

Measurement and Characterization of Helicopter Noise in Steady-State and Maneuvering Flight

Fredric H. Schmitz
Professor

Eric Greenwood and Richard D. Sickenberger
Graduate Research Assistants
Department of Aerospace Engineering, University of Maryland at College Park, MD

Gaurav Gopalan
Assistant Research Scientist

Ben Wel-C Sim,
Senior Research Engineer
University of California, Santa Cruz, CA

David Conner and Ernesto Morales III
Senior Research Engineers
U.S. Army Aeroflightdynamics Directorate

William A. Decker
Senior Research Engineer
NASA Ames Research Center

Abstract

A special acoustic flight test program was performed on the Bell 206B helicopter outfitted with an in-flight microphone boom/array attached to the helicopter while simultaneous acoustic measurements were made using a linear ground array of microphones arranged to be perpendicular to the flight path. Air and ground noise measurements were made in steady-state longitudinal and steady turning flight, and during selected dynamic maneuvers. Special instrumentation, including direct measurement of the helicopter's longitudinal tip-path-plane (TPP) angle, Differential Global Positioning System (DGPS) and Inertial Navigation Unit (INU) measurements, and a pursuit guidance display were used to measure important noise controlling parameters and to make the task of flying precise operating conditions and flight track easier for the pilot. Special care was also made to test only in very low winds. The resulting acoustic data is of relatively high quality and shows the value of carefully monitoring and controlling the helicopter's performance state. This paper has shown experimentally, that microphones close to the helicopter can be used to estimate the specific noise sources that radiate to the far field – if the microphones are positioned correctly relative to the noise source. Directivity patterns for steady, turning flight were also developed, for the first time, and connected to the turning performance of the helicopter. Some of the acoustic benefits of combining normally separated flight segments (i.e. an accelerated segment and a descending segment) were also demonstrated.

Introduction

The main and tail rotors of the modern helicopter are the most important sources of external noise in most flight conditions. The noise from these rotors becomes especially objectionable and often can be detectable when either source becomes impulsive in nature. The form of impulsive noise for either rotor system can be characterized based upon the physics of the noise generation process¹. High-Speed Impulsive (HSI) noise normally occurs when the helicopter is operated at high advancing-tip Mach numbers – something that normally occurs during high-speed cruising flight. HSI noise is radiated ahead of the helicopter near the tip-path-plane of the rotors, and under extreme conditions, can be

heard for great distances from the helicopter. Blade-Vortex Interaction (BVI) noise, is caused when the main rotor blades rotate near or into the trailing vortex system left by the same rotor blades at some earlier time. BVI noise is mostly radiated downward and forward of the helicopter – with much of the intense energy directed forward on the advancing side of the rotor disk. Although sometimes sounding similar, each type of impulsive noise has its own distinct character.

Helicopter manufacturers have been attempting to reduce these impulsive noises, with some success, by introducing new designs with lower hover tip Mach numbers (and corresponding lower advancing tip Mach numbers at the same forward flight Mach numbers) and, hence, reduced noise. This design philosophy has also enabled increases in helicopter cruising performance while sacrificing some of the helicopter's hovering performance compared with helicopters designed with higher hover tip Mach numbers. Unfortunately, neither

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HSI nor BVI noise has been reduced enough to classify the helicopter as being truly quiet. In fact, the reduction in hover tip Mach number is often translated into higher cruising speeds – thus maintaining the relatively high advancing tip Mach number and relatively high noise levels².

It has also been realized for some time that the helicopter’s performance state governs the amount of noise that is radiated. As discussed previously, in high-speed cruising flight, when the advancing tip Mach number of the helicopter

is large, strong HSI noise is radiated. When the helicopter operates such that the rotors pass in close proximity to the helicopter’s shed wake system, strong BVI noise is generated. Based upon this general knowledge and some cabin noise measurements³⁻⁵, the now classical “fried egg” noise plot was developed for steady-state longitudinal flight as sketched in Fig. 1. Based on cabin noise measurements, it clearly shows the regions that a pilot must avoid to keep from radiating impulsive noise (HSI and BVI).

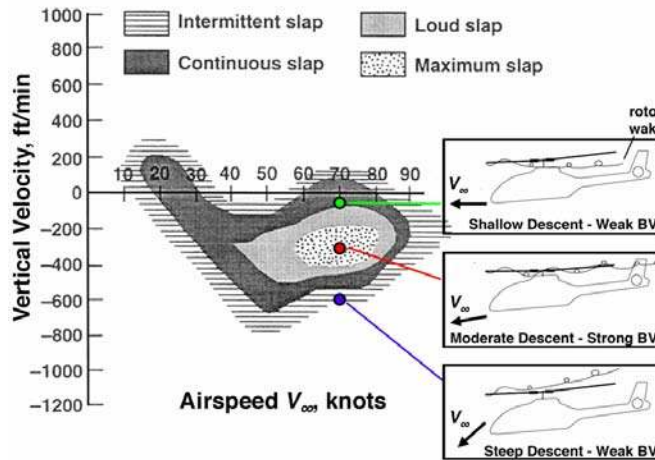


Figure 1: Rate of Sink versus Velocity Regions to Avoid to Reduce Impulsive Noise as Estimated From Cabin Noise Measurement

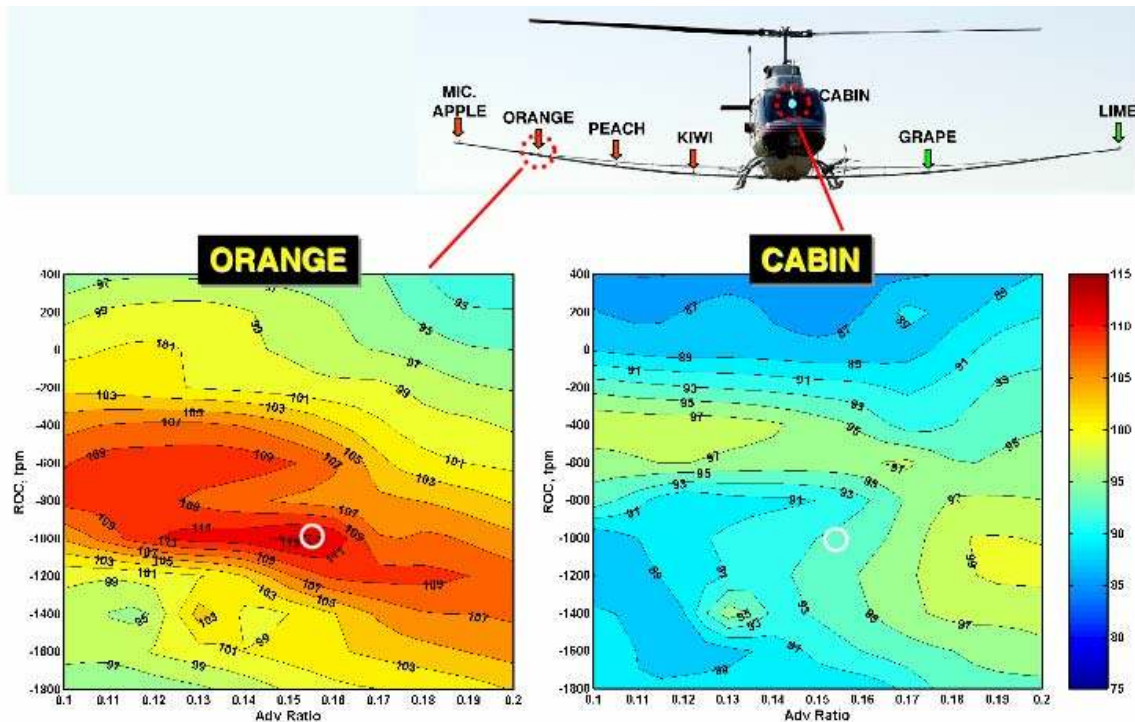


Figure 2: Rate of Sink versus Velocity Regions to Avoid to Reduce Impulsive Noise in the direction of Maximum Noise radiation as Estimated from In-Flight Boom Microphone Measurements

More recently, it has been shown that the noise that is heard in the cabin is not a sufficient basis to judge the absence of helicopter BVI noise⁶. In steady-state flight, noise can also be radiated in other directions that cannot be heard in the cockpit (Fig. 2).

