DESIGN AND TESTING OF A DUCTED TAIL ROTOR CONCEPT DEMONSTRATOR FOR A MODEL 222U HELICOPTER

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Abstract

A Model 222U helicopter was used as a flight test vehicle during a development program that demonstrated the viability of a ducted tail rotor as a concept for antitorque system protection. During the program, the tail rotor technology base was expanded by experimentally determining the effect that thin ducts had on helicopter performance and flight characteristics. Progressive steps were made through a series of whirl stand, wind tunnel, and flight tests to lead to the present successful ducted tail rotor (DTR) configuration. In support of the program, a significant number of test components and equipment modifications were designed and manufactured using "rapid prototyping" techniques to reduce cost and development time. A description of the DTR design as it evolved is provided, as well as procedures, equipment, and results from each phase of testing.

Introduction

A ducted tail rotor antitorque system can reduce the risk of component damage as well as enhance the safety of operators, passengers, and ground personnel. However, development of a practical system must overcome formidable design constraints. The antitorque system design should not adversely affect important operational and flight characteristics such as performance, acoustic signature, and reliability and maintainability, and must meet stringent cost and weight criteria. Bell has examined a number of protected antitorque systems over the years that had the potential for meeting these requirements. Investigations started with a thin ring concept and led to the most recent thin duct concept, which has been called the "ducted tail rotor," or DTR. The DTR addresses antitorque system protection differently than current production helicopters, yet the results are quite similar. This different design solution was arrived at by an evolutionary process. This paper will trace that evolution and provide detail of the design and development activities undertaken.

During the period between 1978 and 1985, Bell conducted extensive wind tunnel and flight tests of a thin structural ring placed around a Model 206 helicopter standard tail rotor (Ref. 1). The ring was less than 2 inches (5 cm) thick, serving as a vertical stabilizer in lieu of the standard vertical fin. Directional stability was enhanced by the integration of a vertical fin on the forward portion of the ring, visible in the sketch of Fig. 1. This design concept was termed the "ring fin." The advantage of the ring fin concept was its ability to protect the tail rotor and reduce tail rotor blockage. Low-speed handling was also improved because of the reduction in fin blockage; but only minor improvements were evident in the acoustic signature. Due to a declining market, the targeted production opportunity did not materialize; however, experience with the ring fin was the beginning of the ducted tail rotor development.

Development of Ducted Tail Rotor Concept

From 1991 to 1996, design and experimentation techniques were used to develop the ducted tail rotor into a viable concept for antitorque system protection. Depicted in Fig. 2 is a summary of the development steps that led to a successful DTR configuration.

Duct Geometry Wind Tunnel Test

Analyses as well as whirl stand and wind tunnel tests were conducted on a 0.82-scale model to develop the optimum duct geometry. The major configuration parameter evaluated was the duct thickness. In determining the optimum duct thickness, several factors are involved in the design tradeoff. A thick duct gives the best hover performance, which allows the rotor diameter to be reduced, thereby improving the vertical fin integration. The thin duct weighs less and has less drag in forward flight. The thin

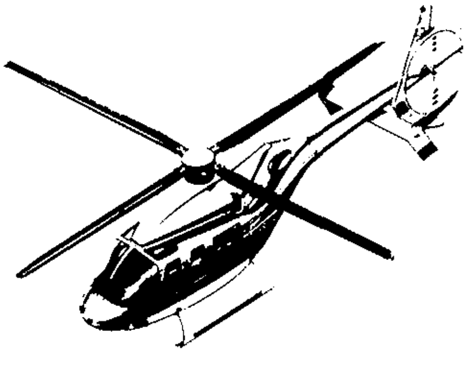

Fig. 1. "Ring fin" tail rotor design.

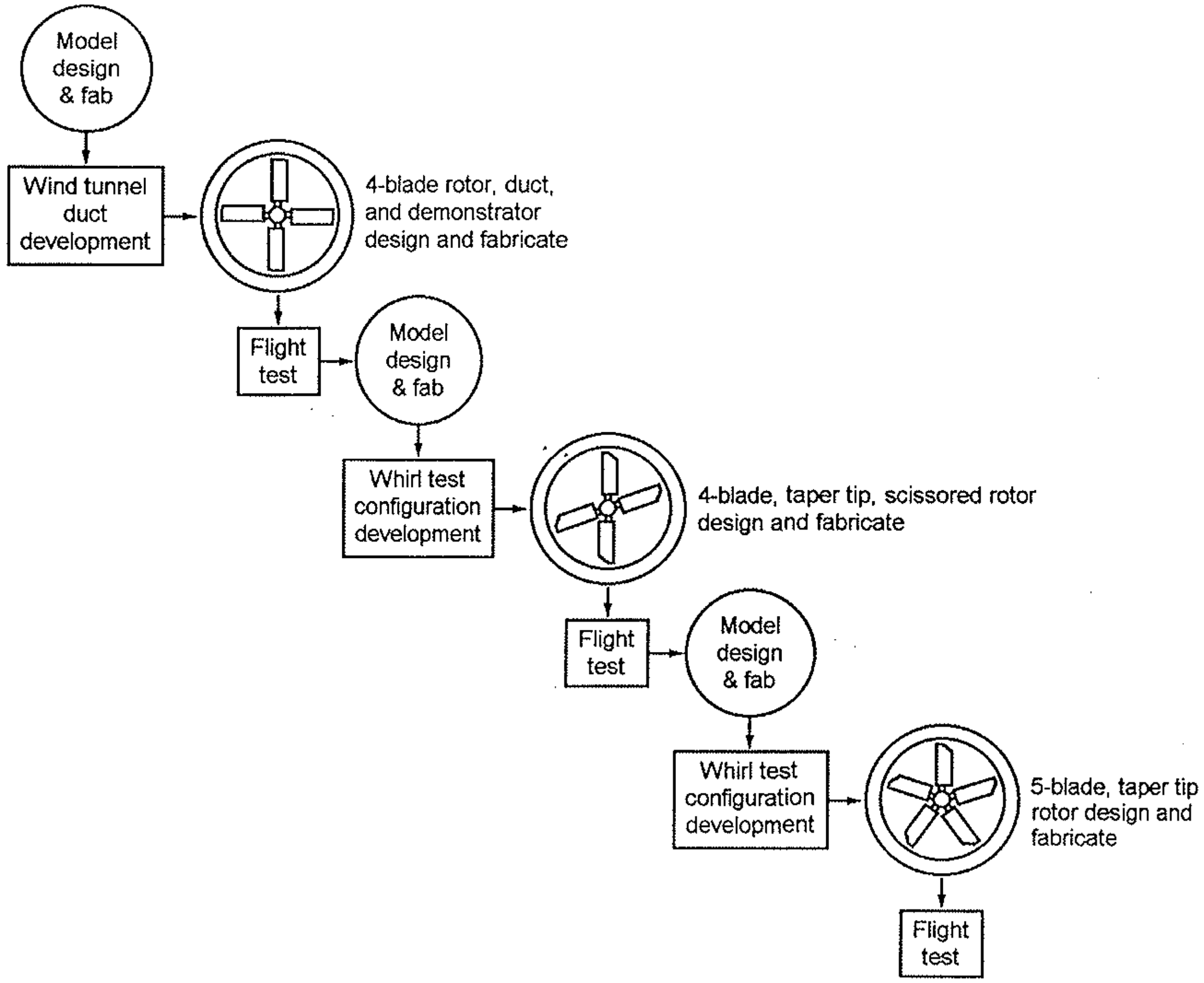

Fig. 2. Ducted tail rotor design and development steps.

duct does not require the large afterbody fairing needed to streamline the thick duct. This reduces the tail side view area and improves right sideward flight performance. The goal of this test was to provide enough data to help make a duct thickness design decision. The system performance for static conditions, left and right sideward flight, and forward flight were determined. The thrust sharing between the rotor and duct, as well as the power and collective pitch requirements, were used to calibrate the analysis. Rotor flapping and loads, which are difficult to predict due to the complex inflow field, were also measured.

Model and Instrumentation. Wind tunnel tests were conducted in the Ling-Temco-Vought 7-ft × 10-ft Low Speed Wind Tunnel. The test stand shown in Fig. 3 was bolted to the test section floor and was capable of yaw angles from 0 deg to 360 deg. The duct and rotor were each supported separately with an internal balance. Two duct-thickness-to-rotor-diameter ratios were tested, 10% and 20%. Radial rings of pressure taps were located on the 20% duct at two locations for a total of 64 taps. The tail rotor consisted of four Model 206 helicopter tail rotor blades modified to attach to a gimbaled hub with a collective range of +20 deg to −16 deg. The rotor system instrumentation included mast torque, blade flapping angle and bending moments, and pitch link axial loads. The model stand drive system included a modified Model 222 helicopter gearbox driven by two 75 hp (56 kW) electric motors.

Test Results. As shown in Fig. 4, the thicker 20% duct had more thrust sharing and less required power than the 10% duct and the isolated rotor. Based on the test results, the best combination of good hover performance and low forward-flight drag without high blade loads was with the 20% thick duct.

