NATIONAL RESEARCH COUNCIL OF CANADA

AERONAUTICAL REPORT

LR - 302

A MODEL-CONTROLLED AUTOPILOT FOR AN AIRBORNE VTOL SIMULATOR

BY

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NATIONAL AERONAUTICAL ESTABLISHMENT

OTTAWA

FEBRUARY 1961

NATIONAL RESEARCH LABORATORIES

Ottawa, Canada

REPORT

National Aeronautical Establishment

Flight Research Section

Pages - Preface	- 6	Report:	LR-302
Text	- 10	Date:	February 1961
Tables	- 2	Lab. Order:	NAE 762
Figures	- 17	File:	CM2-17-13T-6-4

For: Internal

Subject: A MODEL-CONTROLLED AUTOPILOT FOR AN AIRBORNE VTOL SIMULATOR

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SUMMARY

To establish valid handling qualities requirements for VTOL and STOL aircraft a need exists for a simulator which adequately simulates the dynamic response and environment of the vehicle under consideration. To this end a variable stability helicopter is proposed.

This report outlines how a model-controlled autopilot may be used to vary the characteristics of a helicopter, enabling simulation of aircraft having a wide variety of dynamic response characteristics.

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LIST OF SYMBOLS

Symbol	
$AP(s)$	Autopilot transfer function
$C(s)$	Compensating circuit transfer function
E	Magnitude of error between reference model and helicopter response
e	Voltage
g	Acceleration due to gravity
$H(s)$	Helicopter transfer function
I_x, I_y, I_z	Rolling, pitching, and yawing moments of Inertia
i	Angle of incidence of helicopter main rotor
j	$\sqrt{-1}$
K	Autopilot static gain
L, M, N	Rolling, pitching, and yawing aerodynamic moments about helicopter body axes
$L(t)$, $M(t)$, $N(t)$	Rolling, pitching, and yawing forcing functions
L_p	Damping in roll, $\partial L/_{\partial p}$
M_q	Helicopter damping in pitch, $\partial M/_{\partial q}$, ft.lb./rad./sec.
M_u	Helicopter pitching moment due to incremental longitudinal velocity, $\partial M/_{\partial u}$
$M(s)$	Reference model transfer function
N_r	Helicopter damping in yaw
p, q, r	Rolling, pitching, and yawing angular velocities of helicopter body axes
S	Laplace variable

LIST OF SYMBOLS (CONT'D)

Symbol	
u, v, w	Longitudinal, side, and normal linear velocities of helicopter body axes
W	Weight of helicopter
x	Position on blade radius in percent of radius
X, Y, Z	Longitudinal, side, and normal aerodynamic forces with respect to helicopter body axes
X(t), Y(t), Z(t)	Longitudinal, side, and normal forcing functions
X_q	Incremental change of longitudinal aerodynamic force due to pitching velocity
X_u	Incremental change of longitudinal aerodynamic force due to longitudinal velocity
Y_u	Incremental change of aerodynamic side force due to side velocity
Y_p	Incremental change of aerodynamic side force due to rolling velocity
Z_w	Normal velocity damping, $\partial Z/_{\partial w}$
α	Attenuation factor of compensating circuit
$\delta_\theta(s)$	Laplace transform of input
λ	Root of stability characteristic equation
η	Damping ratio
ψ, θ, $\emptyset$	Yaw, pitch, and roll angle of body axes relative to arbitrary earth axes
τ	Helicopter time constant

LIST OF SYMBOLS (CONT'D)

Symbol

ω Angular frequency

Subscripts

M - Reference model

H - Helicopter

A MODEL-CONTROLLED AUTOPILOT FOR AN AIRBORNE VTOL SIMULATOR

1.0 INTRODUCTION

The development of VTOL aircraft has recently received considerable attention. A number of experimental aircraft of this type have been built and flown in various countries. These are aircraft which attempt to combine the ability of the helicopter to take off vertically, to land vertically, and to hover, with the ability of the fixed wing aircraft to fly at high forward speed. Almost without exception these aircraft have displayed marginal or unacceptable handling qualities.

The difficulties with VTOL aircraft arise for several reasons. One reason for poor control characteristics is that the designer must commit a certain percentage of available power to provide control in hovering and low speed flight, thus, to a certain extent, reducing that available for lifting. Designers are quite naturally reluctant to allow this percentage to become too large. Secondly, the aircraft have (generally) very low levels of stability or are in fact unstable. This latter characteristic is also true for the helicopter but control powers are sufficiently high to allow the pilot reasonable control. Thirdly, there is relatively little information available concerning what criteria establish desirable handling qualities. There is information available for helicopters (Ref. 1), but this is certainly not adequate when compared with that available for fixed wing aircraft (Ref. 2).

Some work has been done to determine the effects of varying control power and damping on the pilot's ability to perform various tasks (Ref. 3). However, it is clear from a review of the available information that a great deal more information is required.

To perform the task of increasing this fund of information the use of fixed-base ground simulators has evident limitations. A number of recent investigations (Ref. 4, 5, 6 and 7) show that the representation of aircraft motions and the psychological environment of the pilot may be important in allowing the correct conclusions to be drawn. Therefore, in order to establish valid handling qualities requirements the use of an "airborne simulator" appears to be most desirable.

A helicopter with variable stability and control characteristics would provide such a vehicle. It is the objective of this report to show how a model-controlled autopilot may be used to control three degrees of freedom of a helicopter thus making it possible to vary the characteristics which are of significance in specifying the handling qualities requirements for VTOL aircraft. Structural limitations and component saturation, which must be taken into account in the design of a specific system, are not considered in this analysis.

2.0 PRINCIPLES OF THE MODEL-CONTROLLED AUTOPILOT

The model-controlled autopilot is a simplified version of the self-adaptive flight control system described in Reference 8. This model-controlled system is characterized by two unique features.

First, the dynamic response characteristics of the aircraft under control are made to comply with the dynamic response characteristics of an analogue model. This model may be constructed of passive elements such as resistances, condensers, and inductances, or it may contain active analogue computing components such as operational amplifiers.

The second unique feature of this model-controlled autopilot is the manner in which the loop gain is maintained constant for varying dynamic pressure. With a conventional autopilot constant loop gain is maintained by a compensator unit which modifies the appropriate feedback signals as a function of dynamic pressure. This modification is accomplished by potentiometers driven by an airspeed bellows. Non-linearities, if required, are "programmed" with cams or shaped potentiometers. This "programming" or "scheduling" is accomplished only after the variations of the required loop gains with dynamic pressure have been determined from test flights. The model-controlled autopilot of Reference 8 actively monitors the sensitivity of the autopilot-aircraft closed loop combination and modifies the autopilot gain to keep the closed loop gain constant. This model-controlled autopilot therefore may compensate not only for changes of dynamic pressure but also for any other variables which change the loop gain, such as damage to control surfaces, etc.

2.1 Simplified Model-Controlled Autopilot

Low performance aircraft which do not encounter large changes of dynamic pressure do not require the automatic gain feature of model-controlled autopilots. An autopilot with the model-controlled feature but not the automatic gain feature is described in Reference 9.

The term "simplified model-controlled" has been chosen by the authors to describe this autopilot to avoid confusion with autopilots having an automatic gain feature.

Figure 1 shows in block diagram form a model-controlled autopilot for a single degree of freedom system. If it is assumed that the components are linear and possess the transfer functions as shown, then the over-all transfer function will be:

$$\frac{\dot{\theta}(s)}{\delta_{\theta}(s)} = \frac{M(s)}{G(s) + \dfrac{1}{c(s)\cdot K\cdot AP(s)\cdot H(s)}}$$

The output will follow the model response to the input providing:

(1) The feedback transfer function, $G(s)$, has a modulus equal to unity and an argument of zero degrees. (This condition is met in the rate feedback systems considered in this report by using a rate gyro with a natural frequency that is very high compared with the upper frequency of the bandwidth of interest and with a very low damping ratio.)

(2) The product $c(s)\cdot K\cdot AP(s)\cdot H(s)$ has a large enough modulus to ensure an output of the required accuracy and an argument that is less than 180 degrees over the bandwidth of interest. This condition is met by the proper matching of the compensation network to the other frequency sensitive components of the system and by choosing a sufficiently large value of the gain, K.

Compensation networks may be required to produce either or both of the following effects:

(1) To increase the bandwidth of the system enabling the aircraft to respond to higher frequencies,

(2) To allow for an increase of the gain of the closed loop resulting in a reduction of the error.

The error, or deviation of the output $\dot{\theta}(s)$ from the desired output $\delta_{\theta}(s)\cdot M(s)$ is expressed by:

$$E = \frac{\dot{\theta}(s) - \delta_{\theta}(s)\cdot M(s)}{\delta_{\theta}(s)\cdot M(s)} = \frac{1}{1 + c(s)\cdot K\cdot AP(s)\cdot H(s)}$$

The autopilot of Reference 9 has an additional unique feature in that it is a "bang-bang" servo system which is made to approximate a linear system by the methods described in References 9 and 10. In this system the error signal is used to pulse-width modulate a square wave oscillation having a frequency (called the dither frequency) above the bandwidth of the helicopter. The modulated square wave is applied to a pneumatic servo actuator to produce a control surface displacement as shown in Figure 2. As the linear approximation of this displacement is the integral of the error signal, the transfer function of the autopilot may be approximated by $AP(s) = \frac{1}{S}$.

3.0 AUTOPILOT REQUIREMENTS FOR A VTOL SIMULATOR

In order to determine characteristics which would be representative of those of a helicopter, an analogue computer simulation of a small single rotor helicopter was done. An analogue study of a deflected slipstream VTOL aircraft was also done.

3.1 Helicopter Characteristics

The physical characteristics of the helicopter are detailed in Table I. The simulation of the helicopter was done for the hovering flight case only, the equations for which are shown below.

$$\text{(i)} \quad X_u u + X_q q - W\theta \cos i - \frac{W}{g}(\dot{u} - vr + wq) = X(t)$$

$$\text{(ii)} \quad Z_w w - W\theta \sin i - \frac{W}{g}(\dot{w} - uq + vp) = Z(t)$$

$$\text{(iii)} \quad Y_v v + Y_p p + W\phi - \frac{W}{g}(\dot{v} - wp + ur) = Y(t)$$

$$\text{(iv)} \quad L_v v + L_p p - I_x \dot{p} - (I_z - I_y)\, qr = L(t)$$

$$\text{(v)} \quad M_u u + M_q q - I_y \dot{q} - (I_x - I_z)\, pr = M(t)$$

$$\text{(vi)} \quad N_r r - I_z \dot{r} - (I_y - I_x)\, pq = N(t)$$

The stability derivatives with respect to speed were estimated using the method outlined in Reference 11. The rotary derivatives (X_q, Y_p, etc.) were estimated from information presented in Reference 12. The tail rotor derivative (N_r)

was estimated using simple momentum theory. The values for the derivatives estimated in this way are shown in Table II.

