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FLIGHT INVESTIGATION OF EFFECTS OF A FAN-IN-FIN YAW CONTROL CONCEPT ON HELICOPTER FLYING-QUALITY CHARACTERISTICS

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16. Abstract

Flight-test results which describe flying-quality factors related to the fan-in-fin yaw control concept as utilized on a pre-production version of a European helicopter are presented. Design compromises to be considered with this concept are also presented. The large, fixed vertical fin associated with the fan-in-fin system was helpful in maneuvering flight, but introduced several flying-quality problems when combined with the fan.

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FLIGHT INVESTIGATION OF EFFECTS OF A FAN-IN-FIN YAW CONTROL CONCEPT ON HELICOPTER FLYING-QUALITY CHARACTERISTICS

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SUMMARY

A brief flight investigation was conducted on a pre-production version of a European helicopter that employed a fan-in-fin yaw control system to evaluate flying-quality factors related to the system.

In this report, design considerations which must be evaluated with a fan-in-fin concept are discussed. A summary of results of the flight investigation, the major part of which was directed toward stability, control, trim, and general handling characteristics of the test helicopter, as influenced by the fan in fin, is presented. Principal areas investigated include effects of winds and ground proximity, effects of forward speed and vertical speed on control trim requirements, static stability, angular response and coupling, and autorotation characteristics. Also, a qualitative assessment of maneuvering flight was made both at altitude and near the ground. Airspeeds to 175 knots and sideward and rearward flight to estimated airspeeds of 40 knots were covered in the investigation. The large, fixed vertical-fin associated with the fan-in-fin system was helpful in maneuvering flight, but introduced several flying-quality problems when combined with the fan. In hovering flight out of ground effect in winds of 26 to 32 knots, most of the directional control was required for trim flight in a left crosswind, and a pronounced directional unsteadiness was noted in a right crosswind. In cruising flight, static-directional stability measurements indicated stable gradients over most of the range of sideslip angles investigated, but reduced through neutral to slightly negative values over several degrees of sideslip angles near zero. The reduced directional stability made the aircraft difficult to trim directionally, and, in combination with stable

effective dihedral, caused a slight Dutch roll. Pilot comment indicated that these characteristics might become significant during precision flight tasks.

INTRODUCTION

The fan-in-fin type of yaw control indicated promise when compared with alternative yaw control concepts for helicopters (refs. 1 and 2); however, new design concepts are usually accompanied by disadvantages as well as advantages. Some fan-in-fin concept advantages include increased safety in the presence of ground objects and ground personnel, capability for a controlled landing in event the fan is disabled, structural suitability to high-speed flight because of reduced alternating stresses, and increased stability due to a large vertical fin. Some disadvantages, when compared with the conventional tail rotor, include increased power requirements in hovering flight, effects of asymmetric thrust, and nonlinearity of control response at low thrust levels.

When comparing the shrouded propeller against the conventional tail rotor in the static thrust case for the same total thrust, the shrouded propeller required less ideal power than a rotor of the same diameter. However, for the typical helicopter application, a large reduction in fan diameter is dictated by practical design considerations which, in turn, results in a shrouded fan with a much higher disk loading. This increase in disk loading results in an increase in power required. Sample calculations indicate that the increased power requirements of the fan due to the increased disk loading more than offset the decreased power requirements of shrouding the fan. In practice, the difference in power required is reduced somewhat by factors such as reduced rotor-fin interference effects. On the other hand, one must consider the less-than-ideal design limitations for a shrouded fan in the helicopter fan-in-fin application. (For instance, the ratio of shroud chord to fan diameter must be kept small to keep the fin thickness reasonable.) In forward flight, a large external drag caused by turning the entire mass flow of the ducted fan through an angle of 90° is indicated by momentum analysis. This drag is much greater than the drag of a conventional tail rotor, where the forward velocity adds to the resultant flow through the rotor and produces a major decrease in power consumption with forward speed. One way to minimize the large drag of the fan in forward flight is to unload the fan with a large vertical fin.

Research investigations to provide technical data to design fan-in-fin yaw control systems for helicopters are being conducted by the U. S. Army and the National Aeronautics

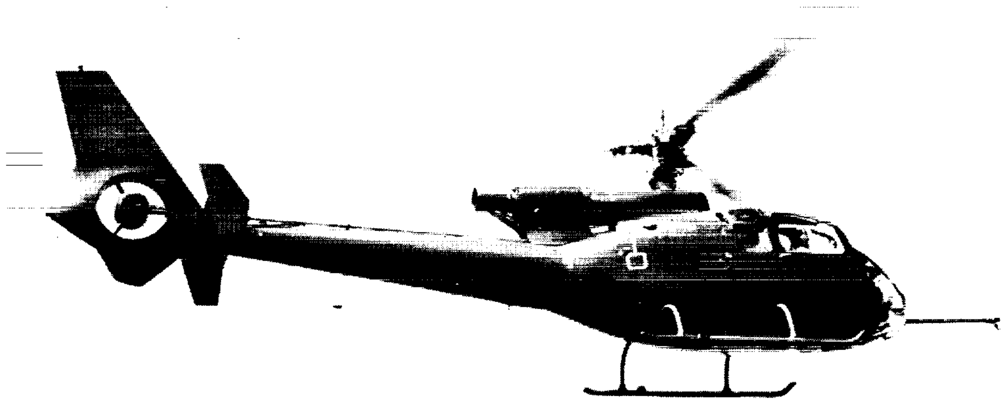

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Figure 1.- Test aircraft.

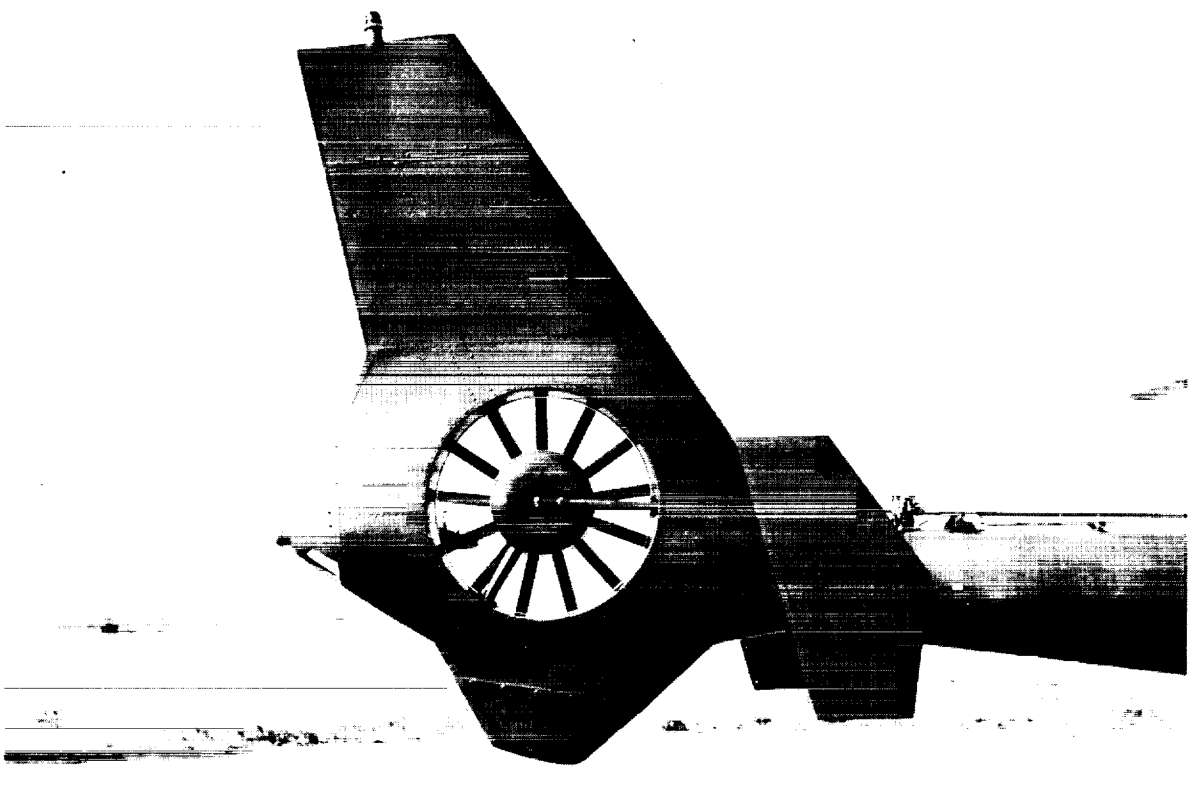

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Figure 2.- Fan-in-fin yaw control system showing the fan outlet side.

and Space Administration. As part of this effort, a brief flight investigation was conducted on a pre-production version of a European helicopter that employed a fan-in-fin yaw control system. (See figs. 1 to 3.) The objective of the tests was to evaluate flying-quality factors related to the system.

In this report, design considerations which must be evaluated with a fan-in-fin concept are discussed. A summary of results of the flight investigation, the major part of which was directed toward stability, control, trim, and general handling characteristics of the test helicopter as influenced by the fan in fin, is presented. Principal areas investigated include effects of winds and ground proximity, effects of forward speed and vertical speed on control trim requirements, static stability, angular response and coupling, and autorotation characteristics. In addition, a qualitative assessment of maneuvering flight both at altitude and near the ground was made. Airspeeds to 175 knots, and sideward and rearward flight to estimated airspeeds of 40 knots were covered in the investigation.

