A Tool for Low Noise Procedures Design and Community Noise Impact Assessment: The Rotorcraft Noise Model (RNM)

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Abstract

To improve aircraft noise impact modeling capabilities and to provide a tool to aid in the development of low noise terminal area operations for rotorcraft and tiltrotors, the Rotorcraft Noise Model (RNM) was developed by the NASA Langley Research Center and Wyle Laboratories. RNM is a simulation program that predicts how sound will propagate through the atmosphere and accumulate at receiver locations located on flat ground or varying terrain, for single and multiple vehicle flight operations. At the core of RNM are the vehicle noise sources, input as sound hemispheres. As the vehicle "flies" along its prescribed flight trajectory, the source sound propagation is simulated and accumulated at the receiver locations (single points of interest or multiple grid points) in a systematic time-based manner. These sound signals at the receiver locations may then be analyzed to obtain single event footprints, integrated noise contours, time histories, or numerous other features. RNM may also be used to generate spectral time history data over a ground mesh for the creation of single event sound animation videos. Acoustic properties of the noise source(s) are defined in terms of sound hemispheres that may be obtained from theoretical predictions, wind tunnel experimental results, flight test measurements, or a combination of the three. The sound hemispheres may contain broadband data (source levels as a function of one-third octave band) and pure-tone data (in the form of specific frequency sound pressure levels and phase). A PC executable version of RNM is publicly available and has been adopted by a number of organizations for Environmental Impact Assessment studies of rotorcraft noise. This paper provides a review of the required input data, the theoretical framework of RNM's propagation model and the output results. Code validation results are provided from a NATO helicopter noise flight test as well as a tiltrotor flight test program that used the RNM as a tool to aid in the development of low noise approach profiles.

Introduction

To more accurately estimate the noise footprint for rotorcraft and tiltrotor operations, and to provide a tool to aid in the development of low noise terminal area operations, Wyle Laboratories developed the Rotorcraft Noise Model[1] (RNM) under contract to the NASA Langley Research Center. The United States Navy has also provided funding for improvements to the propagation algorithms, namely propagation over varying terrain[2].

The Rotorcraft Noise Model (RNM) is a computer program that simulates sound propagation through the atmosphere. As a noise source, rotorcraft and tiltrotors are more complex than fixed-wing aircraft. Rotorcraft sources are three dimensional in nature and the directivity and spectral content vary with flight condition, namely flight speed and flight path angle. A single engine operating state parameter (a generalization not applicable to rotorcraft) typically characterizes fixed wing noise emissions. At its core, RNM utilizes single or multiple sound hemispheres (broadband and pure tone with phase) for a given flight condition to define the three-dimensional vehicle spectral source characteristics.

RNM calculates the noise levels in a variety of metrics at receiver positions on the ground either at points of interest or on a uniform grid. Rotorcraft

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operations are defined as either single flight tracks or as multiple flight tracks with varying vehicle types and flight profiles. Acoustic properties of the noise source(s) are defined in terms of either broadband or pure-tone with phase sound hemispheres and may be obtained from theoretical predictions, wind tunnel experimentation, flight test measurements or a combination of the three. RNM has been recently expanded to include atmospheric sound propagation effects over varying terrain, including hills and mountainous regions, as well as regions of varying acoustical impedance such as coastal regions. The United States Department of Defense and the North Atlantic Treaty Organization (NATO) have adopted RNM as the standard prediction tool for Environmental Impact Assessments of military rotorcraft operations noise.

This paper presents the theoretical framework of the RNM, including the data input, propagation, and data output modules. Results from a NATO flight test designed to validate the RNM are presented. In addition, results are presented from a NASA / Army / Bell Helicopter XV-15 tiltrotor flight test program that utilized RNM as a tool to aid in the development of low noise approach profiles.

Rotorcraft Noise Model

The major computational and physical elements of the RNM are the sound propagation module and the input and output modules. RNM requires as input, source noise hemispheres, vehicle flight track, flight profile orientation and operating state. Vehicle operations are quantified along a set of user defined vectored flight tracks (Figure 1). The vehicle flight is simulated in a time based domain along a prescribed flight track and the sound is analytically propagated through the atmosphere to the specified receiver locations. The propagation model assumes that the acoustic ray paths are straight lines and that there is no wind present. Program plans are to incorporate the current state-of-the-art atmospheric propagation methodology for wind effects into RNM in the near future. RNM currently accounts for spherical spreading, atmospheric absorption, ground reflection and attenuation, Doppler shifts and the difference in phase between the direct and reflected rays. The most recent upgrade to the RNM (version L3.0) allows for the prediction of noise over varying ground terrain using an implementation of the Geometrical Theory of Diffraction, which includes extensions for diffraction as developed by Rasmussen[3]. Prior versions of RNM[4] permitted propagation over flat terrain; applicable only where physical properties of the surrounding area are not significant. RNM performs the acoustical atmospheric propagation for a given vehicle and creates ground noise predictions, detailed time history predictions and other research focused output data. RNM is also capable of outputting the results in a file format that can be imported into a Geographical Information System (GIS). The noise contours can then be overlaid to scale on a background map, which is ideal for performing noise abatement studies, airport and vertiport noise impact evaluations and land-use planning studies. Ground mesh time history data may be post processed into acoustic simulation animations, particularly useful for understanding propagation over varying terrain.

