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STUDY OF AUTOMATIC CONTROL SYSTEMS
FOR AIRCRAFT

FINAL REPORT, PHASE I

10-1-55

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Honeywell

Aeronautical Controls

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Security Information

STUDY OF AUTOMATIC CONTROL SYSTEMS
FOR HELICOPTERS

FINAL REPORT ON PHASE I

M-H Aero Technical Report AD 5143-TR8
Contract Nonr-929(00)

31 July 1953

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This document has been reviewed in accordance with
ENAVINST 5510.17 paragraph 5. The security
classification assigned is correct.

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FOREWARD

This report was prepared by the Research Department, Aeronautical Division, Minneapolis-Honeywell Regulator Company, in accordance with the requirements of Navy Contract No. Nonr-929(00), administered by the Office of Naval Research. The contract was initiated under the research project identified by Expenditure Accounts 46000 (Research Navy) and 46832 (Aircraft and Facilities Navy). This is a contract for research involving the study of helicopter control systems from the point of view of automatic control of attitudes and power. Phase I of this study (for which this is the final report) has been supported by the above contract, which commenced on 15 June 1952 and expires on 31 July 1953. It has been proposed that the next phase of research under this program be supported by the Navy under a continuation of the Nonr-929(00) contract, beginning 1 August 1953.

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ABSTRACT

Under Phase I of the Study of the Automatic Control Systems for Helicopters, the foundations were developed for the analytical determination of automatic control system design criteria. These foundations consist primarily of the theoretical equations describing (1) the transient motion of a hovering, single-rotor helicopter with rotor RPM degree-of-freedom, and (2) the dynamical characteristics of reciprocating and single-spool turbo-prop engine types. In addition, the mechanization of the control system transfer function has been investigated from the view-point of incorporating in the dynamical analysis the characteristics of high-performance components requiring a minimum of additional development.

Also discussed here are several topics remaining under investigation or otherwise not completed at the Phase I termination date (31 July 1953). These include the study of forward-flight transient motion, the initial phases of the complete closed-loop control study, and the REAC study of rotor RPM control in hovering for the case of the turbo-prop engine.

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I INTRODUCTION

The general task with which the present research program was initially confronted was the determination of desirable closed-loop transfer functions for helicopter automatic control systems. These systems were to be of the pilot-relief variety and were to perform the functions commonly associated with an autopilot and a rotor (or engine) RPM governor. While helicopter autopilots and RPM governors were in existence prior to the inception of this study, it had not been determined whether the designs of these controls were optimum from the standpoint of the net performance of the helicopter. In particular, it appeared that previous developments had ignored the possible inter-relationships between transients in rotor RPM and rolling and pitching motions of the aircraft. It was therefore indicated that a study be made to establish the criteria for the design of high-performance automatic control equipment for helicopters, with emphasis on the possibility of integrating the action of autopilot and rotor RPM governor.

The helicopter configuration chosen by mutual agreement for initial consideration under this program was the single main-rotor type with the torque-compensating tail rotor, and powered by a single-spool turbo-prop engine. In accordance with the aforementioned objective of studying the effects of cross-coupling between transients in rotor RPM and helicopter motions on the design and operation of automatic controls, it was necessary to develop the theoretical equations for the dynamical analysis on this basis. As for the turbo-prop engine, it was necessary to establish the acceleration characteristics for the particular unit chosen as the investigation model.

An additional consideration at the outset was the desire to explore the value to the present study of the comparatively new Root Locus method of feedback analysis. This technique was applied in the investigation of rotor RPM control based on relatively simplified flight conditions (see Section V). Of course, also available at Minneapolis-Honeywell as a tool for the analysis of closed loop servo systems, is the REAC analog computer, which was employed in the same investigation as above.

The program of study experienced several alterations in schedule from that originally set up. These had to do primarily with the interest expressed by the Bureau of Aeronautics mid-way in Phase I in having this work give early consideration to the control problems of the helicopter with reciprocating engine, especially for the ASW-type of mission. The effort on the turbo-prop engine was consequently suspended prior to completion. The theoretical determination of the dynamical characteristics of the piston-type engine was then undertaken

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simultaneously with efforts to secure corresponding experimental data from the Aeronautical Engine Laboratory, Naval Air Material Center.

With the development of the equations of motion for the helicopter and the theoretical estimate of the transient behavior of the reciprocating engine, the servo analysis was initiated by a detailed consideration of the means for mechanizing the error sensing, control actuating, and other elements of the closed-loop feedback systems. The status of this work is included in the discussions of Section VI.

The preceding statements were intended to provide an overall picture of the program of activities in Phase I of this study. The sections to follow will discuss this work at greater length, although those topics for which Interim Reports have been issued are only briefly described here.

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II REVIEW OF PRIOR ART

2.1 STUDY OF THE LITERATURE

2.1.1 Basic Helicopter Dynamics

A thorough survey has been made at Minneapolis-Honeywell of the available literature in the field of helicopter dynamics. From the standpoint of the present study, the obvious question at the beginning was whether there already existed the necessary transient data for the helicopter in the form desired for the present application. In particular, there was the problem of including in the theory the effects of variable RPM of the rotor. It was also desired that a perusal of the literature be made for the purpose of determining which theories, experiments, etc., were likely to be most useful in guiding the present development in the event that new stability equations had to be derived.