The equations of motion were scaled using normal analogue techniques and the analogue circuit shown in Figure 3 was set up on an analogue computer. Helicopter response to step inputs was obtained and typical results are shown in Figures 4a, 4b, and 4c. Examination of the results together with an analysis of the helicopter transfer function revealed that the longitudinal and lateral modes could be treated as second order systems and that the directional mode could be considered first order (for hovering flight).

Although the analogue studies indicated a negative value of damping ratio, the installation of an integral rotor stabilizer makes the damping ratio positive (Ref. 13). Therefore, $\eta = +0.234$ is chosen as a representative value. Other helicopter characteristics which were chosen as being representative are specified in Figures 5, 6, and 7.

The open loop characteristics of the helicopter and autopilot with no compensation are shown in Figures. 8, 9, and 10. The helicopter characteristics are those shown in Figures 5, 6, and 7, and the autopilot characteristic is assumed to be simply $AP(s) = \frac{1}{s}$.

Figure 8 shows that the gain of the autopilot pitch amplifier could be set at 3 db. (a voltage gain of 1.4) and maintain a 30-degree phase margin as recommended for such systems (Ref. 14). Over the bandwidth of $0 \lessapprox \frac{\omega}{\omega_H} \lessapprox 1.2$ the minimum magnitude of the error $\frac{1}{1 + K \cdot AP(s) \cdot H(s)} = 42$ percent. For better accuracy and greater bandwidth, compensation of this loop is required.

Figure 9 indicates that compensation of the roll loop and additional gain are required to obtain an increased bandwidth and accuracy.

Figure 10 indicates that the required bandwidth and accuracy may be obtained by increasing the gain. No compensation is necessary. For example, to obtain an accuracy of 10 percent between the helicopter response and model response over a bandwidth of $0 \lessapprox \frac{\omega_M}{\omega_H} \lessapprox \frac{\omega_{M_{max.}}}{\omega_H}$ (where $\frac{\omega_{M_{max.}}}{\omega_H} = 1.7$ from Fig. 6) an additional gain of $(20.3 + 6)$db. = 26.3 db. is necessary.

3.2 Compensated Autopilot and Helicopter Characteristics

3.2.1 Pitch Rate Control Loop

Figure 11 indicates the characteristics of a lead network suitable to compensate the pitch rate control loops and Figure 12 indicates the compensated characteristics of this loop.

A 30-degree phase margin now occurs at $\frac{\omega}{\omega_H} = 32$ when a gain of 21.2 db. (voltage ratio of 11.5) is added. This results in an error between the helicopter response and the model response as shown in Figure 13. A maximum error of 8.5 percent is now obtained over a bandwidth of $0 \lesssim \frac{\omega}{\omega_H}$ 3.5. The error curve for a gain of 15.2 db. (voltage ratio of 5.73) is also shown to illustrate the effect of gain on the error.

3.2.2 Roll Rate Control Loop

The compensation network of Figure 11 may also be used with the roll rate control loop since the pitching and rolling characteristics of the helicopter are essentially the same. Figure 14 shows the compensated roll rate characteristics.

Twenty-one db. of gain may be added to produce a 30-degree phase margin. Figure 15 shows the error curve for the compensated roll rate control loop.

3.3 Characteristics of Models Suitable for Representation of a VTOL Aircraft

The longitudinal characteristics for a deflected slip-stream VTOL aircraft were obtained by performing an analogue computer experiment utilizing data from Reference 15. Results of the simulation are shown in Figure 16. In order that a range of characteristics might be investigated, data from Reference 3 was also used. Models which incorporate characteristics such as those cited could be constructed using resistors, capacitors and inductances (for the case of statically and dynamically stable modes.) For unstable modes, models could be constructed using analogue computer components. Representative ranges of model characteristics are shown in Figures 5, 6, and 7.

4.0 ANALOGUE SIMULATION

The compensated pitch rate control loop of Figure 5 was simulated on an analogue computer. A model natural frequency (ω_M) of 0.566 and damping (η_M) of 0.323 were used. These values were representative of the longitudinal characteristics of a deflected slipstream VTOL aircraft (Fig. 16). The helicopter had characteristics $\omega_M = 0.194$ and $\eta_H = 0.234$ (Fig. 5). The analogue study included a simulation of the "bang-bang" servo system shown in Figure 2 and a fixed time delay of 0.05 second corresponding to the lag in the helicopter control system.

The computer diagram is shown in Figure 17. Shown below are calculations used for computer scaling. The general equation of motion for the helicopter and reference model is of the form:

$$\ddot{\theta} + (2\eta\omega_n)\,\dot{\theta} + \omega_n^2\theta = f(t)$$

The solution of the equation to a step function is of the form:

$$\theta = f(t)\left[\frac{1}{\lambda_1\,\lambda_2} + \frac{e^{\lambda_1 t}}{\lambda_1(\lambda_1 - \lambda_2)} + \frac{e^{\lambda_2 t}}{\lambda_2(\lambda_1 - \lambda_2)}\right]$$

where $\lambda_{1,\,2} = -\,\eta\omega_n \mp j\omega_n\sqrt{1 - \eta^2}$

Using this solution it may be shown that

$\dot{\theta}$ has a maximum value when $\tan \omega_n \sqrt{1 - \eta^2}\,t \cong 2\eta$

$\ddot{\theta}$ has a maximum value when $\tan \omega_n \sqrt{1 - \eta^2}\,t \cong -\dfrac{2\eta\omega_n\sqrt{1 - \eta^2}}{4\eta^2\omega_n^2 - \omega_n^2}$

Using these relationships and assuming f(t) has a value of 0.10 (where f(t) in the physical case is the ratio of moment input to moment of inertia), the maximum values are:

Helicopter Model	Reference Model
$\dot{\theta}_{max.} = 0.85$ rad./sec.	$\dot{\theta}_{max.} = 0.50$
$\ddot{\theta}_{max.} = 0.10$ rad./sec.	$\ddot{\theta}_{max.} = 0.08$

For purposes of computer scaling it was assumed that $\dot{\theta}_{max.} = 1.00$ rad./sec., $\ddot{\theta} = 1.00$ rad./sec.^{2}, $\theta_{max.} = 5.00$ rad.

If the maximum voltage for linear operation of the computer is 100 volts then scaling factors for $\ddot{\theta}$, $\dot{\theta}$, and θ are 100, 100, and 20 respectively.

The amplitude of the sawtooth input to the trigger circuit was chosen so that the circuit would not saturate (i.e. error signal would always be less than 50 volts). Biasing circuits were necessary because of the characteristics of the trigger and to compensate for amplifier drift.

Results of this study indicated that the helicopter followed the model response to step inputs with an accuracy of better than 5 percent at a gain of 12. The 0.05-second time delay did not produce any measurable change in performance.

5.0 CONCLUSIONS

A model-controlled autopilot appears suitable for use with a helicopter as an airborne VTOL simulator. With the following limitations a simplified version of such an autopilot will enable the helicopter to assume the dynamic characteristics of any desired model.

(1) The proposed system only controls the angular motions of the helicopter.

(2) The gain cross-over frequencies of the helicopter may be extended by means of compensation networks to approximately 3.5 times the natural frequencies, in pitch and roll, of the helicopter.

(3) Adding the maximum gains that will permit stable operation within the frequency ranges $0 \lessapprox \omega \lessapprox 3.5\omega_H$ the errors will not exceed 8.5 percent in pitch and roll.

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TABLE I

PHYSICAL CHARACTERISTICS OF A LIGHT SINGLE ROTOR HELICOPTER

Gross Weight	2000 lb.
Pitching Moment of Inertia	1360 slug ft.^{2}
Rolling Moment of Inertia	270 slug ft.^{2}
Yawing Moment of Inertia	1070 slug ft.^{2}
Height of Rotor Hub Above C.G.	4.5 ft.
Rotor Diameter	35.13 ft.
Number of Blades	2
Radius at which Blade Starts	10.8 percent
Blade Chord	1.184-0.351x
Solidity	0.0330
Rotor Angular Velocity	34.9 rad./sec.
Tip Speed	613 f.p.s.
Flapping Moment of Inertia (per blade)	252 slug ft.^{2}
Cyclic Pitch Control Range (Longitudinal)	± 14.3 deg.
Cyclic Pitch Control Range (Lateral)	± 10.8 deg.
Cyclic Pitch per Degree Stabilizer Bar Tilt	0.88
Stabilizer Bar Tilt Between Stops	4.5 deg.
Effective Tail Arm	253 inches
Tail Rotor Diameter	6 ft.
Total Hovering H.P.	180

TABLE II

STABILITY DERIVATIVES FOR A SMALL SINGLE ROTOR HELICOPTER

X_u = -1.140 lb./ft./sec.

X_q = +226 lb./rad./sec.

M_u = +5.14 ft.lb./ft./sec.

M_q = -1016 ft.lb./rad./sec

Z_w = -73.6 lb./ft./sec.

N_r = -660 ft.lb./rad./sec.

