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ACCOMPLISHMENTS AT NASA LANGLEY RESEARCH CENTER IN ROTORCRAFT AERODYNAMICS TECHNOLOGY

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SUMMARY

In recent years, the development of aerodynamic technology for rotorcraft has continued successfully at NASA LaRC. Though the NASA Langley Research Center is not the lead NASA center in this area, the activity has been continued due to the unique facilities and individual capabilities which are recognized as contributing to helicopter research needs of industry and government. Noteworthy accomplishments which contribute to advancing the state of rotorcraft technology in the areas of rotor design, airfoil research, rotor aerodynamics, and rotor/fuselage interaction aerodynamics are described. New rotor designs have been defined for current helicopters and evaluated in wind tunnel testing. These designs have incorporated advanced airfoils defined analytically and also proven in wind tunnel tests. A laser velocimetry system has become a productive tool for experimental definition of rotor inflow/wake and is providing data for rotorcraft aero ynamic code validation.

INTRODUCTION

Since the time that NASA Ames was designated as the lead Center for rotorcraft technology, the activity in rotorcraft aerodynamic technology has been carried on by the U.S. Army Aerostructures Directorate at Langley. Though at a reduced level because of less manpower and resources, significant work has been accomplished in analyses and experimentation for rotorcraft aerodynamics. For the latter activity there are two key facilities at Langley--the 14- by 22-Foot Subsonic Tunnel shown in figure 1 (formerly the 4- by 7-Meter Tunnel - and earlier the V/STOL Tunnel) and the Transonic Dynamics Tunnel shown in figure 2. At the 14- by 22-Foot Subsonic Tunnel, the Rotorcraft Aerodynamics Office comprised of a group of Army aerospace engineers has been performing pioneering work in rotor aerodynamic and acoustic analyses and experimentation. At the Transonic Dynamics Tunnel, another group of Army engineers, the Rotorcraft Aeroelasticity Group, pursues similar interests in rotor dynamics as well as in aerodynamics.

Both facilities have unique capabilities for helicopter technology developments. The 14- by 22-Foot Subsonic Tunnel can be operated with either an open- or closed-throat test section by raising or lowering the side walls, ceiling and floor. Typically, for laser velocimetry measurements of rotor inflow or for rotor acoustic measurements, the open-throat configuration, with floor in place, is used. Wind speeds of up to 200 knots can be generated in the 14.5 ft. high by 21.75 ft. wide test section. Acoustic reverberations in the open-throat test section are reduced by use of sound-absorbing panels on the test chamber walls surrounding the test section. A specially designed laser-velocimeter ("LV") laboratory for set-up (beam alignment and operation) and maintenance of a dedicated LV system is adjacent to the test section and affords efficient preparations for testing. A new rotor model preparation area near the tunnel provides the capability to assemble and test rotor models in hovering conditions prior to actual entry into the tunnel test section.

In 1985, modifications (figure 3) to the 14- by 22-Foot Subsonic Tunnel were completed and have improved and expanded its aerodynamic and acoustic test capability (refs. 1 and 2). One of the more significant aerodynamic improvements was achieved through the use of flow deflectors installed downstream of the first corner of the tunnel circuit to improve the performance of the tunnel fan. The deflectors resulted in a more uniform velocity distribution into the tunnel drive system and eliminated regions of large-scale flow separation in the return leg of the tunnel circuit. A new turbulence reduction system consisting of a grid, a honeycomb, and four fine-mesh screens dramatically reduced the level of longitudinal turbulence intensity in the tunnel test section. The turbulence in the closed test section was reduced from nominally 0.2% to 0.1% as shown in figure 4. In the open test section, turbulence of nominally 10% was reduced to a level of only 1% (figure 5). The 10% level in the unmodified tunnel was caused by periodic flow pulsations which were eliminated by installing a new flow collector in the open test section.

The Transonic Dynamics Tunnel (TDT) is also unique (refs. 3 and 4) in its capabilities for model rotor testing as is illustrated in figure 6. It can use "Freon-12," a heavy gas with a low speed of sound, as the test medium. The tunnel was originally designed to test large dynamic models for the simulation of important aeroelastic structural properties of fixed-wing aircraft at transonic speeds. The TDT is a continuous flow tunnel and can be operated with freestream Mach numbers up to 1.2 and dynamic pressures ranging up to 550 psf. The present capability (figure 7) of the tunnel is the result of modifications completed in 1985. Model rotor testing for performance and rotor-system dynamics takes advantage of these flow characteristics to provide scale simulation of rotor tip Mach number and high Reynolds number. Using Freon 12 as the test medium allows this simulation to be accomplished with substantially reduced requirements for model power and rotor blade spar strength as compared to testing in air (figure 8). Another feature of the tunnel which is useful for rotor research is an airstream oscillator system. A simulated gust field may be applied to the flow through the test section in the form of a sinusoidal oscillation of the flow direction. The oscillating flow is generated by a biplane arrangement of vanes on either side of the entrance to the test section. Both frequency and amplitude of vane motion can be varied to generate a wide range of gust characteristics. These features of TDT have made it an extremely useful tool for aerodynamic and dynamic research for helicopter technology.

A very specialized facility for rotor airfoil development is the Langley 6- by 28-Inch Transonic Tunnel (ref. 5 and 6). This facility is a blowdown tunnel with a slotted floor and ceiling and is generally operated at stagnation pressures from about 30 psia to 90 psia at Mach numbers from 0.35 to 0.90. At a stagnation pressure of 90 psia, the maximum Reynolds number, based on a 6.0 inch chord, varies from about 7.2×10^6 at a Mach number of 0.35 to about 14.3×10^6 at a Mach number of 0.90.

The facilities just described are key to the experimental work in rotorcraft aerodynamic technology developments at Langley, and they are complemented by model rotor test systems especially suited to the special capabilities of each of the facilities. The "General Rotor Model System" (GRMS) shown in figures 9 and 10 (ref. 7), and the "Two Meter Rotor Test System" (2MRTS) shown in figure 11 (ref. 8), are used in the 14- by 22-Foot Subsonic Tunnel; in the TDT, the "Aeroelastic Rotor Experimental System" (ARES) (figure 12) is used. The GRMS has been used to test rotors with diameters of 10 to 13 feet and rotor diameters for the 2MRTS have ranged from 5 feet to 6.5 feet. Both systems test rotors at full-scale tip speeds. On the ARES, the rotors are generally 9 feet in diameter. All three systems have been "work horses" and have been used in many experimental programs described in this paper.

Aerodynamic analyses are conducted as an essential adjunct to the experimental activity. These analyses are used to guide the experimental work in setting test objectives, and are themselves evaluated by the experimental results. The analyses treat the many aspects of helicopter design such as airfoils, rotor performance, rotor blade loads, and the interaction of rotor, airframe, and rotor inflow/wake. Computational codes developed by other research organizations are being used, but, code development is being carried on at Langley as well. Some of the codes in common use include the UTRC Free Wake, CAMRAD, VSAERO, HESS, AMI HOVER, C-81, Langley momentum hover program, and Langley DO 865. A variety of computers, from desktop personal computers to highly sophisticated mainframes such as the Control Data VPS-32, are available and used in rotorcraft aerodynamic analyses.

The following discussion is a review of some of the results of experimental and analytical work in rotorcraft aerodynamics which has been accomplished using the various capabilities at the NASA Langley Research Center.

DISCUSSION

Rotor Design

Over the past seven years, rotor design efforts have been directed toward an optimum combination of airfoils, planform, and twist (ref. 9) to provide advanced rotor designs for possible use on the UH-1 (figure 10, ref. 10), the AH-64 (figure 13, ref. 11), and the UH-60 (figure 12). The designs were evaluated in wind tunnel tests of models of the proposed rotors. The most distinctive feature of these rotor designs is the use of substantial taper of the rotor tip as much as 50 percent for the UH-1 design . Analyses by Gessow (ref. 12) many years ago showed that rotor hover performance could be improved by blade taper; this design philosophy was implemented with a rotor design for the UH-1 helicopter. Tests of a 25-percent scale model of the tapered rotor were conducted along with a model of the standard rotor in the 14- by 22-Foot Subsonic Tunnel using the GRMS. The test results validated the analytic prediction in that rotor performance for the advanced rotor was superior to that of the standard rotor, from hover up to 110 knots as shown in figures 14 and 15. Unfortunately the rotor hub (a 25%-scale model of the UH-1 hub) broke due to a fabrication flaw before the advanced design could be tested at a high thrust level (substantially higher than that for level flight at the design gross weight).