Presented in Appendix A is a bibliography, arranged chronologically, of the documentation examined during the initial phases of the present research project. The list does not include reports dealing primarily with vibration or flutter, nor material which was very recently received and, therefore, had little influence on the developments reported here.

The theory for helicopter dynamics has progressed to a relatively advanced state but for the most part remains without experimental corroboration. Regarding the effect of transients in rotor RPM, previous investigators chose to neglect this effect in their evaluation of helicopter dynamics.

2.1.2 Helicopter Autopilot Development

The reports on earlier work in this field are included in the bibliography in Appendix A. Every effort has been made to benefit the present effort by the experiences of prior developments. Here again, however, the scope of these previous projects was of a more limited nature than that planned here.

2.1.3 Helicopter Rotor RPM Control

A bibliography of previous work in this field is presented in Appendix B. A study of these reports has indicated that a need exists for the establishment of basic theoretical criteria for the design of these controls, including a determination of whether some coupling with the helicopter attitude stabilization system is desirable.

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2.2 SURVEY TRIP

In Interim Report AD 5143-TR1, Reference (1), are presented the results of a survey trip made to secure up-to-the-minute information on various aspects of helicopter automatic control problems. Quoting from the Abstract of Reference (1),

"Research personnel of the Aeronautical Division have completed a program of visits to a group of facilities concerned with helicopter flight control and helicopter engine control. The purpose of these visits was to learn at first hand whether certain information was available at these facilities which could be utilized in the research study under Contract No. Nonr-929(00)—hereinafter referred to as the subject contract or subject study. The information desired included dynamic and static stability derivatives, steady state and transient engine characteristics, pilot opinions on and desires for helicopter handling and flying qualities, and suggestions as to the analytical methods which should be employed in the subject study. This report is a compilation of the information received during the course of the several visits described herein."

The reader is referred to the above report for further details.

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III EQUATIONS OF HELICOPTER MOTION IN HOVERING

Inasmuch as the review described in Section II had indicated that the theoretical equations for helicopter motion had not been previously derived as required for the present study, it was evidently necessary to provide such a development here. This work has been described in three previous Interim Reports, References (2) - (4). The abstracts from these reports are reproduced below:

A. AD 5143-TR2: "A review is presented of the problem of the induced velocity at the rotor of a nominally-hovering helicopter which is undergoing transient motion. It has been suggested that the variation of induced velocity occurring during the disturbance experienced by the helicopter may have a significant effect on the transient motion of the helicopter. It is noted, however, that it has been almost universal practice to ignore the effects of variations in the induced velocity in studying helicopter dynamics, because of the additional labor that would be required to evaluate and include these effects. It is concluded that the effort under Contract No. Nonr-929(00) must of necessity be similarly limited, but it is suggested that the Office of Naval Research consider this problem as worthy of a separate research project for University research personnel, or the National Advisory Committee for Aeronautics."

B. AD 5143-TR3: "This report contains the development of the theoretical equation for the aerodynamic torque absorbed by a helicopter rotor which is experiencing transient disturbances in RPM while the helicopter is hovering. Inasmuch as the dynamical equation for torque was found to include the effects of the simultaneous transients in blade coning angle and vertical velocity of the aircraft, it was necessary to derive auxiliary equations defining these additional variables, and these equations are also shown here."

The system of equations derived in this report is required in the analytical study of controls for automatic regulation of helicopter rotor RPM."

C. AD 5143-TR7: "This report contains the development of the theoretical equations defining the motions of a helicopter experiencing transient disturbances from steady-state hovering. Included in this treatment of helicopter motion is the consideration of the influence of simultaneous transients in rotor RPM. The helicopter chosen for this study was of the single main rotor type, employing a tail rotor for torque compensation."

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On the basis of the linearized analysis, it was established that, while variations in rotor RPM do not couple directly with pitching and rolling motions, by virtue of the action of the tail rotor a secondary type of coupling was found to exist between the aforementioned variables."

While Report -TR7 has included in a more generalized way the material in Report -TR3, the latter report provided the equations on at least an approximate basis for an early attack on the rotor RPM control problem. By thus postponing the consideration of autopilot-RPM coupling requirements, it was possible to gain considerable insight into this problem with a minimum of complication.

The details of this phase of the study effort can be obtained from the aforementioned Interim Reports.

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IV DYNAMICS OF HELICOPTER ENGINES

4.1 TURBO-PROP ENGINE (SINGLE-SPOOL)

The representation of the engine transfer function was determined largely from a study of the reports of the NACA dealing with this subject. Of principal importance in this connection were References (5) and (6). The theoretical transient characteristics obtained from this examination as well as the experimental data (taken from Reference 7) used therewith have been presented in Interim Report -TR4 (Reference 8). As it finally was employed in the present analysis, the transfer function for the single-spool turbo prop engine was characterized by two cascaded, first-order time lags; the first was representative of the delay time between fuel valve actuation and energy availability, while the second was related to the inertia characteristics of the rotating system.