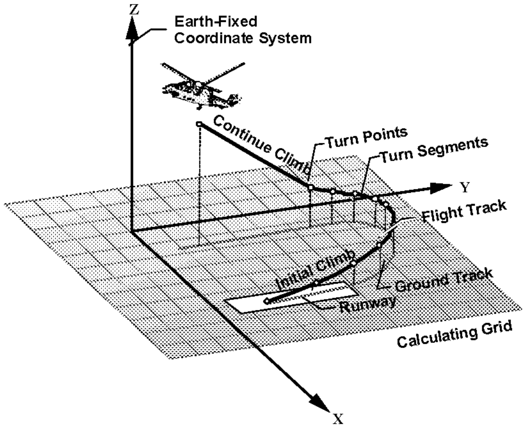


Figure 1. RNM Single Flight Track Definition.

Figure 2 shows the organization of the major modules that form the software package. The "Process" blocks are dedicated to reading the input file provided by the user, scanning rotorcraft noise data files (in binary netCDF[5] format), loading the ground elevation and impedance data if requested, and computing several look-up tables. The core propagation algorithm is nested inside several loops through the vehicle sources, trajectory points and receptor locations. The final block calculates the integrated metrics and writes the output in the form of tables, grid and time history files. The remainder of this section provides an overview of the computational modules presented in Figure 2.

Input Data Module

RNM reads the input files, which define the analysis grid, flight operations, source sound hemispheres and analysis options, and performs rudimentary error checking. The input module calls various routines, which interpolate and integrate flight tracks and profiles into a series of trajectory, orientation, and vehicle state points. Defined at each point are the coordinates (X, Y, Z) for the flight track in the Earth-fixed coordinate system, the rotorcraft speed, yaw angle, the angle of attack, roll angle, and tiltrotor nacelle angle. The input text file contains computational parameters,

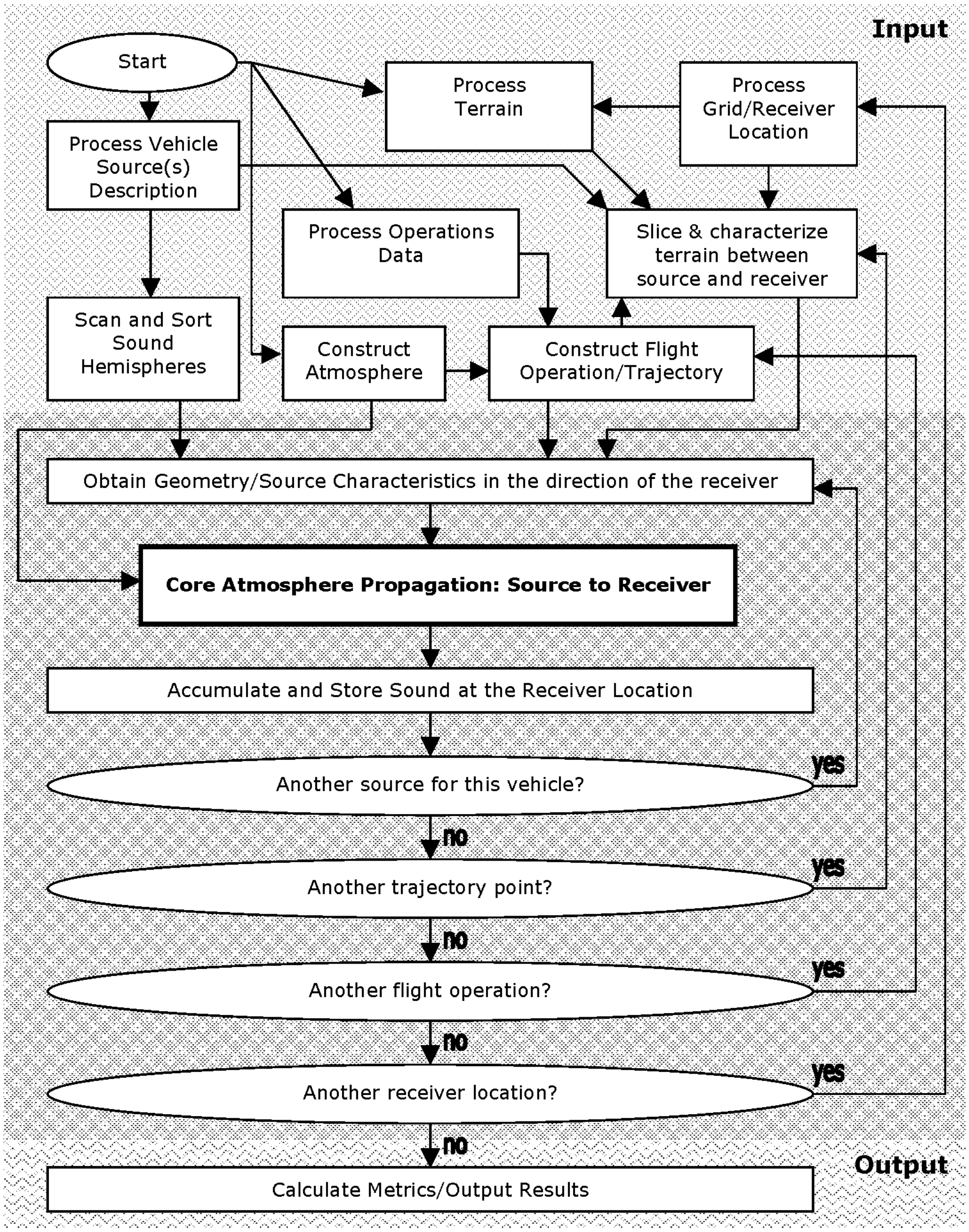


Figure 2. Major RNM modules.

a description of the calculating grid or points of interest, and definition of the flight trajectory, including the rotorcraft operating conditions. The input files are keyword structured with specific formatting requirements for each keyword.