Four-Bladed DTR Concept

DTR Concept Demonstrator Design and Modification

To demonstrate the full-scale performance and acoustic signature, a DTR concept demonstrator was designed and manufactured. A Model 222U helicopter was selected as the flight demonstrator. Modification of the Model 222U

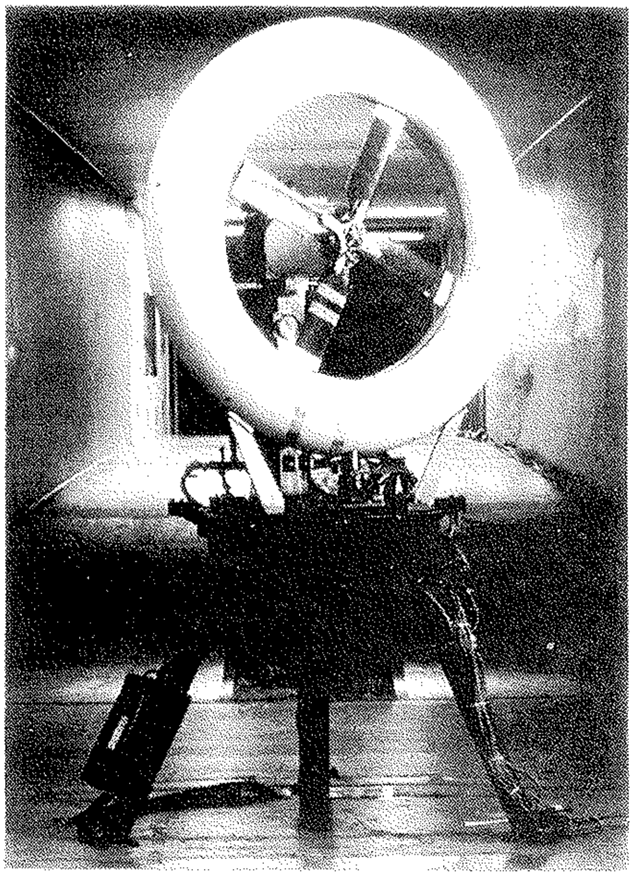

Fig. 3. Wind tunnel test stand and model.

for installation of the DTR resulted in significant redesign of the basic helicopter from the tailboom attachment aft. A "rapid prototyping" approach was used to accomplish the helicopter modification. The design team was collocated with manufacturing personnel at Bell's New Product Development Center. This approach allowed the Model 222U DTR concept demonstrator to make its first flight eight months following design go-ahead.

Design Approach. The design approach for the flight demonstrator was to use readily available materials and quick manufacturing processes to minimize schedule and cost risks. Machined parts and sheet metal assemblies were used to eliminate long-lead, complex tooling. Relatively small composite fairings were used that required simple tooling. Computer-Graphics-Aided Three-Dimensional Interactive Application (CATIA) was utilized in the design to ensure proper fit of the components during assembly. Excess weight was avoided, but structural designs were not refined and iterated to optimum as they would be for a production helicopter. The DTR was designed to provide tail rotor system thrust and vertical fin side force similar to that of the basic Model 222U helicopter. In order to keep the weight, inertia, and drag penalties low, the DTR diameter was set so that there would be only a modest performance degradation compared to the standard tail rotor. A key feature in meeting these requirements was utilizing the relatively thin 20% thickness duct configuration. A comparison of key design parameters for the M222U DTR concept demonstrator and the basic Model 222U is shown in Table 1.

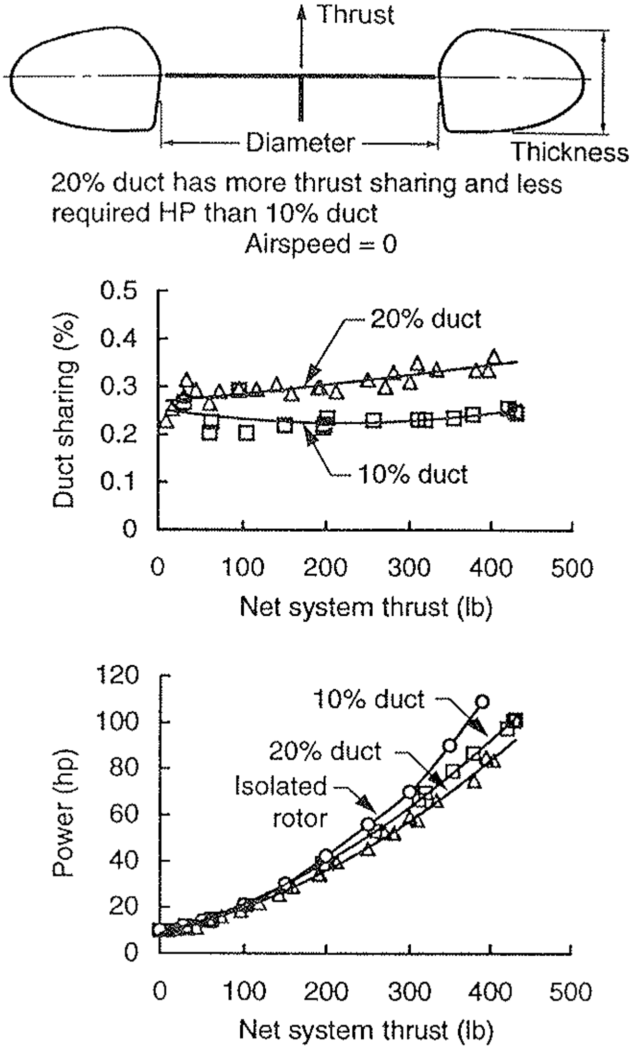

Fig. 4. Duct thrust sharing and power required vs. system thrust for 10% and 20% thick ducts.

Helicopter Modifications. Helicopter modifications included redesign of the tailboom structure and a new gearbox, duct/fin structure, and tail rotor. The tailboom is shown during modification in Fig. 5. Three aluminum bulkheads were added to the aft portion of the basic helicopter tailboom to allow attachment of the duct/fin structure and an aluminum tail rotor gearbox support tube. Additional support of the gearbox was also provided by 2.0-inch (50-mm) diameter steel vertical struts shown in Fig. 6. A new gearbox case and gears were fabricated to allow operation of the rotor at the higher rotational speed required by the DTR. The duct inner surface was a spun aluminum ring with internal aluminum ribs riveted at radial locations for attachment of fin structure. An aluminum skin closed out the aft portion of the duct structure. The duct outer contours were formed using shaped foam and fiberglass fairings bonded to the primary aluminum structure. The vertical fin forward and aft spars, ribs, and

Table 1. Comparison of M222U and M222 DTR.

Aircraft:	M222U	M222 DTR
Gross weight	8,250 lb (3,742 kg)	8,250 lb (3,742 kg)
Tail rotor diameter	6.88 ft (2.1 m)	4.29 ft (1.3 m)
Number of blades	2	4
Solidity	0.154	0.371
Tail rotor blade aspect ratio	4.13	3.43
Duct thickness / diameter	–	0.2
Tail rotor tip speed	678 ft/s (206 m/s)	720 ft/s (220 m/s)
Tail rotor gearbox rating	185 hp (138 kW)	185 hp (138 kW)
Tail rotor rev/min (rpm)	1,882	3,204

skin were formed aluminum riveted assemblies, and the leading edge was graphite fabric. A tail skid was enclosed in the frangible fiberglass ventral fin. The rotor hub and blade assembly is shown in Fig. 7. The four-bladed steel hub with 90-deg spacing used tension–torsion straps for blade retention and bearings for blade pitch change motion. The blade shown in Fig. 7 consisted of an aluminum root end fitting and a closed-cell foam blade with fiberglass "D" spar and afterbody skin. The geometry of the square-tipped blade is shown in Fig. 8.

Helicopter Instrumentation. Critical components of the rotor system, tailboom structure, vertical fin structure, and helicopter control positions and main rotor and tail rotor torque were instrumented. Measured data were recorded on an airborne data acquisition system to ensure safe flight operation and determine rotor system performance, stability and loads, and helicopter performance and handling qualities. Safety-of-flight monitoring and envelope expansion was accomplished through the use of helicopter telemetry equipment. The tailboom lateral bending instrumentation was calibrated to provide duct and rotor combined thrust. Also, the gearbox support tube was calibrated to measure isolated rotor thrust when the vertical struts were not installed.

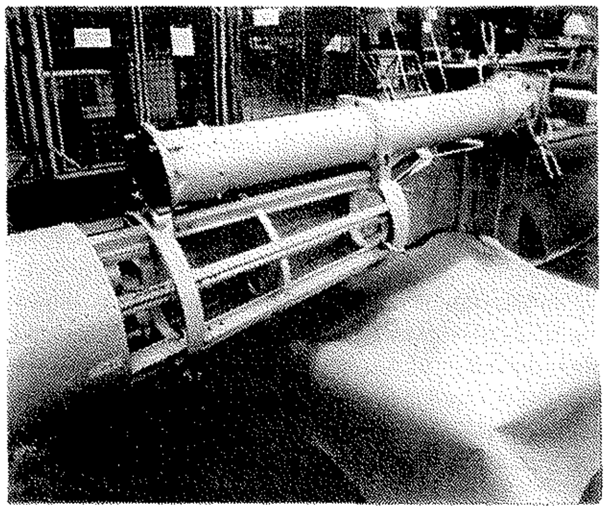

Fig. 5. M222U demonstrator tailboom during manufacture.