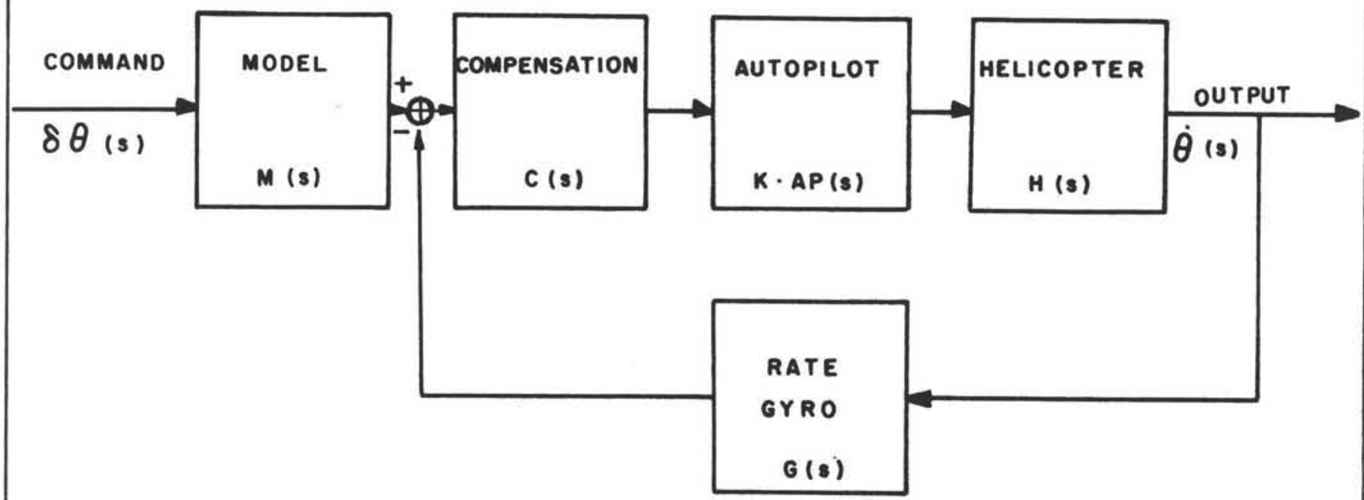
Y_v = X_u

Y_p = X_q

L_v = M_u

The Remaining Derivatives are Insignificant in Hovering Flight

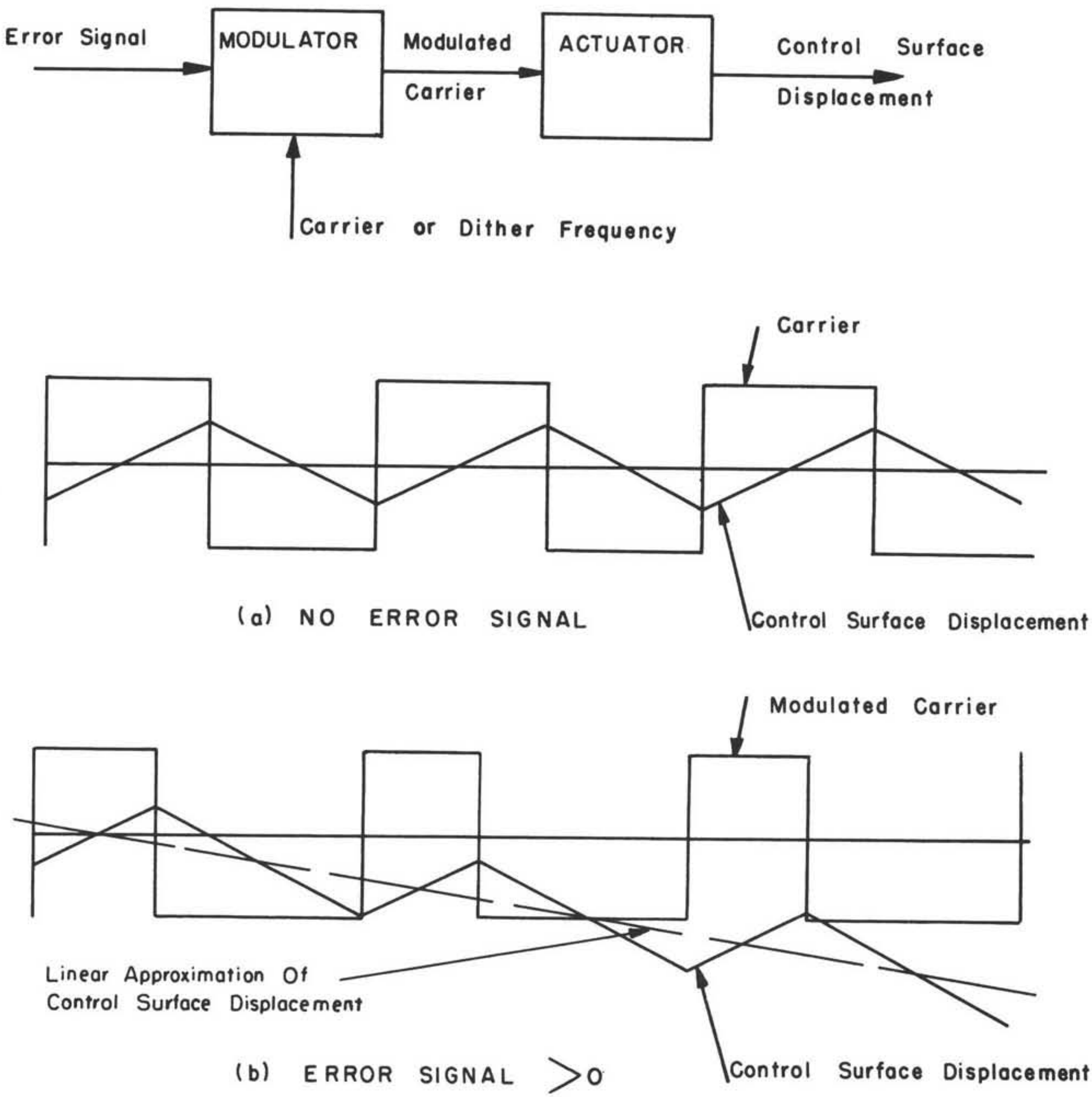
FIG. 1
LR-302



$$\frac{\dot{\theta}(s)}{\delta\theta(s)} = \frac{M(s)}{G(s) + \dfrac{1}{C(s)\cdot K\cdot AP(s)\cdot H(s)}}$$