FAN-IN-FIN DESIGN CONSIDERATIONS

Power Required

It is well known that a shrouded propeller is more efficient in hovering flight than an open propeller. When it is compared with a conventional tail rotor (using a simple momentum theory) having the same total thrust and diameter, and excluding profile-drag losses, the shrouded propeller requires about 27 percent less power. (See ref. 3.) However, for a typical helicopter application, a large reduction in diameter is dictated by the necessity of fitting the fan within the fin. This constraint results in a shrouded fan with a much higher disk loading than the rotor which otherwise would have been used. The increase in disk loading results in an increase in required power. Sample calculations, using the test-helicopter dimensions, indicate that the increased power requirements of the fan due to the increased disk loading more than offset the decreased power requirements of shrouding the fan. (These calculations assumed a tail-rotor diameter of 1.8 m, a fan diameter of 0.7 m, a rotor figure of merit of 0.75, a fan figure of merit of 0.85, and zero profile losses.) Indeed, the shrouded fan required more than twice as

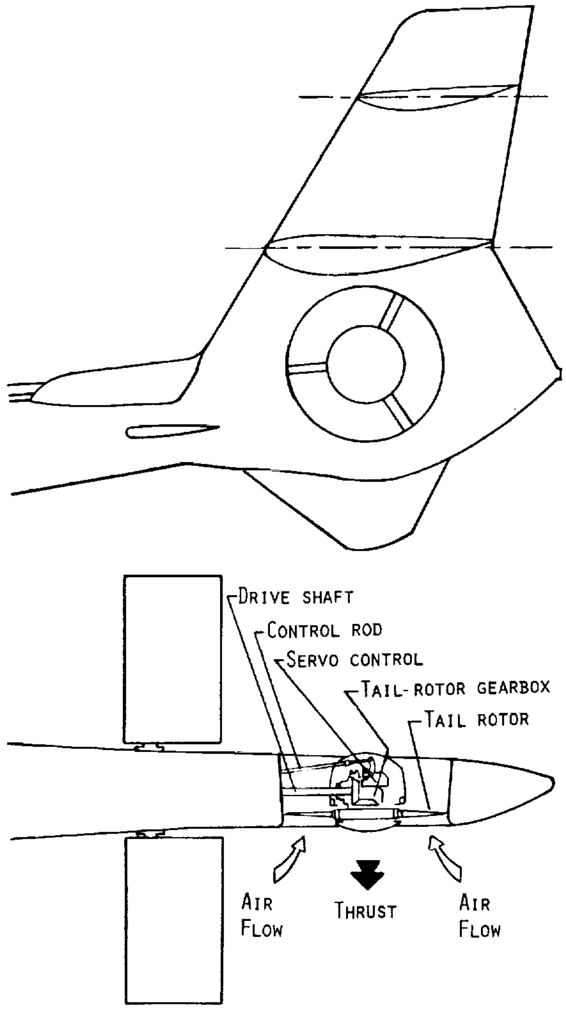

Figure 3.- Sketch of tail fan and tail fins (from ref. 5).

much power as the rotor. In practice, the large difference in power required is reduced somewhat by factors such as reduced rotor-fin interference effects. On the other hand, the fan design is less than optimum since the ratio of shroud chord to fan diameter must be small because of the small fin thickness.

In forward flight, momentum analysis of the ducted fan at zero angle of attack indicates a large external drag caused by turning the entire mass flow of the fan through an angle of 90°. In effect, this turning represents a longitudinal induced velocity equal, but opposite, to the forward velocity. Examination of the resultant velocity at the fan (ref. 4) under such conditions indicates that for constant fan thrust, the resultant velocity, the axial induced velocity, and the shaft power all will be unaffected by forward speed. The total power required will increase as the square of the velocity because of the external momentum drag. In fact, the only significant change in tail-fan shaft power will be caused by changed thrust requirements due to reduced main-rotor torque requirements in forward flight. This behavior is in marked contrast to the behavior of a conventional rotor where the forward velocity adds to the resultant flow through the rotor and produces a major decrease in power consumption with forward speed.

One solution to the problem of large fan power at forward speed is to unload the fan by providing an alternate source of side force with which to balance the rotor torque. A large cambered fin is one such source. In the present configuration, this fin is sized to provide almost all the required force at cruising speed.

A comparison of the power for a tail rotor and for a fan-in-fin configuration (from ref. 5) is presented in figure 4. It should be noted, however, that figure 4 presents only the shaft power. It does not include either the drag of the fin or the external drag of the fan, both of which must be overcome by means of additional power supplied by the main rotor. Furthermore, it does not show the effect of the spindle axis angle on the tail-rotor power; indeed, the shaft power for the rotor could be made negative at forward speed by rotating the spindle axis rearward, provided that the gearing could absorb shaft power transmitted from the tail rotor to the main rotor.

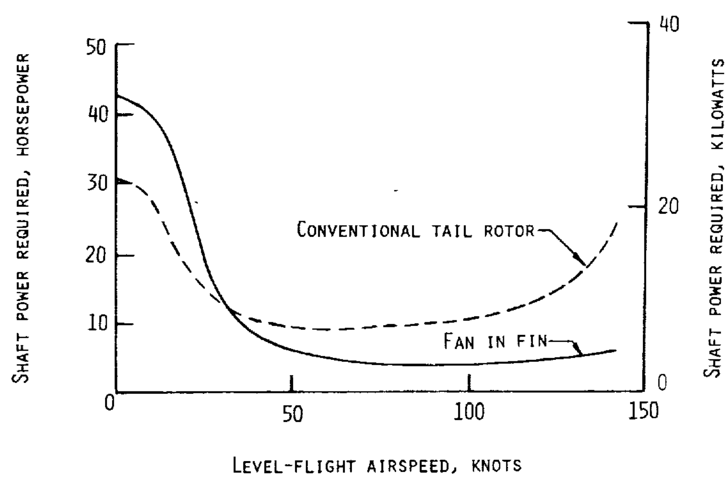

Figure 4.- Shaft power required as a function of trim-level-flight airspeed. Comparison between fan in fin and conventional tail rotor (from ref. 5).

Stability and Control

Performancewise, blade twist is a desirable design feature in a ducted fan; however, it becomes a problem when operating the fan at zero or negative thrust. Since the blade tips operate at a positive angle of attack and the blade roots operate at a negative angle of attack, zero net thrust (part of the fan disk thrusting in one direction and part in the opposite direction) can contribute to airflow spoilage on the fin.

An additional problem is that during autorotation the fan must produce negative thrust to balance the fin force, and the duct is not properly shaped for thrust in this direction. Of course, it is not possible to shape the duct for efficient thrust in both directions.

An advantage one might expect from a large vertical fin is directional stability characteristics similar to fixed-wing aircraft. However, when operating the fan near zero thrust, several aerodynamic and control design problems occur. Operating the fan near zero thrust results in a nonlinear control sensitivity problem. Small changes in thrust occur for large changes in pitch (see fig. 5 from ref. 5) under this condition. Also, the large fin required to unload the fan in forward flight can generate large fin-induced yawing moments in sideward flight at low airspeed as well as when hovering in winds. One possible means to offset the low yaw-control sensitivity in forward flight would be to schedule nonlinear pitch as a function of pedal position so that at low pitch settings (low thrust) small pedal-position changes command large pitch changes. Another design technique would be to use a rudder in the fin; however, this would not only add complexity, but would also present problems in designing the rudder linkage so that the overall effect would be favorable in all regimes of flight.

The foregoing discussion indicates that a fan-in-fin design requires numerous compromises. It is evident that the optimum design will be achieved only after substantial flight experience has been accumulated. The present test helicopter is one early design. This brief flight investigation was conducted primarily to obtain some insight into the effects of some of these design compromises on aircraft handling qualities. It is obvious that design choices, other than those used in this aircraft, undoubtedly would produce significant alterations in the handling qualities.

APPARATUS AND PROCEDURE

Description of Aircraft

General configuration. - The helicopter used for these tests (fig. 1) was a preproduction aircraft, representative of light, turbine-powered, single-rotor helicopters. There were differences between the production helicopter and the test helicopter; therefore, the results given herein should not be construed as being definitive of the production aircraft. Some features of the aircraft include the fan-in-fin yaw control system (fig. 2) and a three-bladed main rotor with blades constructed primarily of glass fiber. The main rotor hub was fully articulated except for an elastomeric damper, which resisted lead-lag displacement and velocity. The main rotor mast was not tilted to balance the tail-fan side force in hovering flight. The aircraft was powered by a fixed-shaft 450-kilowatt gas turbine engine. The take-off mass for this investigation was 1770 kilograms, which was slightly higher than the maximum mass at which the aircraft was designed to operate (1700 kilograms). A list of its principal physical characteristics is presented in table I.

Dual cyclic, collective, and directional controls were operated through a hydraulic boost system. The longitudinal and lateral cyclic control actuators incorporated a feedback to provide positive indication to the pilot that rotor structural limits were being approached. No control-force gradients were provided through the use of springs; however, pilot-adjustable friction devices were provided on the cyclic and collective stick controls. A damper was used on the pedals to prevent large, abrupt inputs. A low-authority (10 percent) stability-augmentation system was provided, but was locked out for these tests. A more detailed description of the aircraft may be found in reference 6.

Fan in fin. - The tail fan (figs. 2 and 3) had 13 die-forged aluminum alloy blades, a diameter of 0.696 meter, and a normal rotational speed of 5774 revolutions per minute. Fan-blade pitch angle was variable from 42.5° to -20.2° (measured at 74 percent of the radius). The blades had a helical twist of -12.5° as measured from the hub boss. The blade chord was 39 millimeters; the airfoil section was NACA 0016; the blades were attached at the root by pitch bearings. No flapping or lead-lag hinges were used. The general performance of the fan-in-fin configuration is given in figures 5 and 6 as supplied by the manufacturer.

