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NASA/ARMY/BELL XV-15 TILTROTOR LOW NOISE TERMINAL AREA OPERATIONS FLIGHT RESEARCH PROGRAM

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Abstract

A series of three XV-15 acoustic flight tests have been conducted over a five year period by a NASA/Army/Bell Helicopter team to evaluate the noise reduction potential for tiltrotor aircraft during terminal area operations. 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. Phase 1 results were used to design 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. This paper will discuss the weather, aircraft, tracking, guidance, and acoustic instrumentation systems, as well as the approach profile design philosophy, and the overall test program philosophy. Acoustic results are presented documenting the variation in tiltrotor noise due to changes in operating condition, indicating the potential for significant noise reduction using the unique tiltrotor capability of nacelle tilt.

Introduction

Many U.S. airports are rapidly reaching their saturation point with regard to the number of daily aircraft operations permitted. Commuter aircraft, flying fairly short routes with relatively few passengers, make up a significant portion of the total airport operations at a large number of these airports, thus significantly limiting the total number of passengers that can use those airports each day.[1] Tiltrotor aircraft, with their unique capability to takeoff and land vertically while still flying like an airplane during cruise, provide a potential alternate means of transportation that could link major cities, thus alleviating some of the demand on airports. Research on tiltrotor aircraft has been conducted for many years using such vehicles as the XV-3 and the XV-15, among others. More recently, the Navy has begun procurement of the V-22 Osprey to utilize the capabilities of the tiltrotor for military applications. However, noise generated by the large tiltrotor aircraft is a potential barrier issue for civil market penetration. Tiltrotor aeroacoustics, including primary noise sources and the current state of the art, has been extensively documented in the literature.[2]

There are two ways to reduce the noise produced by a tiltrotor aircraft. One means is by simply designing a quieter rotor. This approach requires a significant lead-time and involves complex aeroacoustic and structural design tradeoffs. A second approach is to make use of the nacelle tilt capability of a tiltrotor, which allows the aircraft to fly a specified flight path at a number of different rotor operating conditions. To address the issue of noise reduction, NASA initiated an effort with the goal of reducing the overall tiltrotor approach noise within a 40-acre vertiport by 12 dB relative to current (1995) technology. This effort is a key part of the Short-Haul (Civil Tiltrotor) (SH(CT)) program which is an element of the Aviation Systems Capacity Initiative within NASA. The objectives and overall scope of the SH(CT) program have been thoroughly documented.[3] The goal is to obtain half the noise reduction through design and half through operations.

A number of acoustic wind tunnel tests have been conducted under the SH(CT) program. In a joint NASA/Army/Bell Helicopter Textron test of a model tiltrotor in the 14- by 22-Foot Subsonic Tunnel at the NASA Langley Research Center, Marcolini et al. showed significant variations in both noise level and directivity as a function of rotor operating condition.[4] To evaluate industry-developed low noise tiltrotor designs, a one-quarter-scale isolated rotor test was conducted in the NASA Langley 14- by 22-Foot Subsonic Tunnel in 1998.[5,6] Two versions of a Sikorsky Variable Diameter Tiltrotor (VDTR) and two Boeing 5-bladed advanced rotor configurations were compared to a "baseline" V-22 rotor system. Results from this test indicate that the Boeing 5-blade rotors substantially reduced noise for some conditions while the Sikorsky VDTR configurations meet or exceeded the SH(CT) goal of 6 dBA noise reduction for most conditions tested.

The concept of noise reduction by flight operations is not new in the rotorcraft industry and is the basis for a decades old Helicopter Association International (HAI) program referred to as the Fly Neighborly Program.[7] The idea is to avoid operating in those regions of the vehicle flight operations envelope which produce high noise levels relative to other regions of the flight envelope. To explore this concept in detail, the NASA Langley and Ames Research Centers conducted an acoustic flight test using a UH-60 "Blackhawk" helicopter to determine relative noise levels as a function of flight operating condition.[8,9] With a noise mapping of the Blackhawk flight envelope in hand, a noise abatement approach profile was designed. To fly noise abatement approach profiles with precision a flight guidance system was developed at the Ames Research Center which was based on a Global Position by Satellite (GPS) system.[10] A subsequent flight test to assess the noise abatement potential of this approach profile showed no significant differences in the Sound Exposure Level (SEL) at the three FAA noise certification measurement locations when compared to a standard 6° decelerating approach.[11] However, different conclusions may have been reached if a large area noise footprint had been measured. In 1996, large area noise footprints were measured during a noise abatement flight test involving the NASA Langley and Ames Research Centers, the Volpe National Transportation Systems Center (DOT/FAA), Boeing-Mesa, and Sikorsky Aircraft.[12] During this test, a Boeing MD Explorer and a Sikorsky S-76B flew noise abatement approaches over a 49 microphone array which was deployed over an area measuring 3000 feet by 8000 feet. Results for the MD Explorer showed that a two-segmented noise abatement approach profile provided an average 3 to 4 SELdB noise reduction relative to the reference approach profile over a ground area termed as the noise sensitive region under the flight path (3000 to 7000 feet up-range from the landing point).[13] The S-76 noise abatement approach profile showed noise reductions of more than 6 SELdB for distances in excess of 5000 feet up-range of the landing point when compared to a standard FAA noise certification approach.[14] However, this same approach showed no significant noise reductions at the FAA certification distance of 3750 feet up-range of the landing point.

Tiltrotor aircraft have the potential for more significant noise reduction benefits by modification of flight procedures than helicopters due to the additional operational variable of nacelle tilt angle. To design noise abatement procedures for tiltrotors, a detailed knowledge of the noise directivity characteristics for many different operating conditions is required. The XV-15 has been the predominant tiltrotor acoustic research aircraft for approximately the last 20 years. As a joint NASA/Army/Bell venture, two XV-15 aircraft were built, and much acoustic testing has been accomplished using these vehicles. Lee and Mosher showed significant variation (10-15 dB) in noise level as a function of nacelle tilt angle in a test of an XV-15 in the NASA Ames 40x80 Foot Wind Tunnel.[15] However, detailed directivity changes could not be measured because only four microphones were used. Conner and Wellman conducted XV-15 flight tests that successfully mapped the aircraft noise directivity during hover for two different rotor blade sets.[16] Brieger, Maisel, and Gerdes conducted XV-15 flight tests, acquiring acoustic data during level flight, ascent, and descent operating conditions.[17] Their results showed a significant variation in noise generation with nacelle tilt, but since acoustic data were only acquired at two sideline angles to each side of the aircraft; directivity information was limited. Edwards acquired XV-15 acoustics data for a limited test matrix using a large area microphone array to directly measure the noise footprint.[18] More recently, Conner et al. conducted an extensive XV-15 flight test which used a linear microphone array to successfully map the noise directivity for many different ascent, descent, and level flight operating conditions.[19] The potential for significant tiltrotor noise reductions with variations in approach profile design (nacelle angle/airspeed/altitude schedule) was shown in a 1997 XV-15 acoustic flight test which used a large area microphone array to directly measure noise footprints for a large number of candidate low noise profiles.[20] Compared to a standard 6° approach, a noise abatement approach showed a noise reduction of more than 5 SELdB when averaged over all microphones located between 3000 feet and 8000 feet up-range of the landing point and more than 7 SELdB when averaged over all microphones located between 5000 and 8000 feet up-range of the landing point.

In the present paper, results are presented from the most recent series of three XV-15 flight tests conducted by a NASA/Army/Bell Helicopter team that addresses tiltrotor noise reduction by flight operations. These tests were conducted in 1995[19] 1997[20] and 1999 at a remote test site located near Waxahachie, TX. The 1995 test, referred to as phase 1, focused on all aspects of terminal area operations (takeoff, approach, and level flight conditions) while the 1997 (phase 2) and 1999 (phase 3) tests focused exclusively on the approach condition because this was identified as the area of most concern. The overall program approach philosophy as well as the specific objectives for each test are discussed. Results from each test are presented including effective ground contours for steady state flight conditions and measured ground footprints for realistic takeoffs and approaches. These results document the variation in tiltrotor noise due to changes in operating condition, and indicate the potential for significant noise reduction using the unique tiltrotor capability of nacelle tilt. The paper also includes discussions of the weather, aircraft, tracking, guidance, and acoustic instrumentation systems, the low noise approach profile design philosophy, and the use of the Rotorcraft Noise Model (RNM)[21] as an aid in the design of quiet approach profiles.

Overall Program Design

The overall objective of this flight test program was to determine terminal area flight procedures for tiltrotors that are consistently quiet, safe, and easy to fly. An XV-15 flight test program was developed that included three separate flight tests, allowing time between the tests to thoroughly analyze the data and use the results to plan the following test. The phase 1 test[19] was designed to assess the relative noise levels produced by tiltrotor aircraft for a broad range of steady state flight conditions by measuring the lower hemispherical noise characteristics using a linear microphone array. Data were acquired for level flyovers, takeoffs, and approaches. Results indicated that level flyover and takeoff noise levels were insignificant compared to approach noise levels. The remainder of the program, therefore, focused exclusively on developing low noise approaches. Steady state noise characteristics for the approaches flown during phase 1 testing were studied and candidate low noise approach profiles were designed using engineering judgement and the noise prediction program RNM. The candidate low noise approach profiles, originally designed from a purely acoustic point of view, were modified to blend noise reduction and handling qualities. The modified candidate low noise approach profiles were then flown in the phase 2 flight test[20] to assess the noise reduction potential. During this test the noise footprints were directly measured using a large area microphone array. Handling qualities assessments were provided by the pilots after each approach. The most promising approach profiles from phase 2 testing were then modified to further improve handling qualities, thus providing a refined set of low noise approach profiles. In addition, an optimizer was linked with the RNM to provide a couple of new candidate low noise approach profiles that were then modified for improved handling qualities. The refined set of approach profiles, along with the two new approach profiles, were then tested in the Ames Vertical Motion (flight) Simulator VMS to assess and, if necessary, improve the handling qualities characteristics prior to the phase 3 flight test.

Experimental Setup

XV-15 Tiltrotor Aircraft

The XV-15 tiltrotor aircraft[22] (figure 1) was built by Bell Helicopter Textron, Inc. (BHTI), as a proof of concept aircraft and technology demonstrator whose first flight was in May 1977. The XV-15 has two 25-foot diameter rotors mounted on pivoting nacelles that are located on the wing tips. Each nacelle houses a main transmission and a Lycoming T-53 turboshaft engine capable of generating 1800 shaft horsepower. The nacelles are tilted into the vertical position (90° nacelle angle) for vertical takeoffs and landings and rotated to the horizontal (0° nacelle angle) for cruising flight. Each rotor has three highly twisted, square-tip, stainless steel blades which typically operate at 589 RPM during hover and transitional flight modes, and at 517 RPM in cruise, corresponding to 98% and 86% of rotor design speed. The wings have a 6.5° forward sweep to provide clearance for rotor flapping. During this test, the nominal vehicle takeoff gross weight was 13,900 pounds, including about 2000 pounds of fuel. During the period of data acquisition, fuel burn-off resulted in an approximately 10% reduction in the vehicle gross weight. The vehicle was operated by BHTI under contract to NASA. In addition, BHTI furnished research pilots, flight test engineers, ground crew personnel, and other necessary support personnel for operation and maintenance of the aircraft and onboard data acquisition system.

