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Henry L. Kelley
Aerostructures Directorate
USAARTA-AVSCOM
Langley Research Center
Hampton, Virginia

National Aeronautics
and Space Administration

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Summary

The hover performance of a 27-percent-scale model baseline rotor and advanced rotor with a 3:1 tapered tip (TR3) for the AH-64 attack helicopter was investigated in the rotor test cell at the Langley 14- by 22-Foot Subsonic Tunnel as part of on-going efforts to improve rotorcraft efficiency. The hover performance of the baseline rotor was compared with that of the TR3 rotor and with that of a previously tested advanced rotor with 5:1 tapered tip (TR5). Rotor thrust in hover at a rotor height-to-rotor diameter ratio of 1.46 was varied over a range of thrust coefficients for rotor tip Mach numbers of 0.63 and 0.57, respectively. The rotor with the TR3 blades had improved hover performance as compared with the rotor with the TR5 blades, and both the TR3 and the TR5 blades were superior to the baseline rotor in terms of figure of merit for the range of thrust coefficients from 0.0020 to 0.0100. The additional margin in performance for the TR3 blades as compared with the TR5 blades was likely due to an increase in blade area and Reynolds number at the blade tip region brought about by the change in taper ratio from 5:1 to 3:1. Hover performance characteristics measured on the baseline rotor in both the open test section by the Langley 14- by 22-Foot Subsonic Tunnel and in the rotor test cell indicate reduced rotor wake recirculation effects in the test cell.

Introduction

As part of an on-going effort to improve rotorcraft efficiency, the hover performance characteristics of a 27-percent-scale advanced rotor model with a 3:1 tip taper designed to perform the mission of the AH-64 attack helicopter were investigated in the rotor test cell at the Langley 14- by 22-Foot Subsonic Tunnel. A baseline rotor, scaled from the current AH-64 and designed by McDonnell Douglas Helicopter Company was also tested to provide data for correlation purposes. The rotor drive system, fuselage shell, hub, and the two rotor blade sets were the same as those used in an earlier investigation (refs. 1 and 2) except for the change in planform taper over the outer 20 percent of the radius of the advanced rotor. The 3:1 tip taper of the present rotor (TR3) was obtained by modifying the outboard 20 percent of the 5:1 tapered blade (TR5) of reference 2. The advanced rotor was designed by Army researchers in the Aerostructures Directorate, USAARTA, U.S. Army Aviation Systems Command at NASA Langley Research Center (ref. 3) to improve hover performance with no degradation in forward-flight performance and was scaled in mass and stiffness to match the baseline rotor.

The aerodynamic design of the advanced rotor was based on rotor and airfoil technology demonstrated in wind-tunnel tests conducted at Langley on models of the UH-1, UH-60, and AH-64 and generic designs (refs. 3 through 7). In addition, there are many other efforts to improve rotor performance taking place throughout the rotorcraft industry (refs. 8 to 13). The purpose of the reduced taper from 5:1 to 3:1 was to increase the thrust-weighted solidity (an increase of 4.4 percent) and to increase the Reynolds number in the tip region of the blade. These changes were expected to result in an overall performance improvement, especially at high thrust conditions. In addition to the tip taper and the airfoils, the advanced rotor designs (TR3 and TR5) included 12° linear twist compared with 9° for the baseline rotor.

The purpose of this investigation was to measure the hover performance of the advanced rotor with the TR3 blades and compare the results with those of the baseline rotor and of the previously studied advanced rotor with the TR5 blades. The test also provided an opportunity to compare the hover performance of the baseline rotor measured in the open test section of the Langley 14- by 22-Foot Subsonic Tunnel obtained during an earlier investigation with measurements obtained in the rotor test cell. Rotor thrust and torque were measured in hover at a ratio of rotor height to rotor diameter of 1.46. Rotor thrust coefficient was varied incrementally between 0.0017 to 0.0103, as limited by power available, at rotor tip Mach numbers of 0.63 (1070 rpm) and 0.57 (963 rpm).

The results are compared in terms of rotor torque coefficient and figure of merit as functions of rotor thrust coefficient. The improvement in figure of merit between the TR3 and TR5 rotors (data from rotor with TR5 blades taken from ref. 2) is compared with the baseline rotor as a function of rotor thrust coefficient. Performance characteristics measured on the baseline rotor in both the open test section of the 14- by 22-Foot Subsonic Tunnel and the rotor test cell are compared to obtain initial indications of rotor wake recirculation effects in each facility.

Symbols

C_Q	torque coefficient, $Q/\rho\pi R^2(\Omega R)^2 R$
C_T	thrust coefficient, $T/\rho\pi R^2(\Omega R)^2$
c	blade chord, ft
c_e	thrust-weighted equivalent blade chord, $\int_0^1 cx^3\,dx/\int_0^1 x^3\,dx$, ft
D	rotor diameter, 12.96 ft

FM	figure of merit, $0.707C_T^{3/2}/C_Q$
H	height from centerline of rotor hub to floor, ft
M_{tip}	rotor hover tip Mach number
n_r	rotor rotational speed, rpm
Q	torque, ft-lb
R	rotor radius, 6.48 ft
r	radial distance to blade element, ft
T	thrust, lb
TR3	blade planform with a taper ratio of 3:1
TR5	blade planform with a taper ratio of 5:1
V_{tip}	velocity at rotor tip, ΩR, ft/sec
x	nondimensional blade radius, r/R
ρ	local density of air, slugs/ft^3
σ_{th}	thrust-weighted solidity, $4c_e/\pi R$
Ω	rotor angular velocity, rad/sec

Apparatus And Procedure

The investigation was conducted in the rotor test cell at the Langley 14- by 22-Foot Subsonic Tunnel. The experimental hardware included (1) the NASA/Army General Rotor Model System (GRMS, ref. 14), (2) a 27-percent rotor hub dynamically scaled from the AH-64 hub, (3) a set of 27-percent baseline rotor blades scaled geometrically and dynamically from the AH-64 main rotor blade, (4) a set of 27-percent advanced-geometry rotor blades designed to be dynamically similar to the baseline blades, and (5) a model airframe scaled to the AH-64. Pertinent details of the test facility, model hardware, and rotor design considerations are as follows.