This specific approach to testing, in which one design is compared to another during the same test program under the same test conditions provides confidence in the results. By comparing rotor measurements obtained with the same rotor drive system, and data acquisition and reduction system, incremental effects (i.e. performance benefits) are more reliably defined. This approach was used for tests of AH-64 and UH-60 advanced designs.

The advanced AH-64 design shown in figure 13 also used an analytically defined optimum combination of taper, airfoils, and twist. Model rotors were fabricated at 27-percent scale for both the baseline (rectangular with swept tip) and advanced designs, and both rotors were tested with models of the AH-64 hub and fuselage at the same scale. All components were mounted to the GRMS and tested in the Langley 14- by 22-Foot Subsonic Tunnel. As was the case for the UH-1, the advanced design resulted in improved performance throughout most (ref. 11) of the normal operating envelope of the rotor (See figures 16 and 17). At high thrust coefficient in hover, the improvement in figure of merit may decrease to zero. The taper of the original advanced design was 5 to 1, starting at 80 percent radius and it was suspected that reducing the amount of taper to 3 to 1 would improve hover performance. The blade tips were altered to the reduced taper, and hover tests were conducted in the new rotor test cell at the 14- by 22-Foot Subsonic Tunnel. The reduced taper resulted in a hover performance improvement as can be seen in figure 16. It should be realized that the improvement due to reduced taper may be the result of Reynolds number effects and not just taper. Evaluation of forward flight performance for the 3 to 1 taper will be conducted at a future time.

The change of taper for the AH-64 was based on results of exploratory tests which had been conducted on smaller scale tapered blades using the 2MRTS system. Hover tests of three different four-bladed rotors were conducted in the tests of reference 13 to evaluate whether a prescribed wake code could properly predict trends for tapered blades. The three were a swept-tip design based on the UH-60 rotor design, a configuration with 3-to-1 taper over the outboard 20 percent of the blade span, and a configuration with a 5-to-1 taper over the outboard 20 percent of the blade span. The investigation covered a range of tip speeds and thrust levels. The two tapered configurations had better hover performance than the baseline swept-tip configuration, and the 3-to-1 taper configuration was somewhat better than the 5-to-1 configuration as shown in figure 18. The test results were compared with predictions made by using a prescribed wake analysis, a momentum strip-theory analysis and a simplified free-wake analysis. The performance of the baseline blade was in fair agreement with predictions from both momentum strip-theory analysis and the prescribed-wake analysis when appropriate low Reynolds number airfoil data were used. The performance of the two tapered-blade configurations was in fair agreement with the prediction of the momentum strip-theory analysis; however, the prescribed-wake analysis incorrectly predicted performance that was much worse than was measured for the two tapered configurations.

The art of designing "advanced" rotor blades was next applied to the UH-60. A new design incorporating wide blade chord, tip taper, new airfoils, and different twist was defined and tested with the ARES in the TDT tunnel as shown in figure 12. As expected, the advanced rotor design demonstrated better performance than did the baseline UH-60 design. The test results will be published. These three experimental programs of wind-tunnel testing of advanced designs for the UH-1, AH-64, and UH-60 have demonstrated that rotor blades incoporating substantial planform taper, advanced airfoils, and substantial twist will provide significant performance improvements in hover and forward flight.

Designing of advanced rotors such as those described has involved a tedious exercise of rotor performance codes as the three basic design variables of planform, airfoil, and twist were varied to home in on a "best" combination to meet specified performance requirements. But the efforts have paid off in the improved rotor thrust capability available in hover and increased efficiency in forward flight as demonstrated in the model test programs for the UH-1, AH-64 and UH-60. It should be realized that the percentage improvement in thrust is multiplied by a factor of 3 to 5 when useful load capability improvement is considered. In the last couple of years a more systematic approach for the design process has been initiated at Langley (Ref. 14). The Interdisciplinary Research Office has been tasked with the responsibility of integrating the computer codes into a formal optimization procedure for helicopter rotor blade designs. The proposed approach is to couple hover and forward flight analysis programs with a general purpose optimization procedure. The time and cost of designing rotor blades can then be significantly reduced to gain improvements such as demonstrated for the UH-1, AH-64, and UH-60.

A cooperative wind-tunnel test program was recently conducted at the Glenn Martin Wind Tunnel (figure 19) by the Aerostructures Directorate and the University of Maryland to investigate in more detail the effect of tapering of rotor blades on rotor forward flight performance. Analysis with the C-81 code indicated that taper beginning at about 94% blade span resulted in the lowest power required and, therefore, rotor performance improvements seen in earlier programs were, perhaps, attributable only to advanced airfoils and twist variations (ref. 15). However, the tests provided results which were contrary to the C-81 analysis that is, for high speeds as well as hover, tapering of blades inboard of 94% blade span is beneficial.

Rotor Airfoils

The advanced design rotors have incorporated modern airfoils (ref. 16 through 22) designed for rotor applications and tested at the Langley Research Center in the 6- by 28-Inch Transonic Tunnel. A great deal of airfoil design work over many years has been conducted at Langley for fixed wing aircraft, but interest in rotorcraft applications has been relatively recent (in the last 15 years). Of course, designing airfoil sections for a helicopter rotor is more complex than that for a fixed wing aircraft since a rotor airfoil can experience lift coefficients from negative values to the maximum positive value, and Mach numbers from low subsonic to transonic values all in one rotor revolution. Further, since the ranges of lift coefficients and Mach numbers depend on the radial location along the rotor blade and the helicopter flight condition, different airfoils need to be identified for specified ranges of radial positions along the rotor blades. Designing airfoils within the plethora of constraints is an art which has reached a high level of sophistication. At Langley two notable airfoil families for helicopter rotor application have been patented (ref. 21 and 22).

Rotor Inflow and Wake Studies

Defining the inflow to a rotor is a key element in predicting the performance, blade loads, and acoustic characteristics of a rotor. Also, defining the wake generated by the rotor is important in estimating helicopter fuselage aerodynamics. Unfortunately for helicopter designers, the analyses for definition of inflow and wake effects have little experimental data to validate them. Though some work in rotor inflow and wake measurement has been accomplished by Heyson (ref. 23), Landgrebe (ref. 24), De Sopper (ref. 25) and McMahon (ref. 26), much more is needed to provide a comprehensive database describing the time dependent and azimuth dependent flow characteristics. In the last several years the experimental capability needed to acquire such data has been built up at the Langley 14- by 22-Foot Subsonic Tunnel and centers around the use of a high powered laser velocimeter (LV) system (ref. 27). The LV system shown in figure 20 is dedicated to the facility, and was built up by personnel of the Rotorcraft Aerodynamics Office.

The LV is a dual-color four-beam fringe type system operating in a back scatter mode. Positioning of the measurement point within a cube of approximately 2 meters on a side is accomplished with a combination of rotation of mirrors and movement of the entire LV system enclosure within the large traverse apparatus shown in figure 20. Rather complex subsystems for remotely controlling the measurement point, acquiring the data, and reducing the data to engineering units have been developed by the researchers, and they functioned extremely well in recent test programs (ref. 28) to obtain measurements of rotor inflow. Because the LV system is dedicated to research, there is an ongoing program of system enhancements to accelerate the data acquisition process. For example, the flow seeding system presently requires manual translation of a large spray array located in the tunnel settling chamber. Even with this limitation, however, it provided excellent data rates (number of particles passing through the measurement point per unit time) with 1.7 micron particles. The manual system will be replaced with a remote positioning system which will speed up the process of obtaining high data rates. Also, the Langley Instrumentation Research Divison which has contributed to the development of the current LV system has been provided funding for the definition of modifications to obtain a third velocity component.

In its current state the LV system has made it possible to begin mapping the inflow of generic research rotors, and to assess the effect of blade geometry (such as rectangular and tapered planforms) on rotor inflow characteristics (figure 21). Two programs have been conducted this past year and a sampling of the data obtained is shown in figure 22. The data include a full mapping of the rotor disc at approximately 1 blade chord above the rotor tip-path plane. Figure 22 provides a three-dimensional view of average inflow normal to the rotor disk. The time-varying inflow at a point is shown in figure 23. With each model entry, system enhancements have been made and will continue to be made with a view toward investigating the effects of variations of the many parameters such as advance ratio, thrust coefficient, blade number, blade planform, and proximity to the rotor. The early data obtained have already been compared with some of the many coded predictions of inflow for validation of the codes (ref. 28).

