THE DEVELOPMENT AND FLIGHT TEST DEMONSTRATION OF NOISE ABATEMENT APPROACH PROCEDURES FOR THE SIKORSKY S-76

Eric W. Jacobs
Ronald D. Prillwitz
Sikorsky Aircraft Corporation

Robert T.N. Chen
William S. Hindson
NASA Ames Research Center

Odilyn L. Santa Maria
NASA Langley Research Center

ABSTRACT

A joint U.S. Industry/NASA/FAA program was conducted during 1996 to develop and flight test validate noise abatement flight procedures for rotorcraft using Differential Global Position System (DGPS) technology for pilot guidance. Program participants included Boeing-Mesa, Sikorsky Aircraft Corporation, NASA Ames Research Center, NASA Langley Research Center and the Volpe National Transportation Systems Center (DOT/FAA). Key issues included potential noise reduction benefits, flyability, repeatability, passenger and crew acceptability, and potential regulatory approval. The current paper summarizes the development and flight test demonstration of noise abatement approaches for the S-76. Noise reductions exceeding 6 dB were demonstrated and improved "Fly Neighborly" approach conditions were identified.

NOMENCLATURE

ADI	Attitude & Direction Indicator
BVI	Blade Vortex Interaction
DGPS	Differential Global Positioning System
EPNL	Effective Perceived Noise Level (dB)
ILS	Instrument Landing System
KIAS	Indicated Airspeed (kt)
ROD	Rate-of-Descent (fpm)
KTAS	True Airspeed (kt)
SEL	Sound Exposure Level (dB)
α_{tpp}	main rotor angle of attack

Presented at the American Helicopter Society Technical Specialists Meeting For Rotorcraft Acoustics and Aerodynamics, Williamsburg, VA, 28-30 Oct 1997.

INTRODUCTION

Rotorcraft noise continues to present a significant barrier to community acceptance of rotorcraft operations, particularly for approach/landing operations in high air traffic areas such as vertiports. This "noise barrier" results in reduced rotorcraft sales and operations, and may ultimately limit the use of rotorcraft in addressing the anticipated growth in demand for commercial short-haul aviation services. Although potential solutions for achieving reduced noise levels include both aircraft design and flight operation changes, noise reduction efforts to date have primarily concentrated on design changes such as improved tip designs. Recommended noise abatement approach procedures have been published in Fly Neighborly Guides by the Helicopter Association International [1,2]. These recommended procedures were, however, typically derived from limited datasets, have not been optimized, and were intended to be usable with little pilot guidance beyond basic aircraft instrumentation.

Technical tasks described in this document include tasks supported with shared funding by the U.S. rotorcraft industry and government under the RITA/NASA Cooperative Agreement No. NCCW-0076, Advanced Rotorcraft Technology, Aug. 15, 1995.

The development of Differential Global Positioning Systems (DGPS) has presented an opportunity to achieve precisely guided noise abatement approach procedures providing significantly greater noise reduction benefits with improved flyability, repeatability, and passenger/crew acceptability. The initial research into DGPS-guided noise abatement approach procedures for rotorcraft, performed by NASA Ames Research Center in 1994 and 1995 using the UH-60A RASCAL aircraft [3,4], demonstrated the feasibility of using DGPS guidance to achieve noise abatement. The current effort built upon the results of the UH-60A RASCAL testing to develop and flight test demonstrate noise abatement approach procedures for two commercial helicopters, the Boeing MD Explorer and the Sikorsky S-76. Noise abatement procedures for both the 6000 lb MD Explorer and 11,700 lb S-76 were tested and evaluated as noise abatement requirements and pilot/aircraft guidance capabilities are likely to differ with weight class (e.g., pilot controlled versus fully-coupled autopilot), requiring different noise abatement approach procedures. This paper summarizes the development and flight test demonstration effort for the S-76.

Two noise abatement flight tests were completed during 1996. The first was an S-76 Approach Noise Characterization Test conducted by Sikorsky Aircraft during April and May of 1996 at the Sikorsky Acoustics Test Range in West Palm Beach, FL. This test, performed with an S-76C+, provided a five microphone database of S-76 approach noise as a function of constant airspeed and glide slope (rate-of-descent). The resulting approach noise database was used to develop a potential S-76 noise abatement approach profile and guided test matrix development for the second test, the Noise Abatement Flight Procedures Test conducted jointly by Sikorsky, Boeing-Mesa (formerly McDonnell Douglas Helicopter Systems), NASA Langley, NASA Ames, and Volpe Transportation Systems Center during October and November of 1996 at the NASA Ames Crows Landing Test Facility. The joint test employed an 8000' long by 3000' max width array of 55 microphones to further evaluate and develop noise abatement flight procedures for both the Boeing MD Explorer and a Sikorsky S-76B. A total of 137 data runs were performed for the S-76B at Crows Landing. The approach data runs included three baseline approach profiles, i.e., the S-76 noise certification approach (6° @ 74 kt) and two noise abatement approach conditions recommended in the Helicopter Association International (HAI) Fly Neighborly Guides [1,2]. The HAI noise abatement approach conditions were considered the "current technology" procedures.

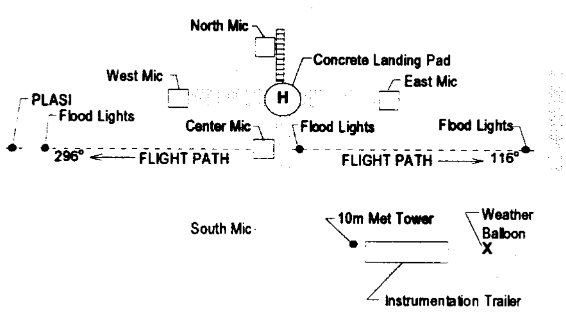
THE S-76 APPROACH NOISE CHARACTERIZATION TEST

The S-76 Approach Noise Characterization Test was conducted at the Sikorsky Acoustics Test Range in West Palm Beach, FL during April and May of 1996. This test provided the approach noise database as a function of constant airspeed and rate-of-descent (ROD) used to develop a potential low noise approach procedure for testing during the Noise Abatement Flight Procedures Test at Crows Landing, CA. The test was performed without Differential Global Positioning System (DGPS) guidance and employed a limited array of five microphone locations.

Test Setup and Procedures

The Sikorsky Acoustics Test Range near West Palm Beach (WPB), Florida has been specifically designed for conducting helicopter external noise testing including certification to FAA and ICAO requirements [5,6]. The site layout for the Sikorsky Acoustics Test Range is shown in Figure 1. For approach noise measurements, the reference flight path extends from 116° to 296° (true). The Acoustics Test Range provides the capability of acquiring five simultaneous acoustic noise measurements including a flight track (centerline) noise measuring station located vertically below the reference flight path and four additional noise measuring stations. Two sideline noise measuring stations are located 150 m (492 ft) to each side of the flight track noise measuring station on a line perpendicular to the reference flight track. Two additional sideline noise measuring stations are located 150 m (492 ft) in both directions from the concrete landing pad (see Figure 1) on a berm 97 m (318 ft) to the right of and parallel to the flight track. The (x,y) coordinates of these five noise measuring stations are (0,0), (0, -150 m), (0, 150 m), (-146 m, 97 m) and (154 m, 97 m).