It has also been shown by many authors that “other factors”, relating to the performance state of the helicopter, can strongly influence BVI noise radiation⁶⁻⁹. In many instances, these “other factors” can determine the level and directivity of the externally radiated impulsive noise that is heard on the ground.

Real world helicopter trajectories are composed of several steady-state, straight and turning flight segments, connected by transient segments, that can result in increases and or decreases in noise radiation. These transient segments are needed to connect the steady-state trim conditions that pilots normally fly from point to point. However, the steady-state segments are normally the most important because the pilot generally tries to fly his helicopter from one steady-state condition to the next and therefore spends most of his time in steady-state flight.

The present flight test and paper explores both the steady-state and transient segments of typical helicopter trajectories. The analytical work that supports this experiment uses a combination of Rotor Noise Model (RNM) to develop steady state hemispheres^{10, 11} and the Quasi-Static Acoustic Mapping^{12, 13} (Q-SAM) perturbation approach to extend the use of these measured hemispheres to equivalent trim states for each segment of a chosen trajectory. The noise radiation patterns due to changes in helicopter performance, including accelerations along and perpendicular the flight path, are represented acoustically by selecting the appropriate hemispheres for an equivalent trim state and then mapping this noise from the hemispheres to any position along the ground, correcting for atmospheric absorption and spherical spreading. The major assumption is that only slow and moderate perturbations (including maneuvering flight) are considered. This assumption is not very restrictive because these slow and moderately aggressive maneuvers are normally the safest, and most likely flown during normal civil helicopter operations. Slow and moderate maneuvers are also the most likely to keep the additional noise generated during these transient maneuvers to a minimum.

Major Test Objectives

In this context, a special acoustic flight test program was conducted by a University of

Maryland lead team at the NASA Ames Research Center, Moffett Field, CA, to carefully look at some “fly quietly” technical issues on June of 2006. This paper presents an overview of that program.

A Bell model 206B helicopter, was instrumented with an in-flight microphone boom, a tip-path-plane (TPP) measurement system, an air-data boom, a digital global positioning system (DGPS) system, and a pursuit guidance system that included an inertial navigation unit (INU) to facilitate trajectory control, and was flown over an array of ground microphones. Steady longitudinal flight, steady turning flight, and maneuvering flight were investigated but limited to the benign performance states normally associated with civilian helicopter operations. A special focus of the effort was the validation of the key noise radiation patterns of BVI noise by using both the ground and in-flight boom mounted microphones.

The overall goal of this research testing was to develop quiet helicopter flight segments and maneuvers and to explore piloting aides that can be used by the pilot to minimize both community annoyance and aural acoustic detection. This goal was achieved through the accomplishment of the following objectives:

- An assessment of the directivity of steady-state and maneuvering flight BVI noise through correlation of the noise measured on a flying microphone array, attached to the helicopter, with noise measured on the ground.
- The identification of quiet flight segments (steady-state & maneuvering flight) through the use of Q-SAM and the verification that these segments are quiet through acoustic flight tests. Recent flight-testing, with the boom-mounted microphones indicates that combinations of maneuvers (climbing turns, accelerating descents, etc.) can be used to mitigate BVI noise.
- An assessment of external noise radiated during constant bank angle steady turns.
- An evaluation of the use of a pursuit guidance display to help the pilot fly selected quiet flight segments.

Test Set-up and Instrumentation

The goal and subsequent objectives of the testing were enabled by some unique instrumentation that are briefly described below:

In-flight acoustic measurements

A specially developed in-flight microphone array, developed by the University of Maryland, was attached to the Bell 206B helicopter and

flown to measure Blade-Vortex Interaction (BVI) noise. The six microphones were positioned along this boom to be in the direction to help assess the radiation patterns of BVI noise. (Fig. 3) The microphone boom (a converted spray boom used for crop dusting) was mounted underneath the helicopter. The free-field B & K microphones were fitted with nose cones to minimize wind noise and were pointed in the general direction of the relative wind. Four previously successful flight tests have been flown using this University of Maryland developed microphone boom array⁶.

A new relatively long air data boom that was developed for this program is also shown in Fig. 3. It is used to determine the relative velocity of the aircraft and the angle of attack and sideslip of the helicopter cabin. The angle of attack of the cabin, together with the measurement of the helicopter's longitudinal tip-path-plane angle with respect to the cabin, is used to develop an estimate of the TPP angle with respect to the velocity of the helicopter. This parameter is used to characterize the general inflow through the rotor disk which is related to BVI noise levels in the Q-SAM method.



Figure 3: In-Flight Boom Mounted Microphone System, Air Data Boom, Pilot Display and TPP Measurement Optical System

Ground acoustic measurements

A major focus of the ground-testing portion of the program was to validate the use of the acoustic data boom to measure the directivity of BVI noise radiation. The ground acoustic data were also used to develop RNM¹⁰ acoustic hemispheres for steady longitudinal and steady turning flight. Eight microphone locations were positioned to form a linear ground array that the helicopter flew over, along specified trajectories, perpendicular to the array. The microphone

spacing along the linear array was chosen to maximize the fidelity of the projected noise hemispheres. A new wireless microphone system, developed by the Army and NASA, was used to take acoustic measurements at each microphone position. Each B&K pre-polarized free-field microphone was fitted with a grid cap and wind screen and mounted to a ground-board. An aerial view of the setup is shown in part A of Fig. 4.

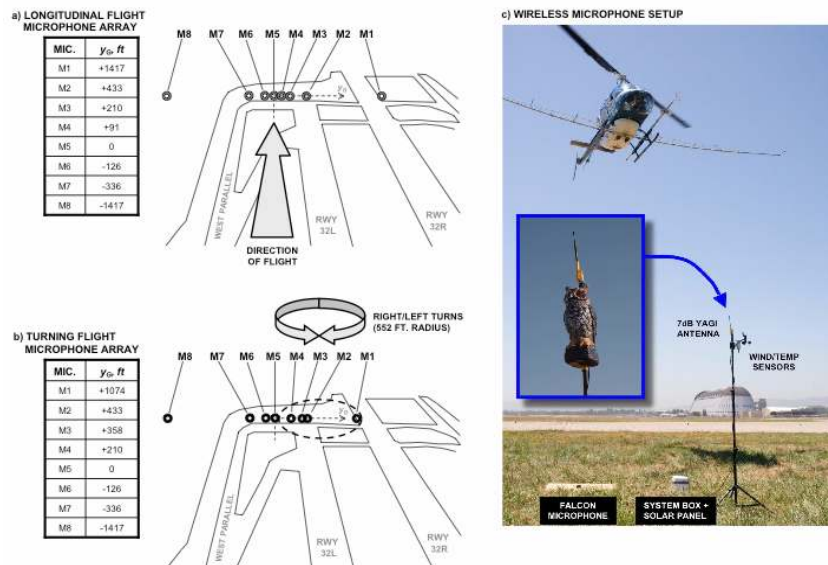


Figure 4: Aerial Sketch and Photograph of the Ground Microphone Placement at Moffett AirField

The microphone locations were chosen to be in relatively quiet site locations – to help minimize the background noise. This tended to shorten the array to keep it away from some unavoidable noise sources. Low background noise measurements were also facilitated by the professionalism of the NASA Ames management, by arranging to have the large wind tunnels not operate for most of the acoustic flight testing period. Unfortunately, some bird noise was measured on many of the ground microphones. “Owls decoys” (inset in Fig. 4) were employed to scare the birds from the microphone vicinity, but with little success. The bird noise was mostly removed through post test signal processing.



Meteorological Measurements

Horizontal wind and wind gradients at the test site are known to reduce the fidelity of helicopter noise measurements. This turns out to be especially true for constant bank angle, steady, turning flight noise. For this reason, every attempt was made to fly early in the morning when the winds were low (less than 5 knots). A NASA tethered weather balloon system was used to measure the ambient wind speed and direction, temperature, and humidity profiles at approximately half hour intervals during the testing. A photo of the set-up along with typical wind profiles are shown in Fig. 5.