Apparatus

Rotor test cell. The rotor test cell was recently completed as part of a program to upgrade the Langley 14- by 22-Foot Subsonic Tunnel facility. It is an addition to the existing model preparation area and is approximately 42 feet wide, 69 feet long, and 48 feet high with louvers on the top and bottom of two adjacent outside walls to reduce ground recirculation effects (fig. 1). This was the first test of a large model rotor which had also been tested in the 14- by 22-Foot Subsonic Tunnel open jet test section configured for hover testing (ceiling and sidewalls raised and test section floor lowered) and provided an opportunity to assess the relative merits of the two test sites for hover testing rotors of this size. A plan-view sketch showing the floor area (lowered during hover testing) relative to the rotor disk area is given in figure 2.

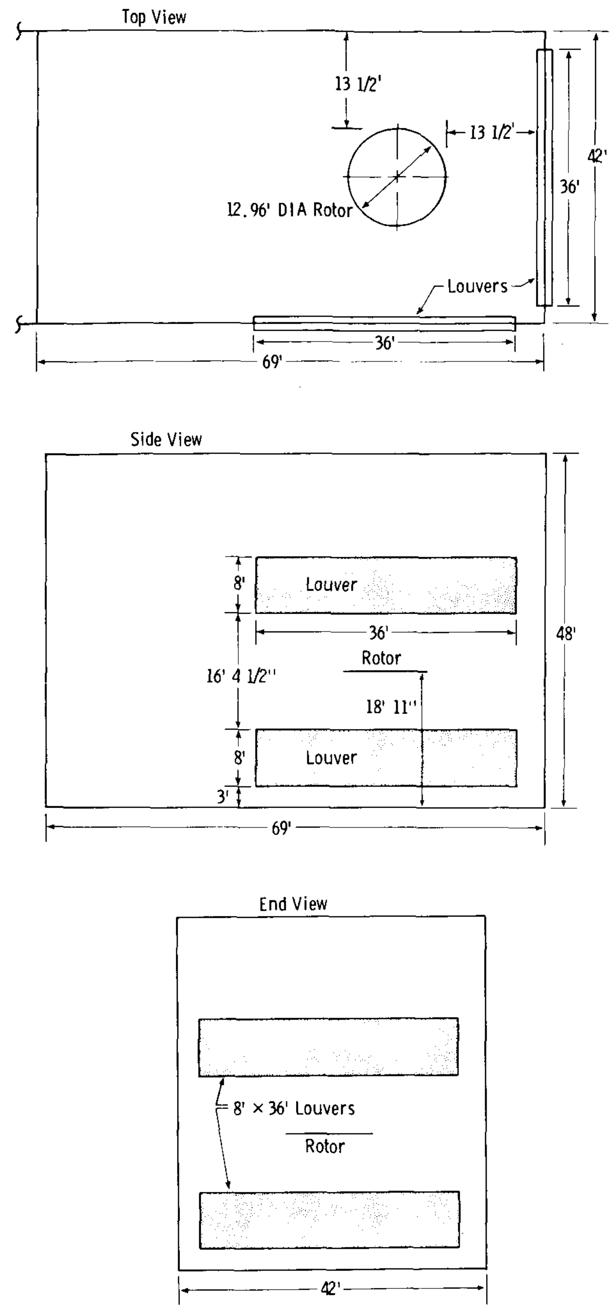

Figure 1. Sketches of rotor test cell showing relative size and placement of rotor as tested.

Rotor drive system. The rotor drive system was the General Rotor Model System (GRMS) which is a fully instrumented rotor drive system that can be configured for a wide variety of rotors (refs. 14 and 15) and consisted of two electric motors, a transmission, and a cyclic and collective control

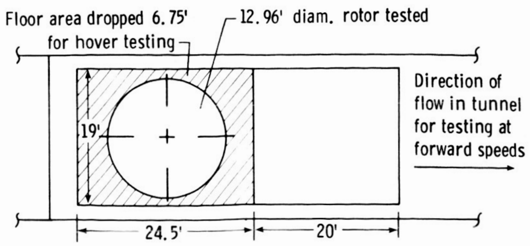

Figure 2. Plan view of test section of Langley 14- by 22-Foot Subsonic Tunnel showing size of rotor area relative to area of floor lowered during hover testing.

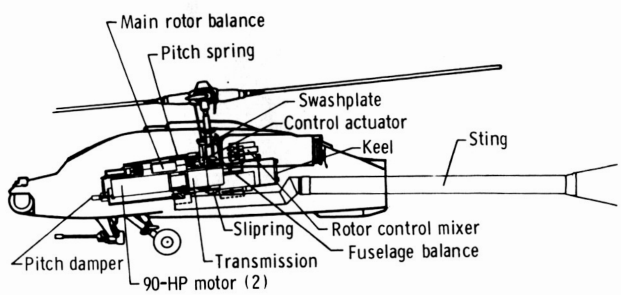

Figure 3. Sketch of model installed on General Rotor Model System (GRMS).

system. Because of a slight mismatch between transmission gearing and rotor design speed, a maximum of 155 hp was available from the two 90-horsepower electric motors during this test. The rotor and power train were mounted on a gimbal which consisted of pitch and roll springs and adjustable dampers. A sketch showing the model of the AH-64 mounted on the GRMS is given in figure 3, and a photograph of the model attached to the GRMS and installed in the rotor test cell is given in figure 4. The advanced rotor with TR3 blades is shown in the photograph.