At the plane of the fan, the shroud had a diameter of 0.700 meter. The duct length was approximately 43 percent of the fan diameter. The inlet lip radius was

TABLE I. - PHYSICAL CHARACTERISTICS OF TEST AIRCRAFT

Main rotor:	
Diameter, m	10.5
Number of blades	3
Blade chord, cm	30
Airfoil section	NACA 0012
Twist, deg	-6
Blade taper ratio	1
Disk area, m^2	86.6
Blade area, m^2	4.73
Solidity	0.055
Normal operating speed, rpm	378
Rotational speed limits, percent	82 to 114
Tail fan:	
Diameter, m	0.696
Number of blades	13
Blade chord, mm	39
Airfoil section	NACA 0016
Twist, deg	-12.5
Blade taper ratio	1
Pitch-angle range, deg	42.5 to -20.2
Blade area, cm^2	1764
Disk area, cm^2	3805
Solidity	0.46
Normal operating speed, rpm	5774
Fin:	
Estimated area (including fins at ends of horizontal stabilizer and duct area), m^2	2.5
Angle of attack for zero lift (ref. 4), deg	-3.5
Estimated lift-curve slope (ref. 4)	0.053
Lift coefficient at zero angle of attack	0.2
Incidence, deg	2
Airfoil (at manufacturing break just above duct)	NACA 4418 (modified)
Airfoil (at upper tip)	NACA 4412 (modified)
Duct:	
Diameter at fan, m	0.700
Diameter of centerbody (approx.), mm	325
Length (approx.), cm	29.7
General:	
Take-off mass, kg	1700
Take-off mass for tests, kg	1770
Overall length (not counting nose boom), m	9.5
Overall height (ground to top of fin), m	3.1
Landing-gear tread, m	1.9
Center of gravity to tail-fan axis, m	5.66
Power, kW	450
Seating capacity (including pilot and copilot)	5
Control travels (from grip centers):	
Lateral stick, cm	
Right	10.72
Left	10.97
Longitudinal stick, cm	
Rearward	15.7
Forward	13.1
Pedals, cm	
Right	7.27
Left	3.23
Control breakout forces (approx.; SAS off):	
Lateral stick, kg	
Right	0.250
Left	0.200
Longitudinal stick, kg	
Rearward	0.080
Forward	0.300
Pedals, kg	
Right	2.100
Left	3.400
Collective stick, kg	
Low range	0.250
High range	0.600
Pedal damper characteristics:	
Threshold, kg	6
Force at pedal rate of 1.8 cm/sec, kg	15
Force at pedal rate of 1.6 cm/sec, kg	13.5
Force at pedal rate of 1.3 cm/sec, kg	9

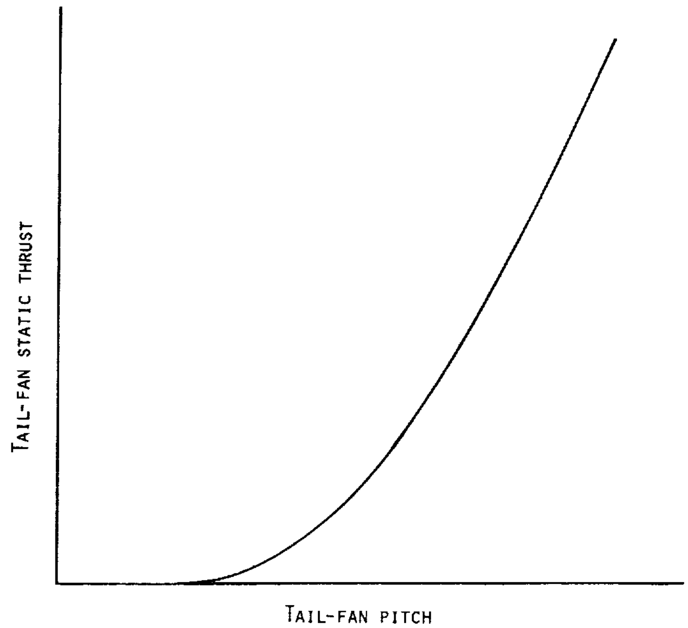

Figure 5.- Tail-fan static thrust as a function of blade pitch (from ref. 5).

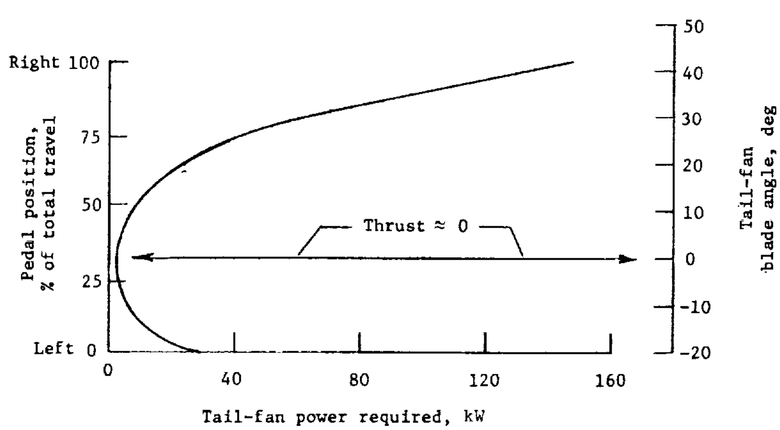

Figure 6.- Variation of tail-fan power required as a function of pedal position and tail-fan blade angle in static thrust (maximum blade angle travel for the test aircraft was 42.5°). (Data supplied by manufacturer.)

5.75 centimeters (constant around the duct) and the inner surface of the duct diverged toward the outlet. The shroud had a sharp corner at the outlet with no radius. Diameter of the duct centerbody at the plane of the fan was 0.325 meter.

The section of the fin above the fan was twisted and cambered with the intention of unloading the fan in forward flight with the fin at a small angle of attack. The airfoil sections of the upper fin are not standard. The manufacturer has indicated the following characteristics: 4-percent camber; 18-percent thickness at the manufacturing break (crease located 2 to 3 centimeters above the shroud (see figs. 2 and 3)); 12-percent thickness at the tip with linear variation in thickness; and 2° incidence. The fin area was estimated from arrangement sketches (fig. 3) to be about 2 square meters (including the duct). In addition, fins mounted at the ends of the horizontal stabilizer (fig. 2) had a combined area of 0.5 square meter. The section of the fin below the fan was symmetrical. Reference 7 indicated that at zero angle of attack, the fin lift coefficient was approximately 0.2; the angle of zero fin lift was -3.5°; and the lift-curve slope was about 0.053 per degree. Additional data on the fan-in-fin configuration are given in references 5 and 8.

Test Conditions

A total of 10 flight hours were obtained on the test helicopter. Throughout the test period the wind varied from 2 to 30 knots; the temperature from 17° to 27° centigrade; the barometric pressure from 1008 to 1070 millibars; and the altitude from sea level to 1200 meters. When possible, flights were arranged to utilize the weather conditions on a given day. In-ground-effect and out-of-ground-effect testing normally occurred at ratios of rotor-plane height to rotor diameter of about 0.4 and 3.0, respectively.

Instrumentation

All instrumentation was furnished by the manufacturer. Recorded parameters pertinent to this investigation were indicated airspeed, sideslip angle, pilots' control positions, tail-fan blade pitch angle, angular velocities about the three axes, roll and pitch attitude, pressure altitude, and main-rotor rotational speed. Airspeed and sideslip sensors were mounted on a nose boom. Control positions were sensed by angular potentiometers, and attitudes and angular velocities were sensed by gyros. A tachometer generator sensed rotor speed, and pressure altitude was sensed at a static-pressure port on the aircraft. Data were recorded on oscillographs. Dial indicators, mounted on the instrument panel, presented lateral cyclic, longitudinal cyclic, and pedal control positions in percent of total travel.

RESULTS AND DISCUSSION

Hovering and Low-Speed Flight Characteristics

Vertical take-offs and landings.- Vertical take-offs and landings were consistent with familiar helicopter procedures with one exception. Since the rotor rotates clockwise (as viewed from above), right pedal was required to trim the change in rotor torque at lift-off. As expected, the pilot adapted to this difference within the first several take-offs. During landings, the reversed pedal requirement was not obvious since the pilot normally related the directional requirements to the outside world, and simply applied the pedal required to maintain heading upon descent and touchdown.

Precision hover.- Precision hover was performed both in and out of ground effect to investigate differences in controllability as influenced by recirculation effects as well as control system quality. In addition, data were obtained by a pilot with considerably more experience in the particular aircraft to investigate differences due to piloting experience level. Ambient winds were 8 to 10 knots. Examination of the flight records and observations in flight indicated negligible differences caused by the pilot experience level. Furthermore, precise controllability in ground effect was only slightly more difficult than out of ground effect.