Rotor/Fuselage Aerodynamic Interaction

The rotor and fuselage interact aerodynamically in a very complex way and there is presently a paucity of test data to validate the analyses currently used to quantify the interaction effects (refs. 26 and 29). To remedy the situation two helicopter models with generic fuselage shapes have been instrumented with miniature transducers and in recent tests at the Langley 14- by 22-Foot Subsonic Tunnel, time dependent pressures were measured to investigate the influence of the rotor wake. In the most recent program a two bladed rotor with over 100 miniature pressure transducers on the blades (figure 24) provided high quality data which are being used to evaluate wake/fuselage interaction codes. Simultaneous measurements of pressures on the blades and fuselage were obtained, along with measurements of blade loads.

Flow distortions caused by the fuselage affect rotor inflow, and the rotor wake in turn affects fuselage pressure distributions. Both average and time-dependent distortions are the result of these mutual perturbations. The extent to which interactional aerodynamics can influence helicopter vibrations was not sufficiently appreciated until recent years when the new series of military helicopters (AH-64, UH-60) began to experience more pronounced aerodynamically excited vibrations. Analytical methodology to predict and study the interactional causes and effects, particularly those related to the time- dependent excitations effecting vibrations, has not yet been fully developed, although, in recent years significant progress has been made toward the development of computerized methods which can take into account the large array of variables which need to be considered.

Two analytic approaches are being studied at Langley. One of these is a contractual effort with UTRC which is leading to a method for a first-order treatment for vibration purposes as represented in figure 25. In this approach, a rotor aeroelastic analysis ("G400" code) for predicting rotor aeroelastic response characteristics, a rotorcraft wake analysis ("RWA" code) for predicting rotor blade and wake induced airflow velocities, and an analysis predicting fuselage pressure distribution ("WABAT" code) are being integrated to predict interactional excitations for vibration analysis. The separate codes are being extended where necessary to model blade, wake, and fuselage surface pressures (including empennage surfaces). It should be recognized that the aerodynamic interactions are very complex and are influenced by features such as hub/pylon separated wake and tail rotor interactions which are beyond the scope of the initial study. It is not a complete treatment, by any means, but it is providing a framework for future refinements.

A second approach to modeling analytically the rotor/fuselage interactive aerodynamics is being developed in which an existing general panel method ("HESS" code) for calculation of flow about arbitrary shapes is being combined with a model ("Crispin" code, ref. 30) of the rotating blade system. The geometry of the rotor wake is computed with the Crispin code and allowed to contribute to the flow field of the total configuration. The integration of the two codes has required substantial changes to both. The capabilities of the Crispin code have been extended by providing for a two-bladed rotor and including a means of accounting for cyclic pitch variations. The wake prediction of the code is shown in figure 26. Both analytic codes are being developed with the objective of being validated by experimental data obtained in the Langley 14- by 22-foot Subsonic Tunnel.

Interactional aerodynamic problems of helicopters are sometimes of a comparatively minor nature and involve separated flows so that experimental methods are the most effective means of study. One such problem is identified in references 31 through 33, and a simple solution is proposed in reference 34. A single-main-rotor helicopter being flown at low speeds has the tail boom immersed in the rotor wake. When flown in right sideward flight, the aerodynamic pressures on the tail boom resulting from the high downwash velocities of the wake can result in adverse side loads on the boom. The side loads contribute a yawing moment which may be beyond the capability of a tail rotor to counteract since it is already burdened by the need to counteract the main rotor torque. Such a limitation has been experienced by the AH-64, AH-1S, and the British Sea King helicopter. A spoiler (or strake) mounted on the upper left shoulder of a tail boom as shown in figure 27 has been shown to be effective in reducing the tail boom yawing moment, thereby improving heading control in sideward flight as shown in figure 28 for the SH-3.

Diagnostic Testing Activities

In addition to the fundamental research studies discussed so far, Army researchers at the Aerostructures Directorate are occasionally asked to investigate the causes of aerodynamic problems encountered in Army helicopter operations, or to develop solutions to problems whose causes have been identified in field operations. The availability of several helicopter modeling systems and full-scale components, along with the wind tunnels and computational capability at the NASA Langley Research Center have made it possible for Aerostructures Directorate researchers to respond quickly to Army needs. Two recent experimental efforts illustrate typical diagnostic testing conducted by researchers at the 14- by 22-Foot Subsonic Tunnel. One of these efforts addressed a concern regarding the AH-64 and the other focused on the UH-60 stabilator.

The AH-64 "Apache" is vulnerable, as many helicopters are, to being blown over by high winds when it is parked but not tied down, but the extent to which the Apache was subject to this danger was not known. A large AH-64 model was tested in the 14- by 22-Foot Subsonic Tunnel as shown in figure 29 to study this problem in detail. The model was yawed through a range of -20 to +160 degrees, and the wind loading which could tip the helicopter over was evaluated. Figure 30 shows tests results in terms of the combination of critical wind speed and azimuth for which tipover could be expected to occur.

A second study used a full scale UH-60 stabilator to measure the airloads which can occur at a combination of high flight speeds and high tail incidence. If the large UH-60 stabilator is inadvertently deflected to high incidence at high flight speed, the resulting pitching moment about the center of gravity would be beyond the capability of the pilot to counteract through rotor cyclic control. A flightworthy stabilator was installed in the tunnel (figure 31), and the airloading on the basic stabilator was measured. Various small spoilers were attached near the leading edge to reduce the lift load at high incidence. Though spoilers were not very effective at angles of attack near 45°, they were very effective at angles of attack of between 10 and 20° where the problem of uncontrollable pitching moment is more likely to occur. Figure 32 summarizes the results of the tests on the UH-60 stabilator.

CONCLUDING REMARKS

The Aerostructures Directorate of USAARTA (AVSCOM) has continued to utlize capabilities in facilities, equipment, and personnel at Langley to make significant contributions to rotorcraft technology. These contributions cover a broad range of research in several areas, including rotor design, rotor airfoils, and rotor/fuselage interactional aerodynamics. Additional testing activities are also conducted to address operational needs on a quick response basis. Key facilities which aid in accomplishments in these facets of helicopter aerodynamics are NASA Langley's 14- by 22-Foot Subsonic Tunnel, the Transonic Dynamics Tunnel, and the 6- by 28-Inch Transonic Tunnel.

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Figure 1. The 14- by 22-Foot Subsonic Tunnel.

Figure 2. Transonic Dynamics Tunnel.

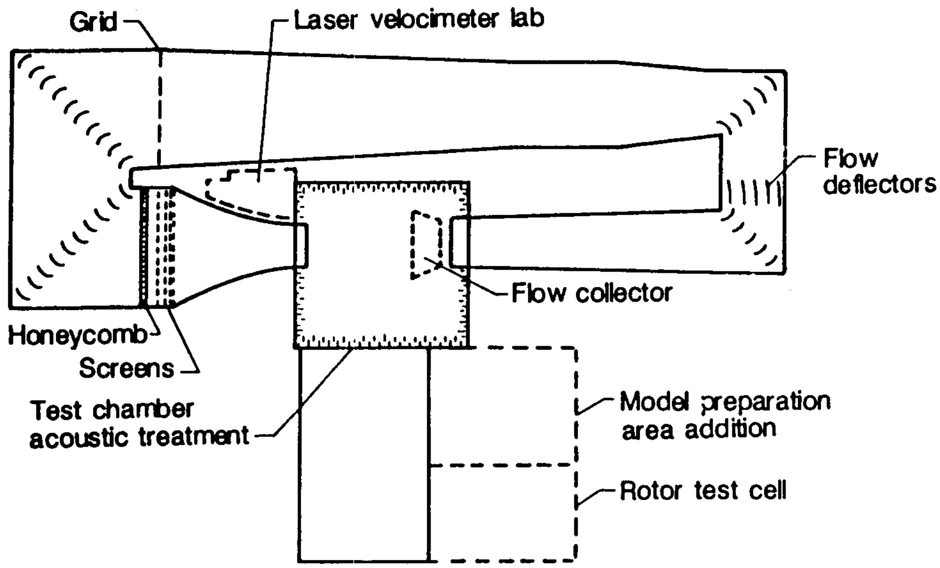

Figure 3. Modifications of the 14- by 22-Foot Subsonic Tunnel.