Aircraft position tracking for the S-76 Approach Noise Characterization Test employed a microwave Aircraft Position and Tracking System (APATS) with two transponders located on the Acoustics Test Range at 1038.1 m (3405.9 ft) (317.26° true) and 551.5 m (1809.5 ft) (83.39° true), respectively, from the centerline microphone. In addition, flood lights along the fight track provided additional flight path guidance and a Pulse Light Approach Slope Indicator provided glide slope guidance for the 6° glide slope data runs. For approaches at other glide slopes, aircraft position was tracked on the ground and glideslope guidance was provided verbally to the pilots via radio.



Not-to-Scale

Figure 1. Layout of the Sikorsky Acoustics Test Range in West Palm Beach, FL

All acoustic and meteorological data acquired at the Acoustics Test Range are recorded in an instrumentation trailer located approximately 40 m (125 ft) from the intersection of the site access road and the foot path to the noise measuring stations. The meteorological data systems include both a tethered weather balloon and a 10 m (33 ft) meteorological tower located near the instrumentation trailer. For the S-76 Approach Noise Characterization Test, the electric winch for the tethered weather balloon was located along the access road approximately 90 m (300 ft) from the foot path as shown in Figure 1.

The S-76 Approach Noise Characterization Test was performed using S-76C aircraft 760269 with Arriel 2S1 engines (the S-76C+ configuration) at the maximum takeoff gross weight of 11,700 lb (+5%/-10%) and maximum normal operating rpm of 107% N_r. A total of 92 data runs were performed with test airspeeds ranging from 40 KIAS to 120 KIAS and glide slopes ranging from 1° to 10°. To permit evaluation of source noise levels with minimal differences in distance attenuation, all data runs were designed to pass over the flight track noise measuring station at 120 m (+/- 9 m) and hence did not have the same landing point. Although both ground plane and 4 ft microphones were deployed at each of the five measurement locations, only the ground plane noise measurements were used in data analyses to minimize the effects of variable ground reflections on the test results.

For each data run, Effective Perceived Noise Levels (EPNL) were determined for all of the ground plane microphone measurements. Because the resulting EPNL were evaluated at the measured and not nominal airspeeds and rates-of-descent, no duration adjustments for airspeed (Delta 2 Part 2) [7] were made to the measured EPNL. The EPNL were, however, adjusted to reference atmospheric conditions (25° C, 70% RH) and reference flight profiles (glideslopes) using the Delta 1 source noise and Delta 2 Part 1 duration (distance) adjustments specified in FAR Part 36 [7]. The corrected EPNL derived for all five ground plane microphones were subsequently averaged to obtain an average corrected EPNL for each data run. Blade vortex interaction noise levels (BVI EPNL) limited to the frequency range from the 200 Hz 1/3-octave to the 1,000 Hz 1/3-octave were also derived to further evaluate airspeed and rate-of-descent effects on BVI noise generation. For the purposes of approach noise abatement flight profile development, however, no fundamental differences were discernible between the EPNL and BVI EPNL datasets.

Test Results and Conclusions

A plot of S-76 approach noise versus measured airspeed and rate-of-descent is shown in Figure 2. For this plot, the average corrected EPNL were divided into 2 dB bins designated Max BVI, High BVI, Moderate/Low BVI and Minimal/No BVI. Although some anomalies are apparent, the results in Figure 2 indicate that the BVI hot spot for the S-76 occurs with high rates-of-descent at low airspeeds and hence any noise abatement approach profile for the S-76 would need relatively low rates-of-descent at low airspeeds to minimize BVI noise generation. Based on the results in Figure 2, the peak BVI condition for the S-76 appears to occur at an airspeed of ~60 KIAS and a rate-of-descent of 800 to 900 fpm.

DESIGN OF A PRETEST S-76 NOISE ABATEMENT APPROACH PROCEDURE

Based on the results of the Phase I S-76 Approach Noise Characterization Flight Test, a "pretest" multi-segmented noise abatement approach profile for the S-76 was designed prior to the Phase II Noise Abatement Flight Procedures Test. In addition to avoiding the high BVI noise observed for higher rates-of-descent at low airspeeds, design constraints

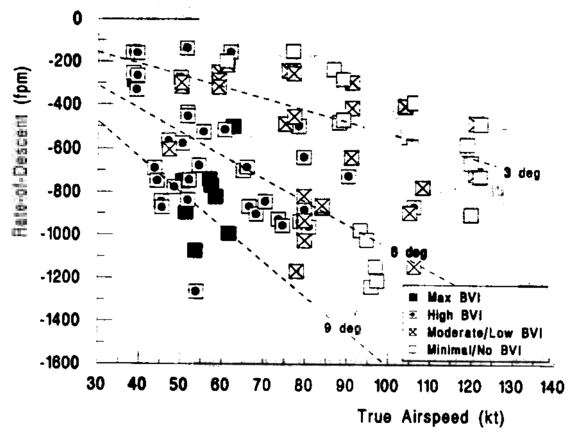


Figure 2. S-76 Approach Noise vs. Airspeed and Rate-of Descent

included (1) maximizing altitude and source-receiver distance during the approach profile to increase source noise attenuation and (2) minimizing aircraft deceleration rate(s) at low airspeeds to maintain lower effective rates-of-descent while decelerating. The higher rates-of-descent desirable to maximize altitude conflicted, however, with the lower rates-of-descent needed to minimize BVI noise generation at low airspeeds. In addition, the higher angle-of-attack (α_{tpp}) and effective rate-of-descent introduced by decelerating the aircraft [3,4] further conflicted with minimizing rates-of-descent and BVI noise generation at low airspeeds. Hence the pretest S-76 noise abatement profile was a compromise between maximizing aircraft altitude and minimizing rates-of-descent and decel rates at low airspeeds to avoid maximum BVI for the S-76.

Additional approach procedure design constraints included (1) safety-of-flight and crew/passenger comfort constraints, (2) the choice of true, indicated or ground speed for speed guidance and (3) the requirement that one design variable (e.g. decel rate) be able to float with ambient wind speeds to maintain the aircraft on reference flight path and airspeed profiles. For the S-76 noise abatement flight test, indicated airspeed was chosen for pilot guidance to avoid the safety-of-flight issues inherent to using ground speed and the airspeed calibration issues inherent to using true airspeed at low airspeeds (40-50 kt). Because the airspeed schedule was fixed as a function of distance to touchdown, the decel rate was the variable chosen to float with ambient windspeed, with headwinds reducing the decel rate and tailwinds increasing the decel rate.

The resulting pretest multi-segmented approach included four segments, i.e., (1) a 1 kt/sec deceleration in level flight to 90 KIAS, (2) a 0.25 kt/sec deceleration at a constant glide slope of 4° to 400 fpm rate-of-descent, (3) a 0.25 kt/sec deceleration at a constant rate-of-descent of 400 fpm to 40 KIAS, and (4) descent at a constant rate-of-descent of 400 fpm and a constant airspeed of 40 KIAS. This approach profile is summarized in Table 1 and approximately overlaid in Figure 3 (using KTAS instead of KIAS) on the approach noise data previously presented in Figure 2.

