A General Rotor Model System for Wind-Tunnel Investigations

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A complex rotorcraft model system has been developed for the NASA Langley Research Center and the U.S. Army Air Mobility R&D Laboratory, Langley Directorate, for aerodynamic and acoustic experimental investigations in the NASA Langley V/STOL tunnel. This generalized rotor model system has a powered main rotor, tail rotor, and auxiliary engine capability. It may be configured to represent a variety of rotorcraft configurations. The first investigation was conducted to determine the performance, acoustic, stability, and control characteristics of the NASA/Army Rotor Systems Research Aircraft with an articulated rotor. In a second investigation, a ¼-scale AH-1G configuration with a teetering rotor is being represented to determine if a V-tail will improve the directional characteristics. Future programs are planned to investigate advanced rotor blade airfoils for improved performance and acoustic characteristics.

Nomenclature

b	= wing span, m (ft)
$\bar{c}$	= wing mean aerodynamic chord, m (ft)
C_D	= drag coefficient, D/qS
C_L	= lift coefficient, L/qS
C_ℓ	= rolling-moment coefficient, M_x/qSb
C_m	= pitching-moment coefficient, $M_y/qS\bar{c}$
C_n	= yawing-moment coefficient, M_z/qSb
D	= drag, N (lbf)
L	= lift, N (lbf)
i_t	= horizontal-tail incidence
i_w	= wing incidence
M_x	= rolling moment, N-m (lbf-ft)
M_y	= pitching moment, N-m (lbf-ft)
M_z	= yawing moment, N-m (lbf-ft)
OASPL	= overall sound pressure level, db
$\bar{q}$	= freestream dynamic pressure, N/m^2 (lbf/ft^2)
S	= wing area, m^2 (ft^2)
V	= freestream velocity, kts
α	= angle of attack, deg
β	= angle of sideslip, deg
δ_f	= flap deflection
δ_3	= pitch-flap coupling ratio

Subscripts

t	= tail
w	= wing

Introduction

SINCE 1970, with the completion of the NASA Langley V/STOL tunnel and the formation of the Langley Directorate, U.S. Army Air Mobility R&D Laboratory (USAAMRDL), there has been an increased emphasis on rotorcraft research at the Langley Research Center. Early in this time period, the need for a versatile experimental model system which would be capable of representing a variety of rotor systems and fuselage-wing-tail configurations was demonstrated.[1,2] Such a system would reduce the delays associated with the design and development of specialized rotor wind-tunnel models for individual investigations. As a result of this need, a general rotor model system (GRMS) was designed and fabricated to conduct the following range of investigations: 1) advanced rotor concepts, 2) advanced rotor airfoils, 3) rotor-wake interference effects on compound helicopter, 4) validation of wall-correction theory for rotor testing, 5) blade "slap," at both high and low speed, investigation, 6) transition-speed stability and control problems, 7) main rotor-tail rotor interference, and 8) rotor-wake theory validation.

One problem area of helicopter rotor aerodynamics which has proven difficult to explore analytically is that of the rotor wake and its influence on the tail rotor and helicopter components. As a result, experimental investigations[3] have been pursued to provide some of the information which cannot readily be obtained from theory. Analytical rotor-wake modeling is evolving only recently.[4] The extension of the theory to deal with the effects of rotor wakes on helicopter components is yet to be accomplished.

The V/STOL tunnel is especially suitable for investigations of low-speed characteristics of lifting systems such as rotors. It is a closed-return atmospheric tunnel capable of producing forward speeds from 0 to 200 knots. The test section is 4.42 m (14.50 ft) high by 6.63 m (21.75 ft) wide. The wall configuration easily can be changed to reduce boundary influence through opening slots or by removing any or all of the two sidewalls or ceiling. The simulation of low-speed flight (both in and out of ground effect) can be enhanced further by use of a floor boundary-layer removal system or a moving ground plane (endless belt). Another unique feature of the tunnel is a special sting support, the high alpha-beta sting. The sting, by movement of three joints in concert, can keep the model at a fixed point in the tunnel (for instance on the centerline) while sweeping angle of attack or sideslip through a range of $\pm 45°$. Keeping the model at a fixed point eases the problem of correcting for tunnel wall effects and permits large angles relative to the freestream. Another characteristic of the tunnel is a relatively low background noise which permits successful acoustic measurements. These features of the V/STOL tunnel plus sophisticated static and dynamic data acquisition and reduction systems serve to provide a comprehensive and unique test capability for rotorcraft investigations.

