# NACA

# RESEARCH MEMORANDUM

HELICOPTER STABILITY

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## SUMMARY

Knowledge of helicopter stability is quite meager as yet. There are, however, a number of fundamental concepts which can already be made use of, and there are likewise several lines of development which appear to warrant current and widespread consideration. A number of these concepts and lines of development are presented and discussed.

## INTRODUCTION

With the increasing commercial use of the helicopter, it inevitably is being expected to be satisfactory for operation under more and more adverse weather conditions. Under blind flying conditions, when the pilot must concentrate on navigation, radio contacts, and flight procedures, undesirable stability characteristics which might normally be acceptable may become intolerable. Increased use further puts the helicopter in the hands of pilots who should not be expected to tolerate undesirable handling characteristics, even though these characteristics could be overlooked on military missions or in an experimental aircraft. Helicopter stability and control characteristics, and flying and handling qualities are thus due for increasing attention.

The determination of a set of flying- and handling-qualities requirements, such as that given for the airplane in reference 1, and research to reveal the most expedient means for meeting or exceeding these requirements, will be necessary before the helicopter can be made to fully realize its latent possibilities. To attempt to formulate tentative requirements or to guess the outcome of the research needed on the effects of various alternative hub and rotor configurations seems too far ahead of the story. There are, however, a number of fundamental concepts which can already be made use of, and there are likewise several lines of development which appear to warrant current and widespread consideration.

## BASIC PRINCIPLES

In order to provide a background for the discussion of possible improvements it may be well to first discuss some of the factors which distinguish the helicopter from the more familiar airplane concepts as regards stability and control. For simplicity it will be assumed that the helicopter has flapping blades (either individually flapping or see-saw) so that no large pitching or rolling moments are applied to the rotor hub by the blades. A single lifting rotor is also assumed for simplicity, but it will generally be apparent that the discussion can be applied as a first step, at least, for multirotor designs.

Method of control.- Pitching and rolling moments on the aircraft are achieved by tilting the rotor tip-path plane so as to displace the line of action of the rotor resultant force from the center of gravity. In order to tilt the tip-path plane, the blade pitch is varied in cyclic fashion (feathering). The control linkage is such that moving the stick rearward increases the blade pitch on the right and decreases it on the left. The flapping arising from this change results in the blades reaching a high position forward and a low position rearward, and the accompanying rearward tilt of the resultant force vector produces a nose-up moment on the machine.

Control lag.- Because the blades must flap to produce a moment, response to sudden control motion is not instantaneous. Available evidence indicates that the time lag between control displacement and rotor tilt is generally only about 0.05 to 0.10 second, however, and this amount is within the acceptable limits specified for aileron response in the NACA requirements as given in reference 1.

Stability characteristics of aircraft.- Unfortunately, this time lag does not tell the whole story as regards response of the aircraft or, in other words, the change in flight path resulting from the control motion. For at least one of the more familiar types of helicopter, the maximum normal acceleration resulting from longitudinal control displacement (in forward flight) occurs several seconds after the maximum control displacement. Consequently, in normal operation the pilot initiates a maneuver by moving the control in the desired direction from trim, but then has to move the control in the opposite direction beyond trim in order to limit the acceleration to the desired value. Apparently, these characteristics represent an instability with angle of attack that (if not controlled for by the pilot) is checked, after several seconds, by the effect of the speed change that occurs as the flight path becomes inclined. Two factors that must contribute heavily to this situation are: (1) The rotor alone is statically unstable with angle of attack, although (like the airplane) it is stable as regards speed change; or, in other words, the rotor tilts back[1], producing a nose-up moment, with either an increase in angle of attack or an increase in speed. (2) The fuselage alone, for the type of helicopter in question, is unstable as regards both angle-of-attack change and speed change.

