT) LRP(FORCES) LRP(PERFORM) LRP(STRNTH)	unit member unit member unit member unit member unit member	LEV LEV LRP LRP LRP	dBA time history at ground observers PNLT time history at ground observers blade airloads tables blade aerodynamic angles & velocities max bound circulation table
OBSERV(COORD)	unit member	user, GRD, MSN	see GRD(COORD) see MSN(OBS1, OBS2) ground observer locations (GEO), bubble observer locations in Cartesian form (LRN, RTN, RBN, TIN)
RIN(QMAT) RIN(VELOCITY) RLD(FORCES) RLD(GAMMA) RLD(MOTION) RRD(ANGLES) RRD(MASS) RSD(BEND) RUA(LIFT) RWG(WKDIST)	unit member unit member unit member unit member unit member unit member table member table member table member unit member	RIN RIN RLD RLD RLD RRD user, LRP user user RWG	wake influence coefficients wake inflow at rotor disk blade airloads table blade bound circulation table section Mach number & angle-of-attack tables rigid flapping harmonic table blade mass distribution blade bending harmonics unsteady aero corrections wake geometry distortion table

Parameter	Form	Created By	Description
SHP(COSC) SHP(SINC) SHP(ZEROC) SFIELD(FREQ) SFIELD(PHI) SFIELD(THETA) STLTIN(ABLOT1) STLTIN(STLOT1)	table member table member table member unit member unit member unit member unit member unit member	user user user user user user ABL STL	from RWGLIB.WRK from RWGLIB.WRK from RWGLIB.WRK 1/3 octave band center frequencies sound bubble observer azimuth angles sound bubble observer polar angles atmospheric turbulence properties rotor inflow distortion tensor
TIM(HIST1) TIM(HIST2) TIP(ANGLE)	unit member unit member table member	LRN, RTN LRN, RTN user	see LRN(TIME) see RTN(TIME) see LRN(TIME) see RTN(TIME) tip angle correction factor
XXXXXX(YYYYYY) YYYYYY(XXXNNN) ZZZZZZ(WWWWWW)	unit member table member unit member	PRO LRN, RTN, MSN, RBN, TIN PRT	see PRO(PRES) see LRN(XXXNNN) see RTN(XXXNNN) see MSN(XXXNNN) see RBN(XXXNNN) see TIN(XXXNNN) SEE PRT(PRES)

APPENDIX C

Example Deck 1

```

ANOPP JECHO=.TRUE. JLOG=.FALSE. NLPPM=55 $
STARTCS $
$
$
$ #####
$
$ File; demo01.inp
$
$ Author; Devon Prichard
$
$ Level; 03/02/11
$
$ Purpose; This input deck computes the blade geometry and aerodynamic
$ characteristics of the MD-500E main rotor.
$
$ Input Libraries; none
$ Output Libraries; DEMO01.WRK
$
$ Modules used;
$
$   IBS - improved blade shape module
$   IBA - improved blade aerodynamics module
$   IBL - improved blade boundary layer module
$
$ !! WARNING !! this demo produces a large output file! think
$               twice before sending output file to printer...
$
$ #####
$               Setup Parameters
$ #####
$
$ Define parameters unique to this rotor, otherwise use defaults;
$
$
PARAM   R           = 13.205      $ blade radius in ft