NASA Langley and USAAMRDL-Langley jointly contracted with Sikorsky Aircraft to develop the general rotor model system (GRMS) to provide a versatile wind-tunnel model. The rotor configuration is designed for a variable diameter of 2.7 m (9 ft) to 3.7 m (12 ft). Though the initial hub was articulated, provisions were made for alternate hubs such as rigid or teetering. Rotor power up to 149 kW (200 hp), from either electric or air motors, was sought to drive the

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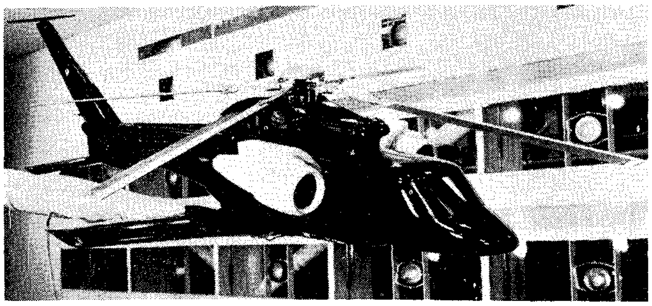

Fig. 1 GRMS installation in Langley V/STOL tunnel (RSRA configuration).

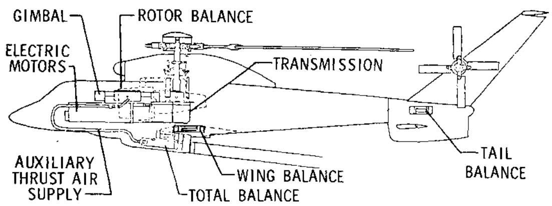

Fig. 2 Internal arrangement of GRMS components.

rotor to full-scale tip speeds [at least 213 m/sec (700 ft/sec)]. Separate force and moment balances measure, independently, rotor loads, wing loads, tail loads, and total loads. In addition to a single main rotor, a tail rotor was provided. These features resulted in a versatile system which proved its value in its first test program – a powered model investigation of the NASA-Army Rotor Systems Research Aircraft (RSRA) configuration (Fig. 1). Earlier, an investigation of this configuration was tested in the V/STOL tunnel without a rotor.[5]

The RSRA itself is a unique rotorcraft[6] which will be completed in the near future. NASA and the USAAMRDL have developed the rotorcraft to investigate advanced rotor concepts. As with the GRMS, the RSRA is equipped with a variable incidence wing to load or unload the rotor and auxiliary thrust engines and drag brakes to cover the full range of rotor propulsive force. Two different tails can be used on the RSRA: a single T-tail for helicopter operations and a combination T-tail and lower horizontal tail for compound operations. Since it is a complex configuration, the predicted aerodynamic characteristics needed verification in the wind tunnel. The GRMS did provide such information and will continue to support the RSRA throughout the flight-test program.

General Rotor Model System

The GRMS finally developed is a complex arrangement of internal balances (Fig. 2), electric motors [134.3 kW (180 hp) total], transmission, and rotor control system within a structural frame which supports the auxiliary thrust engine simulators, the wing, and the tail components. A four-bladed tail rotor and a main rotor were part of the initial system. The GRMS model includes several subsystems: variable frequency electric power supply, cooled oil lubrication system for the transmission, and control consoles for the model controls and electric power.

Rotor

The initial rotor configuration had a four-bladed fully articulated rotor. The coincident flapping hinges and lag hinges were located 7.62 cm (3.0 in.) from the center of rotation. The pitch-flap coupling ratio (δ_3) was adjustable. Initially in the test program, δ_3 was set to -0.51; however, when sufficient test experience was acquired, δ_3 was set to -0.035. Lag motion was restrained by adjustable rotary viscous dampers with a range of 6° lead and 17° lag. Both lag and flap motion were sensed by rotary potentiometers. The rotor diameter was 3.099 m (10.33 ft) which was 1/6-scale of the RSRA rotor. The blades were untwisted and had a NACA 0012 airfoil section with a chord of 10.77 cm (4.24 in.). The main structure of the blade was a formed 7075-96 aluminum "D-spar" which provided the airfoil contour over the front part of the blade. The airfoil contour over the aft part of the blade was provided by a balsa-wood comb covered with a 0.015-cm (0.006-in.) magnesium skin. The resultant structure provided a dynamically scaled blade representative of a typical full-scale blade construction and aeroelastic characteristics capable of being operated at full-scale tip speeds (that is, "Mach-scaled"). On one of the blades, full strain-gage bridges were installed on the spar to measure flatwise bending, chordwise bending, and torsion stresses at four radial stations. The wires to the gages were attached to the spar within the blade and conducted down through the center of the shaft to a slip-ring assembly.