4.2 RECIPROCATING ENGINE (SINGLE STAGE SUPERCHARGER)

The study of piston engines requires first that dynamic equations of motion be derived for the purpose of analysis or simulation. The following is a discussion of the assumptions and decisions made in obtaining the resultant relationship between throttle change and rpm change.

Inasmuch as the determination of the piston engine dynamical characteristics (and the simulation thereof) is accomplished in a more amenable fashion by experimental rather than theoretical means, it was desired to survey the availability of such experimental data (Reference 1). According to the engine manufacturers, no data of the type sought were available. It was therefore concluded that two courses of action were open: (1) obtain the engine dynamic equations mathematically, and (2) set up an engine test program and obtain the equations experimentally. Both courses were adopted and results thus far obtained are given below.

Because the interest here in the piston engine concerns the dynamics between throttle input and RPM output, it was quickly determined that at least one lag would exist because of engine inertia. Whether other lags exist was not immediately obvious. The basic problem here was to determine the dynamic relationship between throttle and engine torque, since the lag mentioned above determines the dynamics between engine torque and RPM. Taylor and Taylor, on page 155 of Reference (9), discuss the problem of delay in acceleration after throttle increase. Apparently some of the additional fuel is not immediately vaporized, but rather flows slowly along the manifold walls, delaying the realization of the required torque

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associated with the throttle change. Partial compensation for this phenomenon is generally obtained through use of accelerating wells which add additional fuel during accelerations. During deceleration the excess fuel which is flowing along the walls causes temporary delay in reducing engine torque output, while this latter phenomenon is of little concern in most instances, for precise RPM control of a helicopter it would appear that some consideration should be given to this deceleration phenomenon. Consequently, further knowledge on this subject was sought from various authoritative sources (References 10-14) which treat the general subject of engine testing, but no new material was derived.

Several reports on the control of piston engines are based on the assumption that no lag exists between throttle and torque; e.g., in a recent report (see Reference 15) the assumption is made that engine torque responds to throttle motion without lag. On the other hand, other reports give the impression that additional lags are important; e.g., in Reference (16) which discusses automobile engine acceleration tests run for the purpose of determining what additional fuel should be injected during acceleration, a number of curves are presented from which it appears that a lag of $1/(1s + 1)$ should be included in the analysis. Reference (17) which contains a dynamic analysis of a turbo-supercharged engine discusses a lag chosen as $1/(.5s + 1)$, which represents the lag in changing the flow of fuel air mixture, and also a lag representing the time required for the gas to enter the engine and develop the associated torque. The only feasible means of determining whether such lags do indeed exist on the R1820-84 engine (chosen as the vehicle for this study) is by engine acceleration tests. AEL is equipped to run such tests and have scheduled same for early September, 1953. Because an R1820-84 engine is not readily available, an R1820-74 which is available is being substituted. From a dynamics standpoint the two engines are similar. The engine tests will also include the dynamics of the supercharger which must be included in the present analysis. Inertia of main rotor, tail rotor, gear box, etc. will be simulated by appropriate inertia on the engine shaft.

With the above considerations in mind an equation expressing the dynamics of the engine was derived, assuming that the AEL test data would be available at some future date to supplement or modify the present analysis. The development of this equation follows.

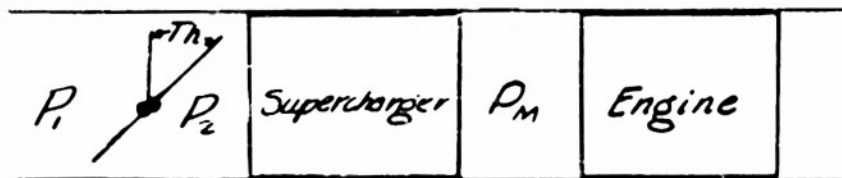


FIGURE 1

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The basic equation expressing the acceleration of the rotor and engine system is

$$\Delta Q_e - \frac{\Delta Q_A}{R_1} = I_{TOT} \Delta \Omega \quad (1)$$

where

ΔQ_e = change in engine torque output
 ΔQ_A = change in rotor load torque
 I_{TOT} = total moment of inertia
 $\Delta \Omega$ = change in engine RPM
 R_1 = engine to rotor gear reduction

The moment of inertia I_{TOT} is composed of I_R , I_E , and I_C , the moments of inertia of the rotor, the engine, and the compressor, respectively.

$$\text{Now } I_{TOT} = I_e + \frac{I_R}{R_1^2} + \frac{I_C}{R_2^2}$$

where R_1 and R_2 are gear reductions between engine and rotor, and engine and compressor, respectively.