A six-component strain-gauge balance supported the rotor system including the actuators, electric drive motors, and transmission. Based on balance design specifications, the rotor balance data are accurate to ± 0.000003 for C_Q and ± 0.00002 for C_T and represent 0.5 percent of full balance load. However, practice has demonstrated accuracy of 0.2 percent of full-scale balance loads. Rotor rotational speed and azimuthal position were measured by an optic tachometer and trigger. Blade flapping, feathering, and control angles were monitored and recorded. Seven channels of blade strain data and one channel of pitch-link strain data were also monitored and recorded, primarily for model safety purposes.

Hub. The AH-64 model hub (fig. 5) was dynamically scaled and duplicates the major features of the full-scale AH-64 hub. A detailed description of the design and development of the hub is presented in reference 1. The hub is fully articulated and features a multilayered strap retention system located inside the pitch cases and elastomeric lead-lag dampers located on either side of the pitch cases. The straps inside the pitch housing transmits the feathering input to the blade. As with the full-scale hub, the lead-lag motion of the blade takes place through a fitting which is mounted at the outboard end of the pitch cases and connects the pitch case, blade, and lead-lag dampers (fig. 5).

Blades. A plan view showing key parameters of the model blades is given in figure 6. Compared with the baseline blade, the advanced blade (TR3) had a linear twist of $-12°$, an increased inboard chord of 7.17 in., and 3:1 planform taper from the 0.8 blade radius to the tip. The TR3 blades were modified from the TR5 blades with the only differences being the tip taper. Three airfoil sections developed at Langley for rotorcraft application were utilized on both advanced rotors. The data for the NASA RC(3)-10 and the NASA RC(3)-08 airfoils are defined in reference 7. Data for the modified RC(3)-10 airfoil are unpublished. Also shown in figure 6 is a sketch of the advanced blade as originally fabricated with the 5:1 taper (TR5).

The baseline blade used a 10.5-percent-thick cambered airfoil developed by the manufacturer (HH-02 airfoil, refs. 16 and 17) outboard to the 0.943 blade radius, and transitioned to a 6.0-percent-thick NACA 64A006 airfoil over the 20° swept tip. Both the baseline rotor and the advanced rotor with the TR5 blades had a thrust-weighted solidity of 0.0928 compared with a thrust-weighted solidity of 0.0969 for the TR3 blades.

All the blade sets were fabricated from composite materials to meet the demanding requirements of dynamic similarity and Mach scaling. Details of the design and development of the baseline model blades are available in reference 1. The model advanced blades were designed and developed with similar methods and materials as the model baseline blades. When the TR5 blades were modified, the original spar was retained in the tip region and the 3:1 taper section was then fabricated around the spar to retain strength. Blade airfoil sections in the modified tapered region were the same as for the original tapered blade (TR5 blade).

The accuracy of the blade set contours was held to 0.005 in. or better. Strain gauges were installed in depressions on the blades which were then filled and smoothed. Wires were run inside a conduit molded into the instrumented blade to maintain a

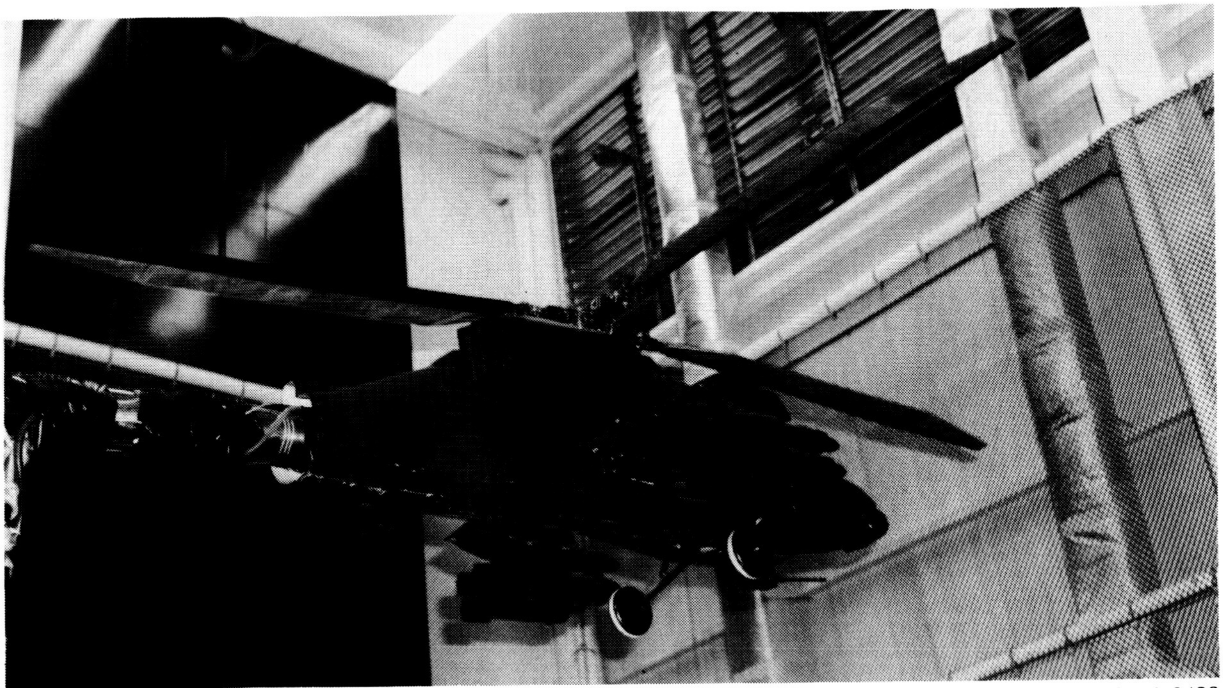

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Figure 4. Model mounted on sting in the rotor test cell with advanced rotor with 3:1 tip taper installed (TR3 blades).

