Summary—Some of the problems of designing a helicopter control stick steering system are presented in this paper, and practical solutions are given to the problems involved in the integration of automatic and primary control systems.

# helicopter control stick steering

By LAWRENCE KAUFMAN

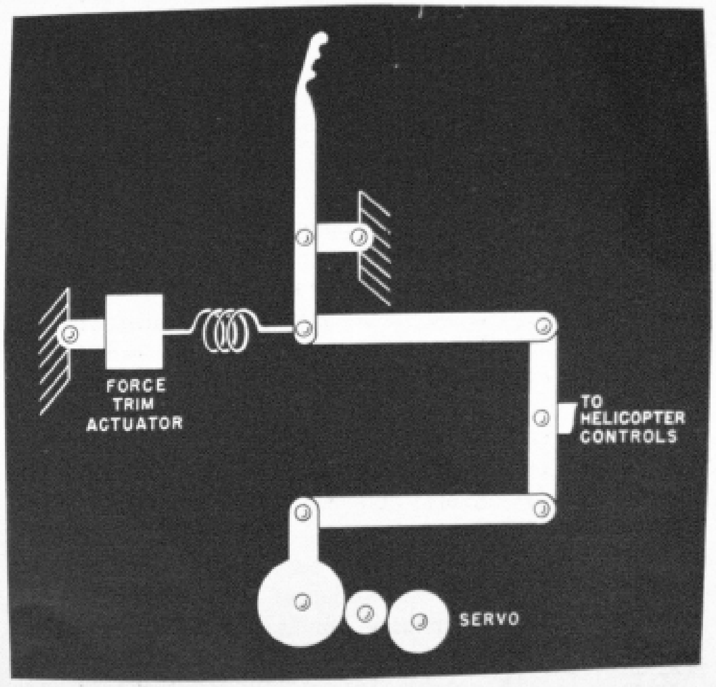
**Introduction**

Automatic control of helicopters has become increasingly important as the operational development of the helicopter has progressed and its inherent stability deficiencies have become more clearly recognized. Unlike the fixed-wing aircraft, which possesses a fair degree of inherent stability, the helicopter is quite unstable. The lack of sufficient inherent stability has not seriously impaired the operational utility of the helicopter under favorable visibility conditions, but has significantly retarded its development as an all-weather vehicle. Thus far, automatic controls have proved to be much more effective in overcoming instability than have attempts to build inherent stability into the aircraft.

One of the first successful efforts in the automatic control of helicopters had been completed by 1950 when Sperry demonstrated its A-12 Gyropilot® flight control on the Piasecki (now Vertol) HUP-2 helicopter. This installation was immediately successful and furnished a vehicle which was stabilized in pitch and roll attitude and in heading. Subsequent helicopter experience with the A-12, however, exposed a need for a different arrangement with respect to command functions. The A-12 system uses a knob operated controller through which the pilot inserts commands to change the reference attitude and heading of the aircraft. While this arrangement is entirely satisfactory in fixed-wing aircraft, it presents a problem in helicopter installations. The high inherent control sensitivity of the helicopter creates a situation in which the pilot is reluctant to remove his hands from the basic controls in order that he be prepared to cope with emergencies. Because he had to remove his hands from the Gyropilot controls to operate the A-12, the pilot was restricted in the degree of manual control he could superimpose on the operation of the automatic control system.

Most of the recent development efforts in the field of helicopter automatic control have accordingly been devoted to control stick steering wherein the human pilot inserts commands into the automatic system by applying forces to the manual controls. This requires a very thorough integration of the manual and automatic control systems. Of particular interest is the development of the differential control stick steering system. This paper discusses some of the leading design problems associated with a control system which will augment the stability of the helicopter without impairing the unique maneuvering characteristics of this type of aircraft.

Fig. 1—This sketch illustrates a simplified differential control stick steering system for helicopter automatic control. This type of arrangement permits pilot motion and servo motion to be summed.