The second test program utilizes a teetering rotor. For this purpose, the control rods and rotor drive shaft were modified to provide the needed rotor controls, teetering pin, and drive power. This illustrates the ability of the GRMS to be modified to represent a variety of rotors.

Drive System

The rotor, rotor swashplate control, two water-cooled variable-frequency electric motors, and drive train were supported on a six-component strain-gage balance for precise determination of rotor system forces and moments. The swashplate control consisted of a mixing unit driven by three small electric motors with the mixing unit driving irreversible mechanical actuators to provide independent lateral, longitudinal, and collective pitch control. The selection of electric motors [67 kW (90 hp)] for driving the main rotor was made after intensive comparison with pneumatic motors. Several factors contributed to the selection of electric motors: more precise rotational speed control, regenerative power capability for dynamic braking of the rotor for autorotative operation, and significantly less noise leading to enhanced rotor acoustic investigations. The electric motors drove the drive right-angle gearbox which was lubricated with oil from an external water-cooled oil system. These components together weighed 160 kg (350 lb), which was supported by the rotor balance.

The balance was supported from the main fuselage structure in a soft, damped, gimbal frame. This unique support system provided a means of coping with potential ground resonance problems, characteristic of articulated or rigid hub rotor systems, through variation of damping and spring rates of the gimbal components for the pitch and roll degrees of freedom. The use of variable-frequency electric motors rather than pneumatic motors resulted in a considerable increase in the pitch and roll inertia of the drive system. This resulted in some loss in hub impedance simulation capability. The necessity of hub impedance scaling varies with experimental program objectives and rotor configuration. For articulated rotors, rotor blade response and loads are relatively insensitive to hub impedance. This is principally because only shears are delivered to the hub, as flatwise and chordwise bending moments essentially go to zero at the hinge. For teetering rotors, soft in-plane and rigid systems which carry bending moment through the hub, impedance can have a significant effect on blade root stresses and aeroelastic and mechanical stability of the system.

Some variation of hub impedance is possible by changes in gimbal springs and dampers, and will be considered for alternate hub systems. Meanwhile, the primary use of the GRMS will be for investigations of performance, static stability and control derivatives, and airframe aerodynamic characteristics. These interests will not require precise scaling of hub impedance. Even for the current teetering rotor configuration under test, the test objectives do not require

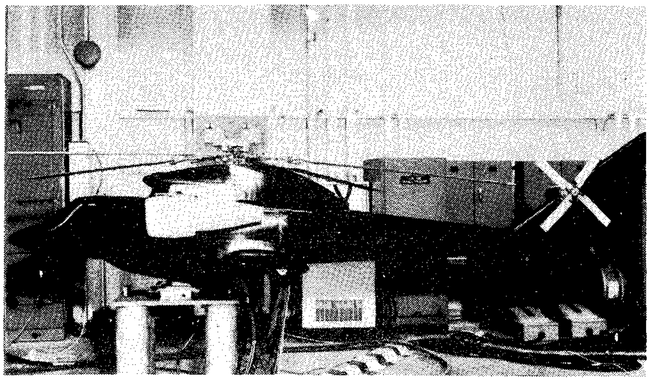

Fig. 3 GRMS with tail rotor installed.

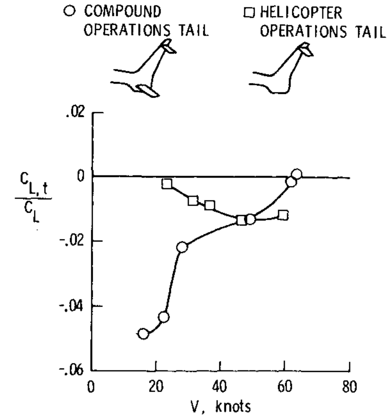

Fig. 4 Effect of tail configuration on the tail lift for the helicopter configuration, $i_t = 0°$, $\alpha = 5°$.