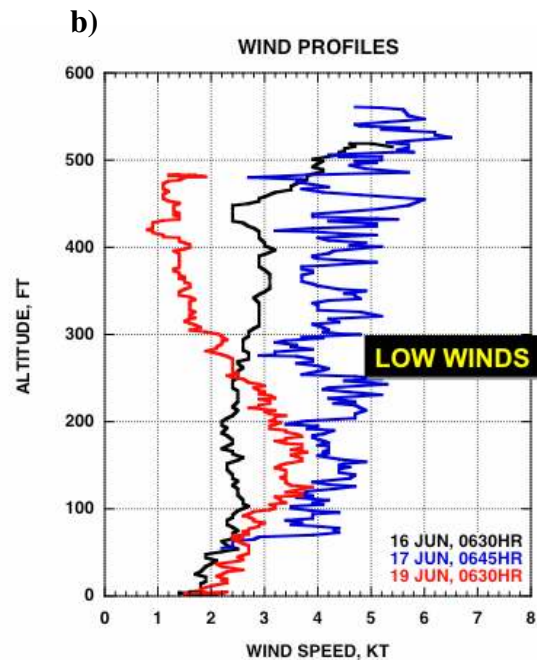


Figure 5: (a) Weather Balloon Measurement System and (b) Some Typical Horizontal Wind Profiles

Measurement of tip-path-plane angle

A key parameter in the estimation of BVI noise is the distances of the shed tip vortices from the rotor blades. These “miss” distances can be qualitatively estimated from the average rotor inflow passing through the rotor disk – which depends, to a great extent, on the position of the rotor’s tip-path-plane (TPP) angle with respect to the free-stream velocity vector of the helicopter^{12, 13}. A novel, non-intrusive, optics-based system was developed by the University of Maryland and was deployed during the acoustic flight test to measure this TPP angle from two independent in-flight angular measurements. First is the use of an angle of attack sensor on the pitot-static probe mounted on the air data boom, as shown in Fig. 3. Because the air data boom is rigidly attached to the helicopter empennage (in

this case the helicopter skid), a direct measurement of the helicopter fuselage’s angular attitude with respect to the forward airspeed is obtained. The second measurement uses a laser/camera system to measure the rotor’s longitudinal TPP angle with respect to the helicopter empennage. It assumes that the rotor shaft is rigidly attached to empennage, so that the rotor’s TPP can be obtained by a simple subtraction of the two angular measurements. The laser/camera system uses a laser to illuminate small reflective targets at the tips of the rotor blades when the rotor is in the fore and aft positions. Two high-speed cameras, one pointed forward and one pointed to the rear, then record the vertical position of these reflections. The aft pointing camera as installed on the Bell 206 helicopter is shown in Figure 6 along with a

view of the retro-reflective tab at the tip of the rotor blade. Using known geometry, data is fed through real-time processing algorithms to first yield TPP angles with respect to the empennage. Using the air data boom's angle of attack measurements, TPP angles with respect to the free-stream velocity of the helicopter were estimated.



Figure 6 Camera and Laser Mounted on the Bell 206B Helicopter

On-Board Piloting Display

A NASA developed “Portable Programmable Guidance Display (PPGD)” for precision pursuit guidance was also successfully used to assist the pilot to perform the required maneuvers. The display casts any maneuver, including flying quietly, in the context of a pursuit task and displays the necessary pursuit guidance information in such a way that the task can be performed accurately and efficiently with minimum control movement (Fig. 7).

Pursuit displays, such as this one, have been shown to improve the pilot’s tracking ability while smoothing out the pilot’s inputs, resulting in reduced workload and much reduced stick agitation. This research work, which has been supported by NASA and the Army over the past 15 years¹⁴, has resulted in a stand-alone PPGD unit that was added to the instrumentation of the Bell 206B helicopter¹⁵. A schematic of the PPDG display is shown in Fig. 7. The pilot’s task is to track the “leader aircraft” (shown in red) by flying his aircraft (shown in blue) to null the position, velocity, and acceleration differences between the aircraft. Use of this display not only improved the quality of the acoustic data for each test point, but, in many cases, also shortened the time it took to gather the acoustic data. (A more complete description of how the display works can be found in Ref. 14 and 15).

A main reason for using the guidance display for this test was to obtain high fidelity acoustic data. This required the pilot to maintain

the target flight performance conditions with minimal error. Small but abrupt changes in velocity and/or rate of sink will cause changes in BVI noise. In addition, for longitudinal steady-state flight, reasonable tracking along a ground fixed flight path was necessary. For these reasons, the pursuit guidance had some “lead” information programmed into the helicopter being tracked with the objective of gently adjusting the guidance of the in-trail helicopter to allow the helicopter pilot to gently and smoothly correct for deviations from the desired performance and tracking conditions. The display that the pilot flew is shown mounted above the Bell 206B flight instrument console in Fig. 8.

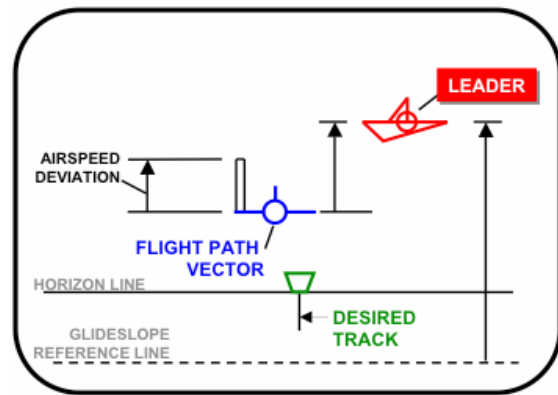


Figure 7 The NASA Developed PPGD in a Pursuit Guidance Mode

Airspeed was provided by the air data boom with all other relevant data provided by the PPGD system that include the INU and DGPS subsystems. The display was considered to be a “secondary display” and is only for voluntary guidance – not primary control of the aircraft. It was flown for most of the longitudinal flight trajectories but was not operational for the steady, turning flight test conditions.



Figure 8 The PPGD Display Mounted Over the Instrument Panel of the Bell 206B Helicopter

Test Conditions Flown:

As shown in the table below, quite a few test points were flown covering most of the aspects of the program – including steady descending/climbing flight at selected airspeeds, accelerating/decelerating flight in the longitudinal plane, steady turning flight, and

some transient maneuvers that are necessary to enter and exit turning and maneuvering flight. Most of the priority #1 test points were successfully flown including many repeat runs to insure the quality of the gathered data. About half of the priority #2 test points were also flown during the testing period.

<ul style="list-style-type: none"> • TEST VEHICLE : HELI-FLIGHT BELL 206B JET-RANGER (N1078Q) • TEST DATE : Planned June 7, 2006 - June 17, 2006 : Actual June 8, 2006 - June 21, 2006 					
Run Category	Description	Num of #1 Test Pts		Num of #2 Test Pts	
		Planned	Actual	Planned	Actual
1	CHECKOUT & PRACTICE FLYING	20	~ 100		~ 30
2	AIRSPPEED CALIBRATION	20	60	6	6
3	STEADY DESCENTS	32	32	25	10
4	ACCELERATION/DECELERATION	20	20	12	3
5	STEADY TURNS	34	10	4	0
6	TRANSIENT MANEUVERS	18	18	10	5
7	DRAG ASSESSMENT	20	20	6	6
TOTAL DATA POINTS		164	160	63	30
EST. FLIGHT TIME (≈ 6 MINS/PT)		16.4 HRS	20.2 HRS	6.3 HRS	4.7 Hrs
ACTUAL FLIGHT TIME (≈ 4.7 MINS/PT)					

Table 1 Test Conditions Planned and Actually Flown

The acoustic testing was done at the Moffett Field in Mountain View California over a 12-day period toward the end of June, 2006. Fortunately, the weather was extremely cooperative helping the team to gather acoustic data in nearly ideal wind conditions (0 to 5 knots), and with no temperature inversion profiles. Background noise was also kept low by testing in the early morning hours and by arranging to have the dominant noise sources in the ground testing area turned off. Nevertheless, very low ambient noise levels were not achieved. The San Francisco Bay area has a background noise level that is about 10 dBA higher than more remote and quiet sites. This required the far-away ground microphones to be re-located somewhat closer to the flight path than originally planned to maintain a reasonable signal-to-noise ratio, thereby limiting angular coverage on the RNM hemisphere of the acoustic data at or near the in-plane position to either side of the vehicle.

Some Results:

PPGD System Tracking Performance

Figure 9 shows the tracking data for a typical steady descent flight case (Run 168) and for a typical accelerating descent case (Run 270). Run 168 corresponds to a 60 knot flight at a glideslope (or flight path) angle of -7.5° and Run 270 corresponds to an accelerating descending flight case which starts at 40 knots and ends at 67 knots, at an acceleration of approximately 0.1g (and the same glideslope angle of Run 168). The tracking is seen to be fairly smooth, with deviations from the prescribed glideslope on the order of ±0.5°. It is to be noted that the acoustic performance of a run should be judged more by the smoothness of velocity, acceleration and glideslope angle than on the absolute vehicle position.