THE S-76 NOISE ABATEMENT FLIGHT PROCEDURES TEST

The S-76 Noise Abatement Flight Procedures Test was conducted jointly by Sikorsky Aircraft, Boeing- Mesa (formerly McDonnell Douglas Helicopter Systems), NASA Langley Research Center, NASA Ames Research Center and the Volpe National Transportation Systems Center (DOT/FAA) during October and November of 1996 at the NASA Ames Crows Landing Test Facility in Crows Landing, CA. The pretest S-76 noise abatement approach profile was tested and further optimized during this test.

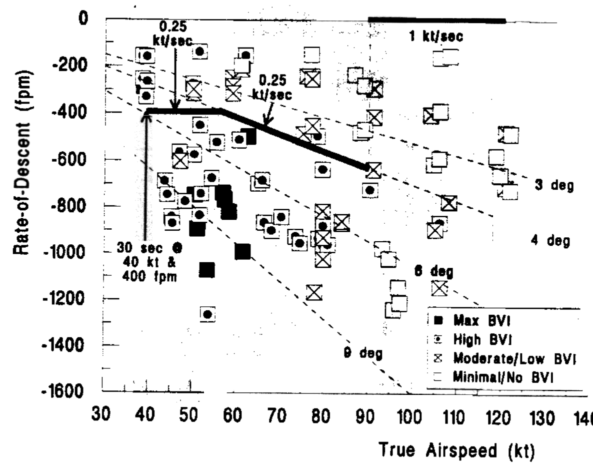


Figure 3. S-76 Approach Noise vs. Airspeed and Rate-of-Descent With Overlay of Pretest Noise Abatement Approach Profile

Test Setup and Procedures

The Noise Abatement Flight Procedures Test was performed at the NASA Ames Crows Landing Test Facility with a Boeing MD Explorer being tested during October and a Sikorsky S-76B being tested in November. Details of the acoustic and meteorological instrumentation, microphone array design and laser tracking system are provided in Reference [8]. To acquire the acoustic data necessary to achieve the objectives of the Noise Abatement Flight Procedures Test, the 55 microphone array shown in Figure 4 was installed at the Crows Landing Test Facility. This array consisted of 49 ground plane and six 4-foot microphones with 30 microphones recorded by NASA Langley, 10 microphones recorded by Volpe Center, 5 microphones recorded by Boeing-Mesa and 10 microphones recorded by Sikorsky Aircraft.

Segment 1	Segment 2	Segment 3	Segment 4
Level Flight Decel @ 1 kt/sec to 90 KIAS	Constant 4° Glide Slope, 0.25 kt/s Decel to 400 fpm ROD	0.25 kt/s Decel @ 400 fpm ROD to 40 KIAS	400 fpm ROD @ 40 KIAS to 100' Decision Height

Table 1. S-76 Approach Profile Designed for the Phase II Noise Abatement Flight Procedures Test

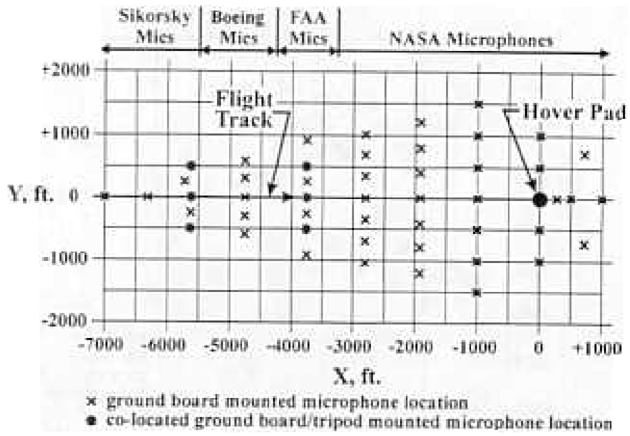


Figure 4. Layout of the Microphone Array at Crows Landing

The microphone array was deployed to provide a reference flight track extending from true south (180°) to true north (360°) with a hover pad located on the runway taxiway as shown in Figure 4. Note that some microphone positions were shifted slightly to accommodate the terrain and avoid obstacles encountered during setup at Crows Landing.

Meteorological data were acquired by NASA Langley from both fixed tower and tethered balloon meteorological data systems and aircraft position data were acquired by NASA Ames from the fixed laser tracking system at Crows Landing [8]. All onboard S-76 aircraft position (DGPS) and performance data were telemetered to the NASA Ames data system for simultaneous recording with the laser tracker data. Real time plots of aircraft vertical and lateral position, airspeed and ground speed as a function of distance to touchdown (x = 0) were provided by NASA Ames (see Figure 5).

All acoustic data were transferred at the end of each test day to NASA Langley for combined storage and processing [8]. NASA Langley subsequently provided onsite Sound Exposure Level (SEL) noise footprint plots with a better than one day turnaround for the S-76 test. These footprints were instrumental in the onsite development of improved noise abatement approach procedures.