```

```

PARAM  IUNITS = 7HENGLISH  $ use english units
PARAM  IPRINT = 3          $ print both input and output data
$
EVALUATE  RINF = 0.23296E+08 * R * 0.3048
          $ COMPUTE SCALING REYNOLD'S NUMBER
$
$
$ #####
$                               Setup Members
$ #####
$
$ Spanwise and chordwise grids defined in the following members;
$ note that span is defined relative to blade radius, and chord
$ is defined in the elliptical coordinate system,
$ where the upper TE is theta=0, LE is theta=0.5, and
$ lower TE is theta=1.0, relative to 2*PI.
$
$ Note that the 500E blade, with basically rectangular planform,
$ linear twist, and constant cross-section, does not require
$ a very detailed blade definition. Blades with tip shapes,
$ airfoil changes, or nonlinear twist distributions need finer
$ descriptions. With increasing resolution comes increased
$ CPU time to execute IBS-IBA-IBL, so use advisedly.
$
$
UPDATE NEWU=GRID SOURCE=* $
  -ADDR OLDLM=* NEWM=XI1 FORMAT=4H*RS$ $
    0.200 0.400 0.600 0.700 0.750 0.80 0.850
    0.900 0.925 0.950 0.975 1.000 $
  -ADDR OLDLM=* NEWM=XI2 FORMAT=4H*RS$ $
    0.00 0.025 0.05 0.10 0.15
    0.20 0.25 0.30 0.35 0.40
    0.41 0.42 0.43 0.44 0.45
    0.46 0.47 0.48 0.49 0.50
    0.51 0.52 0.53 0.54 0.55
    0.56 0.57 0.58 0.59 0.60
    0.625 0.65 0.70 0.75 0.80
    0.85 0.90 0.95 0.975 1.00 $
END* $
$
$
$ The values of sectional Mach number and angle-of-attack in degrees,
$ at which the blade section aerodynamics are computed, are given here;
$
$
UPDATE NEWU=IBA SOURCE=* $
  -ADDR OLDLM=* NEWM=MACH FORMAT=4H*RS$ $
    0.1 0.3 0.5 0.7 $

```

```

-ADDR OLDM=* NEWM=ALPHA FORMAT=4H*RS$ $
-6.0 -3.0 0.0 3.0 6.0 $
END* $
$
$
$ Define the blade geometry. Section is the NACA 0015. Note that
$ the trailing edge tab is not currently modeled. Also recall that,
$ unlike the usual rotor notation, the blade twist is defined relative
$ to zero pitch at the blade root.
$
$
UPDATE NEWU=GEOM SOURCE=* $
-ADDR OLDM=* NEWM=BLADE FORMAT=0 $
5 $ five spanwise stations
5 $ all same airfoil section
0.00 -0.0106 0.000 0.043 0.025 0.00 107 106 $ 0% station
0.25 -0.0106 -0.000 0.043 0.025 -2.25 107 106 $ 25% station
0.50 -0.0106 -0.001 0.043 0.025 -4.50 107 106 $ 50% station
0.75 -0.0106 -0.001 0.043 0.025 -6.75 107 106 $ 75% station
1.00 -0.0106 -0.002 0.043 0.025 -9.00 107 106 $ 100% station
1.00000 .00158 $
.99000 .00332 $
.98000 .00504 $
.97000 .00674 $
.96000 .00842 $
.95000 .01008 $
.94000 .01172 $
.93000 .01334 $
.92000 .01495 $
.91000 .01653 $
.90000 .01810 $
.89000 .01964 $
.88000 .02117 $
.87000 .02269 $
.86000 .02418 $
.85000 .02566 $
.84000 .02712 $
.83000 .02856 $
.82000 .02999 $
.81000 .03140 $
.80000 .03279 $
.79000 .03417 $
.78000 .03552 $
.77000 .03687 $
.76000 .03819 $
.75000 .03950 $
.74000 .04080 $
.73000 .04207 $

