MEASURING BLADE-VORTEX INTERACTION NOISE USING THE YO–3A ACOUSTICS RESEARCH AIRCRAFT

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Abstract

The YO–3A Acoustics Research Aircraft is a quiet airplane used by NASA for acquiring in-flight measurements of rotorcraft noise. Microphones mounted on the YO–3A wing tips and vertical tail measure noise when the airplane is flown in formation with a test rotorcraft. This technique of formation flying to acquire in-flight acoustics was developed in the early 1970s. The In-flight Rotorcraft Acoustics Program (IRAP) was established in 1991 with the goal of using in-flight acoustic data as a validation of wind tunnel measurements. These data provide information on the adequacy of wind tunnel acoustic testing to accurately simulate the "real-world" noise environment. Since IRAP began, four flight test programs have been performed using S–76C, BO 105, and UH–60A helicopters, and the XV–15 tiltrotor. The BO 105 and S–76C flight test data were compared to full-scale rotor data acquired in NASA's 40- by 80-foot and 80- by 120-foot wind tunnels, respectively. Results have been mixed and further research is necessary to understand the differences between in-flight and wind tunnel acoustics. This paper presents a brief history of in-flight acoustic tests performed between 1979 and 1984; describes the current NASA YO–3A aircraft, instrumentation, and flight test procedures; and summarizes the IRAP flight tests performed between 1991 and 1995.

Notation

a	speed of sound (ft/sec)
A	disc area (ft^2), πR^2
α_{tpp}	rotor tip-path-plane angle of attack (rad)
C_T	thrust coefficient, $T/\rho A V_t^2$
dB	decibels, $20\log P_{SL}/P_{ref}$
μ	advance ratio, V/V_t
M_{tip}	hover tip Mach number, V_t/a
P_{ref}	reference pressure, 2.0e-5 (pascals)
P_{SL}	sound level pressure (pascals)
R	blade radius (ft)
T	thrust (lbs)
V	flight speed (ft/sec)
V_t	tip speed, ΩR
ρ	air density (slug/ft^3)
Ω	shaft rotational speed (rad/sec)

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Introduction

An important part of NASA's rotorcraft research is to improve the understanding of the sources and propagation of rotor noise, especially blade-vortex interaction (BVI) noise. BVI noise results from the aerodynamic interaction of a rotor blade with a tip vortex trailed from one or more previous blades. The interaction causes a distinct low- to mid-frequency impulsive noise which can radiate long distances. BVI noise is maximum for a rotorcraft in descending forward flight, typical of an approach to landing. Reducing BVI noise is critical to the public acceptance of helicopters and tiltrotors and is therefore an essential part of NASA's rotorcraft research.

NASA uses the National Full-Scale Aerodynamics Complex (NFAC), which includes the 40- by 80-Foot and 80- by 120-Foot Wind Tunnels, to study BVI noise from full-scale rotors. These wind tunnels provide precise control of rotor operating conditions that allow for a repeatable test environment, but accurate noise measurements are difficult for several reasons. First, the wind tunnel walls cause reflections that may corrupt the acoustic signal. Second, basic background noise from the wind tunnel drive and the test stand may interfere with the acoustical signature of the test rotor. Third, the wall effects of the tunnel prevent the rotor wake from developing exactly as it does in flight. Finally, the character of the rotor wake can also be altered by the rotor test stand which is often not the same shape as the rotorcraft fuselage.

To better understand the limitations of acoustic testing in wind tunnels, comparison with in-flight acoustics is needed. The In-Flight Rotorcraft Acoustics Program (IRAP) was established to measure BVI noise from rotorcraft whose full-scale main rotors have either been or will be tested in the NFAC. IRAP utilizes NASA's YO–3A Acoustics Research Aircraft which has microphones on the wing tips and vertical tail to measure BVI noise while flying in close formation with a test helicopter or tiltrotor. By using the YO–3A as a quiet measuring station, BVI noise can be acquired under a range of steady-state operating conditions similar to those used in wind tunnels. IRAP provides acoustic flight data needed to validate wind tunnel test results, or where the results cannot be validated, provides researchers with information to correct for wind tunnel facility effects.

This paper begins with a history of in-flight rotorcraft noise research performed at NASA between 1979 and 1984. Each of these tests uncovered important aspects of the source and directivity of rotor noise. The majority of these tests were performed with the YO–3A; the aircraft, acoustic instrumentation and flight procedures are briefly discussed here. Finally, a review of the four flight tests performed under IRAP between 1991 and 1995 are described.

History

In the early 1970s, Schmitz and Boxwell (Ref. 1, 2) of the U.S. Army Mobility R&D Laboratory (USAMRDL) at NASA Ames Research Center, conceived the idea of obtaining in-flight acoustic data by flying a measuring station ahead of the subject aircraft. This technique was used in a series of flight test programs to measure the impulsive noise generated by U. S. Army helicopters in high-speed forward flight. The first in-flight acoustic measurements were acquired from a Bell UH–1H "Huey" using an OV–1 Mohawk (Ref. 1). Predominant noise directivity patterns were identified during this initial development of the in-flight concept, done jointly by the USAMRDL and the Army Engineering Flight Activity at Edwards, CA. A matrix of azimuthal and elevation locations, relative to the test helicopter, were flown by the OV–1. The test results identified two locations with peak noise levels. High-speed impulsive (HSI) noise, caused by compressibility effects on the advancing blade, was maximum when the recording microphone was co-planar with the rotor hub. Blade-vortex interaction (BVI) noise, caused by the rotor blades interacting with the rotor wake, was greatest when the microphone was thirty deg below the rotor hub at a rotor azimuth of 135 deg, (where azimuth angle is 0 deg when the blade is over the tail and increases as the blade rotates counter-clockwise as viewed from above).

In 1976, the in-flight HSI noise measurements were compared to noise recorded from a 1/7-scale UH–1H rotor tested in the acoustically treated 7- by 10-Foot Wind Tunnel at NASA Ames Research Center (Ref. 2, 3). Key performance parameters were identified: hover tip Mach number (M_{tip}), advance ratio (μ), thrust coefficient (C_T), and rotor tip-path-plane angle of attack (α_{tpp}). Good agreement between model and full-scale waveforms and peak pressure amplitudes was noted when M_{tip}, μ, C_T, and α_{tpp} were matched.

