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REPUBLIC AVIATION CORP., FARMINGDALE, L.I., N.Y.
(REPORT NO. EDR-F905-601)

PRELIMINARY DESIGN OF SERVOMECHANISMS FOR F-84 FIGHTER STABILIZATION DURING WING TIP ATTACHMENT TO B-50 BOMBER

FRICKE, E.; PIERCE, C.H., JR. 14 JULY'49 43PP DIAGRS, GRAPHS, DRWGS

USAF PROJECT MX-1016

AIRPLANES - WING-TIP COUPLING
PROJECT MX-1016
F-84

AIRPLANE DESIGN (10)
MILITARY AIRPLANES(11)

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REPUBLIC AVIATION CORPORATION

Report No. EDR-F905-601
Page No. 1
Date July 14, 1949

-CONFIDENTIAL-

Preliminary Design of Servomechanisms For F-84 Fighter Stabilization During Wing Tip Attachment To B-50 Bomber

Prepared In Connection With

Phase I of Air Force Project MX-1016

By

E. Fricke
E. Fricke

and

C. H. Pierce, Jr.
C.H. Pierce, Jr.

Approved by: W. J. O'Donnell
~~W. J. O'Donnell~~
Chief Development Engineer

A Kartveli per MEW
A. Kartveli
Chief Engineer

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S-1-72
Rev. 2/49

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I INTRODUCTION

The purpose of Air Force Project MX-1016 is to determine the feasibility of attaching F-84 fighters to the wing tips of B-29 or B-50 bombers for long range towing. This report describes the work accomplished during Phase I of the project in connection with the preliminary design of the control system components required to maintain the F-84 aircraft in proper relationship to the B-50 aircraft.

In the dynamic stability studies of the B-50 - F-84 airplane configuration described in Reference 1, two types of wing tip attachment were considered. These were (A) a coupling in which the F-84 is free to roll about the wing tip joint but restrained both in pitch and yaw, and (B) a coupling in which the F-84 is free to roll and pitch about the wing tip joint but restrained in yaw only. It was assumed in the stability investigations for both types of couplings that an automatic control system could be designed which would operate the F-84 control surfaces to effect a desired damped oscillation determined by the dynamic stability study. The control system was assumed to respond to input signals proportional to the angular misalignment angle between the B-50 and F-84 wings, β, and the rate of change of this angle, $\dot{\beta}$. The results of the dynamic stability study indicate that stabilization of the F-84 may be possible for either of the two types of coupling considered.

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Stabilization of the F-84 when attached to the B-50 by a wing tip coupling which allows freedom in roll only is indicated to be feasible if the F-84 is controlled by its ailerons acting as plain flaps. For this attachment and mode of control the F-84 oscillation resulting from pitch and/or roll disturbance of the B-50 - F-84 combination will be suitably damped if the ailerons are moved, both in the same direction, so that the aileron angle, δ_a, is equal to $K\beta$. Preliminary calculations show that stability will be obtained if K has a value of approximately - 3.

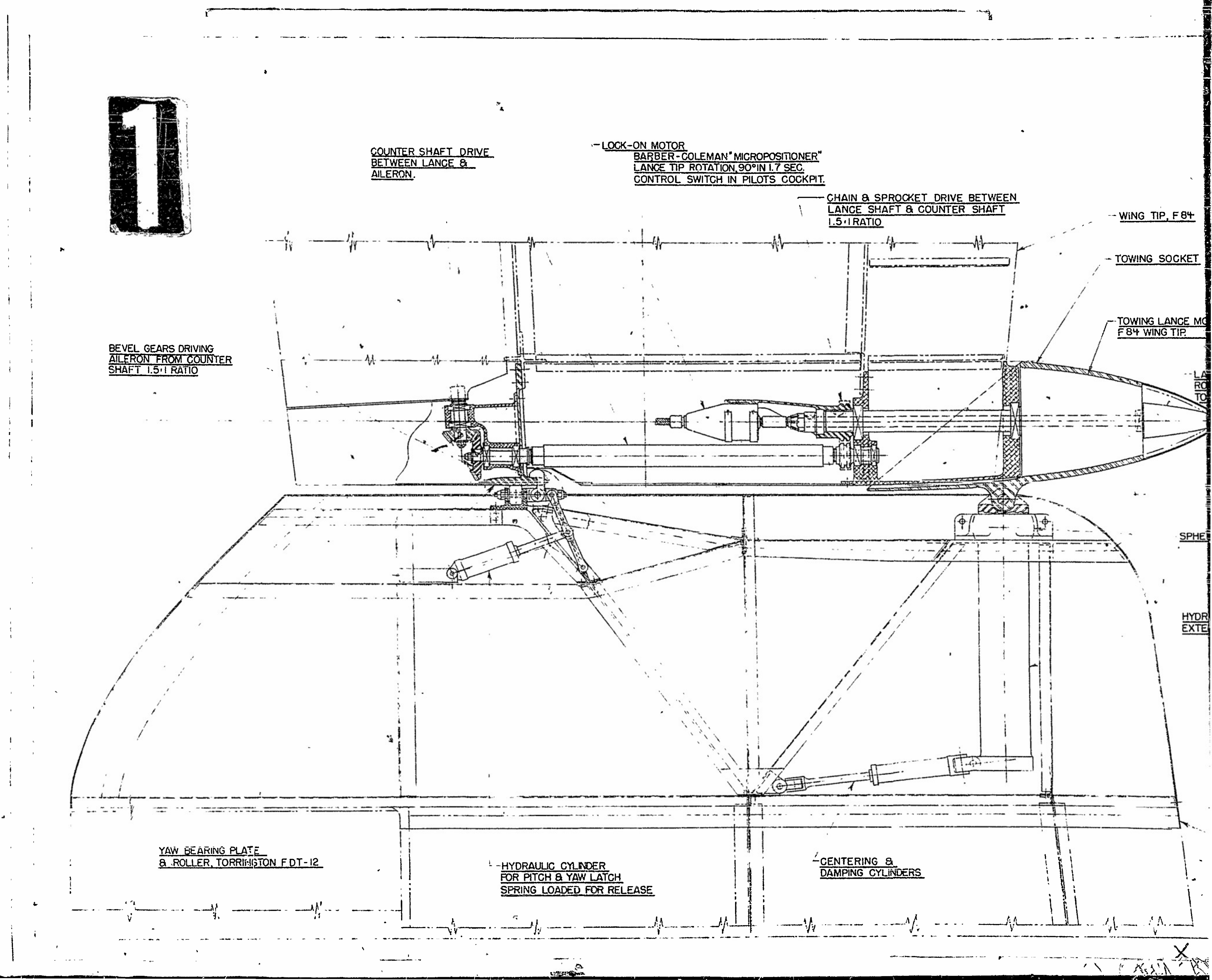
For the coupling in which the F-84 is free to pitch and roll about the wing tip joint but restrained in yaw, the stability study indicates that the oscillations of the F=84 resulting from pitch and/or roll disturbances of the B-50 - F-84 combination will be suitably damped if the F-84 elevator is controlled so that the elevator angle, δ_e, is equal to $a\dot{\beta} + b\beta$ and the B-50 flight is controlled by the B-50 autopilot to reduce gust disturbance effects to a minimum. Preliminary calculations give values for a and b of 0.1 and 0.2 respectively.

II <u>Aileron Control Of F-84 For Coupling With F-84 Free To Roll But Restrained In Pitch and Yaw</u>

With the F-84 and B-50 wing tips coupled by a two point attachment so that the F-84 is free to roll about the attachment but restrained in pitch and yaw, the dynamic stability study indicates that the F-84 can be stabilized by using the ailerons as plain flaps if the aileron motion is defined by the equation $\delta_a = K\beta$ and $K \approx$ approximately - 3. This type of control was investigated separately for pitching and rolling disturbances of the B-50 - F-84 combination but the preliminary studies did not consider simultaneous pitching and rolling disturbances or the effects of wing elasticity. Further investigations may show that the ailerons should be controlled so that the aileron angle varies as a function of both β and $\dot{\beta}$ which will increase the complexity of the necessary automatic control system.

On the assumption that the F-84 can be suitably stabilized by moving the ailerons in proportion to the angular misalignment between the F-84 and B-50 wings, control can be accomplished by either a direct mechanical link between the wing tip coupling mechanism and the aileron system or by a servo system which moves the ailerons in proportion to wing misalignment angles. For the servo system, wing misalignment angles would be detected by a synchro mounted on the rotating shaft of the wing tip attachment lance. If further studies of this mode of control show that addition of rate control is not required, the simple mechanical linkage for operating the aileron as shown in Fig. 1 (R.A.C. Dwg. X-20150) will be satisfactory.

For operation of both ailerons in the same direction a device for changing from differential operation to flap type operation must be included in the F-84 aileron system. R.A.C. Dwg. X-20150 (Fig. 1) shows the proposed F-84 aileron connection linkage at fuselage station 167 in which the right aileron control rods are connected to the left aileron control rods by two hydraulically operated cylinders. For normal aileron operation one cylinder is hydraulically operated to its proper fixed length and locked in position so that the right aileron moves differentially


1
COUNTER SHAFT DRIVE BETWEEN LANCE & AILERON.
LOCK-ON MOTOR
BARBER-COLEMAN "MICROPOSITIONER"
LANCE TIP ROTATION, 90° IN 1.7 SEC.
CONTROL SWITCH IN PILOTS COCKPIT.
CHAIN & SPROCKET DRIVE BETWEEN LANCE SHAFT & COUNTER SHAFT 1.5:1 RATIO
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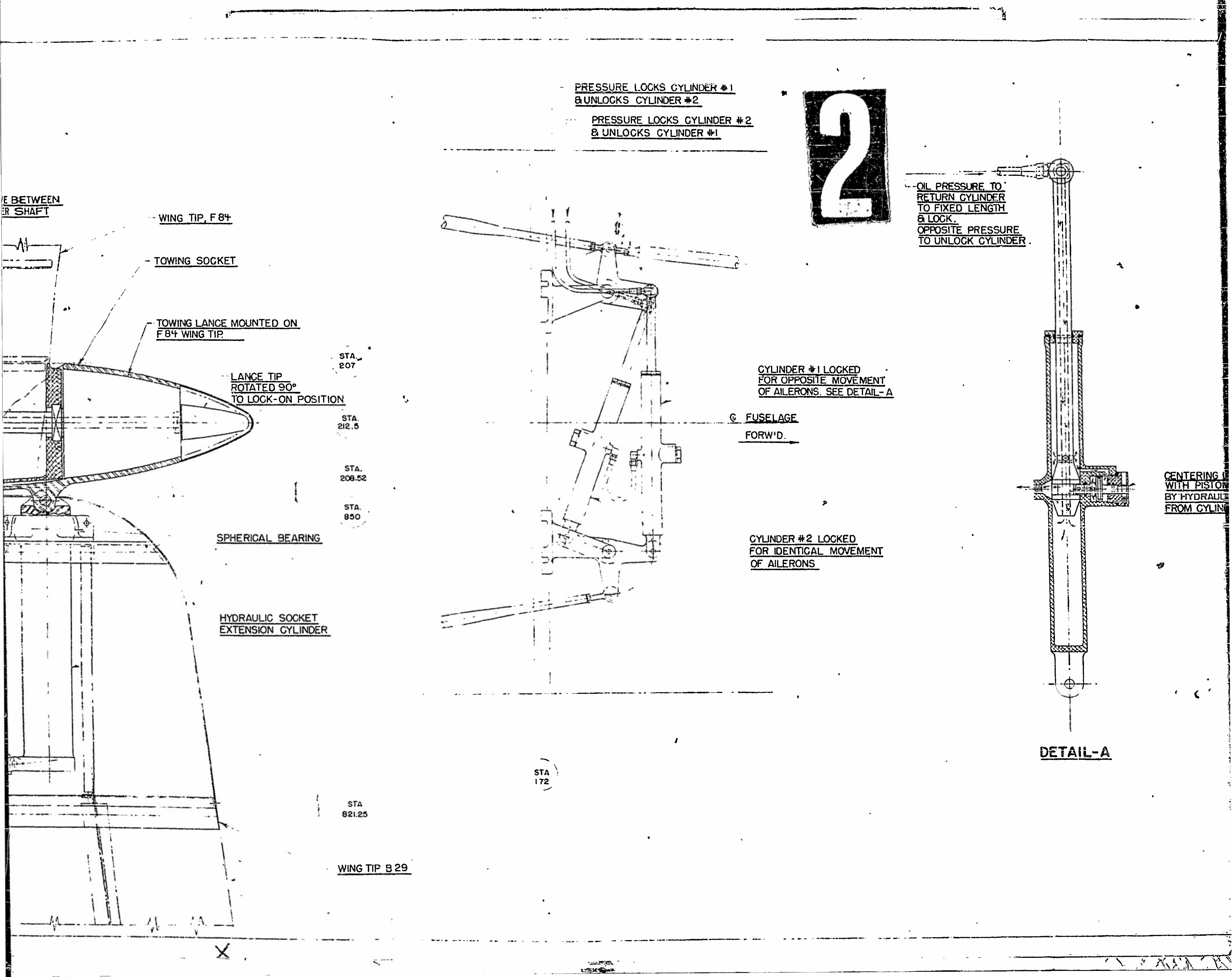
TOWING SOCKET
F84 WING TIP
BEVEL GEARS DRIVING AILERON FROM COUNTER SHAFT 1.5:1 RATIO
YAW BEARING PLATE & ROLLER, TORRINGTON FDT-12
HYDRAULIC CYLINDER FOR PITCH & YAW LATCH SPRING LOADED FOR RELEASE
CENTERING & DAMPING CYLINDERS