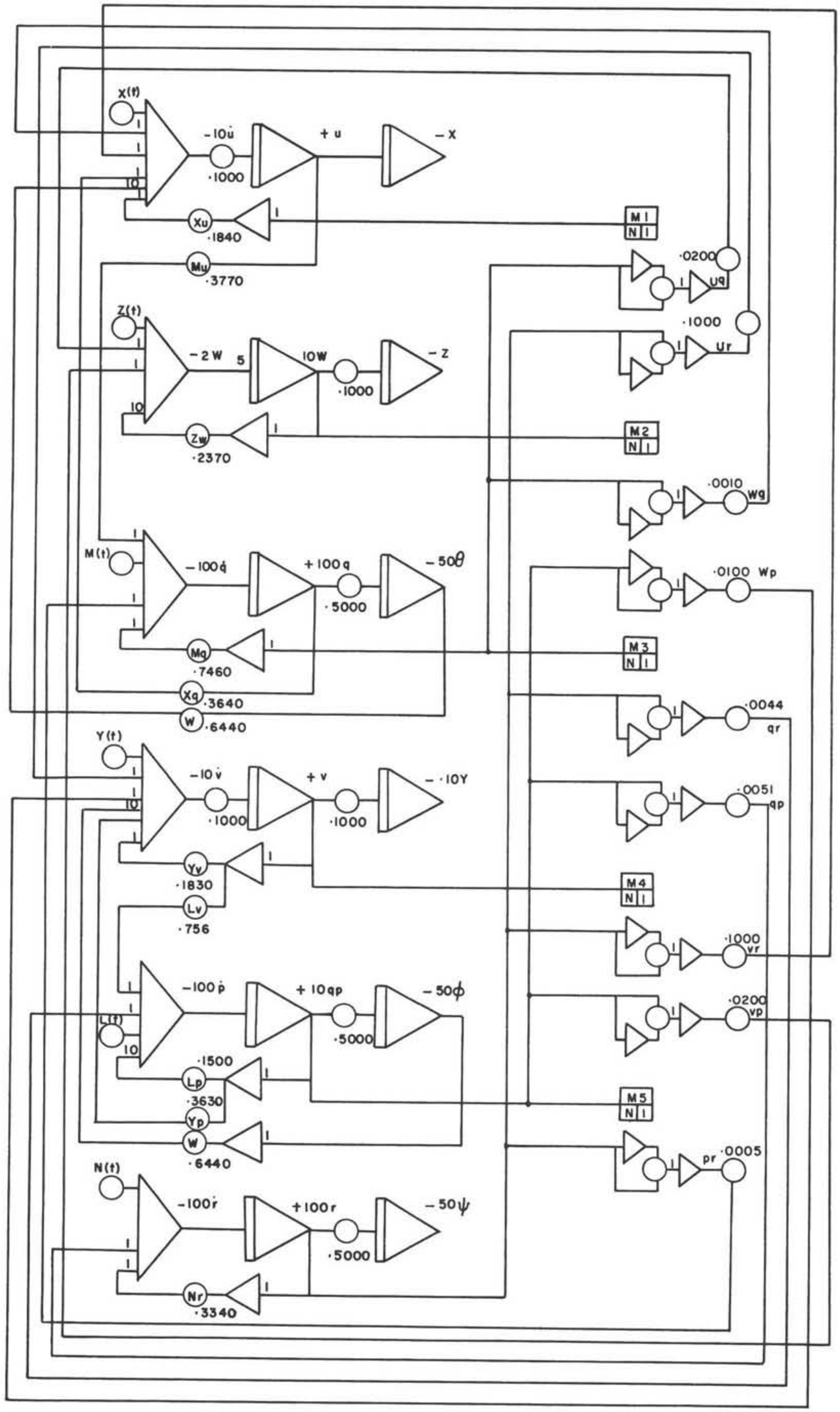
SIMPLIFIED MODEL-CONTROLLED AUTOPILOT

FIG. 2
LR-302



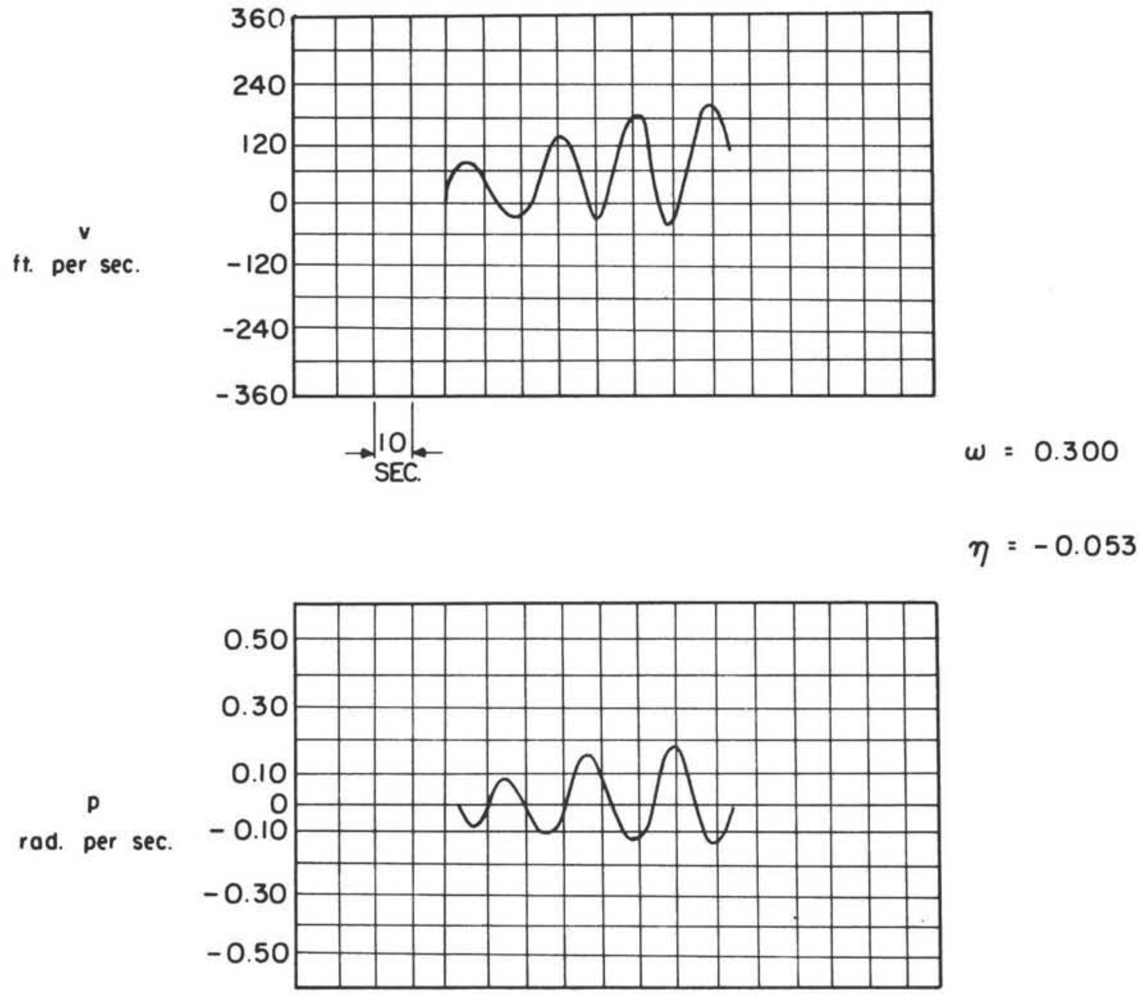
LINEARIZATION OF "BANG-BANG" SERVO ACTUATOR

FIG. 3
LR-302



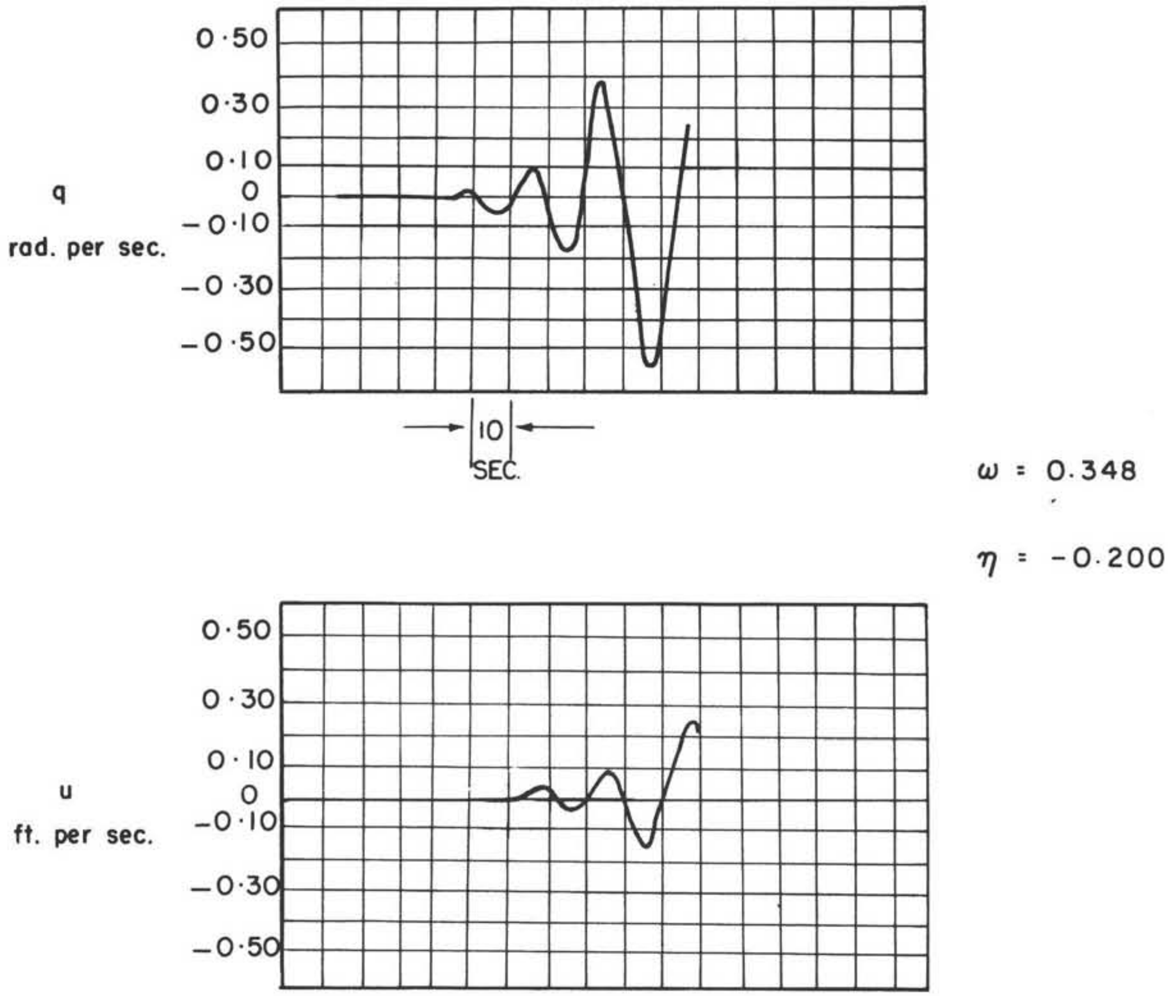
ANALOGUE CIRCUIT FOR HELICOPTER

FIG. 4a
LR-302



RESPONSE TO STEP ROLLING
MOMENT AND Y FORCE INPUT

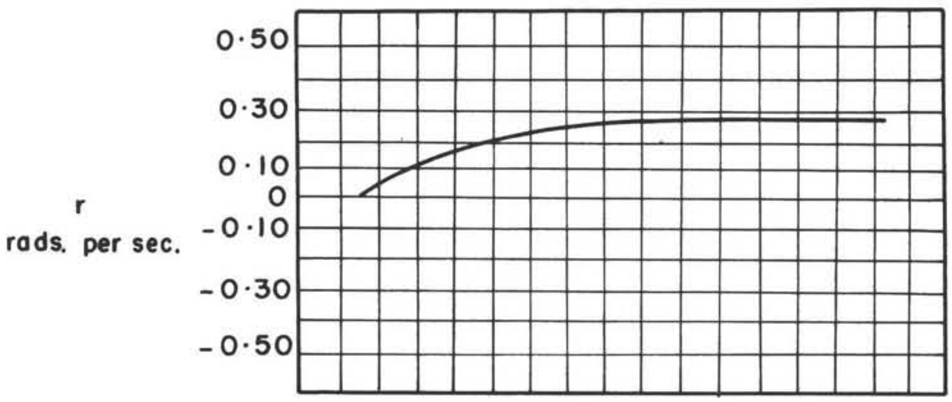
ANALOGUE TRACES FOR HELICOPTER
6 DEGREES OF FREEDOM



RESPONSE TO STEP M and X INPUTS

ANALOGUE TRACES FOR HELICOPTER
6 DEGREES OF FREEDOM

FIG. 4c
LR-302

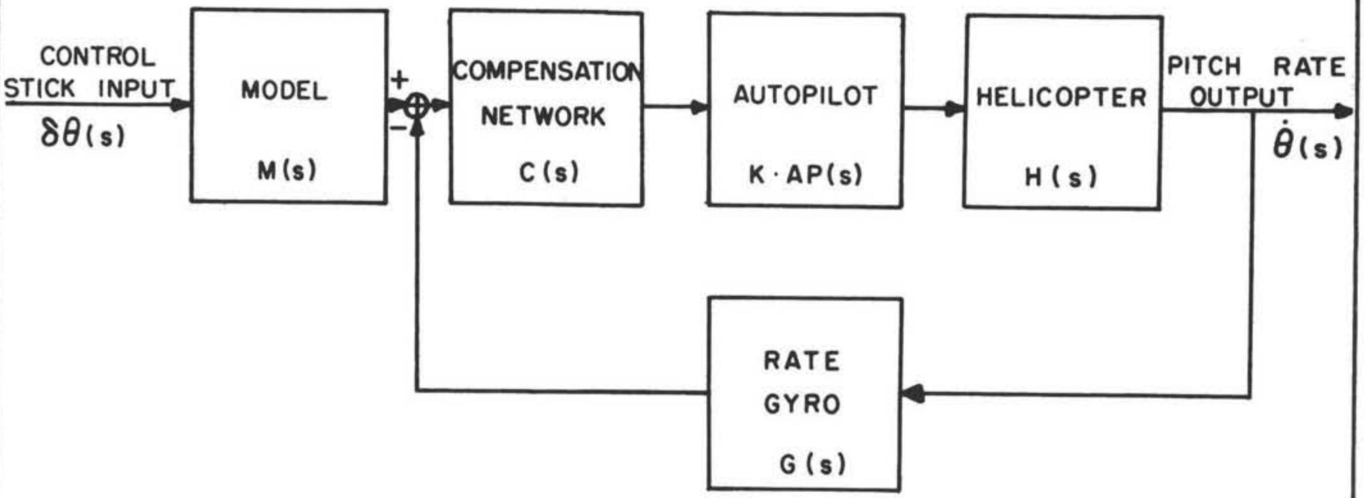


RESPONSE TO STEP N INPUT

NOTE: With excitation of the lateral mode, significant pitch roll coupling became apparent after approximately 60 seconds

ANALOGUE TRACES FOR HELICOPTER
6 DEGREES OF FREEDOM

FIG. 5
LR-302



$$\frac{\dot{\theta}(s)}{\delta\theta(s)} = \frac{M(s)}{G(s) + \dfrac{1}{C(s) \cdot K \cdot AP(s) \cdot H(s)}}$$

$$H(s) = \frac{S\omega_H^2}{S^2 + 2\eta_H\,\omega_H + \omega_H^2}$$

$$\omega_H = 0{\cdot}194 \text{ RAD./SEC.}$$

$$\eta_H = 0{\cdot}234$$

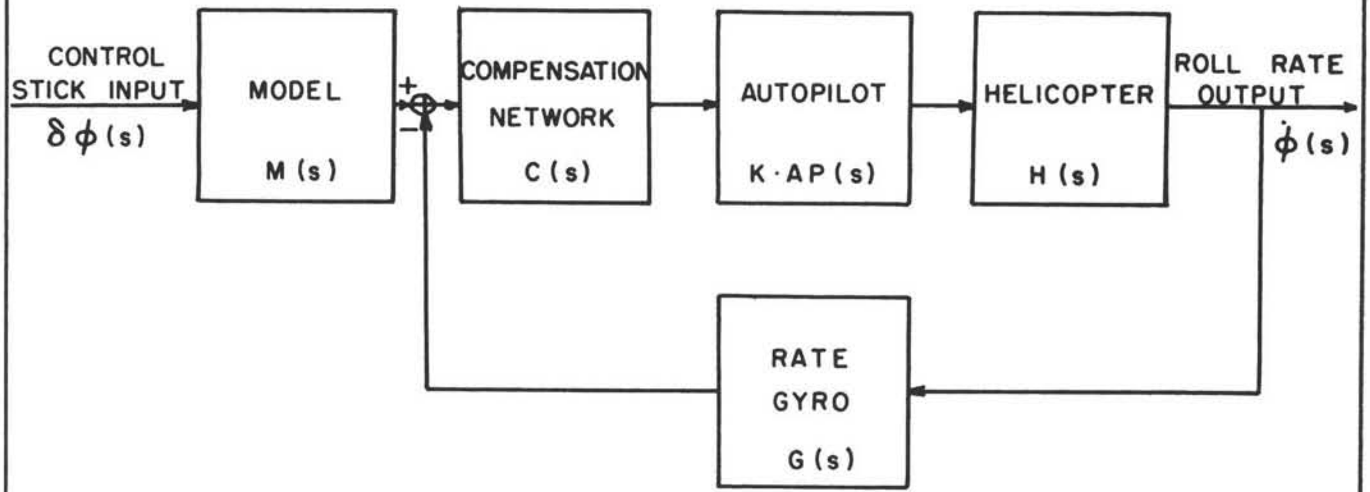
$$M(s) = \frac{S\,\omega_M^2}{S^2 + 2\eta_M\,\omega_M + \omega_M^2} \qquad (\text{Typical})$$

ω_M TO BE ADJUSTABLE 0 to 1.0 RAD./SEC.