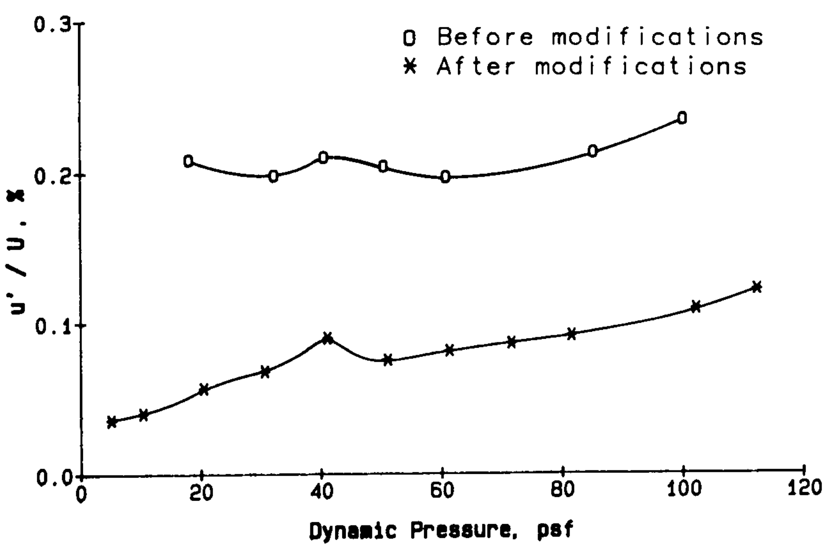

Figure 4. Turbulence intensity in the closed test section of the 14- by 22-Foot Subsonic Tunnel.

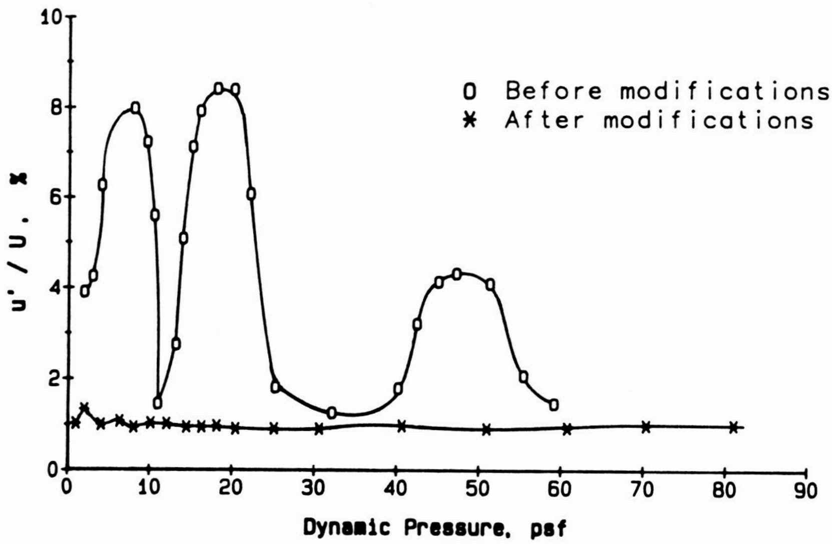

Figure 5. Turbulence intensity in the open test section of the 14- by 22-Foot Subsonic Tunnel.

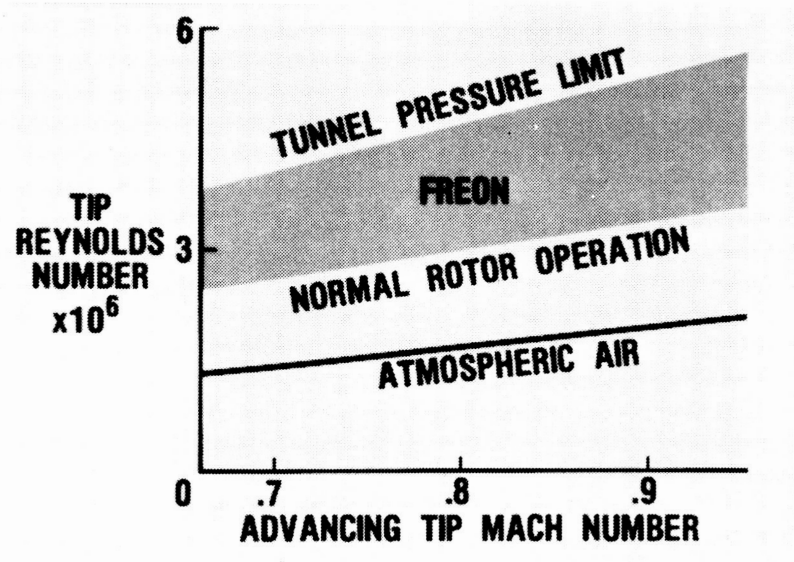

Figure 6. Rotor performance modeling improved at the Transonic Dynamics Tunnel.

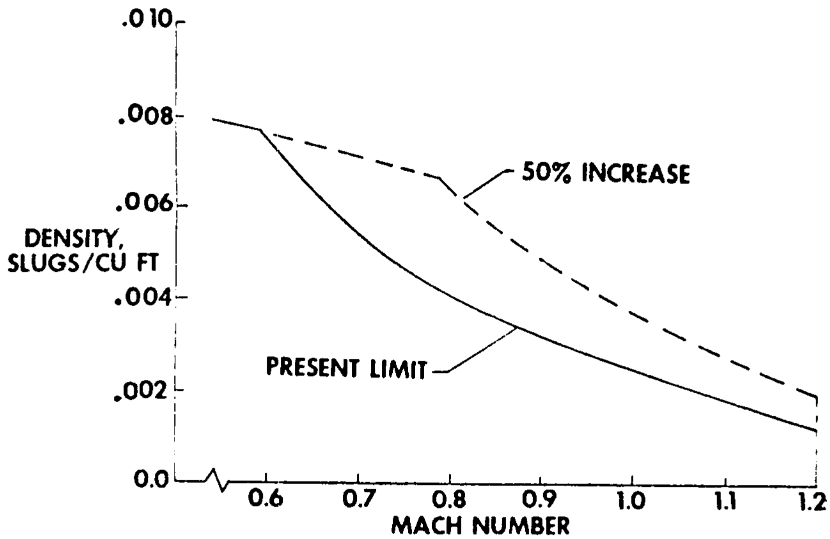

Figure 7. Increased test capability at the Transonic Dynamics Tunnel.

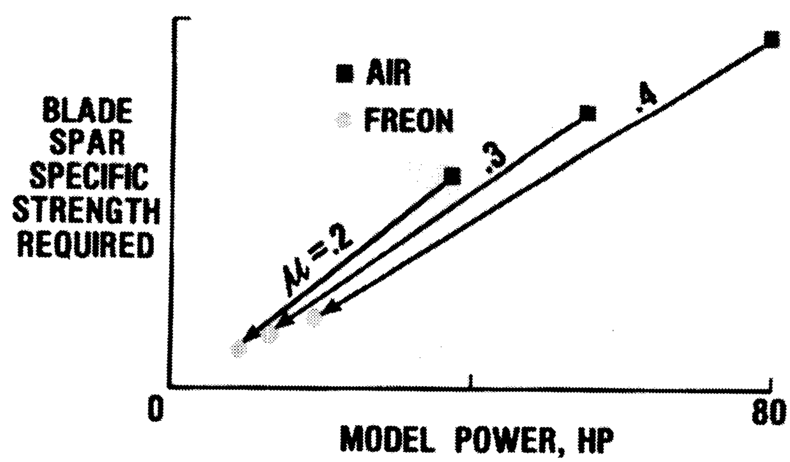

Figure 8. Rotor model torque and required strength reduction in the Transonic Dynamics Tunnel.

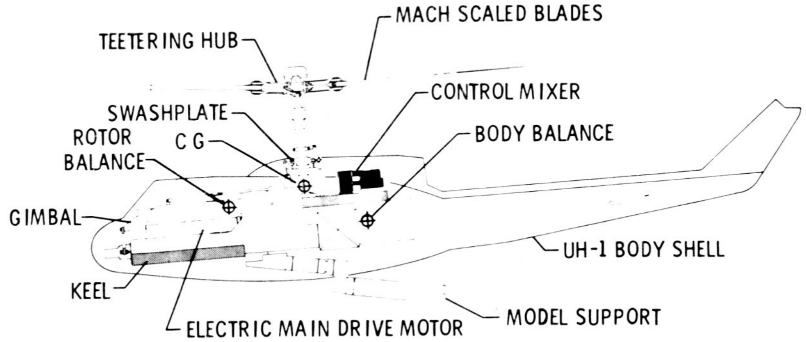

Figure 9. General Rotor Model System.