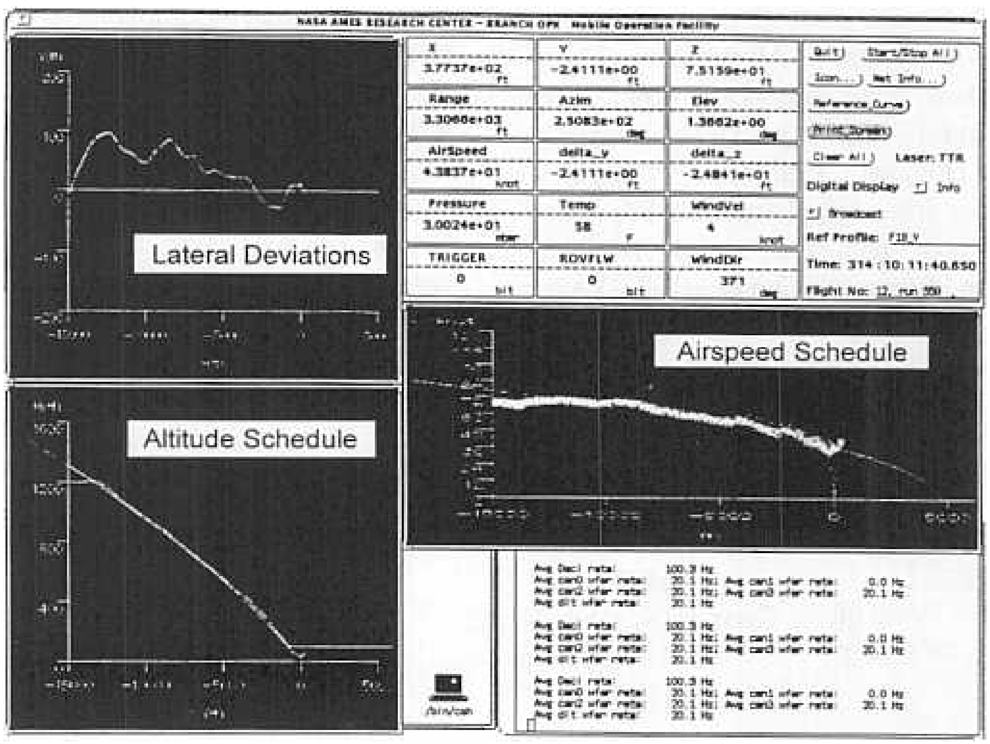


Figure 5. A Typical Real Time Plot Flight Track and Airspeed for the S-76

Although the S-76B guidance system was originally designed to use a DGPS only, schedule constraints dictated that the DGPS position error data be simulated using the NASA Ames laser tracker and ILS at Crows Landing. Hence for position and airspeed guidance, the S-76B test used a combination of the laser tracker and ILS at Crows Landing to provide position guidance and an onboard NavStar XR5 DGPS to provide airspeed schedule guidance (Figure 6) [8]. The NavStar XR5 DGPS is capable of providing an accuracy of better than 1 meter in real time and 10 cm in post-processing at a 4 Hz update rate. All guidance information was displayed to the pilots via the flight director and ADI (Figure 7), and aircraft flight path and speed were manually controlled by the pilot. The flight path deviations were transmitted as vertical and lateral guidance signals to the aircraft via standard ILS frequencies. The sensitivities of the glide slope and localizer were set to +/-80 ft and +/-106 ft full scale, respectively. An onboard computer analyzed the DGPS position and airspeed transducer data to determine airspeed deviations for display on the ADI.

The S-76 Noise Abatement Procedures Flight Test was performed with S-76B aircraft 760330 at a nominal takeoff gross weight of 11,200 lb (+4.5%/-10%). This gross weight is 500 lb less than the max takeoff gross weight for the S-76B, but was chosen to ensure that the actual takeoff gross weight did not exceed 11,700 lb. A total of 137 data runs were performed with the S-76B during 19.8 flight hours between November 6 and 13, 1996. Of these data runs, 29 were performed at constant airspeeds and rates-of-descent (ROD), 39 were performed at constant glide slope and deceleration rates, 24 were performed at constant ROD's and deceleration rates, 12 were multi-segmented noise abatement approaches, 8 were pilot approaches typical of current practice, 8 were takeoffs and 17 were level flight data runs. With the exception of November 6, all of the S-

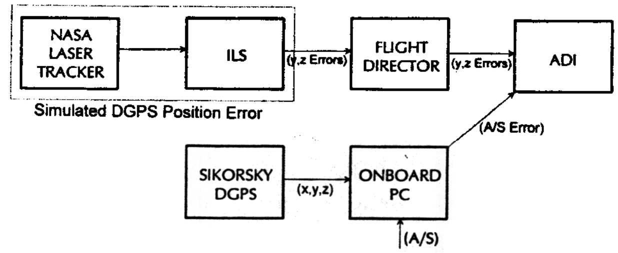


Figure 6. Schematic of the Pilot Guidance System for the S-76 Noise Abatement Flight Procedures Test

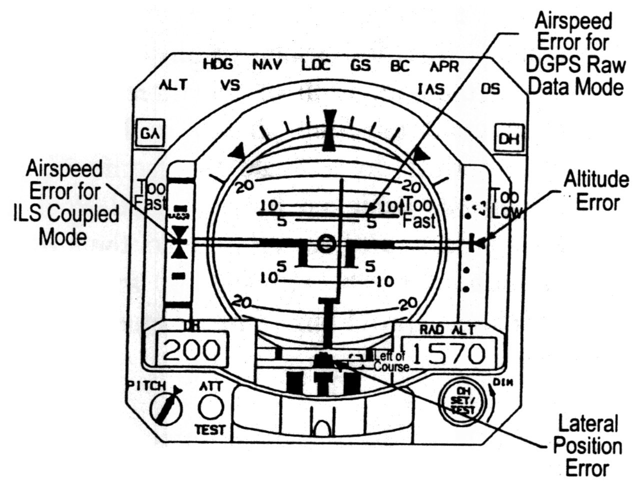


Figure 7. Pilot Cues on the S-76 ADI

76B flight testing was performed with calm air or low wind conditions.

Test Results

The acoustic data acquired during the S-76 Noise Abatement Procedures Test are presented here as acquired during the test. The acoustic data are given in Sound Exposure Levels (SEL) uncorrected to reference flight path or reference meteorological conditions. Weather conditions were very consistent day-to-day during the test and deviations from the reference flight paths were typically small for the data runs used for analysis. Hence the trends observed in the acoustic data were considered reliable for evaluating the noise abatement effectiveness of the tested approach profiles, and the noise reductions achieved with the resulting noise abatement procedures are an order of magnitude greater than the expected corrections to reference flight paths.

The S-76 approach data runs included three baseline approach profiles, i.e., the S-76 noise certification approach (6° @ 74 kt) and two noise abatement approach conditions recommended in the Helicopter Association International (HAI) Fly Neighborly Guides [1,2]. The HAI Pocket Guide noise abatement approach conditions were considered the "current technology" noise abatement procedures. SEL footprints for one of the data runs performed for each of the three baseline approach conditions are shown in Figure 8. These footprints do indicate that some noise abatement was achieved by both HAI Pocket Guide approach profiles relative to the noise certification approach, with the 800 fpm @ 80 kt approach providing the better noise abatement.

During the S-76 flight test, three test pilots each flew two or more "typical" approaches to provide additional "baseline" approach profiles. Although some of these footprints evidence improvements over the certification and fly neighborly approach procedures, the results are inconsistent, further demonstrating that adequate guidance, DGPS-based or otherwise, is needed to achieve consistent and repeatable noise abatement results.

The SEL footprint for one of the data runs performed using the pretest multi-segmented S-76 noise abatement approach procedure is shown in Figure 9. This footprint clearly illustrates that the noise abatement procedure designed prior to the test was not effective and provided little to no improvements relative to the S-76 noise certification approach or the HAI Pocket Guide approach procedures. This result indicated that the S-76 Approach Noise Characterization Test did not provide sufficient information to successfully design a noise abatement approach procedure for the S-76.