```

.72000	.04333	\$
.71000	.04457	\$
.70000	.04580	\$
.69000	.04701	\$
.68000	.04820	\$
.67000	.04937	\$
.66000	.05052	\$
.65000	.05166	\$
.64000	.05277	\$
.63000	.05387	\$
.62000	.05495	\$
.61000	.05600	\$
.60000	.05704	\$
.59000	.05806	\$
.58000	.05905	\$
.57000	.06003	\$
.56000	.06098	\$
.55000	.06191	\$
.54000	.06281	\$
.53000	.06369	\$
.52000	.06454	\$
.51000	.06537	\$
.50000	.06618	\$
.49000	.06695	\$
.48000	.06770	\$
.47000	.06841	\$
.46000	.06910	\$
.45000	.06976	\$
.44000	.07038	\$
.43000	.07097	\$
.42000	.07153	\$
.41000	.07205	\$
.40000	.07254	\$
.39000	.07298	\$
.38000	.07339	\$
.37000	.07376	\$
.36000	.07408	\$
.35000	.07436	\$
.34000	.07459	\$
.33000	.07478	\$
.32000	.07491	\$
.31000	.07499	\$
.30000	.07502	\$
.29000	.07499	\$
.28000	.07491	\$
.27000	.07476	\$
.26000	.07455	\$
.25000	.07427	\$

.24000	.07391	\$
.23000	.07349	\$
.22000	.07298	\$
.21000	.07239	\$
.20000	.07172	\$
.19000	.07095	\$
.18000	.07008	\$
.17000	.06911	\$
.16000	.06802	\$
.15000	.06681	\$
.14000	.06547	\$
.13000	.06399	\$
.12000	.06235	\$
.11000	.06054	\$
.10000	.05853	\$
.09000	.05631	\$
.08000	.05384	\$
.07000	.05108	\$
.06000	.04797	\$
.05000	.04443	\$
.04000	.04035	\$
.03000	.03550	\$
.02000	.02950	\$
.01750	.02772	\$
.01500	.02580	\$
.01250	.02367	\$
.01000	.02130	\$
.00750	.01856	\$
.00500	.01527	\$
.00250	.01090	\$
.00000	.00000	\$
.00250	-.01090	\$
.00500	-.01527	\$
.00750	-.01856	\$
.01000	-.02130	\$
.01250	-.02367	\$
.01500	-.02580	\$
.01750	-.02772	\$
.02000	-.02950	\$
.03000	-.03550	\$
.04000	-.04035	\$
.05000	-.04443	\$
.06000	-.04797	\$
.07000	-.05108	\$
.08000	-.05384	\$
.09000	-.05631	\$
.10000	-.05853	\$
.11000	-.06054	\$

.12000	-.06235	\$
.13000	-.06399	\$
.14000	-.06547	\$
.15000	-.06681	\$
.16000	-.06802	\$
.17000	-.06911	\$
.18000	-.07008	\$
.19000	-.07095	\$
.20000	-.07172	\$
.21000	-.07239	\$
.22000	-.07298	\$
.23000	-.07349	\$
.24000	-.07391	\$
.25000	-.07427	\$
.26000	-.07455	\$
.27000	-.07476	\$
.28000	-.07491	\$
.29000	-.07499	\$
.30000	-.07502	\$
.31000	-.07499	\$
.32000	-.07491	\$
.33000	-.07478	\$
.34000	-.07459	\$
.35000	-.07436	\$
.36000	-.07408	\$
.37000	-.07376	\$
.38000	-.07339	\$
.39000	-.07298	\$
.40000	-.07254	\$
.41000	-.07205	\$
.42000	-.07153	\$
.43000	-.07097	\$
.44000	-.07038	\$
.45000	-.06976	\$
.46000	-.06910	\$
.47000	-.06841	\$
.48000	-.06770	\$
.49000	-.06695	\$
.50000	-.06618	\$
.51000	-.06537	\$
.52000	-.06454	\$
.53000	-.06369	\$
.54000	-.06281	\$
.55000	-.06191	\$
.56000	-.06098	\$
.57000	-.06003	\$
.58000	-.05905	\$
.59000	-.05806	\$