FOR EACH VALUE OF η_M = 0 to 0.35

PITCH RATE CONTROL LOOP

FIG. 6
LR-302



$$\frac{\dot{\phi}(s)}{\delta\phi(s)} = \frac{M(s)}{G(s) + \dfrac{1}{C(s)\cdot K\cdot AP(s)\cdot H(s)}}$$

$$H(s) = \frac{S\,\omega_H^2}{S^2 + 2\eta_H\,\omega_H + \omega_H^2}$$

$\omega_H = 0{\cdot}35$ RAD./SEC.

$\eta_H = 0{\cdot}10$

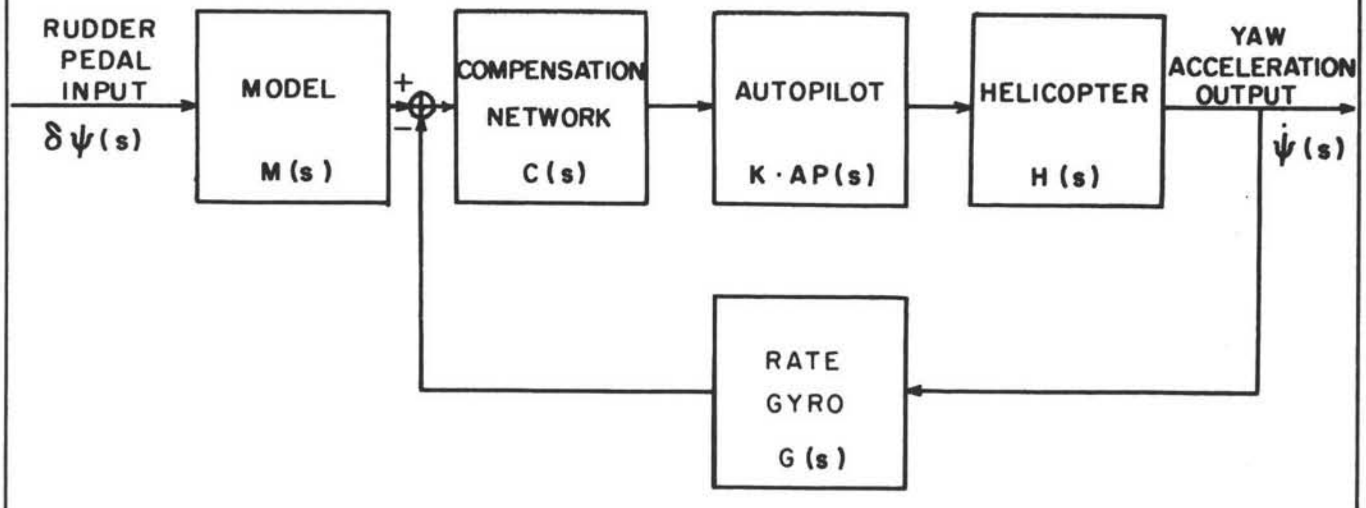
$$M(s) = \frac{1}{1+\tau_M S} \quad \text{(Typical)}$$

τ_M TO BE ADJUSTABLE WITH THE FOLLOWING VALUES

τ_M = 0.17 to 10.0

ROLL RATE CONTROL LOOP

FIG. 7
LR-302



$$\frac{\dot{\psi}(s)}{\delta\psi(s)} = \frac{M(s)}{G(s) + \dfrac{1}{C(s)\cdot K\cdot AP(s)\cdot H(s)}}$$

$$H(s) = \frac{S}{1 + \tau_H S}$$

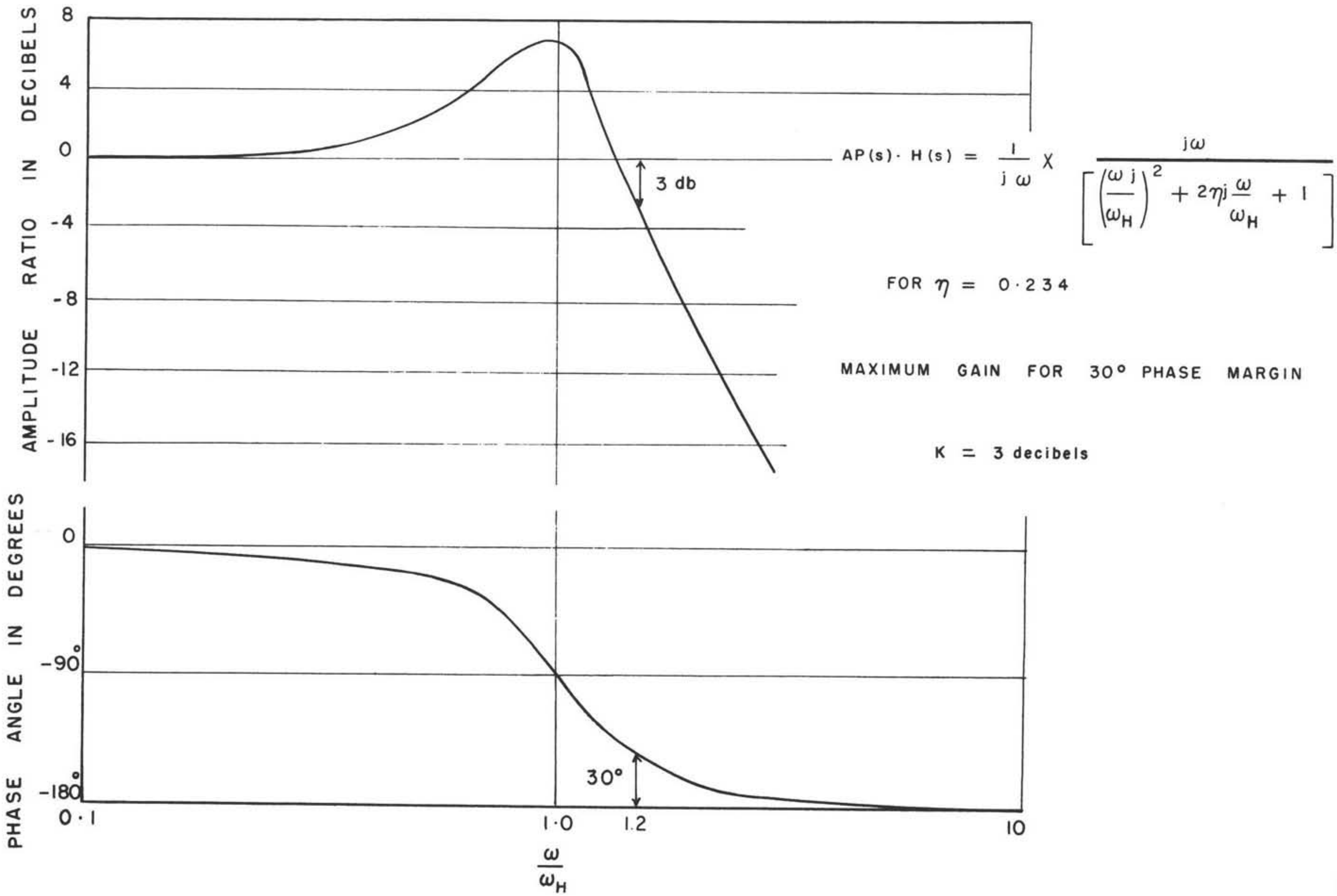
$$\tau_H = 1\cdot 67$$

$$M(s) = \frac{S^2 \omega_M^{\,2}}{S^2 + 2\eta_M \omega_M + \omega_M^{\,2}} \quad (\text{Typical})$$

ω_M TO BE ADJUSTABLE 0 to 1.0 RAD./SEC.