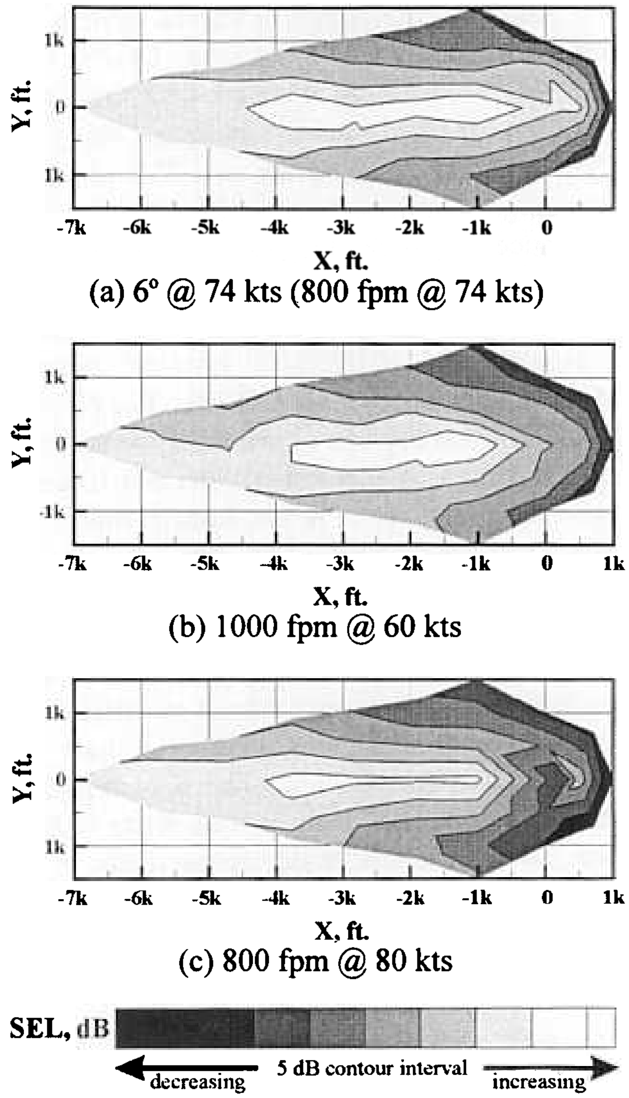


Figure 8. Noise Footprints for the Baseline S-76 Approach Profiles.

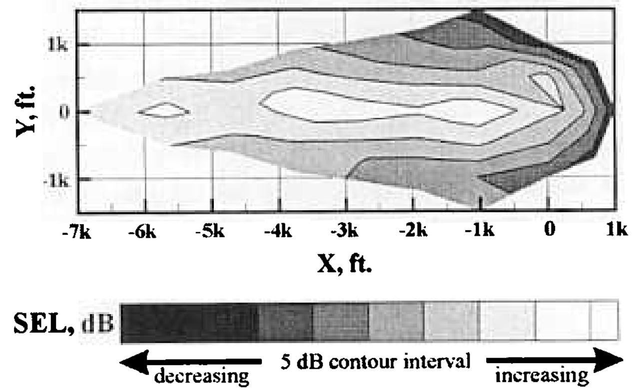
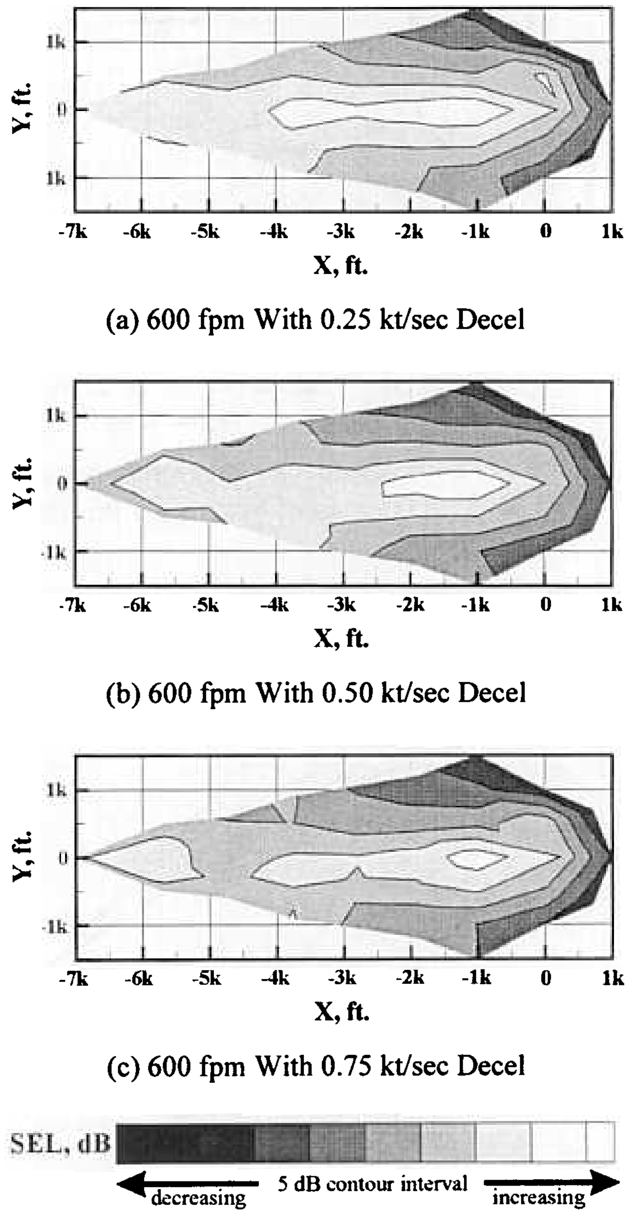


Figure 9. Noise Footprint for the Pretest Multi-Segmented Approach Profile

To expand on the S-76 approach noise database acquired during Phase I and provide information for improving S-76 noise abatement approach procedures, additional approach noise data were acquired for the S-76 with a particular emphasis on determining the effects of increased deceleration rates on BVI noise generation. Hence SEL footprints were acquired for higher glide slopes and rates-of-descent at deceleration rates greater than those employed in the pretest noise abatement approach procedure. These test runs were performed at fixed glide slopes or rates-of-descent while decelerating from 90 to 40 KIAS at a constant deceleration rate. Tested decel rates included 0.25 kt/sec, 0.5 kt/sec, 0.75 kt/sec and 1.0 kt/sec. Typical results are given in Figure 10, which shows SEL footprints obtained for a 600 fpm descents while decelerating at 0.25 kt/sec, 0.50 kt/sec and 0.75 kt/sec deceleration rates. These footprints provided clear evidence that significant S-76 approach noise reductions are achievable at higher rates-of-descent with sufficiently high deceleration rates. This result was consistent with post-flight pilot and flight engineer comments on perceived BVI noise generation.

Improved multi-segmented S-76 approach profiles were subsequently designed and tested using a higher rate-of-descent (600 fpm) and deceleration rates (0.75 kt/sec and 1 kt/sec) for the noise-critical third segment of the pretest multi-segmented approach procedure. The 0.75 kt/sec design was designated Multiseg 2 while the 1 kt/sec design was designated Multiseg 3. Some of the data runs performed for Multiseg 3 included an airspeed overshoot early in the deceleration phase which resulted in a significantly higher deceleration rate than incorporated in Multiseg 3. Because these data runs exhibited significantly higher noise reductions than the Multiseg 3 data runs at the intended deceleration rate, these data runs were redesignated as Multiseg 4 data runs during data analysis.