ΔQ_A is determined as a function of those variables having a bearing on the aerodynamic load of the rotor, while ΔQ_e is expressed as a function of manifold pressure change and engine RPM change, as given normally by performance curves. The latter relationship can be written as:

$$\Delta Q_e = \left. \frac{\partial Q_e}{\partial P_M} \right|_{\Omega} \Delta P_M + \left. \frac{\partial Q_e}{\partial \Omega} \right|_{P_M} \Delta \Omega$$

Writing $\left. \frac{\partial Q_e}{\partial P_M} \right|_{\Omega} = A_1$ and $\left. \frac{\partial Q_e}{\partial \Omega} \right|_{P_M} = A_2$ there results

$$\Delta Q_e = A_1 \Delta P_M + A_2 \Delta \Omega \quad (2)$$

Referring now to Figure 1, the following equations may be written:

$$\Delta P_M = B_1 \Delta P_2 + B_2 \Delta \Omega \quad (3)$$

where

ΔP_M = change in manifold pressure,
 ΔP_2 = change in compressor inlet pressure,
 $B_1 = \left. \frac{\partial P_M}{\partial P_2} \right|_{\Omega}$,
 and $B_2 = \left. \frac{\partial P_M}{\partial \Omega} \right|_{P_2}$.

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$$\Delta P_2 = C_1 \Delta W_a + C_2 \Delta Th \quad (4)$$

where

ΔW_a = change in air mass flow,
 ΔTh = change in throttle angle,

$$\begin{aligned} C_1 &= \left. \frac{\partial P_2}{\partial W_a} \right|_{Th}, \\ \text{and } C_2 &= \left. \frac{\partial P_2}{\partial Th} \right|_{W_a}, \\ \Delta W_a &= D_1 \Delta P_m + D_2 \Delta \Omega \end{aligned} \quad (5)$$

where

$$\begin{aligned} D_1 &= \left. \frac{\partial W_a}{\partial P_m} \right|_{\Omega}, \\ D_2 &= \left. \frac{\partial W_a}{\partial \Omega} \right|_{P_m}. \end{aligned}$$

In equation (5) it is assumed that changes in engine back pressure will be negligible. Other assumptions and approximations involved in equations (3) to (5) inclusive are similar to those of the analysis given in Reference (17).

Combining equations (1) to (5) inclusive results in the simulation equation for the engine. Thus,

$$\begin{aligned} E_1 \Delta \Omega + E_2 \Delta Th - \Delta Q_A / R_1 &= I_{rot} \Delta \dot{\Omega} \\ \text{where } E_1 &= A_2 + A_1 B_2 + \frac{A_1 B_1 (C_1 D_1 B_2 + C_1 D_2)}{1 - C_1 D_1 B_1} \\ \text{and } E_2 &= \frac{A_1 B_1 C_2}{1 - B_1 C_1 D_1} \end{aligned}$$

Rewriting and including the Laplacian operator results in:

$$\begin{aligned} \Delta \Omega &= \frac{K_1}{Ts + 1} \Delta Th - \frac{K_2}{Ts + 1} \Delta Q_A \quad (6) \\ \text{where } T &= \frac{I_{rot}}{E_1}, \\ K_1 &= E_2 / E_1, \\ \text{and } K_2 &= \frac{1}{R_1 E_1}. \end{aligned}$$

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The additional lags* relating throttle change to engine torque change as developed in Reference (17) may be incorporated resulting in:

$$\Delta \Omega = \frac{K_1}{(T_{S+1})(T_{S+1})(T_{S+1})} \Delta Th - \frac{K_2}{T_{S+1}} \Delta Q_A \quad (7)$$

It is expected that the AEL tests will demonstrate that τ_1 and τ_2 will vary with operating condition and will also have different values for acceleration and deceleration. These variations will be taken into account in the simulation as the data become available.

* τ_1 represents the time required for the change in fuel-air flow to enter the engine, be compressed, ignited and expelled, and is taken in Reference (17) to be 0.0444 sec. τ_2 represents the lag in changing the quantity of fuel-air mixture and is taken to be 0.5 sec. after Reference (17).

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V CONTROL OF ROTOR RPM IN HOVERING (TURBO-PROP ENGINE)

5.1 ROOT LOCUS STUDY

On the basis of the approximate relationships for helicopter motion in Reference (3) and the engine transient characteristics in Reference (8), an analytical study of rotor RPM automatic control (presuming no coupling with or from the attitude control system) was undertaken. This has been described in Interim Report AD 5143-TR5 (Reference 18), wherein the Abstract stated, "This report presents the results of a preliminary analytical study of the RPM and temperature control of a helicopter turboprop engine and rotor combination. The system considered is spoken of as being one in which RPM is controlled by the manipulated variable fuel flow, and temperature is controlled by the manipulated variable collective pitch. The following three simple configurations were investigated using root locus procedures:

- 1) Integral control in the RPM feedback loop and proportional control in the temperature feedback loop.
- 2) Proportional control in the RPM feedback loop and integral control in the temperature feedback loop.
- 3) Integral control in the RPM feedback loop and rate control in the temperature feedback loop.

The conclusion reached is that the third configuration listed holds the greatest promise of satisfactory dynamic response of RPM." For further particulars the Interim Report should be consulted.

5.2 REAC STUDY

The use of the analog computer* greatly facilitates the study when it is desired to explore the performance of a great variety of configurations of closed-loop control systems. This approach was employed in the present research program, as described in Interim Report AD 5143-TR4 (Reference 8). The Abstract in that document stated, "This report contains a presentation of the results of an analog (REAC) computer study of the automatic control of rotor RPM of a single-spool

* See also Section VI-B on the question of computer accuracy.