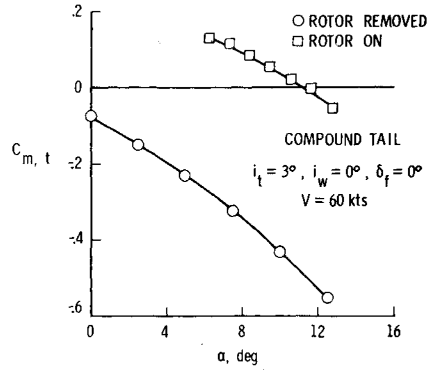

Fig. 5 Effect of the rotor wake on the pitching moment due to the tail for the compound configuration. (Compound operations tail, $i_t = 3°$, $i_w = 0°$, $\delta_f = 0°$, $V = 60$ kts.)

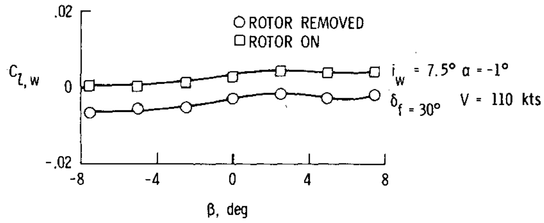

Fig. 6 Effect of the rotor wake on the wing rolling-moment coefficient for the compound configuration. (Compound operations tail, $i_t = 3°$, $i_w = 7.5°$, $\delta_f = 30°$, $\alpha = -1°$, $V = 110$ kts.)

even a correct scaling of pylon natural frequency, so, until new objectives are established, the current gimbal characteristics will be left as is.

Complementary Components

In addition to the rotor balance, there are three other balances; one to measure total loads on the GRMS, one to measure wing loads, and another to measure tail loads. Balance load capabilities are listed in Table 1. The "total" loads balance provided a redundancy to the rotor balance to validate its performance as affected by vibratory loading and temperature effects. The wing balance can be used for fuselage load measurements as well. For the initial configuration, this balance supported the wings which were attached at several incidence angles. In addition, variation in vertical position of the wings was possible. The tail balance supported a tail system comprised of a swept vertical fin with movable rudder, a variable incidence horizontal stabilizer, and a four-bladed tail rotor with a 14.9-kW (20-hp) electric motor (Fig. 3).

The tail rotor diameter was 53.34 cm (21 in.) and the collective pitch was controlled remotely. Flapping motion about hinges 1.9 cm (0.75 in.) from the center of rotation was available. The design of collective push rods and pitch horns provided a pitch-flap coupling ratio of −1 (one degree of decreased pitch per degree of increased flapping). The blades were dynamically scaled with a fiberglass spar and fiberglass-covered plastic foam trailing edge. Like the main rotor, the tail rotor was designed to operate at tip speeds up to 213 m/sec (700 fps). The tail rotor was driven directly by the electric motor which was covered by a fairing. At the end of the hollow motor drive shaft, a slip-ring assembly was mounted for the blade flapping motion and blade strain-gage instrumentation.

The primary structural frame supported a 1/6-scale representation of the RSRA fuselage and auxiliary thrust engine simulator, scaled in size and power for the RSRA. The engine simulators each had a tip-driven fan and a stator. Dry, high-pressure air drove the fans to produce thrust. The high-pressure air was supplied to the fans through tubing which crossed over the total balance with little effect on balance loads measurements. What little effect there was, was established in pretest calibrations.

Table 1 Balance load capacity

	Total	Rotor	Wing	Tail
Normal force, N	13345	6672	8008	4448
(lb)	(3000)	(1500)	(1800)	(1000)
Axial force, N	2224	2669	2224	2224
(lb)	(500)	(600)	(500)	(500)
Pitching moment, m − N	1130	2542	795	452
(in. − lb)	(10000)	(22500)	(7040)	(4000)
Rolling moment, m − N	847	678	452	339
(in. − lb)	(7500)	(6000)	(4000)	(3000)
Yawing moment, m − N	508	1106	343	339
(in. − lb)	(4500)	(9750)	(3040)	(3000)
Side force, N	8008	3336	4448	2224
(lb)	(1800)	(750)	(1000)	(500)