(a) 600 fpm With 0.25 kt/sec Decel

(b) 600 fpm With 0.50 kt/sec Decel

(c) 600 fpm With 0.75 kt/sec Decel

Figure 10. Noise Footprints for 600 fpm Descent @ 0.25, 0.50 and 0.75 kt/sec Deceleration Rates

For comparison to the pretest approach procedure (designated Multiseg 1), the Multiseg 3 approach procedure is approximately overlaid in Figure 11 (using KTAS instead of KIAS) on the data presented previously in Figure 2. The Multiseg 3 altitude profile and airspeed schedule are shown in Figures 12 and 13, respectively. The corresponding profiles for the S-76 noise

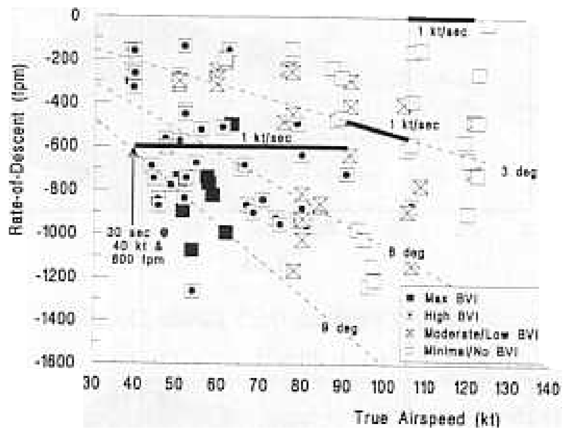


Figure 11. S-76 Approach Noise vs. Airspeed & ROD With Overlay of Multiseg 3 Profile

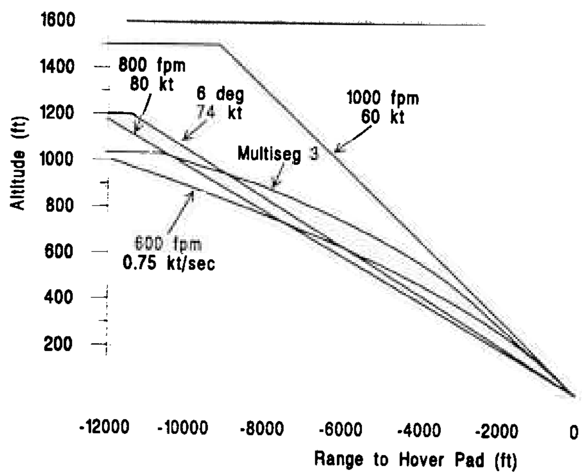


Figure 12. Altitude Profiles for S-76 Noise Abatement Approaches

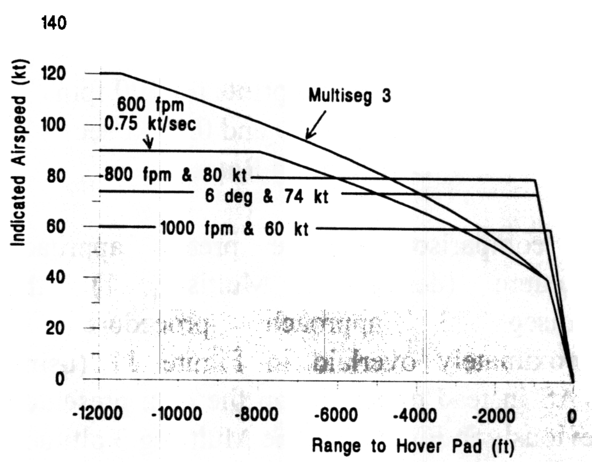
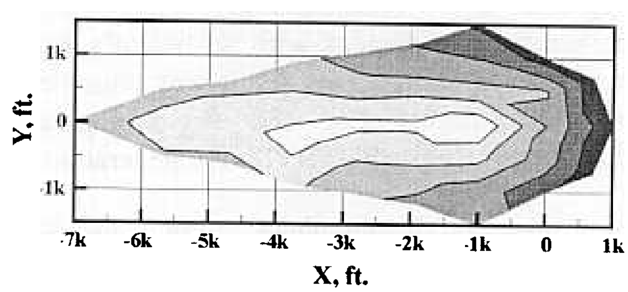


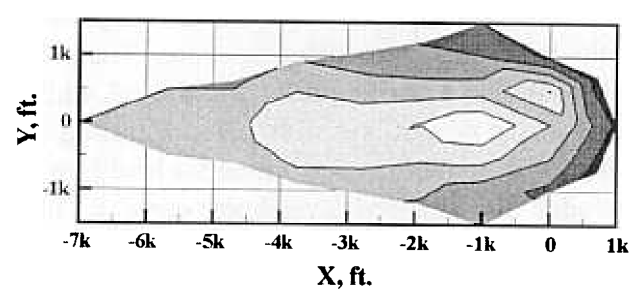
Figure 13. Airspeed Schedules for S-76 Noise Abatement Approaches

certification approach at 6°, the HAI Fly Neighborly noise abatement approaches, and a 600 fpm approach at 0.75 kt/sec decel are also shown for comparison.

SEL footprints obtained for Multiseg 3 and Multiseg 4 are shown in Figure 14. These footprints exhibit significant noise reductions, particularly prior to 4000 ft before the hover pad or touchdown point. The continued high noise levels after x = -4000 ft were attributed to the final segment performed at 40 kt and 600 fpm with no deceleration. Schedule constraints dictated that this final segment remain in the Multiseg 2, 3, and 4 approach profiles for the Noise Abatement Flight Procedures Test. Further optimization of the Multiseg 4 approach profile, however, could reduce the length of this final segment if higher noise reductions, such as measured for the single segment approach at 600 fpm and 0.75 kt/sec decel, are needed closer to a heliport.



(a) Multiseg 3



(b) Multiseg 4

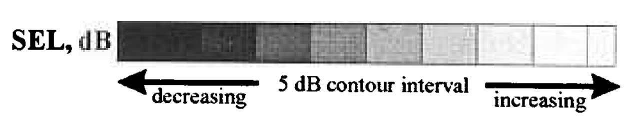
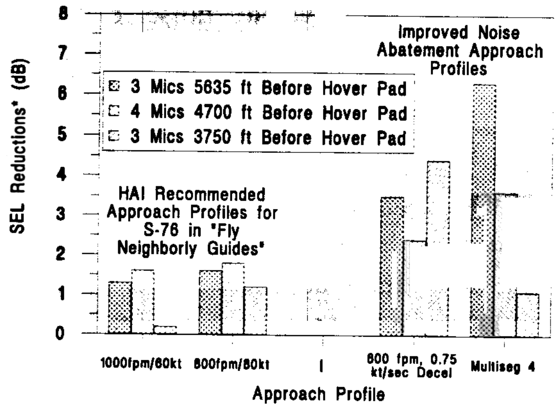


Figure 14. Noise Footprints Obtained for the Multiseg 3 and Multiseg 4 Approach Profiles



* relative to FAA Certification Approach (6 degrees @ 74 KIAS)

Figure 15. Average S-76 Approach SEL Reductions Measured at Various Distances Before the Hover Pad

SEL noise reductions obtained in real time during the test are shown in Figure 15 for the two HAI Pocket Guide noise abatement approaches, the 600 fpm, 0.75 kt/sec decel approach profile and the Multiseg 4 approach profile. These SEL reductions were derived by averaging the center microphone with 2 or 3 sideline microphones at 5635 ft, 4700 ft and 3750 ft before the hover pad. All of the reported reductions are relative to the average SEL acquired for the data runs performed at 6° and 74 kt, i.e., the S-76 noise certification approach profile. Note that 3750 ft represents the distance before the landing point specified in [5] for noise certification approaches at 6°.