.60000	-.05704	\$
.61000	-.05600	\$
.62000	-.05495	\$
.63000	-.05387	\$
.64000	-.05277	\$
.65000	-.05166	\$
.66000	-.05052	\$
.67000	-.04937	\$
.68000	-.04820	\$
.69000	-.04701	\$
.70000	-.04580	\$
.71000	-.04457	\$
.72000	-.04333	\$
.73000	-.04207	\$
.74000	-.04080	\$
.75000	-.03950	\$
.76000	-.03819	\$
.77000	-.03687	\$
.78000	-.03552	\$
.79000	-.03417	\$
.80000	-.03279	\$
.81000	-.03140	\$
.82000	-.02999	\$
.83000	-.02856	\$
.84000	-.02712	\$
.85000	-.02566	\$
.86000	-.02418	\$
.87000	-.02269	\$
.88000	-.02117	\$
.89000	-.01964	\$
.90000	-.01810	\$
.91000	-.01653	\$
.92000	-.01495	\$
.93000	-.01334	\$
.94000	-.01172	\$
.95000	-.01008	\$
.96000	-.00842	\$
.97000	-.00674	\$
.98000	-.00504	\$
.99000	-.00332	\$
1.00000	-.00158	\$

END* \$

\$

\$ #####

\$

Generate Blade Tables

\$

#####

\$

\$ Now generate the blade database and output to a library

```
$ called DEMO1.WRK;  
$  
$  
EXECUTE IBS          $  
EXECUTE IBA          $  
EXECUTE IBL          $  
$  
$  
UNLOAD /DEMO01/ IBS, IBA, IBL, EDGE $  
$  
$  
ENDCS $
```

APPENDIX D

Example Deck 2

```

ANOPP JECHO=.TRUE. JLOG=.FALSE. NLPPM=55 $
STARTCS $
$
$ fixes;
$   activate ABL-STL-TIN executes
$   need flight conditions for tie-down test
$   check LRP->LRN data flow for changed parameters
$   how to do observers for RBN?
$   remove EDGE(THICK), IBA(ZERO) for level 10
$
$ #####
$ File; demo02.inp
$
$ Author; Devon Prichard
$
$ Level; 03/02/09
$
$ Purpose; this input deck computes the performance, tone noise and
$         broadband noise of the MD-500E main rotor.
$
$ Input Libraries; LIBRARY.WRK, DEMO01.WRK
$ Output Libraries; DEMO02.WRK
$
$ Modules used;
$
$   APM - atmospheric properties module
$   LRP - rotor performance module
$   LRN - rotor tone noise module
$   RBN - rotor broadband noise module
$   ABL - atmospheric boundary layer module
$   STL - streamline tracing module
$   TIN - turbulence ingestion noise module
$
$ #####
$                               Setup Parameters

```

```

$ #####
$
$ Load atmospheric data to get sound speed, etc.
$
PARAM IUNITS = 7HENGLISH $ use english units
$LOAD /LIBRARY/ ATM=ATMOS(TMOD=STRD) $ load atmosphere from LIBRARY.WRK
EXECUTE APM $
$PURGE ATM $
$
$ Define parameters unique to this rotor, otherwise use defaults;
$
$
PARAM AO = 0.2 $ initial collective set {recall this
$ is relative to root} in radians
PARAM BETA = 0.0 0.0 0.0 $ initialize flapping to zero
PARAM F = 0.0344 $ vehicle flat plate drag area
PARAM IOUT = 1 $ use spherical option
PARAM IMPROV = .TRUE. $ use blade properties from IBS-IBA-IBL
PARAM IPRINT = 1 $ print input data
PARAM MACHRF = 0.60 $ rotor tip Mach number
PARAM NBLADE = 5 $ number of blades per rotor
PARAM NCOEFF = 3 $ number of flapping/lagging coefficients
PARAM NHARM = 8 $ number of desired harmonics
PARAM NTIME = 32 $ number of desired time steps
PARAM NU = 0.0001572 $ kinematic viscosity @ sea level std., ft^2/s
PARAM R = 13.205 $ blade length in feet
PARAM RX = 5.0 $ nondimensional sound bubble radius {re R}
PARAM LBLCAL = .FALSE. $ assume no LBL-TE noise
PARAM TB2CAL = .TRUE. $ use Brooks TE bluntness noise model
PARAM TBLCAL = .FALSE. $ don't use Schlinker-Amiet TBL-TE model
PARAM TEBCAL = .FALSE. $ don't use Grosveld TE bluntness model
PARAM TETCAL = .TRUE. $ use Brooks TBL-TE model
PARAM TVFCAL = .TRUE. $ include vortex formation noise
PARAM WB = 0.57E-04 $ total blade weight
PARAM ZETA = 0.0 0.0 0.0 $ initialize lagging to zero
EVALUATE RS = RX * R $ dimensional sound bubble radius
$
$ flight conditions
$
PARAM KTS = 95.0 $ aircraft speed in kts
EVALUATE VA = 1.69 * KTS $ flight speed in fps
EVALUATE MZ = VA / CA $ forward flight Mach number
PARAM WT = 0.0051 $ weight coefficient
EVALUATE RINF = CA * R / NU $ scaling Reynold's number for broadband
$
$
$ #####
$ Setup Members
$