Single operation input data. The single operation input file format is designed for studying low noise takeoff and landing profiles and evaluating multiple sound source propagation from a single vehicle.

One single operation application of RNM is to identify low noise takeoff and landing profiles by creating and interpreting detailed information on the noise footprint. To this end research applications of RNM typically involve manual construction of the single flight track input file using a text editor. By wrapping an optimizer around RNM, the code may be exercised by a host program with the objective of searching out a minimum noise footprint for a single departure or arrival track. The single-track mode may also be used to create three dimensional sound simulation videos in order for the viewer to gain a better understanding of the sound propagation characteristics, especially useful over regions of varying terrain. Additional applications for the single-track mode input version of RNM are the development of noise abatement profiles and comparison of sound hemispheres developed using analytical models, flight test acoustic data and wind tunnel measurements.

Multiple operation input data. The multiple operation input file format is structured to model annual rotorcraft noise at an airport or vertiport. The details of the multiple operation format is consistent with the way flight data is logged and collected by personnel at such facilities and the way environmental impact statements are currently performed by the acoustics community.

The vertiport application of RNM is the prediction of community noise impact contours for civilian and military operations. This application requires RNM to simulate all noise-generating activities that result from annual rotorcraft operations. Analyses of aircraft noise exposure and compatible land uses around Department of Defense (DoD) facilities are normally accomplished using a group of computer programs collectively called NOISEMAP[6]. The NOISEMAP suite of computer programs consists of BASEOPS[7], NOISEMAP, NMPLOT[8] and RNM. The BASEOPS program allows entry of runway coordinates, airfield information, vectored flight tracks, flight profiles for each track and for each aircraft, numbers of events, run-up coordinates, run-up profiles, and run-up events. BASEOPS creates and maintains input files for use with NOISEMAP and RNM.

Sound hemispheres. RNM has the capability to accept either analytically or experimentally generated sound hemispheres for multiple sources, both broadband and pure tone with phase. The analytical data may be created using computational fluid dynamics or other techniques and interfaced with RNM via NetCDF[5] files. One-third octave band sound hemispheres may be created from experimental flight test data using the Acoustic Repropagation Technique[9] (ART2) that is included with the RNM distribution. RNM will perform the atmospheric propagation for up to ten independently defined sound sources for a given vehicle. Source level noise data are defined on the surface of a sound hemisphere (Figure 3) and contain one-third octave or pure-tone sound levels and phase. Points on the hemisphere are described in terms of a fixed radius and two spherical angles.

The sound hemisphere contains either broadband or pure-tone noise data for a single aircraft flight condition. Each file contains a set of attributes defining the quasi-steady flight condition, using three independent variables: airspeed, flight path angle, and nacelle pylon angle (for tiltrotor). For conventional helicopters, the nacelle pylon angle is 90 degrees. There may be multiple sound hemispheres, each describing a different noise source, for each flight condition. A flight vehicle may be described with a maximum of ten broadband and ten pure tone sound hemispheres, each located at different points on the rotorcraft (i.e., engine, main rotor, tail rotor, main rotor / tail rotor wake interference sources, etc.).

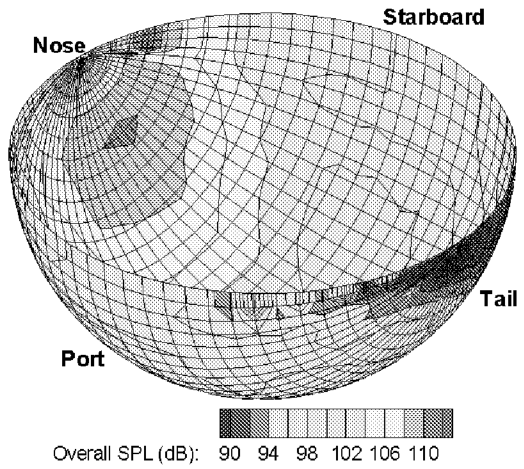


Figure 3. CH-146 Sound Hemisphere.

A sound hemisphere is stored in a packed binary file using Network Common Data Form[5] (netCDF). This data format is an abstract data type (ADT) with access to the data performed by a set of functions or routines. NetCDF efficiently stores and retrieves the data, is self-describing, and is platform independent. Raw binary files can be passed between computers over the network and accessed as long as netCDF functions and utilities are used. Included with the RNM distribution is a utility program SPHERE, which creates a sound hemisphere spectral data file that may be displayed graphically in three dimensions using the commercially available software package, Tecplot.[10]

Atmospheric module. The atmospheric profile (pressure, temperature, and humidity) may be user defined. The RNM default atmosphere is the U.S. Standard Atmospheric Profile, 1976[11]. The sound speed is calculated directly from the temperature profile using the ideal gas law. The air absorption coefficients are determined using methods described in American National Standards Institute (ANSI) S1.26-1978[12] based on the input humidity profile. Weighted averages of sound speed and air absorption coefficient are calculated at each altitude. The sound speed and the air absorption coefficients are tabulated at 1,000-foot intervals and accessed without interpolation by the propagation module.