Wind and ground effects.- Effects of wind velocity, wind direction, and ground proximity on several hovering and low-speed yaw control characteristics are given in figure 7. These data were obtained in and out of ground effect in winds that varied from 26 to 32 knots, and at an aircraft gross mass of about 1675 kilograms. Data were obtained every 15° of aircraft heading. The general trend of these data agrees with results given in references 5 and 8. Results obtained under conditions of lower wind speed had a similar sine-wave shape with less amplitude. Thus, increases in the amplitude of the sine wave depend on the magnitude of the wind velocity as well as on ground proximity. The data points obtained out of ground effect under right-crosswind conditions indicate scatter. For each heading the pilot attempted to hold the aircraft steady for several seconds with the data switch on. The indicated data points show the pedal position obtained

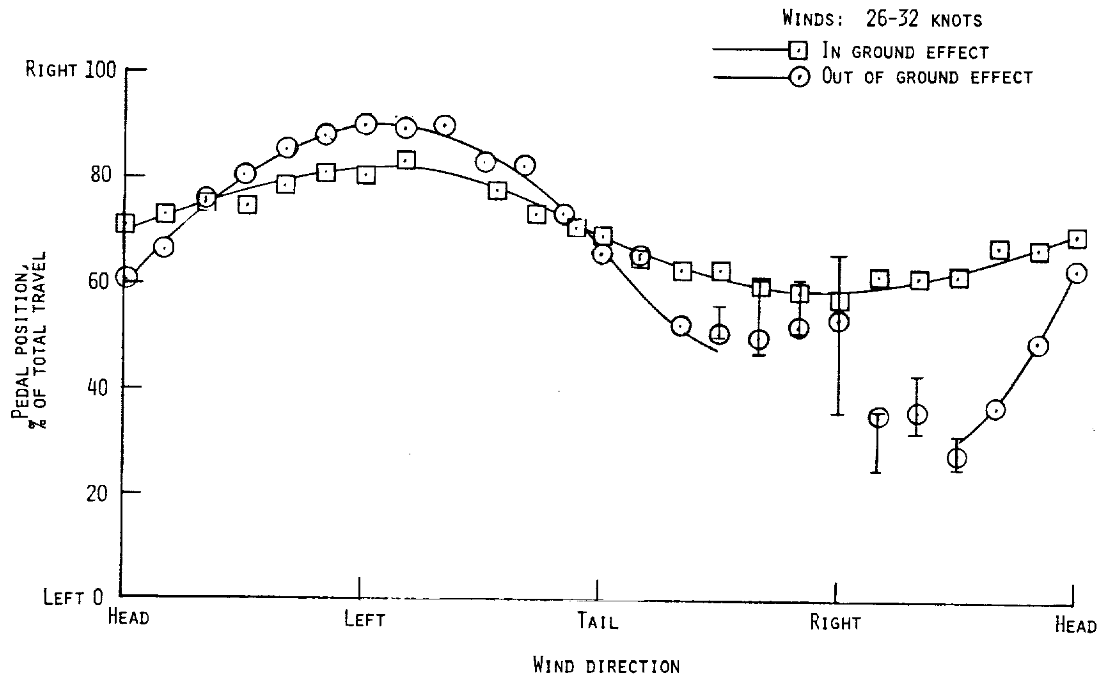

Figure 7.- Effects of wind velocity, wind direction, and ground proximity on low-speed yaw control characteristics.

when the yaw rate was nearly zero for some reasonable length of time. These data points agreed well with the data taken by the pilot from cockpit instrumentation during the flight. The upper and lower ends of the vertical lines running through these data points represent the extremities of pedal travel at each azimuth angle.

Several interesting features are evident in the data of figure 7:

(1) When the aircraft was headed into the wind, about 10 percent more right pedal was required to trim the aircraft in ground effect than out of ground effect. It will be shown in a later figure that the same is true in hover at wind speeds down to 3 to 4 knots. This feature implied that higher tail-fan power was required despite the well-known effects of reduced power required for the main rotor in the ground cushion. (Compare the pedal position in the head wind in fig. 7 with the corresponding tail-fan power required in fig. 6.) This characteristic was noted earlier in reference 5. Although the difference in tail-fan pitch angle was not large (about 10 percent of the total travel), figure 6 would appear to indicate that the power requirements for yaw control were nearly doubled for some operating conditions. The increase in tail-fan power required in ground effect was

probably caused by slipstream rotation from the main rotor causing significant changes in the vertical-fin force. This effect could be reduced by a smaller fin area.

(2) For these wind conditions, maximum right-pedal requirements (maximum tail-fan power) occurred when hovering out of ground effect in a left crosswind. This was the maximum right directional control used during these tests. It is expected that the effects of altitude, air temperature, gross weight, and maneuver control requirements could demand even greater right-pedal input, perhaps even in excess of that available. Again, this effect could be reduced by a smaller fin or by the use of more evenly divided vertical surfaces close to each other for a mutual shielding effect.

(3) The variation of the trim pedal position as a function of wind direction (fig. 7) in ground effect presented no controllability problems according to pilot comment. Analysis of the flight records confirmed these results. The reduced pedal requirement in a left crosswind was probably attributable to reduced fin forces caused by the main rotor wake, which expands laterally in ground effect and thus shields the fin from the external wind. (See ref. 9.) A similar effect probably accounts for increased fan power in ground effect in hovering without wind.

(4) The variation of the trim pedal position as a function of wind direction out of ground effect (fig. 7) presented no particular yaw controllability problem until aircraft headings were reached where the winds were coming from the right (as observed by the pilot). The time histories of the aircraft yaw rate and pedal position indicated increased unsteadiness for a range of wind directions from the right. (See fig. 8 where there is a direct comparison of yaw rate and pedal position.) Differences in steadiness and trim can be noted in figure 8. The excursions in pedal position encountered under right cross-wind conditions are indicated by the vertical lines through the data points of figure 7. Although the aircraft was controllable, successful performance of precision tasks would be doubtful. The directional unsteadiness undoubtedly is caused by operation of the fan in the vortex-ring state. The flow is complicated even more by reversed fan operation and flow separation around the duct and fin. A smaller vertical fin area would allow positive fan thrust for trim and delay these characteristics to wind conditions outside the normal operating envelope of the aircraft.

Low-speed translational flight.- Left and right sideward flight and rearward flight up to estimated airspeeds of 40 knots were performed. During left sideward flight at the maximum speed, the right pedal control stop was contacted; this result confirmed the

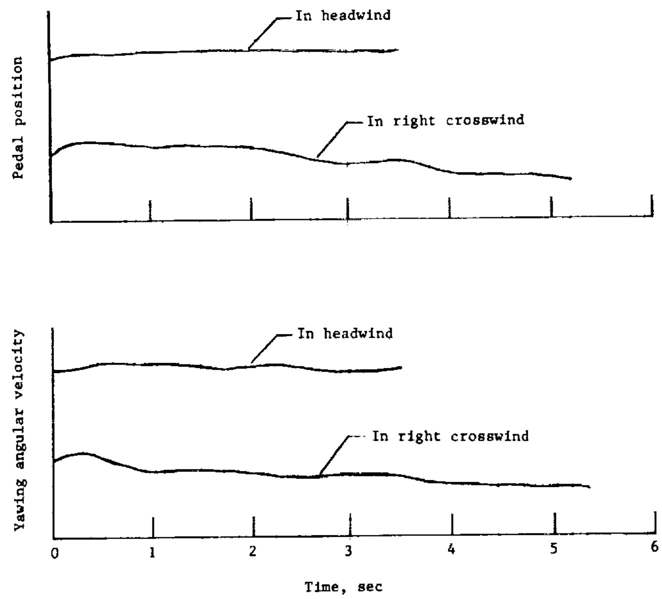

Figure 8.- Comparison of time histories of pedal position and yawing angular velocity for a headwind and a direct right crosswind. Winds: 26 to 32 knots.

small remaining control margin shown in figure 7. Since most control specifications call for the capability to hover in 35-knot winds, this margin of control may be satisfactory. Increased control margin could be obtained by increasing the available fan thrust, use of a smaller vertical fin, or use of self-blocking vertical tails. As expected, during rearward flight, directional control became increasingly difficult with increasing airspeed, most likely because of the unstable-moment contribution of the large vertical fin. With the foregoing exceptions, the test aircraft was satisfactorily controllable in and around the hovering and low-speed flight mode.

Angular response.- Pedal step control inputs were performed out of ground effect to investigate the yawing angular response characteristics. All runs were started headed into the wind. Data were not obtained and, as a result, the degree of analysis desired was not obtained; however, some qualitative impressions were noted. When hovering in light winds (3 to 4 knots) out of ground effect, a 10-percent left or right pedal step-control input resulted in a 360° turn of the aircraft in about 9 to 10 seconds. Response to stopping a turn in either direction was satisfactory. Directional response to step control inputs, when hovering into winds of about 10 knots, was greater to the left than to the right for similar-sized pedal control inputs. The initial response in both directions appeared to be similar but the motion to the right stopped after about 90° of heading change whereas the motion to the left continued until stopped by the pilot, usually after about 130°. Analysis of this characteristic could not be made because of the lack of data.

During hovering and low-speed flight headed into the wind, more tail-fan power was required in ground effect than out of ground effect although the main rotor torque was reduced in the ground cushion. The same characteristic was noted earlier during the discussion of figure 7 where the headwinds were 26 to 32 knots. The magnitude of this effect in terms of pedal trim position required as a function of airspeed is given in figure 9. Conversion of pedal position to tail-fan power required may be accomplished by use of figure 6. The increase in tail-fan power required in ground effect was probably caused by effects of impingement of the expanded wake from the main rotor on the vertical fin.

Forward-Flight Characteristics

Effect of airspeed on trim.- Pedal, longitudinal, lateral and collective control position variation as a function of trim-level-flight airspeed is presented in figure 9. The testing technique used to obtain most of this data included a slow change in airspeed (1 knot/sec or less to achieve quasi-static conditions) at constant altitude from hovering to 140 knots and back to hover in a similarly slow manner. In addition, the data were obtained in hover over a spot, in and out of ground effect, at several wind speeds from 0 to 30 knots. For airspeeds above about 30 knots, trim data extracted from numerous other runs were used as a check. Effects of ground proximity in hovering flight were discussed in a previous section of this paper. Ground effect can be seen to diminish rapidly with forward speed.