In 1979, the OV–1 was replaced by the much quieter YO–3A, which was used to measure BVI noise from a UH–1H and AH–1S (Ref. 4). The investigation measured the acoustics of four different two-bladed rotor systems and helped researchers understand the many complicated unsteady aerodynamic events that cause BVI noise. The UH–1H was tested with its standard rotor while the AH–1S tests included three different rotors: the standard 540 rotor, the Kaman K747 rotor, and the ogee tip rotor. Strong pressure gradients in the UH–1H and AH–1S 540 rotor signatures influenced the subjective annoyance of the rotor. The peak amplitudes and power spectra of the K747 and ogee rotors were about equal and generated less annoyance than the standard AH–1S or UH–1H rotors.

In 1980, a test involving a Hughes (now McDonnell Douglas) 500D was flown at NASA Ames Research Center with the YO–3A (Ref. 5). The purpose of this test was to investigate the acoustic effects of different tail rotor configurations, using fly-over and in-flight tests. Test results showed a cruise noise reduction of 3.2 dB when using a 4-bladed tail rotor relative to the standard two-bladed configuration.

The Tip Aerodynamic and Acoustics Test (TAAT) was an extensive flight test program using an instrumented AH–1G and the YO–3A in 1981 (Ref. 5). The instrumented AH–1G Cobra included one hundred eighty blade pressure transducers arranged in eight radial stations, weighted towards the tip region. Acoustics data and blade pressure data were acquired simultaneously. There were also flight tests with a McDonnell Douglas AH–64 Apache in 1982 where the in-flight noise data were used to determine if the aircraft met acoustic design specifications (Ref. 5). Due to the military nature of the Cobra and Apache helicopters, the acoustic data remain classified.

In 1982, a 1/7-scale model-rotor AH–1S was tested in the three-meter open-section anechoic wind tunnel, CEPRA-19, in France (Ref. 6). Acoustic data were compared to the AH–1S data taken with the YO–3A in 1979. Good agreement between model and full-scale waveforms and amplitude of blade-vortex interaction noise was shown at one advance ratio and over a range of tip-path-plane angles. Some model-rotor testing limitations of the wind tunnel facility were noted.

In 1984, the same 1/7-scale AH–1S model rotor was tested in the anechoic Deutsch-Niederlaendischer Windkanal (DNW) in the Netherlands (Ref. 7). The in-flight acoustic data were compared to the model-rotor data and, at low advance ratios (μ = 0.164 – 0.194), the BVI noise data scaled well in amplitude, waveform, and directivity patterns. At moderate advance radios (μ = 0.224 – 0.270), the scaling deteriorated, suggesting that the model-scale rotor was not adequately simulating the full-scale BVI noise. The measured BVI noise radiation was highly sensitive to all four of the governing nondimensional parameters; M_{tip}, μ, C_T, and α_{tpp} (Ref. 8).

In-Flight Rotorcraft Acoustics Program

In 1987, a modification to the 40- by 80-Foot Wind Tunnel was completed which included the addition of a 6-inch acoustic liner. This improvement allowed acoustic testing of rotorcraft, which was not possible previously due to the reverberant nature of the test section. This re-established interest in acoustic flight testing in order to verify that acoustics data (BVI noise in particular) acquired in the wind tunnel were representative of the "real-world" noise environment. Therefore, the In-Flight Rotorcraft Acoustics Program (IRAP) was established by NASA Ames Research Center in 1991. Four aircraft have been used in IRAP flight tests with the YO–3A airplane: Sikorsky S–76C (Ref. 9), MBB BO 105 (Ref. 10), Sikorsky UH–60A, and Bell XV–15. These flight test programs are discussed in the "IRAP Tests Performed" section of this paper. The execution of these tests utilized the YO–3A aircraft, the on-board acoustic instrumentation, and formation flying with the test rotorcraft, which are described in the following sections.

The YO–3A Airplane

NASA's YO–3A airplane is one of only eleven such aircraft that were built for the U.S. Army by Lockheed Missiles and Space Corporation in Sunnyvale, California in 1969 (Ref. 11). The airplane's original mission was night surveillance in Vietnam. To avoid detection, the airplane was designed for ultra-quiet flight. A surplus YO–3A was acquired by NASA and modified for acoustics research. A photograph of NASA's YO–3A, designated tail number 718, is shown in Fig. 1.

The YO–3A's low acoustic signature is the result of several design features (Ref. 12). A single 210-hp Continental six-cylinder engine drives a three-bladed, variable-pitch wooden propeller. The engine runs at a maximum of 2800 rpm, and the propeller turns at only 840 rpm. This low propeller tip speed contributes to the overall quietness of the aircraft. To reduce engine-propeller transmission noise, 12 automotive fan v-belts are used in place of a geared transmission train. The engine exhaust system is extensively muffled for low noise. Table 1 lists the aircraft general specifications.

The aircraft, in part because of its extremely quiet design, has limited performance. The YO–3A was built from the basic airframe of a Schweitzer SGS 2–32 sailplane which originally had a gross weight of 1500 lbs. NASA's YO–3A has grown, with the engine, drivetrain, bulbous canopy, and acoustic testing equipment, to 3400 lbs. Consequently, the maximum level flight airspeed is approximately 110 knots with a never-exceed airspeed of 133 knots. The maximum rate of climb is 500 feet per minute (Ref. 13).

Aircraft Instrumentation

The YO–3A research aircraft is equipped with special instrumentation to acquire in-flight measurements. The YO–3A has an instrumentation boom mounted on the port wing that measures indicated airspeed, altitude, angles of attack and sideslip, and outside air temperature. The pilot's instruments for airspeed, altitude, and rate of climb operate off a separate pitot-static tube mounted on the starboard wing. Radio links include an IRIG-B time code receiver used for data time correlation, a voice channel, and a once-per-revolution (1/rev) signal broadcast from the test rotorcraft. The 1/rev pulse is important for correlating the rotor blade azimuth location with the acoustic measurements.

Acoustic Instrumentation

Acoustic instrumentation on the YO–3A consists of two dual-channel microphone power supplies, three microphones with preamplifiers, an oscilloscope, and an analog tape recorder. The power supplies use aircraft power and have gain adjustments of ± 10 dB. The power supplies drive the three Brüel and Kjær 0.5-inch condenser microphones. The omni-directional microphones have a frequency response of approximately 5 Hz to 20 kHz and are mounted on aerodynamic struts located on both wing tips and at the tip of the vertical tail. Figure 2 shows the YO–3A's starboard microphone and fairing mounted on the wing tip. The oscilloscope is used by the flight engineer to monitor the acoustic data, time code, or 1/rev to insure proper signal quality during the test flight. The signals from all the sensors, plus voice comments, are recorded on a 14-channel FM wideband tape recorder mounted in the equipment bay behind the pilot. Data are recorded for 30 sec at each test point at a tape speed of 30 in/sec providing a frequency range of 0 – 20 kHz (Ref. 13). Table 2 lists the data acquired on the recorder during each flight test condition.

