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DESIGN, DEVELOPMENT, AND TESTING OF THE NO TAIL ROTOR (NOTAR) DEMONSTRATOR

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ABSTRACT

This paper discusses the design, development, and testing of the No Tail Rotor (NOTAR) aircraft. The NOTAR system replaces the conventional tail rotor with a combined system using a circulation control tailboom and a direct jet thruster. Air for both the circulation control tailboom and the direct jet thruster is provided by a variable pitch fan buried within the fuselage with pitch control provided by the pilot's pedals.

Initial full scale development testing indicated that effective circulation control could be realized at very low pressures of approximately one-half a psi, making the NOTAR power competitive to the tail rotor. Subsequent full scale flight tests demonstrated that the NOTAR aircraft had handling qualities equal to or superior to the baseline tail rotor aircraft. Over 35 test hours have been accumulated on the aircraft and test conditions have included hover and maneuvering flight as well as autorotations. A NOTAR aircraft computer model was taken into a piloted simulation program to evaluate the edges of the flight envelope. This showed the NOTAR performed well over a wide range of design conditions. Current plans incorporate the NOTAR concept into the emerging LHX aircraft design.

INTRODUCTION AND NOTAR DESCRIPTION

Traditionally, the exposed tail rotor has been the primary antitorque and maneuvering system for the single main rotor helicopter. The tail rotor does have major drawbacks, however. In one recent study (Reference 1), of 2108 helicopter accidents, 325 or 15 percent were caused by tail rotor systems. Of that 15 percent, half were caused solely by tail rotor strikes. Tail rotor strikes become more significant with the emphasis on nap-of-the-earth (NOE) flight profiles. The elimination of exposed high speed, whirling tail rotor blades also has an evident contribution to reduction of personnel hazard. Ballistically, a direct hit on the tail rotor can cause sudden and complete loss of antitorque force with catastrophic consequences. The high speed tail rotor tips are also a major contributor to the helicopter's noise signature.

The NOTAR system, Figure 1, eliminates these problems by combining circulation control along the tail boom and a direct jet thruster to provide required antitorque and maneuvering forces in all helicopter flight regimes. A variable pitch fan mounted within the fuselage blows low pressure air axially along the tail boom to provide for both circulation control and the direct jet. The circulation control tail boom generates antitorque force by using the energy in the main rotor wake. As can be seen in Figure 2, an air jet exiting from a slot in the tail boom causes the main rotor wake to remain attached farther around on the slot side. This produces a force analogous to the lift of a fixed wing. By appropriate location of the slot and control of the air jet through the slot, the force is generated in the desired, antitorque direction. The direct jet thruster is a sleeve valve assembly formed by two concentric truncated cones. The inner cone is fixed and contains fixed turning vanes to direct air both right and left. The outer cone rotates and has a constant area cutout. The rotation of the outer cone varies the direct jet exit area to match the commanded requirement for both thrust magnitude and direction (right or left).

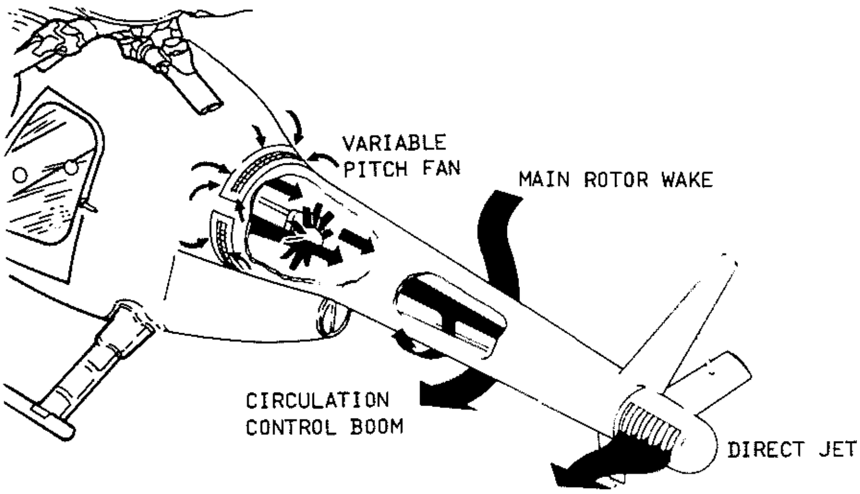

Fig. 1. NOTAR Antitorque System.