It can be seen from figure 9, which presents pedal position as a function of speed that the pedal position remained nearly constant at 30 percent of the total travel for indicated airspeeds between about 80 and 140 knots. Figure 6 shows that the fan power is only 3 to 4 kilowatts for this pedal position and, thus, indicates a nearly zero thrust output. Essentially all directional requirements are satisfied by the vertical fin which was provided to unload the fan in forward flight in order to achieve a small increase in performance. According to pilot comment, the directional trim characteristics were easy and natural to control.

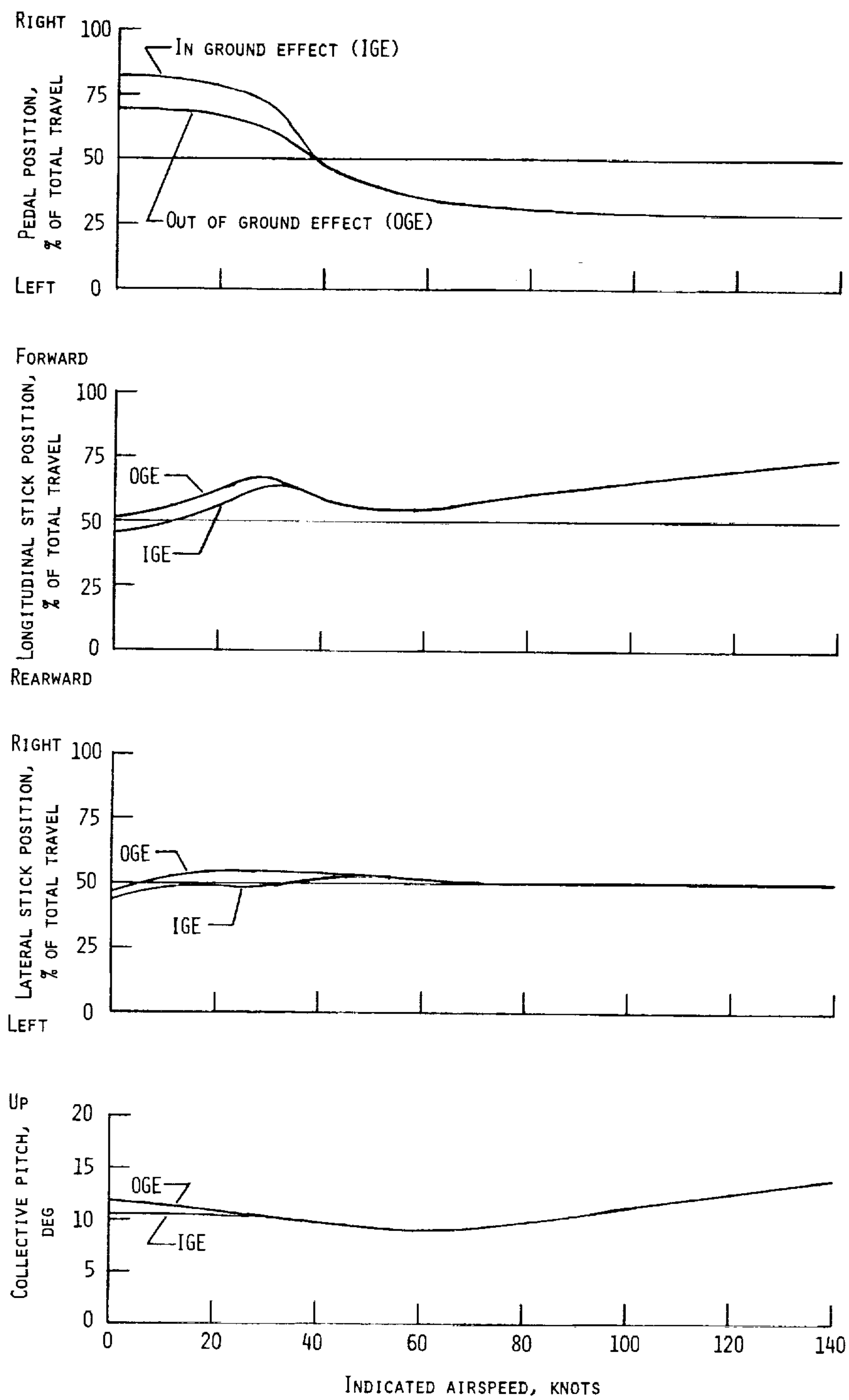

Figure 9.- Variation of four control positions with trim-level-flight airspeed.

The variation of longitudinal stick position with trim airspeed was smooth and in the correct direction except for a reversal in slope at speeds between 30 and 50 knots. This reversal presented no control problems. The occurrence of the slope-reversal characteristic in the transition speed range is common to helicopters.

The lateral stick and the collective pitch trim indicated normal trends. It should be noted that the lateral trim shift was so slight that it was difficult for the pilot to discern, and it was nearly constant for speeds above 50 knots.

Effect of power.- The effect of power on longitudinal, lateral, and directional control trim positions was investigated for airspeeds of 58 and 100 knots. For each speed, power was varied from about flight-idle to the normal-climb power positions. Representative trim data for speeds of 58 to 100 knots are presented in figure 10 as a function of vertical velocity (which was used as an indirect measure of power). It can be seen in this figure that changes in trim with vertical velocity appear to be smooth and continuous. The directional trim change was the largest and used about 40 percent of the total travel at low speed. The longitudinal trim change was always less than about 20 percent of the total travel available, and the lateral trim change was always less than about 5 percent. The pilot indicated that these trim-change characteristics were satisfactory.

Dihedral effect.- The dihedral effect characteristics (fig. 11) were measured and started separately from trim-level-flight airspeeds of 52, 82, 113, and 135 knots. Data for airspeeds of 113 and 135 knots were identical for all practical purposes and, hence, are represented by the same curve. The results, summarized in figure 11, indicate stable levels of dihedral effect for all conditions. Pilot comment indicated that these characteristics were satisfactory.

Directional stability.- The static directional-stability characteristics (fig. 12) were measured concurrently with the dihedral characteristics at trim-level-flight airspeeds of 52, 82, 113, and 135 knots. Again, the data for airspeeds of 113 knots and 135 knots were sufficiently identical to be represented by the same curve.

The negative slopes shown in figure 12 indicate stable levels of static stability over most of the range of sideslip angles of the investigation. Neutral to positive slopes indicate low to unstable levels of static stability for sideslip angles near 0°. Examination of the flight records indicated a slight Dutch roll characteristic. This characteristic may well be anticipated in light of the stable dihedral effect in combination with nearly

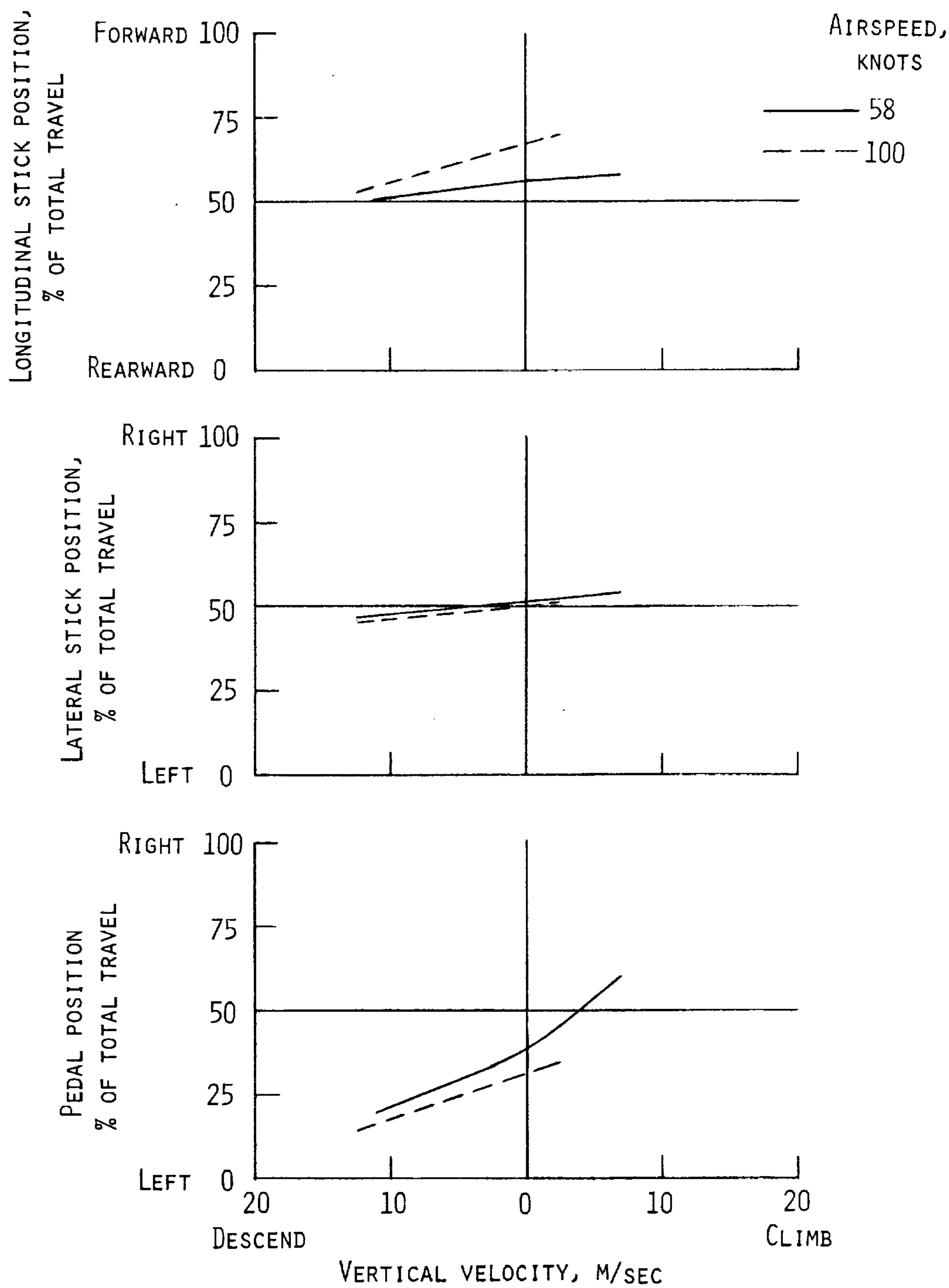

Figure 10.- Variation of longitudinal, lateral, and pedal control position with vertical velocity for two airspeeds. (Vertical velocity is used as a measure of power.)