```

```

$ #####
$
LOAD /DEM001/                $ load blade database members from dem01.
$
$ Use finer spanwise grid than for blade properties run.
$
UPDATE NEWU=GRID SOURCE=* $
  -ADDR OLDLM=* NEWM=XI1 FORMAT=4H*RS$ $
    0.200 0.300 0.400 0.500 0.600
    0.700 0.750 0.800 0.850 0.875
    0.900 0.925 0.950 0.975 1.000 $
  -ADDR OLDLM=* NEWM=PSI FORMAT=4H*RS$ $
    0.00 0.05 0.10 0.15 0.20
    0.25 0.30 0.35 0.40 0.45
    0.50 0.55 0.60 0.65 0.70
    0.75 0.80 0.85 0.90 0.95
    1.00 $
END* $
$
$
TABLE TIP(ANGLE) 1 SOURCE=* $
  INT = 1
  IND1 = RS 1 1 1 1.0
  DEP = RS 1.0
END* $
$
$
UPDATE NEWU=SFIELD SOURCE=* $
  -ADDR OLDLM=* NEWM=THETA FORMAT=4H*RS$ $
    0.0 10.0 20.0 30.0 40.0
    50.0 60.0 70.0 80.0 90.0
    100.0 110.0 120.0 130.0 140.0
    150.0 160.0 170.0 180.0 $
  -ADDR OLDLM=* NEWM=PHI FORMAT=4H*RS$ $
  -60.0 -45.0 -30.0 -15.0 0.0 15.0 30.0 45.0 60.0 $
  -ADDR NEWM=FREQ OLDLM=* FORMAT=4H*RS$ $
    12.5 16.0 20.0 25.0 31.5
    50.0 63.0 80.0 100.0 125.0
    160.0 200.0 250.0 315.0 400.0
    500.0 630.0 800.0 1000.0 1250.0
    1600.0 2000.0 2500.0 3150.0 4000.0
    5000.0 6300.0 8000.0 10000.0 $
END* $
$
$ #####
$ Compute Airloads and Noise
$ #####
$

```

```

UPLIST $
EXECUTE LRP          $ do rotor performance calculation.
EVALUATE BETA(1) = AOL $ put flapping into LRN form
EVALUATE BETA(2) = A1L $
EVALUATE BETA(3) = B1L $
PARAM IPRINT = 3    $ print input and output data
EXECUTE LRN         $ do tone noise.
PARAM IOUT = 1     $ output SPLs only
EXECUTE RBN        $ do broadband noise.
$
$ EXECUTE ABL      $
$ EXECUTE STL     $
$ EXECUTE TIN     $
$
UNLOAD /DEMO02/ SFIELD, LRN, RBN $
$
$
ENDCS $