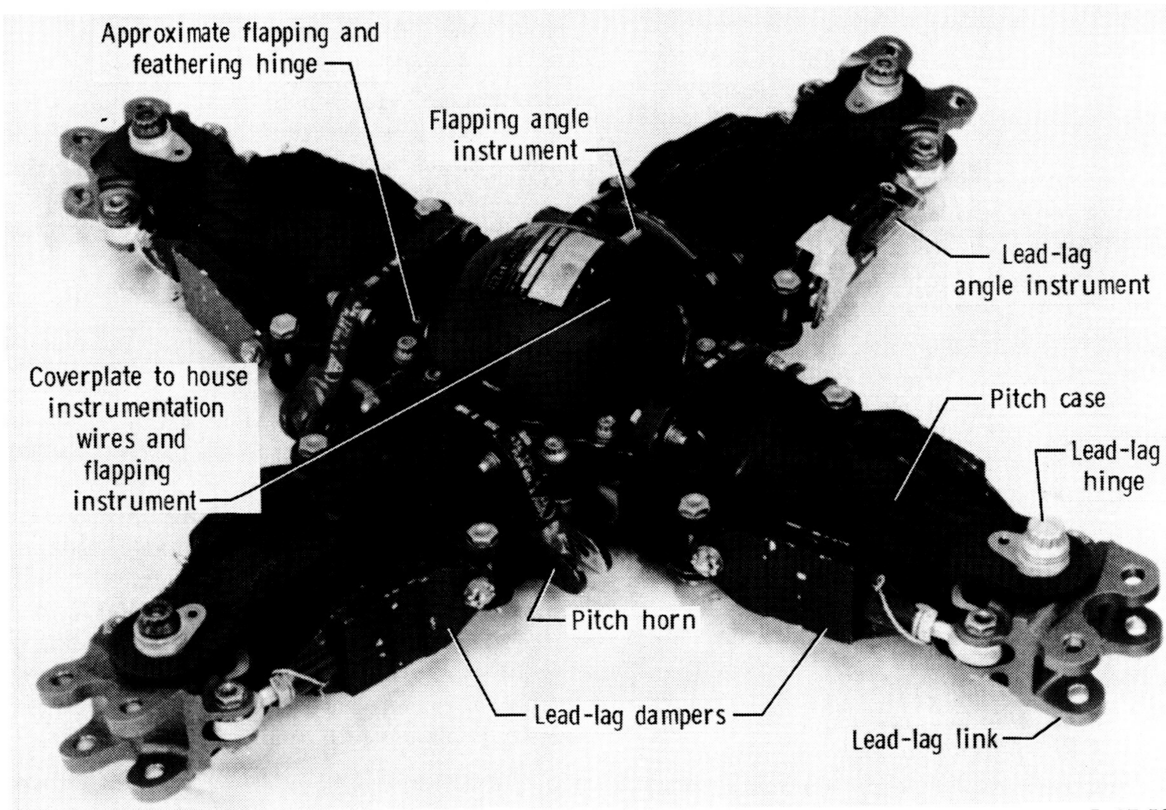

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Figure 5. Model hub with some of the major components indicated.

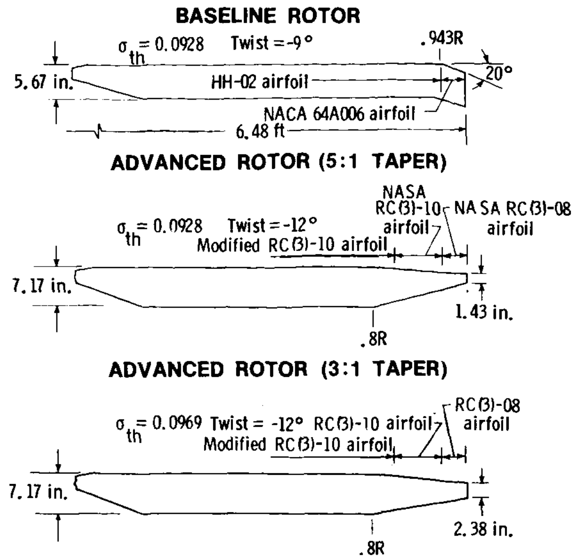

Figure 6. Rotor blade geometric characteristics (5:1 tapered blades tested during an earlier investigation).

smooth outer surface. Surface smoothness for the TR3 and TR5 blades was measured to be 20 to 30 micrometers and the baseline blades had a surface smoothness of 80 to 110 micrometers.