The response of the helicopter to a gust or other disturbance is analogous to its response to control displacement, and the helicopter continually tends to nose up or down. If allowed to do so, the helicopter will go through an oscillation in pitch with a period of about 10 to 20 seconds. This oscillation is more serious than the phugoid oscillation of similar period which is tolerated with airplanes because (particularly at high speeds) the oscillation of the helicopter will increase rapidly to catastrophic proportions if unchecked, and because the pilot must anticipate the eventual response of the helicopter to his corrective control motion, as already discussed.

Control forces.- Control-stick forces, for both steady flight and for maneuvers, have always been a large factor in determining the merit or acceptability of any type of aircraft. With the airplane, it is accepted practice to provide means for trimming out the stick forces in steady flight. Many helicopters have appeared without equivalent devices, possibly because the trim-tab arrangement so readily applied to the airplane is not so readily applied with the rotating-wing system. In maneuvers, the stick forces for the helicopter (so long as reversible controls are used) are subject to added complications due to the inertia of the rotating parts (blades included). In both steady flight and maneuvers, the helicopter control stick (again assuming a reversible system) is subject to periodic stick forces, or in other words vibration.

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[1]The flapping system automatically adjusts itself to any unbalanced lift forces, since the hinges prevent transmission of moments to the hub. When a lifting rotor is moved forward, the advancing blade encounters greater airspeed than does the retreating blade, and tends to produce more lift. This tendency results in an upward flapping velocity on the advancing side, and downward on the retreating side, decreasing the angle of attack on the advancing side and increasing it on the retreating side to the extent needed to restore balance. These flapping velocities at the right and left sides result in a displacement of the blades at the front and rear, and the plane or cone described by the rotor blades is thus tilted aft.

When the angle of attack of the rotor system is increased, the advancing and retreating blades are both subjected to an increased angle of attack. This angle-of-attack increase is inversely proportional to the relative velocities; but since the dynamic pressure is proportional to the velocity squared, the advancing blade nevertheless tends to have the greater increase in lift. The increased flapping motion which serves to avoid the unbalance of lift again tilts the rotor system aft.

For helicopters thus far built, most of the stick vibration experienced has resulted from inaccurate construction and adjustment of the rotor blades and has, in some cases at least, been kept below the objectionable levels by use of highly refined methods of adjustment of blade characteristics. For much faster and much heavier helicopters, however, the inherent periodic forces (that is, the forces due to variation in flow conditions on the advancing and retreating blades, which are still present when all blades are truly identical) must be expected to reach disturbing magnitudes.

Center of gravity.- The effect of horizontal shifting of the helicopter center of gravity is much simpler than for the airplane, and realization of this fact can simplify both the mental concepts and the test procedures. The fuselage tends to act like a pendulum, and a shift in center of gravity tilts the helicopter. If changes in fuselage aerodynamic moments can be neglected (which is a good first approximation for study of the problem), then the control change required to retrim the helicopter with change in center of gravity is independent of speed, and the net effect is a new combination of flapping and rotor feathering. (See appendix of reference 2 for explanation of equivalence of rotor flapping and feathering.) The effect of a center-of-gravity change is then equivalent to shifting the available range of control travel. Since linkage difficulties cause designers to avoid large excess control travel, a rearward shift in center of gravity of a few inches from that for normal loading can sometimes result in inadequate forward stick travel either in the take-off maneuver or in maneuvers at high speed.

The fuselage aerodynamic moments cannot always be neglected even in connection with the effects of center of gravity. In particular, if the fuselage pitching-moment coefficient changes rapidly with angle of attack, then (at high speed) a change in center of gravity will affect the rate of change of control position with speed.

## MEANS FOR IMPROVEMENT

Means for improvement to be discussed are limited to the following: (1) Use of a horizontal tail surface; (2) Use of trim devices; (3) Use of irreversible, power-operated controls with artificial "feel"; (4) Automatic controls, and (5) Choice and grouping of indicating instruments.