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turbo-prop engine. The equations involved in the REAC simulation are included, as well as extended discussion of the simulation and associated research. Results presented include actual REAC runs, and a tabulation showing a comparison of manual control of rotor RPM with the performance of various automatic controls governing rotor RPM. The study also includes consideration of the influence of various automatic RPM control configurations on vertical maneuverability of the helicopter."

One of the special features of this phase of the study was the development of the device "Steady Eddie" for use in conjunction with the REAC. By means of this equipment it was possible to pursue several by-product inquiries of importance to the subject of automatic control of rotor RPM, including the one stated at the end of the above Abstract. The description of "Steady-Eddie" is presented in Interim Report AD 5143-TR6 (Reference 19).

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VI WORK IN PROGRESS

6.1 EQUATIONS OF MOTION IN FORWARD FLIGHT

While the hovering regime represents an important mode for automatic controls operation, especially for ASW-type of duty, it is clearly evident that the criteria for design must also be based on requirements imposed by the forward flight regime. To provide the necessary helicopter transfer functions for controls analyses, an effort is underway to develop the equations of motion in forward flight with rotor RPM degree of freedom.

To date the above development has progressed to the point of the derivation of the transients in blade coning and in tip path plane inclination, where the helicopter C.G. is constrained to motions in the longitudinal plane only. Reproducing this work in detail here does not appear to be warranted, but it is of interest to report the fact that rotor RPM variations proved to be coupling factors in the blade motion equations, along with transients in helicopter C.G. movement. The effect of the coupling has as yet not been determined.

6.2 COMPLETE CLOSED-LOOP CONTROL STUDY

In the initial helicopter control study which will consider the hovering regime of flight, there will be five controlled variables:

1. Ω = Speed of the engine (and thus speed of both the main and tail rotor since both are geared to the engine with a given, fixed gear ratio.
2. α_y = Longitudinal pitch of the helicopter about the y axis.
3. α_x = Roll angle of the helicopter about the x axis.
4. α_z = Heading angle or yaw of the helicopter about the z axis.
5. z = Helicopter altitude or movement in the z direction.

The objective will be to study the responses obtained by various control configurations by REAC and analytical means, and to determine the dynamical characteristics from the absolute

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stability, transient and steady-state performance standpoints. Since the purpose will be to determine and compare the performance of various practical methods of control, and to make specific recommendations from these findings, no minimum design criteria as to speed of response, steady-state error, maximum overshoot or frequency of oscillation need be established at the outset. The simplest and most economical control configuration that results in minimum steady-state errors, and further, that allows the transient deviation to be a minimum both in time duration and amplitude will be judged best.

If the components in the control loop are taken in the order of the information flow the five controlled variables must first be measured. It is these measured quantities that are controlled. Therefore, there should be minimum lags in the sensing units, since it is desirable that their outputs be as representative of the actual physical inputs as possible.

Speed Control: If it is desired to regulate speed using proportional and integral control alone, the Woodward Governor is a compact instrument that combines both the measuring and regulating functions in one component. The transfer function for this unit is usually represented by the integral and proportional operations plus a single order lag with a time constant of about 0.05 sec.

In some applications it is desirable to have controls such as proportional, integral, and/or rate operate on the speed error in the forward loop. Then a D.C. tachometer (which needs a filter) performs the speed-sensing function, and a D.C. network utilizes its output to secure the control configuration.

If output speed control is desired, components such as accelerometers, A.C. tachometers and/or integral devices can be placed in the feedback path. It is also common practice to use a combination of speed error and output speed control, and the desirability of each method depends upon the plant transfer function, and the point of application of the load disturbances.

Roll and Pitch Control: It is conventional to sense roll and pitch displacement with one vertical gyro. This has negligible dynamics, since its rotor is fixed in space, and the displacement function may be considered instantaneous.

The customary method of securing rate is by the use of rate gyros—one for each axis controlled. The single-degree-of freedom, viscous-damped rate gyros are thought unnecessarily accurate and costly for helicopter applications. Their threshold is needlessly low—0.003 deg/sec to 0.0006 deg/sec -- and they require extra equipment such as amplifiers, etc. Damped rate gyros are under development that have a variable frequency and damping ratio range. These will be simulated on the REAC and the characteristics of the gyro simulation varied to secure optimum response.

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It is planned that consideration will also be given to controlling pitch and roll disturbances by means other than the use of the position gyro in the fuselage. Nothing concrete has been established yet in this regard.

Heading Control: Although complete information on the study helicopter has not as yet been received, it is most probable that the helicopter will be completely instrumented and therefore be equipped with a Gyro Magnetic Compass. In this unit a magnetic compass aligns a position gyro to magnetic north and puts out a synchro signal. It is only necessary then to supply a compass coupler, which is essentially a follow-up motor that drives a potentiometer in response to the synchro signal. The important dynamics of this system are in the compass coupler, and a representative simulation would be a second order system with a natural frequency of about 3.2 CPS at a damping ratio of about 0.7. If yaw rate is desired a rate gyro or network must be used.

