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NACA RESEARCH MEMORANDUM

METHODS FOR OBTAINING DESIRED HELICOPTER STABILITY CHARACTERISTICS

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

A brief summary is made of methods available to the helicopter designer for obtaining desired stability characteristics by modifications to the airframe design. The discussion is based on modifications made during the establishment of flying-qualities criteria and includes sample indications of theoretical studies of additional methods.

INTRODUCTION

The problems relating to stability of helicopters have been the subject of numerous published works. Requirements established by the military services for satisfactory helicopter stability are specified in reference 1. Some of the pertinent works on this subject by the NACA are listed as references 2 to 13. The purpose of this paper is to summarize some of the physical methods available to the designer for obtaining desired stability values by changing the airframe design. Although the direct application discussed is with a view to meeting flying-qualities criteria, it may be worth pointing out that other reasons often arise for designing a configuration so that specific amounts of stability are provided; for example, in order to obtain the most efficient combination of autopilot and airframe design.

The scope of the present discussion is outlined in the following table:

Characteristic	Rotor type investigated
Sensitivity in roll	Single and tandem
Maneuver stability	Single and tandem
Speed stability	Single and tandem
Lateral oscillation and turn characteristics	Tandem

Available results on directional weathercock stability of tandem helicopters are not included in this discussion because of thorough coverage in reference 2. For helicopter types other than single-rotor or tandem-rotor configurations, no direct information is provided herein but much can be inferred from the more appropriate of the two types covered.

For each of the stability characteristics covered, modifications made to the design in the process of exploring a range of characteristics during the establishing of desired flying-qualities criteria are discussed. The value of the cases illustrated lies in the fact that they are demonstrated cases for which measured stability-parameter values are available. Optimum design generally requires a choice of methods or combinations of methods; therefore, sample indications of theoretical studies of additional methods are included in each case.

SYMBOLS

L_{δ}	rolling moment due to control deflection
L_p	rolling moment due to rolling angular velocity
ΔW_b	change in weight of blade
R	blade radius
I_1	blade moment of inertia
γ	blade mass factor
M_{α}	pitching moment per unit angle-of-attack change
M_q	pitching moment due to unit pitching angular velocity
L	rolling moment
v	sideslip velocity
Ω	rotor rotational speed
σ	rotor solidity
B_1	longitudinal cyclic pitch
V	forward velocity

c_m section pitching-moment coefficient

$\Delta\theta$ difference between collective pitch of front and rear rotors

$\Delta\alpha_d$ difference in angle of attack of front and rear rotors due to longitudinal swashplate tilt, positive when angle of attack of rear rotor is greater

SENSITIVITY IN ROLL

Sensitivity in roll, which is frequently a major problem in the hovering characteristics of small helicopters, is treated in table I. The test vehicle is a two-place single-rotor helicopter. The parameter discussed is the ratio of control power (that is, the rolling moment per unit stick deflection) to damping, which is the resisting moment per unit angular velocity of the helicopter. Since changes in the value of control power are restricted by trim requirements, this discussion is concerned solely with changes in damping.

The requirement of the current military specification (ref. 1) is that the rate of roll per inch of stick displacement be less than 20° per second. The test helicopter provided the opportunity to explore a fair-sized range of values, always on the satisfactory side, by adjusting a mechanical gyroscopic device. The value of L_δ/L_p of 14 is obtained with the device locked out and the value of 5.2 is with the device as far beyond the production setting as feasible. Both from theory and from flight measurements on other helicopters, it is known that, with lighter blades and no special device, the requirement of reference 1 would not have been met. Therefore, examination of a few additional methods for changing the damping and hence the sensitivity is advisable.

Increased blade inertia is one method. If a tip weight is considered, 60 percent of the blade weight is calculated to be needed to duplicate the full change in L_δ/L_p from 14 to 5.2. Flapping-hinge offset will increase damping, but bear in mind that the control linkage is assumed here to be changed to prevent increase in control power; else little change in sensitivity would result. With the heavy blades of the test helicopter, an offset of only 2-percent radius should be needed to change L_δ/L_p from 14 to 5.2; with light blades, an offset of 5-percent radius would be enough.

A third design approach which makes possible increased damping is the use of aerodynamic servocontrols; as viewed from above the rotor in the sketch of table I, one type uses a surface behind the outer part of the blade and another, a surface attached at right angles at the blade root. Such devices apparently can be designed to provide increases in damping sufficient to cover the test range.

Sensitivity in roll for the tandem helicopter requires no separate discussion since, in roll, it is possible simply to consider two single rotors instead of one.