2
PRESSURE LOCKS CYLINDER #1 & UNLOCKS CYLINDER #2
PRESSURE LOCKS CYLINDER #2 & UNLOCKS CYLINDER #1
E BETWEEN
ER SHAFT
WING TIP, F 84
TOWING SOCKET
TOWING LANCE MOUNTED ON F 84 WING TIP
LANCE TIP ROTATED 90° TO LOCK-ON POSITION
STA. 207
STA. 212.5
STA. 208.52
STA. 850
SPHERICAL BEARING
HYDRAULIC SOCKET EXTENSION CYLINDER
STA 172
STA 821.25
WING TIP B 29
OIL PRESSURE TO RETURN CYLINDER TO FIXED LENGTH & LOCK. OPPOSITE PRESSURE TO UNLOCK CYLINDER.
CYLINDER #1 LOCKED FOR OPPOSITE MOVEMENT OF AILERONS. SEE DETAIL-A
℄ FUSELAGE
FORW'D.
CYLINDER #2 LOCKED FOR IDENTICAL MOVEMENT OF AILERONS
CENTERING
WITH PISTON
BY HYDRAUL
FROM CYLIN
DETAIL-A
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3

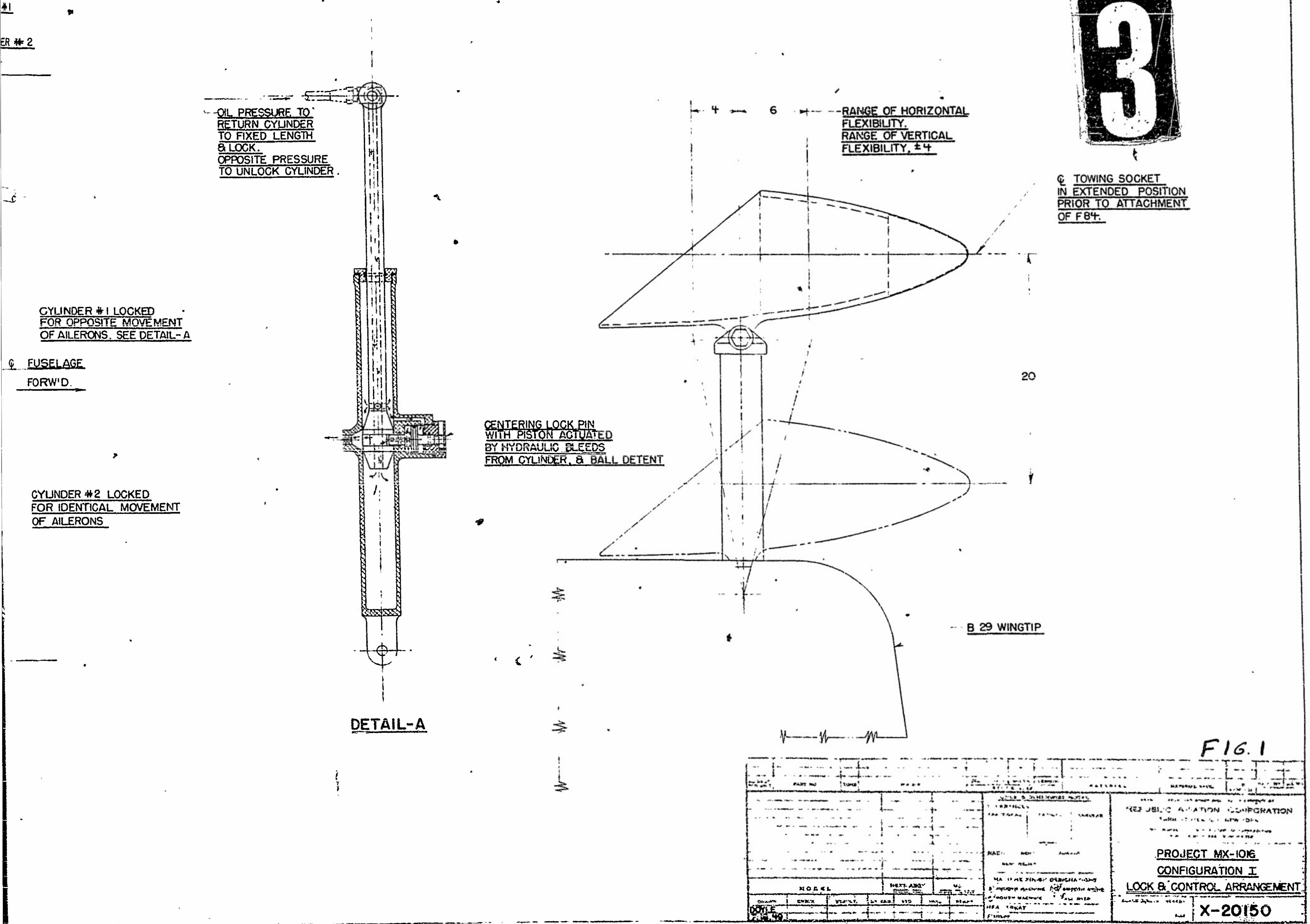

OIL PRESSURE TO RETURN CYLINDER TO FIXED LENGTH & LOCK. OPPOSITE PRESSURE TO UNLOCK CYLINDER.
CYLINDER #1 LOCKED FOR OPPOSITE MOVEMENT OF AILERONS. SEE DETAIL-A
℄ FUSELAGE
FORW'D.
CYLINDER #2 LOCKED FOR IDENTICAL MOVEMENT OF AILERONS
CENTERING LOCK PIN WITH PISTON ACTUATED BY HYDRAULIC BLEEDS FROM CYLINDER, & BALL DETENT
DETAIL-A
4
6
RANGE OF HORIZONTAL FLEXIBILITY.
RANGE OF VERTICAL FLEXIBILITY, ±4
℄ TOWING SOCKET IN EXTENDED POSITION PRIOR TO ATTACHMENT OF F84.
20
B 29 WINGTIP
REPUBLIC AVIATION CORPORATION
PROJECT MX-1016
CONFIGURATION I
LOCK & CONTROL ARRANGEMENT
X-20150

FIG. 1

with respect to the left aileron and the other cylinder is free to lengthen or shorten as required. For the flap type of aileron operation, the other cylinder is hydraulically operated to its proper length and locked in position and the first cylinder is free to change length.

An investigation was made of the servo power and speed required for operating the ailerons in accordance with the equation $\delta a = -3\dot{\beta}$ in order to determine probable servo motor characteristics for use as a basis of servo system design in the event that mechanical coupling of the ailerons to the wing tip attachment mechanism proves undesirable. The amplitudes of the wing misalignment angle, β, and the rate of change of this angle, $\dot{\beta}$, during a rolling oscillation of the F-84 relative to the B-50 were assumed to be greatest for a simultaneous pitching and rolling disturbance of the B-50 - F-84 combination. To estimate the probable order of magnitude of β and $\dot{\beta}$, the curves plotted in the dynamic stability study showing the variation with time of β and $\dot{\beta}$ for separate pitch and roll disturbances at time $t = 0$ were superimposed and resultant curves of β and $\dot{\beta}$ were drawn by adding ordinates algebraically. The resultant $\dot{\beta}$ curve was coordinated with the resultant β curve so that $\dot{\beta}$ was zero for the maximum value of β, thus making the estimate more conservative. The variations of β and $\dot{\beta}$ with time during the latter part of the first quarter cycle of the F-84 rolling oscillation obtained by this method and the corresponding values of $\ddot{\beta}$ are shown in Fig. 2. It is realized that this method of estimating maximum values of β, $\dot{\beta}$ and $\ddot{\beta}$ gives only approximate results but it was used in this instance since no data on oscillations resulting from simultaneous pitching and rolling