Altitude Control: The present preliminary thinking on altitude sensing is along the lines of using a radio altimeter or the sonar cable. Except for cable dynamic lags due to wind loads in the latter, both means of sensing can be thought of as being instantaneous. Pressure sensing altitude controllers might cause trouble because of the difficulty in securing an accurate static pressure source due to the rotor downwash.

Regulation: The first plan is to perform the regulating functions in the following ways:

- 1) Engine speed is to be regulated by a servo motor attached to the throttle lever or carburetor butterfly valve governing throttle position (θ_h).
- 2) Longitudinal pitch will be regulated by a servo motor to cyclic pitch (θ_y).
- 3) Helicopter roll will be regulated by a servo motor to cyclic pitch (θ_x).
- 4) Heading will be regulated by a servo motor attached to the lever controlling tail rotor blade pitch (θ_e).
- 5) Altitude will be controlled by a servo motor regulating main rotor collective pitch (θ_c).

The underlined quantities in the above are, therefore, the manipulated variables.

When both engine speed and helicopter altitude are subject to automatic control, it is presently felt to be more

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desirable to control engine speed with throttle and altitude with collective pitch (as above), than the alternate method of controlling engine speed with collective pitch and altitude with throttle. Collective pitch is usually thought of as a primary control (power required) while engine speed is controlled by the throttle setting (power available) that is dictated by the load requirements of the rotor. (See also Reference (15) for further discussion.)

During the course of the controls analyses, consideration will also be given to cross-coupling in the feedback paths.

The most recent trend in helicopter autopilots is toward the differential system, thus eliminating the formation stick that is permissible in the conventional airplane. In the differential system the pilot controls do not move when the autopilot is operating, and when on autopilot, the helicopter can be controlled from the cockpit in the normal manner. Since the S-58⁺ is thought to have a hydraulic boost control, a differential hydraulic servo will be considered first in the control simulation. Test results show that even for small changes in maximum amplitude the frequency response varies widely, and the unit is therefore quite different from a simple linear system. Further, the amplifier used has a marked effect on the servo response. Because of these complications, for simulation purposes, a simple first-order lag of 5 cps at 45 degrees will be taken to represent the servo units. This specification is far beyond the frequency of any helicopter motor that will be encountered.

Functional Dependency: The most direct way of stating the functional dependency between the variables is to list the effects of a change in the manipulated variables on the dependent variables before the control corrections take place. This is done in the following paragraphs for each controlled variable.

I. Engine speed (Ω) as a controlled variable. $\pm \Delta Th$
(throttle) will affect the following:

1. speed of the main and tail rotor.
2. α_z (yaw) since tail rotor thrust will increase.
3. z (altitude) since main rotor thrust will increase.
- * 4. y (side displacement) since tail rotor thrust will increase.
- * 5. α_x (roll) since tail rotor thrust will increase.

⁺ See Section VII for further reference to the S-58 helicopter (also referred to as the XHSS-1).

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II. Longitudinal Pitch (α_y) as a controlled variable. $+\Delta\theta_y$ will affect the following:

1. x (forward displacement) since main rotor thrust is inclined.
2. α_y (pitch) since a pitching moment is produced by the main rotor thrust component.
- * 3. α_x (roll) because of coupling in main rotor.

III. Roll angle (α_x) as a controlled variable. $+\Delta\theta_x$ will affect the following:

1. y (side displacement) since main rotor thrust is inclined.
2. α_x (roll) since a rolling moment is produced by the main rotor thrust component.
- * 3. α_y (pitch) because of coupling in main rotor.

IV. Yaw Angle (α_z) as a controlled variable. $+\Delta\theta_z$ will affect the following:

1. α_z (yaw) since tail rotor thrust will increase.
- * 2. y (side displacement) since tail rotor thrust will increase.
3. z (altitude) since load on engine is increased.
- * 4. Ω (engine speed) since load on engine is increased.
- * 5. α_x (roll) since tail rotor thrust causes rolling moment.

V. Altitude (z) as a controlled variable. $+\Delta\theta_z$ will affect the following:

1. z (altitude) since thrust of main rotor increases.
2. Ω (engine speed) since load on main rotor increases.
3. α_z (yaw) since engine speed changes and thus also tail rotor thrust.
- * 4. y (side displacement) since tail rotor thrust changes.
- * 5. α_x (roll) since tail rotor thrust changes.

The effect of the independent variables on those dependent variables marked (*) are small and possibly negligible at least for analytical calculations.

The above dependency can be summarized to produce the more convenient block diagram shown in Figure 2. This gives an overall picture of the problem in its most complete form, and is substantially the system that will be placed on the REAC.

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There are 10 equations of dynamics involved (the six degrees of freedom of a body in space, three rotor flapping equations and an engine equation), and as the block diagram shows, for analytical work these 10 must be solved 16 times to produce the indicated transfer functions. $K_{17}G_{17}$, $K_{18}G_{18}$, $K_{19}G_{19}$, $K_{20}G_{20}$, and $K_{21}G_{21}$ are the 5 control blocks and symbolically are thought of as containing the transfer functions of the sensing, regulating and control units.