Horizontal stabilizer.- As has already been mentioned, the undesirable response of the helicopter to gusts or control motions in forward flight is believed to result, to a large extent, from the instability with angle of attack of the rotor and of the fuselage. To indicate whether these sources of instability could be offset by a tail surface of reasonable proportions, a few sample calculations were made. The sample helicopter was assumed to have a rotor 40 feet in diameter and to be traveling at 100 miles per hour, with a tip speed of 400 miles per hour. The fuselage was assumed to have the pitching-moment characteristics given in reference 3 for an actual fuselage. The rotor moment changes (as referenced to the helicopter center of gravity) with change of angle of attack and change of airspeed were calculated by means of the blade-motion expressions of reference 4, using reference 5 to establish the flight condition. These theoretical treatments are considered sufficiently well proven, for the present purpose, by the experimental studies of references 2 and 6. The fuselage angles of attack (including the downwash angle) were obtained from the approximate values given in reference 7 for the same fuselage as that of reference 3 and are considered adequate for the present purpose.

It was found that a tail surface located 15 feet aft of the rotor center and having an area of only 4 square feet would make the fuselage neutrally stable with angle of attack at low angles and stable at larger positive and negative angles. An additional 4 square feet were found to be sufficient to offset the instability of the rotor with angle of attack. These areas seem quite moderate in comparison with the use of about 25 square feet of horizontal surface on one of the most successful wingless autogiros, which had a rotor diameter identical to the present example (40 feet), and the use of about 40 square feet on an airplane of typical proportions and having a 40-foot wing span.

It is interesting to note that the helicopter fuselage in question (with no stabilizer and over a range of angles of attack of about $10^{\circ}$) caused as much instability with angle-of-attack change as did the rotor. Since the stability of the rotor with respect to speed changes is necessarily a large factor in preventing unintentional angle-of-attack changes from becoming catastrophic (when no tail surfaces are used), the effect of the unstable fuselage moment coefficient in offsetting this stability-with-speed was also investigated. It was found that the fuselage moments (with no tail surface) were sufficient to offset the rotor stability-with-speed for the conditions assumed.

In adding a horizontal tail to the helicopter, several precautions must be observed. The addition of the tail surfaces already discussed would give the fuselage considerable positive stability with speed change (at cruising speeds and higher) and, in order to prevent running out of control, would have to be linked to the controls or at least made adjustable. Care must be used in designing the tail surface to be sure that it will not stall during either pull-ups or push-downs. Inspection of the problem also suggests that the tail-surface location should be chosen so that the surface will be either always inside or always outside the rotor slipstream to avoid sudden pitching-moment changes with change in forward speed.

In the past, the use of an adjustable tail surface has often been suggested for the purpose of reducing the amount of control travel required for trim at top speed. If this is done, care should be taken that the control travel supplied is not reduced below the amount needed for maneuvers. An amount of control adequate for fairly high steady-flight speeds has sometimes been found to be inadequate in take-off or in recovery from pull-ups.

An adjustable stabilizer is also sometimes used to permit adjustment of blade flapping and hence reduction of in-plane motion. In any case, full attention should be paid to the function of the surface as regards stability.

Vertical fin.- The familiar tail-rotor arrangement provides considerable weathercock stability and considerable damping in yaw as well. With the tail rotor removed, the fuselage would, in most cases at least, be directionally unstable, in addition to being unstable in pitch as already discussed. For designs which use some means other than a tail rotor for counteracting torque, available evidence indicates that even at the relatively low speeds reached by present helicopters the addition of a tail fin (or some equivalent means of offsetting the fuselage instability) is essential for proper directional handling characteristics. The directional control must then be made powerful enough to overcome the weathercock stability during vertical landings and take-offs made with side winds.

Trim devices.- The adjustment of average stick forces by means of tabs is not as convenient as for the airplane, but adjustable springs, or bungees, can easily be added (in the field if necessary). The tiring effect of a steady stick force may not be remarked upon by the average pilot because of confusion with other irritations such as periodic stick forces. Once the trim device has been added, however, the improvement will be readily appreciated. When the improvement achieved is considered in relation to the weight and expense involved, the incorporation of trim devices in reversible control systems appears mandatory.