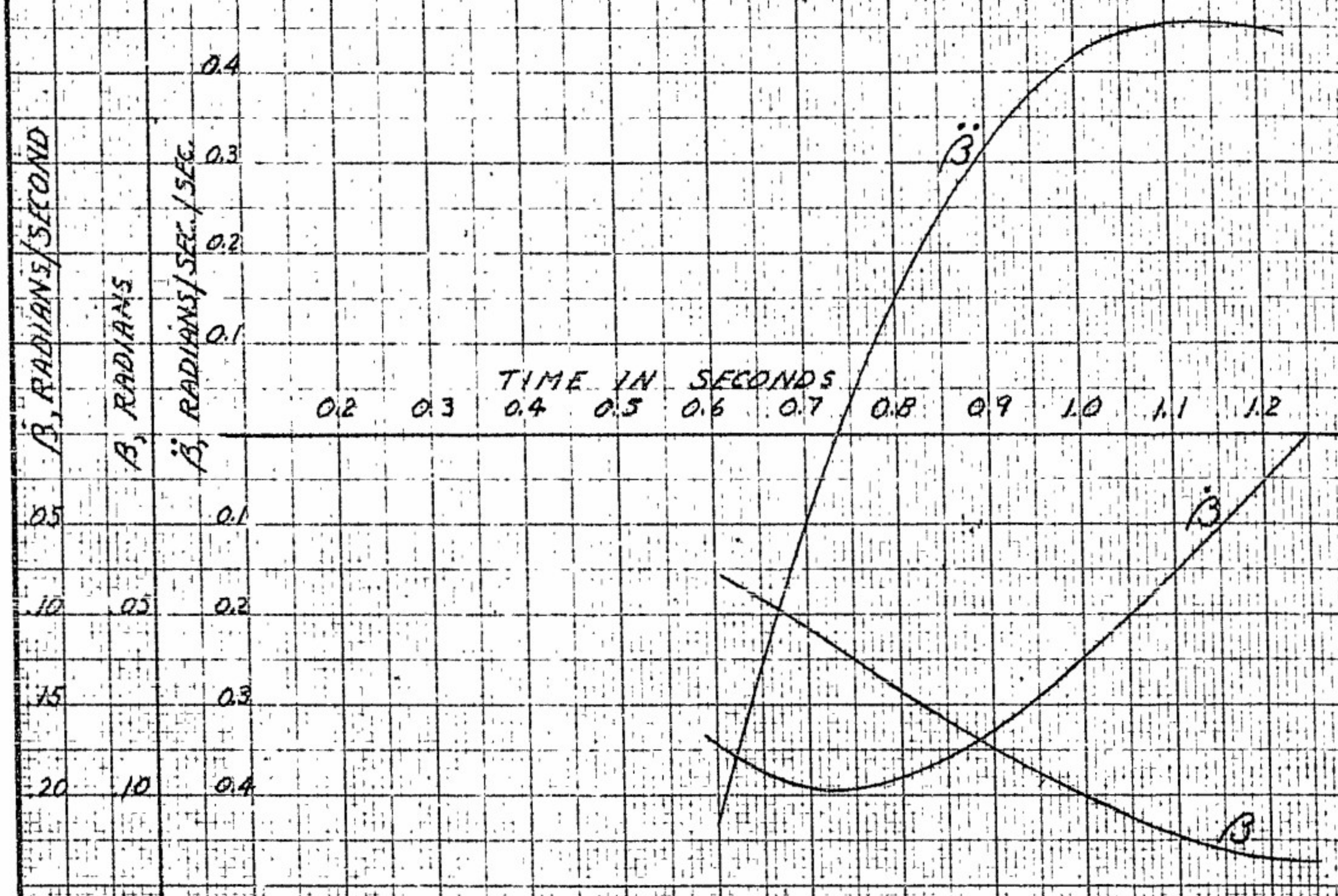


FIG. 2

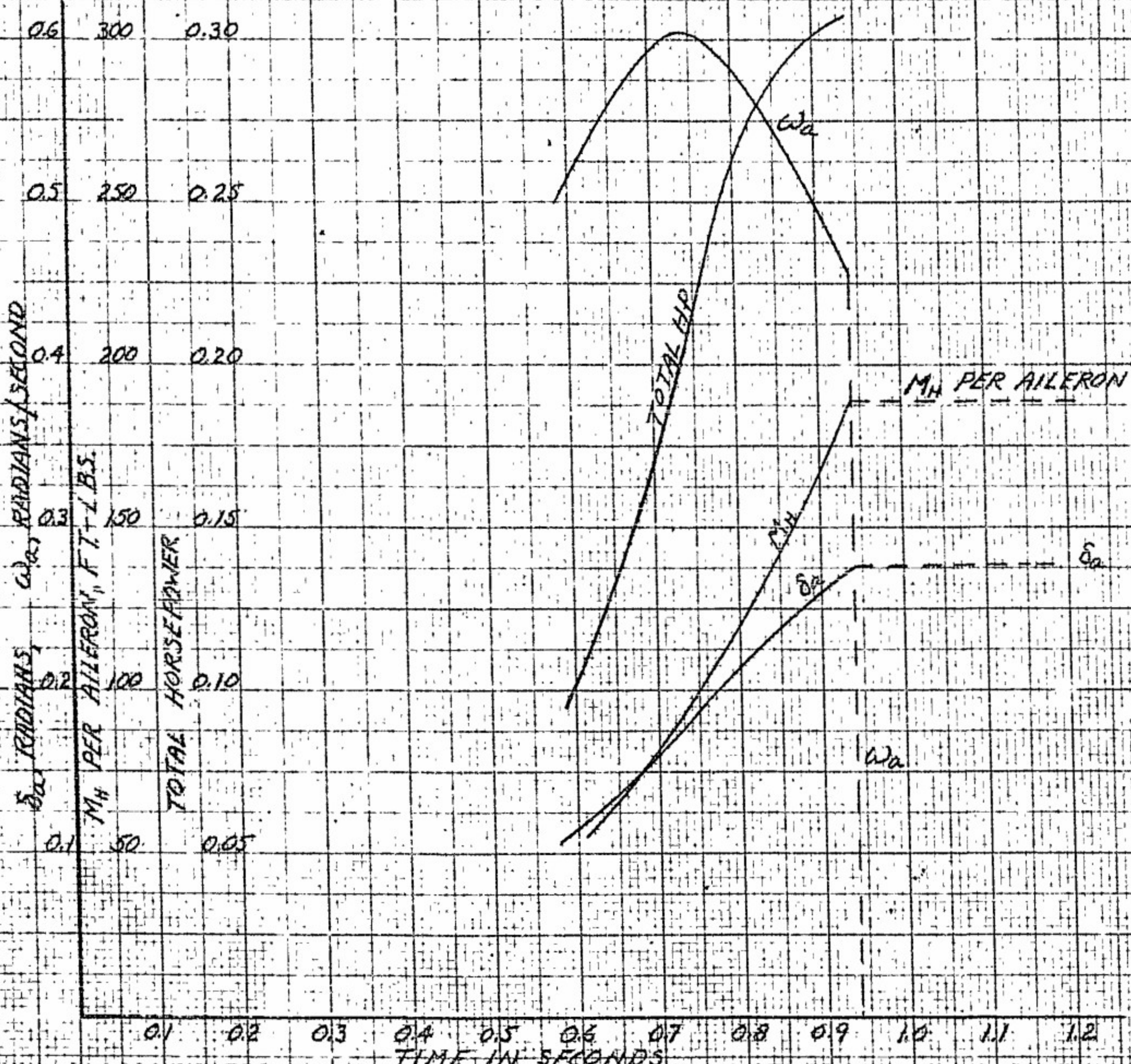
ESTIMATED VALUES OF β, $\dot{\beta}$, AND $\ddot{\beta}$ FOR SIMULTANEOUS ROLL AND PITCH DISTURBANCE disturbances of the B-50 - F-84 combination was determined during the preliminary dynamic stability study.

For aileron control with $\delta_a = -3\beta$, and for negative values of β, positive or downward aileron deflections are required. Movement of the ailerons in direct proportion to β is possible until the ailerons reach their angular deflection limit at + 16 degrees (0.279 radians) which corresponds to a wing misalignment angle of $\beta = -0.093$ radians. Therefore, for the simultaneous pitching and rolling disturbance assumed, the ailerons can move in direct proportion to the wing misalignment angle until they reach their limits, but after that must hold their maximum deflection until the wing misalignment angle passes through its maximum value and reduces to 0.093 radians. This will result in a different type of β versus time curve than that assumed for the simultaneous pitching and rolling disturbance, but for less severe disturbances where the maximum amplitude of β is 0.093 radians or less the probable shape of the oscillation curve will be similar to that shown in Fig. 2.

The maximum servo horsepower required was computed from values of aileron angle, δ_a, aileron angular velocity, ω_a, and hinge moment per aileron, M_H, corresponding to values of β plotted in Fig. 2. δ_a and ω_a were calculated from the relationships $\delta_a = -3\beta$ and $\omega_a = -3\dot{\beta}$ respectively and values of M_H corresponding to δ_a were determined from data presented in Reference 2. Horsepower was computed by the formula $HP = \frac{2 M_H \omega_a}{550}$ which neglects the very small torque required to overcome the aileron inertia. Curves showing the computed values of δ_a, ω_a, M_H, and total horsepower required to drive both ailerons are shown in Fig. 3.

FIG. 3

CALCULATED VALUES OF AILERON MOTION, TOTAL HORSEPOWER, AND HINGE MOMENT



The F-84 aileron control system is shown schematically in Fig. 4. The assumption was made that a two phase induction servo similar to Bendix type 15601-1 will be used to operate the ailerons and that it will be connected to point b of the booster control arm with a linkage that will move lever b in exactly the same way as the pilot's control stick does. On this basis the angular relationship between the servo and the ailerons will be the same as that which exists between the control stick and the ailerons. The angular relationship between control stick travel and left aileron travel, plotted in Fig. 5, was obtained from Reference 3. From this data the angular transfer coefficients, C_T = stick angle divided by aileron angle, was calculated and plotted as shown in Fig. 6. Stick angular velocities, ω_s, corresponding to aileron angular velocities, ω_a, plotted in Fig. 3, were calculated by the formula $\omega_s = C_T \omega_a$ where C_T is the coefficient corresponding to values of δ_a plotted in Fig. 3. The required torque was computed from the relationship $T = \frac{550 \times HP}{\omega_s}$, using values of horsepower plotted in Fig. 3. Assuming that the servo is linked to lever b of the aileron control system in the same manner as the pilots' control stick, the calculated servo speeds and torques are as shown in Fig. 7. The calculation indicates that the servo should have a maximum speed of at least 10 R.P.M. and a stalling torque of about 200 ft.-lb. if the available aileron booster is not used. Utilizing the 10.18 to 1 boost ratio of the hydraulic aileron booster cylinder a servo with a stalling torque of approximately 20 ft.-lbs. might be adequate, providing the aileron booster has sufficiently fast response.