MANEUVER STABILITY OF SINGLE-ROTOR HELICOPTERS

For the maneuver-stability (or divergence) problems with single-rotor helicopters at cruising speed, two separate cases are treated in table II. With one helicopter, the variations were made by way of angle-of-attack stability, and in the other case, by way of damping in pitch. For the first case, a change to a value of angle-of-attack stability of 300 pound-feet per radian was enough to cause the requirement to be met. The range covered went from the unstable value of +7,000 pound-feet per radian to the stable value of -2,100 pound-feet per radian. (Minus is stable in accepted stability theory.) The test conditions actually extended somewhat farther than the value of -2,100 pound-feet per radian on the stable side but the M_{α}-values were not recorded.

The tail assembly used has been discussed in published papers, particularly reference 3. It may bear repeating, however, that a total tail area of 0.5 percent of the rotor area could make the difference between the helicopter's diverging excessively in a few seconds and being able to fly through rough air without the longitudinal control being moved. This result was obtained after linking the tail to the cyclic controls, which so reduced the design compromises as to permit use of a somewhat more effective tail.

Tests were made with a different helicopter (labeled (2) in table II), wherein the damping in pitch was varied in such a way as to bracket the condition for which the requirement was met. The value of -1,200 pound-feet per radian needed to cause the specification to be met falls about midway in the range of -700 to -1,900 pound-feet per radian covered. Damping is another quantity where the minus sign is indicative of a stable condition. As to the method used, the investigation was the same as that which provided the damping-in-roll values given in table I.

As to alternate methods, for large changes in angle-of-attack stability M_{α}, there do not seem to be too many which will cover the range single handed. Increase in rotor speed is listed because the effect of such an increase is calculated to be sufficient to warrant thought of some compromise with design for optimum power. It will be understood that rotational speed is appropriate because in all other respects the design is fixed; more fundamentally, what is implied is lower values of pitch and tip-speed ratio. A 33-percent increase in rotor rotational speed is estimated to give half the range covered and would not have been enough, in itself, to meet the specification. The effects are not linear and much greater increase in stability by this method would cause extreme compromise with performance.

If offset flapping hinges are used, then the aircraft center-of-gravity position affects angle-of-attack stability. An estimate for this helicopter is that, with the hinges at 5-percent blade radius, moving the center of gravity 7 inches (2.5 percent of the rotor radius) forward from the rotor shaft would produce as much change as the 33-percent increase in rotor rotational speed. With the same offset, a center-of-gravity shift of 14 inches, if such is tolerable, would produce the change to the -2,100 value and thus would permit the requirements to be exceeded.

For alternate methods of varying the rotor damping in pitch M_q, the methods given in the roll-sensitivity discussion again apply.

MANEUVER STABILITY OF TANDEM-ROTOR HELICOPTERS

Maneuver stability for the tandem helicopter, again at cruising speed, is treated in table III. The parameter considered is again moment per unit angle-of-attack change, and with the test helicopter the unstable value of 57,000 pound-feet per radian corresponded to a value that would just barely meet the requirements set forth in the specification. The test range shown, from the unstable 72,000 pound-feet per radian to the stable -16,000 pound-feet per radian, went several times farther than just reaching the marginal value. It is desirable to be able to make these larger changes. The test method used was not altogether appropriate for this discussion because so much of the range was obtained by choice of power setting. The available center-of-gravity range produced a useful but subordinate change, forward center of gravity being the more stable.

Calculations, therefore, are again used to illustrate other methods. Changes which affect the relative lift-curve slopes of the front and rear rotors seem especially effective. It is estimated that, if the front-rotor radius is decreased and the rear-rotor radius is increased, with a total difference of 10 percent of the mean radius, the test value of stability increase would be realized. If, instead, the rotor solidities were similarly changed by putting wider blades on the rear rotor and narrower ones on the front rotor, this same stability increase could be obtained with a solidity differential of 45 percent of the mean value.

The size of horizontal-tail surface necessary to contribute the same range was computed, in order to illustrate the conclusion that a horizontal tail is relatively less effective for tandems than for single rotors. A value of 4 percent of rotor area is indicated in distinction to the 0.5 percent used on the single-rotor helicopters. Although the two cases are not strictly comparable, the impression given is considered to be reasonable.

SPEED STABILITY OF SINGLE-ROTOR HELICOPTERS

Table IV treats the speed stability for the single-rotor case. With fixed pitch and throttle, the stick is required to trim farther forward with increase in speed. The parameter used to measure this change is the longitudinal cyclic pitch B_1 per unit velocity V (in knots). The range tested (B_1/V from 0 to 0.06 degrees per knot) was obtained by changes in horizontal-tail setting. When sufficient upload was provided on the tail surface, the stable contribution of the rotor could be cancelled; when download was provided, it could be increased. Incidentally, most of this exploration of near-zero speed stability was obtained with the tail linked to the cyclic stick, the reason being that a high, fixed, nose-up tail setting can be dangerous in event of inadvertent speed increase.