The blade structural and dynamic properties for the baseline blade are presented in reference 1. An effort was made to preserve the full-scale dynamic properties in the model blades but there were difficulties in the tip region with the advanced blades. The combined limitations imposed by taper and scale resulted in insufficient volume at the tip to accurately model the mass and stiffness characteristics of the full-scale baseline rotor. The target scaled weight distribution (baseline blades at flight scale) is compared with the weight distributions of the baseline blades and the TR3 and TR5 blade sets in figure 7. As much weight as feasible was added into the tip region of the TR3 blades in an attempt to match the weight of the baseline blade in that area. As shown in figure 7, an improvement was made but the baseline weight distribution was not matched. As a matter of interest, it was noted that during track-and-balance and hover performance testing of the TR3 blades, the vibration was much less than that experienced with the TR5 blades. The rotor rolling-moment alternating loads were reduced by a factor of about 4. It is not clear whether this improvement came about from aerodynamics (change in tip shape), dynamics (change in weight distribution), or some combination of the two. This change was not expected to affect performance.

Fuselage. The fuselage shell was made from fiberglass-epoxy material and was scaled from the

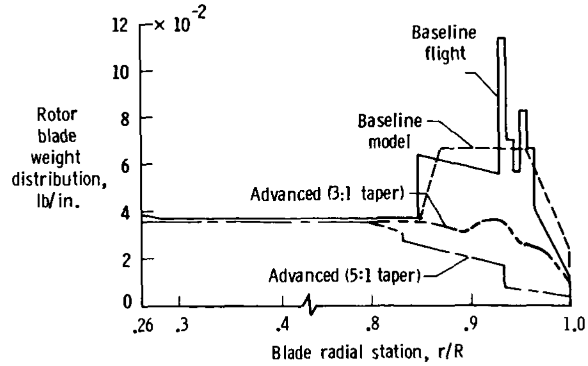

Figure 7. Rotor blade weight distribution versus blade radial station.

full-scale vehicle. The wings, pylons, missile racks, missiles, and landing gear were machined from wood and metal. Because of fouling problems between the sting and tail boom, the portion of the fuselage from the tail-boom juncture rearward was not utilized as shown in figures 3 and 4. The effect of the absence of the tail boom on rotor performance was considered small (0.1 to 0.2 percent of rotor thrust at $C_T = 0.0070$). For this test, the wing stores consisted of 16 model Hellfire missiles. The fuselage download in hover from the TR3 blades was not analyzed but was expected to be virtually the same as from the TR5 blades (ref. 2).

Advanced Rotor Design Considerations

The advanced rotor was designed for the AH-64 mission to provide an improvement in hover thrust performance on the order of 6 percent with no degradation in forward-flight performance. Cambered airfoils, developed at Langley specifically for rotor application (ref. 7), were designed to provide improved maximum lift and improved drag-divergence Mach number characteristics. Trailing-edge reflex was used to minimize pitching moments, created by the camber, about the quarter-chord of the blade (pitch control axis). A linear twist distribution of 12° and planform shape (tapered tip with more blade chord inboard) was used to obtain a more efficient lift distribution over the rotor (distribute more lift inboard). The tools used in the rotor design included the momentum strip-theory analysis for hover and a performance analysis program for forward flight (C-81; ref. 18). Additional detailed information is provided in reference 3 regarding the influence of rotor design variables on performance.

Test Procedures

Hover performance testing was conducted at a constant height above the rotor test cell floor

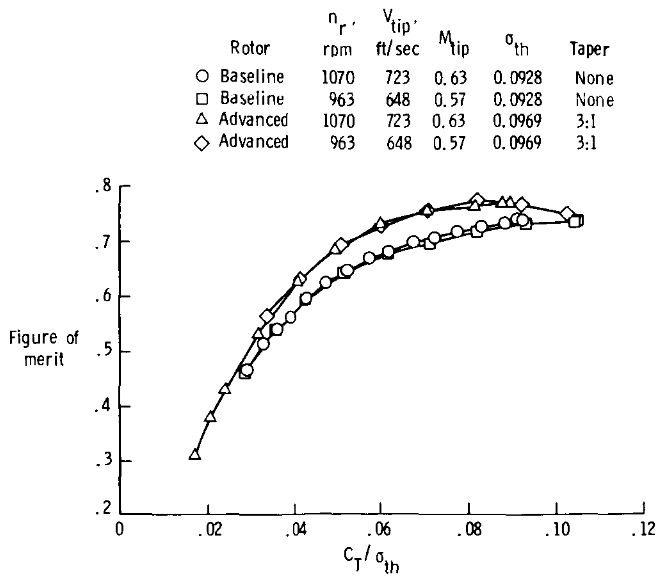

Figure 8. Rotor figure of merit as function of thrust coefficient divided by thrust-weighted solidity for baseline and advanced rotor in hover at $H/D = 1.46$.

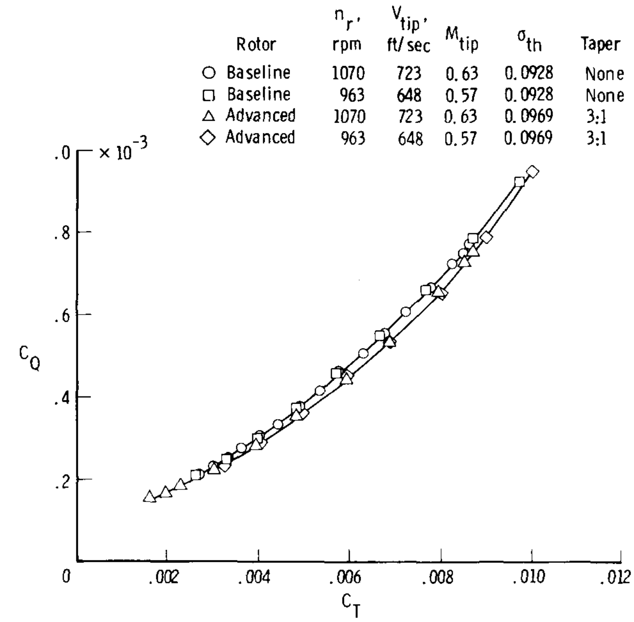

Figure 9. Rotor torque coeffficient versus thrust coefficient for baseline and advanced rotors in hover.