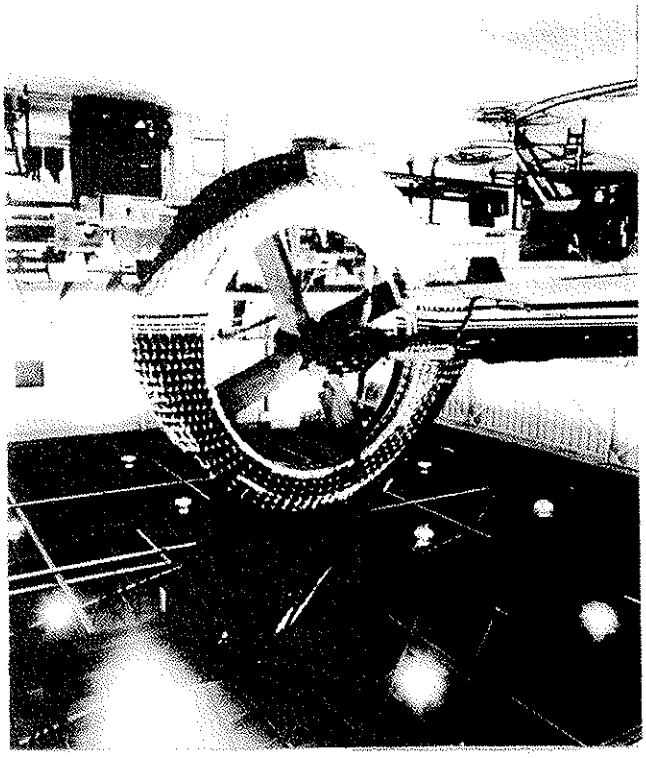

Fig. 6. Four-bladed squared-tipped DTR M222U demonstrator installation with vertical support struts.

Flight Test

62.7 hours of ground and flight testing was conducted at Bell's Flight Research Center in Arlington, Texas and at Leadville, Colorado for high-altitude tests (field elevation 9,920 ft [3,020 m]). Fig. 6 shows the DTR with four 90-deg spaced square-tipped blades installed on the Model 222U test helicopter. During tied-down ground runs, isolated rotor and DTR system performance, loads, dynamic stability, and acoustic signature data were obtained up to the tail rotor gearbox maximum continuous torque limit. Acoustic data were measured azimuthally around the helicopter in 30-deg increments and at varying tip speeds and thrust levels. During flight operations, data were obtained for IGE and OGE hover, hovering turn arrestments up to rates of 60 deg/s, low-speed rearward and sideward flight to 45 kn, climbs and descents to 90 kn, autorotation entries to 80 kn, and lateral-directional tests out to 130 kn. Acoustic data were obtained during IGE hover, 120-kn flyover, and 60-kn approaches and departures.

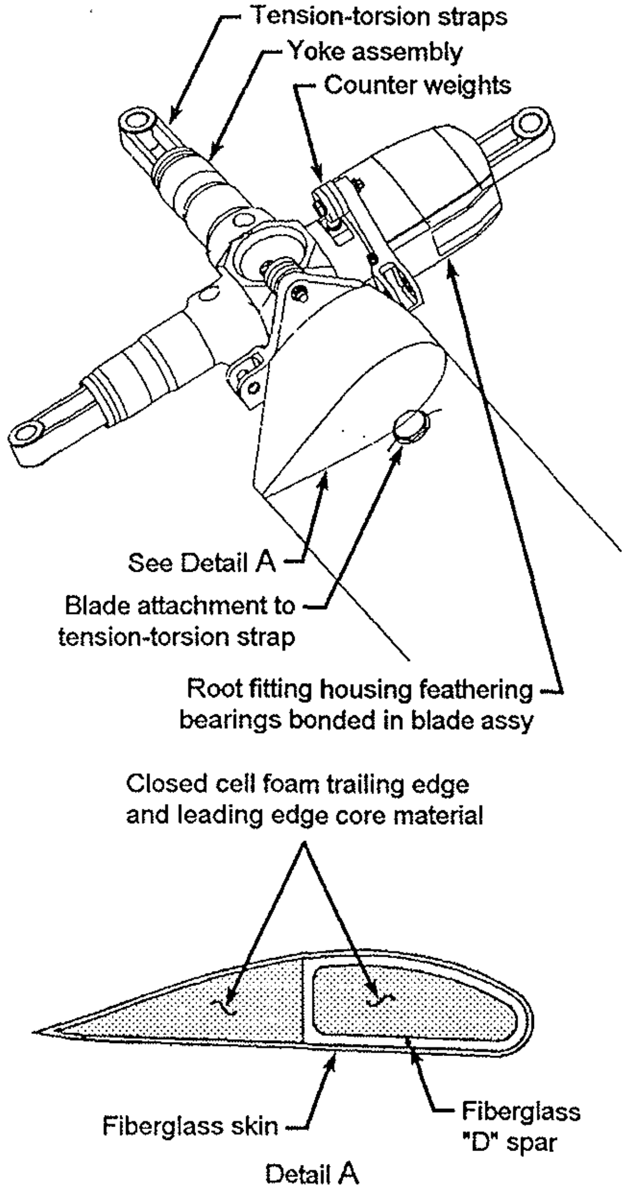

Fig. 7. Four-bladed rotor hub and blade description.

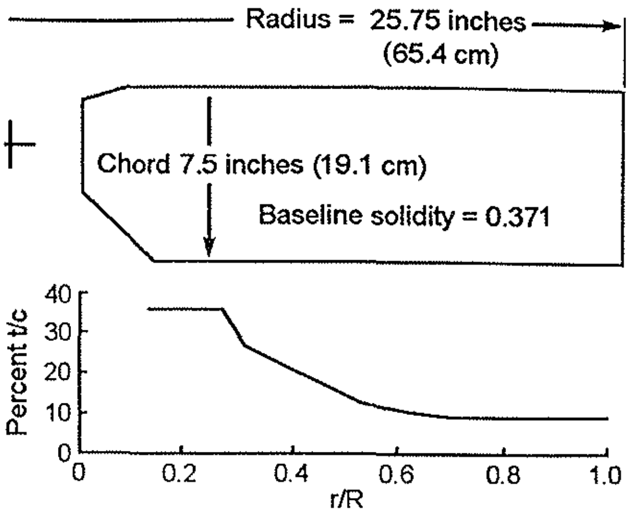

Fig. 8. Square tipped blade geometry for four-bladed rotor.

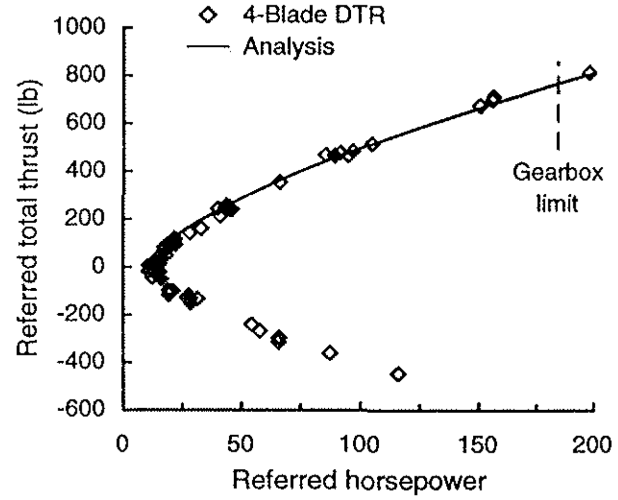

Fig. 9. Measured thrust vs power compared to predictions.

Test Results

Results showed that tail rotor performance, loads, and dynamic stability were very near predicted values.

Ground Run and Hover. Performance data taken during the ground runs show excellent correlation with analysis predictions (Fig. 9). During ground runs, the DTR thrust was derived from tailboom lateral bending. This was found to be reasonably accurate when the main rotor collective was reduced to flat pitch to minimize downwash on the tailboom. Hover performance is shown compared to the standard tail rotor in Fig. 10. For the hover curves the thrust is derived from main rotor torque. This thrust value includes all the side forces generated by the main rotor downwash on the tailboom and horizontal elevator endplates. However, since this is the same for both standard and ducted tail rotors, the comparison is valid. For a typical hover thrust value of 500 lbf (222 daN), the standard tail rotor requires 86 hp (64 kW), and the four-bladed DTR requires 103 hp (77 kW), a 17-hp (13-kW) penalty. This equates to a 1.8% increase in engine shaft power required to hover.