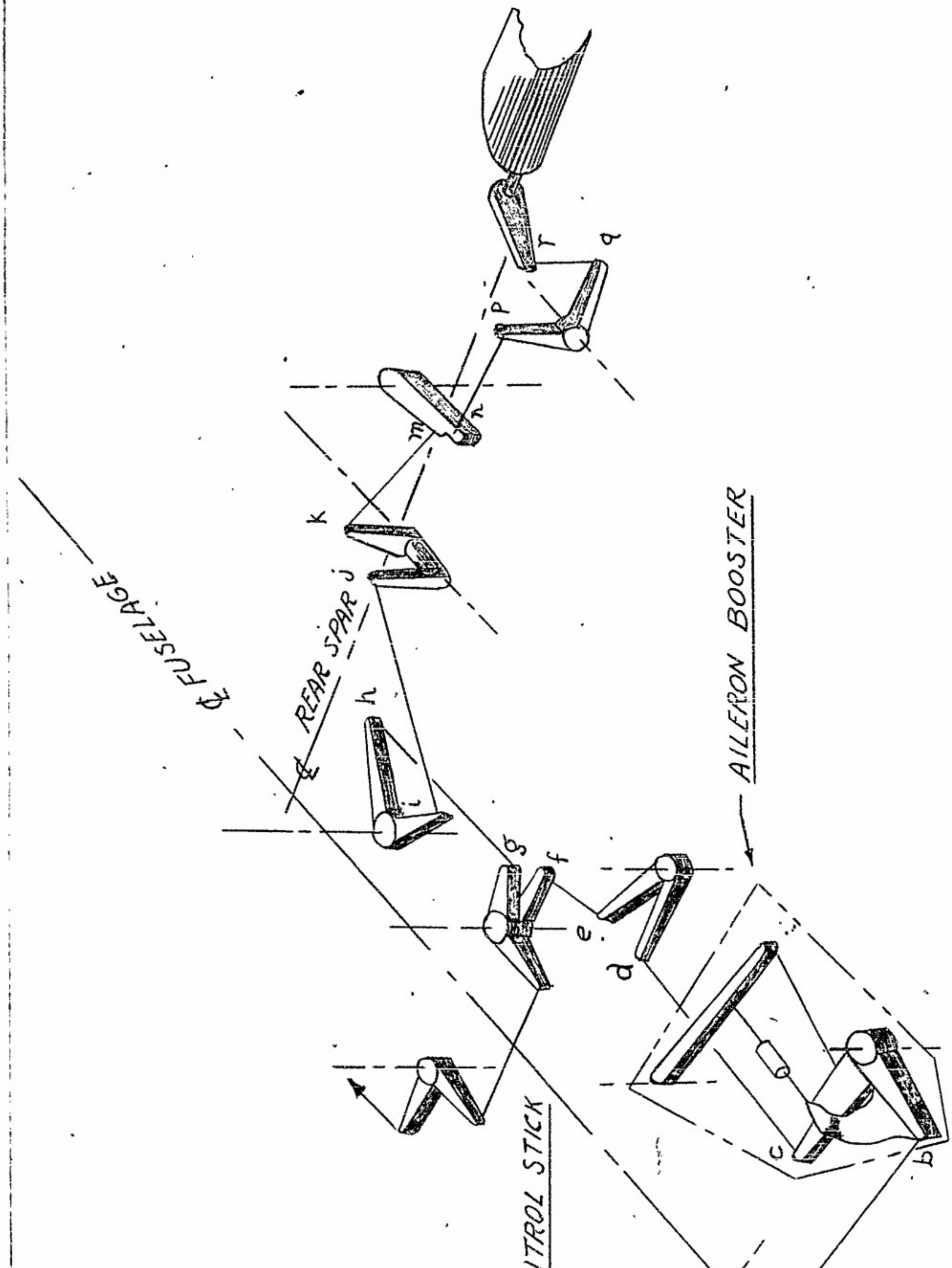
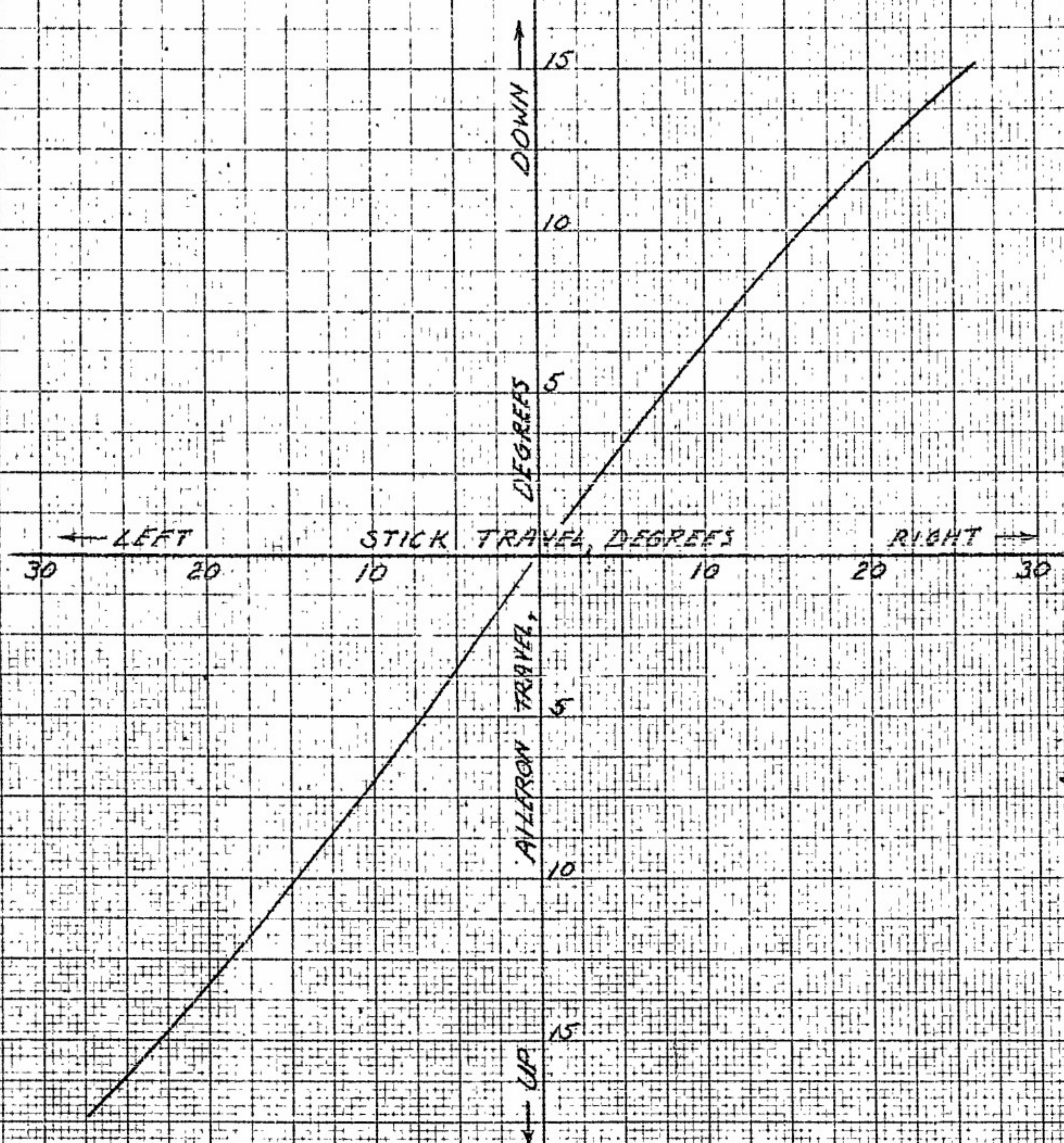


FIG. 4. AILERON CONTROL SYSTEM, F84-E

FIG. 5

ANGULAR RELATIONSHIP BETWEEN STICK TRAVEL AND LEFT AILERON TRAVEL



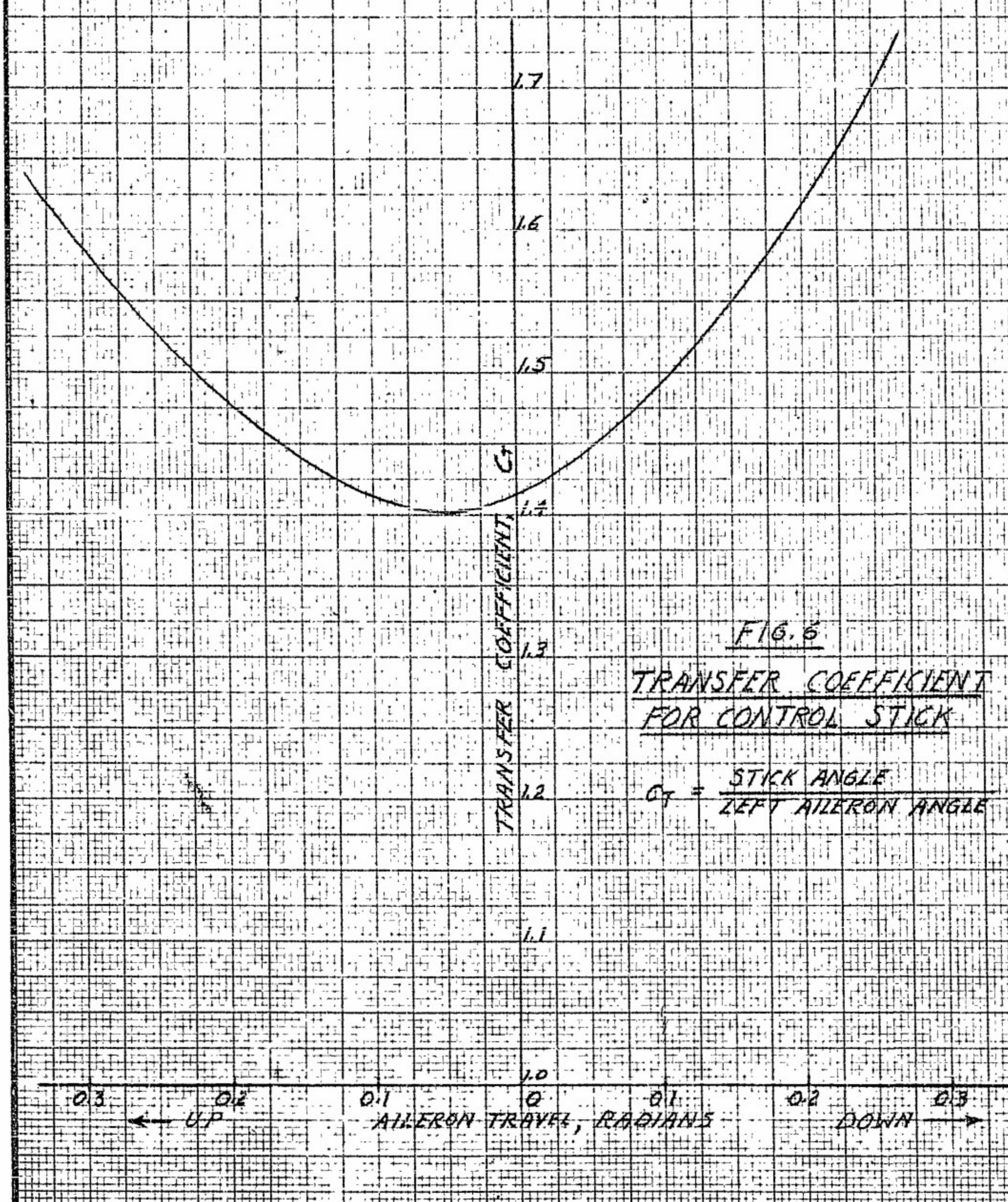


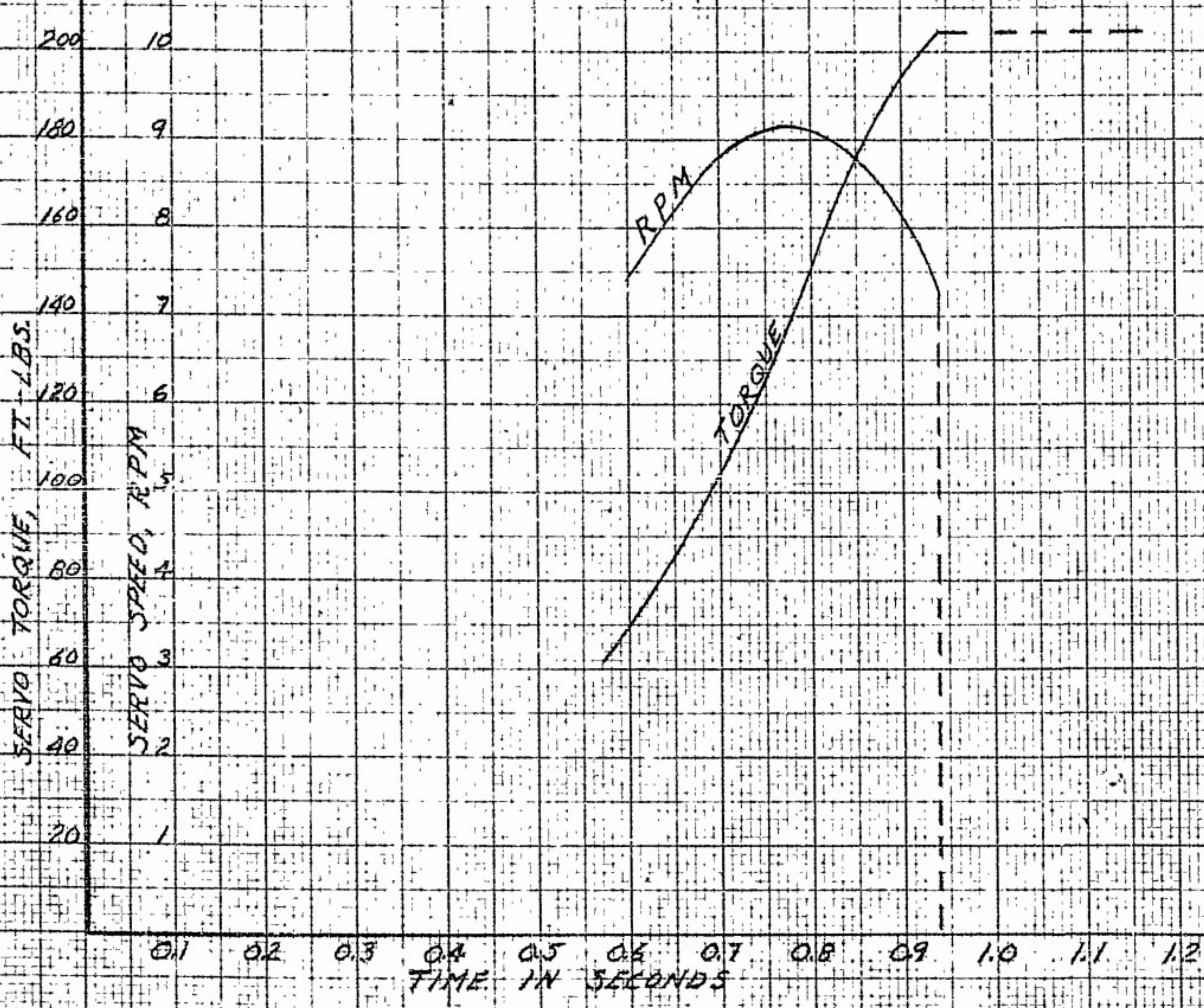
FIG. 6

TRANSFER COEFFICIENT FOR CONTROL STICK

$$C_T = \frac{\text{STICK ANGLE}}{\text{LEFT AILERON ANGLE}}$$

FIG. 7

CALCULATED SERVO SPEED AND TORQUE FOR AILERON CONTROL



A probable servomechanism for controlling the aileron angle in direct proportion to the wing misalignment angle is shown in block diagram form in Fig. 8. Assuming that rate control is not necessary, the system will consist of the following components:

(a) Displacement Signal Autosyn, Similar to Bendix Type AY-101D

(b) Servo, Similar to Bendix Type 15601, With Rate Generator, Magnetic Servo Disconnect and Pulley

(c) Clutch Switch, Bendix Type CQ-9

(d) Pilot's Clutch Release Switch

(e) Aileron Follow-Up Autosyn, Similar to Bendix Type AY-101D

(f) Amplifier Unit, Similar to Bendix Type 12319-1

(g) Power Supply, 3 Phase 115 Volts 400 Cycle A.C. and 28 Volts D.C.

In addition to these components the final design may also include a rate gyro equipped with an inductive type pickup, similar to Bendix type 786972 as shown by dashed lines in the block diagram of Fig. 8. Equations have been derived for use in the design and analysis of the aileron control system, and are described in detail in Section IV.

III Elevator Control Of F-84 For Coupling With F-84 Free To Roll And Pitch But Restrained In Yaw

The dynamic stability study indicates that for the coupling in which the F-84 is free to pitch and roll about the wing tip joint but restrained in yaw the F-84 can be suitably stabilized by moving its elevator

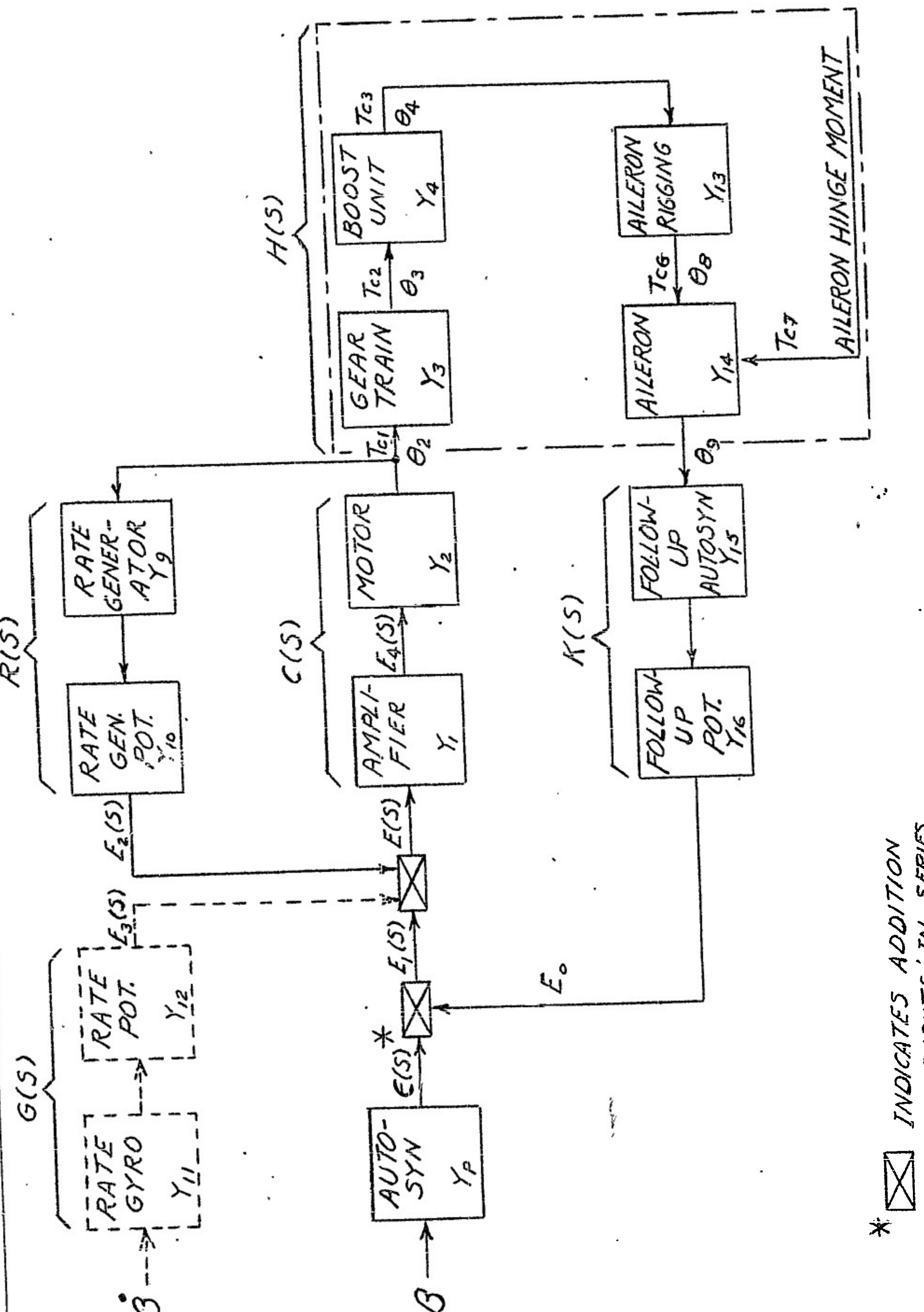


FIG. 8 BLOCK DIAGRAM FOR AILERON CONTROL ANALYSIS

in proportion to the wing misalignment angle and the rate of change of the wing misalignment angle, i.e., $\delta_e = f(\beta, \dot{\beta})$. Independent studies of the flapping and pitching motions of the F-84 for pitching and rolling disturbances of the B-50 - F-84 combination indicate that the oscillations of the F-84 will be suitably damped if $\delta_e = 0.1\,\dot{\beta} + 0.2\,\beta$.

In order to estimate speed and torque requirements for moving the elevator as required, it was assumed that the variation of β, $\dot{\beta}$, and $\ddot{\beta}$ with time when using elevator control and a single point attachment would be similar to that estimated for the two point attachment with aileron control as shown in Fig. 2. The values of δ_e and $\dot{\delta}_e$ during the last half of the first quarter cycle of the F-84 oscillation were computed from the equations $\delta_e = 0.1\,\dot{\beta} + 0.2\,\beta$ and $\dot{\delta}_e = 0.1\,\ddot{\beta} + 0.2\,\dot{\beta}$, using values of β, $\dot{\beta}$, and $\ddot{\beta}$ shown in Fig. 2. The estimated variations of δ_e and $\dot{\delta}_e$ with time for the portion of the F-84 oscillation considered are plotted in Fig. 9. These curves indicate a maximum elevator angle of approximately 2 degrees and a maximum elevator angular velocity of about 4 degrees per second (.67 RPM). Since the elevator hinge moment for the F-84 is about 20 ft. lbs. for an elevator angle of 2 degrees at a cruising speed of 300 miles per hour, the servo motor required for the elevator control system must have a stalling torque of at least 20 ft. lbs. and a maximum speed of about 0.67 RPM. The rate gyro must be sensitive to wing angular velocities up to 11.5 degrees per second.

The proposed servomechanism for controlling the F-84 elevator as a function of β and $\dot{\beta}$ is very similar to that required for aileron

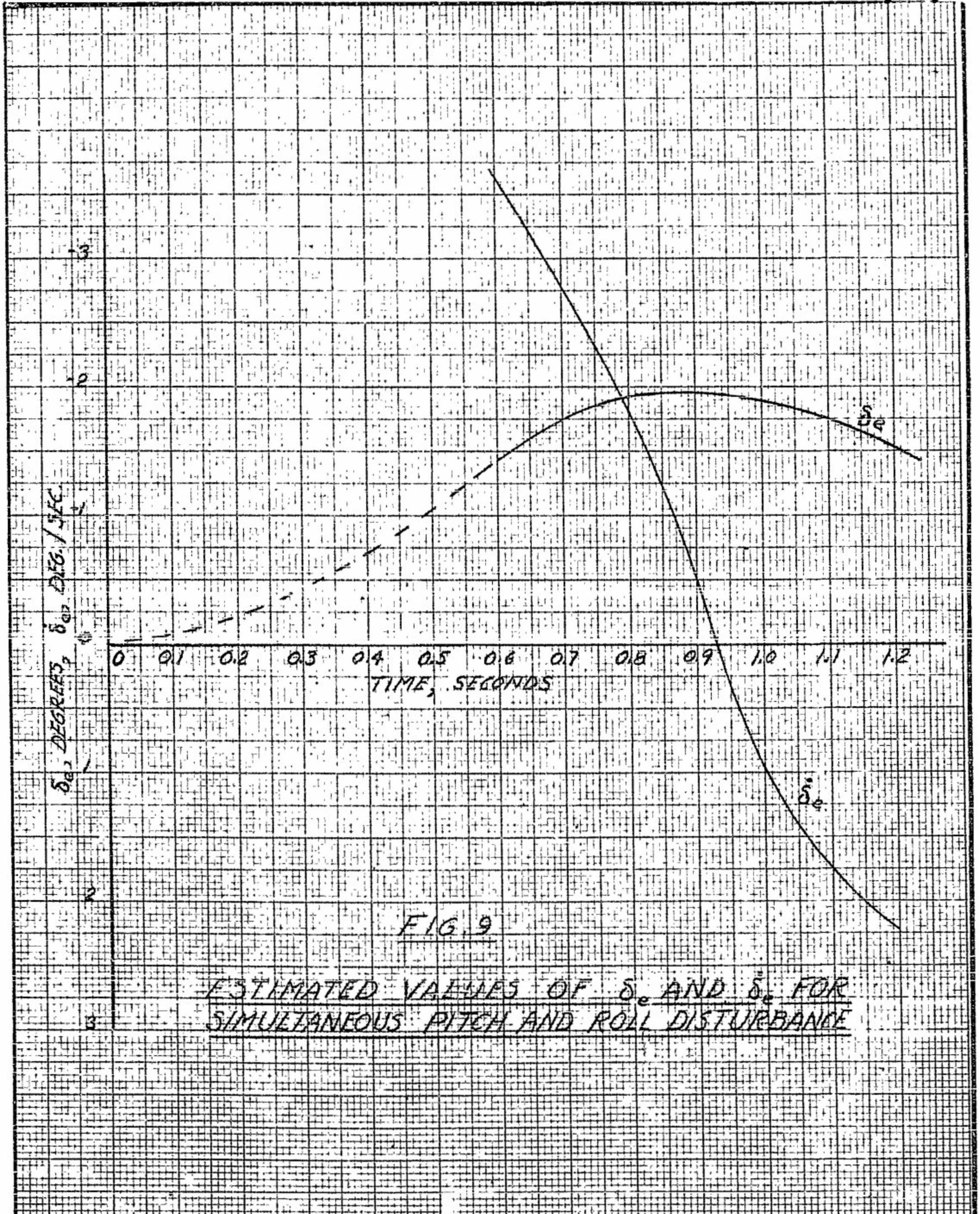


FIG. 9

ESTIMATED VALUES OF δ_e AND $\dot{\delta}_e$ FOR SIMULTANEOUS PITCH AND ROLL DISTURBANCE control with the two point attachment as discussed in Section II and is shown in block diagram form in Fig. 10. The system will consist of the following components:

(a) Displacement Signal Autosyn, Similar to Bendix Type AY-101D

(b) Servo, Similar to Bendix Type 15602-0 With Rate Generator, Magnetic Servo Disconnect, and Pulley

(c) Clutch Switch, Bendix Type CQ-9

(d) Pilot's Clutch Release Switch

(e) Elevator Follow-Up Autosyn, Similar to Bendix Type AY-101D

(f) Amplifier Unit, Similar to Bendix Type 12319-1

(g) Rate Gyro With Inductive Type Pick-Up, Similar to Bendix Type 786972

(h) Power Supply, 150 VA, 400 Cycles, 3 Phase, 115 Volts A.C. and 28 Volts D.C.