Figure 15 shows that Multiseg 4 provides significant noise reductions exceeding 6 dB for more than one mile before the hover pad but little benefit at 3750 ft before the hover pad. The 600 fpm, 0.75 kt/sec approach does provide better noise reductions (>4 dB) at 3750 ft but sacrifices ~3 dB at 5635 ft. The tradeoff is also evident in the SEL footprints for the 600 fpm, 0.75 kt/sec and Multiseg 4 approaches shown in Figure 16. These results further indicate that S-76 noise abatement approach procedures can be tailored to better meet specific heliport siting requirements.

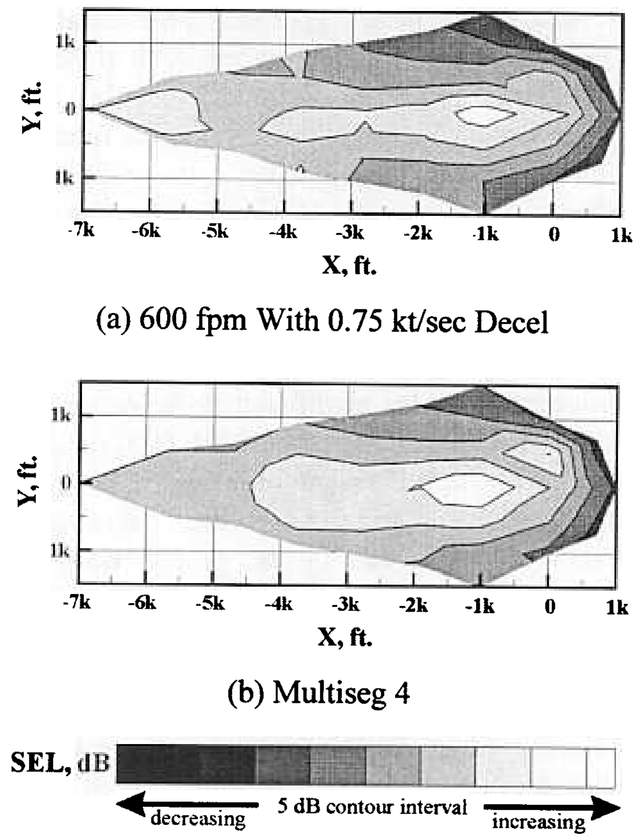
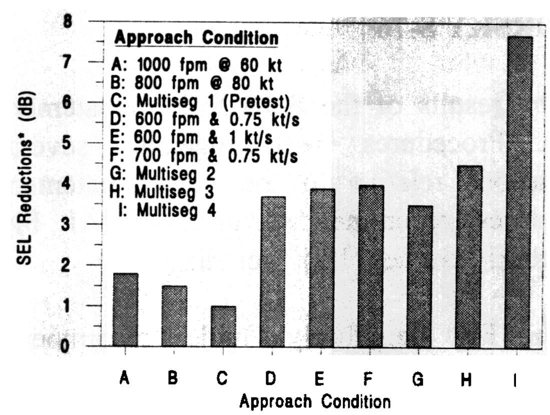


Figure 16. Noise Footprints Obtained for 600 fpm with 0.75 kt/sec Decel and Multiseg 4



* relative to FAA Certification Approach (6 degrees @ 74 kts)

Figure 17. Flight Track SEL Reductions at 7000 ft Before the Hover Pad for S-76 Noise Abatement Approaches

Figure 17 shows the average SEL reductions (relative to the S-76 noise certification approach data runs) measured for several of the tested approach profiles at the flight track microphone placed 7000 ft before the hover pad (see Figure 5). The SEL reductions in Figure 17 reflect: (1) the minimal reductions provided by the "current technology" noise abatement approach conditions recommended in the HAI Pocket Guide; (2) the disappointingly small noise reduction benefits provided by the pretest designed S-76 noise abatement approach procedure; (3) the significant noise reductions found for high rates-of-descent (600 to 700 fpm) with high deceleration rates (0.75 kt/sec or higher); and (4) the significant improvements made in the pretest designed noise abatement approach procedure demonstrated by Multiseg 2, Multiseg 3 and Multiseg 4. Multiseg 4 indicates that even more dramatic approach noise reductions will be achieved by further increasing deceleration rates above 1 kt/sec. Deceleration rates of up to 2 kt/sec may ultimately be achievable within passenger/crew comfort constraints.

COMMENTS ON "FLY NEIGHBORLY" APPROACH PROCEDURES FOR THE SIKORSKY S-76

The results of the S-76 Noise Abatement Flight Procedures Test engender several conclusions relative to the noise abatement procedures recommended in the HAI Fly Neighborly Guides [1,2], including:

1 The Fly Neighborly Guides recommend that noise sensitive areas be kept to the right of the aircraft during an S-76 approach. Examination of the noise footprints obtained during the S-76 Noise Abatement Flight Procedures Test have clearly shown, however, that noise sensitive areas should be kept to the left of an S-76 during approach. This result can be readily seen in Figures 8, 10, 11 and 14.
2. The HAI "Fly Neighborly" approaches for the S-76 do provide 1 to 2 dB noise reductions relative to noise certification approaches with the 80 kt, 800 fpm approach being slightly better than the 60 kt, 1000 fpm approach. The 80 kt, 800 fpm approach should also be more tolerant of ROD deviations.
3. The noise abatement achieved with the 80 kt, 800 fpm approach can be further enhanced by increasing the airspeed to 90+ kts. In addition, near the end of the approach, fairly rapid deceleration (~1 kt/sec) to 40 kt position the aircraft to make a Cat A landing while continuing to achieve significant noise abatement. These modifications will be proposed for the next revision of the Fly Neighborly Guides.
4. Reducing the rate-of-descent to 400 - 500 fpm at 90 - 95 kts (3 - 4° glide slope) would provide even greater noise abatement for S-76 approaches. Deceleration should again be limited to near the end of the approach and be performed as rapidly as possible while increasing the ROD to 600+ fpm. This approach will also be proposed for the next revision of the Fly Neighborly Guides.

THE FLYABILITY, REPEATABILITY, PASSENGER ACCEPTABILITY AND REGULATORY APPROVAL OF S-76 NOISE ABATEMENT APPROACHES

Because the position and airspeed guidance employed at Crows Landing were not coupled to aircraft controls as is anticipated for full implementation of S-76 noise abatement flight procedures using DGPS guidance, the flyability, repeatability and passenger/crew acceptability issues were not addressed in detail for the noise abatement procedures development and test effort. Some observations can be made regarding these issues, however, based on the test results obtained at Crows Landing.