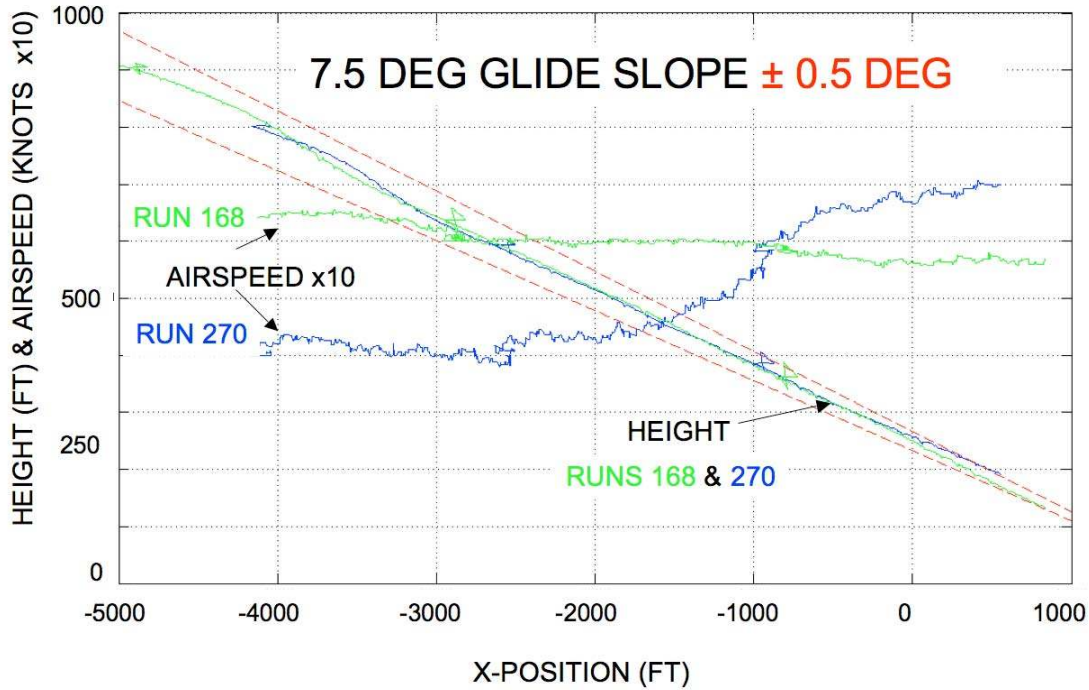


Figure 9: Height and Velocity Tracking Data from the PPGD System for a Steady State Descent Flight (Run 168) and an Accelerating Descent Flight (Run 270)

In-flight/Ground Measurement & Correlation of BVI Noise

A primary objective of this test program was the correlation of the noise that was measured at specific microphone positions on the test boom with the noise that was measured on the ground at the same directivity angles from the noise source. A good way to do this comparison was to first focus on the development of the sound hemispheres using the standard back-propagation techniques of RNM (Fig. 10) so that the areas of largest noise radiation can be identified.

To create these hemispheres, the effective sound source location was assumed to be at the

hub of the helicopter. At each position measured noise was digitally filtered to obtain BVI-SPL levels and related to a retarded time and position on the hemisphere. The BVI-SPL levels were then grouped in one-third octave bands and corrected for reverse spherical spreading and atmospheric absorption. It was been assumed that the flight condition is held constant so that the positions on the sphere could be populated by ground acoustic measurements taken as the helicopter flies over the microphone array. A schematic of this process is shown in Fig. 10, with additional details provided in Ref. 16.

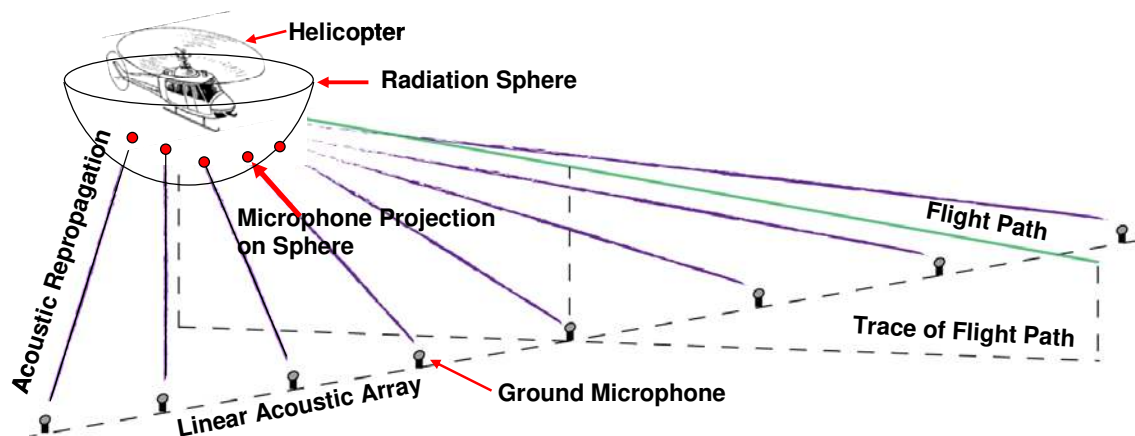


Figure 10: Linear Flight Trajectory Hemisphere Creation

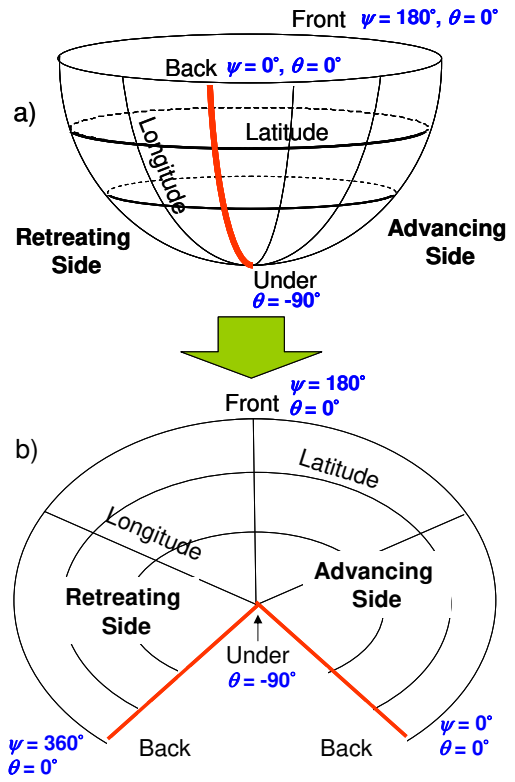


Figure 11: BVI-SPL Data Presentation

Unfortunately, the BVI-SPL levels cannot be easily seen from any one view of the hemisphere. To overcome this data display issue, the data is re-plotted in a slightly modified format as depicted in Fig. 11. The viewpoint is now of an observer riding with the hemisphere, with the advancing blade to the right of the observer and the retreating blade to the left. The radiation hemisphere around the helicopter is unraveled onto a two dimensional surface. A "cut" is made along the zero degree azimuth longitude (along the "back" of the helicopter), and the hemisphere is opened out and presented in two-dimensions in a way that preserves the relative lengths of the "latitudes" and "longitudes". The outer circular arc represents the zero degree elevation circle or the "equator", with the top of the figure representing a point directly ahead of the helicopter in the plane of the horizon (or in the tip-path plane). Latitudes are represented by circular arcs with the uppermost representing the in-plane circle. Longitudes are represented by (radial) straight lines, all intersecting at the "south pole" or the point directly below the helicopter, the -90° elevation angle position.