The XV-15 featured an impressive suite of onboard instrumentation. Approximately 150 aircraft state parameters were measured and recorded on magnetic tape. Transducers included attitude and rate gyros, strain gauges, temperature sensors, accelerometers, and control position sensors. In addition to the standard onboard instrumentation package, a modified ILS system was installed for pilot guidance during phase 1 testing and a Differential Global Positioning System (DGPS) and flight director system[23] were installed to provide tracking and pilot guidance during phase 2 and phase 3 testing.

The nominal XV-15 flight envelope, shown in figure 2, illustrates the combination of nacelle angle and airspeed necessary to achieve stabilized level flight conditions. It should be noted that a fairly broad range of nacelle angles and airspeeds is possible within this operating envelope. The acoustic effects of avoiding certain portions of this range can guide flight operations of the XV-15 (and presumably other tiltrotor aircraft) in minimizing external noise. The flight test series discussed here was designed to define and quantify these effects during terminal area operations.

Figure 1. XV-15 tiltrotor aircraft approaching the landing point at the test site near Waxahachie, TX, during the phase 3 test.

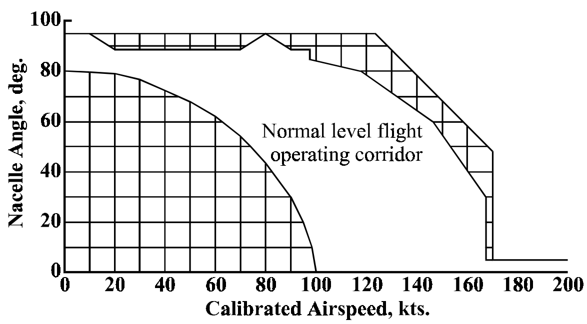


Figure 2. XV-15 flight envelope.

Aircraft Tracking and Pilot Guidance Systems

During the phase 1 test, aircraft tracking was provided by the NASA Ames Precision Automated Tracking System (PATS). The PATS system used a pulsed laser beam with a 100 Hz pulse rate to measure the position of the aircraft within 0.1 mrad in azimuth and elevation and ±1 ft in range. These measurements were then converted to absolute X, Y, and Z coordinates with respect to the acoustic reference location. Along with tracking aircraft position, the Ames Instrument Positioning System (IPS) was used to provide flight path guidance information to the pilots. The IPS system compared the actual aircraft position to a pre-selected desired flight profile, and transmitted an error signal to a traditional Instrument Landing System (ILS) receiver and display installed on board the XV-15. This system provided real-time feedback to the pilots regarding their position with respect to the desired flight profile. In addition to the IPS, three 1000-watt metal halide lights with parabolic reflectors oriented towards the aircraft when inbound were deployed along the desired flight path approximately 25 feet above ground level at both ends and at the center of the test range property. These lights were visible to the pilots several miles out and provided very useful visual cues of the desired flight path.

During the phase 2 and 3 tests, aircraft tracking was provided by a 12-channel, dual frequency Ashtech Model Z-12 GPS receiver installed on board the XV-15. Differential corrections were received from a reference ground GPS unit using a VHF radio modem. The GPS reference ground station consisted of a matching GPS receiver and radio modem. Differential corrections were determined and transmitted to the aircraft twice per second at 19,200 baud. The information from the onboard DGPS receiver was passed from a serial data port to a Bell-designed interface unit. This unit parsed the serial GPS data stream and formatted the values into data words, which were inserted into the aircraft's pulse-code modulated (PCM) data stream. This approach allowed the GPS measurements to be correlated in time with the remainder of the approximately 150 measured aircraft parameters. The PCM data stream, including the GPS parameters, was simultaneously recorded onboard the aircraft and transmitted to the ground telemetry station for real-time monitoring. The three 1000 watt metal halide lights were also deployed during the phase 2 and phase 3 tests to provide the pilots with visual ground cues of the desired flight track.

An advanced flight guidance system was used during the 1997 and 1999 flight tests. The XV-15 was fitted with a Silicon Graphics, Inc. computer that calculated the flight director guidance parameters required to perform complex, multi-segmented, decelerating approaches with the required precision.[23] The flight director computer utilized guidance control laws developed in NASA/Bell simulations specifically for tiltrotor operations.[24] The computer received DGPS information and other aircraft state parameters by means of an Ethernet communications link with the interface unit. The XV-15 copilot's instrument panel was modified with the installation of a color liquid crystal display (LCD). The display, shown in figure 3, provided essential information for piloting the aircraft, and also provided the information needed for flight director guidance. The flight director provided guidance commands for the desired aircraft configuration, as well as for the desired flight path and velocity profile. Commands were given for the operation of flaps, landing gear, and nacelle conversion angle. Conventional command bars were used for flight path guidance and raw data for horizontal and vertical position errors were also provided. Ground speed errors were displayed, and power lever commands were given for airspeed and descent rate control. The nacelle conversion angle and flaps can be used very effectively to reduce pilot workload and control fuselage attitude while flying very precise approach paths.

Figure 3. Flight director cockpit display used during the phase 2 and phase 3 tests.

Meteorological Instrumentation

Two data systems were used to acquire weather information, a tethered weather balloon system and a weather profiler system. The tethered weather balloon system consisted of an electric winch-controlled, tethered, helium-filled balloon, an instrument/telemetry pod, a ground-based receiver/data-controller, and a ground-based support computer. Profiles of temperature, relative humidity, wind speed, and wind direction were acquired up to 1000-ft altitude before, during, and after each test flight. An example of the weather data profiles for a typical test period is presented in figure 4. The weather profiler system consisted of a 10-meter tower with ten temperature sensors, five anemometers, and three wind direction sensors. The weather profiler was used to obtain detailed weather information near the ground. Weather data from both systems were acquired at a rate of at least 6 points per minute, displayed in real time, and recorded, along with time code, on magnetic disk.

Acoustic Instrumentation

Several different microphone array configurations and two different data acquisition systems were used to acquire acoustic data during this flight test program. NASA Langley's Digital Acoustic Measurement System (DAMS) was used to deploy a maximum of 30 microphones. With this system the microphone signals are digitized at the microphone (20 kHz sample rate in phase 1 and phase 2, 24 kHz sample rate in phase 3), transmitted via cables to a data van, multiplexed with time and run information, and then recorded on magnetic media.[25] A maximum of three Langley acoustic data vans were deployed, and each data van handled 10 microphone systems. During most of this flight test program, seven additional microphone systems were deployed by BHTI, using a Sony PC208Ax 8-channel DAT recorder. The eighth channel was used to record a time code signal. With this system the analog microphone signals were transmitted via cables to the DAT recorder where they are digitized (24 kHz sample rate) and recorded on 4-mm tape.

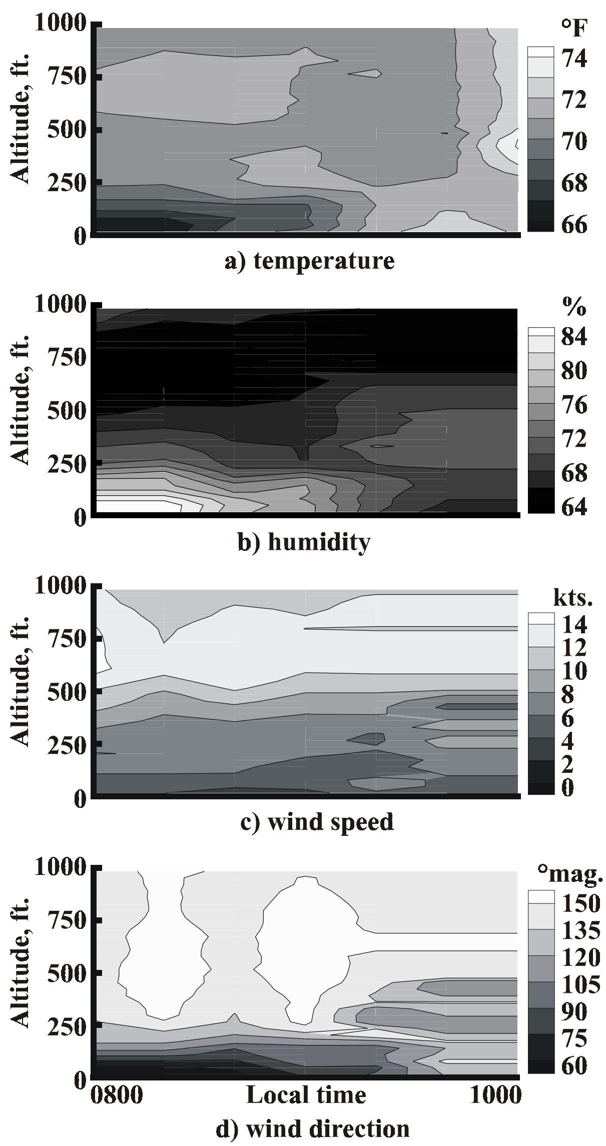


Figure 4. Weather profiles for a typical test period.

A linear microphone array was primarily used to acquire acoustic data during phase 1 testing. This array, deployed using Langley's DAMS, consisted of 17 ground board mounted microphones placed along a line perpendicular to the aircraft flight track as shown in figure 5. The unequal spacing of the microphones was designed to provide a 10° angular resolution to both sidelines when the aircraft passed over the reference microphone at an altitude of 394 feet. This microphone array design is useful for measuring the lower hemispherical acoustic characteristics of the test vehicle performing steady state flight operations (constant airspeed, constant glideslope, fixed nacelle angle)[9] and to provide data for code validations.

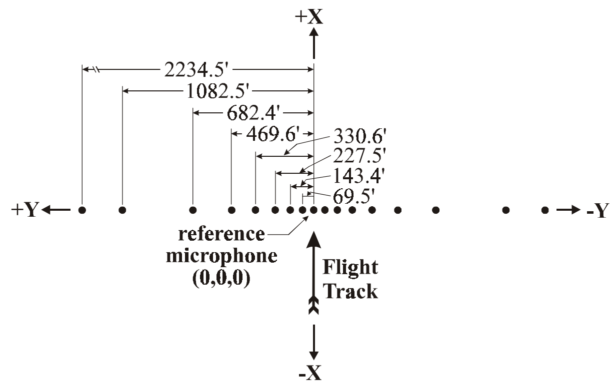


Figure 5. Linear microphone array used during the phase 1 test.

A large area microphone array was deployed to acquire acoustic data during the phase 2 test. The array consisted of 30 NASA operated, and 7 BHTI operated ground board mounted microphones arranged over a 2000-foot by almost 9000-foot area as shown in figure 6. The center of the hover pad, shown as a black-filled circle, was the origin of the coordinate system used during the test (X = Y = 0). The desired flight track passed directly overhead of the line of microphones located at Y = 0, with the aircraft approaching from the -X direction towards the +X direction. The typical run terminated in an IGE hover over the hover pad. Taking advantage of the symmetry of the acoustic radiation pattern about the XV-15's longitudinal axis,[19] the microphone array was designed to measure the noise directly beneath the vehicle and off to the port side only. For the noise data presented in this paper, the representation of noise to the starboard side is the mirror image of the acoustic data measured off the port side of the vehicle. The large area microphone array is useful for measuring actual ground footprints for any type of tiltrotor flight operations, and is particularly useful for quantification of the acoustic characteristics of a tiltrotor performing highly complex, non-steady state approaches. The shape of this array was designed to capture the roughly teardrop shape of the anticipated noise contours for a tiltrotor performing approaches to the hover pad. The array is widest where the noise levels were anticipated to be the greatest, and the width is reduced with increasing distance from the hover pad.