Core Algorithms

The propagation algorithms are contained in the core module, which is nested inside several loops that increment the vehicle source, the vehicle type, and the receiver locations. Receiver locations are described either as the location of specific points under the flight track or as a uniform grid of points, either on a flat ground or over a specified terrain.

The location of the vehicle origin in the Earth-fixed coordinate system (X, Y, Z), the rotorcraft operating state (velocity, flight path angle, and nacelle tilt angle), as well as the vehicle orientation are user defined in terms of the input flight track and flight profile. The vehicle orientation is defined in terms of a flight path angle, heading angle, pitch, roll and yaw.

RNM accepts the location of the aircraft defined by a separate set of vectored ground tracks and flight profiles. Additionally, RNM, in single-track mode, accepts a three dimensional integrated flight track and profile as input. A vectored ground track is defined by a series of straight line and turn segments. A departure track begins at the helipad and proceeds in the direction of travel. The starting point is defined when the vehicle lifts off the ground. An arrival track is defined in a sequence opposite the actual direction of flight. An arrival track is defined from the helipad and proceeds as if the aircraft is flying away from the airfield rather than towards the airfield. The aircraft flight profile is defined in terms of aircraft altitude above the reference ground level, indicated airspeed, yaw angle, angle of attack, roll angle, and pylon angle as a function of the cumulative flight track reference ground distance. The cumulative flight track ground distance is a running index constructed in the same order as the ground track. One role of the flight trajectory module is to combine the ground track and flight profile into an integrated trajectory in the Earth-fixed coordinate system. The acoustical analysis within RNM simulates motion in the true direction of travel.

Flight trajectory module. The flight track module is capable of handling point-to-point integrated 3-D flight trajectories, or integrating vectored ground flight tracks and separate profiles. In single-track mode either form of track definition may be utilized. For multiple operation analyses the vectored flight track and separate flight profile definition must be used. The flight track module calculates the vehicle location (X, Y, Z, in the Earth-fixed coordinate system, see Figure 1) and orientation (roll, angles of attack and sideslip (yaw), nacelle position) as well as vehicle trajectory (heading, flight path angle, velocity, turn rate) in the earth fixed coordinate system. This is passed directly to the propagation module, which constructs the sound spectra at each receiver position as a function of time. The sound is summed at the receiver locations and binned according to arrival time. The broadband and pure tones (with phase) are tracked independently and combined, accounting for phase and coherence. Lastly, the requested integrated metrics are calculated and output.

When exercising RNM in multiple track mode, a default maximum track point spacing of 2.0 seconds is used. Generally, a 500-foot or coarser ground mesh is used for community environmental noise impact analysis. A maximum forward flight speed in the vicinity of the airfield for a typical helicopter (120 knots), yields a flight path spacing commensurate with this ground mesh resolution. If smaller time step flight path definition is required the single-track analysis method should be used multiple times, and the ground noise contours added together. If specified in the single-track input, RNM will provide to the computational module a higher resolution flight trajectory.

In order to interpolate between user defined segment endpoints, RNM uses a kinematics relationship based on constant acceleration. A combination of straight and curved segments is interpolated linearly and the vehicle location, orientation, and operating state calculated. The interpolated flight trajectory is written to the main RNM output file. If video generation is enabled a separate synchronized trajectory file is also created.

Geometry Module. The location and orientation of a rotorcraft relative to the Earth-fixed coordinate system is specified in terms of a flight path-fixed coordinate system and three Euler angles. The flight path-fixed coordinate system is tangent to the integrated three-dimensional flight trajectory. RNM gives the user the freedom to orient the rotorcraft arbitrarily with respect to the flight path-fixed coordinate system. When calculating the location of the individual sound source hemispheres RNM rigorously accounts for the position of the vehicle along the flight trajectory (X, Y, Z), the direction of the flight trajectory, and a full complement of vehicle orientation angles (roll, angles of attack and sideslip (yaw)) in addition to the individual source location relative to the vehicle-fixed coordinate system origin.

As the vehicle advances from point to point along the flight track, the primary Euler angles for each sound hemisphere source are calculated in the Earth-fixed coordinate system. The sound propagating in the direction of the receiver is obtained from the location on the source hemisphere, intersected by a straight line between the source center and receiver. These spherical angles are the hemisphere azimuth and elevation, and are dependent on the location of the source and the location of the receiver in the earth-fixed coordinate system and the vehicle orientation relative to the flight path-fixed coordinate system. This geometric implementation presently in RNM remains unchanged since RNM version 1.0. It assumes a zero roll angle and makes small angle approximations for all angles except yaw and heading when computing the sound hemisphere Euler angles (in order to simplify the geometry and avoid iterative solvers). For small angles of roll and sideslip this difference is minimal. This simplification will be addressed in a future version of RNM.

Hemisphere Selection. RNM performs a two dimensional interpolation considering both airspeed and flight path angle. Each RNM sound hemisphere represents constant airspeed flight conditions at a given flight path angle for a fixed nacelle angle. RNM performs a prioritization of the available sound hemispheres utilizing a hierarchical search of nacelle angle, flight path angle and aircraft speed. At each point along the flight trajectory the source sound characteristics are extracted from the hemisphere files using a linear interpolation in the energy domain (pressure squared) at the required airspeed, followed by a second linear interpolation in the energy domain on the vehicle flight path angle. These interpolation procedures are utilized when sufficient hemisphere flight resolution is available[13]. For vehicles with sparsely populated acoustic hemispheres flight conditions, the prior RNM methodology of selecting the closest matching flight condition available hemisphere, without interpolation, is utilized.