The V/STOL high $\alpha\beta$ sting was chosen because of its capability to provide a wide range of angle of attack, yaw, and roll angle and to vary these parameters smoothly while the GRMS with all components attached weighed 523 kg (1150 lb). However, it was recognized that two problems would be introduced because of the sting mount: that of the flowfield interference near the tail components, and potential ground resonance. Early in the test program, the interference was measured and found to be relative small. Ground resonance was of great concern, even though the rotor gimbal mounting served to provide a means of alleviation. Classical ground resonance instabilities have resulted in catastrophic failures of large, full-scale tip-speed, rotor models similar to the GRMS. A thorough investigation of the GRMS and sting mount impedance characteristics was conducted. Using the data from this investigation and the analyses of Ref. 7, gimbal spring rate and damping were tuned to eliminate the potential problem. Also, two rotary viscous dampers were

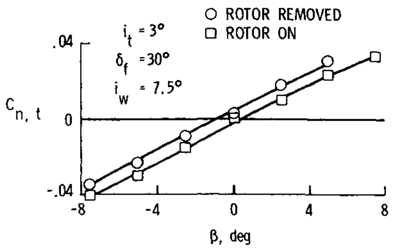

Fig. 7 Effect of rotor wake on the yawing moment due to the tail for the compound configuration. (Compound operations tail, $i_t = 3°$, $i_w = 7.5°$, $\delta_f = 30°$, $\alpha = -1°$, $V = 110$ kts.)

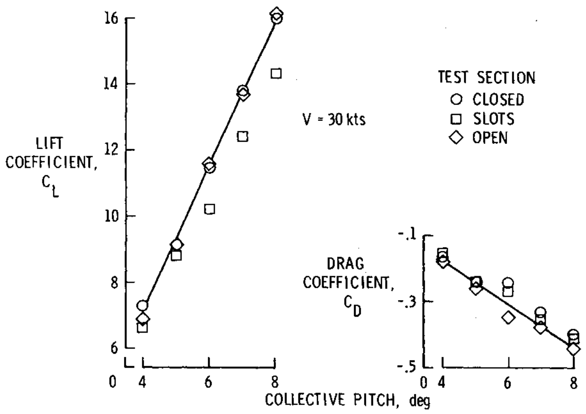

Fig. 8 Comparison of corrected lift and drag for three test-section configurations, windspeed 30 kts.

placed on the structural frame with attachments to the sting which insured sufficient system damping without total load balance interference.

First Wind-Tunnel Test Program

The GRMS was not related directly to the RSRA, in that the GRMS development was a separate program. However, interest in data directly applicable to the RSRA concept resulted in configurating GRMS to represent the RSRA. The first test program was established to acquire data describing main rotor wake effects on fuselage, wing, and tail components; auxiliary thrust jet wake effect on tail components (including tail rotor); and tail rotor performance as affected by the close proximity of the large vertical fin. In addition to the primary program, a supplementary investigation of rotor acoustics was planned, the purpose of which was to determine whether blade slap noise could be demonstrated in the V/STOL tunnel and to evaluate instrumentation and analytical techniques for precise location of the origin of the impulse.

RSRA Configuration Results

A successful test program was completed and from it a great amount of data was obtained. Some significant control and stability characteristics have been measured which will affect the RSRA flight testing. For instance, in low-speed flight, out of ground effect, there will be a larger download on the tail used for compound operations than the one for helicopter operations (see Fig. 4). This effect is largest at the lower speed where the lower horizontal tail of the compound is in the rotor wake. The effect of the rotor wake on the pitching moment due to the horizontal tail is presented in Fig. 5 for a flight speed of 60 kts. These results have been used to improve the flight dynamics simulation analysis of the RSRA.

The rotor wake effects are also important factors in determining the lateral aerodynamic characteristics. The effect of the rotor wake on the rolling moment produced by the wing was measured with the wing balance. Some of the results, presented in Fig. 6, show that the rotor wake adds a positive increment to the rolling moment. The wake from the advancing blades induces a larger reduction in the lift on the right wing than the retreating blade induces on the left wing. The effect of the rotor wake on the yawing moment due to the tail is presented in Fig. 7. The rotor wake has a small effect on the tail at high forward speeds.