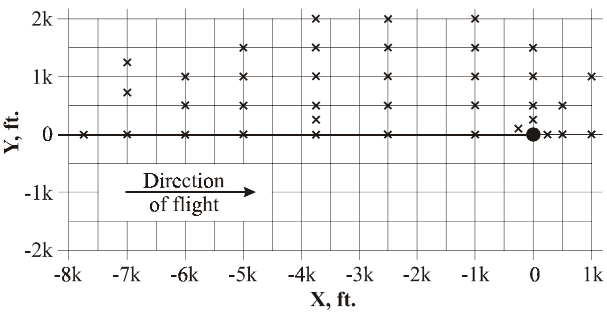


Figure 6. Large area microphone array used during the phase 2 test.

A large area microphone array was again deployed to acquire acoustic data during the phase 3 test. The array again consisted of 30 NASA operated, and 7 BHTI operated ground board mounted microphones, but this time arranged over a 2000-foot by 8000-foot area as shown in figure 7. During this test it was decided that a more thorough study of the noise reductions provided by the noise abatement approaches at the farther up-range distances would be desirable since this is the area where the most significant noise differences occur. To accomplish this with the same number of microphones as were available for the phase 2 test, no microphones were placed near the landing point, as this is the area of least significant noise reductions. Six microphones were located 9000 feet up-range of the landing point, between the centerline and 2000 feet to the sideline, compared to one centerline microphone located 7800 feet up-range during phase 2. In addition, to avoid excessive lost test time due to unfavorable wind directions, as was the case during the phase 2 test, this array was designed to allow for two different approach headings that were 180° apart. The two landing points are shown as large black circles located at 0,0 and –10000,0. To provide noise footprints of the same dimensions independent of the approach direction, the array was symmetric about a line at X = -5000 feet. This provided a much greater test window with regards to acceptable wind conditions, defined as predominantly head winds. Testing was terminated if cross winds exceeded 10 knots at any altitude up to 1000 feet. The desired flight track passed directly over the line of microphones located at Y = 0. Again, taking advantage of the symmetry of the acoustic radiation pattern about the XV-15's longitudinal axis,[19] the microphone array was designed to measure the noise directly beneath and off to one side of the vehicle only. For the noise data presented in this paper, the noise measured to the one side of the aircraft is mirrored to represent the noise on the opposite side of the vehicle.

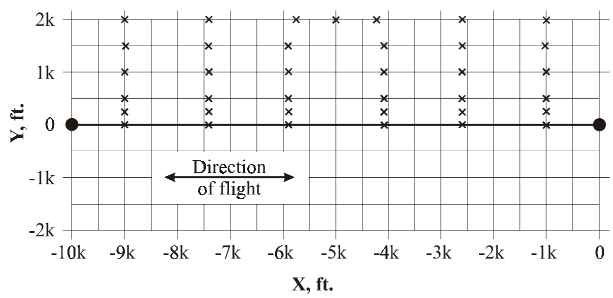


Figure 7. Large area microphone array used during the phase 3 test.

On-Site Acoustic Data Processing

At the conclusion of testing each day, the magnetic media containing the digitized acoustic signals from Langley's DAMS were read into DEC Alpha workstations for signal processing. Likewise, 4-mm tapes containing the digitized acoustic signals from the Sony DAT recorder were read into an IBM compatible PC running the LINUX operating system. Start and stop times were selected at the endpoints in time where all data systems (acoustic, aircraft tracking and state, and weather) were simultaneously acquiring data.

During the phase 1 test, the digital acoustic time domain data were transformed to the frequency domain using 8192-point FFTs with a Hamming window, corresponding to 0.4096-second blocks of data. The average narrowband spectra were integrated to obtain one-third-octave spectra, which were then integrated to obtain Overall Sound Pressure Levels (OASPL). In addition, an A-weighting was applied to each one-third-octave spectrum before integration to provide A-weighted Overall Sound Pressure Levels (L_A). By relating the time-dependent OASPL and L_A acoustic measurements to the corresponding aircraft position data, effective contours of OASPL and L_A were computed using the technique described in Reference 9. The technique for performing this computation is depicted graphically in figure 8. In figure 8a, the aircraft flies at a constant operating condition over a linear microphone array that is perpendicular to the flight track. Each data block is related to the aircraft position as shown in figure 8b, which provides noise levels as a function of observer and sideline emission angles. By freezing the aircraft at a point in space, these noise directivity data can be projected onto a ground plane, as shown in figure 8c, producing a detailed, high-resolution effective noise contour. While the example presents a level flight condition, the same technique can also be used for ascending or descending flight conditions; however, the data as measured project onto a plane that is slanted at the same angle as the flight path. The noise directivity data can also be projected onto a hemisphere, as shown in figure 8d, which provides the data in a format required for input to RNM. It should be emphasized that this approach is useful only when the aircraft is operated in a steady-state condition throughout the flyover. In addition to time histories and effective contours, Sound Exposure levels (SEL) were calculated and plotted as a function of sideline position to help facilitate comparisons of the different test conditions.

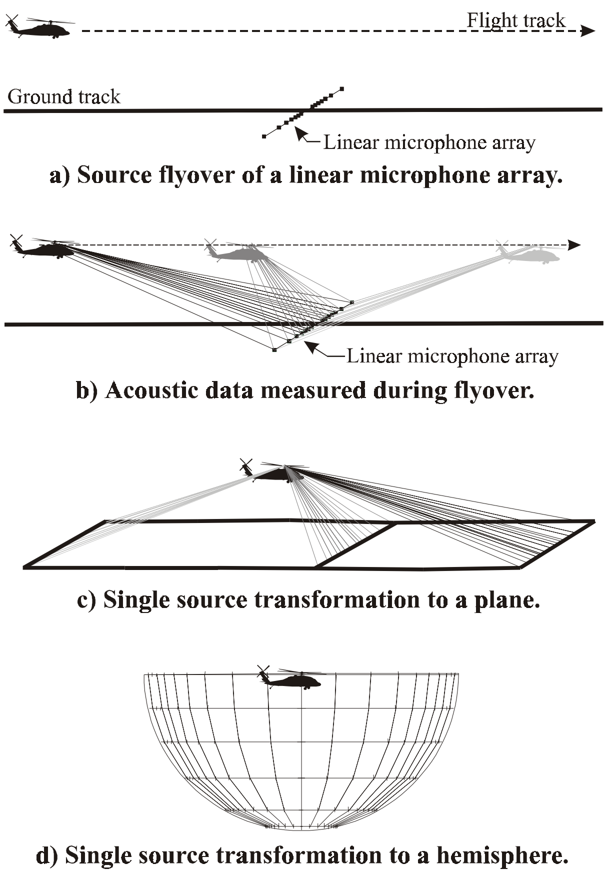


Figure 8. Single source effective surface contour calculation.

During the phase 2 and phase 3 tests, the digital acoustic time domain data were transformed to the frequency domain using the average of five 4096-point FFTs with a Hamming window and 50% overlap applied. This resulted in 0.6144-second blocks of data for the phase 2 DAMS data and 0.5120 second blocks of data for the phase 3 DAMS data and the DAT data. These averaged narrowband spectra were computed beginning every 0.5 seconds for the duration of each run. The average narrowband spectra were then integrated to obtain one-third-octave spectra, and for the DAT data only, corrections were applied to account for analog signal line losses. Line loss corrections were not required for the DAMS data since the microphone signals were digitized at the microphone. The corrected one-third-octave band spectra were then integrated to obtain Overall Sound Pressure Levels (OASPL). In addition, an A-weighting was applied to each one-third-octave spectrum before integration to provide A-weighted Overall Sound Pressure Levels (L_A). These L_A results were then integrated over the time period corresponding to the 10 dB down point from the maximum level for computation of Sound Exposure Level (SEL). Data plots were generally available the day following acquisition.

Flight Procedures

During these tests, real-time communications were established between project control, each acoustic site, and the meteorological test site. Real-time communications were established on a different channel between project control and the XV-15 aircraft. Each time the XV-15 arrived at the test site, a level flight pass was made at 60° nacelle angle and 90 knots airspeed, and a target altitude of 394 feet above ground level (AGL). These "housekeeping" passes were conducted to check the day-to-day consistency of the measurements, and as a quick check to verify the proper operation of all systems.

The aircraft flew steady-state level flyover, takeoff, and approach profiles during the phase 1 test. All profiles were designed such that the aircraft passed over the reference microphone at an altitude of 394 feet. For the level flyover and takeoff profiles, data acquisition began and ended when the aircraft was approximately one mile from the linear microphone array. For the takeoff profiles, the aircraft approached the microphone array at 100 feet altitude at the velocity for best-rate-of-climb, V_y, and pulled up into a best-rate-of-climb ascent at an up-range distance that would put the aircraft at about 394 feet altitude when it passed over the microphone array. The run was terminated when the aircraft was about one mile down-range. For the approach profiles, the aircraft approached in level flight at an altitude that allowed the selected glideslope (3°, 6°, 9°, or 12°) to be intercepted at a point about three miles up-range. Data acquisition began when the aircraft was about 2½ miles up-range, which allowed sufficient time for the pilot to obtain steady-state conditions on the prescribed glide slope. The approach continued, passing over the microphone array at about 394 feet altitude, until the aircraft was at an altitude of

100 feet or less, at which time the pilot radioed "prime data off" just prior to pulling the aircraft out of the steady-state descent condition.

During phase 2 testing, each approach began approximately 5 miles up-range of the microphone array, at an altitude of 1500 to 2000 feet AGL. At approximately 3 miles up-range, the desired flight procedure was initiated, and the test director radioed "prime data on." The XV-15 continued along the flight track passing over the microphone array and decelerating to an IGE hover over the center of the hover pad. At this point the test director radioed "prime data off" and data acquisition was discontinued. The XV-15 then climbed out and set up for the next data pass. In addition to the housekeeping pass, approximately 6 approaches were conducted during a single data flight before refueling of the aircraft was required.

Phase 3 approaches were conducted nearly identically to the phase 2 approaches with the exception that they did not terminate with the aircraft in an IGE hover over the hover point. Instead, the pilot held the prescribed approach conditions until the aircraft had flared and slowed to about 20 knots airspeed at an up-range distance of no more than a couple of hundred feet and an altitude of 50 to 100 feet. The pilot then radioed "prime data off", and immediately performed a climb out to set up for the next data run. It was determined that an IGE hover was not required since the closest microphone was located 1000 feet up-range of the landing point. This procedure, which required slightly less flight time, combined with a small increase in the XV-15 fuel capacity, permitted 7 approaches per flight in addition to the housekeeping pass.

Since information on handling qualities for each of the phase 2 and phase 3 approach procedures was desired, the pilot was requested to make comments after each approach. An onboard video recorder had been installed to record the flight director screen during each pass. Pilot comments were recorded on the audio track of this recorder and then transcribed for future reference.

Approach Profile Design Philosophy

Designing approach profiles that are quiet, safe, easy to fly, and repeatable requires interdisciplinary cooperation between acousticians, handling qualities experts, and pilots. Constraints are imposed by the capabilities of the specific aircraft and its control systems. For this test program, the initial candidate low-noise profiles were developed primarily using acoustic considerations, tempered with some minimal constraints concerning maximum deceleration and descent rates, along with nacelle angle conversion times. Slightly different techniques were used to design the approaches for phase 2 and phase 3, however. In both cases, the authors used measured results from the phase 1 test[19] as input into the Rotorcraft Noise Model (RNM)[21]. Although it was not yet complete when planning for phase 2 began, RNM still provided a tool to assess the resulting noise produced when combining several different flight procedures into a candidate approach profile. Noise footprints produced by using different combinations of airspeed, nacelle angle, and glideslope were examined and compared with a baseline 6° glideslope, 70-knot, 85° nacelle angle approach.