Rotorcraft Instrumentation

The tests performed under IRAP include both instrumented and uninstrumented test rotorcraft. On uninstrumented aircraft, portable systems are installed on board to measure critical parameters. These systems include a portable gyroscope box with a computer to measure aircraft attitude, a hand-held laser rangefinder and data recorder to measure distance between the test aircraft and the YO–3A, and a 1/rev transmitter to broadcast a 1/rev pulse to the transceiver in the YO–3A.

For comparison to wind tunnel data, reliable estimates of M_{tip}, μ, C_T, and α_{tpp} for each flight condition are necessary. Measurements of rotor speed from the 1/rev transmitted signal, together with airspeed and temperature, as measured by the YO–3A, determine M_{tip} and μ. Thrust is estimated from the rotorcraft weight and is adjusted for fuel burn and lift and drag on the aircraft. On an uninstrumented rotorcraft, α_{tpp} is estimated from a force balance equation and corrected for rate of descent as measured by the YO-3A (Refs. 9,10). Instrumented test vehicles can provide additional measurements (such as blade flapping or gimbal angle) to more accurately estimate α_{tpp}.

Experimental Method

To acquire in-flight blade-vortex interaction noise, the aircraft formation consists of the YO–3A flying lead in a position below and to the starboard of the rotor hub. One of the three YO–3A microphones is selected as the primary microphone and is positioned approximately 20 to 30 deg below the rotor hub at an azimuth of approximately 135 deg. The exact formation geometry for each test is dependent on several other parameters such as pilot visibility and the corresponding wind tunnel test. The rotorcraft pilot must be able to see and set up on markings on the YO–3A in order to confidently repeat the aircraft's relative position. The formation must also establish a rotor and microphone position that was or can be duplicated in the wind tunnel test section.

The formation is initiated by the test rotorcraft pilot establishing a position behind and above the YO–3A. The proper elevation and azimuth are determined by the pilot lining up on markings on the YO–3A wing and tail. Figure 3 is an example of the rotorcraft pilot's view when in proper position. Note that the horizontal black lines on the tail line up with the lines on the wing and the diagonal line on the wing lines up with the leading edge of the vertical tail.

Separation distance is measured by using a portable, eye-safe laser rangefinder located in the test rotorcraft. This rangefinder is used as a real time indicator and recorder of distance between the test rotorcraft and the YO–3A and is operated by the rotorcraft co-pilot or on-board flight engineer. A small section of the YO–3A wing is used as a target and the distances are viewed by means of a digital display. The values are downloaded to a lap-top computer and are synchronized through a time code with the acoustic data recorded on the YO–3A data system.

The test matrix is flown to maintain several nondimensional parameters constant: M_{tip}, μ, and C_T (Ref. 8). Keeping these parameters constant implies differences in acoustic measurements are caused by rate of descent. An example test matrix is shown in Table 3. The test procedures require the YO–3A pilot to set up on the specified airspeed and an altitude above that of the test condition. When stable, the helicopter or tiltrotor pilot maneuvers into position using visual cues on the YO–3A and the laser distance readout. The YO-3A pilot begins the descent at an altitude which will allow the formation to pass through the target altitude at the midpoint of the data record. During this time, the YO–3A flight engineer adjusts the microphone gain settings to maximize the signal response. Once the proper formation is obtained, the test rotorcraft pilot reports "on condition" and the flight engineer begins recording the acoustic data approximately 15 sec ahead of the target altitude and continues recording 15 sec after. During data recording, the pilot minimizes control inputs to prevent altering the radiated acoustics. Each data record begins with comments denoting the test condition and run number and ends with the pilots' comments. The YO–3A pilot comments on airspeed, rate of descent, and steadiness of the aircraft. The rotorcraft pilot comments on the positioning of the aircraft and any control inputs.

Steady conditions are necessary for quality flight test data and pilot assessment of air turbulence is required for every formation flight. Several data runs under the same condition are flown to ensure data repeatability. Time histories of separation distance, aircraft state, and pilot comments are examined to select the steadiest section of the 30-sec data record for analysis.

The steadiest 32 revolutions of data are selected for processing. The data are digitized at 2048 points/rev and low-pass filtered to prevent aliasing. The data are then averaged based on manual selection of a repeating acoustic peak for each blade of each revolution. This isolates the blade-to-blade differences and rpm inconsistencies and eliminates smearing of the peak BVI signals from standard averaging techniques. An acoustic time history and frequency spectrum is generated for each flight condition and is compared to corresponding wind tunnel data processed in a similar fashion.

IRAP Tests Performed

The In-Flight Rotorcraft Acoustics Program has conducted four flight tests since 1991 using the YO–3A airplane. In addition, a test of the YO–3A alone was flown for a matrix of test conditions to acquire background noise. This background noise was measured in both level flight and for various rates of descent. Flights were also made with the spoilers deployed and with the engine at idle to determine their effect on the background noise levels. Figure 4 is a frequency spectrum of the background noise of the YO–3A in comparison to typical BVI noise and illustrates the high signal to noise ratio typical for the in-flight tests.

Sikorsky S–76C

In late 1992, in-flight acoustic measurements of a Sikorsky S–76C helicopter were acquired. Comparisons were made with data from a full-scale S–76 rotor tested in early 1992 in the 80- by 120-Foot Wind Tunnel at NASA Ames Research Center in a joint Sikorsky/NASA program (Ref. 9). Both rotor sets, although different, were made to the same production standards. These results provided the first comparison of in-flight acoustic measurements with full-scale wind tunnel data.

Figure 5 is a photograph of the S–76C helicopter and the YO–3A aircraft in formation flight. The helicopter was positioned so that the tail microphone on the YO–3A was located 25 deg below the rotor hub at a rotor azimuth of 150 deg. The distance between the rotor hub and the tail microphone was nominally two rotor diameters (88 ft). The angular alignment of the two aircraft was established visually by the helicopter pilot, who aligned the top of the YO–3A tail with a target on the right wing of the YO–3A, similar to Fig. 3.