Sideward Flight. Right sideward flight performance is shown in Fig. 11 for the four-bladed DTR at a density altitude of 9,000 ft (2,750 m). At 45 kn, the power required is 170 hp (127 kW). With the gearbox rated at 185 hp (138 kW) maximum continuous power, this leaves margin for maneuvers or gusts. The pilots commented that the low-speed workload was less than that of the standard tail rotor in left sideward flight. This was due in part to the DTR's higher rotor disk loading. The pedal activity required to hold heading in left sideward flight is shown in Fig. 12 compared to the standard tail rotor.

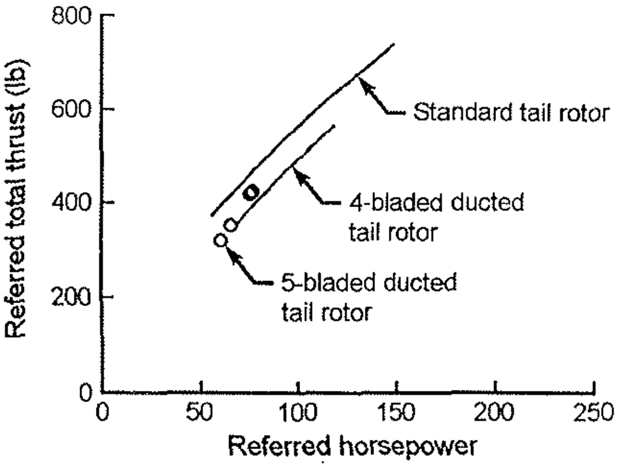

Fig. 10. **Measured four-bladed DTR thrust vs power compared to standard tail rotor.**

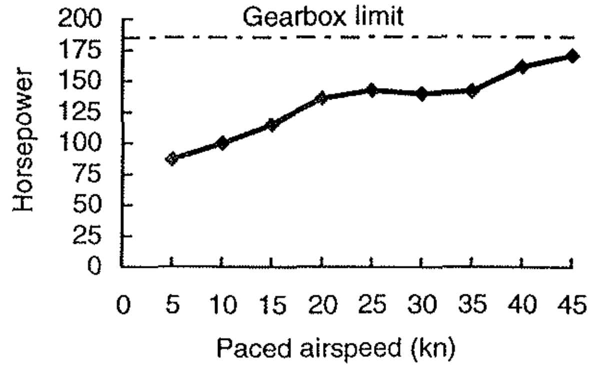

Fig. 11. **Right sideward flight performance at density altitude of 9,000 ft.**

During high-altitude tests at Leadville, the DTR demonstrated sufficient thrust capability in winds up to 35 kn for an increase in referred gross weight of 800 lb (363 kg) compared to the standard tail rotor. This performance was achieved without exceeding the standard M222U tail rotor drive train power rating.

Forward Flight. The measured drag increase over the baseline Model 222U was 1.4 ft^2 (0.13 m^2). Because of the high fin incidence and shrouding of the tail rotor, the DTR required less power than the standard tail rotor in forward flight (Fig. 13). The higher drag and lower power required combine to produce a 2-kn penalty compared to the standard tail rotor.

During right sideslip, the directional stability was equivalent to that of the standard M222U. During left sideslip, a lateral-directional longitudinal-pitch coupled oscillation was present and the directional stability was about half that of the standard M222U. Flight tests with the fin tufted for airflow visualization indicated that the lower half of the vertical fin was separated during left sideslip, but attached with zero or right sideslip. A limited amount of testing was done to evaluate configuration effects, with the most improvement provided by a vertical fin Gurney flap. A final solution would require additional testing.

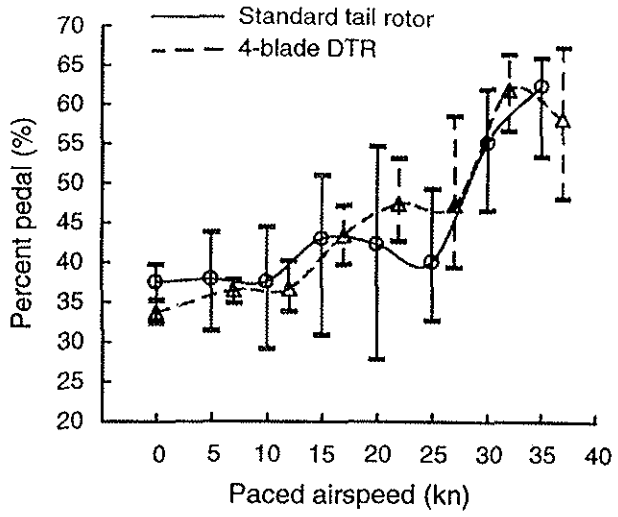

Fig. 12. **Pedal activity in left sideward flight.**

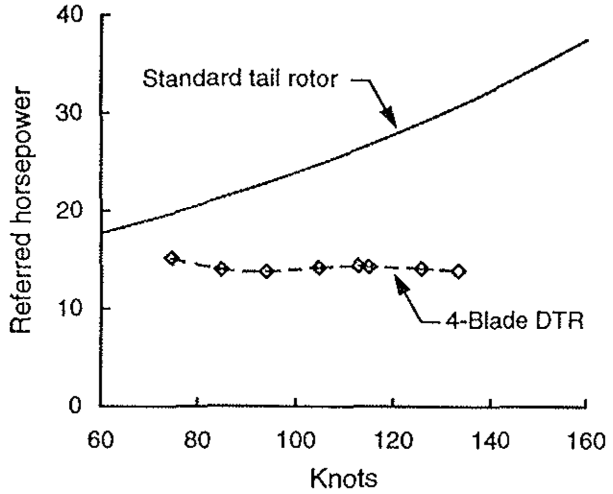

Fig. 13. **Four-bladed DTR tail rotor power required in forward flight compared to standard tail rotor.**

Loads. Measured four-bladed rotor hub and blade oscillatory loads data are compared with analysis predictions in Fig. 14 for V_H level flight. These loads were within predicted design values.

Acoustic Signature. During initial ground run testing of the four-bladed DTR, the acoustic signature quality and level was considered unacceptable. Fig. 15 shows a comparison of the four-bladed DTR with the standard tail rotor during hover. The DTR was found to have higher amplitude harmonics which extended above the standard tail rotor's frequency range, and well into the frequency range in which human hearing is most sensitive. The combined tail rotor harmonics on the DTR was 6 dBA

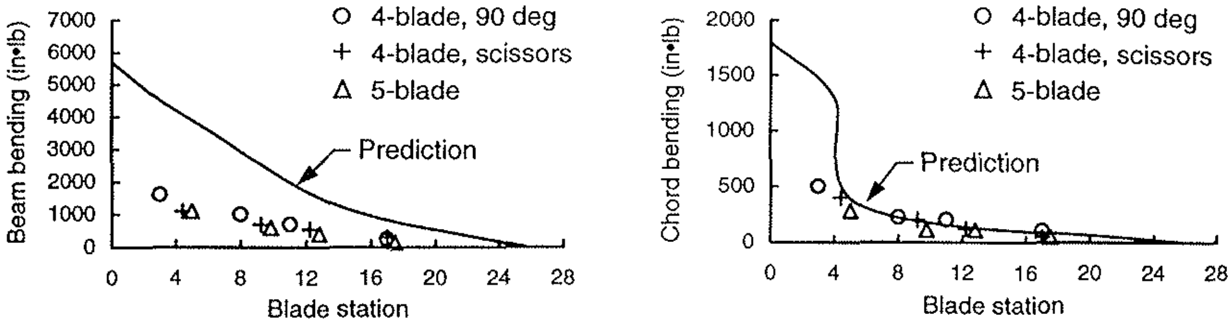

Fig. 14. Measured vs predicted rotor hub and blade V_H level flight oscillatory loads for four-bladed, four-bladed scissors, and 5-bladed rotors.

higher than on the standard tail rotor. In addition, the quality of the DTR was judged to be worse because of a fluctuating high-pitched "buzzing" sound.

In order to investigate the cause of this noise and hopefully to find a solution, a series of configuration changes to the duct, rotor spinner, rotor tip clearance, tail rotor gearbox and support structure, and changes in tip speed were evaluated. Slight improvements in acoustic signature quality and level were obtained by using a rotor spinner and a smaller diameter gearbox support tube, but these improvements were not considered adequate for customer acceptance.

Four-Bladed Scissored DTR Concept

Whirl Stand Test

Model testing was conducted in the Bell whirl test facility to investigate potential methods for improving the DTR sound quality, reducing sound levels, and broadening the understanding of how such sound is generated. The walls of this facility form a cylindrical chamber that can be vented near the floor and ceiling to minimize recirculation of air when the model is being tested. Acquisition of data and control and monitoring of the model was accomplished in a separate blockhouse room overlooking the whirl cage.