Propagation module. The propagation algorithms are embodied within the core computational model loop, which advances point by point through the flight trajectory. For each point along the flight track, each noise source characterizing the vehicle is propagated independently. RNM is a source time based model, which uses the flight track based source time directly, "binning" sound at the receiver locations based on arrival time. Only after the propagation has been completed are the receiver sounds interpolated onto a uniform time mesh and summed.

Propagation Physics. In general, sound levels at a distance r from a source can be expressed as the sum of the source sound level, the spherical spreading loss, the atmospheric absorption, ground reflection and attenuation with terrain, and the effects due to wind. This may be written mathematically as:

$$L(r) = L(r_0) + A_{spread} + A_{atm} + A_{grd} + A_{wind} + A_{topo}$$

where:

$L(r_0)$ = Free field loss-less sound level at a distance r_0 from the source directed from the source to the receiver.

A_{spread} = Geometrical spherical spreading loss, (point source).

A_{atm} = ANSI/ISO atmospheric absorption.[12]

A_{grd} = Ground reflection and attenuation losses, caused by the ground and the resultant interaction between direct and reflected acoustic rays. The ground surface is characterized as a complex acoustic impedance. The calculations are based on a study made by Chien and Soroka[14] and Chessel[15] with corrections noted by Daigle.[16] The algorithm uses the Doppler shifted frequencies that are based on the speed of the rotorcraft and direction of the rotorcraft relative to the receiver.

A_{topo}= Topography attenuation caused by the reflection and absorption that occurs from barriers formed by the terrain located between the source and the receiver. Within RNM, the topography propagation module combines the ground reflection and attenuation A_{grd}, and topographic attenuation A_{topo}, as a single term. Echo effects as would be found in deep canyons or from surfaces behind the receiver relative to the source are not presently treated by RNM.

A_{wind}= Wind attenuation or amplification, caused by the wind profile that exists between the source and the receiver. Presently, RNM does not account for winds; however, program plans are to incorporate the current state-of-the-art atmospheric propagation methodology for wind effects in the near future.

The RNM propagation model assumes that the ray paths are straight lines and there is no wind present. Temperature gradients that occur in the atmosphere are modeled using the weighted average sound speed and air absorption coefficients calculated in the atmospheric module. Day-to-day variations in the atmosphere, important when modeling community noise, can be treated by performing multiple analyses of flight operations with varying atmospheric parameters and summing the results. The source term $L(r_0)$ is calculated by interpolating data from the appropriately selected sound hemisphere(s) as described earlier. Spherical spreading, A_{spread}, is calculated by modeling the sound source as a point source with the total acoustic power spreading over a hemisphere having an area proportional to r. The sound energy reaching the receiver decreases at a rate proportional to $1/r^2$, or at the well-known rate of 6 dB per doubling of the separation distance between the sound source and the point of observation.

Atmospheric losses A_{atm}, are calculated by multiplying the slant distance by the air absorption coefficient. RNM uses an altitude average air absorption coefficient calculated in the atmospheric module.

Ground reflection and attenuation A_{grd}, are calculated by considering the propagation of the sound field along a boundary having finite impedance[14]. The user, who also has the option of selecting a program default value, provides the ground impedance. The sound field has both a direct and a reflected ray that produce two wave fronts that interact to produce either sound attenuation or amplification. The exact outcome of the interaction is dependent on the source and receiver height, the distance between the sound source and the receiver, and the impedance of the ground plane. Returned to the propagation module are the values, in decibels, for the excess ground attenuation.

The RNM methodology for ground reflection and attenuation over areas where topographic features are significant is twofold: First, the effects of terrain and receiver altitude relative to vehicle location (slant range) are computed. Second, the effects of terrain and ground cover on ground reflection and attenuation due to the multiple ray paths are computed with Rasmussen's algorithms[3]. These algorithms account for shielding (modeled as wedges) and structures (modeled as thin screens), multiple reflections in valleys, the effects of ground impedance and diffraction.

Rasmussen's theoretical model for the calculation of sound propagation over varying terrain is based on the Geometrical Theory of Diffraction (GTD). RNM contains the extensions of the GTD to finite impedance terrain, by means of formulae which are "not mathematically rigorous but physically plausible"[3]. The effects of wind and temperature gradients are not included in the current topography model. The sound field at a receiver point can be described as the sum of direct, reflected and diffracted waves. Keller[17] originally introduced the GTD. Rasmussen, by hypothesis, developed a technique for predicting diffracted waves, as determined by local geometry between the source and receiver. A series of approximate solutions based upon the assumption that the distances are long with respect to the wavelength were categorized and implemented for several geometric configurations.

RNM performs a geometric 'slice' through the three dimensional terrain from the source to the receiver location, and using a numerical fitting technique classifies the principal features into one of the following geometric models:

1. Two points: flat terrain.
2. Three points, concave: uphill or valley.
3. Three points, convex: down hill.
4. Four points: wedge or screen with one flat
5. Five points: wedge or screen with two flats.

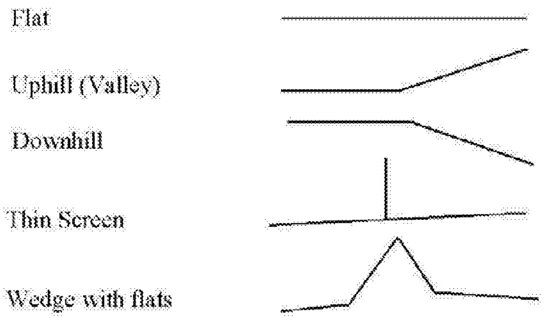


Figure 4. Geometric Terrain Classifications.