Flight conditions were selected from within the flight envelope of the two aircraft and as close as possible to conditions tested with the full-scale rotor in the 80- by 120-Foot Wind Tunnel. Figure 6 is a photograph of the S–76 rotor installed on the Rotor Test Apparatus (RTA) in the wind tunnel. Three conditions were compared; results for advance ratios of 0.16 and 0.20 showed a reasonable match, with similar BVI pulse widths and overall sound pressure levels. Figures 7 and 8 show acoustic pressure time histories, comparing flight and wind tunnel data. The wind tunnel data show small impulses before and after the BVI event that are believed to be caused by wall reflections. One condition at a higher advance ratio, (μ = 0.25), did not show good comparisons (Fig. 9). For this case, the wind tunnel data showed greater blade-to-blade and rev-to-rev variability than the flight test data. Figure 10 illustrates the wind tunnel blade-to-blade variability which was seen only at the μ = 0.25 condition. Further research is currently underway to investigate the cause of the problems encountered in this test program at higher advance ratios.

MBB BO 105

In 1993, in-flight acoustic measurements of a Messerschmitt-Bölkow-Blohm (MBB) BO 105 helicopter were acquired (Ref. 10). Figure 11 is a photograph of the BO 105 in formation with the YO–3A. The helicopter was positioned so that the tail microphone on the YO–3A was located 33 deg below the rotor hub and at a rotor azimuth of 155 deg. The distance between the rotor hub and the tail microphone was 1.14 rotor diameters (37 ft). Acoustic data were compared to full-scale BO 105 data obtained in the 40- by 80-Foot Wind Tunnel and also to small-scale data acquired in the DNW (Ref. 14). Figure 12 shows the BO 105 rotor installed on the RTA in the 40- by 80-Foot Wind Tunnel. Figure 13 compares the pressure time histories for 1/2 revolution for flight, 40- by 80-foot, and DNW wind tunnel data. Comparisons show significant differences in the magnitude and shape of the BVI events measured in the DNW and the 40- by 80-Foot Wind Tunnel as compared to the flight data. The disagreement may be a result of the differences in rotor trim, inaccurate estimation of the α_{tpp} in flight, differences in rotor control system dynamics and/or the distortion of the rotor wake due to the tunnel walls and rotor test stand.

For any rotorcraft flight test, the rotor is trimmed to balance forces and moments on the aircraft, but a rotor tested in a wind tunnel is usually trimmed to zero flapping. To investigate the effect of trim on BVI noise for the full-scale BO 105 rotor, a second test in the 40- by 80-Foot Wind Tunnel was performed (Ref. 15). The flight trim conditions were matched and then small longitudinal and lateral cyclic excursions (~1 deg) were input to the rotor to account for variations which might have occurred in flight. No significant effects on measured BVI noise were observed for the single microphone location. During more recent testing of the small-scale BO 105 rotor in the DNW in 1994, the measured BVI noise time histories were similar to those acquired in the 40- by 80-Foot Wind Tunnel. Small trim variations were also performed during this recent test, and preliminary results implied no significant effect of trim on BVI noise. However, these data are currently unpublished and more research is required in this area to confidently understand the effect of trim on BVI noise.

Several estimations were required for determining α_{tpp} for the BO 105 flight test conditions (Ref. 10). The effect of α_{tpp} on BVI noise directivity was investigated in an extensive study of a dynamically-scaled 40% BO 105 rotor in the DNW (Refs. 14,16,17). Results showed the directionality, noise levels, and impulsive content of both advancing and retreating side BVI vary significantly with α_{tpp}. Accurately matching α_{tpp} remains an important requirement when comparing wind tunnel noise measurements with in-flight noise data.

Understanding differences due to rotor control system dynamics and distortion of the rotor wake are facility effects that require further research. An extensive study may help develop corrections for these effects so wind tunnel acoustics, once processed, could accurately represent flight.

Sikorsky UH–60A

In 1993, in-flight acoustic measurements were acquired as part of the NASA/Army UH–60A Airloads Program along with extensive blade pressure data (Ref. 18). The UH–60A had 221 pressure transducers at nine radial stations with another 21 specifically located to measure the effects of BVI. In addition, the UH–60A had a measurement of blade root flapping which provided an improved estimation of the α_{tpp}.

Six flights were performed with the YO–3A and UH–60A flying in close formation (Fig. 14). The starboard wing tip microphone of the YO–3A was positioned 22 deg below the rotor hub at a rotor azimuth of 150 deg. The distance between the starboard wing tip microphone and the rotor hub was 1.5 rotor diameters (80.5 ft). Target flight conditions included $\mu = 0.175 - 0.250$, $M_{tip} = 0.636$ and 0.66, $C_T = 0.0058$ and 0.0071, and descent rates of 200 – 900 ft/min. These data are currently classified.

A subset of these flight conditions matched test points measured previously in the DNW (Ref. 19). During the DNW test, acoustic and blade pressure data from a 1: 5.73 scale model of the UH–60 rotor were acquired. Preparations are underway to test the UH–60A Airloads blades in the NASA Ames 40- by 80-Foot Wind Tunnel using the Large Rotor Test Apparatus. Acoustic and blade pressure data will be acquired for conditions matching the flight and DNW tests.

Bell XV–15

In 1995, in-flight acoustics measurements of the Bell XV–15 Tiltrotor Research Aircraft were performed at the Bell Helicopter Flight Test Center in Arlington, Texas. The XV–15 tiltrotor has highly twisted, highly loaded rotors with different performance and noise characteristics than conventional helicopter rotors. This test vehicle had a direct measurement of gimbal angle allowing for an improved estimation of α_{tpp}.

Four flights were performed with the YO–3A and XV–15. Figure 15 shows the two aircraft in formation. The flight conditions and microphone location were selected to measure the BVI noise from the right rotor. The starboard wing tip microphone of the YO–3A was positioned 20 deg below the right rotor hub and at a rotor azimuth of 150 deg. The distance between the starboard wing tip microphone and the right rotor hub was three rotor diameters (75 feet). Target flight conditions included $M_{tip} = 0.69$, $\mu = 0.165$ and 0.185, $C_T = 0.0111$, and descent rates of 300–1100 fpm, all with the XV–15 nacelles at 90 deg.

The flight test conditions were used to determine equivalent test conditions for a subsequent wind tunnel test. A single XV–15 right rotor was tested in the 80- by 120-Foot Wind Tunnel test section, with the rotor mounted on the RTA, shown in Fig. 16. A microphone was placed in the test section in the same relative location to the rotor hub as the YO–3A starboard microphone was positioned in flight. A second microphone was placed in a "mirror-image" position in the wind tunnel test section to attempt to simulate the noise of the XV-15 left-hand rotor as measured by the YO–3A starboard microphone. Rotor test conditions, including forward airspeed, tip speed, rotor torque, angle of attack, gimbal angle, and collective and cyclic control positions, were all measured in real time during the IRAP flights and were duplicated as much as possible during the wind tunnel test. Comparisons are in progress.