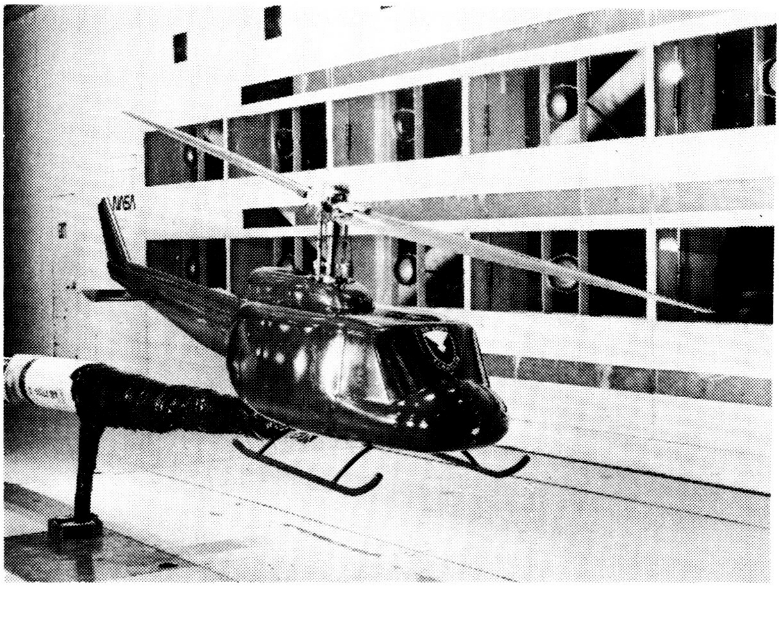

Figure 10. Installation of 1/4 scale UH-1 on the GRMS in the 14- by 22-Foot Subsonic Tunnel.

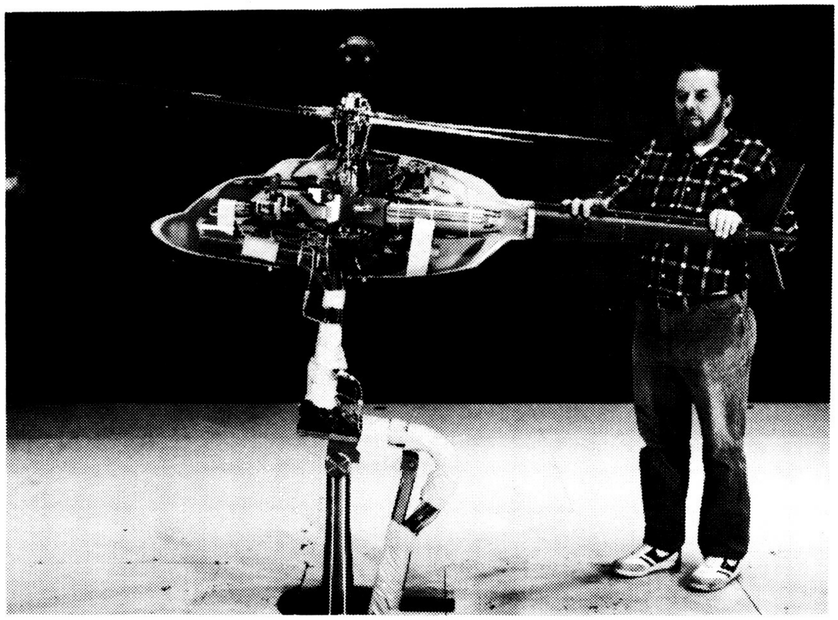

Figure 11. Installation of AHIP model on the 2MRTS in the 14- by 22-Foot Subsonic Tunnel.

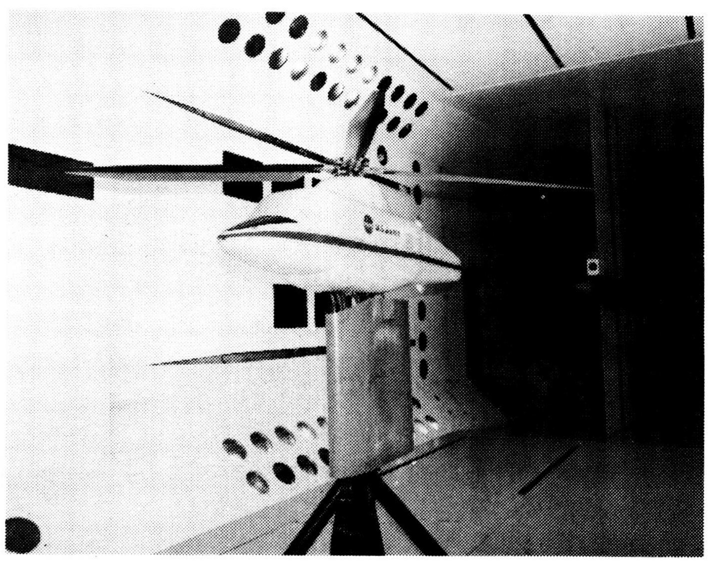

Figure 12. Installation of ARES with advanced design UH-60 rotor blades in the Transonic Dynamics Tunnel.

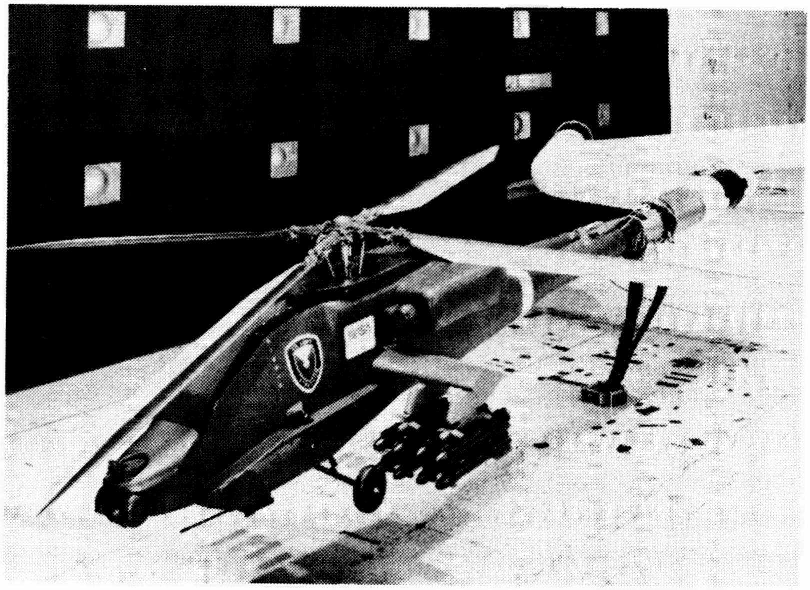

Figure 13. 27-percent scale AH-64 model on the GRMS in the 14- by 22-Foot Subsonic Tunnel.

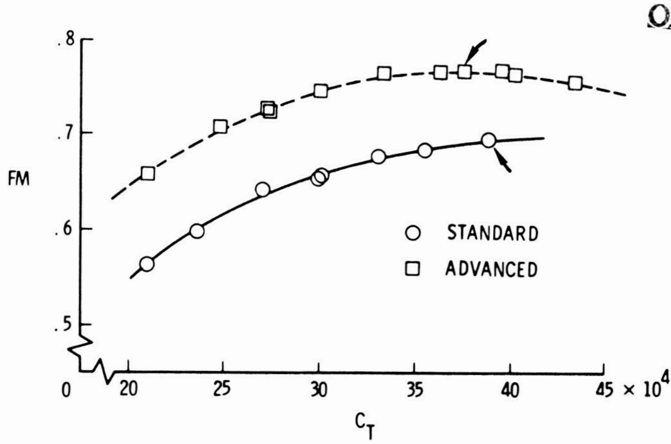

Figure 14. Hover performance (figure of merit) improvement for the advanced design UH-1 rotor.

IN HOVER (O.G.E.)

	STANDARD	ADVANCED	CHANGE	%
FIGURE OF MERIT	0.695	0.766	0.071	10.2
SHAFT HORSEPOWER*	1100	1003	97	8.8
GROSS WEIGHT, LBS*	9336	10000	664	7.1

IN FORWARD FLIGHT

POWER REDUCTION

	SPEED, KNOTS		
	60	90	110
SHAFT HORSEPOWER*	137	164	222
PERCENT (%)	19.3	19.7	20.6

*SEA LEVEL STANDARD ATMOSPHERE

Figure 15. Summary of model UH-1 rotor test results (converted to full scale)

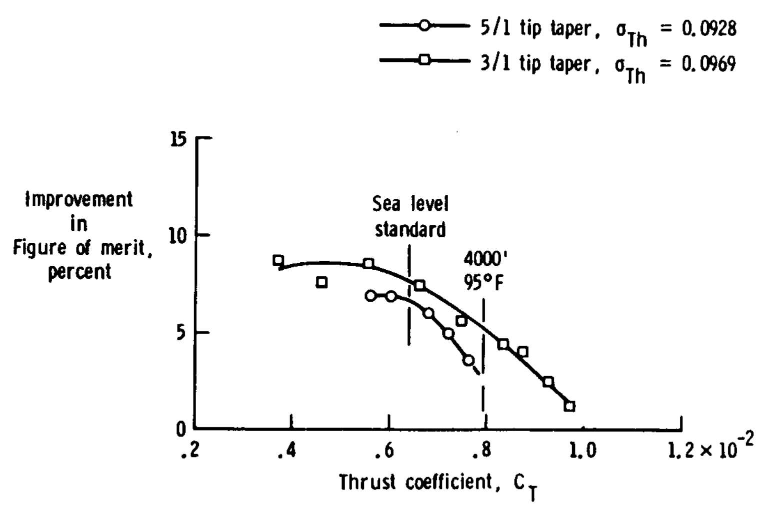

Figure 16. Hover performance improvement for the advanced design AH-64 rotor.