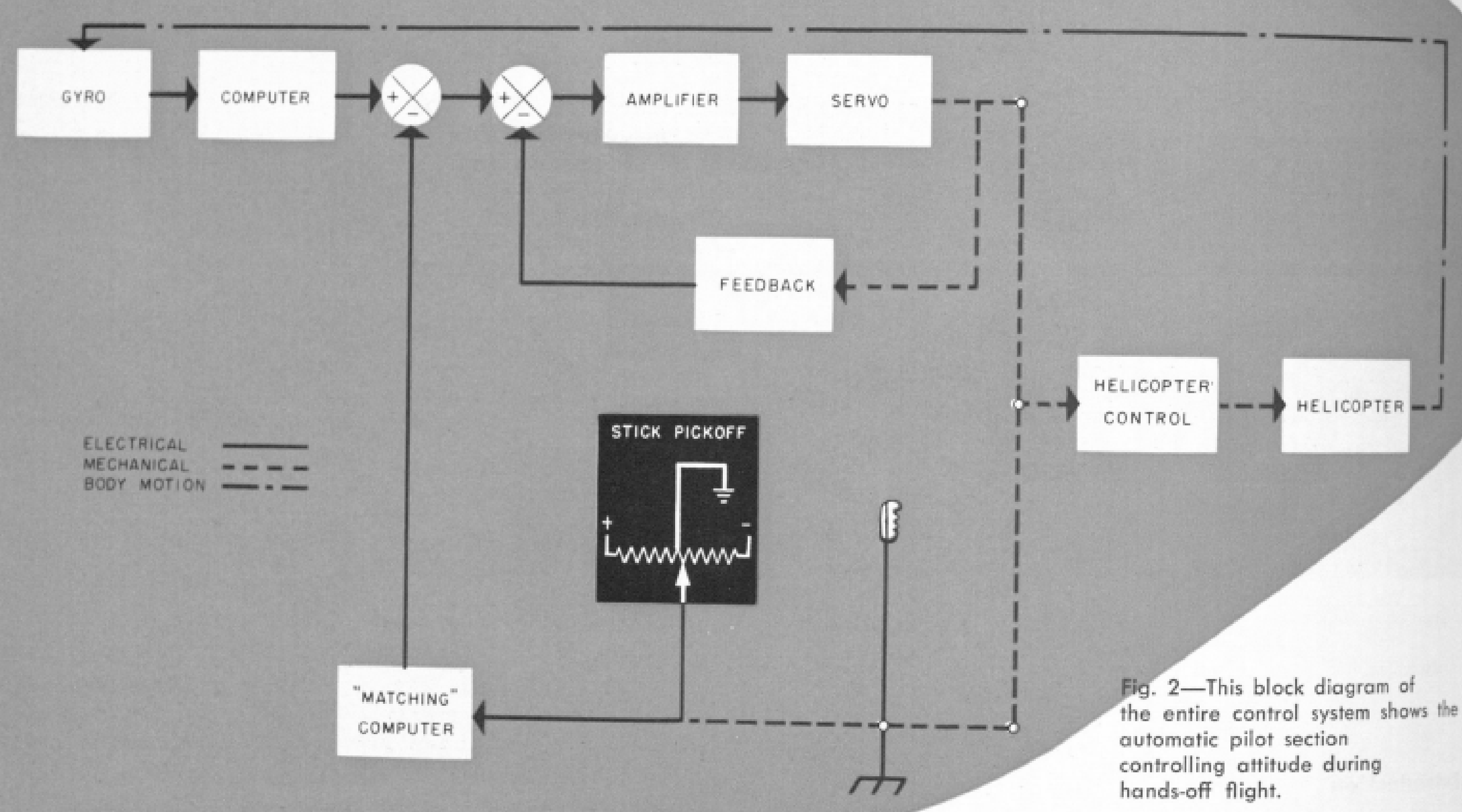



Fig. 2—This block diagram of the entire control system shows the automatic pilot section controlling attitude during hands-off flight.

## Differential Control Stick Steering System

In the differential control stick steering system (Fig. 1) the automatic control servo is connected to the helicopter swashplate (control surface) through a differential linkage in a manner that permits stabilization motions to be transmitted to the swashplate without causing movement of the pilot's cyclic stick (control stick). With this arrangement both pilot motions and automatic control servo motions are added to form the net swashplate motion. A simple system has thus been synthesized which integrates the basic control system and the automatic control system.

One serious problem is immediately apparent in the differential system. If the automatic control system should malfunction and drive the servo hardover in a given direction, the pilot could, at best, cancel this spurious motion by applying correcting motion in the opposite direction. Beyond this point, he would have no control in one direction. This potential difficulty may be largely eliminated by limiting the travel of the automatic control servo (servo authority) to a fraction of the total available control travel and by providing fail-safe mechanical centering devices which will quickly center the automatic control servo in the event of a system malfunction.

From this brief discussion it is apparent that a well designed differential control stick steering system should use a minimum amount of servo authority. Equally important in a successful design are adequate "hands-off" stability and good maneuver "feel." The following sections are devoted to a discussion of the design problems associated with maximizing hands-off stability and maneuver feel with a minimum of servo authority.

## "Hands-off" Stability

A large part of any practical helicopter flight is usually directed along some predetermined path. The automatic control system may be used under such conditions to maintain accurately the proper attitudes and heading. Hence, under hands-off flight the differential control stick steering system is reduced to a conventional automatic pilot which functions to maintain a prescribed attitude and heading. Fig. 2, which is a block diagram of the complete differential control system, shows the automatic pilot section of this system. This illustration shows that during hands-off flight the automatic pilot is the only part of the flight control system which is functioning and that, therefore, the characteristics of the automatic pilot must be established independently to satisfy the requirements for hands-off stability.

To examine requirements for hands-off stability, it is necessary to examine first the response characteristics of a typical helicopter. The pitch attitude response of the S-55 helicopter is shown in Fig. 3 over an airspeed range extending from hovering flight to 75 knots: roll and heading response characteristics are somewhat similar. (The characteristics of this helicopter are used throughout this paper since they are typical of modern helicopters.) The curves in this figure have been derived theoretically to correspond to the three speeds for which experimental data are available. Each of these responses is unstable. The stabilization which is possible by establishing suitable automatic pilot characteristics is shown in the frequency response of Fig. 4. To obtain this stabilization the automatic pilot is set up with feedback gains of about one degree of cyclic stick per degree of pitch attitude error and about one degree of cyclic stick

Fig. 3—The frequency response of a typical modern helicopter is given in these curves for pitch attitude over an airspeed range of 75 knots. The design of an automatic pilot must be based closely on these response characteristics.