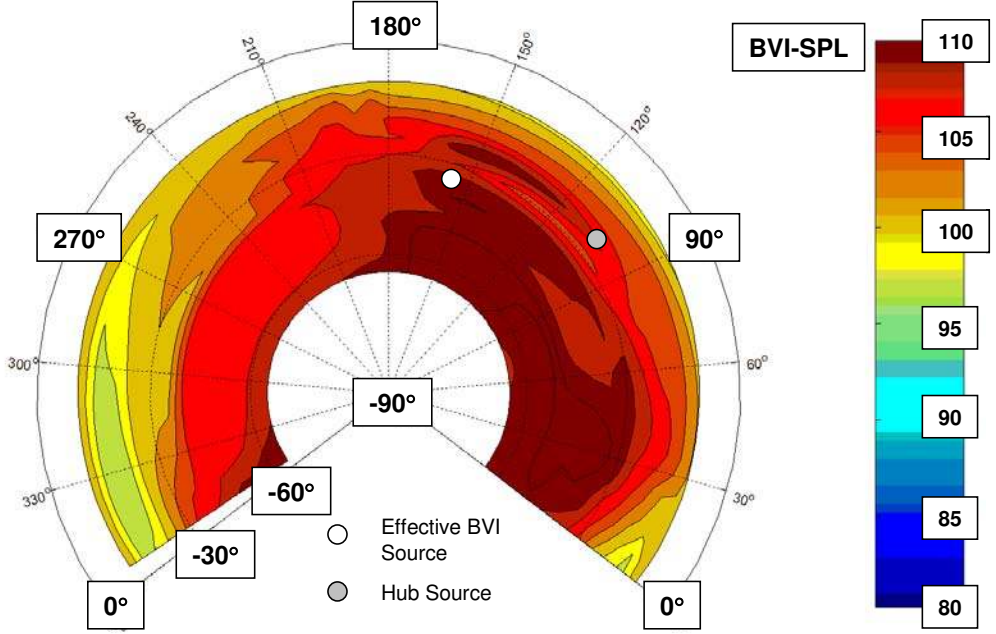


Figure 12: Bell 206B BVI-SPL Noise Hemisphere for Descent Flight at 60 knots

A typical noise hemisphere has been created for the 7.5° descending flight case for the Bell 206B helicopter at a forward airspeed of 60 knots. (Fig. 12). BVI-SPL noise contours are shown at all locations except near the center and in-plane positions of the hemisphere. These data

voids are caused by not having enough microphones at these locations or not having enough microphone positions to confidently interpolate the data in these areas.

Remembering that the right side represents the advancing side of the helicopter while the left

side represents the retreating side of the helicopter, it becomes obvious that the most intense BVI-SPL levels are on the advancing side of the rotor (150°) and down (45°) as developed by using the ground microphone array. To re-create the ground noise measurements, one needs only to propagate the sound from the center of the hemisphere to the ground points, using the spherical spreading and atmospheric absorption algorithms in reverse. If the source of the noise were assumed to originate at some other position in the rotor disk, these far field noise directivity calculations would also change. However, since the angles are determined from measurements far from the rotor, changes in directivity angles on the acoustic hemisphere are small and can usually be neglected.

The boom-mounted microphones (shown in Fig. 3) also measure the directivity of noise sources. But because the microphones are located relatively close to the noise source, the assumed noise source location strongly determines the directivity of the radiated noise field. This can be illustrated in a sketch as in Fig. 13. If it is assumed that the noise source is effectively centered at the hub of the rotor, the azimuth and elevation angle location on the hemisphere is determined by a line connecting the hub, at the time of acoustic emission, to the selected microphone position at some later time. If this line is extended to the ground, it determines the ground position where this same noise is measured at some even later time. For this case where the rotor hub is chosen as the effective noise source, the azimuth and elevations angles for microphone orange are 104.6° and 26.1° respectively. The point of intersection on the noise hemisphere indicates that this is not in the direction of maximum BVI noise.

Because our main interest in this test was on BVI noise radiation, the choice of the hub to represent the effective BVI noise source is not very good. If, instead, the approximate center of BVI activity is chosen as the effective source of the BVI noise (60° azimuth at 80% radial location), then the azimuth and elevation angle also change, becoming, for microphone orange, 156° and 34.8° respectively. This point of intersection on the noise hemisphere is closer to the peak area of BVI noise radiation (Fig. 12). Similar studies of BVI source location and its effect on BVI radiation patterns were done for model rotors in wind tunnels with similar outcomes¹⁷.

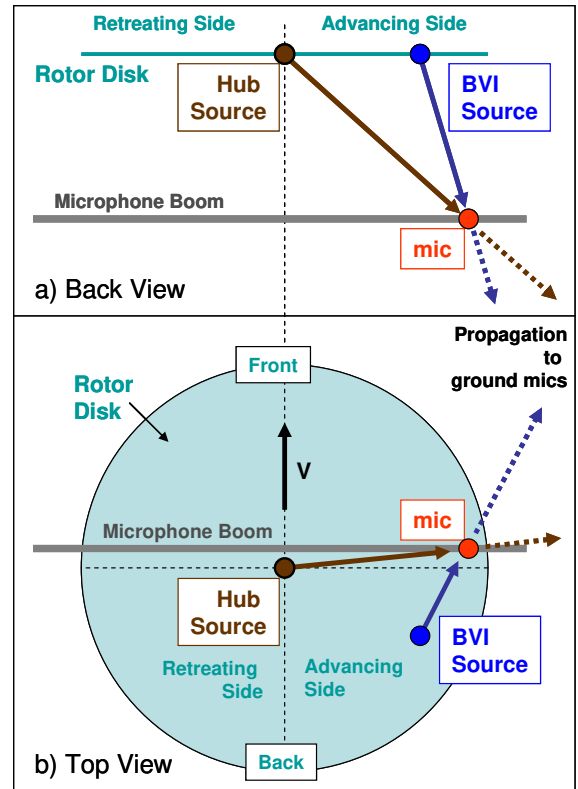


Figure 13: Hub versus BVI source: Directivity Differences

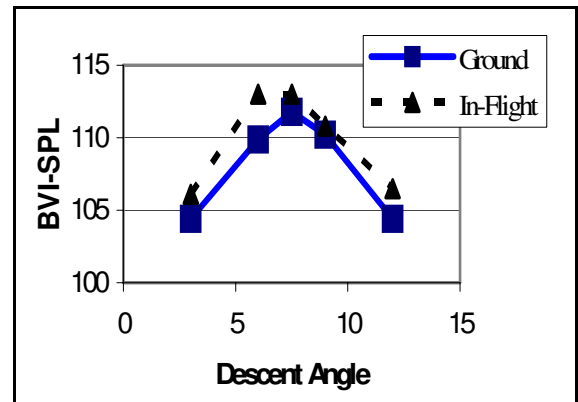


Figure 14: BVI-SPL Measurements along an Acoustic Ray as a function of Descent Angle

To ascertain the fidelity of using the boom mounted microphones to predict the ground noise, it is necessary to determine those ground microphone positions that are located along the same sound ray. A plot of the BVI-SPL levels is shown in Fig. 14 for boom-mounted microphone orange and a nearby ground microphone. It is evident that the changes in the BVI noise levels with descent angle, as measured on boom microphone “orange”, follow the

ground noise measurement trends, microphone #4) quite well. BVI noise levels increase with increasing descent angles, peaking at 5.5° to

7.5°, and then decrease with further increases in descent angle.