In phase 2, a set of 10 initial candidate profiles were developed using a somewhat ad hoc approach based on examination of the phase 1 results. These initial profiles were then modified to reflect prior simulator experience with tiltrotor instrument approach procedures, as well as attempting to provide acceptable handling qualities. Approach profile design priorities were: First, to maximize the maneuvering portion of the approach over the 8000 feet of microphone array. Second, to aim for low noise flight conditions identified in the Phase 1 test. Finally, the resulting profiles were adjusted in an attempt to provide acceptable handling qualities (priority to tracking performance) for the rate-stabilized XV-15. Examples of modifications made to the approach profiles include: specifying the time required to change the glideslope (rate of flight path angle change of 0.5 degrees/second), modeling the natural braking effect produced when the nacelle angle is increased as part of selecting the deceleration rates (0.063 g deceleration matched average decelerations with nacelle moves for the XV-15), and including a 5-second buffer after a glideslope change or nacelle movement to provide time for the pilot to stabilize on the new flight condition and to prepare for the next change command. Four additional profiles were developed based on previous flight simulations done in the Vertical Motion Simulator (VMS) at NASA Ames. These procedures had acceptable handling qualities, but their noise impact was unknown. All of the profiles discussed here were designed for "zero wind" conditions. During phase 2 testing, which was limited to a single approach direction, the test site experienced significant prevailing winds that forced the XV-15 to operate with a tail wind in excess of ten knots most days, since the microphone array and the landing pad were fixed on the ground. In an attempt to accommodate these weather conditions, some of the approach profiles were modified with increased commanded (inertial) ground speed.

To design the approach profiles for the phase 3 test, a similar technique was used as in phase 2, and the results of that testing were incorporated as well. However, a more systematic procedure was followed this time, based on the experience gained during phase 2. First, several of the quieter approaches from phase 2 that also had fairly acceptable handling qualities were included with very little modification. However, in an attempt to identify alternative low noise approach profiles, RNM was coupled with iSIGHT[26], a commercially available optimizer. Since it was not practical to optimize based on contour information, the optimization was performed based on the noise predicted by RNM at three microphone locations directly below the flight path, at 2000, 4000, and 6000 feet upstream of the landing point. Constraints were used to prevent the optimizer from selecting flight conditions that were outside the XV-15 flight envelope, and to ensure that the approach ended in an aircraft state viable for landing. The optimized approach profiles were then slightly adapted using the lessons learned from the phase 2 testing to try to produce acceptable handling qualities, and then input to RNM to produce a predicted noise footprint for each candidate approach. All profiles were then tested using a real-time simulation model on a development workstation while several were also tested in the VMS to refine handling qualities profile design constraints. Smoothed guidance inputs for all candidate phase 3 profiles were developed on the real-time simulation workstation associated with the VMS. The potential for use of the XV-15's full flap position, rarely used due to its higher hover download, was noted during this development. The 75° flap position provided a more desirable body pitch attitude while increasing the rotor-engine power requirement to a more controllable state during steep descents. The profiles were then implemented for the test aircraft guidance system, then checked and evaluated in the XV-15 simulator at Bell. Based on feedback from the pilots, these approach profiles were further modified before the beginning of the phase 3 testing. Once testing began, all of the approaches were then evaluated in the aircraft itself, and further refinements were made if necessary. Once the approach profiles were finalized, multiple repeats of each one were made over the microphone array. Since the array used in the phase 3 testing could accommodate two flight directions, 180° apart, no adaptation for tailwinds was required during this testing.

Results and Analysis

Data Repeatability

As an example of the repeatability of the data acquired during this test program, sound exposure levels for the most densely populated line of microphones during the phase 2 test, located 3750 feet up-range, are presented as a function of the sideline distance for all the housekeeping runs and for all the 6° approaches in figures 9a and 9b, respectively. The figures show that, as one would expect, the maximum sound exposure levels were measured on the flight path centerline and the levels decrease rapidly with increasing sideline distance. For the housekeeping runs of figure 9a, the SEL variation for the centerline microphone and all microphones up to 1000 feet to the sideline are approximately ±0.6 dB or less. The largest SEL variations are approximately ±1.6 dB for the microphones located 1500 and 2000 feet to the sideline. Figure 9b shows that the SEL variations for the 6° approaches was approximately ±2.25 dB or less for all microphones except the farthest out microphone located 2000 feet to the sideline, which had a slightly greater variation of ± 2.75 dB. These variations are consistent with what was measured during the phase 1 and phase 3 tests.

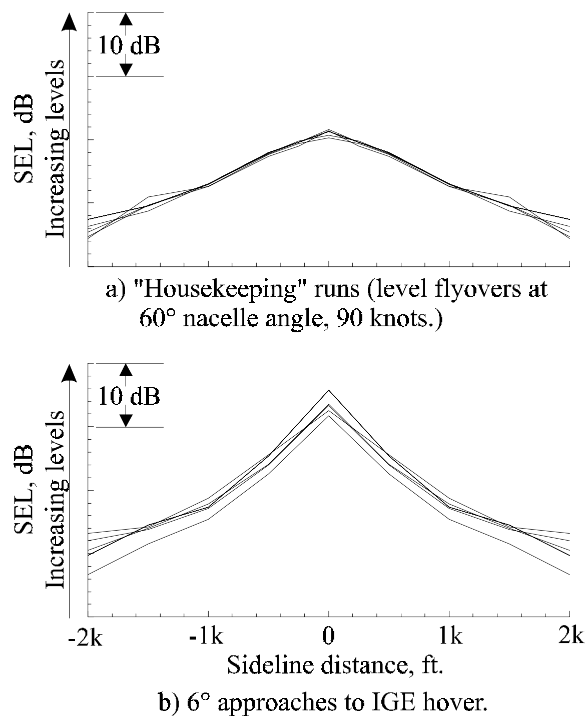


Figure 9. Sound exposure levels for multiple runs at the same flight condition, as measured 3750 feet up-range of the landing point during the phase 2 test.

Phase 1 Results

The types of analyses that were used to judge the relative noise levels of all the steady-state approaches flown during phase 1 testing are presented below. In addition, lower hemispherical noise contours were developed for all phase 1 approaches and level flyovers, and used as input to RNM. When there were multiple runs of the same flight condition, the data were averaged over those runs to provide a single average noise hemisphere. A total of 76 hemispheres were generated, including 3°, 6°. 9° and 12° approaches for a range of airspeeds and nacelle angles.

Figure 10 presents the SEL as a function of the sideline distance for 9°, 70 knot, steady-state approaches at nacelle angles of 60°, 70°, 80°, 85°, and 90°. In general, the SEL increases with increasing nacelle angle. The greatest variation occurs directly under the flight track, where the difference between the minimum and maximum level is 10 dB. The variation decreases with increasing sideline distance and is less than 2 dB at 2200 feet to either side of the flight track. The variation in SEL is somewhat greater to the port side of the aircraft (positive sideline direction) than to the starboard side. This is due to differences in the actual flight tracks from the desired flight track of Y=0. The flight tracks for the 60° and 70° nacelle angle approaches were -49 feet and -100 feet to the sideline when the aircraft passed over the microphone array, while the other approaches were -2, 7, and 17 feet to the sideline. Hence, if these differences in track were taken into account the noise directivity to the port and starboard sides would be symmetrical.

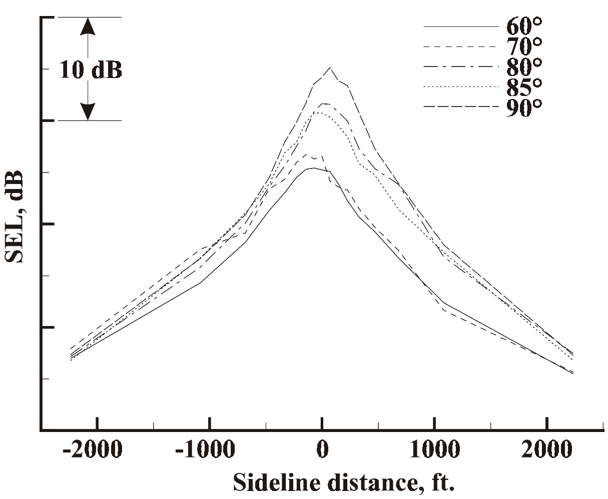


Figure 10. Variation of SEL with nacelle angle for constant conditions of 70 knots airspeed, 9°, approach angle, as measured in the phase 1 test.

Figure 11 presents A-weighted OASPL noise contours for the 60° and 90° nacelle angle approaches presented in figure 10. These contours were developed using the technique described in the discussion of figure 8. The contours represent the noise radiated from the XV-15 to a ground plane that is tilted at the 9° approach angle and moving with the aircraft, which is located 394 feet above the point marked with a + at (0,0). The contours extend over different ranges of X due to differences in the aircraft distance from the microphone array when data acquisition began and ended. The 60° nacelle angle approach (figure 11b) shows that the area contained within any given contour level has been reduced significantly compared to the 90° nacelle angle approach (figure 11a), and the maximum contour level has been reduced by 5 dBA. Figures 10 and 11 illustrate the significant noise abatement potential offered by the unique tiltrotor capability of nacelle tilt during approach operations. However, the amount of noise reduction appears to decrease with increasing sideline distance, as is the case for helicopters using noise abatement procedures.[27]

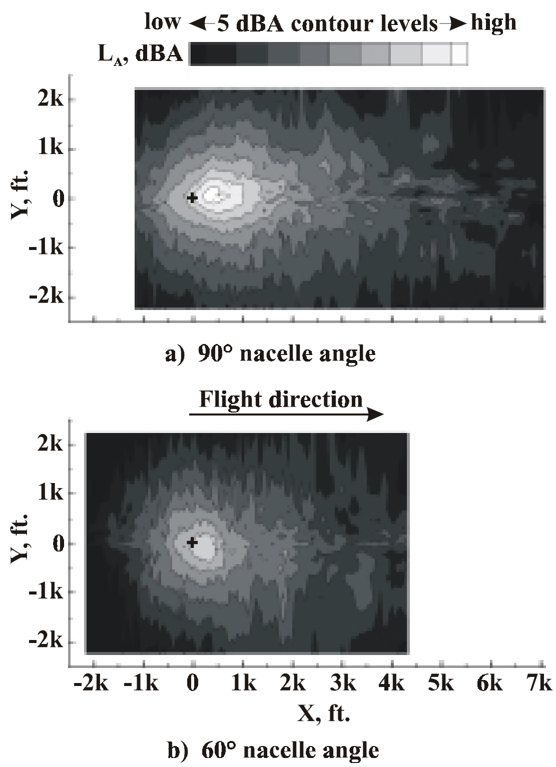


Figure 11. L_A contours for 70 knot, 9° approaches, as measured in the phase 1 test.