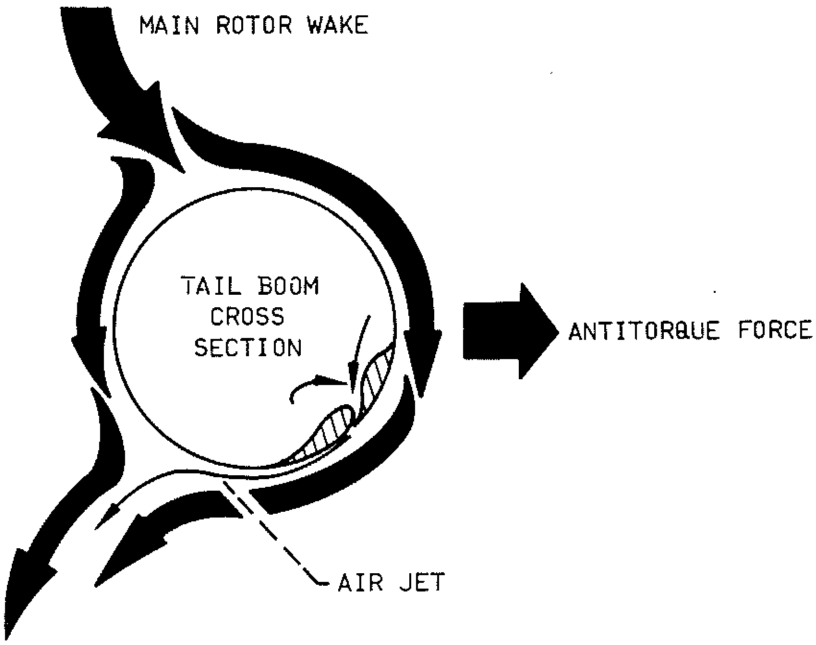

Fig. 2. Tail Boom Circulation Control.

Figure 3 shows the division of antitorque and maneuver forces between each of the NOTAR components as a function of flight mode. In hover, the circulation control tail boom provides the major portion of the required force. In translation flight at low speeds, the main rotor wake begins to move off the tail boom and the direct jet supplies the major portion of the required force. At high forward speeds, the vertical fin provides a significant portion of the force needed.

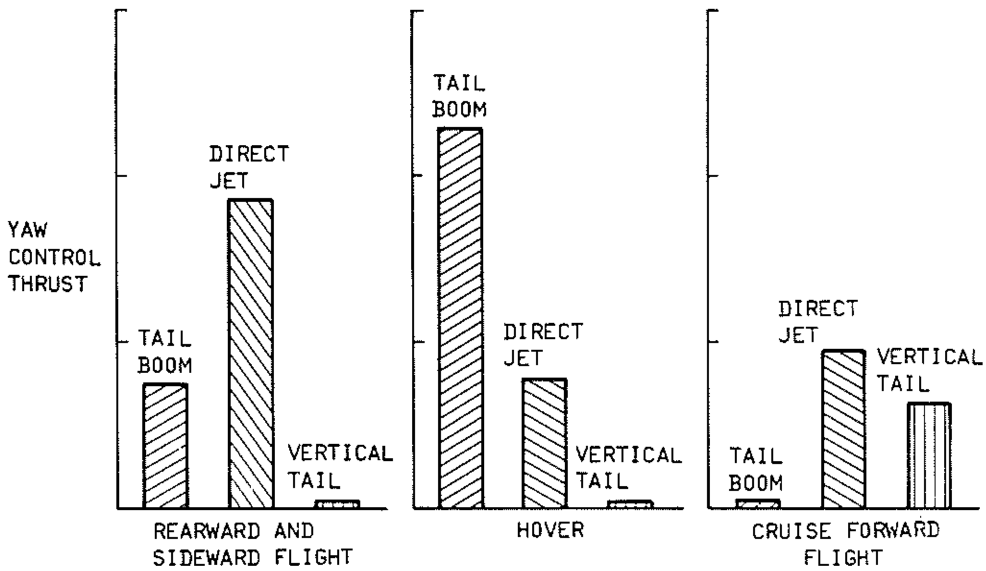

Fig. 3. Division of Yaw Control Forces.