```



```

PARAM      IOUT = 1           $ make SFO output FLI(PATH)
PARAM      IUNITS = 7HENGLISH $ use english units
PARAM      IPRINT = 3        $ print input and output
$
$ define trajectory stuff
$
PARAM      JF = 200           $ total number of time steps
PARAM      XA = -2000.0       $ starting location
PARAM      XF = 2000.0       $ ending location
PARAM      YA = 0.0          $ starting location
PARAM      ENGNAM = 3HXXX     $ make consistent with LRN, RBN defaults
PARAM      DELF = 41.0       $ narrowband bandwidth, Hz
$
$ flight conditions
$
PARAM      ALPHA = -0.0981    $ shaft angle from LRP calculation {rad}
PARAM      KTS = 95.0         $ aircraft speed in kts
EVALUATE   VA = 1.69 * KTS    $ flight speed in fps
PARAM      ZA = 250.0        $ starting location
$
$ #####
$                               Setup Members
$ #####
$
LOAD       /LIBRARY/ ATM=ATMOS(AAC=SAEABS TMOD=STRD) $
LOAD       /DEMO02/          $ load source noise data from demo2 run
$
UPDATE NEWU=OBSERV SOURCE=* $
      -ADDR OLDM=* NEWM=COORD FORMAT=4H3RS$ $
      0.0 -500.0 0.0 $
      0.0 -250.0 0.0 $
      0.0 0.0 0.0 $
      0.0 250.0 0.0 $
      0.0 500.0 0.0 $
END* $
$
$
$ #####
$                               Compute Trajectory Info
$ #####
$
EXECUTE   ABS                 $ atmospheris absorption
EXECUTE   SFO                 $ steady flyover trajectory
EXECUTE   GEO                 $ source/observer geometry
$
$
$ Load atmospheric data to get sound speed, etc.
$

```

```

EXECUTE APM          $
PURGE   ATM         $
$
$
$ Define parameters unique to this rotor, otherwise use defaults;
$
$
PARAM      IOUT = 1          $ output SPLs
PARAM      IPNLT = .TRUE.    $ ask for PNLT calculations
PARAM      IPRINT = 0        $ print nothing
PARAM      MEMSUM = 5HPRO    5HPRES $ have LEV use PRO results
PARAM      MEMSUMN = 5HPRT   5HPRES $ have LEV use PRT results
PARAM      PROSUM = 4HRBN     $ have PRO use the RBN tables
PARAM      PROTIME = 3HXXX    $ have PRO use the RBN tables
PARAM      PRTTIME = 3HXXX    $ have PRT use the LRN tables
PARAM      SURFACE = 4HHARD   $ use hard surface model
PARAM      R = 13.205        $ blade length in feet
PARAM      RX = 5.0          $ nondimensional sound bubble radius {re R}
EVALUATE   RS = RX * R      $ dimensional sound bubble radius
$
$ #####
$                               Propagate Noise
$ #####
$
EXECUTE PRO YYYYYY=RBN GEOM=BODY $ propagate broadband noise
EXECUTE PRT YYYYYY=LRN GEOM=BODY $ propagate tone noise
EXECUTE LEV                      $ compute OASPL, PNLT, etc.
PARAM IPRINT = 2                  $ print EPNL outputs
EXECUTE EFF                       $ compute EPNLs
$
$
ENDCS $