Phase 2 Results

During the phase 2 flight test, noise footprints were measured for candidate low noise approaches. The measured noise footprints extended from 1000 feet down-range to 8000 feet up-range, and up to 2000 feet to the sideline of the landing point. These initial candidate low-noise profiles were developed primarily using acoustic considerations, but tempered with handling qualities concerns under IFR conditions. A total of nineteen different approach profiles were flown, in addition to the baseline 6° approach. Four approaches were selected for presentation in this paper. The first was a standard 6° approach that was derived from the phase 1 test. This approach was determined to be a very comfortable (workload) approach by the pilots, with excellent handling qualities, and is also very close to a typical FAA noise certification type approach for conventional helicopters. For these reasons, the 6° approach was selected to be the "baseline" approach against which all other approach profiles would be compared. In addition to the 6° approach results, results from a 3° and a 9° approach, and a 3° to 9° segmented approach are presented. The approach conditions will first be described in detail, followed by a discussion of the noise footprint characteristics and comparisons with the 6° approach profile.

Approach Profiles

The primary approach profile parameters for the four selected approaches are shown in figures 12a through 12d. Each part of the figure presents the altitude, airspeed, and nacelle angle as a function of the up-range distance for a single approach. The initial glideslope was intercepted at a distance of 18,000 feet up-range of the landing point for all approaches. A dash-dot line indicates the intended or desired flight path. It should be noted that while the approach profiles were designed using airspeed, they were flown using ground speed. Prevailing tailwinds of approximately 10 to 15 knots persisted during much of this test, resulting in lower airspeeds than the profiles were designed for. All the phase 2 profiles presented in this paper were flown with tailwinds of about 10 knots.

For the 6° approach profile (figure 12a), the aircraft intercepted the 6° glideslope at an altitude of about 1900 feet with approximately 60 knots airspeed and a nacelle angle of 85°. This approach was designed for a 70-knot airspeed; however, 10-knot tailwinds resulted in an airspeed of about 60 knots. The 85° nacelle angle, 60 knots condition was maintained until the aircraft was approximately 3300 feet up-range, where the nacelles were rotated to 90° and a deceleration to 40 knots was begun. At about 1800 feet up-range the aircraft began decelerating to achieve an IGE hover at the landing point. As mentioned earlier, the pilot considered this to be a very comfortable approach.

For the 3° approach profile (figure 12b), the aircraft intercepted the 3° glideslope at an altitude of about 950 feet and followed a nacelle angle/airspeed schedule very different from that of the 6° approach. This approach began with a nacelle angle of 60° and airspeed of about 100 knots. This nacelle angle and airspeed were maintained until the aircraft was 7500 feet up-range, where the nacelles were rotated to 80° and a deceleration to 60 knots was initiated. At a distance of about 3300 feet up-range, the nacelles were rotated to 85° and a deceleration to 40 knots was initiated. Finally, the nacelles were rotated to 90° at the point about 1800 feet up-range and the final deceleration to an IGE hover at the landing point was initiated. The pilot described this approach as "controllable, adequate performance and tolerable workload." However, he also commented he would have preferred to convert to a 90° nacelle angle sooner and to be allowed to convert to 95° towards the end to decrease the nose up attitude to provide a better visual view of the landing point. Conversions to 95° were not allowed due to the IFR approach constraints and for possible safety considerations in the case of an engine out.

For the 9° approach profile (figure 12c), the aircraft intercepted the 9° glideslope at an altitude of about 2900 feet and followed the same nacelle angle/airspeed schedule as that of the 6° approach. The approach began with approximately 60 knots airspeed and a nacelle angle of 85°. At an up-range distance of about 3300 feet the nacelles were rotated to 90° and a deceleration to 40 knots was initiated. Deceleration to an IGE hover at the landing point was initiated about 1800 feet up-range. The pilot considered this to be a comfortable approach all the way in and commented "very controllable, achieved adequate performance, tolerable workload."

The 3° to 9° segmented approach, shown in figure 12d, followed a nacelle angle/airspeed schedule similar to that of the 3° approach. It had a glideslope intercept of the initial 3° glideslope at an altitude of about 1250 feet with approximately 80 knots airspeed and a nacelle angle of 60°. At a distance of about 4800 feet up-range the nacelles were rotated to 80° and a deceleration to about 60 knots was initiated. The guidance provided by the flight director system during this test did not include compensation for the aerodynamic coupling between nacelle rotation and rate of climb due to the rotation of the thrust vector. Just prior to interception of the 9° glideslope, at about 2700 feet up-range and an intended altitude of about 450 feet, the aircraft deviated above the intended glideslope path by more than 100 feet due to nacelle rotation. Compensation for nacelle rotation, integrated into the flight director system during a subsequent flight director development program that is documented in Reference 23, was available for the phase 3 test. At about 2100 feet up-range, the nacelles were rotated to 85° and a deceleration to 40 knots was begun. At about 1500 feet up-range the nacelles were rotated to 90° and the final deceleration to an IGE hover was initiated. The pilot found this approach unacceptable because "the profile keeps too high a nacelle angle for the airspeed. …don't like the (tail) buffeting vibrations on the descent."

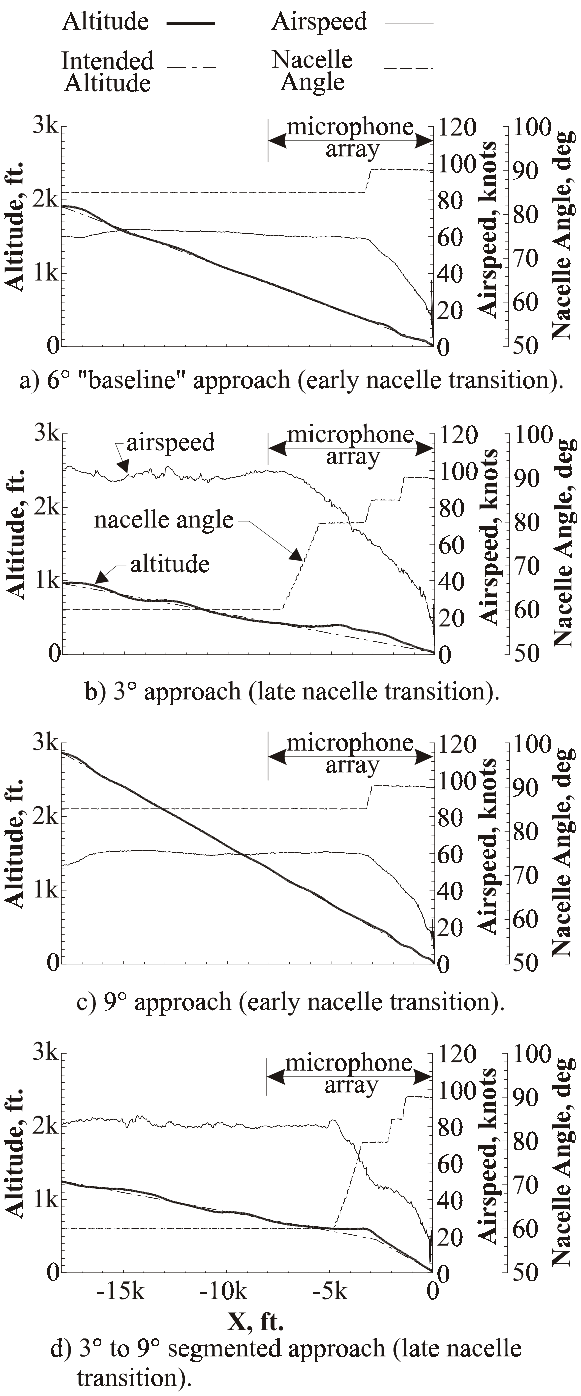


Figure 12. Altitude, airspeed and nacelle angle schedules as measured during the phase 2 test.

Ground Contours

Figure 13 shows the characteristics of the resulting noise footprints for the same four approaches presented in figure 12. The separation in the contour levels is 5 SELdB and the contour levels are labeled from A to G with A representing the lowest SEL, shown as black in the figure, and G representing the highest SEL, shown as white in the figure. The contour scales for all parts of the figure represent equal values to allow for direct comparisons. 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 X = Y = 0. The noise footprints are most useful to provide a qualitative assessment of the noise abatement potential of the different approach profiles. The contour data will be presented in other formats later in this section that will provide for an easier quantitative assessment.

The noise footprint for the 6° "baseline" approach is presented in figure 13a. The highest SEL contour is located along the flight path between approximately 200 and 500 feet up-range of the hover pad ($-500 \leq X \leq -200$) and extends about 150 feet to the sidelines. 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. In general, the maximum levels are located about the hover point and decrease rapidly with increasing sideline distance and with increasing down-range distance. The contours decrease least rapidly along the flight path up-range of the hover point, i.e. the area the aircraft actually flies over. More specifically, the F contour level extends from about X = 0 to X = -1000 and about 250 feet to both sidelines with a narrow "tail" that extends to about 1700 feet up-range. Each successively lower SEL contour is a little larger, extending a little further in front of and to the sides of the hover pad. Up-range along the flight path the contour "tails" increase in both length and width with decreasing contour level. For the contour levels of D and below, the contour "tails" extend up-range beyond the area of the measured noise footprint.

Figure 13b shows the noise footprint for the 3° approach. Compared to the 6° approach, the contour levels generally fall off more rapidly with increasing distance from the landing point. While the E contour level extends about 500 feet further up-range, the D contour level has been shortened significantly and is contained within the boundaries of the measurement area. For the SEL contour levels below E, the decreased sideline width far up-range indicates that the up-range lengths of these contours have also been significantly decreased. This 3° approach appears to be somewhat less noisy compared to the 6° approach and in fact the average SEL for all microphones has been reduced by 3.3 dB.

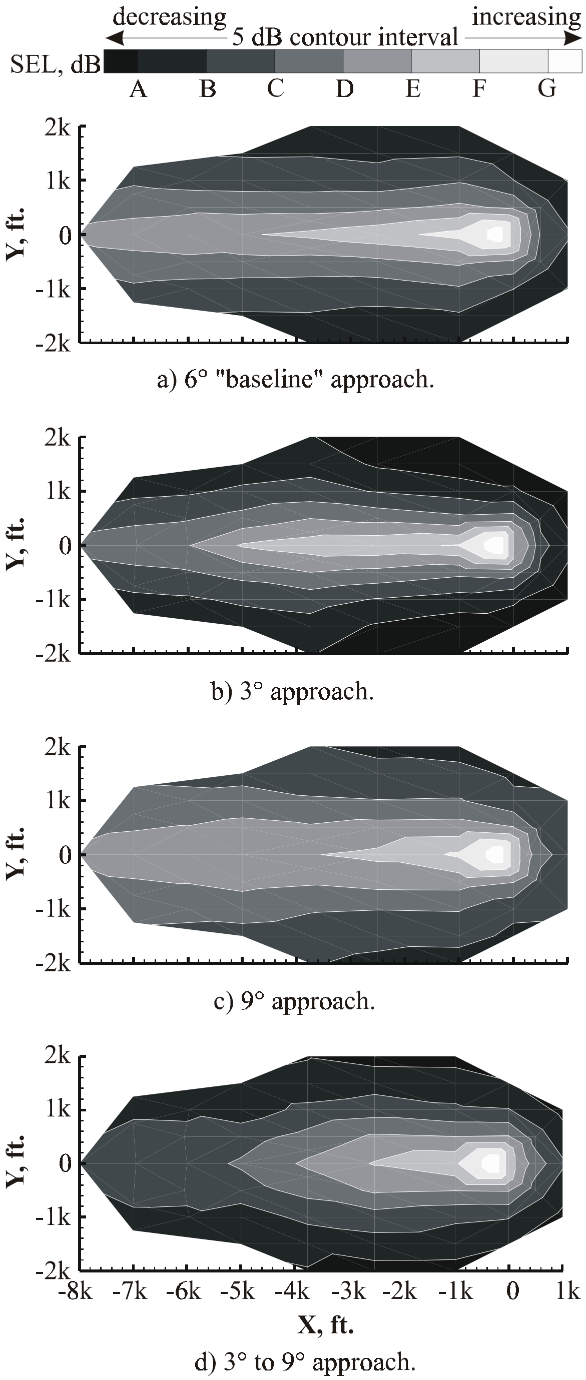


Figure 13. SEL ground contours as measured during the phase 2 test.