($H/D = 1.46$) and at a single rotor shaft angle (0°). The rotor height above the floor was limited by sting geometry and was close to the value used in the tunnel test section ($H/D = 1.40$). Rotor flapping angle was also held constant at nominally 0° during the runs as rotor thrust coefficient was varied between 0.0020 and 0.0100. Data were measured in increments of thrust as collective pitch was increased and then decreased during each run, at 100 percent n_r (1070 rpm; $M_{tip} = 0.63$) and 90 percent n_r (963 rpm; $M_{tip} = 0.57$). The louvers in the walls of the test cell were fully open for all tests.

Results And Discussion

Hover Performance

Hover performance results for the baseline rotor are compared in terms of figure of merit and rotor torque coefficient versus rotor thrust coefficient in figures 8 and 9, respectively. Thrust sweeps were made at 1070 rpm (100 percent of full-scale tip speed) and at 963 rpm (90 percent of full-scale tip speed) to permit higher thrust coefficients to be obtained from the power available. The tip Mach number was 0.63 and 0.57 at 1070 rpm and 963 rpm, respectively.

For the full-scale helicopter at an operational weight of 14 667 pounds, standard sea-level conditions yields a $C_T/\sigma_{th} = 0.067$, and the Army "high and hot day" conditions (4000 feet altitude, 95°F ambient air temperature) yields a $C_T/\sigma_{th} = 0.084$. Figure 8 shows that, compared with the baseline rotor, the figure of merit for the TR3 rotor was 7 to 8 percent higher for $C_T/\sigma_T = 0.067$ (standard sea-level condition) and 5 to 6 percent higher for $C_T/\sigma_T = 0.084$ (4000 feet, 95°F condition). Little difference in overall performance was noted when the tip speed was varied for the same rotor. The maximum figure of merit for the TR3 rotor occurred at a value of C_T/σ_{th} of about 0.086. This is in contrast to the baseline rotor which did not reach a maximum FM at the highest thrust tested ($C_T/\sigma_{th} = 0.105$).

The performance advantage for the advanced rotor is shown to diminish at high thrust coefficients with a projected crossover occurring at a value of C_T/σ_T of 0.108. When the hover performance is compared in terms of C_Q versus C_T (fig. 9), a thrust advantage is shown for the advanced rotor. In fact, at sea-level standard (14 667 pounds full-scale) and 4000 feet, 95°F (14 667 pounds), an increase in thrust of 6.7 percent and 4.1 percent, respectively, was derived from the data in the figure.

The improvement in figure of merit for the TR3 rotor compared with the baseline rotor is presented in figure 10 as a function of rotor thrust coefficient. Data for the TR5 rotor from reference 2, taken in the open test section of the tunnel with the floor dropped, is also shown for correlation. Results from the TR3 and TR5 rotors show a further increase in the figure-of-merit margin over the baseline rotor by an additional 1 to 2 percent over the range of thrust coefficients from 0.0055 to 0.0087, with a larger improvement (3 to 6 percent) indicated by extrapolating results from the TR5 rotor at the higher thrust coefficients. This difference in figure

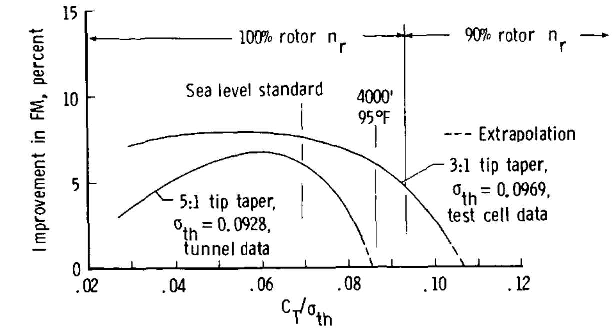

Figure 10. Improvement in hover figure of merit for advanced rotors (5:1 and 3:1 tip tapers) compared with baseline rotor versus rotor thrust coefficient.

of merit between TR3 and TR5 rotors may well be even larger since the TR5 was tested in the open tunnel test section and perhaps experienced additional benefit from recirculation effects. (See next section.)

The reduced taper on the TR3 rotor increased the thrust-weighted solidity by 4.4 percent when compared with the TR5 rotor and increased the tip Reynolds number from 550 000 to 917 000. Both changes were expected to improve the efficiency of the TR3 rotor. It is of interest to note that the performance margin of the TR5 rotor is projected to cross the zero improvement line at $C_T/\sigma_{th} = 0.085$, which is inside the current envelope of the AH-64 (fig. 10). The crossover of the performance margin for the TR3 rotor is projected to occur at $C_T/\sigma_{th} = 0.106$, which is outside the current operational envelope of the AH-64 ($C_T/\sigma_{th} = 0.106$ represents a hover out-of-ground-effect full-scale aircraft weight of about 23 600 pounds at sea-level standard conditions). The highest measured hover out-of-ground-effect C_T/σ_{th} for the AH-64 is 0.099 as indicated in reference 19 (21 080 pounds at sea-level standard conditions). Results for full-scale rotors with tapered tips are needed to determine whether the performance decrease occurs at high C_T.