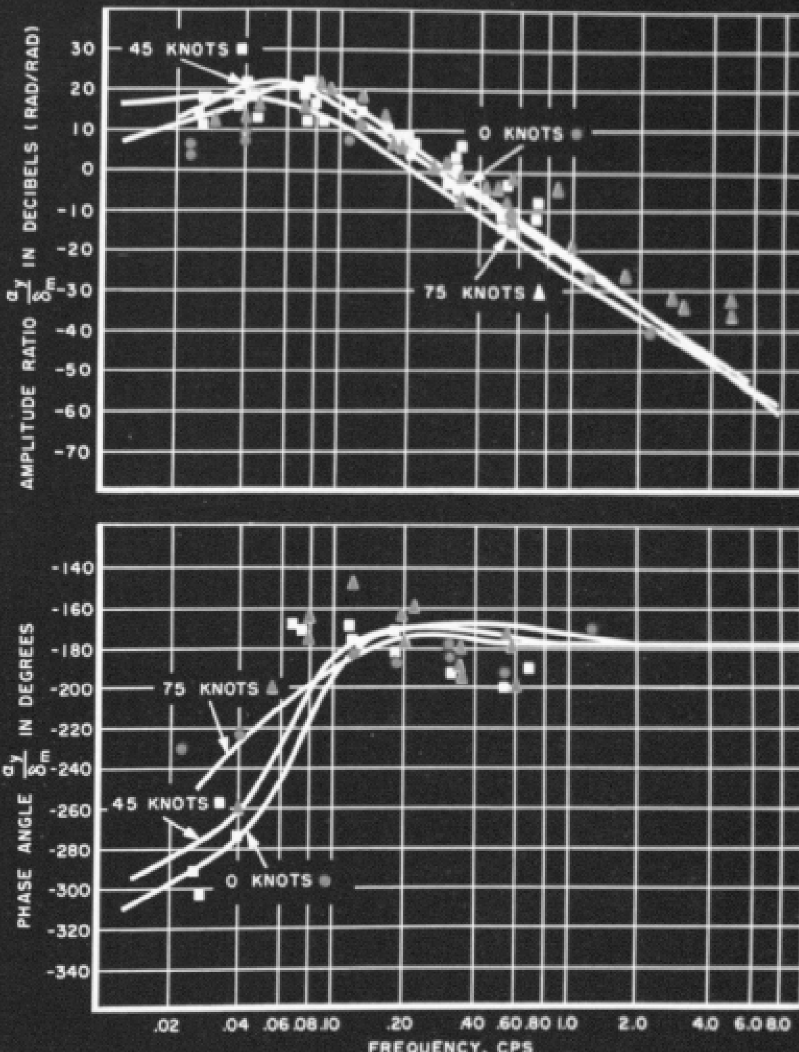
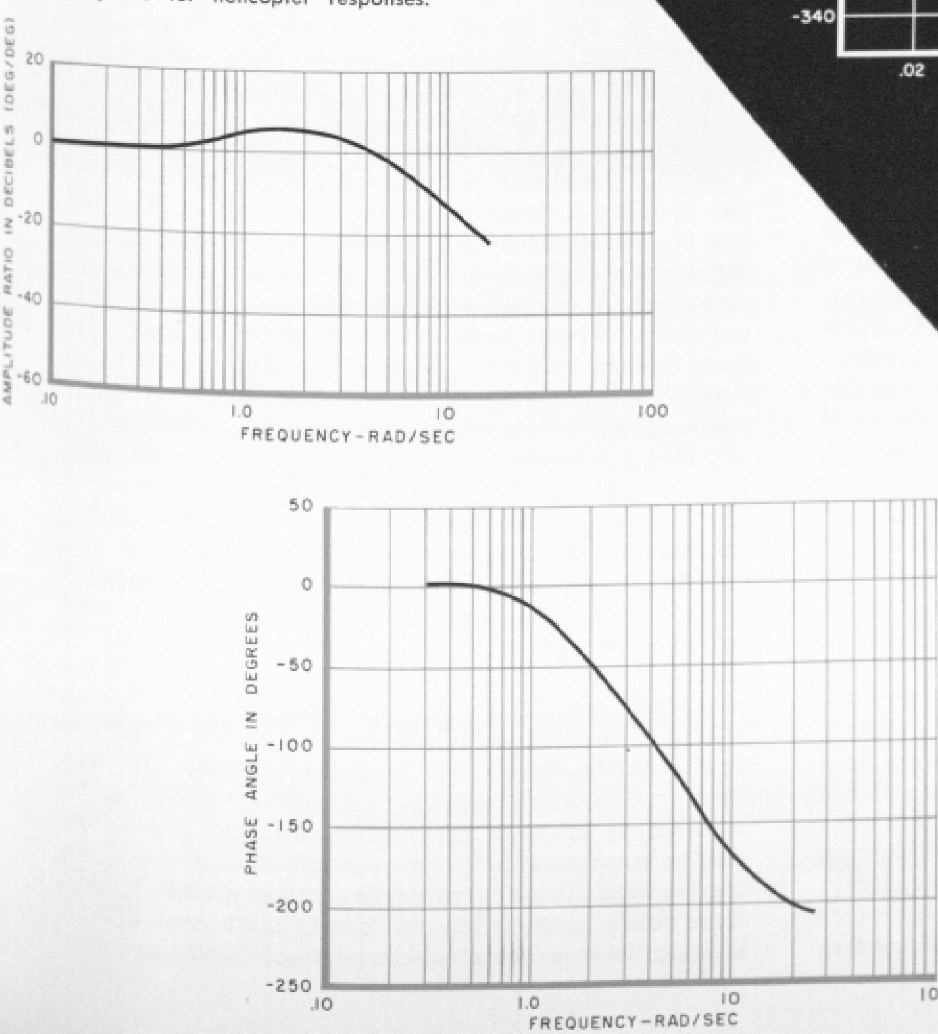



Fig. 4—The pitch axis frequency response curves shown here demonstrate clearly the high degree of stabilization possible when an automatic pilot is properly designed with characteristics appropriate for helicopter responses.



per degree per second of attitude rate. An S-55 helicopter has, in actual practice, been equipped with an experimental automatic pilot to achieve the dynamic response shown in Fig. 4. When operated in this fashion, helicopter dynamic attitude accuracy has been maintained within one quarter of a degree, even in pronounced turbulence.

Fig. 5—The man-machine combination involved in the analysis of maneuver stability requirements is illustrated in this simplified block diagram.