The NOTAR system is controlled by the pilot's rudder pedals in a manner similar to the tail rotor. The relationship of the control pedals, fan, and direct jet thrust is shown in Figure 4. With the pedals in neutral, the fan pitch is low and the thruster exit area is directed to the left and sized to provide the hover requirement. With full left pedal, the fan pitch is increased and the outer sleeve valve rotated to provide increased exit area to the left. With full right pedal, the fan pitch increases relative to neutral, but not as much as full left pedal, and the outer sleeve valve rotates to provide exit area to the right. The control system is geared such that the increase in blade pitch and the increase in direct jet exit area are matched to provide approximately constant total pressure in the boom, leading to nearly constant flow out the slot.

BACKGROUND

Hughes Helicopters, Inc. has been investigating circulation control as a means for counteracting main rotor torque since 1976. Previous circulation control research[2,3] and applications have shown that the use of circulation control indicated potential benefits when used to generate the antitorque force needed by helicopters. HHI initiated its circulation control work by mounting an experimental circulation control tail boom under a thrusting rotor on a whirl tower[4] (Figure 5). This boom was a scaled experimental boom positioned as it would be in flight.

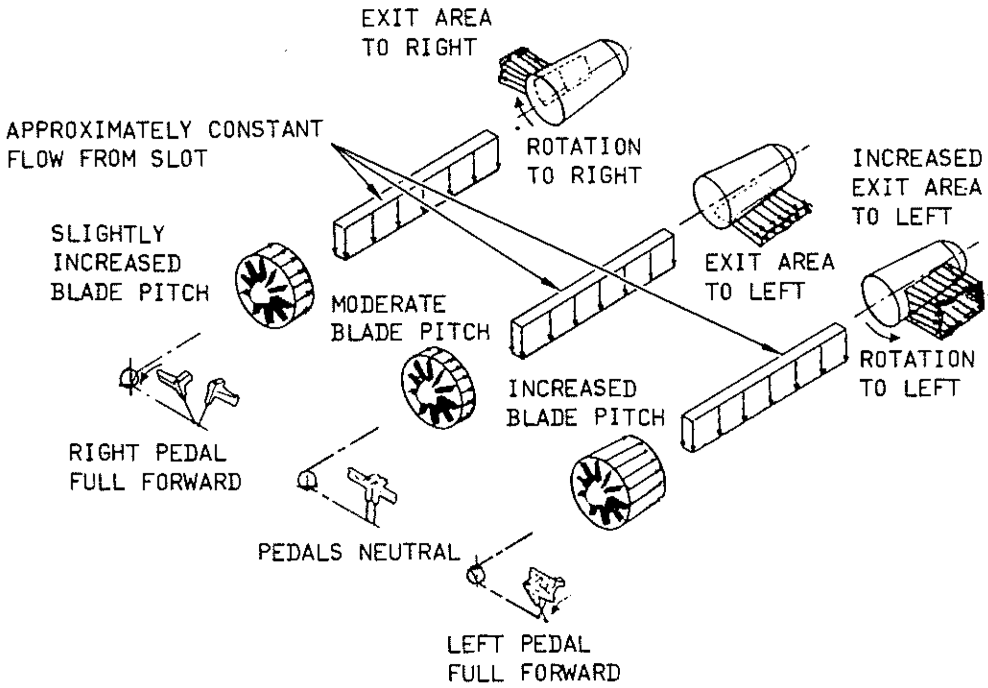

Fig. 4. NOTAR System Function.

This test determined the optimum slot velocities, slot location, and momentum coefficient for helicopter applications. The tests demonstrated that effective circulation control force could be generated at pressure ratios lower than those previously used. Figure 6 shows the variation of circulation control force with jet velocity ratio, indicating that a ratio of approximately 3.5 was the minimum required. For the OH-6A, this resulted in a velocity of 220 fps or less than a one-half psi internal pressure. Similar data were generated for the minimum required momentum coefficient. This low pressure system made it possible for the NOTAR to be power competitive with the conventional tail rotor.

This experimental tail boom was then flight tested under U.S. Army support to demonstrate the circulation control principles[5] (Figure 7). For this flight test, the circulation control air was provided by side mounted electrical fans and the tail rotor was retained. The tail empennage was removed so that tail rotor thrust could be measured directly. Flight conditions were flown with and without circulation control and changes in tail rotor thrust were used as a measure of circulation control effectiveness.