Every effort will be made to simplify the analytical treatment wherever engineering judgment indicates such simplification to be feasible.

Use of the Analog Computer: There has recently been some discussion in regard to the possible inadequacy of the REAC as a means of simulating a helicopter control problem. (See for example, Reference 21.) The point raised seems to be that because of the widely different frequencies of the helicopter motion and rotor motion, difficulty will be encountered in that the analog computer dynamics will obscure the high speed rotor dynamics; and that if the time scale is adjusted to avoid this difficulty, computer drift and long solution times are limiting factors. It is the purpose in what follows to indicate that in all probability computer dynamics do not affect the helicopter simulation, and thus the time scale need not be changed.

It is recognized here that the electronic differential analyzers utilize elements that unavoidably introduce errors in the simulation. Reference (22) states that in certain extreme cases an error of 1 percent can be produced by an adding unit having a bandwidth two thousand times the highest frequency present in the simulation. This order of magnitude is within the accuracy of any helicopter characteristics used in the simulation. Reference (22) also states that these errors are most important for simulations having characteristic roots lying near the imaginary axis.

A simulation of the stabilized helicopter with rotor dynamics included, results in roots of the following three general classes:

1. Low frequency poles (less than 2 rad/sec) and of damping greater than 0.6.
2. Moderately high frequency, moderately damped blade-motion poles.
3. A high frequency (35 rad/sec), low damped ($DR = .2$) blade-flapping-motion complex pair, together with a set of complex zeros in the same position on the right hand plane.

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The most difficult task for the computer then is the simulation of the high frequency pair near the imaginary axis.

As is well known, high frequency poles have a negligible effect on the shape of a response determined by low frequency roots. However, they do have a marked effect on the response magnitude. In the helicopter simulation the complex zeros in the right hand plane nullify even the effect the high frequency complex pair would have on the gain if they existed alone. It therefore seems logical to conclude that the simulation errors (if they exist) are unimportant, since the error-sensitive, high-frequency poles themselves are unimportant.

It is important to realize that the above statement should not be interpreted to mean that the rotor dynamics themselves can be disregarded. It is suggested that only the high frequency, low damped pole-zero pairs that make up a portion of the response can be neglected. If any appreciable errors occur in the REAC simulation, the major portion is in these unimportant roots.

In order to further substantiate the validity of the REAC simulation the following simple test was conducted on the REAC:

1. A step function input was introduced into the transfer function.

A

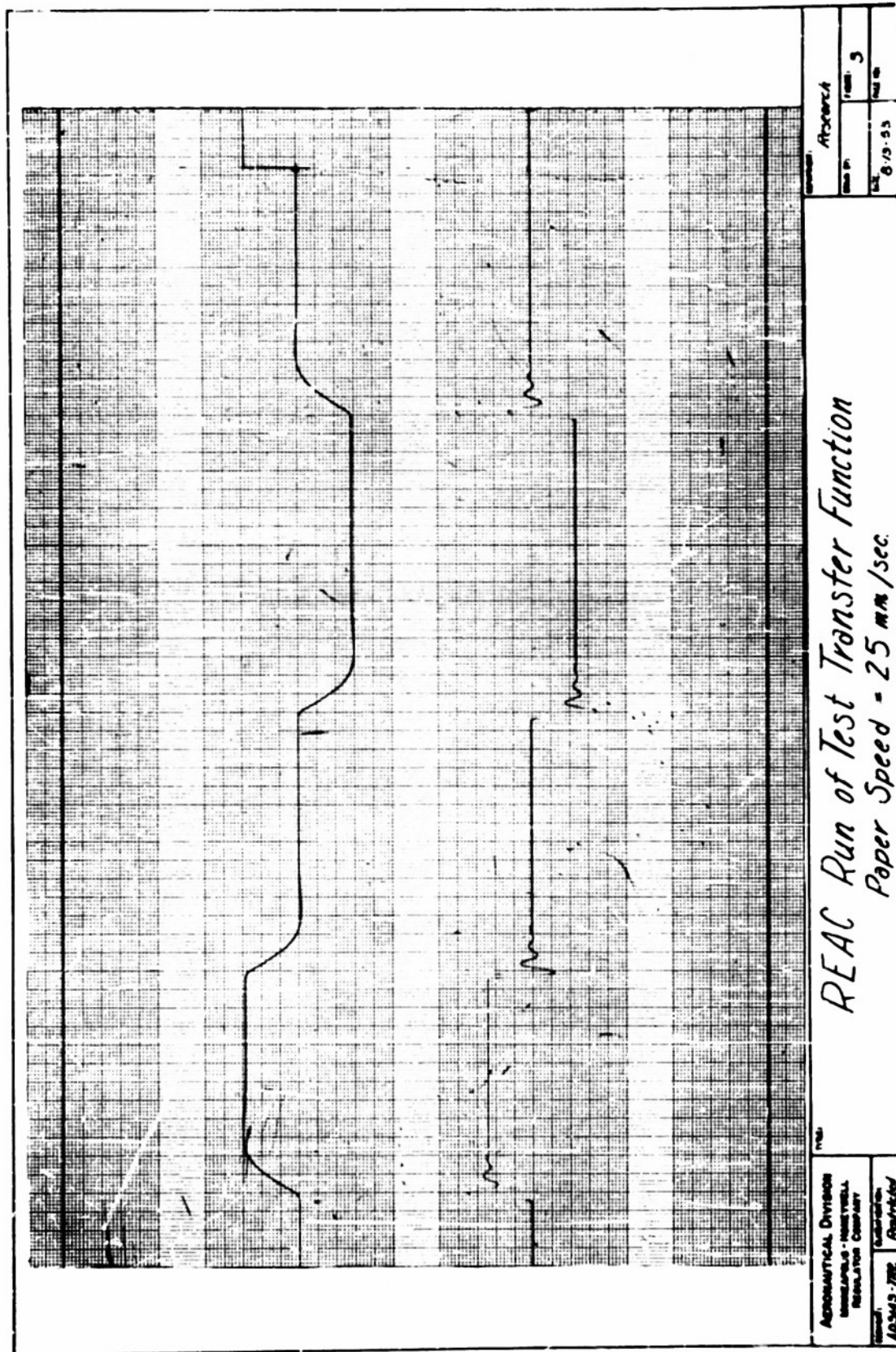
$$\frac{[s^2 + (2 \times 7.76)s + 36] \cdot [s^2 + (2 \times 209)(33.55)s + (33.55)^2]}{[s^2 + (2 \times 7.76)s + 36] \cdot [s^2 + (2 \times 209)(33.55)s + (33.55)^2]}$$