### Maneuver Feel and Stability—General Considerations

The preceding section has treated the behavior of the automatic control system when it is merely functioning as a conventional autopilot, and the section has illustrated how a properly designed automatic pilot subsystem can transform the helicopter into a stable vehicle. In the previous paragraphs the requirements for the automatic pilot have been shown to be quite similar to those for a fixed-wing aircraft autopilot, i.e., both aircraft require feedback proportional to attitude error and rate of attitude change. The new problem areas in the differential control stick steering system lie outside the automatic pilot subsystem and are associated with the concepts of maneuver feel and maneuver stability.

To understand these problems it is necessary to recall the differential servo arrangement which was illustrated in Fig. 1. In this arrangement the total control motion transmitted to the swashplate is the algebraic sum of the servo travel and the pilot's control motion. The servo motions are a result of attitude deviations from a selected reference attitude, with the automatic pilot functioning continuously to restore the helicopter whenever it is disturbed. It is apparent, therefore, that whenever the pilot inserts a control motion through the cyclic stick, the resulting automatic pilot correction will tend to oppose this command. With no compensation for the automatic pilot in maneuvers, the human pilot would experience reduced control effectiveness, i.e., from each unit of his own input would be subtracted the automatic pilot opposition. To prevent, or rather control, this opposition to the pilot's command, it is necessary to introduce a signal to "match" (or cancel) the signal generated by the automatic pilot sensor (gyro). In addition to fulfilling the need for proper matching as a means of achieving satisfactory maneuver feel, this method will also allow the use of a minimum amount of servo authority, as will be shown later. In the absence of adequate matching the opposing servo motion caused by the pilot's command would require relatively large servo authority to prevent prolonged bottoming of the servo in maneuvers.

To achieve effective cancellation of the automatic pilot signal, it is necessary to introduce a bucking signal derived from the pilot's cyclic stick as shown in Fig. 2. For complete cancellation the signal would have to pass through a computer which exactly simulates the attitude response of the helicopter to cyclic stick motion. The requirements for this computer could be eased by restricting the computer simulation to a frequency range consistent with the capabilities of the human pilot which lie between zero and about 0.5 cps. Even this simplification, however, would require a rather complicated computer as indicated by the frequency response of the helicopter shown in Fig. 3. Fortunately it is undesirable as well as impractical to achieve complete cancellation. Complete cancellation during maneuvers would indicate complete ineffectiveness of the automatic control system in imparting maneuver stability. The ideal matching computer should be designed to effect the best over-all compromise between feel, authority, and maneuver stability.

In order to select the matching computer characteristics effectively, it is necessary to define the maneuver stability requirements of the flight control system. Such a definition can be made only if the over-all system, consisting of the human pilot, the flight control system, and the helicopter, is analyzed. The following section is devoted to such an analysis.

### Analysis of Maneuver Stability Requirements

The purpose of this analysis is to consider the combination of man (pilot) and machine (helicopter plus automatic controls) to determine the maneuver stability requirements for the automatic flight control system. This analysis is limited to exclude two fields. The first of these involves the physiology of flight which includes a study of the pilot's environment and the measures that can be taken to improve his physical comfort. The second field which is excluded covers the so-called human engineering problems: display of system elements, arrangement of cockpit controls, etc. Exclusion of these two fields in this analysis is not intended to imply that these are not important fields of investigation, but that they are of secondary importance for the specific problem considered here. The primary field covered is the role that the human pilot plays in a closed-loop control system of which he is one of the dynamic elements.

The man-machine combination which is considered in this analysis is illustrated in Fig. 5. The machine is represented by some transfer characteristic $M$ determined by the basic vehicle (the helicopter) and the automatic stabilization equipment. The pilot is characterized by a general transfer characteristic $P$, which converts errors sensed into force commands applied to the machine.

A great deal of work has been undertaken to provide the approximations which predict dynamic response of the pilot under various control situations. The investigations have, in many cases, produced interesting results since they have been based on a study of the sensing and actuating properties of the human.[1] While these data are available, they are in most cases difficult to apply because the characteristics of the human vary