Summary

The in-flight technique for measuring rotorcraft blade-vortex interaction noise by station-keeping with an instrumented fixed-wing aircraft was described. A history of how the method originated and a review of the tests that have been performed was presented. The YO–3A Acoustics Research Aircraft, instrumentation, and formation flight procedures were described. A summary of the four tests performed under the In-flight Rotorcraft Acoustic Program was presented. The in-flight S–76C and BO 105 test data were compared to wind tunnel test data with mixed results. The UH–60A and XV–15 rotorcraft were heavily instrumented and test data comparison is in progress. The goal of IRAP is to have validated test methodologies for small- and full-scale rotor wind tunnel testing to simulate blade-vortex interaction in-flight noise.

Recommended Improvements

Two instrumentation upgrades are recommended to improve the efficiency and productivity of the in-flight test technique. First, the analog tape recorder on the YO–3A should be replaced with a digital recorder. A digital recorder allows more data channels, longer data records, and easier access of recorded data, all in a smaller and lighter package. Second, establishing the formation using the laser rangefinder and visual cues creates a heavy pilot and co-pilot workload. Using a differential global positioning system (DGPS) to establish and maintain the formation should reduce the workload and ultimately be more accurate. The use of a DGPS will eliminate the co-pilot use of the laser rangefinder and will more accurately define the test rotorcraft position in relation to the YO–3A in 3-dimensional space.

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17) Splettstoesser, W.R., Schultz, K.J., and Martin, R.M., "Rotor Blade-Vortex Interaction Impulsive Noise Source Identification and Correlation with Rotor Wake Predictions," AIAA-87-2744, 11th Aeroacoustics Conference, Sunnyvale, CA October 1987.

18) Kufeld, R., Balough, D.L., Cross, J.L., Studebaker, K.F., Jennison, C.D., and Bousman, W.G., "Flight Testing of the UH–60A Airloads Aircraft," 50th Annual Forum of the American Helicopter Society, Washington, D.C., May 1994.

19) Liu, S.R. and Marcolini, M.A., "The Acoustic Results of a United Technologies Scale Model Helicopter Rotor Tested at the DNW," 46th Annual Forum of the American Helicopter Society, Washington, D.C., May 1990.

Table 1. NASA YO–3A Aircraft Specifications

Parameter	Specifications
Aircraft type	single engine, conventional landing gear
Crew	2 (Pilot and Test Engineer)
Wing span	57 ft (17.4 m)
Length	29.3 ft (8.93 m)
Height	9.1 ft (2.77 m)
Max. gross takeoff weight	3800 lbs (1722 kg)
Power plant, Continental	210 hp (156.6 kW)
Stall speed	60 kts (111 km/h)
Maximum Level Flight	110 kts (204 km/h)
Never Exceed speed	133 kts (247 km/h)
Propeller blades	3
Propeller diameter	8.33 ft (2.54 m)
Propeller tip speed	360 ft/s (109.7 m/s)

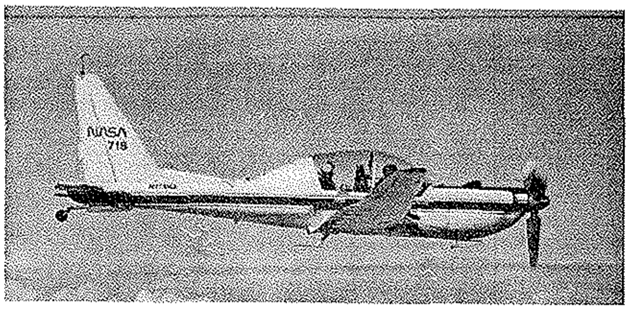

Figure 1. The NASA YO–3A Acoustic Research Aircraft.

Table 2. Flight test data acquired on YO–3A.

Tape Channel	Parameter recorded
1	port microphone
2	altitude
3	tail microphone
4	outside air temperature
5	starboard microphone
6	-
7	indicated airspeed
8	-
9	1/rev (from rotorcraft)
10	-
11	time code
12	angle of attack
13	sideslip angle
14	voice

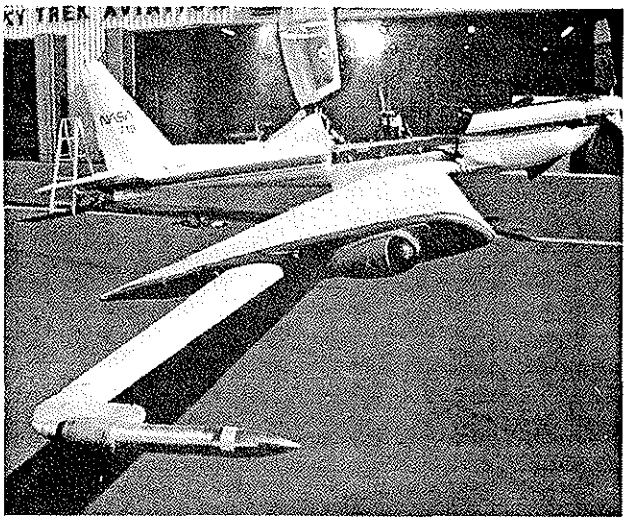

Figure 2. The YO–3A starboard microphone.

Table 3. Example of flight test matrix.

C_T	M_{tip}	μ	Rate of Descent (ft/m)
0.011	.6	.15	0 – 1000
0.011	.7	.15	400 – 1000
0.011	.7	.2	400 – 1000

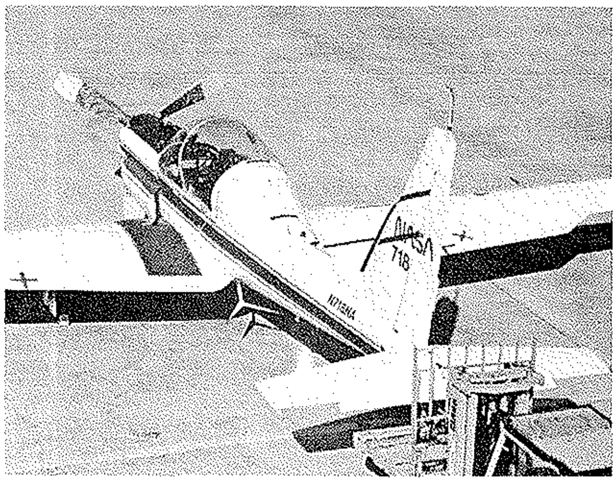

Figure 3. Example of visual line-up markers as seen by the rotorcraft pilot when in position.