The performance characteristics of the baseline rotor was surprisingly good considering that it was designed a number of years ago (around 1971; 9 years before the TR5). A high figure of merit, sustained over a large range of C_T (fig. 8), indicate a good capability in lift, normal load factor, and continued efficiency at the higher gross weights expected due to normal growth over the life of the AH-64. Data on the baseline rotor at higher C_T would be desirable in this regard. High load factors demonstrated in high-speed flight by the full-scale aircraft (ref. 10) confirm good performance at high C_T for the baseline rotor.

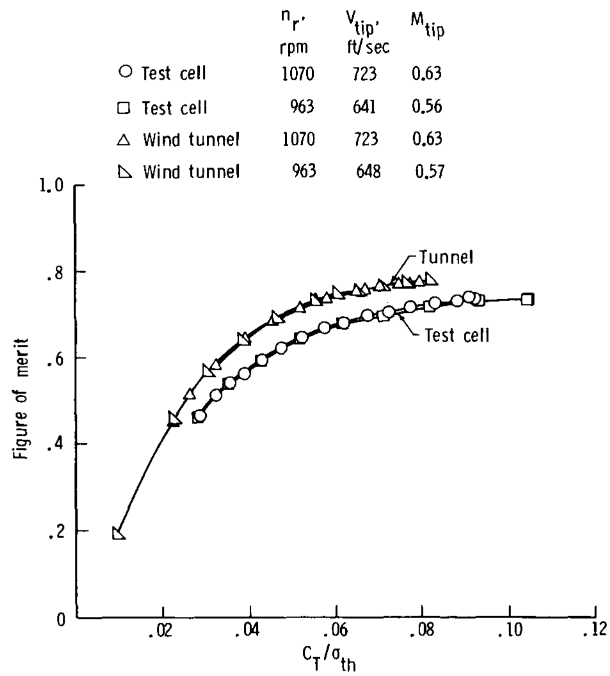

Figure 11. Effect of test facility on hover performance on baseline rotor. Thrust-weighted solidity = 0.0928.

Comparison of Test Facilities for Hover Testing

Comparison of hover performance results obtained in the rotor test cell and the 14- by 22-Foot Subsonic Tunnel offered an opportunity to evaluate the relative suitability of each facility for testing rotors of this size and thrust range. The baseline rotor model was tested in the Langley 14- by 22-Foot Subsonic Tunnel during an earlier investigation (ref. 2) and the results are presented in figure 11 in terms of figure of merit versus rotor thrust coefficient and correlated with measurements obtained from the present investigation in the rotor test cell. The height of the rotor in the test cell ($H/D = 1.46$) was nearly the same as in the tunnel ($H/D = 1.40$). In the tunnel, the test section walls and ceiling were raised and a section (19 by 24.5 feet) of the floor under the rotor was lowered (fig. 2) to achieve H/D of 1.4; in the test cell, the louvers on the two side walls were fully open to minimize recirculation effects.

The results show that within a range of C_T from 0.005 to 0.008, tested, a figure of merit several percent higher was measured in the open test section of the tunnel than in the test cell thus indicating more recirculation in the tunnel. Additional tests are needed on various rotor sizes and configurations before general conclusions can be drawn regarding the limits of these facilities in terms of rotor size, thrust range, and recirculation effects. It is of interest to note that the maximum figure of merit on the full-scale rotor was determined by the manufacturer from whirl tower tests to be about 0.74, which is the same value measured in the test cell. The correlation is somewhat surprising, since it would be expected (based on numerous performance comparisons between full-scale and model rotors; for example, see fig. 7 in ref. 8) that model results generally result in reduced performance in terms of power required when compared with full-scale results due primarily to viscous effects.

Conclusions

Hover performance characteristics of 27-percent-scale rotor models designed for the U.S. Army AH-64 helicopter were investigated in the rotor test cell located at the Langley 14- by 22-Foot Subsonic Tunnel. Tests were conducted on an advanced rotor designed for the AH-64 mission and on a baseline rotor scaled from the current AH-64 rotor. The advanced rotor was designed at Langley and utilized advanced airfoils, 12° of linear twist, and a 3:1 tip taper which began at 0.8 rotor radius. The primary purpose of the investigation was to measure the hover performance of the advanced rotor, which was modified to a 3:1 tip taper (TR3) from an existing model having 5:1 taper (TR5). The TR3 rotor was designed to have improved aerodynamic performance in hover with no degradation in forward-flight performance when compared with the baseline rotor. The data from the present investigation were compared to results of an earlier tunnel investigation of a similarly designed 5:1 taper advanced blade. The following conclusions are drawn:

1. Decreasing taper from 5:1 (TR5 rotor) to 3:1 (TR3 rotor) on the advanced rotor resulted in an additional increase in figure of merit over the baseline blade of about 1 to 2 percent over a range of thrust coefficient C_T between 0.0055 and 0.0076. Extrapolation of data indicated a 3- to 6-percent margin in figure of merit at $C_T/\sigma_{th} = 0.085$ (σ_{th} is the thrust-weighted solidity). This increase is likely due to an increase in blade area and Reynolds number in the blade tip region.

2. The projected crossover point at which the advanced blade performance was equal to baseline blade performance was shifted from $C_T/\sigma_{th} = 0.085$ for the TR5 rotor to $C_T/\sigma_{th} = 0.106$ for the TR3 rotor.

3. Comparison of results for the baseline rotor obtained in the open test section of the Langley 14- by 22-Foot Subsonic Tunnel with those obtained in the rotor test cell indicate that rotor wake recirculation effects were decreased in the test cell. The figure of merit measured in the rotor test cell was several percent less than the tunnel data within a range of C_T from 0.005 to 0.008.