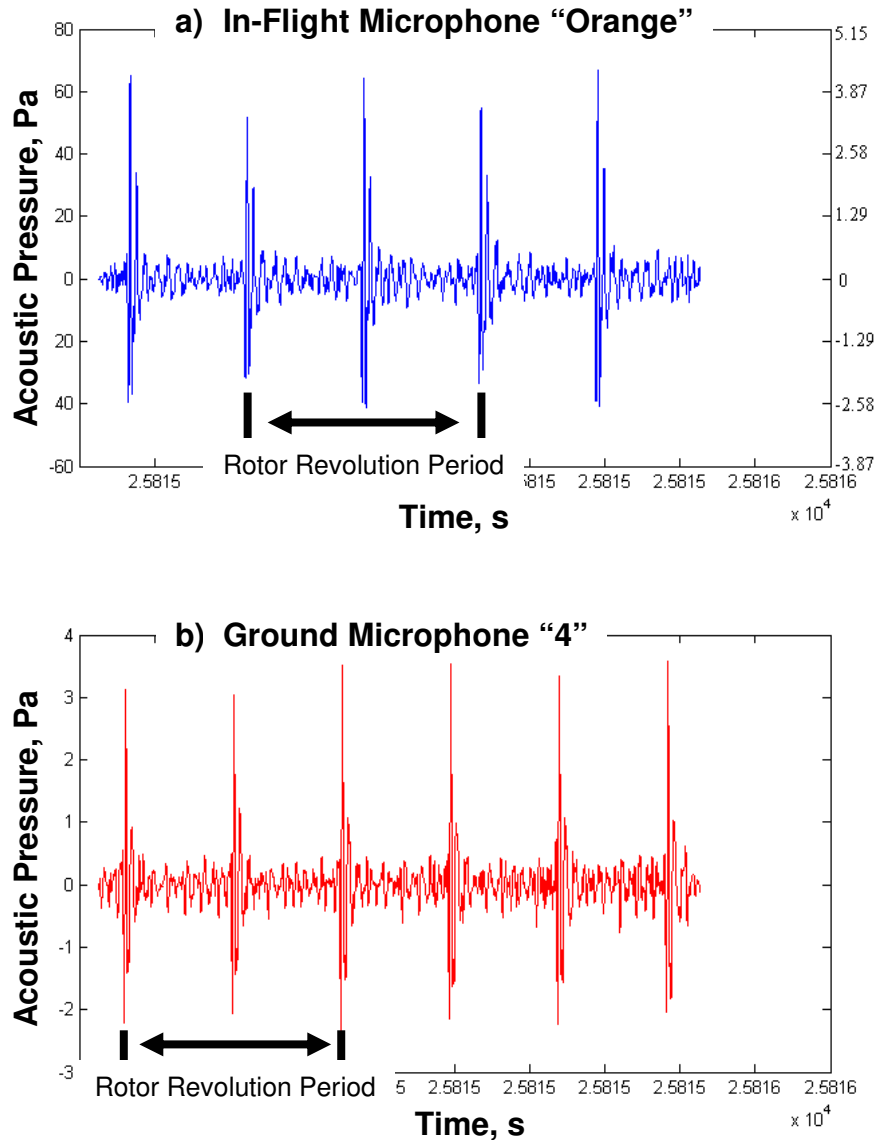


Figure 15: Time History Comparisons between Boom Mounted Microphone Orange and Ground Microphone Number Four

A comparison of the waveforms for this condition is shown for a 7.5° descent angle case in Fig. 15. The comparison is done by comparing the time history of microphone orange with microphone #4 (which is nearly positioned along the sound ray that passes through microphone orange), at the correct retarded time. The boom mounted microphone time history amplitude (with filtering applied below the sixth harmonic of main rotor noise) is shown in part A of figure. The left most scale

represents the microphone orange amplitudes, while the right scale has been adjusted for spherical spreading.

Part B of Fig. 15 represents the measured acoustic signal that was emitted at the correct retarded time and along a ray that emanated from the BVI source, passed through the boom microphone, “orange”, and was measured at the ground on microphone #4. BVI noise is shown to be of the same amplitude and character on both microphones – showing that it is possible to

use the Boom microphones to judge the level and character of BVI noise. As stated previously, a necessary condition for this replication of the acoustic signal is that the origin of the sound source must be known.

It is also quite interesting to note that tail rotor harmonic noise is also present in these signals – albeit at lower levels for this strong BVI condition. Tail rotor noise has its own directivity characteristics that can be measured using either the ground or boom mounted microphones. The large span of the boom makes it possible to measure some of the important directivity trends of tail rotor noise for turning and maneuvering flight.

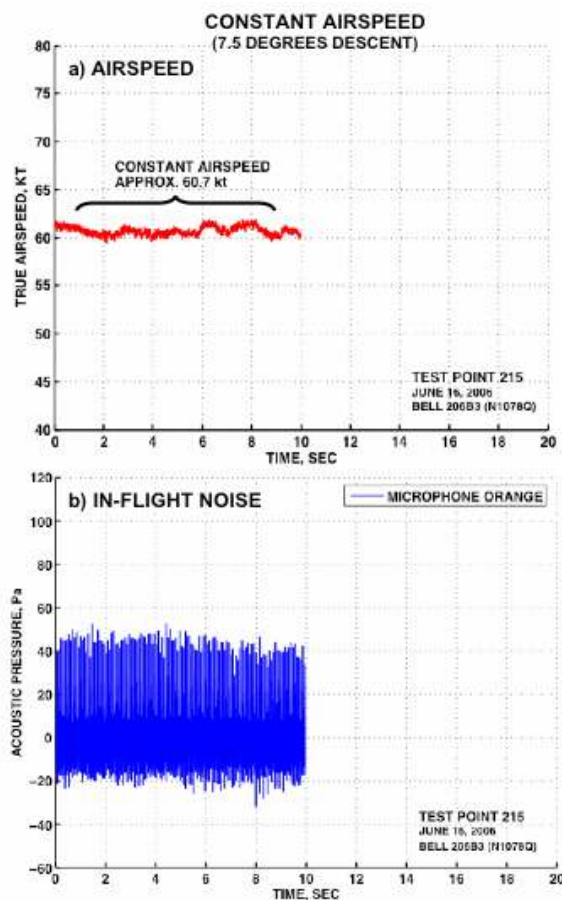


Figure 16: Measured a) Flight Velocity and b) Acoustic Pressure (In-Flight Microphone) Profiles for Straight Steady-State Descent Flight at 60 Knots and a Glideslope Angle of -7.5°

Effect of Acceleration/Deceleration on BVI Noise

The consistency of the boom mounted acoustic flight data is indicated in Fig. 16 below for a constant 7.5° approach at 60 knots airspeed. Boom microphone “orange” was located on the

advancing side of the helicopter and clearly indicates that BVI is the dominant source of noise. The acoustic record was taken for 15 seconds as the helicopter approached the ground along a 7.5° glide path angle. The peak BVI pulses are seen to vary by about 20% off of their peak values (.6 dB) during the entire run.

If instead, the helicopter were to descend along a similar flight path of 7.5°, but now accelerate at .084g from 47 Knots to 67 knots, a dramatic reduction in noise is seen over a slightly longer period of time as shown in Fig. 17.

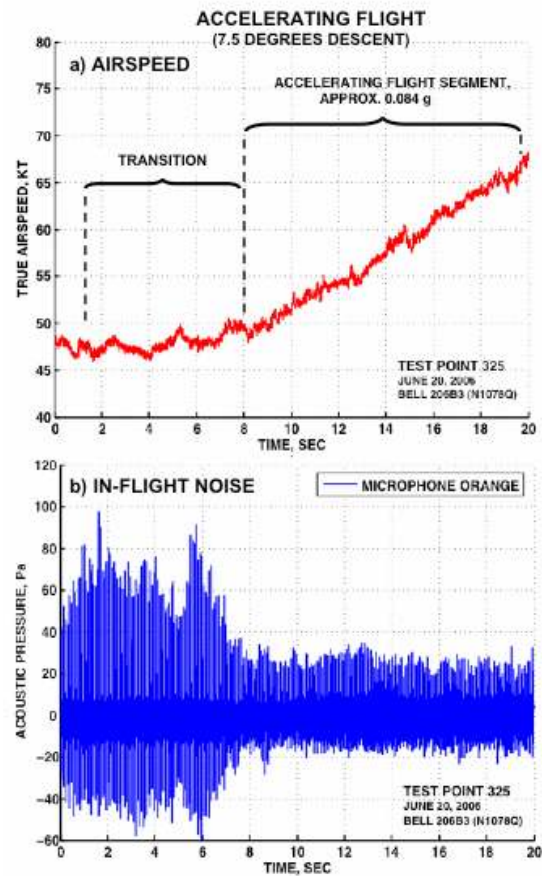


Figure 17: Measured a) Flight Velocity and b) Acoustic Pressure (In-Flight Microphone) Profiles for Straight Descending Accelerating Flight at a Glideslope Angle of -7.5°

Beginning at roughly 8 seconds into the run, the BVI noise is reduced, on average, by up to 9 dB from the value measured at 47 knots airspeed before the acceleration was begun. The data clearly indicate that acceleration (and by similar reasoning, deceleration) can have a very strong influence on the radiated BVI noise. Similar benefits were shown experimentally for the S-76 helicopter when deceleration and steep descents were noted to markedly reduce BVI noise.¹⁷

Direct TPP Angle Measurements

The results of the tip-path plane measurement system are presented in Fig. 18¹⁸. The horizontal axis represents the theoretical tip-path plane angle based on the fuselage drag-to-weight ratio, flight path angle, and acceleration¹³. The vertical axis represents the measured tip-path plane angle.