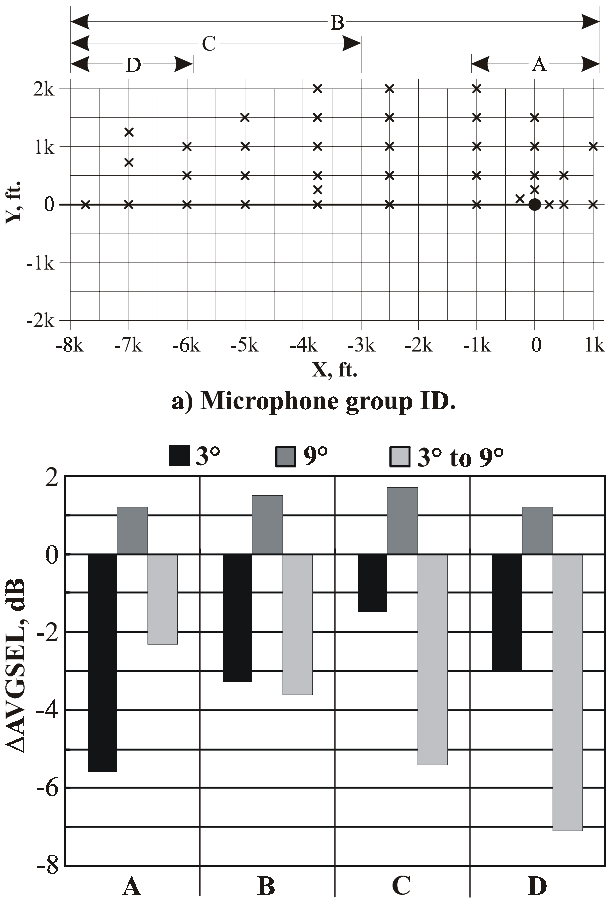
The noise footprint for the 9° approach is presented in figure 13c. Compared to the 6° approach, the contour levels generally fall off less rapidly with increasing distance from the landing point. For this approach, the E and F contour levels are a little smaller while all the contour levels below E are somewhat larger. This 9° approach appears somewhat louder than the 6° approach even though the aircraft was at a higher altitude and thus a greater distance from the microphones. The average SEL for all microphones has increased by 1.5 dB compared to the 6° approach.

The approach footprint for the 3° to 9° segmented approach is presented in figure 13d. All SEL contour levels for this approach are smaller when compared to those for the 6° approach. In fact, the contour levels of E and below are significantly smaller and contour levels C through G are all completely contained within the measurement area. This approach appears to be the quietest approach presented with a reduction in the average SEL of 3.6 dB.

Average Sound Exposure Levels

A more quantitative way to assess the SEL differences for the different approach profiles is to compare the average SEL (AVGSEL) for all microphones, or for a given subset of the microphones. Figure 14a and table 1 identify the different microphone groupings which were averaged and presented here. Figure 14b presents the difference between the average SEL for the 6° approach and the average SEL for each of the other approaches as a function of the microphone group. A negative ΔAVGSEL means that the average SEL has been reduced compared to the 6° baseline approach. This figure shows that the 9° approach had the highest levels for all microphone groups presented with an ΔAVGSEL of between 1 and 2 dB. The 3° approach is the quietest approach around the landing point (group A) with an ΔAVGSEL of about –5.5 dB. This may be because the lower rate of descent requires less of a flare at the end of the approach to achieve a hover condition. The 3° approach is a little more than 3 dBSEL quieter than the baseline approach for the average SEL using all the microphones (group B), while groups C and D show more modest noise reductions of about –1.5 and –3 dBSEL, respectively. The 3° to 9° approach shows the greatest noise reduction for all microphone groups except around the hover pad. The noise benefits for this approach increase as you move to the progressively up-range microphone sets. For group

D, the average SEL has been reduced by more than 7 dBSEL compared to the 6° baseline approach. This figure indicates that the 3° to 9° approach provides the greatest noise abatement for all areas of the measured footprint except near the landing point.



a) Microphone group ID.

b) SEL difference from 6° baseline approach.

Figure 14. Average SEL differences for selected microphone groupings, as measured during the phase 2 test.

Contour Areas

Another way to assess the noise abatement potential of the different approach profiles is to compare the ground contour areas exposed to a given noise level. Figure 15 presents the contour area, in percentage of the total measurement area, as a function of the relative SEL for the four different approaches. At the lowest levels, all the approaches converge to 100% of the measurement area, while at the highest levels all approaches eventually converge to 0% of the measurement area. For a given contour level, the largest differences in area between the different approaches are found at the lowest noise levels while the smallest differences are found at the highest noise levels. This figure clearly shows that the 9° approach had the largest contour areas for all but the highest levels. The 3° approach has the smallest areas at the lower levels while the 3° to 9° segmented approach has smallest areas at the higher levels. This figure also clearly demonstrates that the 3° approach and the 3° to 9° segmented approach are the quietest of the four runs considered here. Again, it should be noted that, although for convenience the approach procedures are denoted by calling out their glide slopes, the acoustic characteristics are strongly influenced by the nacelle angle/airspeed schedule as well as glideslope.

Table 1. Microphone grouping ID (phase 2 test).

Microphone group ID	Microphones used in average
A	All microphones between 1000 feet down-range and 1000 feet up-range of the landing point
B	All microphones
C	All microphones between 3000 and 8000 feet up-range of the landing point
D	All microphones between 6000 and 8000 feet up-range of the landing point

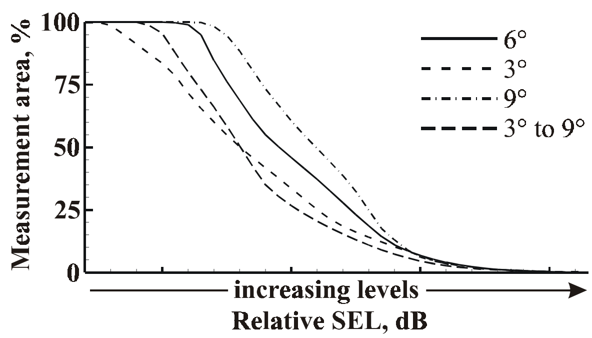


Figure 15. SEL ground contour areas as a percentage of the total measurement area, as measured during the phase 2 test.

Impact of the Flight Director and Handling Qualities on Noise Abatement Procedures

During phase 2 testing the profiles were flown as "Instrument Flight Rules" (IFR) approaches using the newly developed flight director. This allowed much more repeatable, precise profiles, but ones which were necessarily limited by the pilot's IFR workload. To allow enough time for the pilot to assimilate the flight director's visual cues and translate them into control inputs, an approximately 5 second time delay, or buffer, had to be allowed for after each pilot instruction. This buffer produced an elongated approach compared to "Visual Flight Rules" (VFR) approaches, thus limiting the terminal area noise-reduction potential. Improvements in control systems and future flight directors will allow the quieter low-nacelle flight operations to be brought nearer the terminal area. As higher levels of control augmentation and other improvements are incorporated, future pilot workload will be reduced, allowing precise, repeatable approaches to be made in a shorter time/distance interval. This will allow approaches that *tend* more toward the shorter VFR-type approaches. Within the next 10 years, civil tiltrotor operations will make use of the information derived from both VFR- and IFR-type acoustic testing to combine handling qualities and acoustic constraints in an automated, efficient flight director. This will allow the noise-reduction potential of the tiltrotor to be applied in precise, repeatable approaches to the public benefit.

Summary of Phase 2 Noise Abatement Approaches

All of the above results lead the authors to make the following assessments. The 3° approach and the 3° to 9° segmented approach were the quietest approaches tested during the phase 2 test. This is primarily due to the fact that these approaches maintained a lower 60° nacelle angle until about one mile from the landing point. The combination of nacelle angle, airspeed, and glideslope appear to orient the rotor tip-path-planes to a condition that avoids blade-vortex interactions (BVI). The 6° and 9° approaches began at a nacelle angle of 80° from nearly three miles out, thus putting the rotors into a flight condition more likely to generate BVI noise. The 3° approach was the quietest around the hover pad, probably due to the lower descent rate requiring less of a decelerating flare to achieve hover at the landing point. The 3° to 9° segmented approach was much quieter at the far up-range distances, probably because the aircraft was on the quieter 3° glideslope but about 300 feet higher in altitude than the 3° approach due to the steeper 9° segment towards the end of the approach. For the final portion of the approach, from about 2500 feet up-range to the landing point, the 3° to 9° segmented approach was quieter on and around the centerline of the flight path while the 3° approach was quieter to the sidelines. This was probably because the 3° to 9° approach had transitioned to the noisier condition of the 9° glideslope. Comparing the 3°, 6°, and 9° approaches, the 6° approach tended to be the loudest on centerline at all up-range distances measured; however, this difference was usually quite small. The noise levels to the sidelines at all up-range distances increased with increasing glideslope angle. Noise levels around the landing point also increased with increasing glideslope angle. Overall, the 9° approach was the loudest and the 3° approach was the quietest.

Phase 3 Results

The purpose of the phase 3 test was to quantify the noise reduction provided by optimized noise abatement approaches. The design process for the approach profiles that were tested used results from the phase 1 and phase 2 tests while fully coupling noise reduction with handling qualities. The flight director system was modified in an attempt to compensate for the aerodynamic coupling between nacelle rotation and rate of climb due to the rotation of the thrust vector. Noise footprints were measured for a rectangular grid that extended from 1000 feet to 9000 feet up-range and 2000 feet to the sideline of the landing point. A total of eight different approach profiles were flown, in addition to the 6° baseline approach. The 6° baseline approach profile tested in phase 3 was, for all practical purposes, identical to the one flown during the phase 2 test (figure 12a). Two low noise approaches profiles have been selected for presentation here, the 3° approach and a 3° to 9° segmented approach. Each of these approaches was flown six times during this test and the acoustic values presented are the average values over the six runs. These approach profiles were selected for presentation because the 3° profile provided significant and uniform noise reduction over the entire measurement area while the 3° to 9° profile provided the greatest noise reductions at the farther up-range areas. The approach conditions and the average noise footprints are presented, followed by comparisons to the 6° baseline approach.

Approach Profiles

Measured altitude, airspeed, and nacelle angle schedules for one run for each of the two selected approach profiles are shown in figure 16. While the approach profiles for the six runs used in the calculation of the average noise levels were nearly identical, slight variations did exist. Comparison of the six runs showed that altitude variations were generally less than ±25 feet, airspeed variations were generally less than ±3 knots, and variations of less than ±100 feet in the up-range distance at which nacelle angle changes were initiated. For the phase 3 approaches, the initial glideslope was intercepted at a distance of 18,000 feet up-range of the landing point. All phase 3 approaches were flown with a headwind component of between 5 and 15 knots.