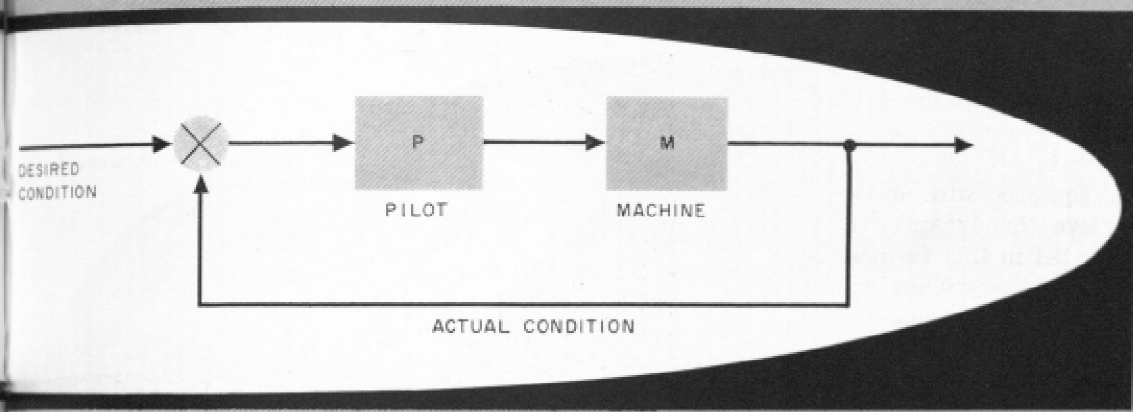
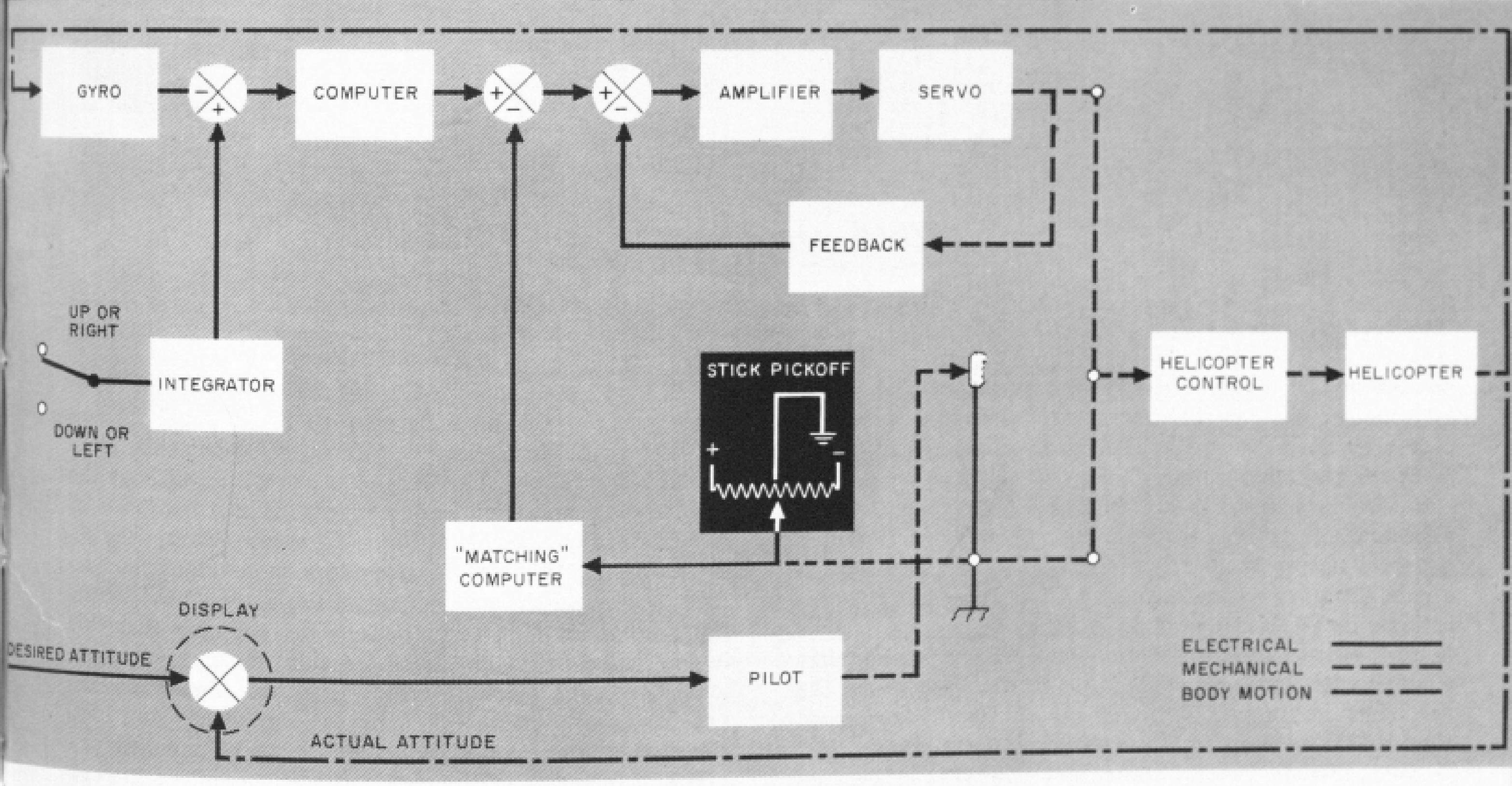



Fig. 6—The basic differential command system has been modified here to include the pilot in the diagram. Pilot operates the stick on the basis of attitude errors displayed on gyro horizon.




significantly with the kind of task he is trying to perform. It is difficult, if not impossible, to produce any results which can be generalized. One may, however, resort to an inverse procedure to determine the adequacy of a system based on minimum utilization of the human operator. Stated another way, the dynamic characteristics of the human operator can be specified from a "least work" point of view to determine if the machine can be operated successfully under these conditions.

It is a well-known fact that the human operator can operate as a very skilled control element. Experimental evidence is available which indicates that he can successfully provide integral, proportional, and rate feedback to provide effective control over a variety of machines under a variety of external conditions. It is also well-known that when he is operating at a high skill level, his burden is correspondingly high and his ability to share his activity over a number of functions diminishes. It has been stated that a "man-machine continuous control system should be designed so that the task of the operator is . . . whenever feasible, no more complex than that of analog amplification,"[2] i.e., the operator will sense an error and provide a control force whose magnitude is proportional to this error. A second principle is that the system should be designed so that a bandpass of less than three radians per second (approximately 0.5 cps) is required of the pilot.[2] This latter principle roughly takes into account both the sensing and actuating lags of the human pilot.

The control stick steering system may be analyzed using these basic design principles. The pilot may be assumed to have ideal transfer characteristics from a "least work" point of view, viz., an amplifier having a bandpass of less than three radians per second. These characteristics are applied to the helicopter automatic control system to determine its adequacy.