Power controls.- With very large helicopters the use of bungees or other trim devices will hardly be an adequate solution even for the steady forces, since the trim adjustments would have to be made simultaneously with changes in speed, angle of attack, or control displacement. Further (with a reversible system) blade inequalities would have to be maintained within still finer percentage tolerances than is true for present sizes in order to prevent excessive periodic stick forces. Again, with increase in either size or speed, the inherent periodic forces (for example, those due to the reversed-velocity region on the retreating side of the rotor) will grow in magnitude. Power controls providing a high degree of irreversibility appear to be an answer to all of these problems. If the system is provided with artificial control "feel," the development work required to produce reasonably good stick forces in maneuvers with each new helicopter design, large or small, will be greatly reduced. Irreversible mechanisms involving friction, such as a worm and gear system or a cam and follower system, may, of course, be adequate for very small helicopters; but since they increase the forces required to move the controls and do not prevent periodic stick forces while the controls are being moved, such systems do not appear to offer a general solution.

One type of power boost which apparently should prove satisfactory for the helicopter is described in reference 8. This system permits use of any desired amount of boost, up to infinite boost, and has a time lag which (at least unless combined with other sources) is negligible.

Automatic controls.- The simplification of helicopter controls is obviously desirable, the coordination required under some flight conditions being excessive, at least for the average or near-average individual. A great deal of effort has already been applied toward the automatic coordination of the throttle and pitch controls. Quite commonly the attempt has been to achieve, with this same mechanism, an automatic change to autorotative pitch in event of power failure. At the present time it appears that achieving both of these ends with the same device is still too difficult. Considerable success has been reported for the throttle governor, however, for the purpose of reducing the coordination required in power-on flight. This type of governor regulates the throttle to achieve constant rotor rpm. When the rotor rpm drops due to power failure, governor operation of the throttle is obviously ineffective, but separate precautions such as incorporation of a moderate rate of change of blade pitch with lag angle have been effective in reducing the alertness and skill required of the pilot following power failure. Further development of safety devices appears essential, particularly for helicopters operating at the high pitch settings required for high rates of climb and for maximum efficiency. In the meantime, however, it appears that advantage should be taken of the ability of the throttle-type governor in making the helicopter easier to fly.

The airplane variety of automatic pilot could probably be used for directional control in present production helicopters. For maintaining level flight, however, an automatic pilot responding to the change of attitude angle of the fuselage would be expected to encounter difficulties in overcoming the pitching instability and oscillations already discussed. Difficulty would be expected primarily because the changes in attitude of the fuselage do not correspond to the changes in attitude of the rotor tip-path plane. It would appear that greatly increased success might be had if the rotor virtual axis (the axis of the cone described by the rotating blades) were controlled instead of the fuselage axis, or if fuselage velocity or acceleration were used instead of position.

Instruments for blind flying.- Initial attempts to fly "under the hood" in helicopters, using the normal instruments plus an airplane-type artificial horizon, proved discouraging because of the excessive effort required to maintain the correct attitude angle and airspeed. The Coast Guard helicopter development unit at Elizabeth City, North

Carolina, has subsequently been conducting experiments to determine the degree of success which might be achieved by means of relatively simple modifications in the flight instruments normally used. One of the changes made was the addition of modified airplane-type attitude and directional gyros. The attitude angle in both pitch and roll is observed by looking down at a mark on top of a sphere, the sphere being stationary in space, while another mark, attached to the fuselage, is seen in relation to the mark on the sphere. Another change was the rearranging of the other instruments so that these could be quickly checked while giving primary attention to the attitude gyro. The improvement obtained suggests that, even with the present degree of stability, the helicopter can be flown without benefit of visual reference by making inexpensive changes in instrumentation. For example, flying at night in clear weather, even though all ground objects or marker lights are occasionally lost sight of, should be practical with the Coast Guard instrument arrangement. True instrument flight, however, involving navigation by radio signals, requires so much of the pilot's powers of concentration that improvement in stability and simplicity of control, as well as in the instrumentation, would seem essential.

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