Figure 4 contains the classifications for the various terrain models. Only the terrain either in the line of sight or the broken line of sight is considered. The shielding algorithms transition continuously from a Pierce wedge to a Maekawa screen. The effect of terrain on the sound propagation is then applied to each one-third-octave band in turn for each source and receiver point along the flight trajectory. When terrain is flat, Rasmussen's algorithms reduce to the flat earth ground attenuation model described earlier in this section.

Superposition of Sound. RNM is capable of analyzing multiple broadband and pure tone sound hemispheres on one vehicle. For a given noise source, the arrival time is calculated based on a straight line propagation path from the sound hemisphere center to the receiver using the local speed of sound at the vehicle. For computational efficiency, the vehicle center is used for broadband arrival time since phase is not a concern with broadband (incoherent) noise signals. This imparts the assumption that the distance between multiple broadband sound hemispheres is small compared with the propagation path length. For pure tone (coherent noise source) propagation the phasing between multiple hemispheres and any slight difference in propagation path length is critical. In addition, there are potential phasing differences from one source hemisphere and trajectory point to another that must be considered. RNM sequences the source signals in terms of absolute phase. The source hemispheres are referenced from the first time point in the flight trajectory. This sequencing is necessary to ensure proper phase alignment between multiple source hemispheres as required by the varying operational conditions. The resultant phase of a given signal at the receiver point is a sum of the original defined source hemisphere phase plus the phase change between the beginning of the flight track and the vehicle flight track location (time) from which the pure tone hemisphere is propagated. The propagation module handles any phase changes due to different propagation path lengths from the pure tone hemisphere centers to the receiver location. For book keeping purposes and summation (incoherently) with broadband noise, the arrival time is considered to be the absolute time at which a signal travels from the vehicle origin to the receiver location. The coherent signal addition is performed using the fully synchronized phase from the start of the flight track in order to capture the constructive / destructive interference patterns for each pure tone frequency.

Output Data Modules

RNM can output cumulative sound exposure using a variety of measures. These are shown in Table 1. RNM is capable of presenting the time history of a noise event at a single observer position, the noise footprint on the ground at a given time, or the noise contours for many different noise metrics. The output results are in a file format that can be imported into a Geographical Information System (GIS). The noise contours may then be overlaid to scale on a background map. This is the ideal process for performing noise abatement studies, evaluating noise impacts at airports and vertiports, and performing land-use noise studies. All RNM graphical output is in the form of ASCII and binary grid files that are ready for importing directly into TECPLOT[10] and NMPLOT[8], respectively, for graphical display.

RNM outputs the sound levels at specific points of interest. Contained within the RNM main text output file will be an ASCII art graphic of the time history at the points of interest. The time history of the overall SPL, the A-weighted SPL, and the PNLT are written in TECPLOT format to an ASCII file. For multiple track analyses a ranked specific point output format is generated by RNM, which permits rapid identification of critical noise contributing flights.

NATO Flight Test

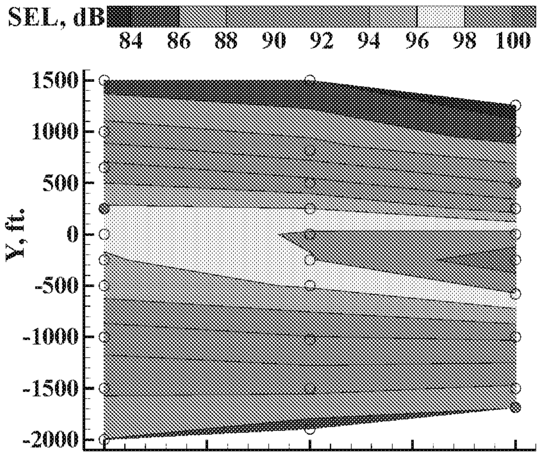
NATO/CCMS (Committee on the Current Challenges of Modern Society) Helicopter Noise Trials were conducted at Canadian Forces Base (CFB) Moose Jaw, Saskatchewan, Canada, in June 1998. The primary purposes for the test were to develop an international standard for measuring and analyzing the noise directivity characteristics of helicopters[18] and to acquire a database to validate the RNM[19]. The test vehicle was a Bell 412SP (Canadian military designation CH-146 "Griffon"). Acoustic data were acquired by organizations from the U.S. (NASA Langley Research Center and Wright Patterson Air Force Base (AFB)), the U.K. (Royal Air Force and Defense Evaluation and Research Agency), Germany, Norway, and Denmark. Wright Patterson AFB personnel deployed a linear microphone array to acquire the acoustic data that were used to generate noise hemispheres for RNM predictions. NASA Langley personnel deployed a 30-microphone array over an area 4000 feet long by approximately 3500 feet wide area to simultaneously measure the noise footprint.