Fig. 6, a modification of Fig. 2, presents a block diagram of the differential command system. The modification consists of the insertion of the human pilot into the control loop. The problem under consideration is not that of the helicopter under stabilized hands-off flight conditions inasmuch as the pilot is not an active part of this control loop. In this role he acts only as a monitor. The problem which is of concern here is the ability of the pilot to change his established flight conditions easily. (By "easily," it is meant that he can operate as an amplifier with a bandpass of less than three radians per second.) The loop is constructed with the basic input as

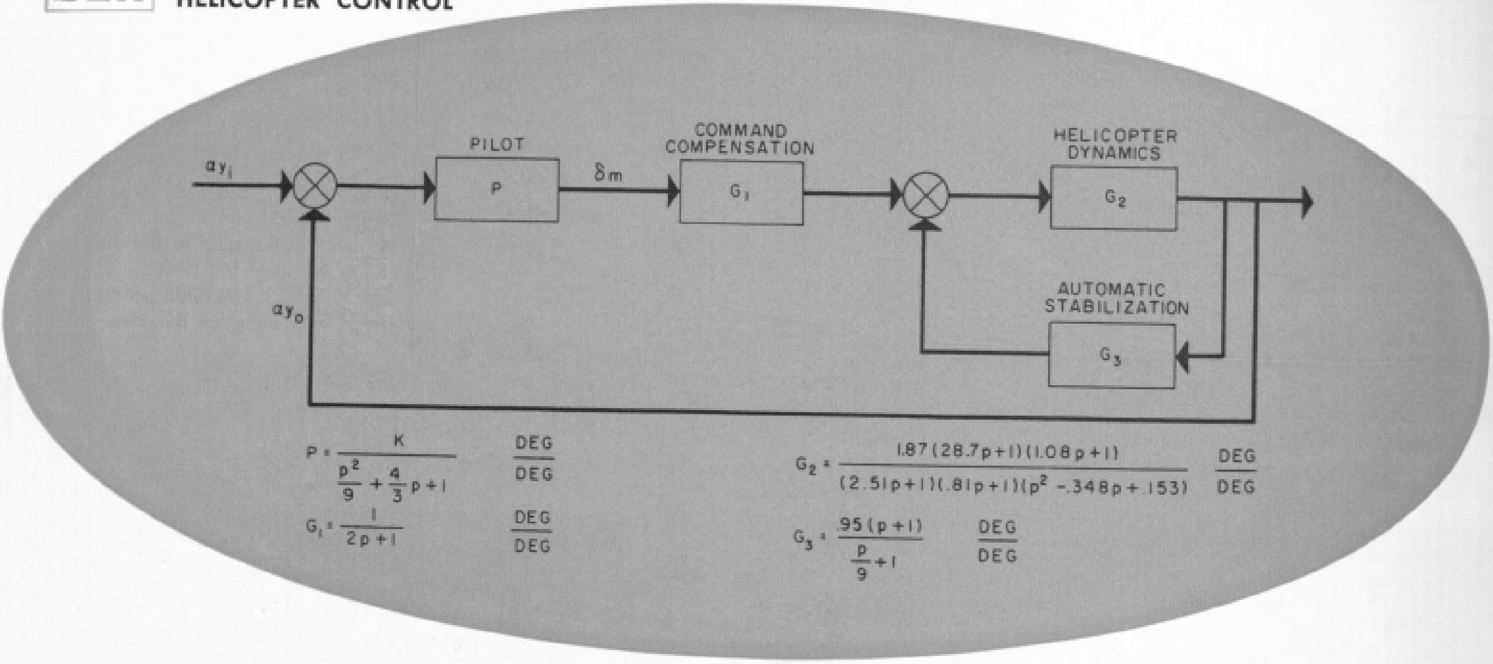



Fig. 7—This simplified block diagram presents the combination of the pliot, helicopter, and differential command system for ease of analysis. The command compensation characteristics include both the automatic control transfer characteristics and the uncompensated, direct pilot inputs.

a pilot-applied force $F$ and the basic output as a pitch attitude $\alpha_y$. (In this helicopter control system, where a centering spring is used, pilot force and stick displacement are used interchangeably.)

Several assumptions are implicit in Fig. 6: (1) the pilot is obtaining his attitude data from a source which provides nothing but displacement information; for example, from a gyro-horizon under instrument flight conditions, and (2) the pilot is not accepting cues derived from his sense of equilibrium. These assumptions, when coupled with the major design principles, imply that the pilot has minimum skill and experience. This method then would tend to produce conservative results.

Another more general assumption is used in this analysis. Both the response of the man and the machine are linearized, making the analysis valid for small displacements only.

A simplified diagram representing the machine elements of Fig. 6, in condensed form, is presented in Fig. 7. It has been noted previously that the autopilot characteristics $G_3$ are established on the basis of hands-off stability requirements. The command compensation characteristics $G_1$, which are of primary concern in this analysis, include both the direct pilot input as well as the compensated, or matched, component. The helicopter characteristics $G_2$ are obtained from Fig. 3 for the S-55. Consistent with the basic design principles used in this analysis, the pilot transfer function is represented by an amplification with a bandpass of three radians per second.

If the matching computer is assumed to provide a simple time lag, analysis leads to the stability curve shown in Fig. 8. Also shown on this diagram is a curve using the same transfer function $P$ for the pilot, but with no stabilization equipment. In both cases the pilot static gain characteristic is set equal to unity, i.e., for one degree of attitude error the pilot moves the cyclic stick one degree ($K = 1$).

In Fig. 8 it is evident that the use of the automatic stabilization equipment with the simple matching computer permits the pilot to operate in an ideal fashion without encountering any instability under this pitch attitude command task. On the other hand, without the stabilization equipment, pilot operation in a "least work" capacity is not possible because an unstable response results. Hence, this simple example demonstrates the sufficiency of, and the necessity for, the control stick steering system for this task. It does not indicate that this is the optimum system or that a more efficient arrangement, in which machine complexity and pilot work load are better apportioned, is not possible. The considerations of system optimization will best be handled empirically in terms of the over-all development of the art.

It is now of interest to study the servo authority requirements which would exist in a system which is synthesized according to Fig. 2. These are discussed in the following section.