This contains a pair of high frequency low damped poles simulating two of the blade motion roots, and a low frequency, moderately damped complex pair simulating the helicopter motion. The result was recorded at a paper speed of 25 mm/sec, and reproduced in Figure 3.

2. The time scale of the above simulation was then reduced by a factor of ten (thus reducing the frequencies by a factor of ten), and the response to a step function recorded at a paper speed of 2.5 mm/sec. This is reproduced in Figure 4.

It is immediately apparent from a comparison of the two figures that they are identical. It seems logical to assume that if any simulation errors existed in Figure 3, they would be reduced by a factor of 10 in Figure 4. The automatic amplifier balance feature of the REAC seems to stabilize the results even at the low paper speed.

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The analytical solution of the response for the magnitude of step input chosen is

$$y = 2.47 - e^{-4.2t}(2.52 \sin 4.29t + 2.42 \cos 4.29t) \\ + e^{-7t}(.0314 \sin 32.8t \\ + .0788 \cos 32.8t)$$

It can be seen from a comparison of the coefficients of sin and cos terms why the high frequency motion does not affect the total response shape. The time to first reach the final value calculated from the low frequency poles is 0.52 sec. This checks both Figure 3 and Figure 4. The percent overshoot determined from calculations on the low frequency poles is 4.6 percent which is, within the degree of reading accuracy, what Figure 3 and Figure 4 indicate.

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VII PROPOSED PHASE II PROGRAM

In Phase II of this research project, as has been indicated in previous sections, the effort will be directed toward the development of design criteria for automatic controls of ASW-type helicopters, as exemplified by the XHSS-1. The program has been outlined in some detail in Reference (20), and it essentially tends to limit the scope of activity in a manner which is most apt to produce tangible results for the type of helicopter configuration indicated above.

Initial concern under the continuation program will be with the following:

- A. Determination of the analytical processes to be employed in the automatic control system investigation which can proceed with the receipt of various data on the XHSS-1 helicopter;
- B. Completion of the development of the forward flight equations of motion;
- C. Analysis of the data secured by AEL on reciprocating engine transient behavior.

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VIII SUMMARY

In Phase I of the study of automatic control systems for helicopters, the principal accomplishments were related to laying the foundations for servo analysis. These foundations include (a) the development of the equations of motion for hovering and for forward-flight, (b) the development of the equations for the transient characteristics of turbo-prop and reciprocating engines, and (c) the determination of the dynamics of various elements of the closed-loop systems to be analyzed. While some work remains to be done in connection with the above, it will be possible to undertake the controls study with the receipt of the numerical data on the XHSS-1 helicopter which has been chosen as the research vehicle for the present project.

The study of the automatic control of rotor RPM for the case of the turbo-prop engine has been partially completed. It was found that from the standpoint of minimum complexity the use of a control involving only proportional and integral feedbacks would be advisable; but to gain maximum tightness of control, rate feedback should be added.

In Phase II of this research program, the principal effort will consist in the main of servo analyses aimed at determination of the control system design criteria for the ASW-type helicopter. Additional study will also be given to the development of the forward flight equations motion with RPM degree of freedom and to other basic material needed for extension of the controls analyses to include all of the primary modes of helicopter operation.

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X. APPENDIX

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* Most of the early documents listed are chiefly of historical interest only. Material which was concerned principally with blade motion, vibration, flutter, etc., has been omitted. It is also recognized that there are in all likelihood many interesting and pertinent documents that are not included in this listing because they were not made available to the present research project.

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