	Type of Receiver	**Description of Output**
Single Track Format	GRAPHICAL OUTPUT	
	Grid of Receivers	Noise Footprints At Each Turn Point – SPL, SPL(A), PNLT
	Grid of Receivers	Noise Contours - SEL, SEL(C), SEL(A), L_{max}(A), EPNL
	Points of Interest	Time History Plot - Overall SPL, SPL(A), PNLT
	TABULATED OUTPUT	
	Points of Interest	Time History Tabulated - L_{max}(A), SEL, SEL(C), SEL(A), EPNL
	Points of Interest	Table of Levels - Overall SPL, SPL(C), SPL(A), PNL, PNLT
Multiple Track Format	GRAPHICAL OUTPUT	
	Grid of Receivers	Noise Exposure Contours - DNL, CNEL, NEF, WECPNL
	Points of Interest	Time History Plot - Overall SPL, SPL(A), PNLT
	TABULATED OUTPUT	
	Points of Interest	Ranked Events - SEL(A), L_{max}(A), R_{min}
	Points of Interest	Table of Levels - DNL, Leq, Leq(C), Leq(A), L_{max}(A)

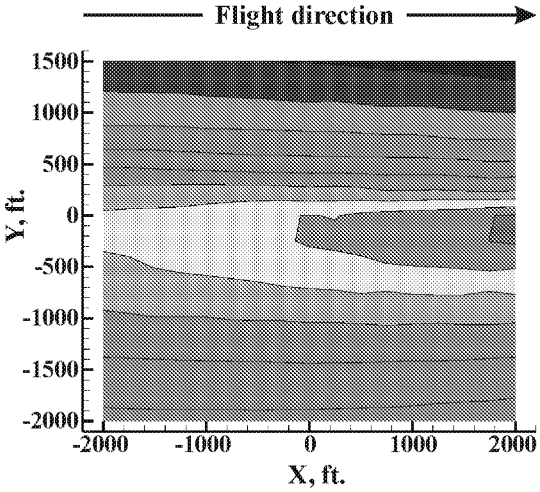
Table 1. RNM Output Metrics

A comparison of measured and RNM predicted Sound Exposure Level (SEL) noise footprints for a 6° approach at 103 knots is shown in Figure 5. RNM was run in single-track mode using measured GPS position information for the RNM flight track input data, and with all Euler angles set to zero because roll, pitch and yaw were not measured on the test vehicle. The flow resistance parameter (expresses the ground specific acoustic impedance) was set to 300 cgs Rayls, which is typical for soil, and RNM was forced to use only the noise hemisphere that was acquired simultaneously with the measured noise footprint. The helicopter traveled from left to right in the figure, with the flight path nominally along a line at $Y = 0$, descending along a 6° glideslope that passed through $X = 0$ at an altitude of approximately 470 feet. The circles in Figure 5a indicate the actual microphone locations while the red-filled circles indicate malfunctioning microphones that were not used in the generation of the noise footprint. The predicted noise footprint has a 250 foot grid resolution in both X and Y. This figure shows excellent agreement between the measured and predicted noise footprints directly beneath the vehicle and to the sideline on the retreating side of the vehicle (+Y). On the advancing side (-Y), RNM has over-predicted the noise level by as much as 3 SEL, dB. This is believed to result from extrapolated data in the source sound hemisphere. The current technique for obtaining source hemispheres (ART2[9]) requires a synchronized steady-state flight over a microphone measurement array. The measured data is then re-propagated back to a fixed radius hemisphere centered on the vehicle, thereby defining the three-dimensional spectral source characteristics. The lateral extent of the microphone array for validating the propagation (Figure 5a) extended beyond the width of the microphone array used to generate the source hemisphere, resulting in the use of data from an extrapolated region on the source hemisphere. For approach flight conditions the extrapolated region tends towards the front of the sound hemisphere. This is a purely geometric phenomenon due to the location of the vehicle with respect to the measurement microphone array.

Figure 6 provides a comparison of the predicted and measured A-weighted overall sound pressure level (L_A) time-histories on the flight path centerline, at the point (-2000,0) in Figure 5. Excellent agreement is shown between the measured and predicted L_A between approximately 10 seconds and 35 seconds. RNM is over-predicting the levels for times less than 10 seconds (out in front of the helicopter near the rotor tip-path-plane) and for times greater than 35 seconds (to the rear of the helicopter near the rotor tip-path-plane). Again, this is believed to result from the use of extrapolated data in the source sound hemisphere, predominately near the rotor tip-path-plane, due to the location of the vehicle with respect to the measurement microphone array. However, these over-predictions will not significantly affect community noise impact predictions because the integrated noise metrics used are dominated by audible signals within 10 dB of the maximum levels, where very good agreement is shown in Figure 6. For situations where long-range propagation of noise emanating from the region near the rotor tip-path-plane is important, the experimental test setup and test procedures for measurement of the sound hemispheres are being refined to improve the source sound hemispheres by reducing the areas of extrapolated data.



a) Measured footprint.



b) RNM predicted footprint.

Figure 5. Bell 412SP Noise footprints; 6° approach at 103 knots.

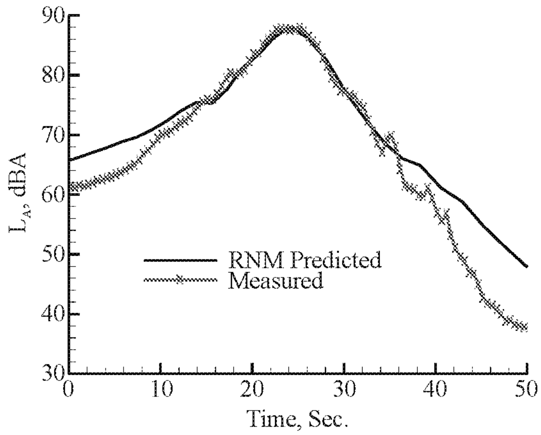
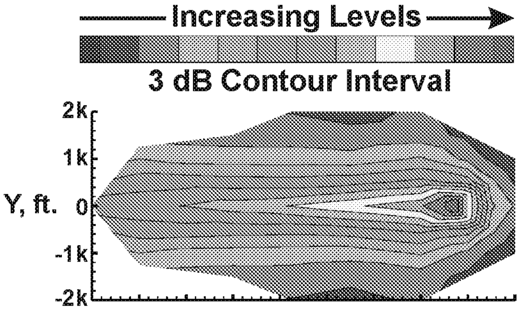


Figure 6. Centerline microphone A-weighted overall sound pressure level (L_A) time-history comparison.