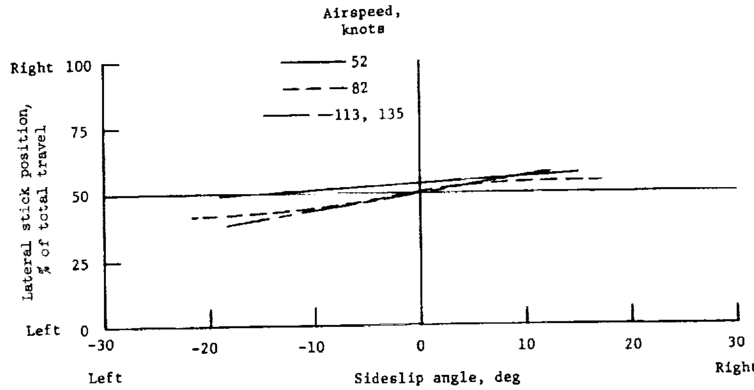

Figure 11.- Summary of dihedral effect results. Positive slope indicates positive stability.

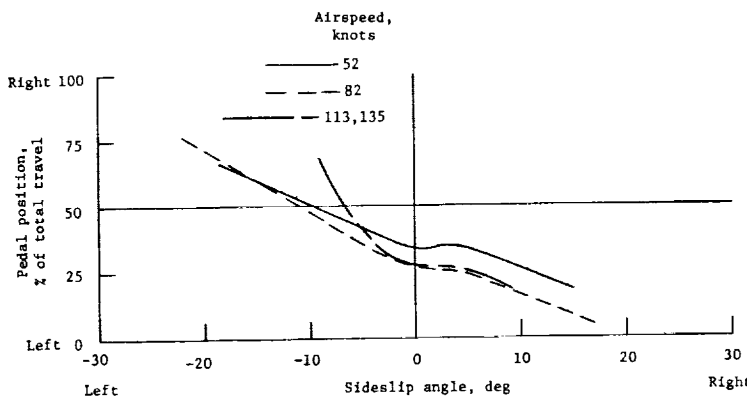

Figure 12.- Summary of static-directional stability results. Negative slope indicates positive stability.

neutral or unstable values of static directional stability for sideslip angles near 0°. Another characteristic worthy of note in figure 12 is the increasingly steep slope in left sideslip for airspeeds of 113 and 135 knots. Although high levels of static stability have been known to contribute to harsh riding qualities in rough-air conditions, no unpleasant characteristics were noted during this investigation, probably because of the nearly neutral directional stability near zero sideslip. A heading wander of about $\pm 2^{\circ}$ was exhibited by the aircraft in cruise flight. The pilot indicated that this problem was of minor consequence for most operational tasks, however, it might become more significant during precision tasks such as tracking or instrument flight. The pilot also noted that the directional stability appeared to be higher in left sideslip compared with right sideslip. This characteristic is generally apparent in figure 12.

The reduced stability near zero sideslip angles is a matter of concern and deserves some analysis. It can be noted that the reduced stability occurs when the pedal displacement required to sideslip the aircraft corresponds to near-zero values of tail-fan thrust. (See figs. 6 and 12.) In an effort to provide a solution, the designer increased the vertical fin area and reduced the twist and camber of the vertical fin so that the tail fan supplied slight antitorque thrust in forward flight and thereby shifted the region of reduced stability out to larger sideslip angles. (See ref. 5.)

Examination of figure 5 indicates that the variation of tail-fan thrust with pitch becomes both nonlinear and less sensitive at low values of tail-fan thrust where the reduced stability occurs; however, a possible explanation would be that the reduced stability characteristics are dominated by destabilizing aerodynamic yawing moments. The trend whereby the reduced stability occurs repeatedly at near-zero values of tail-fan thrust offers reason to suspect unfavorable aerodynamic interference between the fan and fin as one source. In particular, when the fan operates at or near zero net thrust, the inner and outer parts of the disk thrust in opposite directions due to the effect of blade twist. This air, ejecting normal to both sides of the fin, could act as a spoiler to the airflow on the fin and thereby reduce the fin effectiveness.

High-speed flight.- Trim-flight characteristics were obtained for indicated airspeeds of 155 knots and 175 knots at dive angles of approximately 6.5° and 11.5°, respectively. (See figs. 13 and 14.) Examination of the time histories for the 155-knot run (fig. 13) indicated stable and trim flight characteristics with an absence of unusual control motion and with no indication of a divergence tendency. However, there is some indication in the lateral axis of a slight rolling motion. Examination of the time histories for the 175-knot run indicated satisfactory characteristics similar to those described for the 155-knot run. Pilot comments agreed with the data.

The rolling motion (figs. 13 and 14) during attempted balanced, high-speed flight is not surprising in light of the low static stability characteristics near zero sideslip (fig. 12) in combination with the stable dihedral effect (fig. 11) measured at lower airspeeds. Also, for the 175-knot case (fig. 14), based on the pedal position time history, the fan thrust is opposite to the design direction. This effect is anticipated for high-speed,

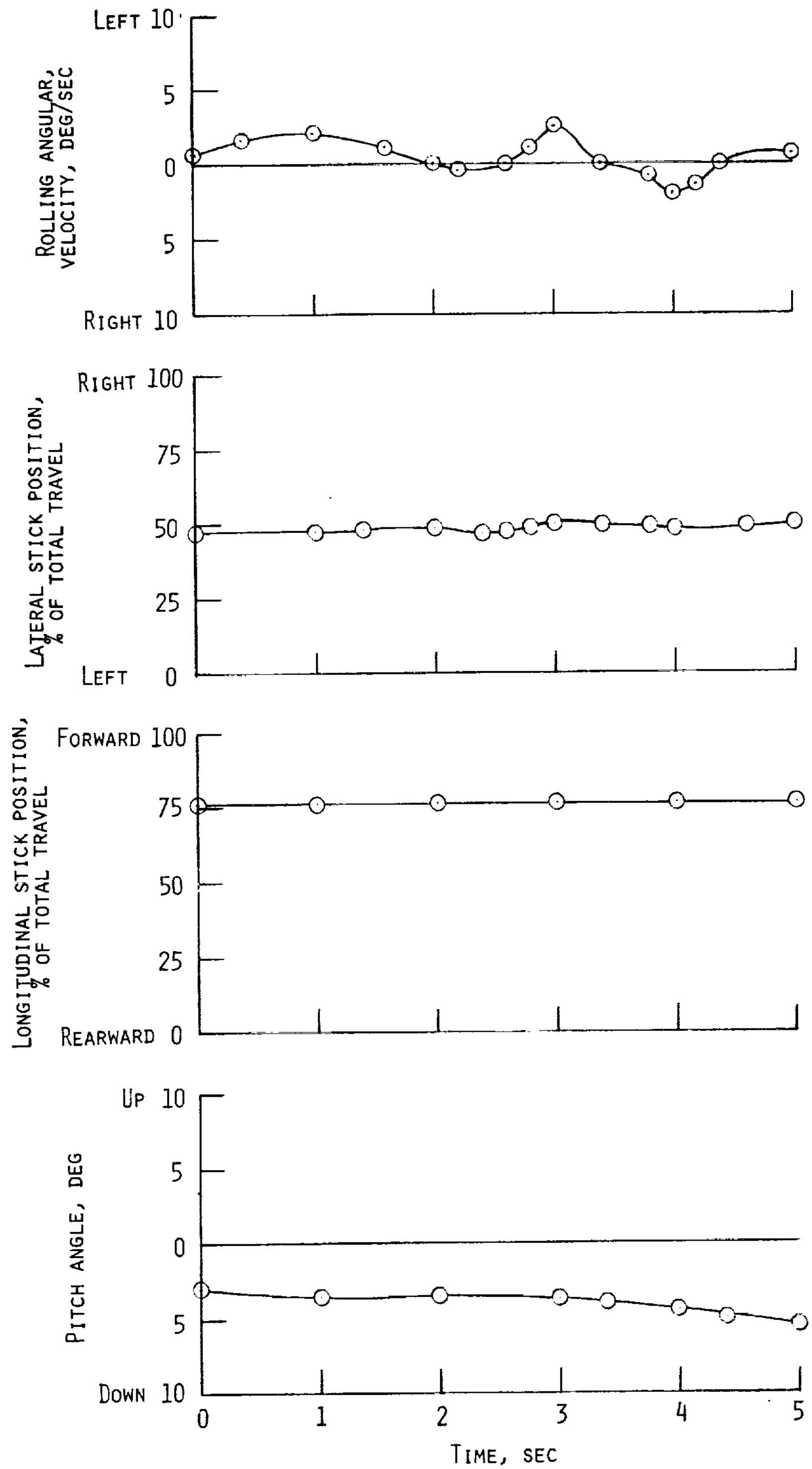

Figure 13.- Time histories of trim-flight characteristics for an airspeed of 155 knots at a dive angle of approximately 6.5° (Collective pitch = 14°; Rotor speed = 377 rpm).