The 3° approach profile characteristics are presented in figure 16a. The aircraft intercepted the 3° glideslope at an altitude of about 950 feet with a nacelle angle of 60° and airspeed of about 95 knots. This nacelle angle and airspeed were maintained until the aircraft was about 7000 feet up-range, where the nacelles were rotated to 75° and a nearly constant deceleration rate, sufficient to achieve a hover condition over the landing point, was initiated. The nacelles were rotated in 5° increments to 80, 85, and 90° at up-range distances of about 4600, 3200, and 1200 feet, respectively. The approach was terminated at an up-range distance of about 300 feet when the aircraft was at an altitude of about 50 feet and airspeed of about 25 knots.

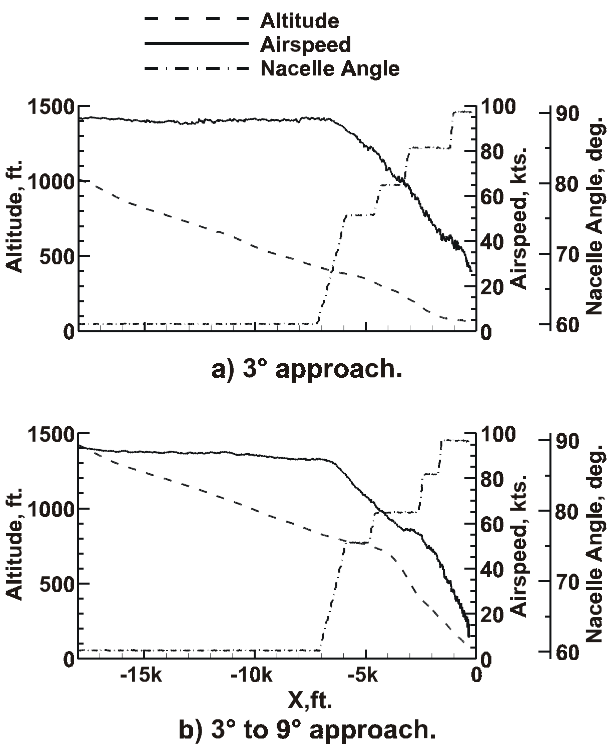


Figure 16. Altitude, airspeed, and nacelle angle schedules as measured during the phase 3 test.

The 3° to 9° segmented approach profile characteristics are presented in figure 16b. This approach had a glideslope intercept of the initial 3° glideslope at an altitude of about 1400 feet with an airspeed of 93 knots and a nacelle angle of 60°. At a distance of about 7000 feet up-range the nacelles were rotated to 75° and a deceleration to about 55 knots was initiated. The nacelles were then rotated to 80° at an up-range distance of about 5000 feet, followed by the 9° glideslope intercept at an up-range distance of about 4000 feet. At about 2500 feet up-range, the nacelles were rotated to 85° and the final deceleration to a hover condition was initiated. The final nacelle rotation to 90° was initiated at about 1800 feet up-range of the landing point. The approach was terminated at an up-range distance of about 300 feet when the aircraft was at an altitude of less than 100 feet and airspeed of about 10 knots.

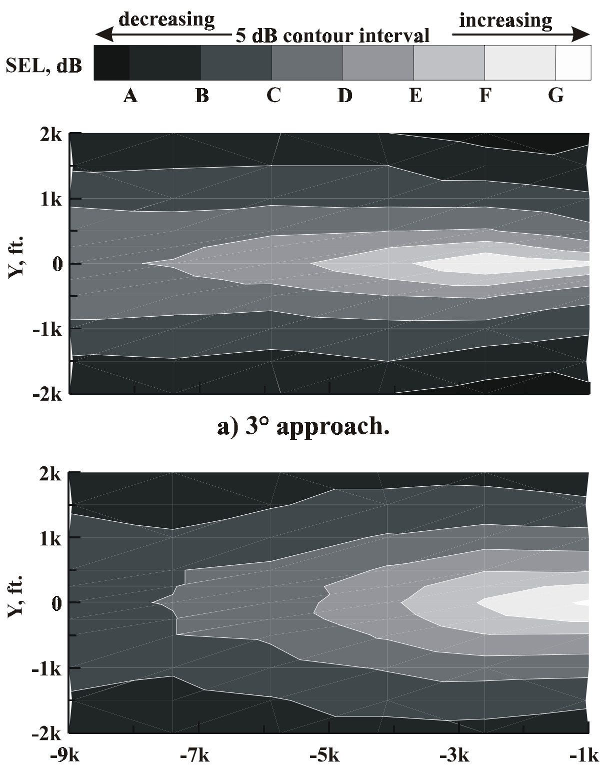
As is evident in figure 16, the nacelle angle/airspeed schedules are very similar for these two quiet approaches, each being significantly different from the 6° baseline approach shown earlier (figure 12a).

<u>Ground Contours</u>

Figure 17 shows the average noise footprints for the approach profiles presented in figure 16. The contour format is identical to that of the earlier contours (figure 13), though the shape of the contours is different due to the microphone array layout differences between the phase 2 and phase 3 tests. Figure 18 presents contours of the SEL difference from the average 6° baseline approach levels. Four runs were used in the calculation of the average SEL values for the 6° baseline approach. A negative contour level indicated a reduction in the noise level compared to the 6° baseline approach while a positive value indicates an increase in the noise level. Because noise measurements were made directly beneath and to one side of the aircraft flight path only, these noise footprints should be symmetric about Y = 0. However, these footprints are not exactly symmetric due to the linear interpolation scheme used by the plotting program. Each noise footprint in these two figures extend from 1000 feet to 9000 feet up-range of the landing point and span to 2000 feet to either side of the landing point, covering an area of 735 acres. The XV-15 approached from the left in the figure, along a line at Y = 0, and held the desired approach conditions until reaching a point approximately 300 feet up-range (X = -300 feet) of the landing point.

The noise footprint for the 3° approach is presented in figure 17a. The highest SEL contour (G) is located along the flight path between approximately 1000 and 3700 feet up-range of the landing point (-1000 ≤ X ≤ -3700) and extends about 200 feet to the sidelines at it's widest point which was located at the line of microphone 2600 feet up-range. This "hot spot" is just ahead of the aircraft location when a the nacelles were moved from 80° to 85° and is likely due to the occurrence of blade-vortex interactions at this airspeed/nacelle angle/descent rate combination. In general, the levels decrease rapidly with increasing sideline distance. The contour levels decrease least rapidly along the flight path. More specifically, the F contour level extends about one mile up-range with a maximum width of about 700 feet while the E contour extends nearly 8000 feet up-range with a maximum width of about 1100 feet. The D and C contour levels appear to extend well beyond the furthest up-range measurement location.

The noise footprint for the 3° to 9° segmented approach is presented in figure 17b. The maximum contour level (G) extends to 2600 feet up-range and the width of this contour increases with decreasing up-range distance. The F, E, and D contour levels extend to about 3800, 5200, and 7700 feet up-range, respectively, while the C contour level extends beyond the furthest up-range measurement location.

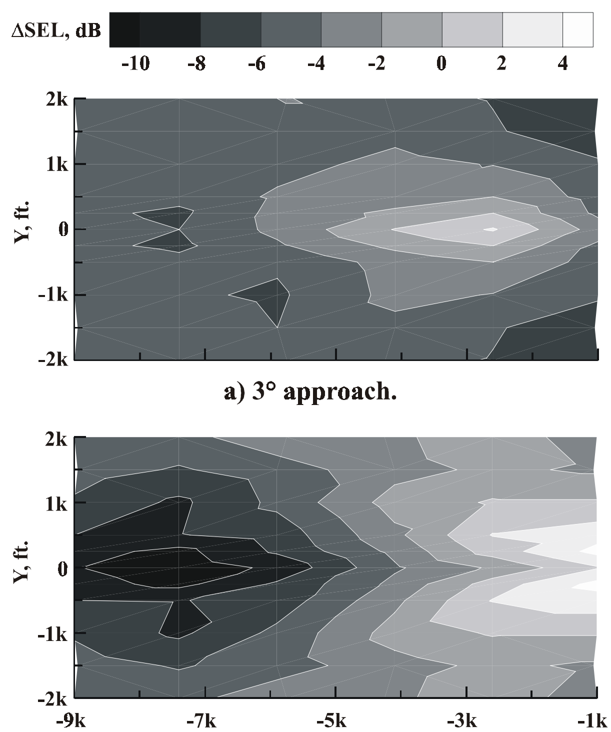


b) 3° to 9° approach.

Figure 17. SEL ground contours as measured during the phase 3 test.

Figure 18a shows an area along the flight path between about 1900 and 4200 feet up-range, with a maximum width of 500 feet, where the levels are as much as 2 SELdB higher than measured for the 6° baseline approach. A very small area directly beneath the flight path at 2600 feet up-range shows an increase of greater than 2 SELdB. Around this pocket of increased noise levels is an area where the levels have decreased by as much as 4 SELdB. The majority of the area contained in this footprint shows a noise reduction of between 4 and 6 SELdB with small pockets showing reductions of greater than 6 SELdB.

Figure 18b presents a footprint of the average SEL difference between the 3° to 9° segmented approach and the 6° baseline approach. The figure shows areas of increased noise levels between 1000 and 3500 feet up-range, centered along lines 500 feet to either side of the flight track centerline. The level of noise reduction increases with increasing up-range distance with the maximum noise reductions occurring along the flight path centerline. A maximum noise reduction of greater than 10 SELdB is shown along the flight path centerline between about 6300 and 8800 feet up-range.



b) 3° to 9° approach.

Figure 18. Contours of the difference from the 6° baseline approach SEL, as measured during the phase 3 test.

Average Sound Exposure Levels

A more quantitative assessment of the noise reductions is presented in figure 19. This figure presents the difference between the average SEL for the 6° approach and the average SEL for the two approach profiles of figure 16, for a number of different microphone groups, as labeled directly beneath the bar graph. A negative ΔAVGSEL means that the average SEL has been reduced compared to the 6° baseline approach. Compared to the 6° baseline approach, the

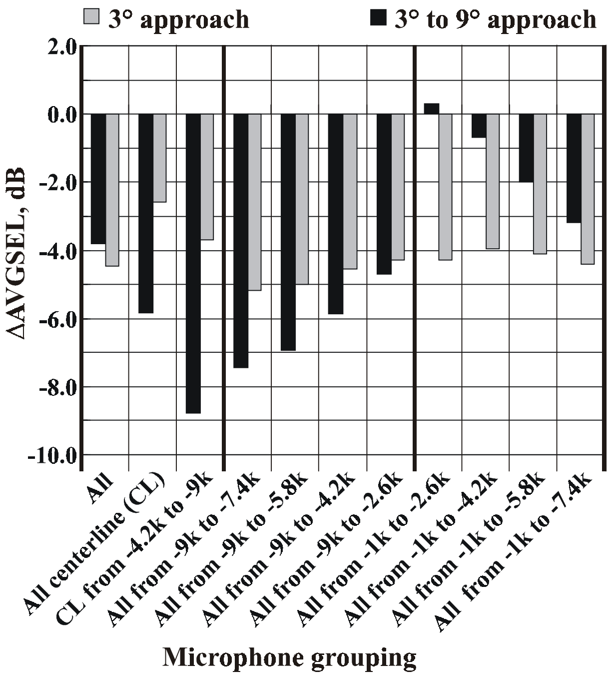


Figure 19. Average SEL difference from the 6° baseline approach for different microphone groups, as measured during the phase 3 test.