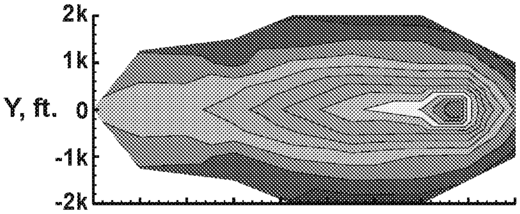
XV-15 Flight Test Program

A series of three XV-15 acoustic flight tests were conducted over a five-year period by a NASA / Army Bell Helicopter team.[20] The purpose of the test program was to evaluate the noise reduction potential for tiltrotor aircraft during terminal area operations by altering the nacelle angle / airspeed / altitude schedule. Lower hemispherical noise characteristics for a wide range of steady-state terminal area type operating conditions were measured during the phase 1 test and indicated that the takeoff and level flight conditions were not significant contributors to the total noise of tiltrotor operations.[21] Noise hemispheres measured during the phase 1 test were then used with RNM to aid in the design of low noise approach profiles that were tested during the phase 2 and phase 3 tests, which used large area microphone arrays to directly measure the ground noise footprints. Approach profile designs emphasized noise reduction while maintaining handling qualities sufficient for tiltrotor commercial passenger ride comfort and flight safety under Instrument Flight Rules (IFR) conditions. Results showed that significant noise reductions were achievable over much of the measurement area through the modification of the approach profile.

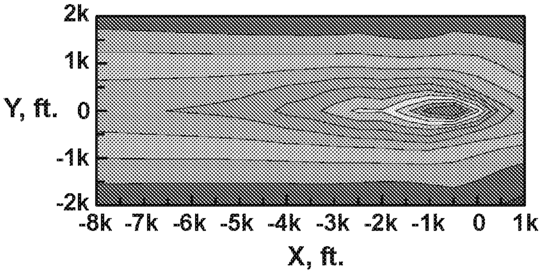
Figure 7 shows measured and RNM predicted XV-15 noise footprints. Each footprint extends from 1000 feet down-range to 8000 feet up-range of the landing point and spans up to 2000 feet to either side of the landing point, covering an area of more than 650 acres. The XV-15 approached from the left in the figure, along a line at Y = 0, coming to an IGE hover at about 20 feet AGL over the hover pad located at (0,0). The maximum SEL is not located about the hover pad due to a combination of the microphone distribution around the hover pad and the linear interpolation technique between the measurement locations used by the graphics software. Safety concerns, as well as rotor-downwash-generated wind noise, precluded locating a microphone on the hover pad. Figure 7a shows the footprint for a standard 6° approach profile. Significant noise reductions can be seen by comparing the noise footprint for a noise abatement 3° to 9° segmented approach profile (Figure 7b) to that for the standard 6° approach profile. Figure 7c shows the RNM predicted noise footprint for the same 3° to 9° approach profile presented in Figure 7b. RNM was again run in the single-track mode using measured GPS position information for the RNM flight track input data, and all Euler angles were set to zero. The flow resistance parameter was set to 1000 cgs Rayls because the soil was very dry and hard. The grid resolution was set to 500 feet in X by 400 feet in Y. Very good agreement can be seen between the measured and RNM predicted noise footprints. It should be noted that the source noise data used by RNM to predict the noise footprint of Figure 7c were obtained during Phase 1 testing while the measured noise footprint was obtained during Phase 2 testing that was conducted nearly two years later.



a) Measured 6° “baseline” approach.



b) Measured 3° to 9° segmented approach.



c) RNM predicted 3° to 9° segmented approach.

Figure 7. XV-15 ground noise footprints.

Concluding Remarks

The Rotorcraft Noise Model (RNM) has been developed by the NASA Langley Research Center and Wyle Laboratories to estimate the noise footprint for rotorcraft and tiltrotor operations, and to provide a tool to aid in the development of low noise terminal area operations. RNM requires source noise hemispheres for the vehicle of interest, operating conditions and flight trajectory information as input data. Output options include a time history of a noise event at a single observer position, the noise footprint on the ground at a given instance in time, or noise contours for many different noise metrics. RNM is also capable of outputting the results in a file format that can be imported into a Geographical Information System (GIS) for land-use planning studies. RNM has been recently enhanced to include the effects of sound propagation over varying terrain. RNM has been validated in the audible frequency range using data acquired during a number of different flight test programs. Additional experimentation of the propagation over varying terrain is planned. The United States Department of Defense (DoD) and the North Atlantic Treaty Organization (NATO) have adopted RNM for Environmental Impact Assessment of rotorcraft noise. A PC executable version of RNM is available publicly in the U.S., and to foreign government representatives, by contacting the author at d.a.conner@larc.nasa.gov. The public distribution of RNM includes a set of noise hemispheres for the Canadian Forces CH-146 (BELL 412SP). Sound hemisphere sets for other vehicles may be available from NASA or the DoD.

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