FLIGHT TEST

As a result of the previous work, HHI received support from the U.S. Army and DARPA to build and test a NOTAR flight demonstrator. The initial flight (Figure 8) was on December 17, 1981 — 78 years after the first Wright Brothers' flight. Full details of the NOTAR aircraft design and its testing are presented in References 6 and 7.

The initial flight testing indicated that the circulation control tail boom was not as effective as the whirl tower and previous flight test demonstrator showed the tail boom to be (Figure 9). To combat low speed flow separation over the tail boom, two design

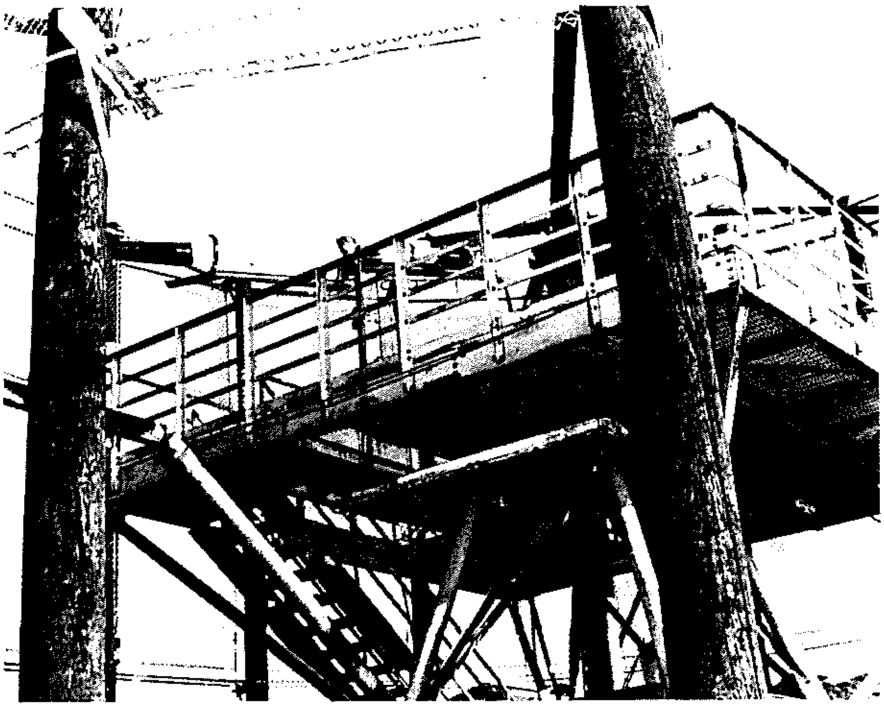

Fig. 5. Circulation Control Tail Boom Installed on Whirl Stand.

modifications were developed: an engine exhaust deflector and boundary layer fences. The engine exhaust deflection prevented the entrainment by the circulation control jet of hot engine exhausts and the fences isolated the circulation control tail boom from the rest of the aircraft. The fences were placed at the ends of the circulation control slot and ran the complete tail boom circumference. With incorporation of these two design changes, the circulation control tail boom operated as predicted.

The NOTAR helicopter was flight tested over the complete range of the basic OH-6A envelope. The testing included IGE and OGE hover, sideward/rearward flight, pedal steps, turns, pull-up and push-over maneuvers, as well as autorotations. In all, over 37 hours of ground and flight testing have been accomplished. The handling qualities have met or exceeded the baseline tail rotor equipped aircraft at low speeds. In hover, rearward, and sideward flight, excellent handling qualities ratings were recorded. There was a noticeable absence of disturbance caused by main rotor-tail rotor interaction. The low yaw damping did not prove to be a problem because of the absence of a disturbing force when the tail rotor was removed. The initiation and stopping of turns was accomplished with normal effort. The turn response of the aircraft was smooth and crisp, achieving the same rates as the tail rotor equipped baseline. In forward flight maneuvers, the aircraft performed similarly to the baseline aircraft with one exception. Above approximately 60 knots, the NOTAR aircraft evidenced a lateral-directional instability during turns. The cause of the instability was traced to the circulation control tail boom. Flights were made with the circulation control tail boom slot taped closed and no instability was evidenced during turns. The interaction of the circulation control tail boom was unexpected because all previous testing and simulation indicated that the tail boom was uneffective above approximately 30 knots due to the main rotor wake moving off the boom. The testing to date shows that future designs should include a closable circulation control slot.