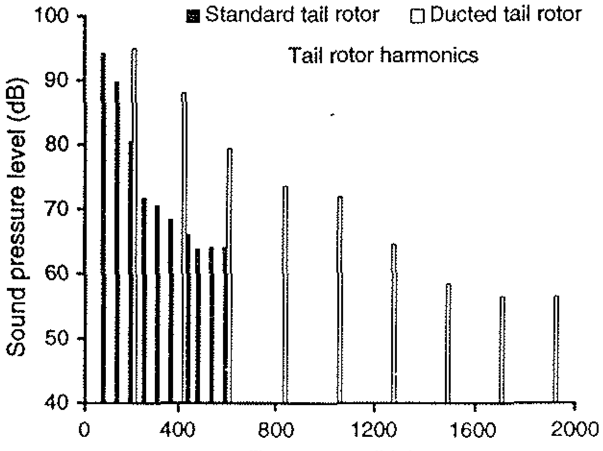

Fig. 15. Four-bladed DTR acoustic signature during hover compared to standard tail rotor.

Model and Instrumentation Description. Testing was conducted on a 0.82-scale model tail rotor and duct scaled to the flight test configuration. The rotor blades consisted of four Bell Model 206 tail rotor blades modified to a 21.1-inch (53.6-cm) radius to fit inside the 20% thick wooden duct with a 0.38-inch (0.95-cm) tip clearance. The rotor configurations tested included the baseline four-bladed rotor with 90-deg blade spacing, a four-bladed rotor with 90-deg blade spacing with tapered blade thickness, a four-bladed uneven or "scissored" rotor with 70-/110-deg blade spacing, and a four-bladed scissored rotor with 55-/125-deg blade spacing. All rotors tested had square tips. The model DTR was mounted with its rotor plane vertical, and was powered by a direct drive 75-hp (56-kW) electric motor. The available power was sufficient for operating the rotor at the desired tip speed of 720 ft/s (220 m/s) with collective pitch settings to 12 deg. An array of four microphones was placed azimuthally around the model. Recordings from each microphone were stored on magnetic recording tape and later processed using an FFT analyzer.

Test Procedures. Data for each configuration change were compared to the baseline rotor to quantify reductions for each change. Data were obtained for each of the rotor configurations at variations in collective pitch and tip speed. Also, variations in rotor spinner diameter and gearbox support structure diameter and location were investigated. "Trip plates" mounted perpendicular to the duct inlet surface were used to determine the effect of inflow turbulence for select configurations.

Test Results. Two configuration changes that did provide notable noise reductions were the thinner airfoils at the tip and the 70-/110-deg scissored rotor. The first large-amplitude harmonic for the equal blade spacing corresponds to a 4/rev tone, while the first large-amplitude harmonic for the scissored rotor corresponds to 2/rev tone. Essentially the acoustic energy had been shifted to a lower frequency where it was less annoying. The effect seen earlier during flight test of the spinner and smaller gearbox support tube diameter reducing noise levels was not duplicated on the whirl stand. It was felt these configuration changes reduced the DTR inflow turbulence on the M222U DTR concept demonstrator and this effect was not properly duplicated in the test setup.

Helicopter Modifications for Four-bladed Scissored DTR

From the results of the whirl test, a four-bladed 70-/110-deg scissored rotor, two additional thin tip blade configurations, and smaller diameter gearbox drive shaft segment and support tube were designed and fabricated for flight test evaluation on the M222U DTR concept demonstrator.

Rotor. The same basic rotor hub design concept used previously was modified to incorporate the 70-/110-deg blade spacing. The incorporation of the thin tip concept blades was through the use of a tapered planform tip shape. The use of a planform taper had the double benefit of a dimensionally thinner tip and moving the blade loading inboard. The two tip shapes shown in Fig. 16 were designed and fabricated for testing. The tip region of the earlier blade design was modified to incorporate the smaller chords, and the airfoil distribution from Fig. 8 was retained.

Smaller Drive Shaft and Support Tube Diameter. The diameter of the last segment of the tail rotor drive shaft which passed through the gearbox support was reduced to allow reduction of the diameter of the support tube. To provide proper support of the smaller drive shaft, an additional bearing was placed within the gearbox support tube.

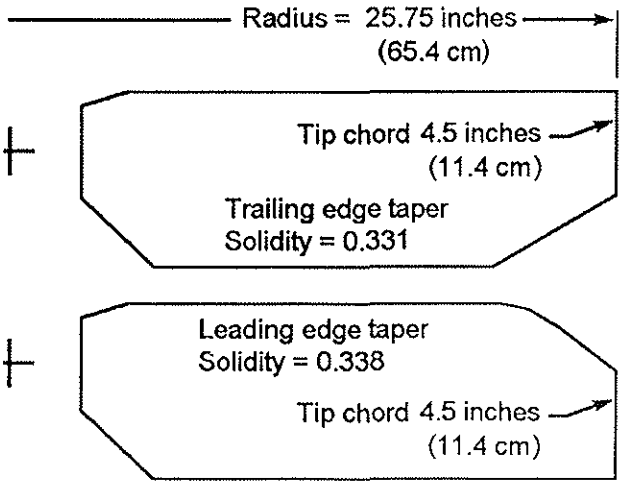

Fig. 16. **Leading-edge taper and trailing-edge taper tip blade geometry.**

Flight Test of Four-Bladed Scissored DTR

25.6 hours of ground and flight testing was conducted at the Bell Flight Research Center in Arlington, Texas. Fig. 17 shows the four-bladed scissored DTR installed on the Model 222U DTR concept demonstrator. Ground run, hover, low-speed, and forward-flight test conditions conducted during the previous flight test were repeated to obtain acoustic, loads, dynamic stability, and performance data.

Test Results. The rotor loads, performance, and stability of the configurations tested were as analytically predicted and acceptable. The tapered tips had a slight performance degradation compared to the square tip rotor. As can be seen in Fig. 8, the inboard end of the blade is fairly thick. By reducing the amount of efficient tip airfoil, the average blade profile drag coefficient increased. In addition, by reducing the blade loading at the tip, the suction on the duct decreased, resulting in a 6% reduction in thrust produced by the duct. Overall the three configurations flew well. The trailing-edge taper tip (termed the aft taper tip) proved to be the quietest of the three tips. Results of the scissored DTR acoustic data demonstrated improvements in sound quality and levels; however, it still had a high-frequency sound quality that was considered very annoying which would not be accepted by our customers.

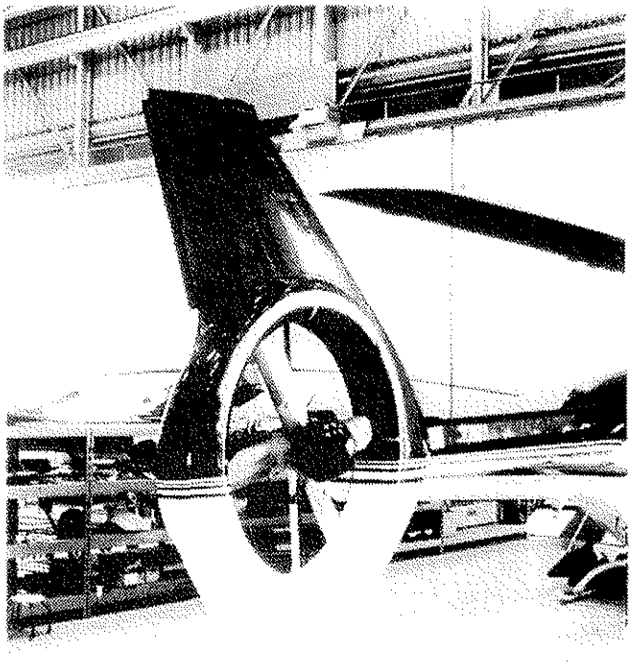

Fig. 17. **Four-bladed aft tapered tip scissored DTR installed on the M222U demonstrator.**

Five-bladed DTR Concept

Whirl Stand Test

Additional model rotor hover testing was conducted in the Bell whirl stand test facility to continue development effort toward a DTR configuration with an acceptable acoustic signature. The configuration variations that were effective in reducing sound levels and improving sound quality from previous whirl stand and flight tests were used to establish an expanded matrix of model test configurations. The beneficial effect of blade spacing and reduced tip speed was investigated further by applying variations to five-bladed configurations and comparing results to the baseline four-bladed scissors. The test setup was changed from the previous whirl test to add performance measurement, reduce acoustic reflections, and more closely simulate the flight test airflow environment. The addition of performance measurement ensured that acoustic data were taken for each rotor configuration at comparable thrust levels.

Design Approach. The sinusoidal modulation analytical techniques described by Riley (Ref. 2) were utilized in determining three uneven model rotor blade-spacing combinations to investigate. This sinusoidal modulation technique reduced the magnitude of the acoustic harmonics and provided statically balanced rotors. Three blade-spacing configurations were tested in order to select an optimal design and validate analytical techniques. To investigate a greater number of rotor configurations than in the previous whirl stand test and to meet cost and schedule constraints, a simple approach for model rotor fabrication was adopted. The blades were constructed of steel spars with laminations of wood and fiberglass, with monoball bearings installed at the root end of the spars to provide blade pitch movement. Three steel hubs were used that had multiple sets of hole patterns to accommodate the variations in number of blades and blade spacings tested.