The estimated maximum weight of the complete servomechanism, less the power supply, is 20 lbs.

In the proposed system the wing misalignment angle would be measured by the displacement signal autosyn mounted on the rotating shaft of the F-84's wing tip attachment lance. Rate of change of the wing misalignment angle would be measured by the rate gyro mounted in the wing tip. The servo should be mounted as close to the elevator as possible and coupled to the elevator torque tube by a cable and pulley type of rigging. The follow-up autosyn would be mounted directly on the elevator torque tube. Equations based on the block diagram of Fig. 10 for use in the design and analysis of the elevator control system have been derived and are outlined in Section IV.

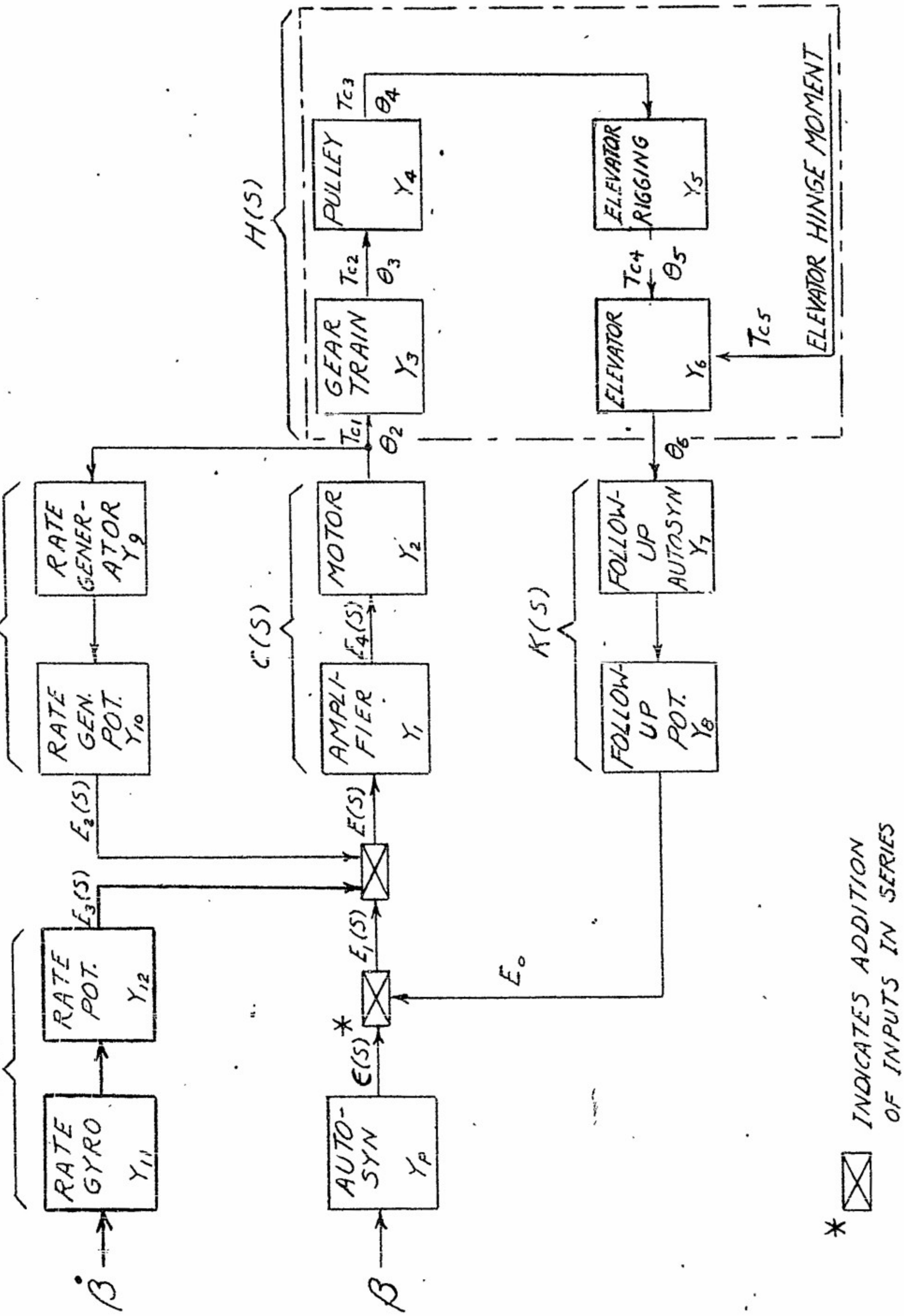


FIG. 10 BLOCK DIAGRAM FOR ELEVATOR CONTROL ANALYSIS

IV Equations For Analysis Of Aileron Control For System With Freedom In Roll Only And Elevator Control For System With Freedom In Roll And Pitch

1. Symbols

Symbols used in the equations developed in parts 2 and 3 are defined as follows:

β	Angular displacement in roll of F-84 relative to B-50.
$\dot{\beta}$	Angular roll velocity of F-84 relative to B-50.
θ_2	Angle of rotation of servo motor shaft.
θ_3	Angle of rotation of servo motor gear train output shaft.
θ_4	Angle of rotation of aileron booster output lever (in aileron control system) or servo output pulley (in elevator control system).
θ_5	Angle of rotation of elevator rigging output shaft.
θ_6	Angle of rotation of elevator with reference to zeroed position when β is zero.
θ_8	Angle of rotation of aileron rigging output lever.
θ_9	Angle of rotation of aileron relative to zeroed position when β is zero.
Y_1	Transfer function for amplifier.
Y_2	Transfer function for motor.
Y_3	Transfer function for gear train.
Y_4	Transfer function for aileron booster (in aileron control system) or servo pulley (in elevator control system).
Y_5	Transfer function for elevator rigging.
Y_6	Transfer function for elevator.

Y_7	Transfer function for elevator follow-up autosyn.
Y_8	Transfer function for elevator follow-up potentiometer.
Y_9	Transfer function for servo rate generator.
Y_{10}	Transfer function for rate generator potentiometer.
Y_{11}	Transfer function for rate gyro.
Y_{12}	Transfer function for rate gyro potentiometer.
Y_{13}	Transfer function for aileron rigging.
Y_{14}	Transfer function for aileron.
Y_{15}	Transfer function for aileron follow-up autosyn.
Y_{16}	Transfer function for aileron follow-up potentiometer.
Y_p	Transfer function for signal autosyn at wing tip joint.
T_{c1}	Output torque of servo motor.
T_{c2}	Output Torque of gear train.
T_{c3}	Output torque of aileron booster (in aileron control system) or servo pulley (in elevator control system).
T_{c4}	Output torque of elevator rigging.
T_{c5}	Elevator hinge moment.
T_{c6}	Output torque of aileron rigging.
T_{c7}	Aileron hinge moment.
T_{cs1}	Inertia and damping torque within the servo.
T_{cs2}	Inertia and damping torque of ailerons or elevator.
E	Input signal to amplifier grid.
E_o	Follow-up autosyn feedback signal.
E_1	Error signal.
E_2	Internal feedback signal from servo rate generator.
E_3	Signal from rate gyro.

E_4	Input signal to servo motor.
ϵ	Input signal to control system.
k_r	Response function for rate generator.
k_m	Angular transfer function for servo motor.
k_d	Angular transfer function for gear train.
k_g	Response function for rate gyro.
k_1	Angular transfer function for elevator rigging.
k_2	Angular aileron transfer function.
k_{10}	Elevator stiffness.
k_{20}	Aileron stiffness.
k_B	Mechanical advantage of aileron booster.
k_c	Linear stiffness of elevator cable according to Young's law.
k_e	Elevator rigging stiffness.
J_1	Effective moment of inertia of servo system relative to motor shaft.
J_2	Effective moment of inertia of aileron or elevator about hinge.
J_9	Moment of inertia of servo gear train less input and output gears relative to servo motor shaft.
J_r	Effective moment of inertia of elevator rigging relative to servo motor shaft.
J_m	Moment of inertia of servo motor shaft including one gear.
f_1	Effective friction coefficient of servo.
f_2	Effective friction and vortice damping coefficient for aileron or elevator.
α	Angle of attack, F-84 wing.
α_t	Angle of attack, F-84 tail.
C_{10}	Elevator hinge moment coefficient ratio.

C_{20}	Aileron hinge moment coefficient ratio.
C_{He}	Elevator hinge moment coefficient.
C_{Ha}	Aileron hinge moment coefficient.
C_e	Mean elevator chord aft of hinge.
C_a	Mean aileron chord aft of hinge.
S_e	Total surface area of elevator aft of hinge.
S_a	Total surface area of ailerons aft of hinge.
P_d	Dynamic air pressure on elevator or aileron.
s	Laplace operator.
r_1	Radius of servo pulley for elevator control system.
r_2	Radius of elevator pulley.
L	One half the length of the elevator cable.
C	Effective torque transfer function for amplifier and motor.
H	Effective torque transfer function for entire load.
K	Transfer function for follow-up autosyn unit.
G	Transfer function for rate gyro unit.
R	Transfer function for rate generator unit.
(S)	Symbol indicating a function of a complex variable.