The noise abatement approach profiles developed and tested during the S-76 Noise

Abatement Flight Procedures Test did not push the performance envelope for the S-76 and hence were flyable and, in general, repeatable based on pilot performance and comments. The flyability and repeatability decreased, however, with increasing deceleration rate. Although not required to achieve significant noise abatement, future implementations of noise abatement flight procedures for the S-76 will potentially include full coupling of the guidance system to aircraft controls, thereby improving both flyability and repeatability. In addition, a fully coupled configuration would reduce pilot workload and better support higher deceleration rates of up to 2 kt/sec. Both Sikorsky and NASA pilot comments have indicated, however, that deceleration rates exceeding ~2 kt/sec will be too aggressive for both passengers and crew.

Establishing the flyability and repeatability of noise abatement flight procedures will be crucial to achieving regulatory approval of reduced noise levels. Both flyability and repeatability may potentially be established with uncoupled guidance for the simpler noise abatement procedures (e.g., 600 to 700 fpm @ ~1 kt/sec), but a fully coupled configuration is likely to be needed for more complex procedures such as the multi-segmented approaches tested for the S-76.

As future noise abatement procedures tests are unlikely to have the large area microphone array deployed in the current test, the establishment of a valid testing procedure employing a significantly smaller microphone array is another issue remaining to be addressed. The current database will provide valuable information needed to determine minimum microphone array requirements. Regulatory approval remains a major issue to be addressed in implementing noise abatement flight procedures using DGPS guidance with much of the process to be determined by the FAA and other regulatory agencies.

SUMMARY AND CONCLUSIONS

The results of the S-76 Noise Abatement Flight Procedures Test support the following conclusions:

1. Approach noise reductions exceeding the project goal of 4 dB were demonstrated during flight testing of S-76 noise abatement approach procedures. Although the noise abatement approach procedure developed using the Phase I S-76 Approach Noise Characterization test data provided only minimal noise reduction benefits, additional flight procedure development during the Phase II S-76 Noise Abatement Flight Procedures Test led to S-76 approaches with noise reductions exceeding 6 dB prior to one mile before the hover pad.
2. Although the HAI "Fly Neighborly" approaches for the S-76 do provide small (1 to 2 dB) noise reductions relative to noise certification approaches, additional "Fly Neighborly" approach profiles can be defined to achieve greater noise reductions, including a simple change of increasing the airspeed to 90 - 95 kt and reducing the rate of descent to 400 - 500 fpm. In addition, contrary to the recommended procedure in the Fly Neighborly Guides, noise sensitive areas should be kept to the left of an S-76 during approach.
3. The Phase I S-76 Approach Noise Characterization Test had indicated that the BVI hot spot for high rates-of-descent at low airspeeds could not be avoided at high rates-of-descent until employing rates-of-descent that were not passenger/crew acceptable or flyable. The Phase II S-76 Noise Abatement Flight Procedures Test results showed, however, that with a sufficiently high deceleration rate (1 kt/sec or higher) at passenger/crew-acceptable rates-of-descent (600 to 700 fpm), the

resulting increase in angle-of-attack provides a sufficient increase in the effective glide slope (rate-of-descent) to avoid the BVI hot spot.

4. The S-76 Noise Abatement Flight Procedures Test results also indicate that S-76 noise abatement approach procedures can be tailored to address specific heliport siting noise issues. Noise reductions exceeding 4 dB can be obtained over a broad area beneath the flight path or maximized either within or beyond one mile prior to the hover pad/heliport.

REFERENCES

1. Fly Neighborly Guide, Helicopter Association International, Revised February 1993.

2. Fly Neighborly Pocket Guide, Helicopter Association International, 1992.

3. Hindson, W.S. and Chen, R.T.N, "Flight Tests of Noise Abatement Approaches for Rotorcraft Using Differential GPS Guidance," 51st Annual Forum Proceedings, American Helicopter Society, Ft. Worth, TX, 9-11 May, 1995, Vol. I, pp. 681-694.

4. Chen, R.T.N., Hindson, W.S. and Mueller, A.W., "Acoustic Flight Tests of Rotorcraft Noise-Abatement Approaches Using Local Differential GPS Guidance," NASA TM 110370, September 1995.

5. Jacobs, E.W., Mancini, J., Visintainer, J.A. and Jackson, T.A., "Acoustic Flight Test Results for the Sikorsky S-76 Quiet Tail Rotor at Reduced Tip Speed," Proceedings of the 53rd Annual Forum, American Helicopter Society, Virginia Beach, VA, 29 April - 1 May 1997, pp. 23-41.

6. Jacobs, E.W., Prillwitz, R.D., Johnson, J.R. and Yoerkie Jr., C.A., "Stage 2 Noise Certification of the Sikorsky S-76A and S-76C Helicopters," Proceedings of the 47th Annual Forum, American Helicopter Society, Phoenix, AZ, 6-8 May 1991, pp. 829-840.

7. Federal Register, Vol. 53, No. 24, Friday, February 5, 1988, Rules and Regulations, Part V, Department of Transportation, FAA 14 CFR Parts 21 and 36, Noise Standards for Helicopters in the Normal, Transport, and Restricted Categories, Final Rule.

8. Jacobs, E.W., O'Connell, J.M., Conner, D.A., Rutledge, C.K., Wilson, M., Shigemoto, F., Chen, R.T.N., and Fleming, G.G., "Acoustic Flight Testing of a McDonnell Douglas MD Explorer and a Sikorsky S-76B Using a Large Area Microphone Array," Proceedings of the Rotorcraft Acoustics and Aerodynamics Specialists Meeting, American Helicopter Society, Williamsburg, VA, 28-30 Oct, 1997.

ACKNOWLEDGEMENTS

The authors would like to express their appreciation for the outstanding support of the S-76 Noise Abatement Flight Procedures Test provided by the following people:

Boeing-Mesa: Dan Fanning, Mark Hardesty, Scott Kehl, Jim O'Connell; **FAA:** Ken Jones; **Lockheed Engineering & Sciences:** Ken Rutledge, Mark Wilson; **NASA Ames:** Mitch Aoyagi, Nancy Bafhford, Don Billings, Wes Gidcumb, Joe Leung, Pam Pfohl, Mei Lin, Sunny Ng, Fred Shigemoto, Austin Somes; **NASA Langley:** Dave Conner, D.C. Davis, Jaye Moen, Arnold Mueller; **NRTC:** Tom Snyder; **Recom Technologies:** Julie Brantley, Ed Farr, Bruce Gallmeyer, Rob Honeyman, Rick Taylor; **Sikorsky Aircraft:** Jim Andrews, Stuart Drost, Blake Dunne, Lee Erickson, Joe Holt, Charles Iorio, Tracy Jackson, John Mancini, Greg Mandanici, Rick Mastalski, Elmer Morann, John Pandoli, Courtney Payne, Art Raymore, Bill Terrell, Art Tobey, Dave Wright; **Volpe Center:** Greg Fleming, Cynthia Lee, Dave Read, Chris Roof; **Wyle Labs:** Tom Baxter, Nick Karangelen, Virgilio Marcello, Keith Scudder, John Swain