Model and Instrumentation Description. To reduce acoustic reflections, absorptive panels, visible in the photograph of Fig. 18, were installed on the walls, ceiling, and floor. The 82% model was mounted with its rotor plane horizontal, and positioned 10.6 ft (3.23 m) above the test facility floor. The 20% thick wooden duct from the previous whirl test was used.

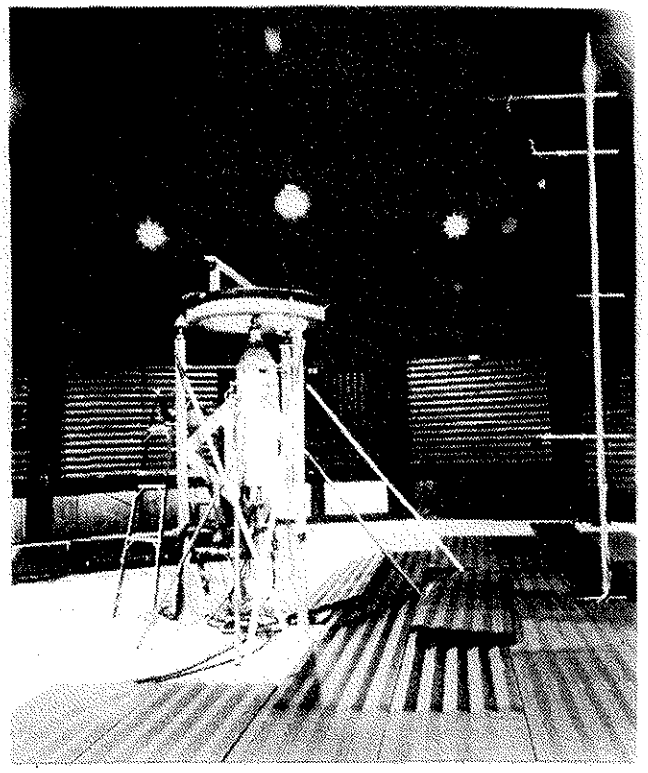

Fig. 18. Five-bladed DTR model and whirl stand.

The reference point or baseline rotor for testing was the four-bladed, square-tipped scissored rotor. The rotor configurations tested included the baseline and nine different five-bladed rotors with varying solidity, tip shape, blade spacing, and airfoil. Square and aft tapered planform tips, evenly spaced blades, and three different unevenly spaced blade rotor configurations were tested. The physical characteristics of the principal rotor configurations that were of fundamental interest or represented a marked improvement during the evaluation process are listed in Table 2.

Four microphones, also visible in the photograph of Fig. 18, were positioned 10 ft (3 m) from the rotor hub. The microphones were located 45 deg above, 30 deg above, 30 deg below, and in the plane of the rotor. The rotor was supported by three load cells to provide thrust measurement. The rotor mast or drive shaft was instrumented for torque measurement. Measurement of the duct thrust augmentation was not provided in order to minimize instrumentation complexity.

Table 2. Principal rotor configurations tested.

Configuration	No. of blades	Spacing	Chord		Tip shape	Solidity	Tip speed	
1	4	Uneven	5.27 in	13.4 cm	Square	0.317	720 ft/s	220 m/s
2	5	Even	4.23 in	10.7 cm	Square	0.318	720 ft/s	220 m/s
3	5	Even	4.23 in	10.7 cm	Taper	0.284	720 ft/s	220 m/s
4	5	Uneven	4.23 in	10.7 cm	Square	0.318	720 ft/s	220 m/s
5	5	Uneven	4.23 in	10.7 cm	Taper	0.284	720 ft/s	220 m/s
6	5	Uneven	5.27 in	13.4 cm	Square	0.396	640 ft/s	195 m/s

Test Procedure. As in the previous whirl test, acoustic data comparisons were made against a baseline rotor configuration to identify the best configuration. However, more test time was directed than previously toward making the baseline model configuration emulate the noise characteristic recorded during ground run and hovering of the M222U DTR concept demonstrator. The noise had been characterized by an annoying sound in which the tail rotor harmonics increased and their levels fluctuated. Speculation was that this sound fluctuation was caused by a combination of inflow turbulence induced by the main rotor downwash, ingestion of the engine exhaust, and unsteady airflow over the gearbox support tube and struts. After experimentation with various means of introducing small-scale turbulence at the blade tips, the best approximation of the flight test noise characteristic was obtained by introduction of large-scale turbulence over the entire rotor disc. The device utilized was a 3.5-inch (8.9-cm) wide board mounted nonradially across the duct inlet 1 ft (0.3 m) upstream of the rotor. This installation is shown in the photograph of Fig. 19.

The effect of variations in the rotor spinner and gearbox support structure location and size on the baseline rotor noise was also evaluated. The effects were considered slight and second-order, so the majority of data measurements were taken using a configuration that duplicated the flight test DTR.

Each rotor configuration was tested at three thrust values and four tip speeds. Thrust values ranged from flat pitch of the rotor to a pitch setting limited by the power capability of the test stand. Considerable effort was spent in keeping these thrust values constant with each rotor configuration in order to make accurate acoustic data comparisons.

Two techniques were used to arrive at the rotor configuration with the best sound quality; an acoustic metric with a single number that considered the dominant 1st through 12th harmonic tones and the ranking of a panel of listeners. The acoustic metric was determined by applying an A-weighting filter that simulates the hearing response of the human ear to the measured harmonic data and logarithmically summing them to a single number. The panel of listeners used a computer "point-and-click" program to select the digitized recordings of each principle rotor configuration tested.

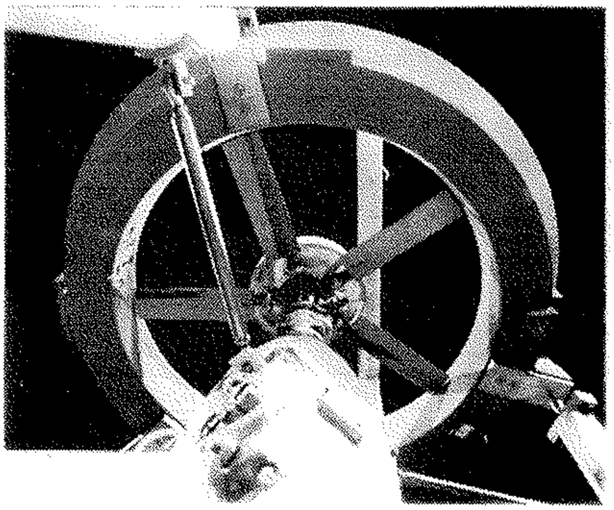

Fig. 19. Five-bladed model rotor with turbulence generator.

Test Results. The whirl stand test results directly showed that the baseline rotor harmonic noise could be reduced by 10.6 dBA by selecting a rotor with five unevenly spaced blades and by reducing tip speed to 640 ft/s (195 m/s). The taper tip could provide an additional 0.3 to 1.6 dBA reduction. The uneven blade spacing combination that produced the best sound quality and on which the testing concentrated had 83-deg, 63-deg, 75.5-deg, 75.5-deg, and 63-deg blade spacing. A relative comparison of the principle rotor configurations tested with the baseline four-bladed scissors rotor is shown in Fig. 20. Also shown is a comparison of the frequency characteristics of the uneven and evenly spaced five-bladed rotor. The data show that the effect of uneven spacing is to redistribute the acoustic energy, reducing the energy present in the dominant 5/rev tone and its harmonics, and distributing it more uniformly throughout the audible spectrum. This redistribution, discussed in detail in Ref. 2, has the effect of making the tonal content less objectionable and more like a broadband "hum" rather than a tonal "buzz." A more detailed discussion of acoustic test results can be found in Edwards (Ref. 3).

Flight Test Design

The optimum five-bladed spacing design was next fabricated for full-scale flight test evaluation. To minimize design and fabrication time and cost of the five-bladed flight test rotor, the existing aft tapered tip flight test blade design and blade cavity tools were used. The solidity was increased to 0.422 by retaining the same chord (7.5 in [19.1 cm]) as the four-bladed rotor and adding a fifth blade. The fifth blade allowed the maximum thrust capability to be maintained with the tip speed reduced to 640 ft/s (195 m/s) from the original 720 ft/s (220 m/s). A new hub was designed to incorporate the rephased blade spacing. Because of the reduced rotor tip speed, redesigned gears for the M222U DTR concept demonstrator tail rotor gearbox were fabricated and installed in the existing gear case.