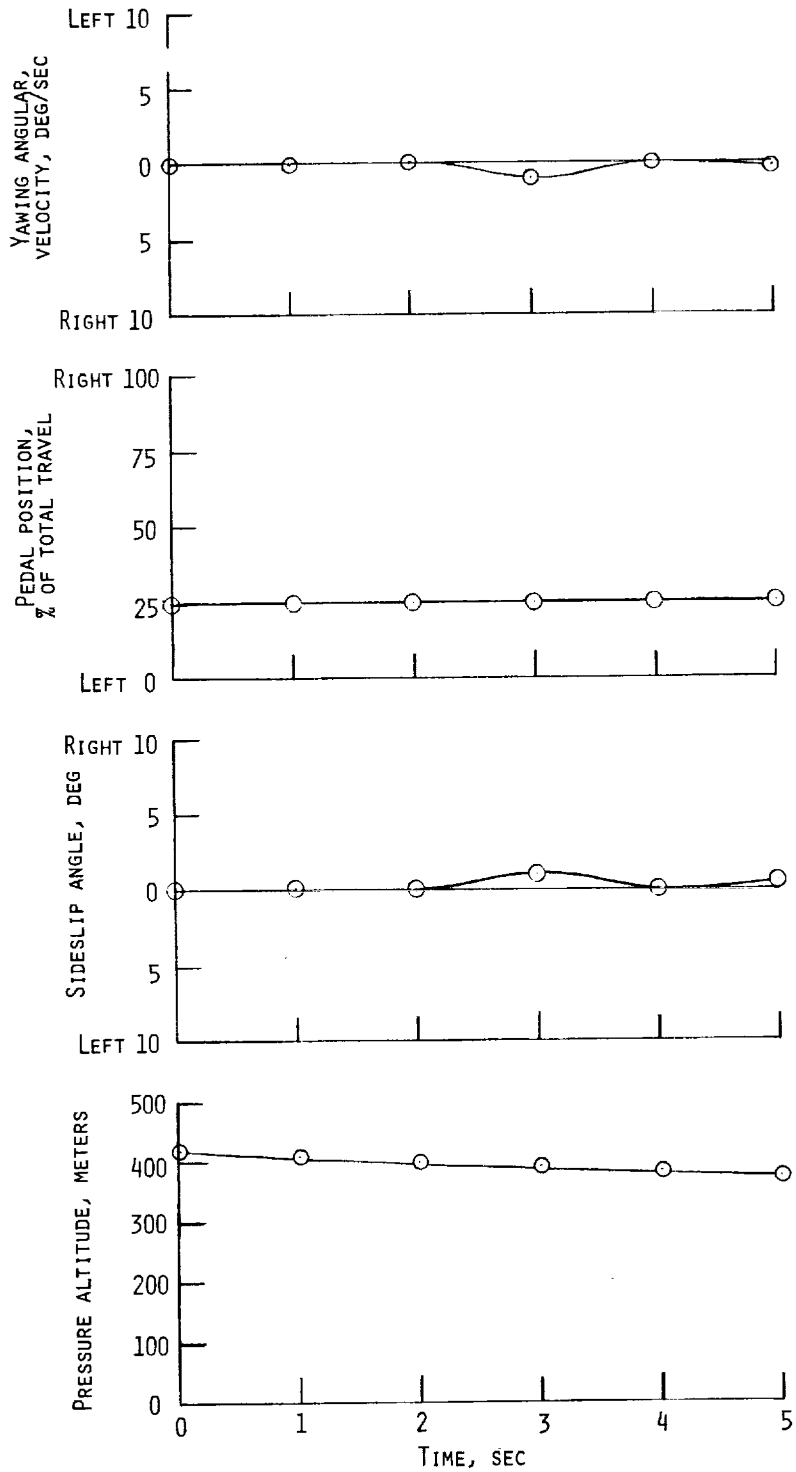

Figure 13.- Concluded.

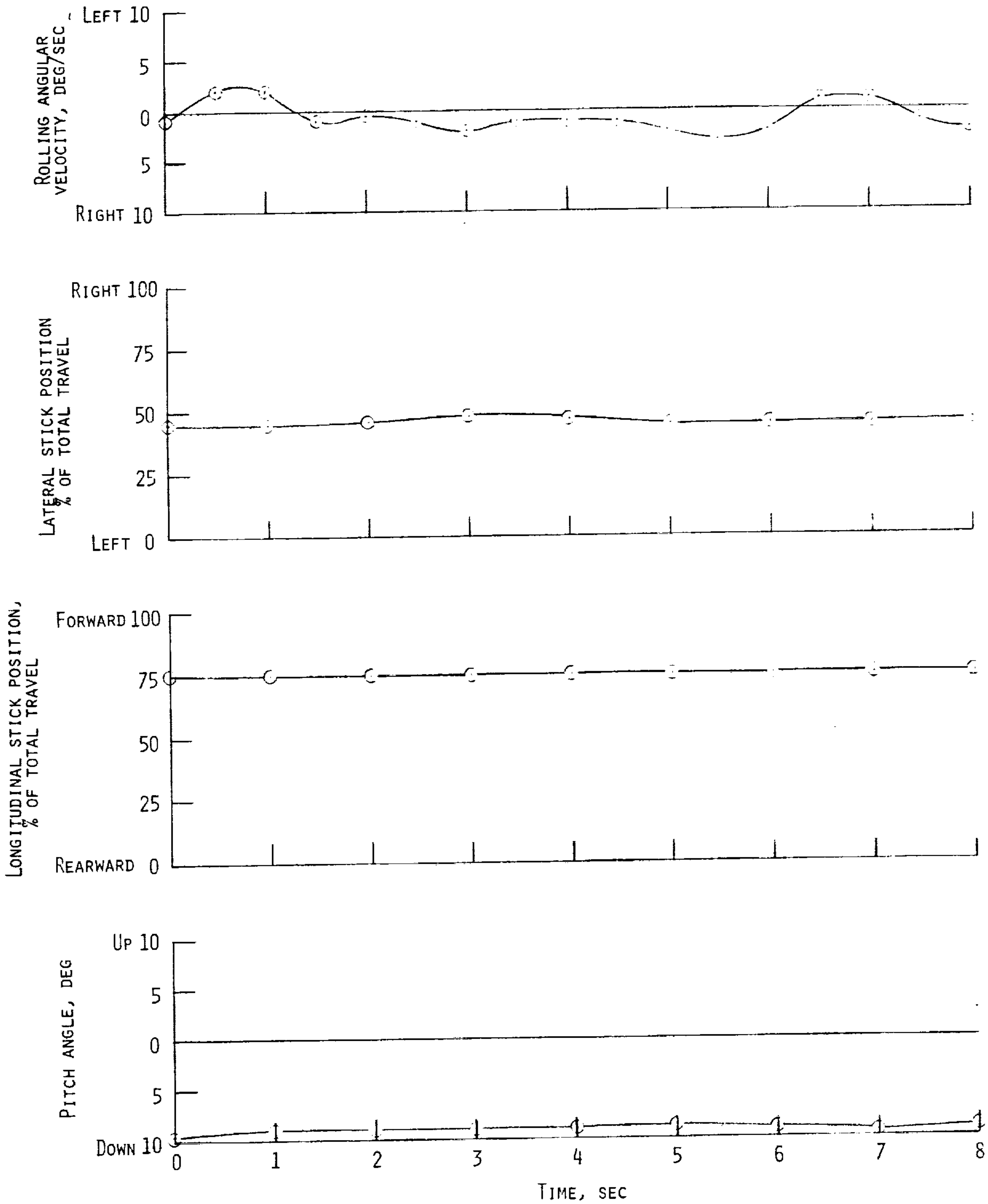

Figure 14.- Time histories of trim-flight characteristics for an airspeed of 175 knots at a dive angle of approximately 11.5°