2. Aileron Control For System With Freedom In Roll Only

A. Response Functions

Consideration of Fig. 8 leads to the following evaluation of response functions, all of which are functions of a complex variable, the symbol (S) being omitted in some instances for simplification:

$$E_1 = \epsilon - E_o = \beta Y_p - E_o = \text{Error Function} \tag{1}$$

$$E = E_1 - E_2 - E_3 = \beta Y_p - E_o - E_2 - E_3 = \text{Amplifier Input} \tag{2}$$

$$T_{c1} = EC(S) = (\beta Y_p - E_o - E_2 - E_3)\, C(S) = \text{Servo Motor Torque} \tag{3}$$

$$\theta_2 = k_m T_{c1} \tag{4}$$

$$\theta_9 = H(S)\, T_{c1} = H(S)\, C(S)\, (\beta Y_p - E_o - E_2 - E_3) \tag{5}$$

$$E_o = K(S)\, \theta_9 = H(S)\, C(S)\, K(S)\, (\beta Y_p - E_o - E_2 - E_3) \tag{6}$$

$$E_2 = R(S)\, \theta_2 = R(S)\, k_m T_{c1} = R(S)\, C(S)\, k_m (\beta Y_p - E_o - E_2 - E_3) \tag{7}$$

$$E_3 = G(S)\beta = Y_{12} k_g s \beta \tag{8}$$

$$E = \frac{T_{c1}}{C(S)} = \frac{\theta_9}{C(S)\, H(S)} \tag{9}$$

$$\beta Y_p - K(S)\, \theta_9 - R(S)\, \theta_2 - G(S)\beta = \frac{\theta_9}{C(S)\, H(S)} \tag{10}$$

$$\beta Y_p - K(S)\, \theta_9 - \frac{R(S)\, k_m \theta_9}{H(S)} - G(S) = \frac{\theta_9}{C(S)\, H(S)} \tag{11}$$

$$\theta_9 \left[1 + R(S)\, C(S)\, k_m + K(S)\, C(S)\, H(S)\right] = C(S)\cdot H(S) \left[Y_p - G(S)\right] \tag{12}$$

$$\frac{\theta_9}{\beta} = \frac{\left[Y_p - G(S)\right]\, C(S)\, H(S)}{1 + R(S)\, C(S)\, k_m + K(S)\, C(S)\, H(S)} = \text{Aileron Angle to Signal Angle Ratio} \tag{13}$$

$$\frac{\theta_9}{\beta} = \frac{Y_p\ C(S)\ H(S)}{1 + R(S)\ C(S)\ k_m + K(S)\ C(S)\ H(S)} - \frac{G(S)\ C(S)\ H(S)}{1 + R(S)\ C(S)\ k_m + K(S)\ C(S)\ H(S)} \tag{14}$$

The last term of equation 14 is the rate gyro's contribution to this response ratio. When there is no rate gyro G(S) is zero and the last term of equation 14 disappears so that

$$\frac{\theta_9}{\beta} = \frac{Y_p\ C(S)\ H(S)}{1 + R(S)\ C(S)\ k_m + K(S)\ C(S)\ H(S)} \tag{15}$$

According to the dynamic stability analysis of the F-84 - B-50 combination, the oscillation of the F-84 resulting from a pitch or roll disturbance will be suitably damped if

$$\theta_9 = -3\beta \tag{16}$$

If this is true then equation 15 can be rewritten

$$\frac{Y_p\ C(S)\ H(S)}{1 + R(S)\ C(S)\ k_m + K(S)\ C(S)\ H(S)} = -3 \tag{17}$$

Therefore, a condition for stability is that equation 17 be approximately maintained. In addition to equations 15, 16, and 17, an equation for the damped servo oscillation is required. This can be obtained from an investigation of the ratio of E_o to ϵ as follows:

For one case,

$$\frac{E_o}{\epsilon} = \frac{E_o}{Y_p \beta} = \frac{K(S)\,\theta_9}{Y_p \beta}$$

$$= \frac{K(S)\ C(S)\ H(S)}{1+R(S)\ C(S)\ k_m + K(S)\ C(S)\ H(S)} - \frac{G(S)\ C(S)\ H(S)\ K(S)}{Y_p+Y_p\ R(S)\ C(S)\ k_m + Y_p\ K(S)\ C(S)\ H(S)} \tag{18}$$

With no rate gyro, equation 18 becomes

$$\frac{E_o}{\epsilon} = \frac{K(S)\ C(S)\ H(S)}{1 + R(S)\ C(S)\ k_m + K(S)\ C(S)\ H(S)} = \frac{E_o}{Y_p \beta} \tag{19}$$

Equations 18 and 19 express the ratio of the feedback signal to the originating signal ϵ. It is a differential equation which is periodic and damped.

Equation 19 may be rewritten

$$E_o = \frac{Y_p\ H(S)\ K(S)\ C(S)}{1 + R(S)\ C(S)\ k_m + K(S)\ C(S)\ H(S)} \cdot \beta \tag{20}$$

The transfer coefficients and final solution of this differential equation will be considered later.

Another equation which can be used for stability consideration is

$$\frac{E_o}{E_1} = \frac{E_o}{\epsilon} \times \frac{\epsilon}{E_1} = \frac{E_o/\epsilon}{1 - E_o/\epsilon} \tag{21}$$

$$\frac{E_c}{E_1} = \frac{K(S)\ C(S)\ H(S)\ \left[Y_p - G(S)\right]}{Y_p + Y_p\ R(S)\ C(S)\ k_m + G(S)\ C(S)\ H(S)\ K(S)} \qquad (22)$$

For no rate gyro equation 22 becomes

$$\frac{E_c}{E_1} = \frac{K(S)\ C(S)\ H(S)}{1 + R(S)\ C(S)\ k_m} \qquad (23)$$

Equations 22 and 23 represent the ratio of the feedback signal voltage to the error signal voltage. They are differential equations whose solutions are damped oscillations.

A third equation for use in stability consideration is concerned with the ratio of E_2 to E for the internal feedback loop.

$$\frac{E_2}{E} = R(S)\ C(S)\ k_m \qquad (24)$$

The nature of this equation and the selection of the proper transfer functions will prevent unstable oscillation of the internal loop.

B. Evaluation of Transfer Functions

The load transfer function H(S) is a function which transfers motor torque into an angle of rotation of the ailerons. All of the torques which the motor must overcome in order to create an angle of rotation of the ailerons, θ_9 , must be considered.

$$\theta_9 = H(S)\ T_{c1} \qquad (25)$$

The inertia and damping torque within the servo system is given by the equation

$$T_{cs1} = J_1 s^2 \theta_2 + f_1 s \theta_2 \tag{26}$$

In equation 26, J_1 is the effective moment of inertia of the moving components of the servo with respect to the motor shaft and f_1 is the viscous damping coefficient. The term $f_1 s \theta_2$ is the damping torque which the motor must overcome.

In addition to the torques shown by equation 26 there will be an inertia and damping torque exerted by the ailerons, an aerodynamic hinge moment on the aileron torque tubes, and a viscous damping due to the aileron booster.

The inertia and damping torque exerted by the ailerons on their torque tubes is

$$T_{sc2} = J_2 s^2 \theta_9 + f_2 s \theta_9 \tag{27}$$

The hinge moment due to the aerodynamic load will be

$$T_{c7} = C_{Ha} P_d S_a C_a \tag{28}$$

where

$$C_{Ha} = \frac{d\,C_{Ha}}{d\,\theta_9} \cdot \theta_9 + \frac{d\,CH_a}{d\,\alpha} \cdot \alpha \tag{29}$$

Assuming the aileron stiffness, k_{20}, is

$$k_{20} = P_d S_a C_a \frac{d\,C_{Ha}}{d\,\theta_9} \tag{30}$$

and the aileron hinge moment coefficient ratio is

$$C_{20} = \frac{d\,C_{Ha}/d\alpha}{d\,C_{Ha}/d\,\theta_9} \tag{31}$$

then

$$T_{c7} = k_{20}\,\theta_9 + k_{20}\,C_{20} \tag{32}$$

The total torque which must be applied to the aileron torque tube by the aileron rigging is

$$T_{c6} = J_2 s^2 \theta_9 + f_2 s\,\theta_9 + k_{20}\,\theta_9 + k_{20}\,C_{20}\,\alpha \tag{33}$$

If it is assumed that there is no time element between the aileron and the booster, then the torque delivered by the booster to the first lever arm after the booster will be

$$T_{c3} = \frac{T_{c6}}{Y_{13}} \tag{34}$$

The transmission of the servo torque T_{c2} through the booster to produce the effective torque T_{c3} is not independent of time and the time element of the booster may cause a severe "clipping" of T_{c3} and also of θ_9. It is only in the case where θ_3 and θ_4 are in phase that the maximum mechanical advantage of the booster can be obtained. The variation of θ_9 as a function of θ_3 can be determined experimentally.

For driving frequencies much lower than the resonance frequency of the booster the aileron angle θ_9 will be able to keep up with the servo gear train output shaft angle θ_3. For such a case,

$$\theta_9 = k(\theta_9, \theta_3)\,\theta_3 \tag{35}$$

where $k(\theta_9, \theta_3)$ is an unsymmetrical parabolic locus coefficient. A plot of θ_9 versus θ_3 will reveal the nature of this coefficient. For frequencies of servo output shaft (gear train) oscillation greater than the booster resonance frequency θ_9 will lag behind θ_3 so that $k(\theta_9, \theta_3)$ will be time dependent. This coefficient can be readily obtained from experiment.

Since, for the gear train, assuming no back-lash,

$$\theta_3 = k_d\,\theta_2 \tag{36}$$

the relationship between θ_9 and θ_2 is

$$\theta_9 = k(\theta_9, k_d\,\theta_2, s)\,\theta_2 \tag{37}$$

where the time element is included by considering θ_9 and θ_2 as functions of the complex variable s. In view of these facts it is assumed that

$$T_{c3} = Y_4\,T_{c2} \tag{38}$$

where Y_4 is the booster transfer function which accounts for the lag of adjustment between θ_3 and θ_4. This transfer function is the effective mechanical advantage of the booster at any instant and must be experimentally determined.

The torque delivered by the servo gear train output shaft is T_{c2}. If there is back-lash in the gear train Y_3 will also be time dependent so that θ_3 will not be proportional to θ_2 at every instant.

Therefore,

$$T_{c2} = Y_3 \, T_{c1} \tag{39}$$

The actual torque which the motor shaft must deliver to the gear train is therefore, from equations 26, 33, 34, 38 and 39,

$$T_{c1} = \frac{T_{c6}}{Y_3 \, Y_4 \, Y_{13}} + T_{cs1} \tag{40}$$

$$T_{c1} = (J_1 s^2 + f_1 s)\,\theta_2 + \frac{(J_2 s^2 + f_2 s + k_{20})\theta_9}{Y_3 \, Y_4 \, Y_{13}} + \frac{k_{20} \, C_{20} \, \alpha}{Y_3 \, Y_4 \, Y_{13}} \tag{41}$$

Since

$$\theta_2 = \frac{k_m}{Y_2} \, T_{c1} \tag{42}$$

then

$$\left[1 - (J_1 s^2 + f_1 s)\frac{k_m}{Y_2}\right] T_{c1} = \frac{(J_2 s^2 + f_2 s + k_{20})\theta_9}{Y_3 \, Y_4 \, Y_{13}} + \frac{k_{20} \, C_{20}}{Y_3 \, Y_4 \, Y_{13}} \tag{43}$$

The last term of equation 43 is small in comparison to the others so that H(S), the load transfer function, is

$$\frac{\theta_9}{T_{c1}} = \frac{Y_2 \, Y_3 \, Y_4 \, Y_{13} - Y_3 \, Y_4 \, Y_{13} \, k_m (J_1 s^2 + f_1 s)}{Y_2 (J_2 s^2 + f_2 s + k_{20})} \tag{44}$$

The transfer functions G(S) for the rate gyro, if used, R(S) for the servo motor rate generator, C(S) for the amplifier unit and servo motor, and K(S) for the follow-up autosyn can not be evaluated until particular components for the control system are selected and then they must be determined from experimental data.

3. Elevator Control For System With Freedom In Roll And Pitch

A. Response Functions

Equations for the response functions for the elevator control system are developed in the same way as those outlined for the aileron control system in part 2. Reference to Fig. 10 and substitution of θ_6 for θ_9 in equations 1 through 14 results in the elevator angle to signal angle ratio

$$\frac{\theta_6}{\beta} = \frac{Y_p\, C(S)\, H(S)}{1 + R(S)C(S)\, k_m + K(S)C(S)H(S)} - \frac{G(S)\, C(S)\, H(S)}{1 + R(S)C(S)\, k_m + K(S)\, C(S)\, H(S)} \qquad (45)$$

The first and second terms on the right hand side of equation 45 are the respective contributions of the displacement signal and the rate signal to this response ratio. This is a differential equation which specifies the relationship existing between the elevator angle and the wing misalignment angle at any instant of time when the transfer functions are properly expressed as complex variables. However, it has been determined by the aerodynamic stability analysis that a second relationship must also exist between θ_6, β, and $\dot{\beta}$, that is at any instant of time

$$\theta_6 = 0.1\,\dot{\beta} + 0.2\,\beta \qquad (46)$$

or

$$\theta_6 = a\,s\,\beta + b\,\beta\,, \quad \theta_6 = (as + b)\,\beta \qquad (47)$$

where a and b are used in place of the approximate constants 0.1 and 0.2 and the Laplace operator s is used to convert $\dot{\beta}$ to β.