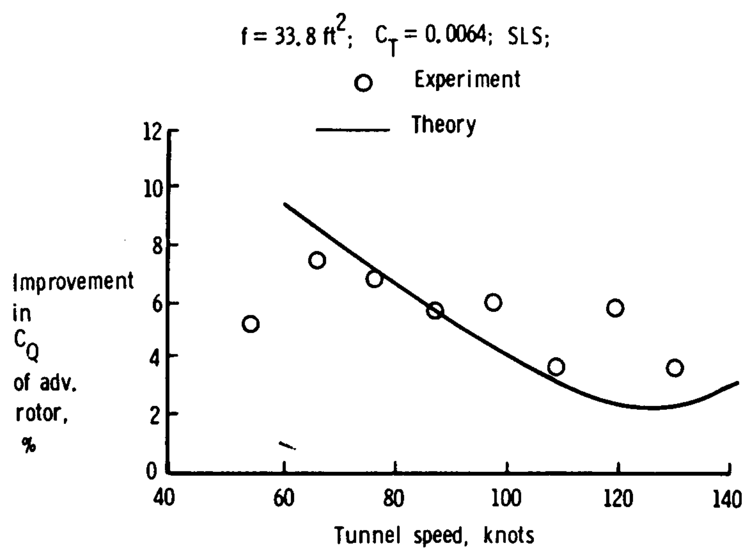

Figure 17. Forward flight performance improvement for the advanced design (5/1 tip taper) AH-64 rotor.

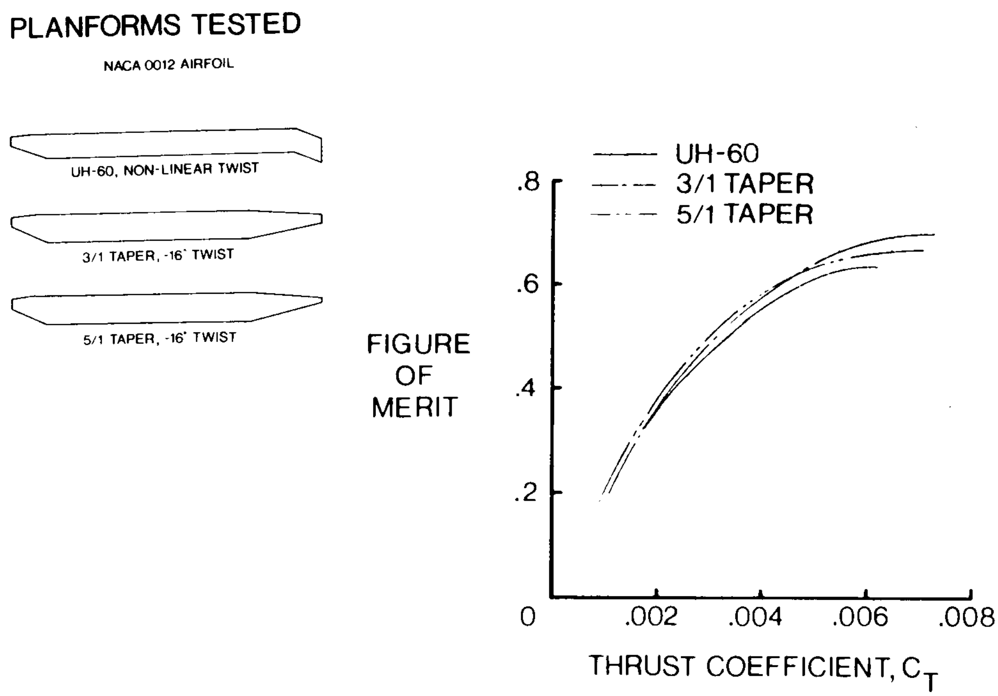

Figure 18. Effect of tip taper ratio on hover performance as measured with the 2MRTS.

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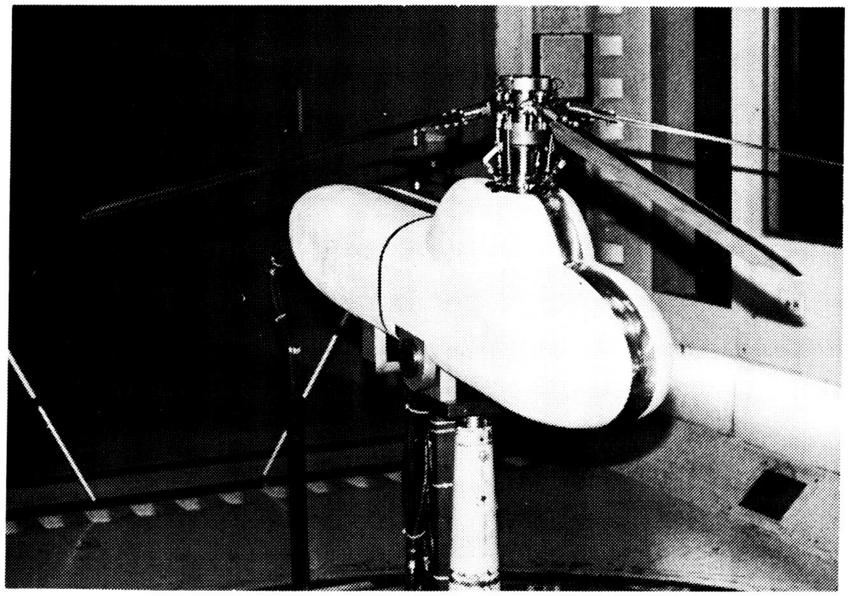

Figure 19. Tapered rotor blade test installation in the University of Maryland wind tunnel.

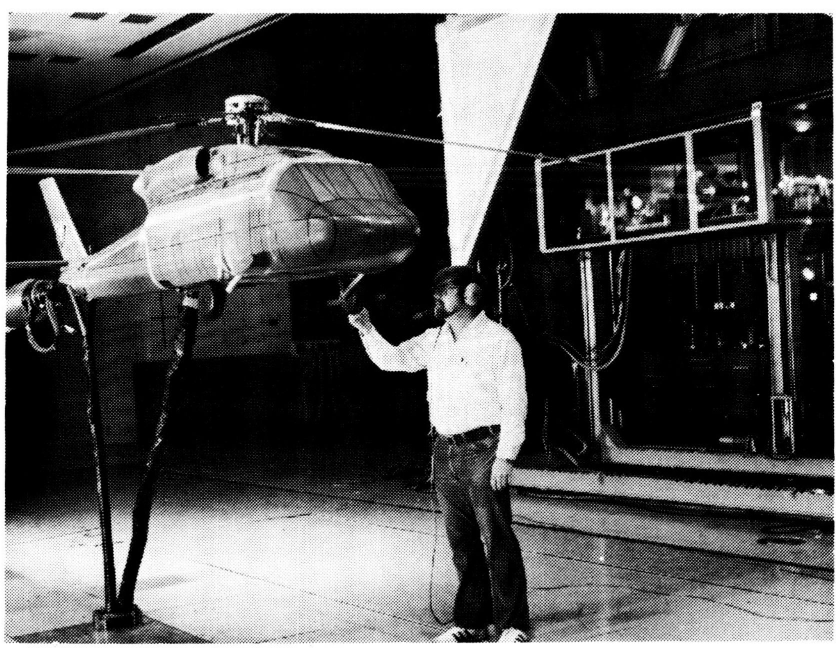

Figure 20. Laser velocimetry installation in the 14- by 22-Foot Subsonic Tunnel.