```

APPENDIX F

Glossary

A-weighting	frequency weighting with highest gain at around 2000 Hz. Used for approximating the varying human response to sound at differing frequencies
absorption	loss of wave energy due to viscous losses, heat losses, molecular energy losses
airloads	aerodynamic forces on the rotor blade, either expressed as surface pressure or lift per unit span
band	a range of frequencies, typically used to partition the total frequency range of interest into a set of adjacent bands
BPF	Blade Passage Frequency, equal to $2\pi\Omega N_b$
CFD	Computational Fluid Dynamics, a category of methods used to compute the nonlinear aerodynamic response of complex shapes to the flow conditions

diffraction	deflection of wave path around an obstacle which is large compared to the acoustic wavelength
DNL	Day-Night Level, sometimes denoted L_{dn} , expressed in dB; an A-weighted time average of noise over a 24 hour period, requiring knowledge of flights per hour.
Doppler shift	<p>the change in frequency due to relative motion between the source and observer, for example the Doppler shift for a source moving directly toward a stationary observer is</p> $\frac{f'}{f} = \left(\frac{c+V_s}{c} \right)$ <p>where; f is the frequency of the source when stationary, f' is the perceived source frequency with relative motion, V_s is the source speed (positive on approach)</p>
emission time	time at which event had to be emitted by the source in order for the event to be received at time t at the observer location. Also called source time and retarded time.
EPNL	(Effective Perceived Noise Level) a noise metric based on time integration of PNL
FW-H equation	the Ffowcs Williams-Hawkings equation, a

	form of wave equation governing aeroacoustic noise generated by an arbitrary body (see Equation 3.1)
help files	documentation for all Functional Modules in VAX/VMS Help format (also called “pseudocode”)
Hz	Hertz, frequency in cycles per second
interference	superposition of waves with same or near frequencies
L_{dn}	see DNL
log identities	$x = a^y \Rightarrow y = \log_a x$ $\log(xy) = \log x + \log y$ $\log \frac{x}{y} = \log x - \log y$ $\log(x^n) = n \log x$
man pages	documentation for all Functional Modules in Unix <i>man</i> format
narrowband	band which is wider than 1% of center frequency but smaller than $\frac{1}{3}$ -octave; for rotorcraft noise, bandwidth of narrowband analysis ranges from 1 Hz to 10 Hz.
OASPL	(OverAll Sound Pressure Level); a frequency integration of a noise spectrum at a given

	observer location and reception time, with equal weighting for each frequency band
observer time	time at which a sound is heard or received, also called reception time
Pascal	denoted Pa, a unit of pressure in SI (N/m^2)
PNL	Perceived Noise Level a weighted frequency integration of noise at a particular observer position and time, similar to dBA in concept
PNLT	Perceived Noise Level (Tone-Corrected) based on adding tone corrections to the PNL-weighted $\frac{1}{3}$ -octave band spectrum, then performing a frequency integration as for PNL
pitch	pure tone frequency (standard acoustics usage), also the aerodynamic angle relative to the incident airstream (standard aerodynamics usage)
reception time	time at which a sound is heard or received, also called observer time
reflection	a return of wave energy partly in the direction of the source, occurs at all interfaces in

transmission media, can be gas/gas, gas/liquid, gas/solid, etc.

refraction change in wave direction of travel due to change in medium; depending on the angle between wave and interface, some energy passes through at a new angle, and some reflects. In aeroacoustics, due to change in atmospheric sound speed with altitude.

retarded time time at which event had to be emitted by the source in order for the event to be received at time t at the observer location. Also called source time and emission time.

scattering deflection of wave path around obstacle which is small compared to wavelength

sound bubble a hypothetical sphere surrounding the aircraft where information is transferred from the source noise models in the aircraft reference frame to the propagation models in the ground-fixed frame

Sound Pressure Level (SPL)

$$SPL = 20 \log_{10} \left(\frac{p}{p_0} \right) = 20 \log_{10} p + 94 \text{ (dB)}$$

$$= 10 \log_{10} \left(\frac{p^2}{p_0^2} \right) = 10 \log_{10} (p^2) + 94 \text{ (dB)}$$

source time time at which event had to be emitted by the source

in order for the event to be received at time t at the observer location. Also called retarded time and emission time.