The aerodynamic interference of the tunnel boundaries was accounted for with the computational routines based on the theory of Ref. 8 for the open and closed test sections. There are no theories for correcting the interference for a slotted test section for this type of model. The interference becomes quite significant at low windspeeds. To understand the interference better, low-windspeed testing was conducted with the three test-section configurations – closed, open, and slotted. A sample of the data for a windspeed of 30 kts is shown in Fig. 8. In general, there is little need to improve the routines to correlate data of the open and closed test-section configurations. It is apparent that the data from the slotted test-section configuration requires some correction to achieve complete agreement with the other data.

The data presented are only a sampling of a great amount which is now available to the RSRA Project Office and will soon be available to the public as a formal NASA publication. Still to be accomplished is a review of blade stress data, though all of the dynamic data acquired have been analyzed for harmonic content. The influence of the wing on stresses is yet to be determined. The test results to date have contributed to greater confidence in the integrity of the RSRA system.

Rotor Acoustic Results

Rotorcraft can be noisy in certain flight conditions. The blade slap noise, when present, is considered to be the most annoying. Blade slap (or impulsive noise) is attributable to several mechanisms. Two of the most predominant mechanisms may be the following: 1) blade tip vortex interaction usually occurring in low-speed descending flight, and 2) advancing blade impulsive noise occurring in high-speed flight when the rotor tip is subjected to local sonic flow on the airfoil. A short test program was directed toward both mechanisms of blade slap, but concentrated more on the low-speed flight mechanism.

To minimize acoustic wall reflections during these tests, the walls were removed and the ceiling raised to its maximum height, which was approximately 4.6 m (15 ft) above the rotor. Six 1.28-cm. (0.50-in.) diam. condensor microphones were mounted on special stands near the plane of the rotor in a circle about 0.61 m (2 ft) larger than the rotor diameter (Fig. 9). The placement of the microphones, relatively close to the rotor blade tips, permitted the direct acoustic pressure signal to dominate the reflected signals.

The rotor was operated at constant rotor speed and constant lift at windspeeds of 31 to 62 m/sec (60 to 120 kts). Different descent speeds were simulated by varying propulsive

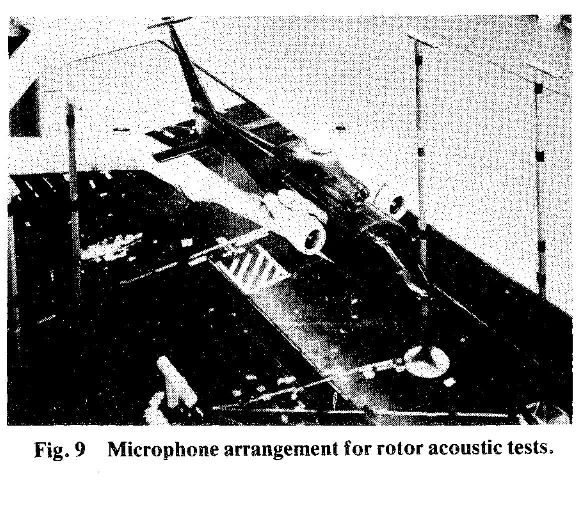

Fig. 9 Microphone arrangement for rotor acoustic tests.

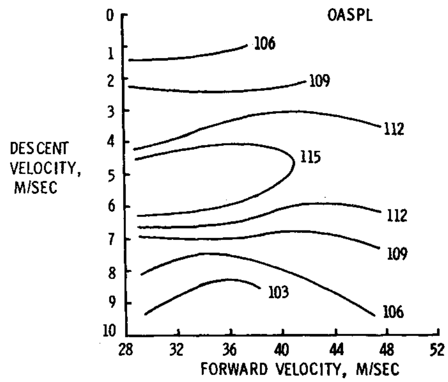

Fig. 10 Sound pressure levels measured by microphone near front right quadrant of rotor disk.

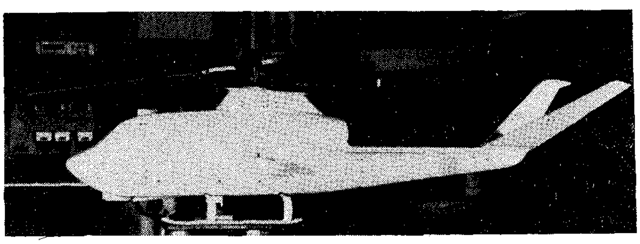

Fig. 11 AH-1G configuration with V-tail.

force (that is, lift/drag ratio) using the longitudinal cyclic pitch control. The microphone data were analyzed using high-pass 500-Hz filtering to emphasize the blade slap noise. These overall sound pressure levels are presented in Fig. 10 as contour fairings. The maximum blade slap for the flight conditions tested is readily apparent. One conclusion of this acoustic investigation is that impulsive noise of rotors can be measured in the V/STOL tunnel.