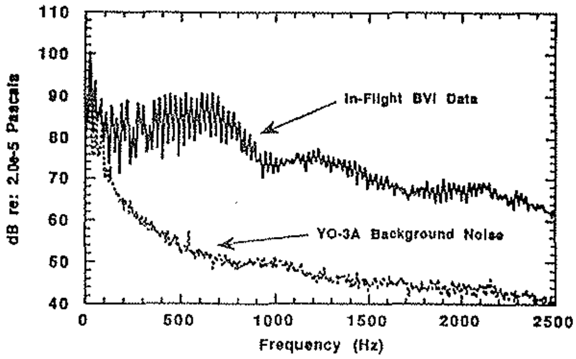

Figure 4. Frequency spectrum of YO–3A background noise and typical BVI data (Ref. 10).

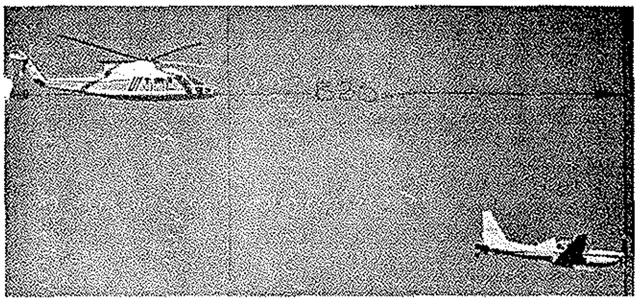

Figure 5. The S–76C and YO–3A aircraft in formation flight.

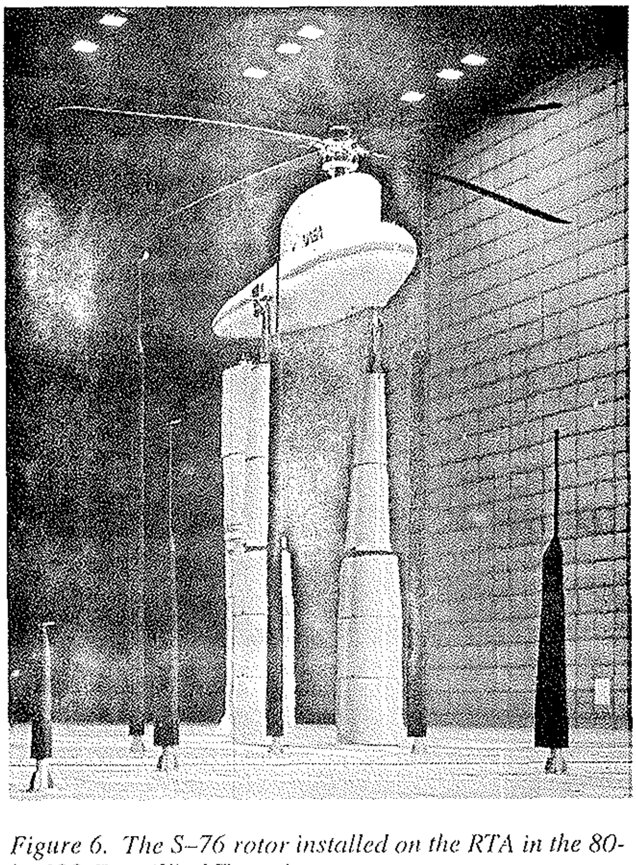

Figure 6. The S–76 rotor installed on the RTA in the 80- by 120-Foot Wind Tunnel.

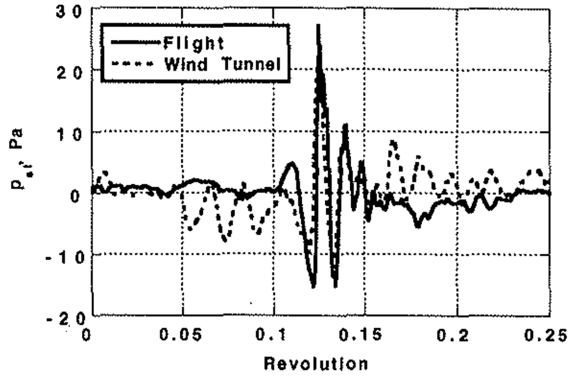

Figure 7. Flight and wind tunnel comparison of averaged time histories for 1/4 revolution (Ref. 9). Flight pt. 203 conditions: $C_T = 0.00778$, $M_{tip} = 0.603$, $\mu = 0.164$, $\alpha_{tpp} = 5.6$ deg. Wind Tunnel Run 39_24 conditions: $C_T = 0.00753$, $M_{tip} = 0.605$, $\mu = 0.173$, $\alpha_{tpp} = 5.0$ deg.

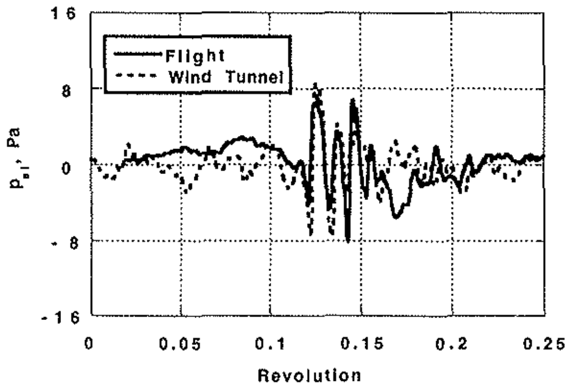

Figure 8. Flight and wind tunnel comparison of averaged time histories for 1/4 revolution (Ref. 9). Flight pt. 307 conditions: $C_T = 0.00605$, $M_{tip} = 0.606$, $\mu = 0.203$ $\alpha_{tpp} = 0.5$ deg. Wind Tunnel Run 48_19 conditions: $C_T = 0.00599$, $M_{tip} = 0.605$, $\mu = 0.200$, $\alpha_{tpp} = 0.0$ deg.