Flight Test of Five-Bladed DTR

8.1 hours of ground and flight testing was conducted at the Bell Flight Research Center in Arlington, Texas. The photo of Fig. 21 shows the five-bladed DTR configuration installed on the helicopter. A limited flight test program was conducted to obtain rotor loads, stability,

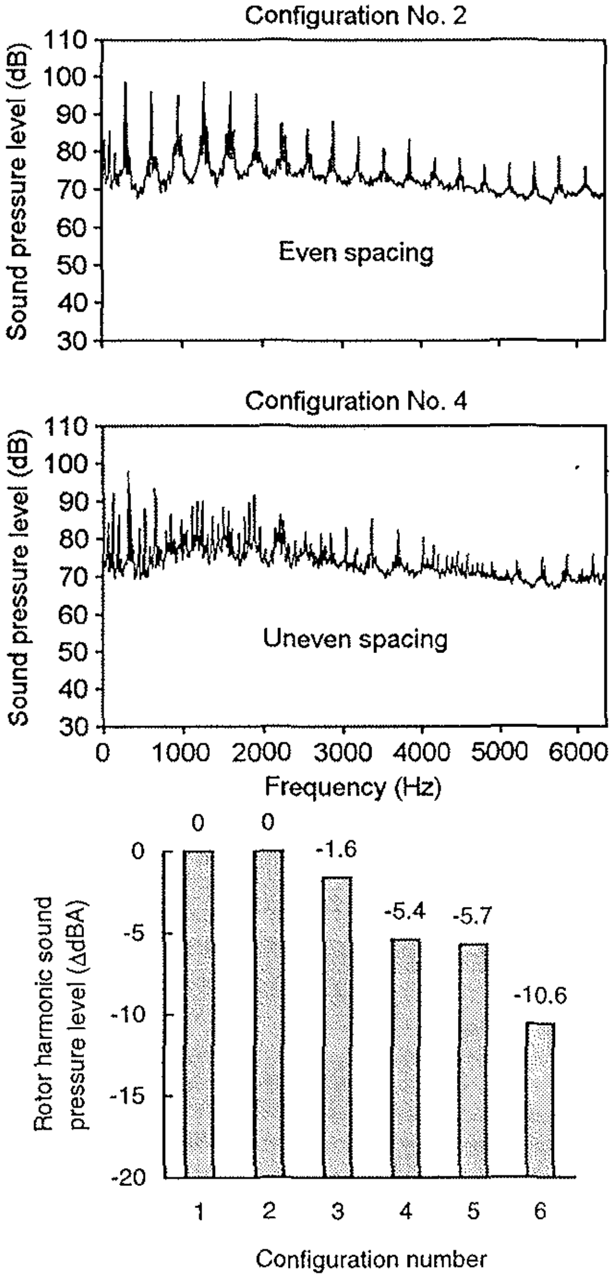

Fig. 20. Sound pressure level reductions and frequency characteristics of five-bladed rotor compared to four-bladed baseline.

performance and acoustic signature, and helicopter handling qualities and performance data.

An acoustic flight demonstration was conducted to compare the Model 222U DTR concept demonstrator with a production Model 230 equipped with a standard two-bladed tail rotor. Flight conditions tested included in-ground-effect (IGE) hover with left and right pedal turns, 120-kn flyovers at 500 ft (150 m) altitude, 6-deg approach at 60 kn, and a maximum power climb at 70 kn. Both aircraft flew each condition one after the other in the presence of a listening jury comprised of marketing and engineering personnel. Three tripod-mounted microphones were deployed in a straight line perpendicular to the flight track, one directly under the helicopter's flight path and the others at 500 ft (150 m) to either side of the flight track.

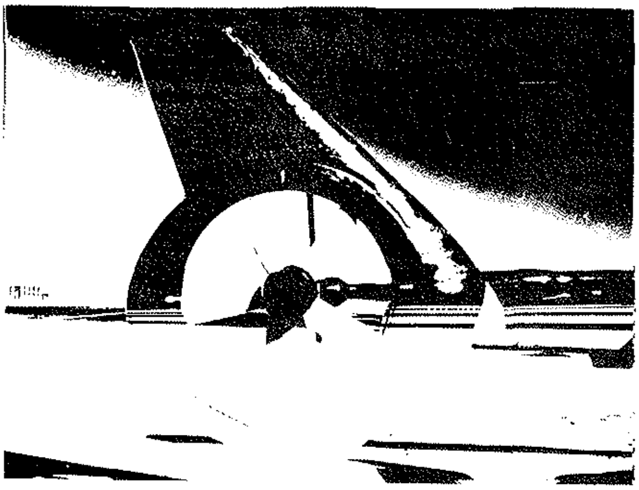

Fig. 21. Five-bladed aft tapered tip unevenly spaced DTR installed on the M222U concept demonstrator.

Test Results.

The acoustic measurements are considered preliminary, since the wind conditions during the demonstration were less than ideal. However, they provide a valid comparison between the two types of antitorque systems and illustrate the qualitative acoustic benefits of the five-bladed DTR. In all the flight demonstrations, the sound quality of the DTR was markedly improved over that of a standard tail rotor. This improvement is due to the uneven blade spacing, lower rotational tip speed, and blade tip shape.

Ground Run. The ground run data in Fig. 22 show no measurable difference between the four- and five-bladed designs. The only other difference between the four- and five-bladed designs is that the five-bladed design requires

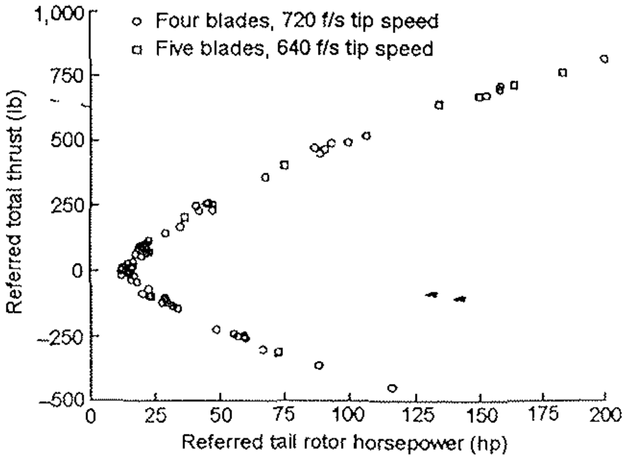

Fig. 22. Measured thrust vs power comparisons for four-bladed and five-bladed rotors.

an additional 1 to 2 deg of blade pitch to maintain maximum thrust capability resulting from the tip speed reduction.

Hover and Sideward Flight. The DTR showed a dramatic acoustic improvement during hover, which included slow left and right 360-deg pedal turns. The DTR noise levels were lower than those of the standard tail rotor, and its tonal content changed from the traditional discrete frequency "buzz" to a more broadly distributed "hum." This beneficial characteristic was readily evident during the hover test as it had been during the whirl tests. Fig. 23 shows the average A-weighted sound pressure level (SPL) measured during the hover test. The DTR reduced total helicopter noise 2 to 6 dBA during hover. The DTR's noise benefit is most noticeable at viewing angles aft of the helicopter, where tail rotor noise typically dominates during hover.

Due to the emphasis on acoustic testing, only four hover performance points were taken of the five-bladed rotor in calm conditions. Since this is a statistically small sample, the DTR hover performance is best determined by using the four-bladed rotor data and noting that the five-bladed rotor is equivalent. The four-bladed and five-bladed DTR hover performance is shown compared to the standard tail rotor in Fig. 10. Comparable performance to the four-bladed rotor was achieved with the five-bladed rotor in sideward flight.

Forward Flight. During forward flight, as in the hover condition, the DTR showed the same dramatic acoustic improvement. The beneficial effects of the DTR are most pronounced when the helicopter is uprange of and over the head of the observer. Tail rotor sound is most dominant during this uprange portion of a flyover. The spectral content of the noise measured at about 1,000 ft (300 m) uprange, shown in Fig. 24, indicates most tail rotor harmonics were reduced by 5 to 20 dB, and total helicopter noise reduced by 6 dBA. Overhead, the DTR was 5 dBA quieter than the standard tail rotor. The acoustic benefits of the DTR are more pronounced directly under the flight track than at the 500-ft (150-m) sideline microphones, presumably because of the shielding effects of the duct structure itself. After the helicopter passes overhead, tail rotor noise becomes less dominant, and the difference between the DTR and the standard tail rotor becomes less pronounced. Another metric used in the noise certification of helicopters is effective perceived noise decibels (EPNdB). This metric accounts for both the tonal quality and the duration of a helicopter overflight. Fig. 25 shows the effective perceived noise level (EPNL) results for the centerline microphone. These data show significant noise reductions due to the DTR at 5.2, 2.5, and 2.4 EPNdB. For all flight conditions and microphones combined, the DTR reduced the total helicopter noise by 3 EPNdB.

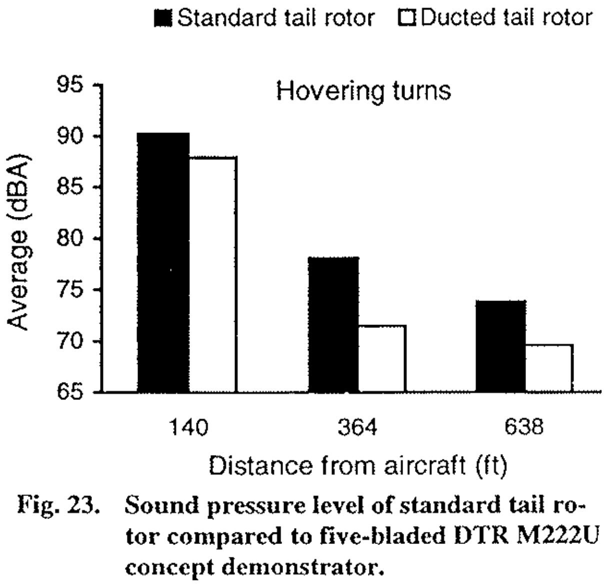

Fig. 23. Sound pressure level of standard tail rotor compared to five-bladed DTR M222U concept demonstrator.