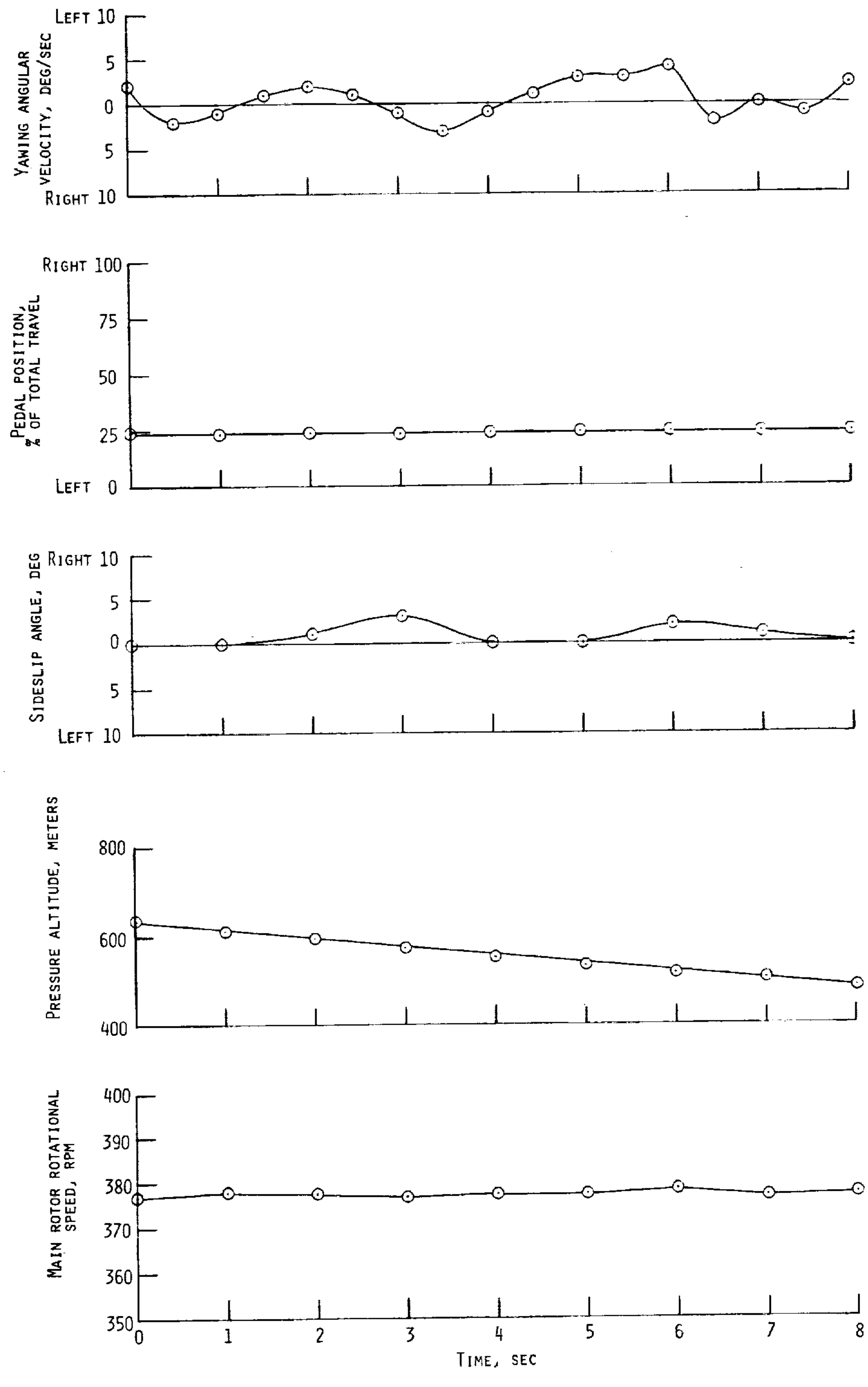

Figure 14.- Concluded.

diving flight when the tail was designed for near-zero fan thrust in cruise flight. Since the high speed was achieved chiefly by entering a dive (note the lower collective setting for the 175-knot run) which does not increase main rotor torque, the main rotor torque is overbalanced by the fin.

Maneuvering flight.- Pedals-fixed rolling and turning maneuvers starting both from level flight and from climbing and descending flight were performed to investigate characteristics such as adverse yaw, turn following, and angular-velocity cross-coupling.

The roll reversals starting in a steady, banked turn of about 30° and rolling the aircraft to a bank angle of about 30° to 40° in the opposite direction using moderate rates of roll were performed. Examination of data, in conjunction with pilot comment, indicated an adverse yaw characteristic that became less noticeable at higher airspeeds. In fact, for the higher airspeeds, the pilot comments indicated that little or no pedal compensation was required to achieve satisfactory coordinated turns and indicated that these characteristics were comparable to those of fixed-wing aircraft. These characteristics are attributable to the directional stability provided by the large vertical fin.

Other coupling characteristics were noted during controls-fixed pedal inputs in level flight. A very weak positive dihedral effect along with a small pitching motion was indicated. The aircraft rolled left and pitched down for left pedal inputs, and rolled right and pitched up for right pedal inputs. These characteristics were difficult to notice, except during intentional departure from coordinated flight. Also, at an airspeed of about 110 knots, a small amount of yaw coupling was noted with large longitudinal control inputs. Forward cyclic inputs produced left yaw, and rearward cyclic inputs produced right yaw. The pilot estimated the yaw excursions to be less than 3° and they were not objectionable.

Maneuvering characteristics were found to be similar in climbing and descending flight. However, as expected during partial power descents, the pedal trim required moved toward the left stop. About 10 percent of the total pedal travel remained for maneuvers. At reduced power levels the cambered fin provides a yawing moment which must be balanced with left pedal. Under these conditions, the fan thrust opposes the fin side force. This effect was treated in previous sections of this paper.

Simulated combat maneuvers.- Maneuvers were performed near the ground to investigate qualitatively the aircraft characteristics during highly demanding maneuver tasks. Rolling dives starting at a cruise speed of about 100 knots, acquisition of an imaginary ground target and pullout, and nap-of-the-earth flight (80 to 140 knots) were the tasks used. The results are given in the following paragraphs as pilot comment.

The first maneuver, a rolling dive on a ground target, was initiated at an altitude of 300 meters and an airspeed of 100 knots. A target was then acquired 90° from the original direction of flight followed by a rolling (80°) dive (30° pitch down), and 180° reversal in direction (flight path). The target was acquired and held as long as possible and then a rolling pullup to the left followed. Airspeed was permitted to increase to 160 knots in the dive. The target was easily acquired and held within a simulated sight until pullup was initiated. Requirement for pedal coordination throughout the maneuver was very small with respect to increasing airspeed or rolling.

After the pullout, a dive maneuver was performed, followed by high-speed nap-of-the-earth flight (80 to 140 knots) over hills and in valleys sufficiently demanding to require large and continuing changes in attitude, direction, and airspeed. Throughout the airspeed range, relative altitudes above the ground from 3 to 15 meters were maintained. Aircraft response to large control inputs was good.

Autorotation.- Autorotations were performed at incremental airspeeds from 40 to 120 knots. During autorotation entries, the controls were held fixed for at least 2 seconds or until the minimum allowable rotor speed was reached. The purpose was to investigate changes in aircraft attitude and rotor-speed decay rate. According to pilot comment, aircraft response following simulated engine failure was mild. Pitch and roll excursions were negligible for all airspeeds tested. Typical yaw excursions of 15° to 20° to the right were encountered. The yaw excursion was sufficient to warn the pilot that engine failure had occurred. The rotor-speed decay rate increased with an increase in airspeed. At an indicated airspeed of 120 knots, following an entry with collective pitch fixed, the rotor speed nearly reached the minimum allowable in 2 seconds.

Establishment of steady autorotative flight was easy to perform since it was only necessary to apply left pedal to correct the yaw excursion, and to lower the collective pitch lever in order to regain normal rotor speed. Main-rotor speed recovery was rapid and required pilot attention since full-down collective pitch would result in overspeeding the rotor. Stabilized airspeed was easily established and maintained. The airspeed for minimum rate of descent was about 60 knots. At this speed, the rate of descent was about 10 meters per second. Just prior to touchdown, rotor speed decay with a collective pitch increase was sufficiently low to allow adequate time to perform a smooth landing. With the fan-in-fin configuration, the pilot was less apprehensive about the tail striking the ground during the autorotation flare maneuver.

During one autorotation that included moderate banking and turning maneuvers, the left pedal stop was contacted for several seconds. Since, in autorotative flight, there is essentially no rotor torque to overcome, the fan thrust must cancel the fin force completely. This condition required appreciable left pedal. Furthermore, the fan thrust is opposite to the design direction in this case and the loss in efficiency increases the pedal travel. Even so, if the pilot is able to accept sideslip angles during autorotation, the large fin provides sufficient directional stability to insure that an equilibrium sideslip angle will be reached eventually. However, the pilot's ability to perform coordinated maneuvers is limited. It is obvious that a larger margin of control would have been available in autorotation if the fin had been substantially smaller.

CONCLUSIONS

A brief flight investigation was conducted to evaluate the effect of a fan-in-fin yaw control system on the flying-quality characteristics of a helicopter. The large, fixed vertical fin associated with the fan-in-fin system was helpful in maneuvering flight, but introduced several flying-quality problems when combined with the fan. More specifically, the results of this investigation are as follows:

1. During hovering flight out of ground effect in winds of 26 to 32 knots emanating from the pilot's right, a pronounced directional unsteadiness was noted. Low induced velocities from the fan, in combination with the opposing wind velocity, would indicate that the fan was operating in the vortex-ring state and would account for the directional unsteadiness. Use of a smaller vertical fin would alleviate this problem by allowing the fan to carry more positive thrust. This problem probably was not encountered in ground effect because the main rotor wake reduced the fin effectiveness and the fan had to carry more positive thrust.

2. Maximum tail-fan power requirements (maximum right directional control power requirements) occurred during steady hovering flight out of ground effect in a left cross-wind (26 to 32 knots). Additional requirements (climbing and maneuver) would require even more control.

3. Static-directional stability measurements for cruising flight airspeeds (80 to 130 knots) indicated stable gradients over most of the range of sideslip angles, but reduced to neutral to slightly negative values over several degrees of sideslip angles near zero. Measurements of effective dihedral indicated stable gradients for all sideslip angles. The reduced directional stability made the aircraft difficult to trim directionally, and in combination with the stable effective dihedral, caused a slight Dutch roll. Pilot comment indicated that these characteristics might become significant during precision flight tasks.

4. The reduced directional stability mentioned in the previous conclusion occurred repeatedly at pedal positions corresponding to low values of tail-fan thrust. At low values of thrust, the fan is ejecting air normally to both sides of the fin (part of disk at negative angles of attack since blades are highly twisted). Reduced fin effectiveness due to flow spoilage caused by air emanating from both sides of the fan was probably the major source of the reduced stability near zero sideslip. The use of a smaller fin which would permit positive thrust to be carried on the fan would probably postpone this problem to flight regimes used less frequently.

5. Nearly full yaw control was required to trim the fin forces during autorotation in forward flight.

6. The tail-fan power required was higher when hovering into the wind in ground effect than out of ground effect although the main rotor torque was reduced in the ground cushion. The increase was probably caused by effects of impingement of the expanded wake from the main rotor on the vertical fin.

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