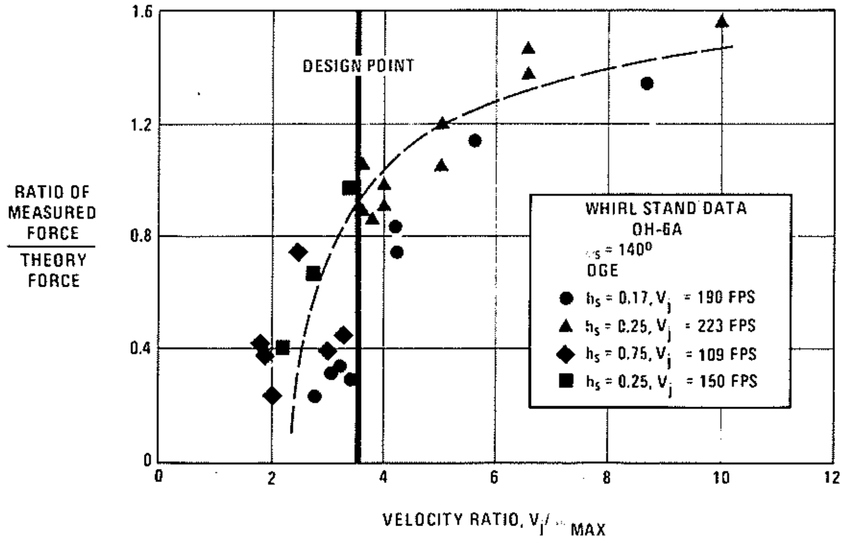

Fig. 6. Required Variation of Circulation Control Force with Jet Velocity Ratio.

Fig. 7. Flight Test of a Circulation Control Tail Boom Installed on OH-6A.

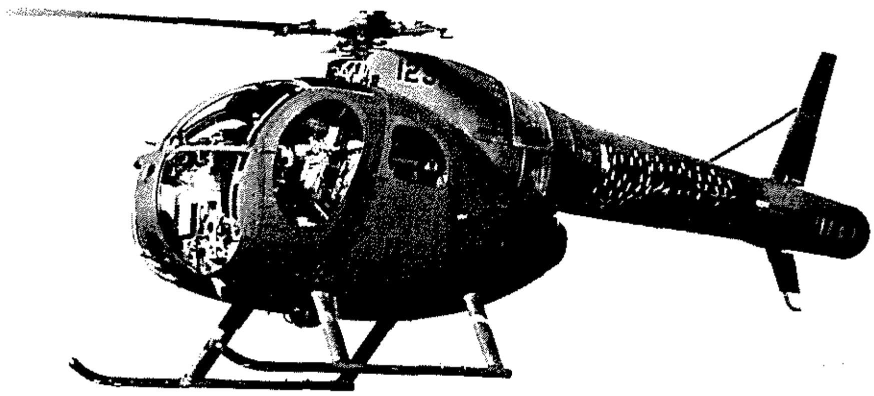

Fig. 8. First Flight of NOTAR System, 17 December 1981.

The flight test data indicated that the NOTAR aircraft could be power competitive with the tail rotor. Due to schedule and cost considerations, a Fenestron tail fan was chosen as the NOTAR system's air source. The Fenestron was flightworthy, variable pitch, the proper diameter, and in ground test demonstrated the required pressure rise and flow characteristics. The Fenestron was not designed for the NOTAR application and consequently showed very low efficiencies on the order of 40%. As a consequence, the NOTAR flight demonstrator absorbs more power than the tail rotor equipped OH-6A (Figure 10), but a properly designed NOTAR fan will use approximately the same power. Flight test data was used to correlate with a computer simulation of the NOTAR concept. Using the computer simulation, the performance characteristics of a properly designed NOTAR fan were input and the simulation "flown" throughout the test envelope demonstrating power requirements equivalent to a tail rotor.

This same computer simulation was also used for moving base, man-in-the-loop simulations on the Flight Simulator for Advanced Aircraft (FSAA) at NASA/Ames. During these tests, the NOTAR was flown at a variety of gross weights and disc loadings to generate additional design data. The tests indicated that the NOTAR characteristics are essentially unchanged with variations in design parameters. In addition, a rudder was simulated to improve the autorotational entry and flight characteristics of the NOTAR aircraft. This is a design flexibility not found in tail rotor equipped aircraft.