Since the rotor tends to be stable, most concern is felt over destabilizing factors. Fuselage shape can be as destabilizing as a nose-up tail setting, although a range of 30 foot-pounds per knot would be rather large. A large rotor-blade-section diving moment could more than cancel the stable tendency of the rotor. The increment Δc_m of 0.06 actually was suggested by the dangerous characteristics which arose with autogiros having $c_m = -0.06$. A rough estimate indicated the value of 0.06 to be the right order of magnitude to produce the change under discussion as well.

SPEED STABILITY OF TANDEM-ROTOR HELICOPTERS

Table V relates to speed stability of the tandem-rotor type. The longitudinal control of this configuration is obtained primarily by changing the pitch-setting difference between front and rear rotors, and the parameter is written to correspond as $\Delta\theta/V$. This quantity was varied from -0.01 to 0.003; thus, the requirement of at least zero is bracketed. This change was accomplished by changing the tilt angle between the front and rear rotor systems. The unstable setting was 0°; the stable one, 1.8° "toe-in."

Calculations indicate that a center-of-gravity shift from midway between the shafts to 22 percent ahead of the midpoint should produce the equivalent range. The 22-percent value is based on total distance between shafts. Similarly, giving the rear rotor higher solidity and the front less, with a total difference $\Delta\sigma$ of 34 percent of the mean should achieve this same result. These values are for cruising speed; at low speeds the effect of center of gravity can even reverse, whereas the solidity change becomes more effective. The use of some of each method thus holds special interest. It is also worth noting that these effects act in the same direction for speed stability as they do for maneuver stability.

LATERAL-OSCILLATION AND TURN CHARACTERISTICS OF TANDEM-ROTOR HELICOPTERS

Tandem-rotor lateral-oscillation and turn characteristics at cruise speed are treated in table VI. One of the most effective parameters for both is roll due to sideslip velocity, or L/v, measured as foot-pounds of rolling moment per foot per second of sideslip velocity. Fortunately, this quantity, which is the effective dihedral, is not critical in its own right, provided it stays on the stable side. (By convention, stable values are negative.) Most of the required change was obtained by attaching small wings (surface area, 7 sq ft) to the landing gear. The front view and side view are shown. It was most convenient in these flying-qualities trials to further extend the test conditions by change in flight condition; but with so many designs sprouting modest-sized wings (much bigger than the panels used in these tests), making the full change needed may often require only that the right geometric dihedral be determined.

One additional method is to change the vertical location of the center of gravity relative to the side-view area. Only a major change in power-plant location, such as overhead turbines, seems likely to make a change of this magnitude (9 in. shift in center of gravity). Contributing changes, though, including some ventral fin area, may often prove feasible.

Increased damping in roll is another effective parameter that can be considered. This method is discussed, along with still other approaches, in reference 4.

CONCLUDING REMARKS

Examples have been presented to illustrate methods for improving helicopter stability. It will be realized that many of the numerical values which have been given apply only for the case studied. For example, a tandem helicopter might already have lower effective dihedral or might somehow be designed with less nose-down inclination of the principal inertia axis and, in either event, might meet the lateral requirements without reduction in effective dihedral.

The cases presented are believed to illustrate that it is now feasible to choose one or more important stability parameters from theoretical studies and, in turn, to find a combination of methods whereby parameter values are realized which provide the desired stability characteristics.

Aside from the degree of fundamental understanding, which involves the usability of theory, a variety of choice of methods is suggested as the key to the obtainance of desired characteristics with a minimum of design compromise. It is hoped that these sample methods may be helpful in suggesting still more approaches to the helicopter designer.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., June 16, 1954.

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TABLE I

SENSITIVITY IN ROLL

SINGLE ROTOR; 2,200-LB GROSS WT.