3° approach provides nearly 4.5 SELdB noise reduction and the 3° to 9° approach provides about 3.8 SELdB noise reduction when averaged over all the microphones used during this test (far left bars, labeled "All"). Moving from left to right in the figure, the next pair of bars show that the 3° to 9° approach provides the greatest noise reduction along the centerline, almost 6 SELdB, compared to about 2.5 SELdB for the 3° approach. Averaging the centerline microphones located between 4000 and 9000 feet up-range, the 3° to 9° approach provides nearly 9 SELdB noise reduction while the 3° approach provides only 3.7 SELdB noise reduction. The next four pairs of bars show the average noise reduction starting at the far end of the noise footprint (9000 feet up-range), progressively including areas closer to the landing point with each successive pair. The first pair averages the SEL from the microphones in the two farthest up-range lines of microphones, located 9000 and 7400 feet up-range. Each of the next three pairs progressively includes the next line of microphones closer to the landing point (5800, 4200, and 2600 feet up-range). This set shows the trend of decreasing noise reduction with increasing area when starting at the end of the noise footprint farthest from landing point. The 3° to 9° approach provides an average of 7.4 SELdB noise reduction when including the area from 7400 to 9000 feet up-range, and 4.7 SELdB noise reduction when including the area from 2600 to 9000 feet up-range. The 3° approach shows the same trend as the 3° to 9°approach over these same areas, but provides less noise reduction, decreasing from 5.2 SELdB to 4.3 SELdB noise reduction. The next set of four pairs of bars is similar to the previous set, except that it includes the areas starting closest to the landing point and progressive includes areas farther from the landing point, as indicated in the figure. The first pair, which includes the area from 1000 to 2600 feet up-range, shows that the 3° approach provided 4.2 SELdB noise reduction while the 3° to 9° approach had a slightly increased noise level. Noise reduction provided by the 3° to 9° approach increased with increasing up-range area with about 3.2 SELdB noise reduction over the area from 1000 to 7400 feet up-range. The 3° approach held a relatively constant noise reduction of about 4 SELdB over all the areas included in this set.

Use of Drag Flaps

Poor engine power response and high nose up pitch attitudes during the initial powered lift portion (60° nacelle angle) of steep, low-powered descents resulted in less than desirable handling qualities ratings. Increasing the flap position from the normal maximum setting of 40° to the vehicle limit of 75° would increase the nose down pitching moment and increase the aerodynamic drag. Increased drag requires increased thrust and hence, increased power to maintain the same airspeed, potentially moving the engine power into a better response region. In addition, the increased thrust in the x-direction will alter the rotor tip-path-plane and rotor wake geometry, thus altering the BVI noise characteristics.[28]

Almost all XV-15 testing, including the phase 1 and phase 2 acoustics tests discussed in this paper, has been done using a maximum flap setting of 40° because earlier testing revealed increased hover downloads with the 75° flap position. One approach profile, identified during profile development and confirmed early in the phase 3 test, was selected for testing at the 75° flap setting. This was the first time in many years the XV-15 had been flown at this flap setting. Pilot comments during the flight immediately confirmed the desirability of full flap use. At 90 knots and 60° nacelle angle, the body attitude was reduced from an uncomfortable 8° with 40° flaps to an acceptable 3° with 75° flaps. The post-flight debrief revealed several additional benefits. Tail buffet was reduced from 'moderate' to 'minimal'. Further, sloppy lateral control that occurred with the high body pitch attitude and low power setting was immediately tightened up, resulting in greatly reduced pilot attention to this control function, thus reducing pilot workload throughout the required operation. In addition, the 75° flap setting provided an average noise reduction of approximately 1 SELdB compared to the 40° flap setting. After this point all phase 3 approach profiles, with the exception of the 3° and the 6° baseline approach profiles, were flown using the 75° flap position.

Summary of Phase 3 Noise Abatement Approaches

The purpose of the phase 3 test was to quantify the noise reduction potential, compared to the 6° baseline approach, of optimized noise abatement approach profiles that fully coupled noise reduction with handling qualities concerns. Eight different noise abatement approach profiles, in addition to the 6° baseline approach profile, were flown repeatedly to obtain statistical confidence in the results. The 3° approach profile and a 3° to 9° approach profile were selected for presentation in this paper. The 75° flap setting was found to greatly improve the handling quality characteristics of the 3° to 9° approach profile while the 40° flap setting provided adequate handling quality characteristics for the 3° approach profile. Both these approach profiles were rated to have acceptable handling qualities for commercial passenger operations. The 3° approach profile provided a very uniform noise reduction over much of the measured footprint area. A 4 to 6 SELdB noise reduction was measured over most of the footprint area, with small areas showing greater than of 6 SELdB noise reduction. A small area, between 2000 and 4000 feet up-range and extending from the centerline to as much as 500 feet to the sideline, showed increased noise levels of no more than about 2 SELdB. The 3° to 9° approach profile provided the greatest noise reductions on the flight path centerline and for the farther up-range measurement areas. Slightly less than 6 SELdB noise reduction was measured when averaged over all the centerline microphones while nearly 9 SELdB noise reduction was measured when averaged over the centerline microphones located between 4200 and 9000 feet up-range. Greater than 10 SELdB noise reduction was measured on centerline for a small area between 6300 and 8800 feet up-range. However, noise increases were measured between 1000 and 3000 feet up-range and up to 1000 feet to either sideline, with some very small pockets showing as much as a 4 to 6 SELdB increase. Several other 3° to 9° approach profiles were tested during the phase 3 test. Some of these profiles provided nearly as much noise reduction as the selected profile while others provided significantly less noise reduction. It is the author's opinion that there is no one single approach profile that will provide the appropriate noise abatement characteristics to fit all possible landing sites. Rather, the approach profile will have to be tailored to each type of landing site. For instance, if the landing site is located on the top of a building in the center of a city, it might be appropriate to use a 3° approach profile since it provides the most uniform noise abatement over the entire noise footprint. However, a 3° to 9° approach profile may be more appropriate for a landing site located at an airport or an industrial area that is surrounded by residential neighborhoods. If a landing point can be provided that is at least 2000 to 3000 feet beyond the residential neighborhoods, then a 3° to 9° approach profile would again provide the greatest noise reductions in those surrounding neighborhoods.

Concluding Remarks

Tiltrotor aircraft, with their unique capability to fly at relatively high cruise speeds like an airplane while maintaining the ability to takeoff and land vertically, provide a potential alternate means of transportation that could link major cities and alleviate some of the demand on airport runway usage. However, noise generated by the large tiltrotor aircraft is a potential barrier issue for civil market penetration. To address the issue of noise reduction, NASA initiated an effort with the goal of reducing the overall tiltrotor approach noise within a 40-acre vertiport by 12 dB relative to current (1995) technology. The goal is to obtain half the noise reduction through design and half through operations. A series of three XV-15 acoustic flight tests have been conducted by a NASA/Army/Bell Helicopter team to evaluate the noise reduction potential for tiltrotor aircraft during terminal area operations by altering the nacelle angle/airspeed/altitude schedule.

During phase 1 testing, acoustic measurements were obtained using a linear microphone array to measure the effective ground-plane noise contours for steady state flight operations. Results indicated that the takeoff and level flyover conditions had only a secondary effect on the total noise of tiltrotor operations, impacting land areas which are an order of magnitude less than those impacted during approach conditions. In addition, the effective ground-plane noise contours were converted to fixed radius lower hemispherical noise contours that were used as input to the Rotorcraft Noise Model (RNM). RNM was then used to predict noise footprints for complex, multi-segmented, decelerating approaches.

The effective ground-plane noise contours from the phase 1 test, along with the RNM predictions, were used to develop candidate low noise ILS-type approach profiles for phase 2 testing. Handling qualities considerations also played an important role in the design of the noise abatement approach profiles. An advanced flight guidance system, which was linked to the DGPS tracking system, was utilized to perform these complex approach profiles with precision. During phase 2 testing a large area microphones array was used to directly measure the ground noise footprints. Results indicated significant noise abatement potential by varying the approach profile parameters. In general, noise levels decreased with decreasing approach angles. The 3° to 9° approach profile provided the greatest noise abatement at the far up-range distances, probably because the aircraft was on the quieter 3° glideslope but about 300 feet higher in altitude than the 3° approach due to the steeper 9° segment during the final portion of the approach. The noise reductions measured reflected lower BVI noise generation resulting from more favorable nacelle angle/airspeed/altitude schedules. The data strongly suggested approaching at nacelle angles no higher than 60° and maintaining these low nacelle angles for as long as possible.

The approach profiles from the phase 2 test that provided the greatest noise reduction were further optimized and fully coupled with handling qualities considerations for testing during the phase 3 test. In addition, the RNM was linked to an optimizer to develop additional approach profiles. All of the approach profiles were designed to be IFR approaches with the goal of achieving a handling qualities rating of three or better, which is sufficient for commercial passenger operations. The purpose of the final phase 3 test was to demonstrate an integrated system approach to optimize the noise abatement for low noise approaches while fully coupling handling qualities with noise reduction, and to quantify the noise reductions provided by these approach profiles. The use of the 75° flap setting was found to greatly improve the XV-15 handling quality characteristics during the steep, low-powered descent conditions that occurred during many of the approach profiles. Compared to the 6° baseline approach profile, the 3° approach profile provided a relatively uniform 4 to 6 SELdB noise reduction over much of the measurement area. The 3° to 9° approach profile provided the greatest noise reductions on the flight path centerline and for the farther up-range measurement areas. Nearly 6 SELdB noise reduction was measured when averaged over all the centerline microphones (between 1000 and 9000 feet up-range) while almost 9 SELdB noise reduction was measured when averaged over the centerline microphones located between 4200 and 9000 feet up-range. Greater than 10 SELdB noise reduction was measured on centerline for a small area between 6300 and 8800 feet up-range. More than 6 SELdB noise reduction was measured for much of the measurement area beyond 5000 feet up-range of the landing point.

The results of these tests indicate that there is no one single approach profile that is best for all landing sites. Rather, the approach profile should be tailored to the type of landing site. For instance, if the landing site is located on the top of a building in the center of a city, it might be appropriate to use a 3° approach profile since it provides the most uniform noise abatement over the entire noise footprint. However, if the landing point has a 2000 to 3000 foot buffer zone which is surrounded by a noise-sensitive area, then a 3° to 9° approach profile may be more appropriate, since it provides the greatest noise reductions beyond the buffer zone even while generating increased levels within the non-noise-sensitive buffer area.

During these tests, the profiles were flown as "Instrument Flight Rules" (IFR) approaches using the newly developed flight director. This allowed much more repeatable, precise profiles, but ones which were necessarily limited by the pilot's IFR workload. To allow enough time for the pilot to assimilate the flight director's visual cues and translate them into control inputs, an approximately 5 second time delay, or buffer, had to be allowed for after each pilot instruction. This buffer produces elongated approaches compared to "Visual Flight Rules" (VFR) approaches, where the aircraft can remain in the relatively quiet low-nacelle flight regime until very near the landing point. In the next few years, as these advanced DGPS based guidance systems are directly coupled to the aircraft control systems thus reducing the pilot workload, precise, repeatable approaches will be possible in a shorter time/distance interval. This will allow approaches that *tend* more toward the shorter VFR-type approaches. Civil tiltrotor operations will make use of the information derived from both VFR- and IFR-type acoustic testing to combine handling qualities and acoustic constraints in a highly efficient manner, thus allowing the noise reduction potential of the tiltrotor to be applied in precise, repeatable approaches to the public benefit.

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