FUTURE WORK

The design development of the NOTAR aircraft is continuing. A more efficient NOTAR fan has been designed. The improved NOTAR fan incorporates approximately double the solidity (0.589 vs. 0.312), increased twist (14.7° vs. 7.07 °), higher lift airfoil sections (NACA 65-7XX vs. NACA 65A 2XX), and reduced diameter (25.5 inches vs. 27.56 inches) as compared to the Fenestron. In addition, movable stators are coordinated with the fan pitch. This raises the hover fan efficiency to approximately 73% making the NOTAR power competitive with the tail rotor.

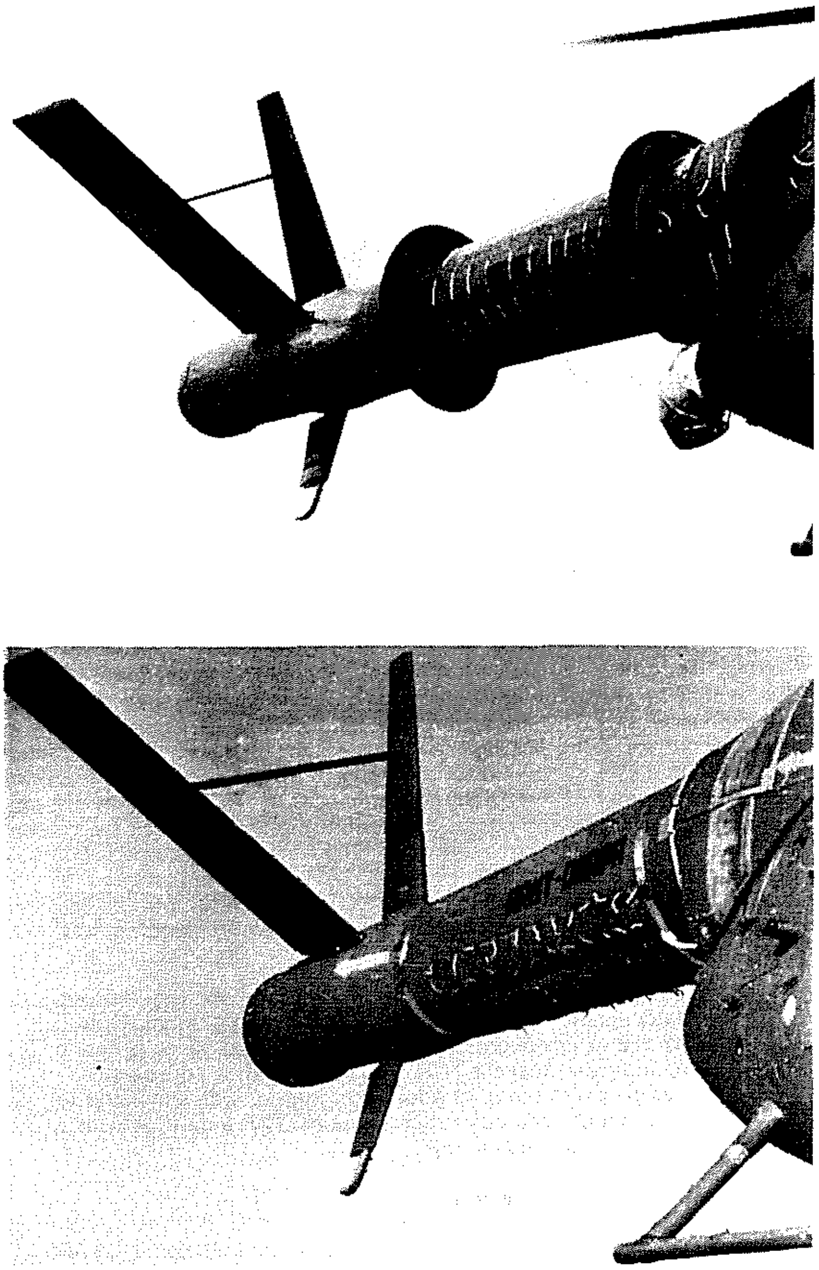

Fig. 9. NOTAR Circulation Control Tail Boom Flow in Hover.

In addition, the NOTAR aircraft is being tested in a controlled environment on HHI's whirl tower. During this testing, main rotor wake flow visualization will identify the cause of the circulation control tail boom flow disturbance. Using that information, design variations will be developed to eliminate the need for the fences, resulting in a low drag configuration.