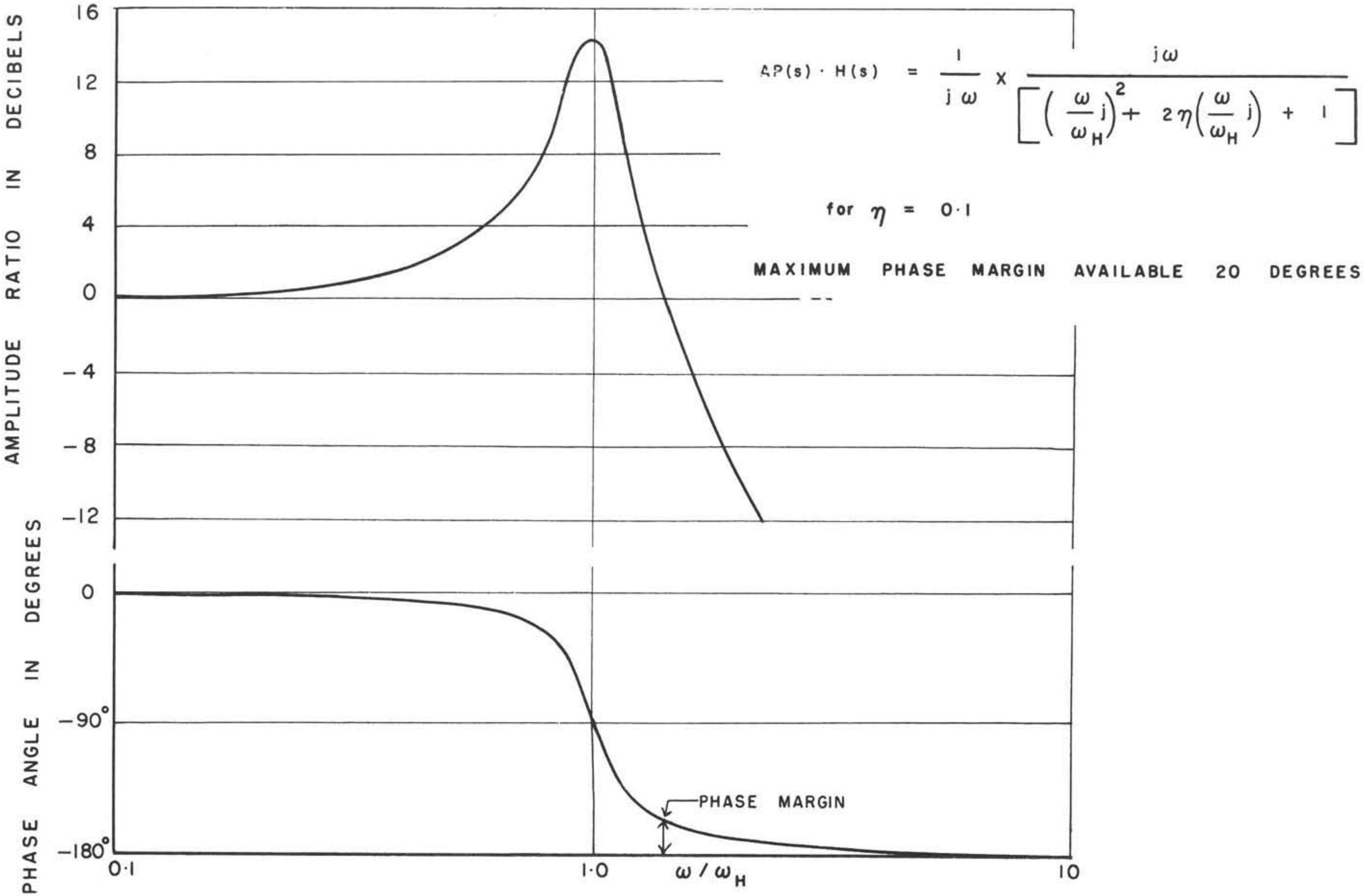
FOR EACH VALUE OF η_M = 0 to 0.35

YAW RATE CONTROL LOOP



UNCOMPENSATED AUTOPILOT AND HELICOPTER RESPONSE IN PITCH

FIG. 8
LR-302



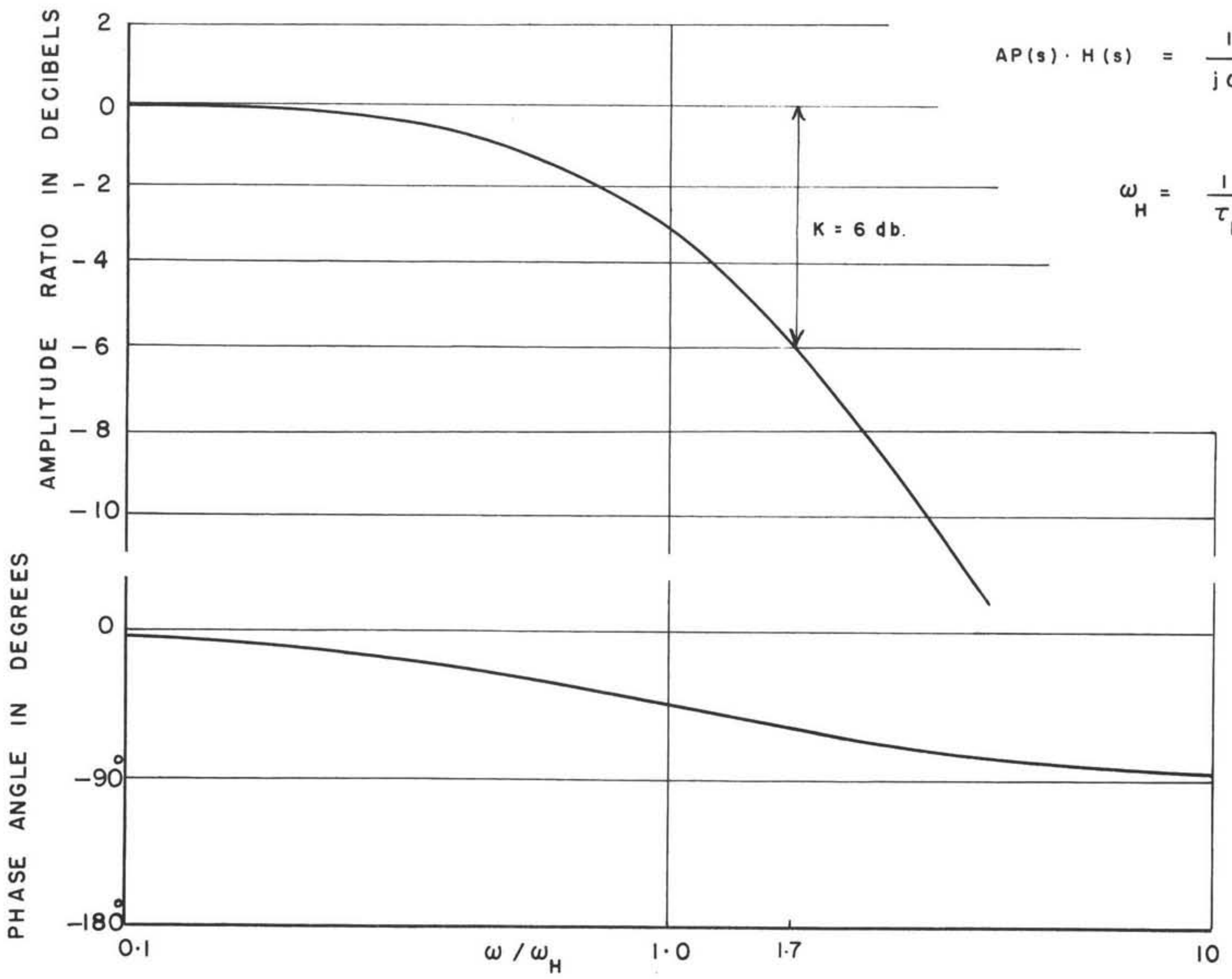
UNCOMPENSATED AUTOPILOT AND HELICOPTER RESPONSE IN ROLL

FIG. 9
LR-302

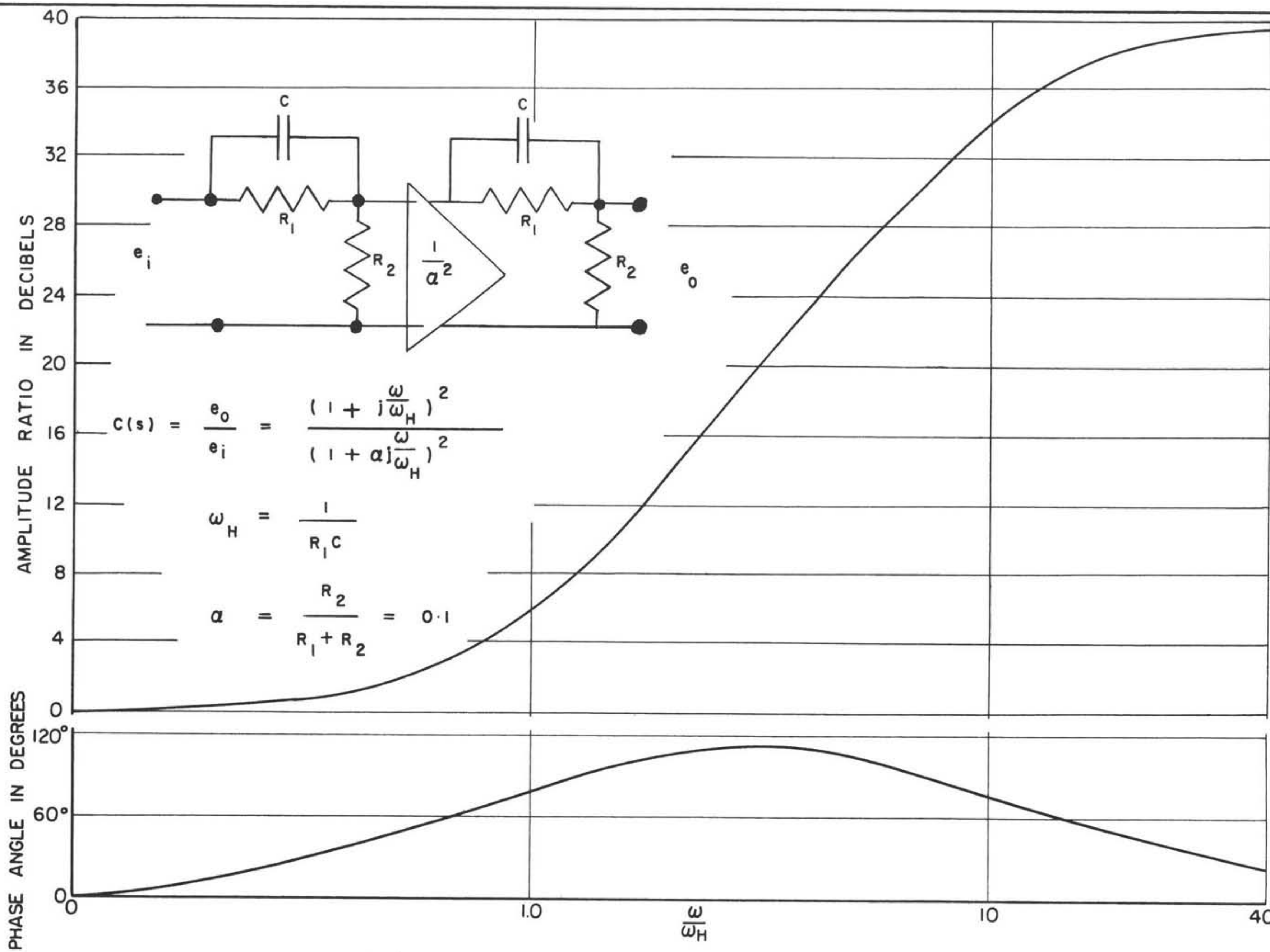
FIG. 10
LR-302

$$AP(s) \cdot H(s) = \frac{1}{j\omega} \times \frac{j\omega}{1 + j\frac{\omega}{\omega_H}}$$