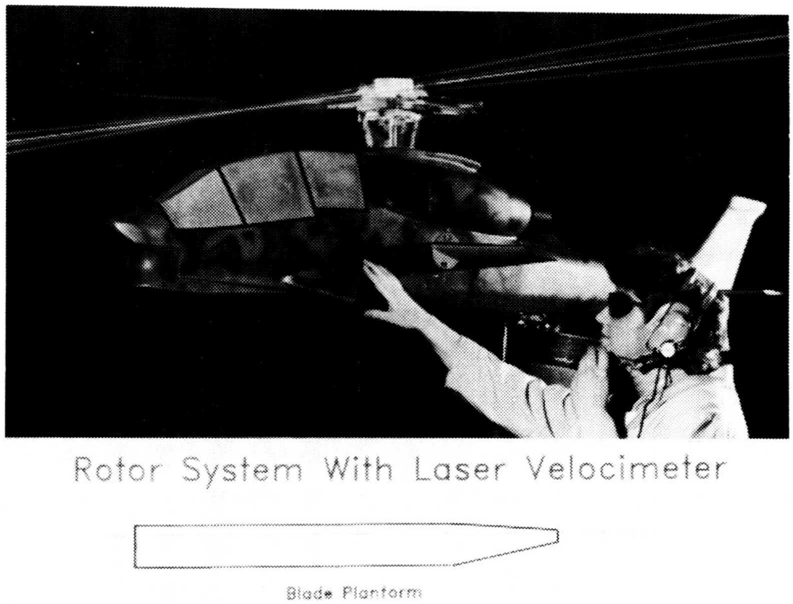

Figure 21. Rotor inflow measurement installation.

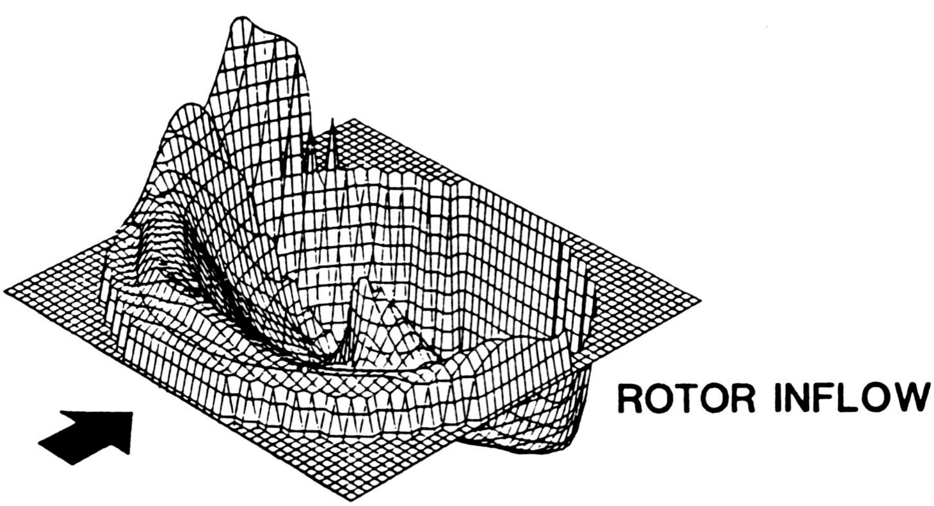

Figure 22. Three-dimensional plotting of measured average inflow velocities normal to rotor tip path plane.

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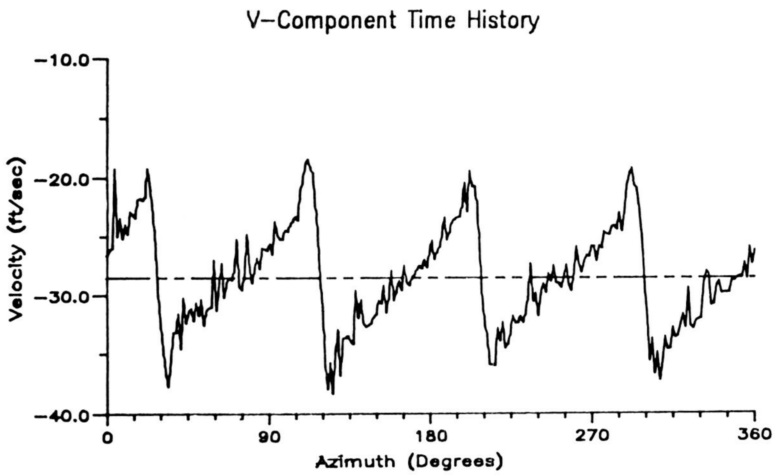

Figure 23. Inflow velocity at a point above the rotor disc varying with time.

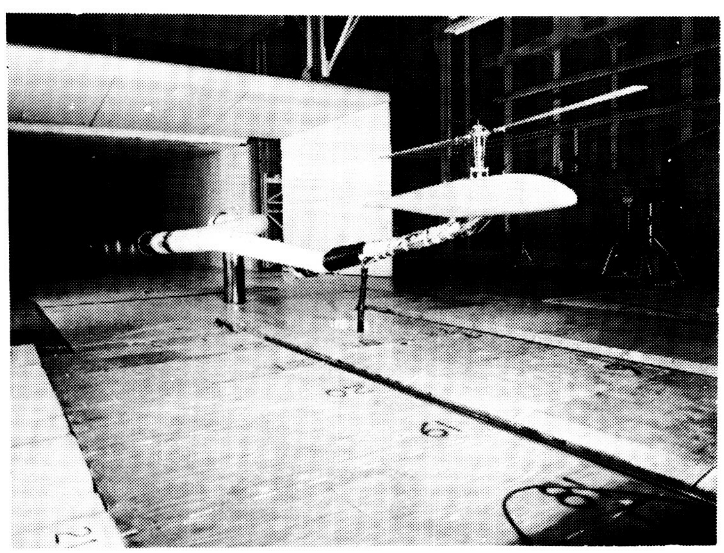

Figure 24. Pressure instrumented rotor installation in the 14- by 22-Foot Subsonic Tunnel.

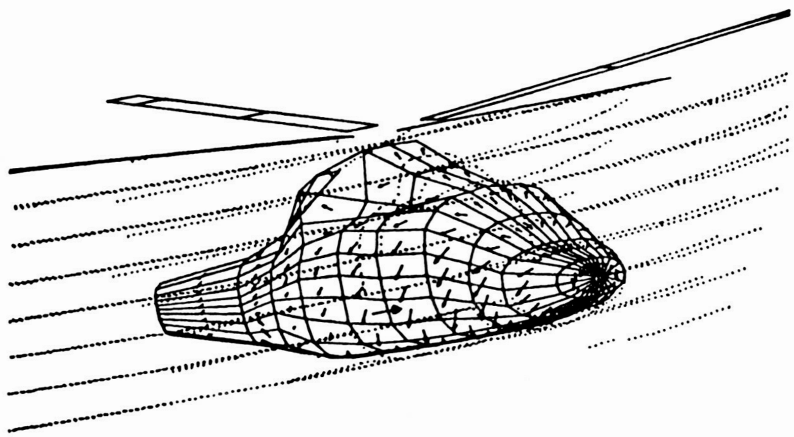

Figure 25. Interactive aerodynamics code development.

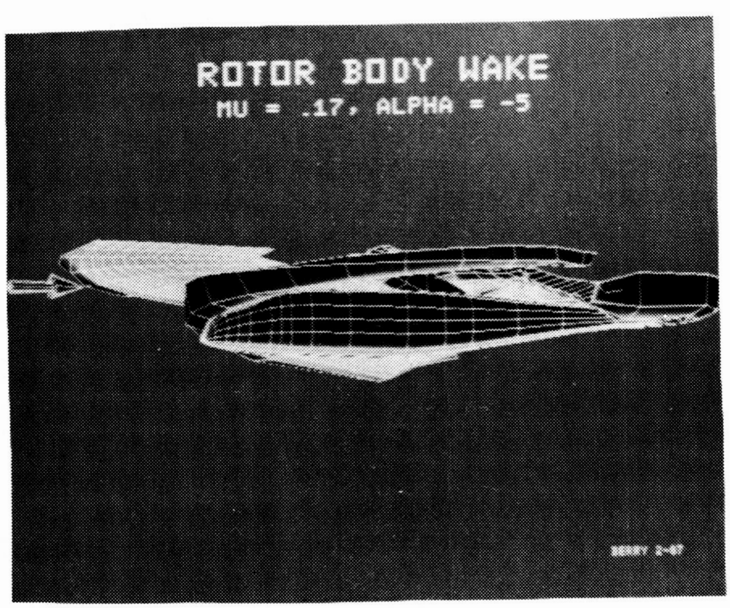

Figure 26. Wake prediction code development.