Overall, the system proved to be highly repeatable over a variety of quasi-steady and steady-state flight conditions, with a standard deviation of less than 1.5°. Much of this error came from the air data boom measurements of the empennage angle of attack with respect to the free-stream velocity vector. Linear regression analysis of the measured TPP angles demonstrated that the system was tracking the general trends quite well over a wide range of angles of attack. Further examinations, reported in Ref. 19 also found that the measured tip-path-

plane angles vary linearly with the square of the velocity; linearly with flight path angle; and linearly with acceleration - all of which points to a well-behaved measurement concept/prototype system that was able to capture the first-order physical attributes of the main rotor's tip-path-plane angle and its associated trends at various flight conditions.

Figure 18 also highlights a 2° bias between measurement and theory. Although calibration scales were applied to compensate for wake effects on the wind vane measurements in flight, this bias remains constant over the range of flight conditions and is most likely the result of an air data boom positioning error. It is believed that with an improved free-stream velocity angle measurement, it will be feasible to use an optics-based system to accurately track the tip-path plane relative to the free-stream velocity.

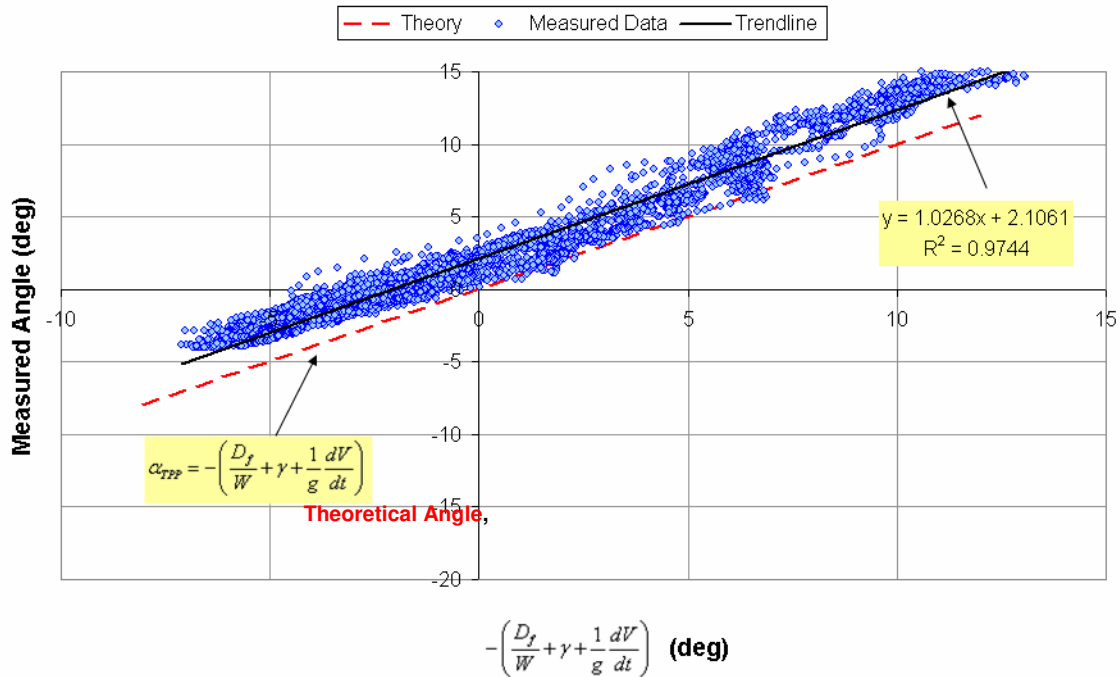


Figure 18: Tip-Path Plane Results: Measurements versus Theory

Noise Radiation During Steady Turning Flight

Steady turns were executed about a fixed point in space at different airspeeds, flight path angles and bank angles. The wind velocity during the turning flight tests was nearly negligible (less than 5 knots) – this was essential to ensure that the turn would be steady, with little longitudinal

inertial acceleration. The turn was conducted over a linear microphone array such that the array coincided with a diameter of the circle traced out by the helicopter (Fig. 19). Exploiting the cylindrical symmetry of the problem, the linear array was extended off of only one end of the diameter.

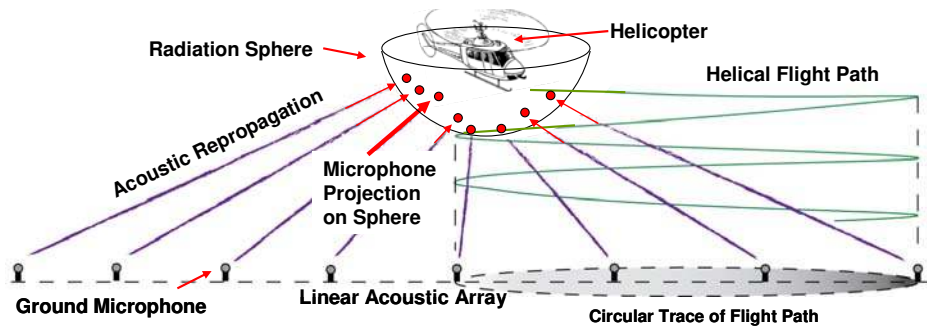


Figure 19: Turning Flight Hemisphere Measurement

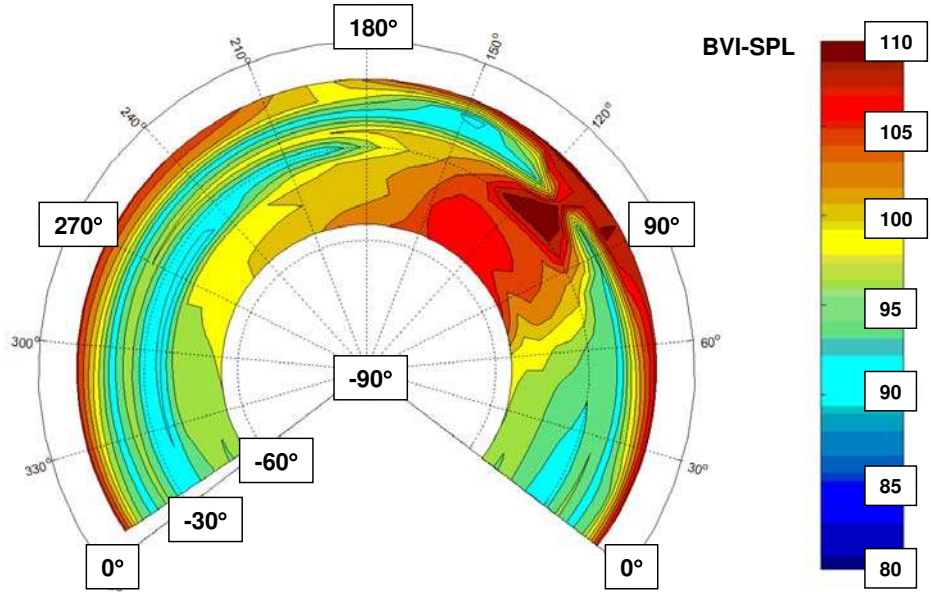


Figure 20: Horizon-Fixed Hemisphere Applied to 60kts Level Right Turning Flight Measurements

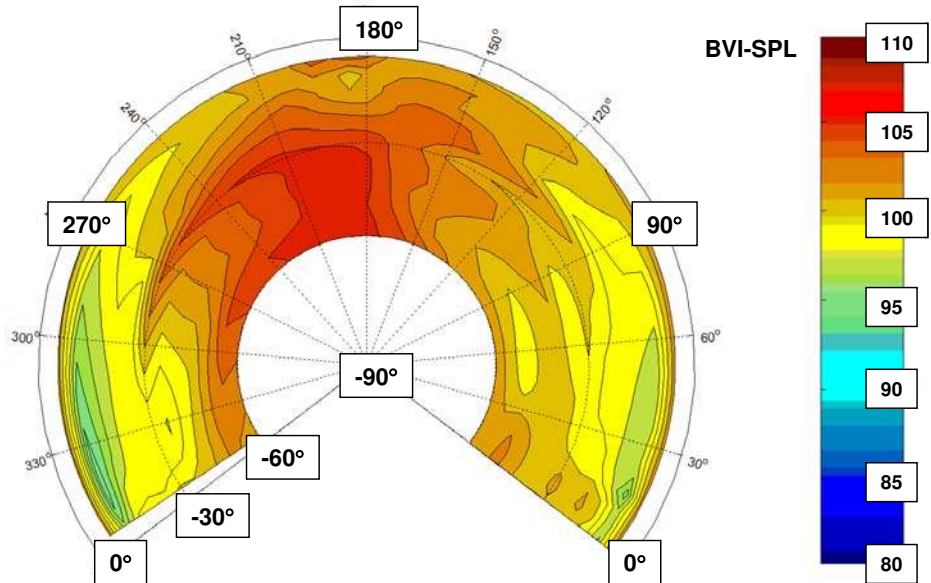


Figure 21: Horizon-Fixed Hemisphere Applied to 60kts Level Flight Measurements

Figure 19 also shows the geometric trace of the linear microphone array relative to the rotor hub, on a horizon level hemisphere fixed to the helicopter. Using acoustic mapping factors, noise levels are calculated at these locations on the hemisphere and then interpolated onto a uniform grid. This resulting distribution of BVI-SPL on a typical hemisphere is shown in Fig. 20 for the helicopter turning right at a bank angle of 30° and at a level flight velocity of 60 knots. More

comprehensive results and analysis of turning flight runs can be found in Ref. 16.