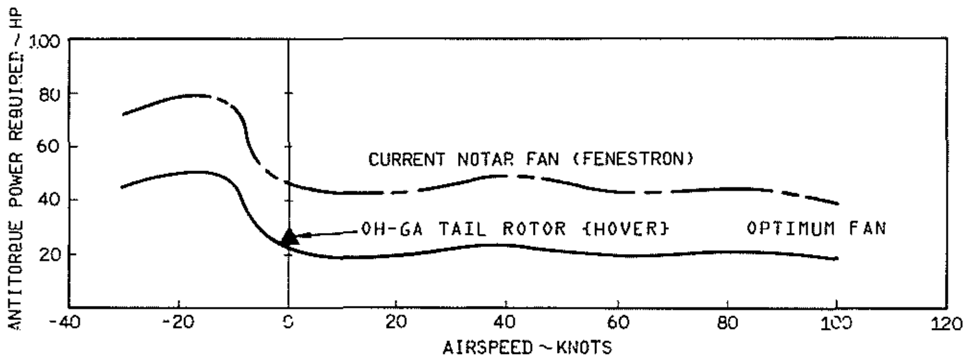

Fig. 10. Comparison of Trimmed Antitorque Power Required for Current and Optimized NOTAR Fans.

The NOTAR is also being incorporated in HHI's emerging aircraft designs, both commercial and military. The LHX is a perfect candidate for the NOTAR (Figure 11). The LHX has a requirement for high maneuverability, low detectables, and the capability of NOE flight in confined space, all of which are enhanced by replacing the tail rotor with the NOTAR system.

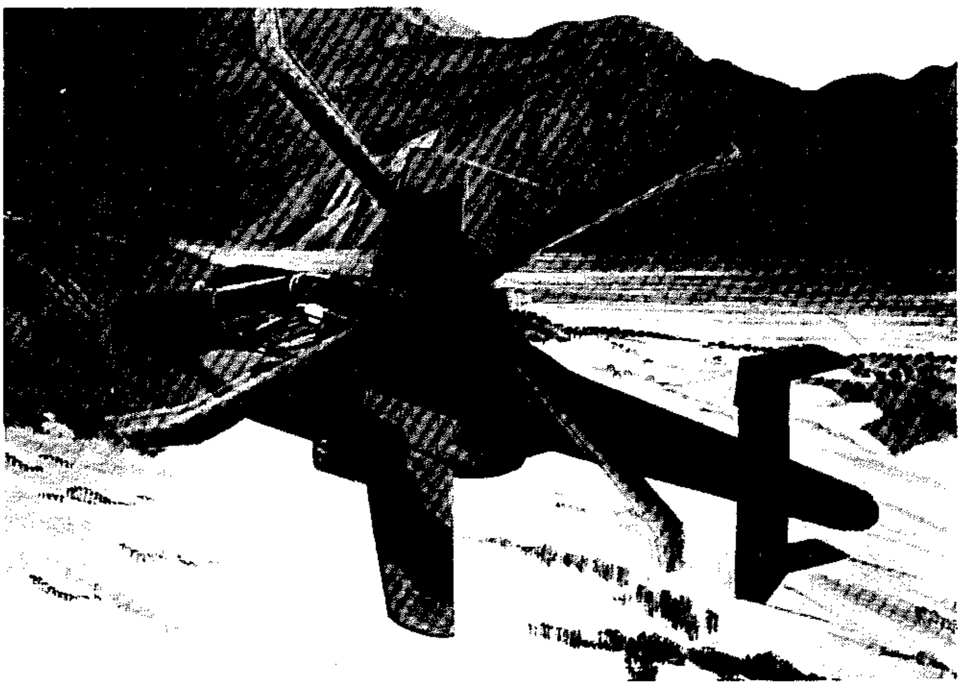

Fig. 11. Artist's Rendition of LHX/NOTAR.

CONCLUSIONS

As a result of the development and flight test work, the NOTAR concept has been demonstrated to be a viable alternative to the tail rotor. The handling qualities have been shown to be exceptionally smooth due to the absence of tail rotor disturbances. Continued design development has shown that NOTAR can provide the antcipated operational, life cycle cost, safety, and acoustic benefits by eliminating the tail rotor on the next generation of rotorcraft.

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DEDICATION

This paper is dedicated to the memory of Charles E. (Chuck) Hench, the first pilot to fly the NOTAR system. His expertise and enthusiasm helped make the NOTAR program a success.