$$\omega_H = \frac{1}{\tau_H} = 0 \cdot 6$$

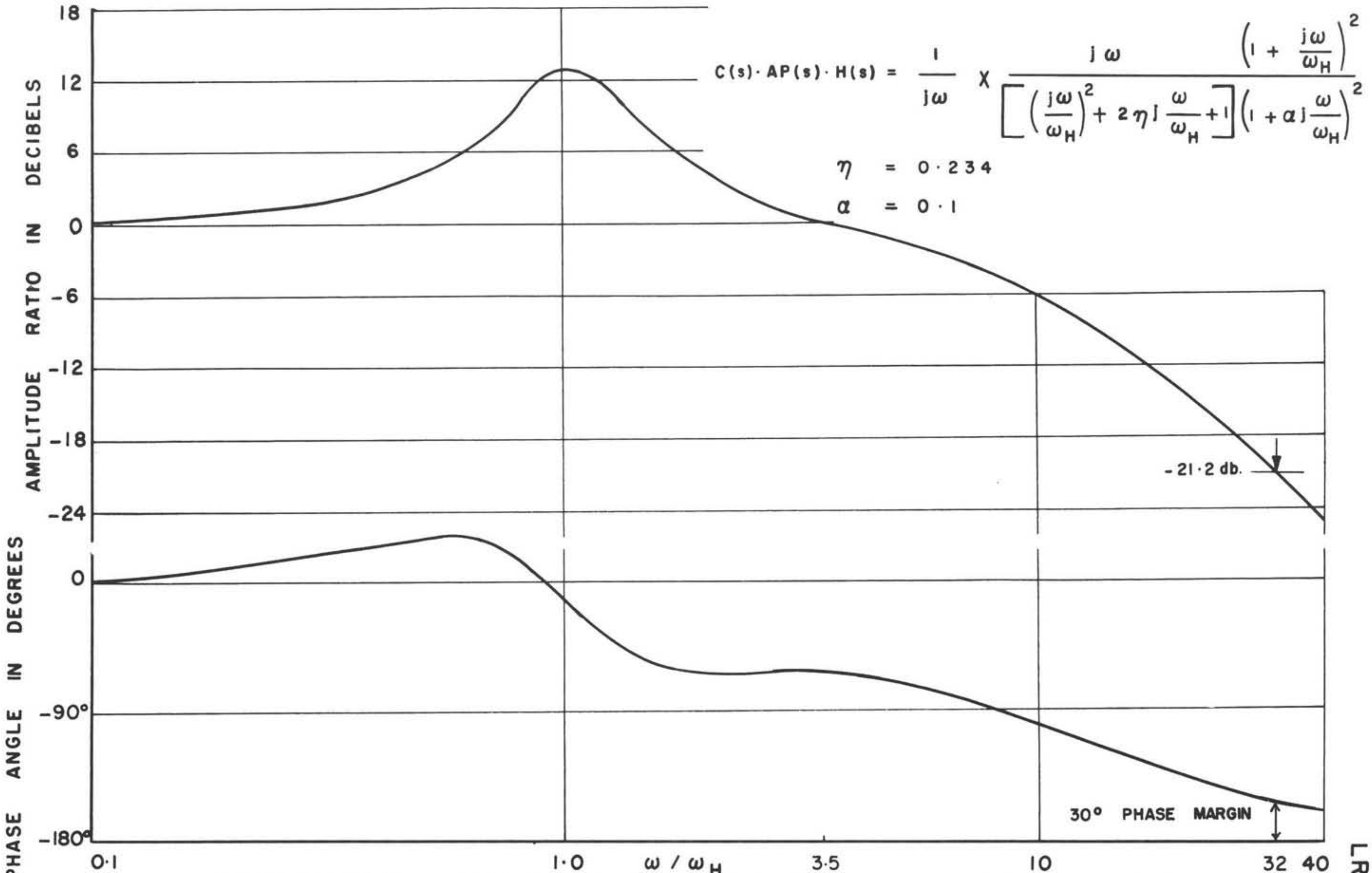


UNCOMPENSATED AUTOPILOT AND HELICOPTER RESPONSE IN YAW



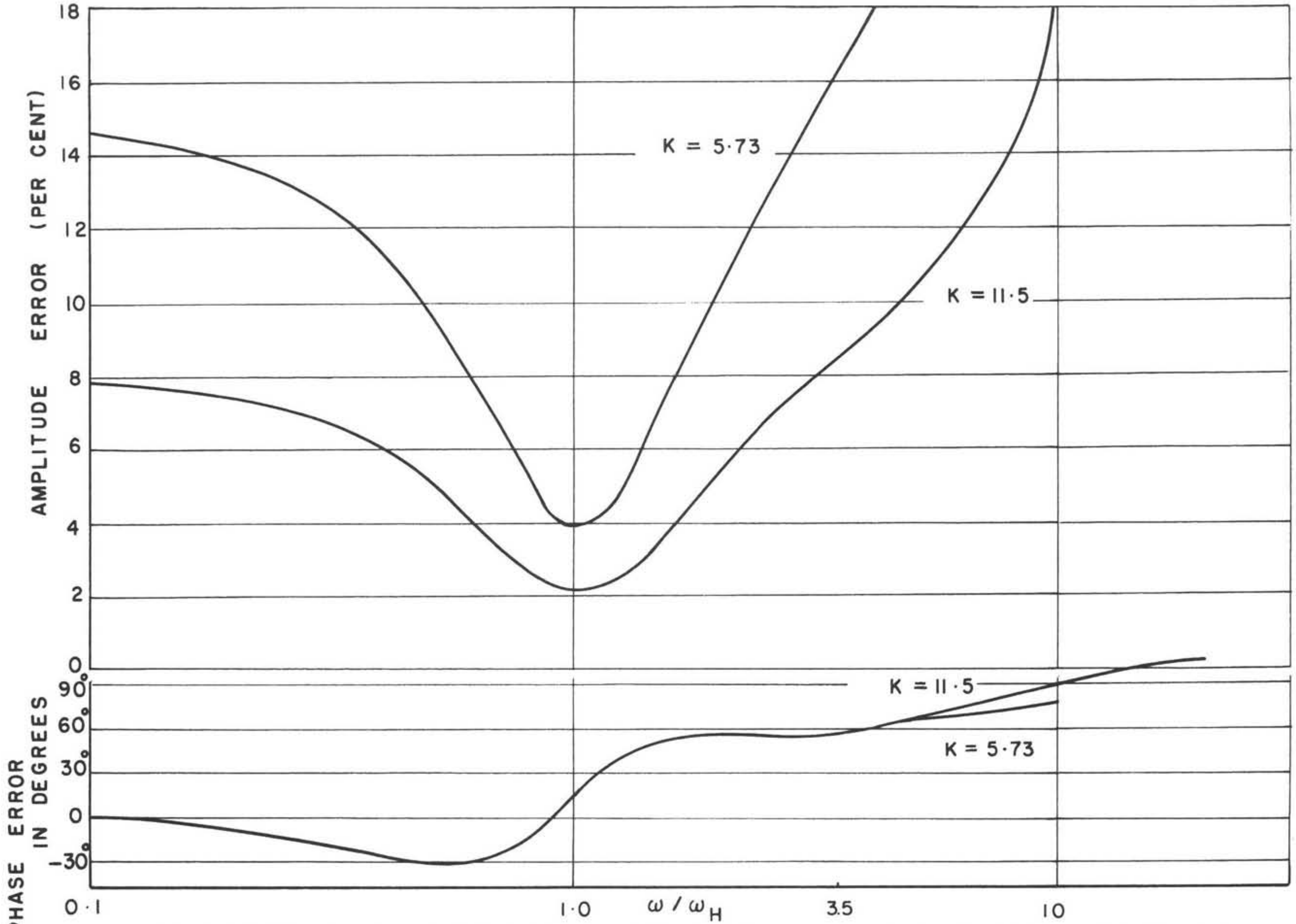
COMPENSATION FOR PITCH RATE CONTROL LOOP