NASA Langley Research Center
Hampton, VA 23665-5225
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References

1. Straub, F. K.; Johnston, R. A.; Head, R. E.; and Kelley, H. L.: Design and Development of a Dynamically Scaled Model AH-64 Main Rotor. *Vertica*, vol. 9, no. 2, 1985, pp. 165–180.
2. Kelley, H. L.; and Wilson, J. C.: Aerodynamic Performance of a 27-Percent-Scale AH-64 Wind-Tunnel Model With Baseline/Advanced Rotor Blades. *Proceedings of the 41st Annual Forum*, American Helicopter Soc., May 1985, pp. 491–499.
3. Bingham, Gene J.: The Aerodynamic Influences of Rotor Blade Airfoils, Twist, Taper and Solidity on Hover and Forward Flight Performance. *37th Annual Forum Proceedings*, American Helicopter Soc., May 1981, pp. 37–50.
4. Berry, John D.: Quarter-Scale Testing of an Advanced Rotor System for the UH-1 Helicopter. *37th Annual Forum Proceedings*, American Helicopter Soc., Inc., 1981, pp. 456–462.
5. Berry, John D.: *Performance Testing of a Main Rotor System for a Utility Helicopter at 1/4 Scale.* NASA TM-83274, AVRADCOM TR 82-B-3, 1982.
6. Phelps, Arthur E., III; and Althoff, Susan L.: *Effects of Planform Geometry on Hover Performance of a 2-Meter-Diameter Model of a Four-Bladed Rotor.* NASA TP-87607, AVSCOM TR 85-B-6, 1986.
7. Bingham, Gene J.; and Noonan, Kevin W.: *Two-Dimensional Aerodynamic Characteristics of Three Rotorcraft Airfoils at Mach Numbers From 0.35 to 0.90.* NASA TP-2000, AVRADCOM TR 82-B-2, 1982.
8. Keys, Charles N.; McVeigh, Michael A.; Dadone, Leo; and McHugh, Francis J.: Considerations in the Estimation of Full-Scale Rotor Performance From Model Rotor Test Data. *39th Annual Forum Proceedings*, American Helicopter Society, May 1983, pp. 34–43.
9. Fradenburgh, Evan A.: Aerodynamic Factors Influencing Overall Hover Performance. *Aerodynamics of Rotary Wings*, AGARD-CP-111, Feb. 1973, pp. 7-1–7-11.
10. Amer, Kenneth B.; and Prouty, Raymond W.: Technology Advances in the AH-64 Apache Advanced Attack Helicopter. *39th Annual Forum Proceedings,* American Helicopter Soc., 1983, pp. 550–568.
11. McVeigh, Michael A.; and McHugh, Francis J.: Influence of Tip Shape, Chord, Blade Number, and Airfoil on Advanced Rotor Performance. *J. American Helicopter Soc.*, vol. 29, no. 4, Oct. 1984, pp. 55–62.

12. Balch, David T.: Experimental Study of Main Rotor/Tail Rotor/Airframe Interaction in Hover. *39th Annual Forum Proceedings*, American Helicopter Soc., 1983, pp. 1–14.
13. Fradenburgh, Evan A.: Aerodynamic Design of the Sikorsky S-76 Helicopter. Preprint No. 78-06, 34th Annual National Forum, American Helicopter Soc., Inc., May 1978.
14. Murrill, Robert J.: *Operation and Maintenance Manual for the General Rotor Model System.* NASA CR-145230, 1977.
15. Wilson, John C.: A General Rotor Model System for Wind-Tunnel Investigations. *J. Aircr.*, vol. 14, no. 7, July 1977, pp. 639–643.
16. McCroskey, W. J.; McAlister, K. W.; Carr, L. W.; Pucci, S. L.; Lambert, O.; and Indergrand, R. F.: Dynamic Stall on Advanced Airfoil Sections. *J. American Helicopter Soc.*, vol. 26, no. 3, July 1981, pp. 40–50.
17. Taylor, H. E.; Acker, G. F.; Okamoto, F. S.; and LaForge, S. V.: *Air Vehicle Technical Description Data for the YAH-64 Advanced Attack Helicopter.* Rep. No. 77-X-8002-2, Hughes Helicopters, Sept. 1978.
18. Van Gaasbeek, J. R.; McLarty, T. T.; and Sadler, S. G.: *Rotorcraft Flight Simulation, Computer Program C81—Volume 1: Engineer's Manual.* USARTL-TR-77-54A, U.S. Army, Oct. 1979. (Available from DTIC as AD A079 631.)
19. Bender, Gary L.; Higgins, Larry B.; Savage, Richard; Ottomeyer, John D.; Picasso, Bartholomew D., III; and Morris, Patrick M.: *Airworthiness and Flight Characteristics Test. Part 1—YAH-64 Advanced Attack Helicopter.* USAAEFA No. 80-17-1, U.S. Army, Sept. 1981. (Available from DTIC as AD A118 490.)

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16. Abstract
The hover performance of a 27-percent-scale model baseline rotor and advanced rotor with a 3:1 tapered tip (TR3) was investigated and compared. Hover results from a previously tested advanced rotor with a 5:1 tapered tip (TR5) were also compared. Rotor thrust was varied over a range for two tip Mach numbers. The results indicated that the TR3 blades had improved performance compared with the TR5 blades, and both the TR3 and TR5 blades were superior to the baseline rotor. The additional margin in performance for the TR3 blades was likely due to an increase in blade area and Reynolds number in the tip region of the blades.

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