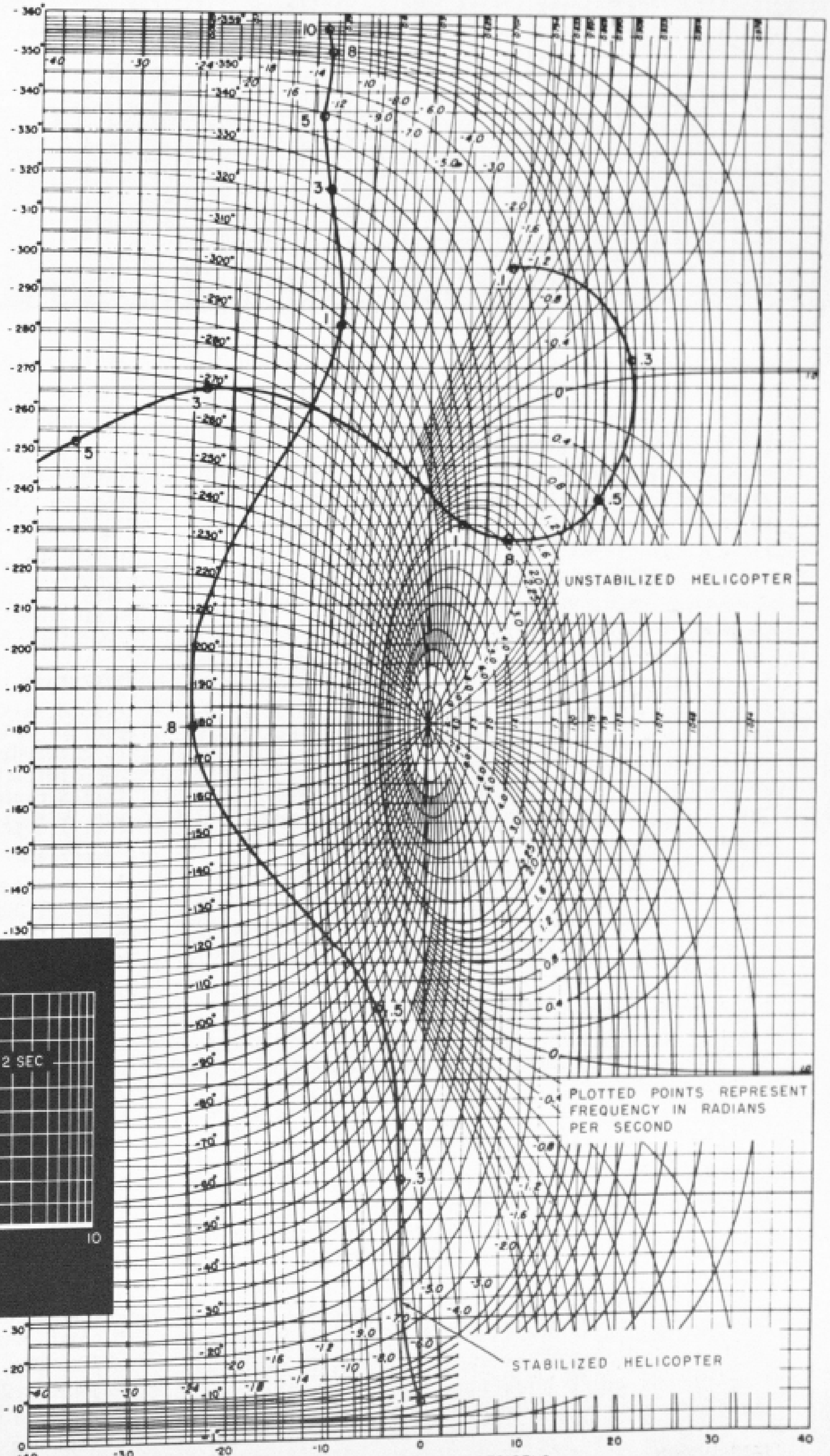
## Authority Requirements

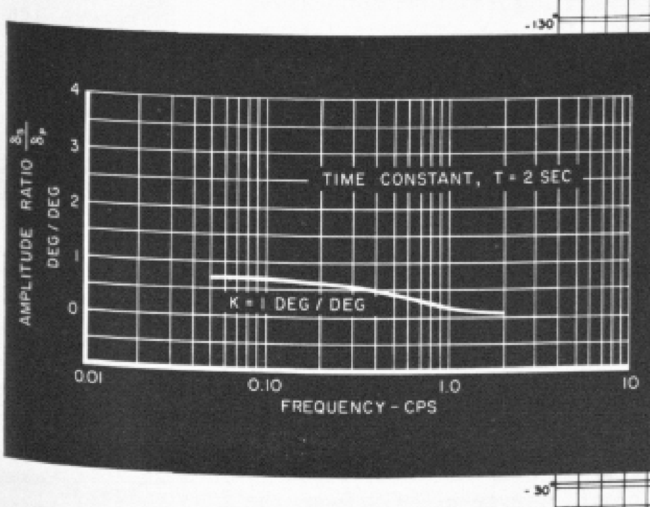
The preceding section has treated the maneuver feel requirements of the control stick steering system and has demonstrated that a simple system can be synthesized which can lead to stable maneuver characteristics. It has also been shown that this satisfactory maneuver feel can be achieved without compromise of autopilot or hands-off stability requirements. There is only one remaining question: can the servo authority be kept reasonably small with such a system configuration?