Second Wind-Tunnel Test Program

At this time, a second test program is being conducted in the Langley V/STOL tunnel. The configuration is a ¼-scale AH-1G (Fig. 11) with a teetering rotor. The primary purpose of the test program is to determine if a V-tail will improve helicopter directional characteristics. Variations of tail span and dihedral angle are being investigated and compared with results from the standard tail.

For the Future

Now that there is confidence in the capability and integrity of the GRMS, a series of wind-tunnel experimental programs are being planned. The GRMS will be used for additional investigations of the RSRA to supplement what has been done in the V/STOL tunnel and explore characteristics for the RSRA flight-test program. The AH-1G configuration will be used again to measure rotor wake characteristics. The experimental data will be correlated with analyses such as in Ref. 4. Two flow measurement techniques will be used to define wake structure. The first technique uses helium-filled bubbles which follow streamlines. The second technique is a laser doppler velocimeter system which will measure flow velocities with no disturbance to the flow patterns.

Rotors with advanced airfoils and rotor tip modifications also are scheduled for tunnel testing. Definition of the advantages of advanced airfoils which typically have higher pitching moments and rotor and blade configuration modifications can be made. The benefits of advanced airfoils need to be established firmly through experimental investigations. For that matter, airfoil design analysis for rotor still is evolving and experimental proof of benefits can be defined economically with the GRMS before expensive flight-test programs are planned.

For blade slap, rotor blade modifications to alter the acoustics will be defined and tested. There are some tip modifications which are promising cures but which have not been comprehensively investigated to define their acoustic and performance characteristics on a common basis. Analysis has yet to provide a precise understanding of the mechanisms involved, so it is appropriate to obtain data to enhance the analyses and attempt to cure the problem.

The Langley V/STOL tunnel facility and staff have the capabilities, experimental and analytical, to carry out programs for the improvement of rotorcraft aerodynamics and acoustics. These capabilities are the unique V/STOL tunnel, a reasonably scaled general rotor model system (GRMS), data acquisition and reduction systems, and computational analysis routines. The GRMS should serve as a useful tool for many years.

References

[1] Wilson, J.C. and Mineck, R.E., "Wind-Tunnel Investigation of Helicopter-Rotor Wake Effects on Three Helicopter Fuselage Models," Langley Directorate, USAAMRDL, Hampton, Va., NASA TMX-3185, 1975.

[2] Wilson, J.C., Mineck, R.E., and Freeman, C.E., "Aerodynamic Characteristics of a Powered Tilt-Proprotor Wind-Tunnel Model," Langley Directorate, USAAMRDL, Hampton, Va., NASA TMX-72818, 1976.

[3] Bain, L.J. and Landgrebe, A.J., "Investigation of Compound Helicopter Aerodynamic Interference Effects," U.S. Army, USAAVLABS-TR-67-44, Nov. 1967.

[4] Landgrebe, A.J. and Egolf, A.T., "Rotorcraft Wake Analysis for the Prediction of Induced Velocities," U.S. Army USAAMRDL-TR-75-45, Jan. 1976.

[5] Mineck, R.E., Freeman, C.E., and Hassell, J.L. Jr., "Aerodynamic Characteristics of a 1/6-Scale Model of the Rotor Systems Research Aircraft with Rotors Off," NASA TN D-8198, 1976.

[6] Linden, A.W. and Hellyar, M.W., "The Rotor Systems Research Aircraft, A Flying Wind Tunnel," AIAA Paper 74-1277, Oct. 1974.

[7] Done, G.T.S., "A Simplified Approach to Helicopter Ground Resonance," *Aeronautical Journal,* Vol. 78, May 1974, pp. 204-208.

[8] Heyson, H.H., "Use of Superposition in Digital Computers to Obtain Wind-Tunnel Interference Factors for Arbitrary Configurations, With Particular Reference to V/STOL Models," NASA TR R-302, 1969.