SPL additive property $SPL_{12} = 20 \log_{10} [e^{(SPL_1/20)} + e^{(SPL_2/20)}]$

specific acoustic impedance $Z = \frac{p}{v}$
(pressure/particle velocity)

speed of sound $c = \sqrt{\frac{\gamma p}{\rho}}$ (length/time)

spherical spreading reduction in pressure wave strength with increasing time; for the spherical wave emanating from an ideal point source, the pressure field can be written as $p(r, t) = \frac{A}{r} e^{i(\omega t - kr)}$ where $k = \omega/c$, and A is a magnitude constant. $\Delta SPL = 20 \log_{10} (p_2/p_1) = 20 \log \left(\frac{r_1}{r_2} e^{-ik(r_2-r_1)} \right)$ for $r_2 = 2r_1$, ignoring harmonic component, $\Rightarrow \Delta SPL = 20 \log_{10}(\frac{1}{2}) = -6dB$ i . e . a 6 dB reduction in SPL with every doubling of distance.

wavelength distance between wave peaks, meters
 $\lambda = \frac{c}{f}$

wave number number of waves per unit length, 1/meter
 $k = \frac{1}{\lambda}$

wave equation

an equation describing phenomena with wave behavior, in this case noise, which has the form

$$\nabla^2 p = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2}$$

for the acoustic pressure field of an inviscid, ideal gas with constant sound speed

$\frac{1}{3}$ -octave band

interval between two frequencies having a $\sqrt{2}$:1 ratio, and successive center frequencies having a ratio of 5:4 (standard center frequencies are 50 Hz, 63, 80, 100, ...)

APPENDIX G

Symbols

c	sound speed, meters/second
dS	differential unit of body surface, m^2
\mathcal{F}	body function for which $\mathcal{F} = 0$ defines the surface
f	frequency, Hz
$H ()$	Heaviside step operator
i	$\sqrt{-1}$
j	coordinate index used for indicial vector notation
k	wave number, 1/meters
l_j	aerodynamic force in the i -th direction, N/m^2
l_r	aerodynamic force along the source/observer direction, N/m^2
m	direction index
M	Mach number
M_j	source velocity in the j -th direction
M_r	Mach number of source/observer relative motion in the radiation direction
N	number of data points in a time series
N_b	number of blades on the rotor
n	direction index, band counter
p	acoustic pressure, N/m^2
\tilde{p}	total pressure, Pascals

	$\tilde{p} = \bar{p} + p$
p_{ref}	reference pressure, N/m ² (2.0x10 ⁻⁵ for air)
p_{rms}	root mean square pressure, N/m ² = $\sqrt{\langle p^2 \rangle}$
\bar{p}	mean (time-averaged) pressure, Pa
p_L	loading noise, N/m ²
p_T	thickness noise, N/m ²
$\langle p^2 \rangle$	mean square pressure, {N/m ² } ²
\mathcal{P}	Fourier transform of acoustic pressure
r	distance between source and observer, meters
\vec{r}	radiation vector, i . e . vector between source and observer, meters
\hat{r}_j	j -th component of the radiation vector, normalized by r
t	observer (reception) time, seconds
$T_{j,l}$	Lighthill stress tensor
\tilde{u}	particle displacement, meters
\tilde{v}	particle velocity, meters/second
v_n	local normal velocity of blade surface, meters/second
\vec{x}	observer position vector, meters
\vec{y}	source position vector, meters
X, Y, Z	ground-fixed coordinates, meters (X is the longitudinal direction, Y is the lateral direction, Z is the vertical direction)
$\tilde{\gamma}$	specific heat ratio
λ	wavelength, meters

ρ	air density, kg/m ³
ρ_∞	freestream air density, kg/m ³
τ	source (emission) time, seconds
Ω	rotor rotational speed, radians/second
ω	circular frequency, Hz = $2\pi f$
∂	partial derivative operator
$\delta ()$	Dirac delta function
∇	gradient operator
$()_{ret}$	quantity at retarded (emission) time
$(\dot{ })$	time derivative