By carrying out a frequency response analysis of the complete system it is possible to determine what amplitude magnification exists between pilot stick motions and the autopilot servo. Fig. 9 has been prepared, from the same characteristics used in Fig. 7, to show the relationship between pilot stick motion and autopilot servo motion. In this figure, for the usual pilot input frequencies (about 0.2 to 0.5 cps), the servo amplitude is less than 50 per cent of the pilot applied stick motion. This would indicate that 50 per cent authority would

The stability curves in Fig. 8, right, present graphic evidence of the necessity for stabilization in a system if the pilot is to operate at the "least work" level.

Fig. 9, inset below, shows that the response of the automatic control servo to pilot input motions may be kept quite small. This permits the use of limited servo authority.



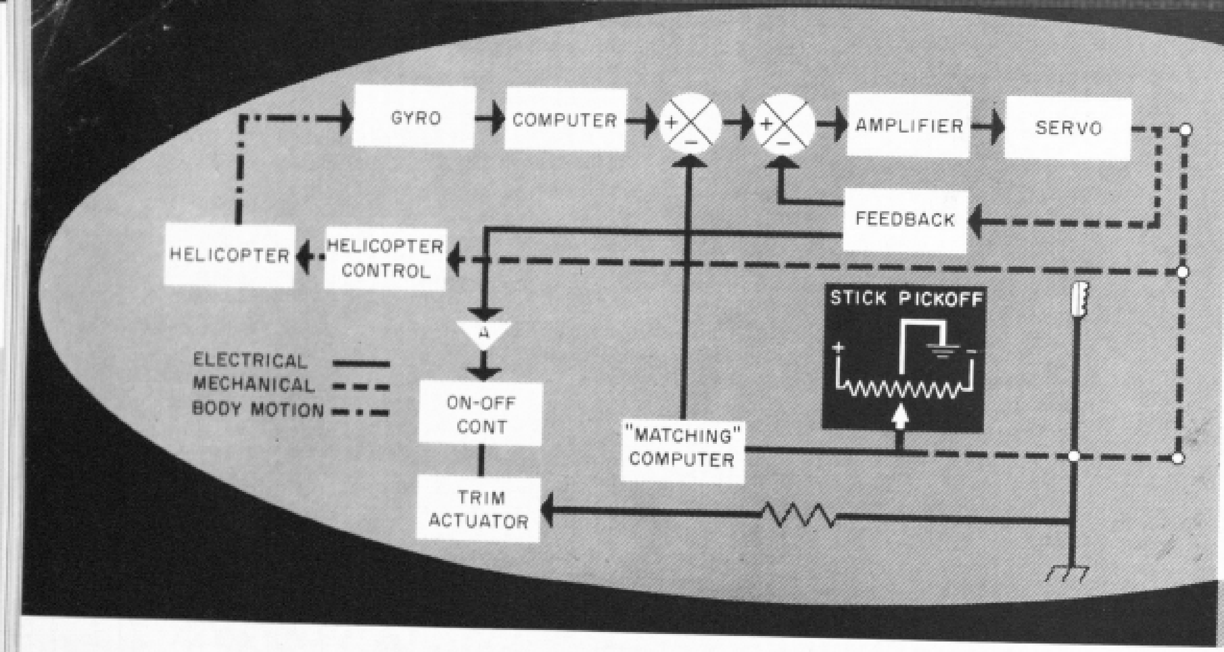



Fig. 10—A special problem of servo bottoming with large trim changes is overcome by the automatic trimming system shown in this block diagram.

provide sufficient servo travel to prevent servo bottoming for all typical pilot maneuvers. If temporary bottoming can be tolerated (and this has been found to be the case in flight test), the servo authority can be reduced below this 50 per cent level. In practical designs which are operational today, servo authorities as low as 20-25 per cent have been used. In such installations only extreme maneuvers will cause servo bottoming.

It is also evident from Fig. 9 that on a static basis (frequency approaching zero) the amplitude ratio between servo motion and pilot motion approaches 70 per cent. This indicates that, for large trim changes, permanent bottoming of the servo would be quite likely with only 25 per cent authority. This discrepancy can be removed by providing an automatic trimming system which will slowly trim the pilot's control to such a position as to recenter the automatic control servo. A system of this type has been successfully flight tested by Sperry. The automatic trim function is achieved by operating a single-speed trim motor connected to the pilot's control stick whenever the automatic control servo has exhausted a small fraction of its total available travel. A schematic block diagram of the automatic trim system is presented in Fig. 10.

## Problems in Tandem Helicopters

All of the discussion to this point has been based on the single rotor helicopter of the S-55 type. The ability to effect satisfactory compromises in stability, feel, and authority for this type of aircraft is, to a large measure, a consequence of a well defined, almost linear, relationship between attitude and stick position. This is not at all the case in the tandem helicopter in which the interference effects between forward and rear rotors destroy the desirably linear attitude-stick relationship. In this case it is obvious that a rather complex and impractical computer would be required to match properly the pilot and autopilot inputs. In flight test it has been found that the most practical compromise involves little or no matching. Consequently either large servo authority or prolonged servo bottoming in maneuvers must be tolerated.

## Conclusion

The successful design of control stick steering systems for helicopters requires that several conditions must be satisfied simultaneously. These requirements include hands-off stability, maneuver stability, maneuver feel, and servo authority. Several designs which are currently in use have proven that these requirements can be met in a practical manner and that automatic controls have extended the operational capabilities of helicopters. Flight under instrument conditions is now a reality for helicopters.

The work described in this paper was performed for the Signal Corps Engineering Laboratories, U. S. Army, under contract number DA-36-039 SC-72412.

## References

[1] R. G. E. Epple, *The Human Pilot*, Bureau of Aeronautics Report AE-61-6 III (August, 1954).

[2] H. P. Birmingham and F. V. Taylor, "A Human Engineering Approach to the Design of Man-Operated Continuous Control Systems," Office of Naval Research Symposium Report ACR 11 (October, 1955).

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