PARAMETER	VALUE TO MEET MIL-H-8501	RANGE TESTED	METHOD USED
$\frac{\text{CONTROL POWER}}{\text{DAMPING}}$, $\frac{L_\delta}{L_p}$, $\frac{\text{DEG/SEC}}{\text{IN.}}$	<20	14 TO 5.2	AVAILABLE GYRO DEVICE; L_δ FIXED

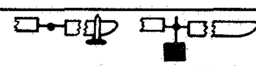
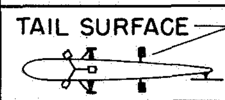
ADDITIONAL METHODS (L_δ FIXED)	AMOUNT FOR RANGE TESTED
INCREASE IN I_1 VIA TIP WT. 	ΔW_b = 0.6
HINGE OFFSET WITH γ = 4.7 	2% R
AERO SERVOS 	--------

TABLE II

MANEUVER STABILITY

SINGLE ROTOR; GROSS WTS.: (1) 5,000 LB AND (2) 2,200 LB; CRUISE SPEED

	MAJOR PARAMETER VARIED	VALUE TO MEET MIL-H-8501	RANGE TESTED	METHOD USED
(1)	M_α, $\frac{\text{LB-FT}}{\text{RADIAN}}$	< 300	7,000 TO -2,100	TAIL SURFACE 
(2)	M_q, $\frac{\text{LB-FT}}{\text{RADIAN/SEC}}$	<-1,200 (ROTOR)	-710 TO -1,930	AVAILABLE GYRO DEVICE

PARAMETER	ADDITIONAL METHODS	AMOUNT FOR 1/2 RANGE TESTED
M_α	INCREASED RPM	33%
	FORWARD C.G. WITH OFFSET HINGES	Δ C.G. = 2.5% R WITH 5% OFFSET
M_q	SIMILAR TO ROLL SENSITIVITY	

TABLE III

MANEUVER STABILITY

TANDEM ROTOR; 7,000-LB GROSS WT.; CRUISE SPEED

MAJOR PARAMETER	VALUE TO MEET MIL-H-8501	RANGE TESTED	METHOD USED
M_α, $\frac{\text{LB-FT}}{\text{RADIAN}}$	<57,000	72,000 TO −16,000	C.G. AND POWER SETTING

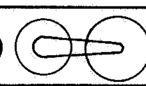
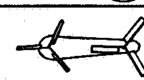
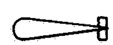
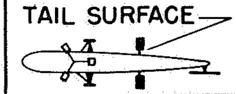
ADDITIONAL METHODS	AMOUNT FOR RANGE TESTED
ΔR (SAME Ω) 	10%
Δσ 	45%
TAIL SURFACE 	100 SQ FT OR 4% OF TOTAL ROTOR AREA

TABLE IV

SPEED STABILITY

SINGLE ROTOR; 5,000-LB GROSS WT.; CRUISE SPEED

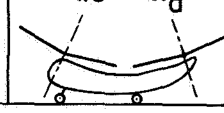
PARAMETER	VALUE TO MEET MIL-H-8501	RANGE TESTED	METHOD USED
$\frac{B_1}{V}$, $\frac{\text{DEG}}{\text{KNOT}}$	>0	0 TO 0.06	TAIL SURFACE 

ADDITIONAL FACTORS	AMOUNT FOR RANGE TESTED
MOMENTS, FUSELAGE LESS TAIL	$\Delta \frac{\text{FT-LB}}{\text{KNOT}} = 30$
BLADE SECTION PITCHING-MOMENT COEFFICIENT	$\Delta c_m \approx 0.06$

TABLE V

SPEED STABILITY

TANDEM ROTOR; 7,000-LB GROSS WT.; CRUISE SPEED

PARAMETER	VALUE TO MEET MIL-H-8501	RANGE TESTED	METHOD USED
$\frac{\Delta\theta}{V}$, $\frac{\text{DEG}}{\text{KNOT}}$	>0	-0.01 TO 0.003	$-1.8° \Delta\alpha_d$ 

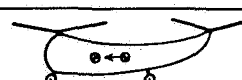
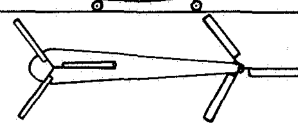
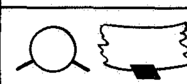
ADDITIONAL FACTORS	AMOUNT FOR RANGE TESTED
C.G. SHIFT 	22%
$\Delta\sigma$ 	34%

TABLE VI

LATERAL OSCILLATION AND TURN CHARACTERISTICS

TANDEM ROTOR; 7,000-LB GROSS WT.; CRUISE SPEED

MAJOR PARAMETER	VALUE TO MEET MIL-H-8501	RANGE TESTED	METHOD USED
ROLL DUE TO SIDESLIP, $\frac{L}{V}$, $\frac{\text{FT-LB}}{\text{FT/SEC}}$	>-26	-75 TO -37	 TWO WINGS, 7 SQ FT EACH

ADDITIONAL METHOD [1]	AMOUNT FOR RANGE TESTED
VERTICAL C.G.-LATERAL C.P. RELATIONSHIP	9 IN.