The desired transfer function is therefore

$$\frac{\theta_6}{\beta} = a s + b \tag{48}$$

Since equations 48 and 45 are equivalent the overall transfer functions must be equal so that

$$a s + b = \frac{Y_p\, C(S)\, H(S)}{1+R(S)C(S)k_m + K(S)C(S)H(S)} - \frac{G(S)C(S)H(S)}{1+R(S)C(S)k_m + K(S)C(S)H(S)} \tag{49}$$

That is, the equivalence can be obtained between the aerodynamic and servo transfer functions by suitably adjusting the gain parameters of the servo system. Equation 49 thus represents the ideal goal in the design of this servomechanism. The gain parameters Y_p, $G(S)$, $C(S)$, $H(S)$, $K(S)$, and $R(S)$ can be evaluated for each component of the servo system.

In addition to equations 45 through 49, equations for the response function for the servo system itself must be derived for use in investigating its frequency characteristics.

Since $$E_o = K(S)\, \theta_6 \tag{50}$$

and $$\epsilon = Y_p\, \beta \,, \tag{51}$$

equation 45 can be rewritten in terms of E_o and ϵ and the ratio of the feedback signal voltage to the originating displacement signal voltage is the same as expressed in equation 18. The proper relationship for adjusting the feedback voltage (since Y_p is nearly constant) can be obtained from differential equation 18 expressed as a complex variable, keeping in mind that equation 49 must be satisfied at all times.

The differential equation for the ratio of feedback signal to error signal is the same as equation 22 and is derived in the same way.

The equation for use in considering the stability of the internal feedback loop is the same as written in equation 24 and the selection of the proper transfer functions R(S) and C(S) will prevent unstable oscillation.

B. Evaluation of Transfer Functions

The load transfer function H(S) for the elevator control is derived in the same way as the aileron control load transfer function was evaluated. The relationship existing between the servo motor output torque and the elevator angle is

$$\theta_6 = H(S)\, T_{c1} \tag{52}$$

Since T_{c1} is the torque applied to the load by the servo motor, all of the opposing torques which the motor must overcome to drive the elevator to the angle θ_6 must be considered.

The inertia and damping torque within the servo itself is expressed by equation 26.

Since the elevator control is to be accomplished by linking the servo motor to the elevator torque tube by means of a pulley and cable system, whereas in the aileron control system a push-pull rod and lever system is used, the rigging torque must be evaluated. The rigging torque depends on the tension of the cable, i.e., its linear stiffness. When the servo pulley rotates θ_4 radians the cable tension changes by $k_c\, r1\, \theta_4$. The elevator pulley will rotate θ_6 radians and the change in length of one half of the cable will be

$$\Delta L = r_1 \theta_4 - r_2 \theta_6 \qquad (53)$$

Experimentally it can be shown that

$$\theta_6 = k_1 \theta_4 \qquad (54)$$

where k_1 is a transfer function which changes radians of servo pulley rotation into radians of elevator pulley rotation.

Then,

$$\Delta L = (r_1 - r_2 k_1)\theta_4 = \left(\frac{r_1}{k_1} - r_2\right)\theta_6 \qquad (55)$$

If it is assumed that the stretching force applied to the cable when the motor turns the elevator is $k_c \Delta L$ and this force is applied at a distance r_1 from the center of the gear train output shaft, then the stretching torque on one half of the cable length will be $k_c \Delta L r_1$ and for the whole cable

$$T_{c2} = 2 k_c \Delta L r_1 = 2 k_c r_1 \left(\frac{r_1}{k_1} - r_2\right)\theta_6 \qquad (56)$$

T_{c2} will apply torque to the elevator and turn it θ_6 radians. The actual torque applied to the elevator shaft will be

$$T_{c4} = 2 k_c r_2 (r_1 \theta_4 - r_2 \theta_6) \qquad (57)$$

For a zeroed value of θ_4 the torque on the elevator shaft is

$$T_{c4} = -2 k_c r_2^2 \theta_6 \qquad (58)$$

Therefore, the elevator rigging stiffness is

$$k_e = 2 k_c r_2^2 \qquad (59)$$

and

$$T_{c4} = -k_e \theta_6 \qquad (60)$$

The transfer function which transforms a torque into an actual angle of rotation of the elevator shaft is $\frac{1}{k_e}$. The torque T_{c4} must act against a hinge moment T_{c5} caused by aerodynamic forces on the elevator together with inertia and damping torques which also must be overcome by the motor. The elevator rigging stiffness k_e is evaluated as follows:

The torque exerted by the motor will be the sum of the gear train and motor inertia and damping torque plus the reaction torque of the gear train on the pulley.

$$T_{c1} = J_1 s^2 \theta_2 + f_1 s \theta_2 + \frac{T_{c2}}{Y_3} \qquad (61)$$

Since $$\theta_2 = \frac{\theta_3}{k_d} \qquad (62)$$

and $$\theta_3 = \theta_4 \qquad (63)$$

$$\theta_2 = \frac{\theta_4}{k_d} = \frac{\theta_6}{k_1 k_d} \qquad (64)$$

$$T_{c1} = \frac{\theta_6}{k_1 k_d Y_3} \left(J_1 s^2 Y_3 + f_1 s Y_3 + 2 k_c k_d r_1^2 - 2 k_c k_1 k_d r_1 r_2\right) \qquad (65)$$

The inertia and damping torque exerted by the elevator on its torque tube is similar to that shown for the aileron control system in equation 27 and is

$$T_{cs2} = J_2 s^2 \theta_6 + f_2 s \theta_6 \qquad (66)$$

The hinge moment due to the aerodynamic load will be

$$T_{c5} = C_{He} P_d S_e C_e \qquad (67)$$

where

$$C_{He} = \frac{d\,C_{He}}{d\,\theta_6} \cdot \theta_6 + \frac{d\,C_{He}}{d\,\alpha} \cdot \alpha_t \qquad (68)$$

Assuming the elevator stiffness, k_{10}, is

$$k_{10} = P_d\,S_e\,C_e\,\frac{d\,C_{He}}{d\,\theta_6} \qquad (69)$$

and the elevator hinge moment coefficient ratio is

$$C_{10} = \frac{d\,C_{He}/d\,\alpha_t}{d\,C_{He}/d\,\theta_6} \qquad (70)$$

then

$$T_{c5} = k_{10}\,\theta_6 + k_{10}\,C_{10}\,\alpha_t \qquad (71)$$

The total torque which must be applied to the elevator torque tube by the elevator rigging is

$$T_{c4} = J_2\,s^2\,\theta_6 + f_2 s \theta_6 + k_{10}\,\theta_6 + k_{10}\,C_{10}\,\alpha_t \qquad (72)$$

Equating the expressions for T_{c4} of equations 57 and 72,

$$2\,k_c\,r_2\,(r_1\,\theta_4 - r_2\,\theta_6) = J_2\,s^2\,\theta_6 + f_2\,s\,\theta_6 + k_{10}\,\theta_6 + k_{10}\,C_{10}\,\alpha_t \qquad (73)$$

or

$$2\,k_c\,r_2\,\theta_6\left(\frac{r_1}{k_1} - r_2\right) = J_2\,s^2\,\theta_6 + f_2\,s\,\theta_6 + k_{10}\,\theta_6 + k_{10}\,C_{10}\,\alpha_t \qquad (74)$$

$$k_c = \frac{k_1}{2\,r_2\,(r_1 - k_1\,r_2)}\left[J_2\,s^2 + f_2\,s + k_{10} + k_{10}\,C_{10}\,\frac{\alpha_t}{\theta_6}\right] \qquad (75)$$

The elevator rigging stiffness is therefore, from equation 59,

$$k_e = \frac{k_1 \; r_2}{r_1 - k_1 \; r_2} \left[J_2 \; s^2 + f_2 \; s + k_{10} \; C_{10} \; \frac{\alpha_t}{\theta_6} + k_{10} \right] \tag{76}$$

From equation 65 it is seen that

$$\theta_6 = \left[\frac{k_1 \; k_d \; Y_3}{J_1 \; s^2 \; Y_3 + f_1 \; s \; Y_3 + 2 \; k_c \; k_d \; r_1^2 - 2 \; k_c \; k_1 \; k_d \; r_1 \; r_2} \right] T_{c1} \tag{77}$$

Substituting for k_c from equation 75, equation 77 becomes

$$\theta_6 = \frac{k_1 \; k_d \; Y_3}{\frac{k_1 \; k_d \; r_1}{r_2} \left[J_2 \; s^2 + f_2 \; s + k_{10} + k_{10} \; C_{10} \frac{\alpha_t}{\theta_6} \right] + J_1 \; s^2 \; Y_3 + f_1 \; s \; Y_3} \cdot T_{c1} \tag{78}$$

From equation 52, therefore, it is seen that the load transfer function is

$$H(S) = \frac{k_1 \; k_d \; Y_3}{\frac{k_1 \; k_d \; r_1}{r_2} \left[J_2 \; s^2 + f_2 \; s + k_{10} + k_{10} \; C_{10} \; \frac{\alpha_t}{\theta_6} \right] + J_1 \; s^2 \; Y_3 + f_1 \; s \; Y_3} \tag{79}$$

The transfer functions G(S) for the rate gyro, R(S) for the servo motor rate generator, C(S) for the amplifier unit and servo motor, and K(S) for the follow-up autosyn can not be evaluated until particular components for the control system are selected and then they must be determined from experimental data.

4. Design Of The Control System

For either the aileron control system for the wing tip attachment with freedom in roll only or the elevator control system for the attachment with freedom in both roll and pitch, a suitable servomechanism can be designed through use of the equations set up in parts 2 and 3 of this section. After selection of the particular type of control to be used, i.e., aileron or elevator, the steps to be followed are:

(a) Select components for the complete system on the basis of estimated torque and speed requirements of the servo motor and estimated values of β and $\dot{\beta}$.

(b) Determine transfer functions for each component experimentally so that G(S), R(S), C(S), K(S), and H(S) may be expressed as functions of complex variables. For the aileron system this will include evaluation of the time response of the F-84 hydraulic aileron boost cylinder and valve.

(c) Substitute these transfer functions in the approximate equations of part 2 or part 3 and analyze the stability of the servo system by examining these differential equations by Nyquist's method. By varying parameters as required a servomechanism which will restrict the rolling of the F-84 about its wing tip attachment to suitably damped oscillations can be designed.

V. Discussion

For the two point attachment in which the F-84 is free to roll but restrained in pitch and yaw, control may be possible by either (a) direct mechanical operation of the ailerons in direct proportion to wing misalignment angle or (b) by operation of the ailerons through a servomechanism in proportion to both wing misalignment angle and rate of change of wing misalignment angle. Either of these two methods of aileron control will require modification of the F-84 aileron system to provide means of operating the ailerons both in the same direction.

The control system in which the ailerons are driven by direct linkage from the wing tip attachment mechanism can not be adapted to displacement plus rate control and may therefore prove less desirable than the servo operated control system under the varying flight conditions which will be encountered.

Operation of the ailerons through a servomechanism will require an extremely large servo motor unless the F-84 aileron booster is included in the system. The use of the booster will complicate the system through introduction of time lag and a non-linear torque transfer function as well as a requirement for an electrically operated hydraulic pump and additional hydraulic valves.

For the attachment in which the F-84 is free to both roll and pitch but restrained in yaw, control can be accomplished by operating the elevator to vary the angle of attack and thereby vary the wing lift. The servomechanism for this mode of control can be made available by modifying existing Bendix autopilot components. Of the three systems considered this system appears to be the most desirable from the standpoint of availability of control system components, adaptability to various control signal inputs, and minimum F-84 control system modification.

VI References

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