The five-bladed DTR's performance in forward flight is essentially the same as that of the four-bladed DTR. During the five-bladed DTR testing, the forward flight envelope was expanded to 150 kn.

Loads. Five-bladed rotor measured hub and blade steady loads shown in Fig. 26 and oscillatory loads in Fig. 14 are within or slightly greater than predicted design load values. These data were obtained during in-ground effect hover and level flight conditions. Also shown in Fig. 14, the effect of rotor configuration on oscillatory loads is not significant when accounted for in the design.

Summary

The DTR configuration tested on the M222U concept demonstrator with five unevenly spaced blades and an aft tapered tip, operating at a reduced tip speed, substantially decreased tail rotor noise and dramatically improved the sound quality of the helicopter. Total helicopter noise reductions of up to 6 dBA were realized during hover and forward flight, along with reductions in individual tail rotor harmonics of 5 to 20 dB. Effective perceived noise levels were reduced 3 EPNdB (three-microphone average) for takeoff, level flight, and approach conditions.

Hover power required is increased 1.8% from the use of the DTR. Drag increases of the DTR resulted in a 2-kn decrease in maximum level flight speed.

The design and development of the DTR has brought the concept to the point that it can be considered for application to the production flight line. The M222U DTR concept demonstrator used prototype materials and manufacturing techniques and was not designed to meet today's operational demands. However, because of the significant growth in the ducted tail rotor technological data base, resulting from research and experimentation with the

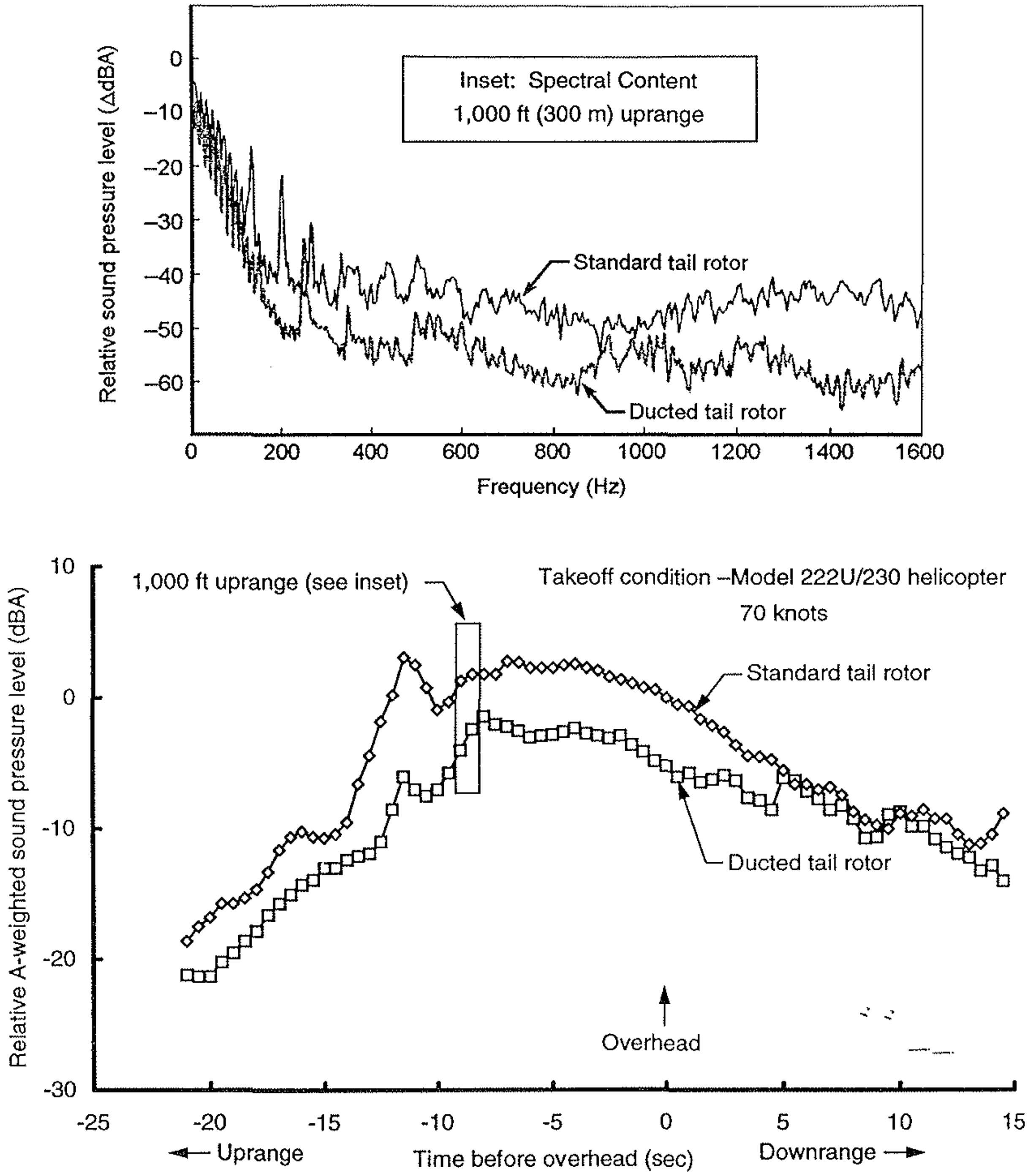

Fig. 24. Improved noise characteristics with ducted tail rotor.

M222U DTR concept demonstrator, the five-bladed unevenly spaced DTR concept will soon meet today's standard of performance, acoustics, weight, cost, and reliability and maintainability.

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2. Riley, Richard G., Jr., "Effects of Uneven Blade Spacing on Ducted Tail Rotor Acoustics," American Helicopter Society 52nd Annual Forum, Washington, D.C., June 4–6, 1996.

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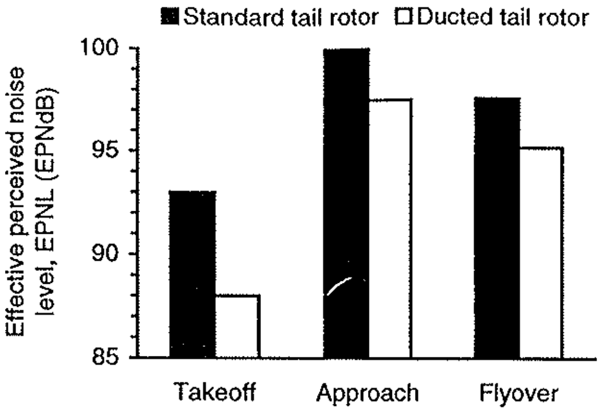

Fig. 25. Flight test results (center microphone).

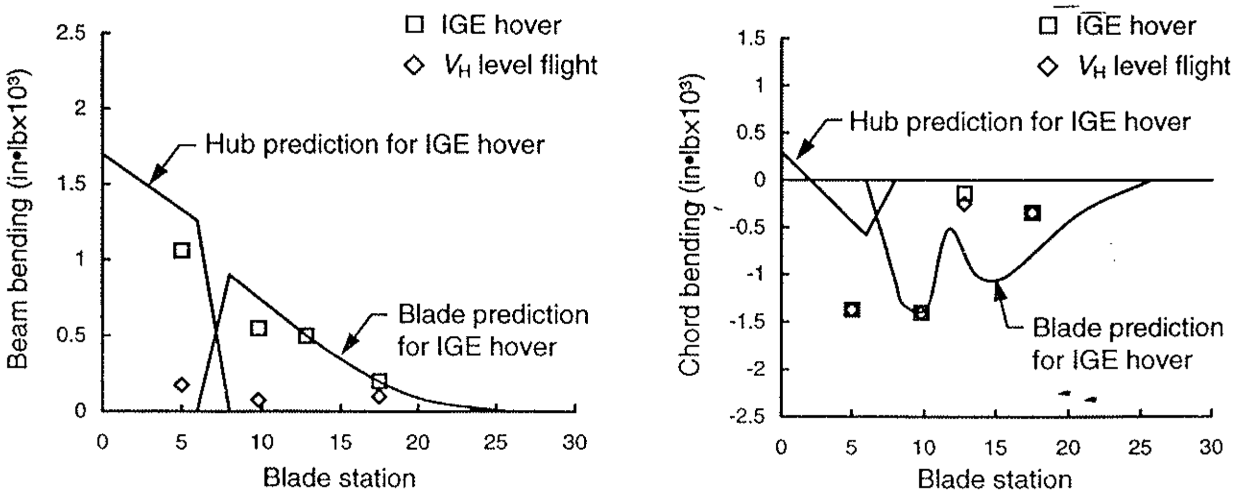

Fig. 26. Measured vs predicted rotor hub and blade IGE hover and V_H level flight steady loads for five-bladed unevenly spaced rotors.