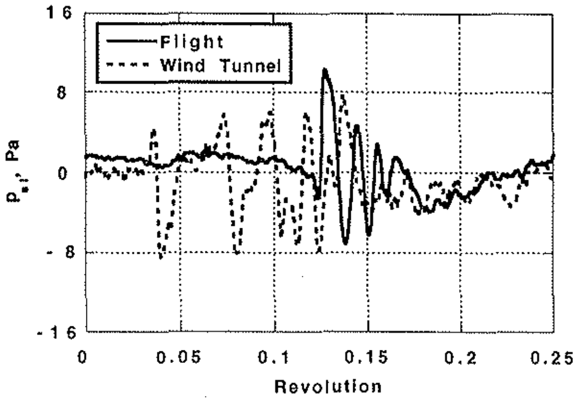

Figure 9. Flight and wind tunnel comparison of averaged time histories for 1/4 revolution (Ref. 9). Flight pt. 315 conditions: C_T = 0.00600, M_{tip} = 0.606, μ = 0.254, α_{tpp} = 0.4 deg. Wind Tunnel Run 48_18 conditions: C_T = 0.00597, M_{tip} = 0.605, μ = 0.251, α_{tpp} = 0.0 deg.

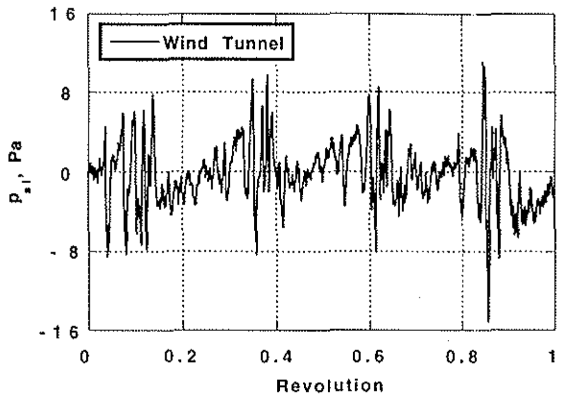

Figure 10. Wind tunnel blade-to-blade variability seen at the higher advance ratio (Ref. 9). Run 48_18 conditions: C_T = 0.00597, M_{tip} = 0.605, μ = 0.251, α_{tpp} = 0.0 deg.

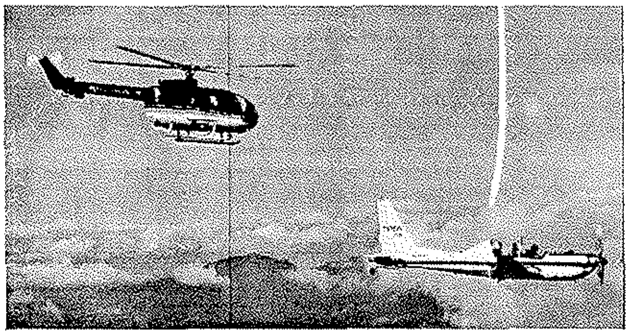

Figure 11. The BO 105 in formation with the YO–3A aircraft.

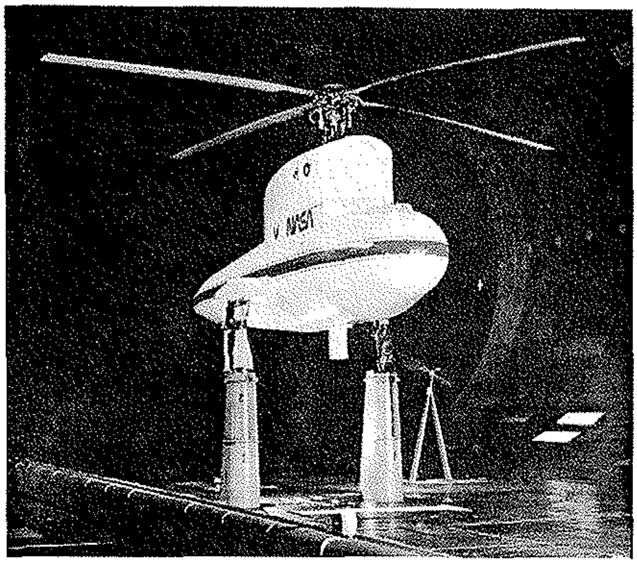

Figure 12. The BO 105 rotor installed on the RTA in the 40-by 80-Foot Wind Tunnel.

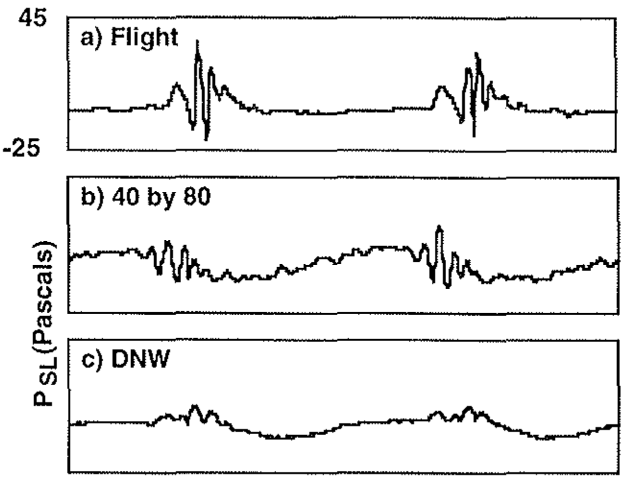

Figure 13. Acoustic pressure time histories for 1/2 revolution (Ref. 10). Condition #1; $\alpha_{tpp} \approx 2.4$ deg, $\mu \approx 0.185$, $C_w \approx 0.00465$, $M_{tip} \approx 0.64$, a) Flight, b) 40-by 80, c) DNW.