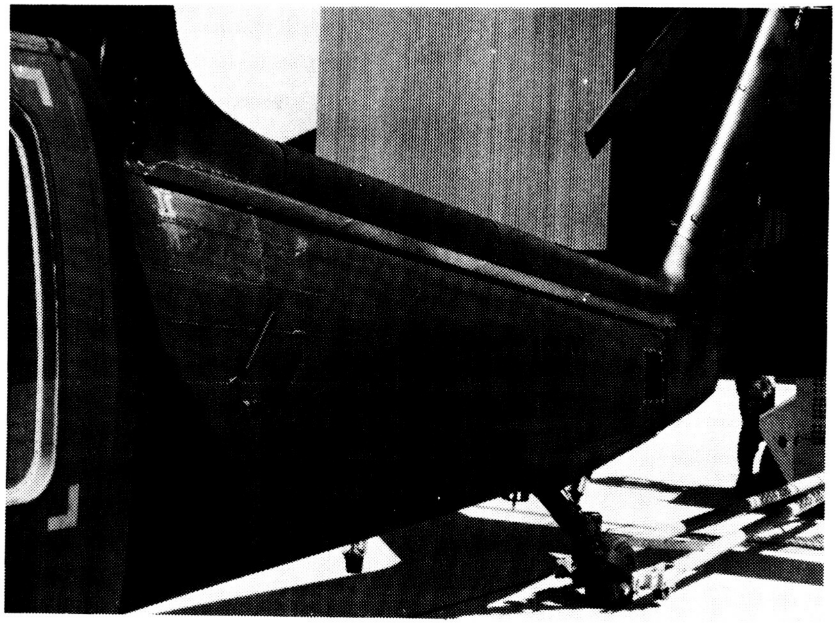

Figure 27. Strake installation on the UH-60 tail boom.

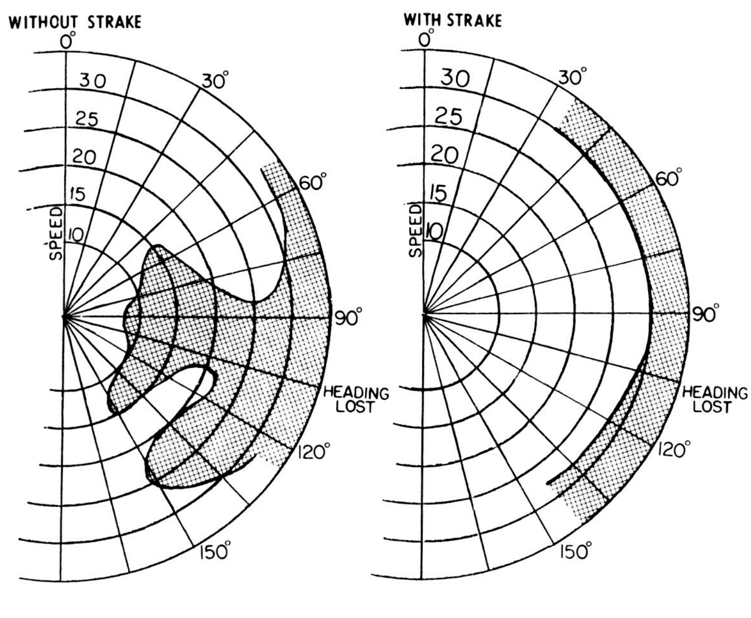

Figure 28. Sideward flight limitation of the SH-3 alleviated with a strake.

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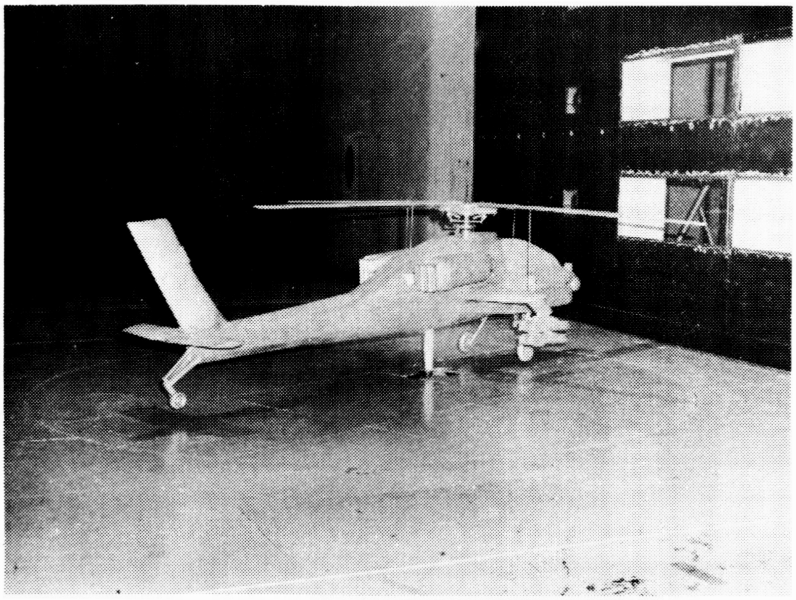

Figure 29. AH-64 "tipover" test installation in the 14- by 22-Foot Subsonic Tunnel.

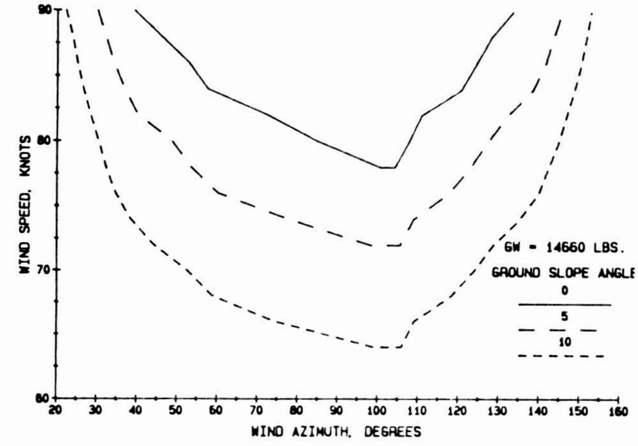

Figure 30. Critical wind velocities and azimuth for a parked AH-64.

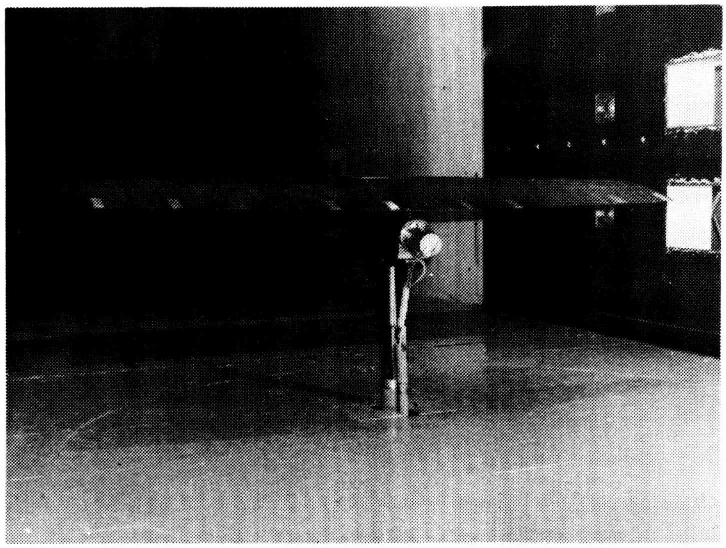

Figure 31. UH-60 stabilator installation in the 14-by 22-Foot Subsonic Tunnel.

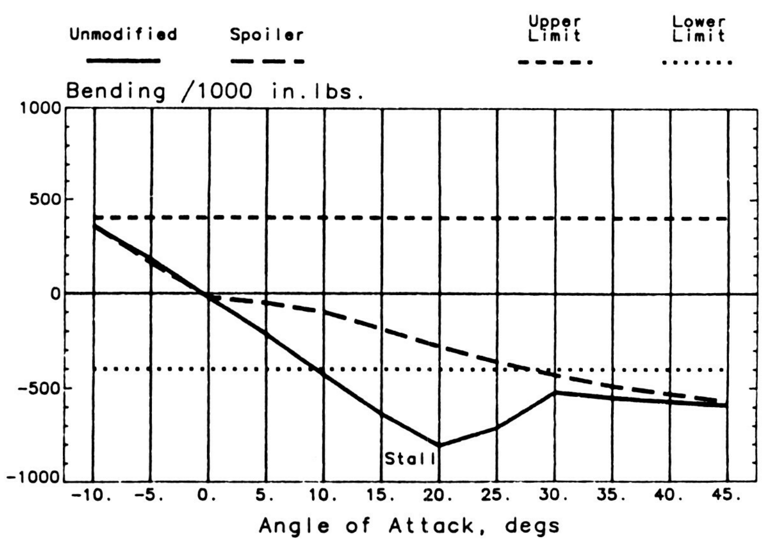

Figure 32. UH-60 stabilator contribution to rotor shaft bending moment at a flight speed of 120 knots.