Figure 21 shows the BVI-SPL on distribution for level longitudinal flight at 60 knots. Compared to turns this semi-sphere is seen to exhibit much lower SPL values. Notice that these level flight directivity patterns are quite different from the patterns in descent (Fig. 12), when BVI is the dominant noise source.

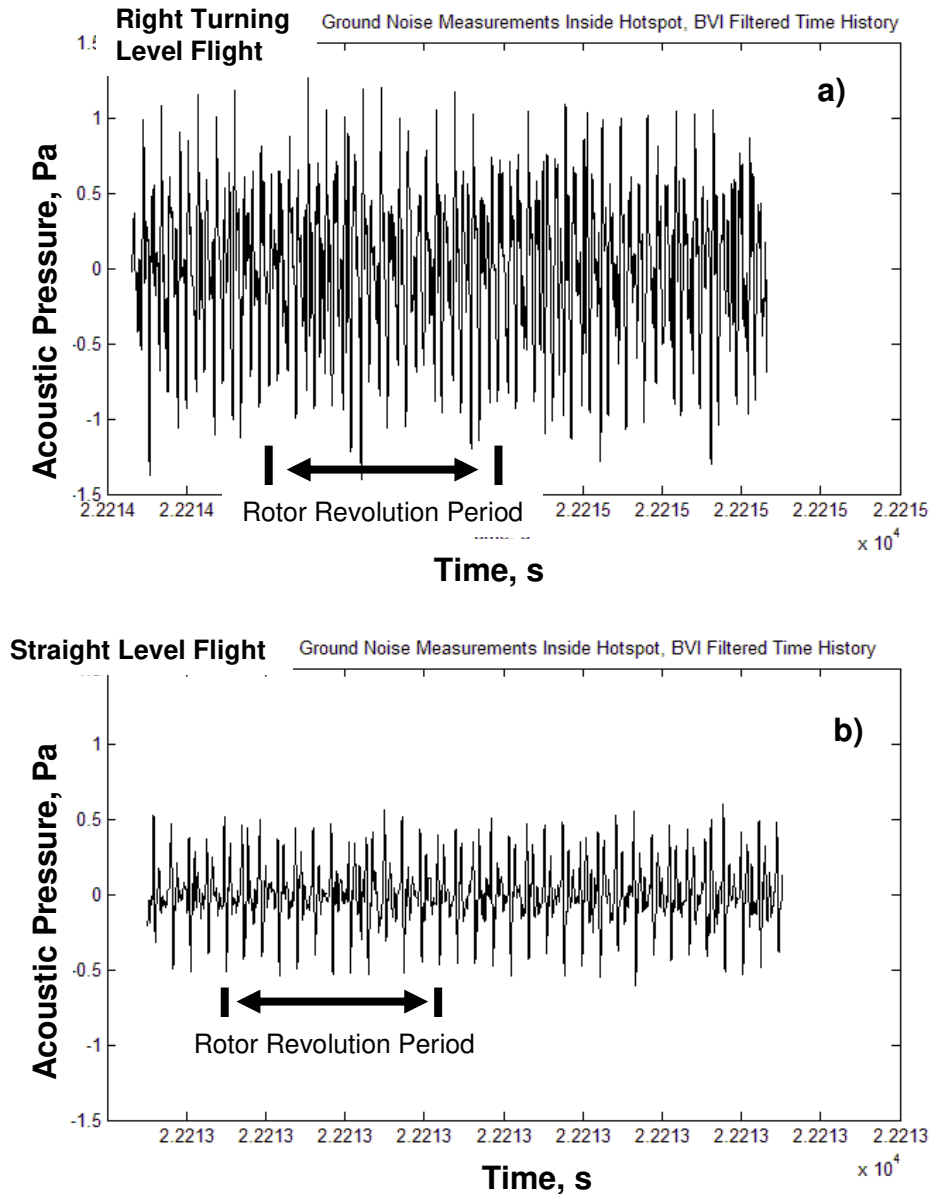


Figure 22: Acoustic Time Histories: 60kts Level Flight for a) Right Turn at 60 knots and 30° bank angle and b) Level flight at 60 knots

To investigate the increase in SPL values during turns, the time history trends at the representative “hot spots” on the two spheres are

compared in Fig. 22a for a right turn at 60 knots and a bank angle of 30° and Fig. 22b for straight and level flight at 60 knots. Figure 22b shows

that the SPL is dominated by tail rotor noise for the longitudinal level flight at 60 knots. Tail rotor harmonic noise dominates the time pressure history as indicated by the repetitive pulses at the tail rotor harmonic frequency times the number of tail rotor blades. These repetitive pulses become much larger during the right turn, as shown in Fig. 22a.

One major reason for this increase in tail rotor harmonic noise is that an increase in main rotor thrust is required to maintain steady flight in the turn. This increase in thrust causes an increase in main rotor torque which requires a corresponding increase in tail rotor thrust, which cause higher levels of tail rotor harmonic noise radiation.

Figure 22 also illustrates that there is a strong change in the directivity pattern between level and turning flight. The noise is shifted to the advancing side of the rotor during right steady, turning flight. This is most likely due to the tilting of the tail rotor, exposing a more dominant noise directivity lobe of the tail rotor to the ground noise measurements, rather than to large changes in tail rotor operating conditions. Additional analysis of the data should confirm this hypothesis.

Conclusions

Based upon the on-going work reported in this paper, it is obvious that there is much to learn about helicopter acoustic flight testing during all phases of flight – but especially during steady turns and maneuvers. The data-gathering problem is complex and quite interactive and requires very controlled performance states. In most instances, providing assistance and guidance to the pilot to fly the helicopter along the chosen flight trajectories at the prescribed operating condition facilitates the acquisition of high quality acoustic data. For the Bell 206B helicopter in this paper, a precision pursuit guidance display was quite helpful in helping the pilot perform his assigned flight tasks in steady, longitudinal flight. It was also apparent that for more demanding combination maneuvers and/or unsteady flight maneuvers, some sort of piloting guidance is required.

The ambient site conditions must be chosen to be near ideal during acoustic flight testing. It is important to test in low ambient wind conditions and with little or no horizontal wind or temperature gradients. This is especially important for the construction of RNM noise hemispheres for turning flight, where the steadiness of the turn can be compromised by small, steady, horizontal wind velocities.

A set of RNM noise hemispheres has been constructed for steady, turning flight from ground noise data for the first time. The resulting hemispheres have indicated that the tail rotor on the Bell 206B single rotor helicopter has a strong influence the helicopter's noise directivity pattern during turns. This is partially explained by the increasing tail rotor thrust required and the tilting of the tail rotor disk during turning flight.

In-flight microphones can be quite helpful in predicting the level of particular helicopter noise sources. Under the conditions of strong BVI, the microphone attached to the helicopter and aligned in the direction of near-maximum BVI, estimates the levels and occurrences of BVI both qualitatively and quantitatively. The results suggest that it may be easier and more definitive to measure and identify turning flight noise sources using boom mounted microphones instead of constructing similar information from ground arrays.

The use of compound flight profiles and maneuvers to control the noise radiation levels has been suggested and demonstrated using boom acoustic measurements. During a 7.5° approach, a small acceleration parallel to the flight path, accelerating the helicopter from 47 knots to 67 knots, was shown to reduce BVI noise by as much as 9 dB. Other compound flight profiles and maneuvers in straight or turning flight may offer similar benefits and might be useful in reducing the annoyance and/or the detection of an approaching helicopter.

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