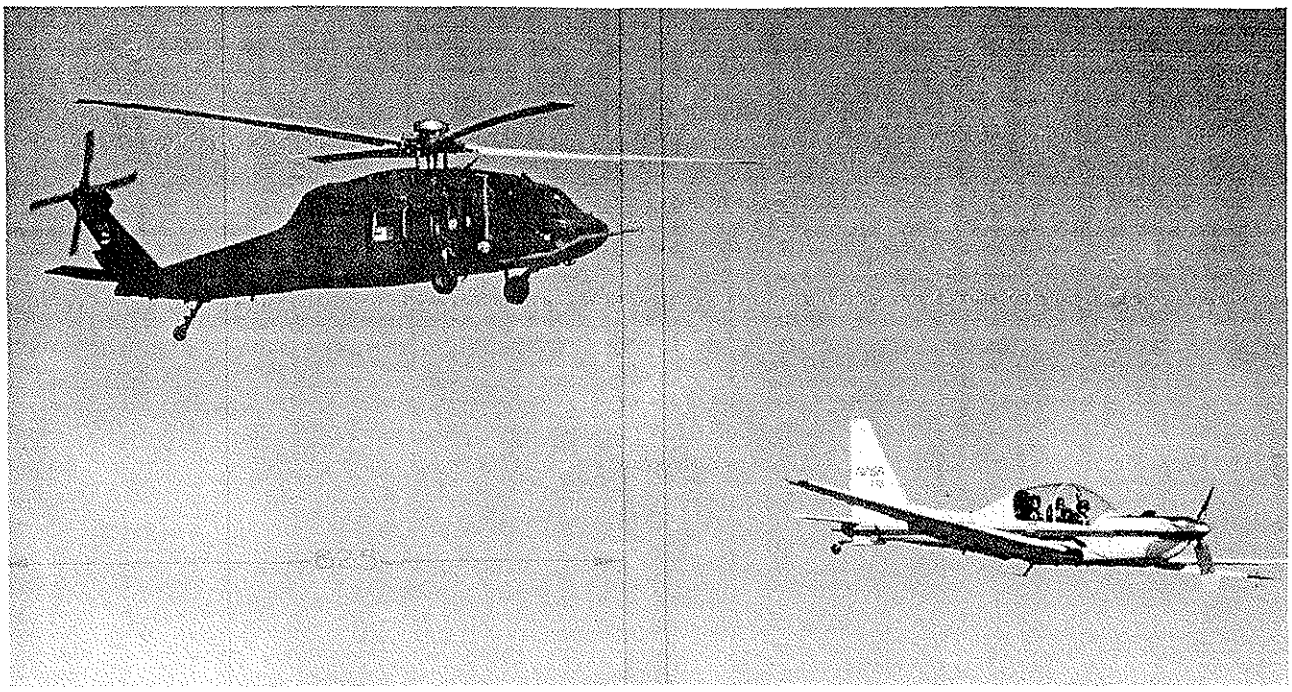

Figure 14. The UH-60A in formation with the YO-3A.

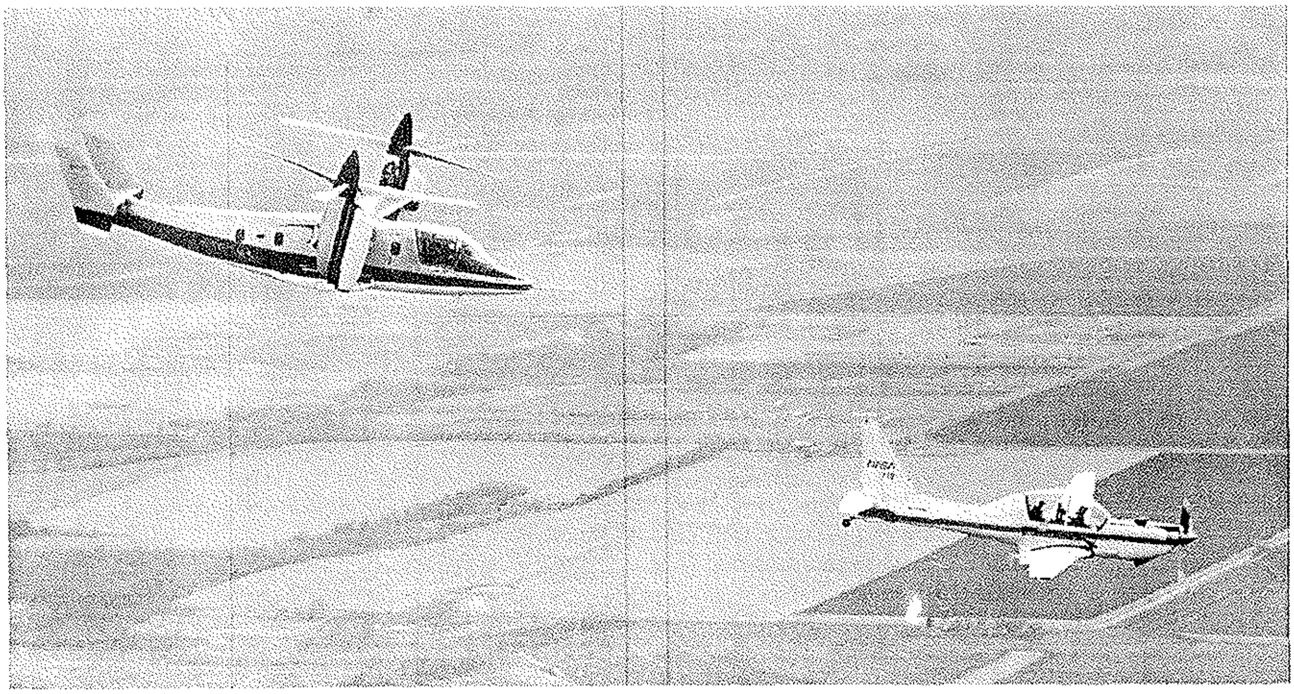

Figure 15. The XV-15 in formation with the YO-3A.

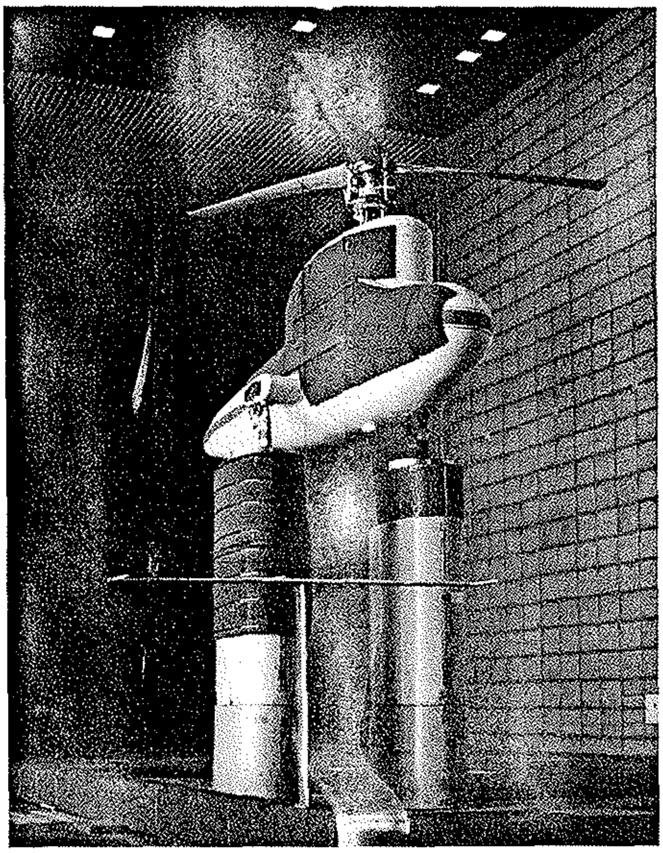

Figure 16. The XV–15 right-hand rotor mounted on the RTA in the 80- by 120-Foot Wind Tunnel.