FIG. 11
LR-302



COMPENSATED AUTOPILOT AND HELICOPTER CHARACTERISTICS
PITCH RATE

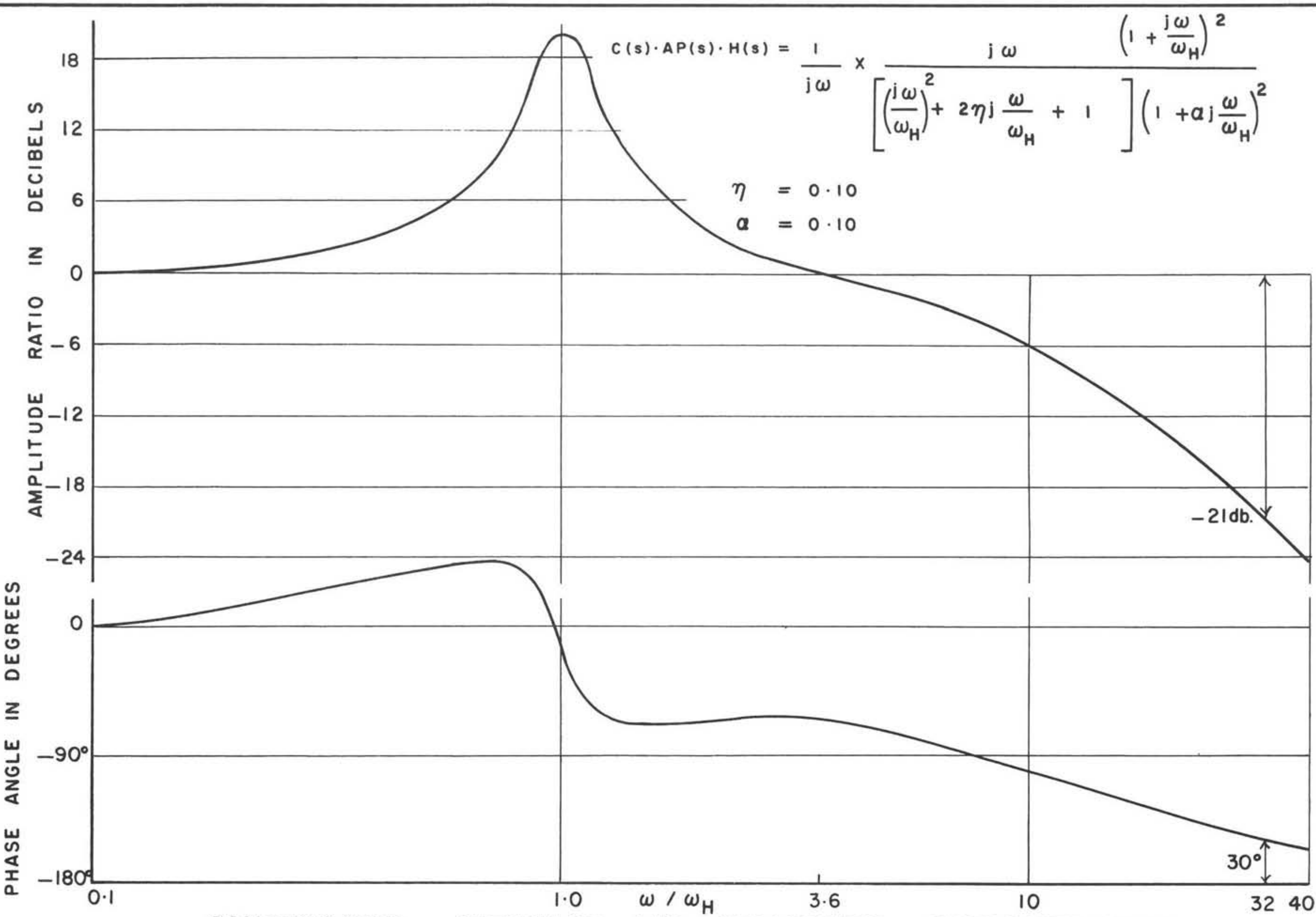
FIG. 12
LR-302



VARIATION WITH FREQUENCY OF ERROR IN HELICOPTER RESPONSE

PITCH RATE CONTROL LOOP

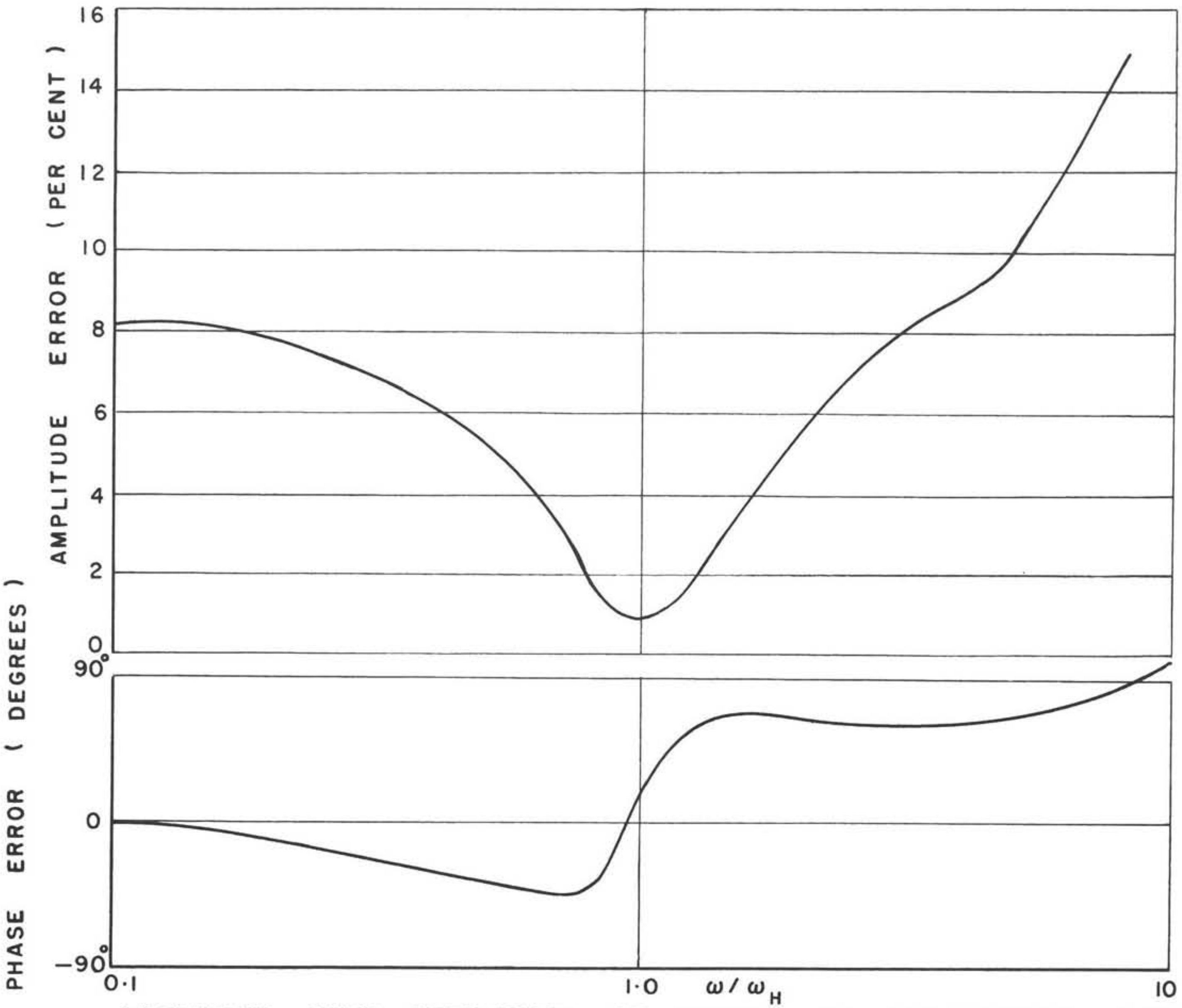
FIG. 13
LR-302



COMPENSATED AUTOPILOT AND HELICOPTER CHARACTERISTICS

ROLL RATE

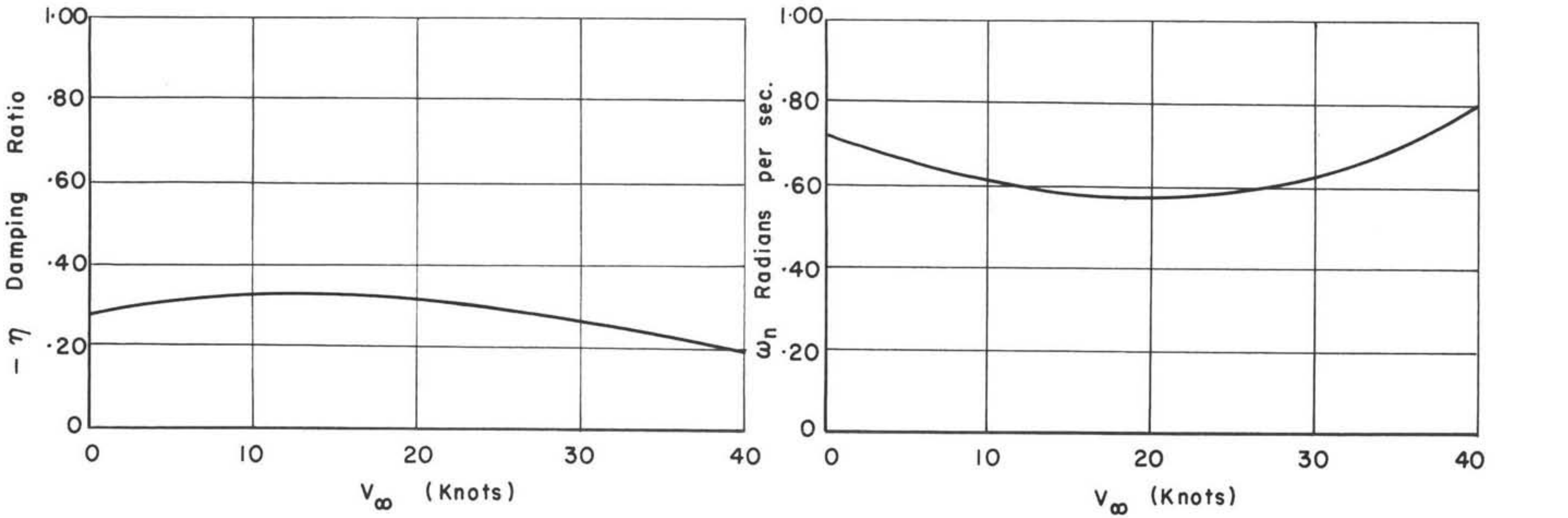
FIG. 14
LR-302



VARIATION WITH FREQUENCY OF ERROR IN HELICOPTER RESPONSE

ROLL RATE CONTROL LOOP K = 21 db.

FIG. 15
LR-302

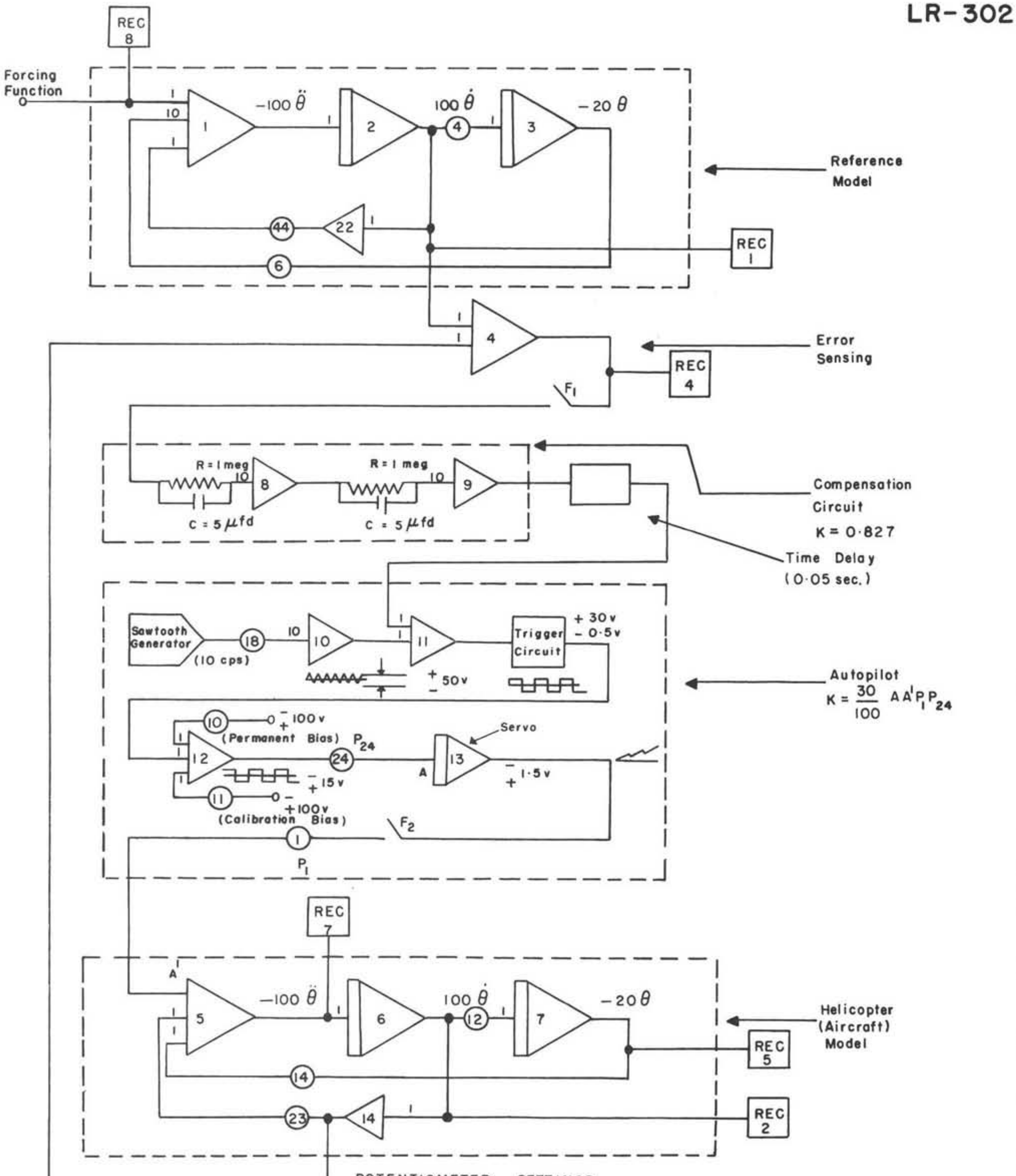


FREQUENCY AND DAMPING RATIO
LONGITUDINAL MODE (6 DEGREES OF FREEDOM)

DEFLECTED SLIPSTREAM VTOL AIRCRAFT

FIG. 16
LR- 302

FIG. 17
LR-302



POTENTIOMETER SETTINGS

POT. No.	SETTING
4	0·2000
44	0·3600
6	0·1600
12	0·2000
14	0·1880
28	0·0907
10	0·150 (approx.)
11	0·150 (approx.)

The remainder of the potentiometers were set to give desired amplitudes as indicated

COMPUTER CONNECTION DIAGRAM
COMPENSATED PITCH RATE CONTROL LOOP

NRC LR-302 National Research Council, Canada. National Aeronautical Establishment A MODEL-CONTROLLED AUTOPILOT FOR AN AIRBORNE VTOL SIMULATOR. D.F. Daw and L.V. Ursel. February 1961. 18 pp. + 17 figs. To establish valid handling qualities requirements for VTOL and STOL aircraft a need exists for a simulator which adequately simulates the dynamic response and environment of the vehicle under consideration. To this end a variable stability helicopter is proposed. This report outlines how a model-controlled autopilot may be used to vary the characteristics of a helicopter, enabling simulation of aircraft having a wide variety of dynamic response characteristics.	UNCLASSIFIED 1. Automatic pilots 2. Flight simulators 3. Vertical take-off planes - Handling 4. Helicopters - Stability I. Daw, D.F. II. Ursel, L.V. III. NRC LR-302

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