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DESIGN, FABRICATION, AND FLIGHT TESTING OF SELF-ORGANIZING FLIGHT CONTROL SYSTEM

Adaptronics, Inc.

FOREWORD

This report was prepared for the Air Force Systems Command (AFSC), United States Air Force, by Adaptronics, Inc., McLean, Virginia, under the terms of contract AF 33(615)-5141, BPSN 6(63822508-62405364), 6(61822601-62405334), 6(67416005-62405274), "Development and Flight Test of a Self-Organizing Flight Control System." The report covers work performed during the period 31 May 1966 to 15 January 1970.

Robert C. Lorenzetti, Major, USAF, Control Elements Branch, Flight Control Division, Air Force Flight Dynamics Laboratory, served as Project Engineer and Mr. William H. Ahrendt, Avionics Branch, Flight Test Engineering Division, Directorate of Flight Test, ASD, served as Test Director during the installation and flight test phases of this project. Mr. Paul E. Blatt, Control Elements Branch, was Project Engineer during the design, fabrication, and flight worthiness test phases. Mr. Alfred C. Speake monitored the project in behalf of the Air Force Avionics Laboratory, during the same first three phases. The Contractor gratefully acknowledges the support, encouragement and valuable guidance in this work provided by Major Lorenzetti, Messrs. Ahrendt, Blatt, and Speake, and numerous others in AFSC. The contributions of Mr. Blatt and Mr. Cecil W. Gwinn, Avionics Laboratory, in initiating this project and following it closely through the years are particularly appreciated.

Contractor participation in this project has been a team effort on the part of a great many individuals of which only some can be mentioned here. Mr. Roger L. Barron was Principal Investigator and Project Manager for Adaptronics, Inc. throughout the work. In particular, Mr. Barron was responsible for the basic design of the self-organizing controller, its release for flight testing, and the contents of this report. Messrs. James R. Gouge, Jr., Robert M. McKechnie, III, and George C. Vieth, Jr., performed all logic and circuit design tasks. The leadership and technical contribution of Mr. Gouge throughout the project were instrumental in its success. Mr. Dixon Cleveland contributed to system simulations and analyses of simulation and flight test data. Mr. Claude A. Crow, Jr., served as Field Representative for Adaptronics at Wright-Patterson Air Force Base during system checkout and flight testing. Messrs. Robert Gallo and Norman E. Wilson performed most of the detailed hardware layout, assembly, and modification tasks. Mr. Richard F. Snyder supervised contract purchasing and property control.

Mr. Daniel O. Dommasch and his associates at DODCO, Inc., Princeton, New Jersey, performed the digital computer analyses referred to in this report. Mr. Dommasch conceived the Mach Trim loop incorporated in the experimental flight control system.

The contributions of Bird Engineering-Research Associates Inc., Vienna, Virginia, in reliability, maintainability, and safety analyses are also gratefully acknowledged.

This report was submitted by Adaptronics, Inc., May 1970.

This technical report has been reviewed and is approved.

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ABSTRACT

This report summarizes design characteristics, simulations, bench tests, and flight tests of an elementary self-organizing controller (SOC) for the pitch axis of the F-101B aircraft. This controller was flown with a cockpit electric side stick in a pseudo-fly-by-wire configuration, that is, as a fly-by-wire system with a normally disengaged mechanical backup. Blended pitch-rate and forward normal acceleration feedback (C*) and stabilator position feedback were the primary return signals used by the SOC. An optional Mach Trim loop was also investigated. The SOC, which incorporated unique modulated-noise circuits to minimize adverse effects of control-loop nonlinearities, had full authority over the aircraft stabilator within the inherent rate and position limits of the actuator. 32 test flights were conducted with the SOC, constituting a total flying time of approximately 40 hours. These flights encompassed nearly the entire performance envelope of the F-101B and included piloting tasks representative of missions flown with current fighter aircraft. The Air Force pilots rated the SOC between A1 and A2 on the Cornell Aeronautical Laboratory (CAL) Revised Pilot Rating Scale. There were no in-flight malfunctions of the SOC equipment.

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LIST OF ABBREVIATIONS

ADYN	-	Airframe Pitch-Axis Dynamics
AFCS	-	Automatic Flight Control System (Autopilot)
BITE	-	Built-in Test Equipment
CADC	-	Central Air Data Computer
CSC	-	Command Signal Coupler
EFC	-	Error Function Coupler
ESS	-	Electric Side Stick
FBW	-	Fly-by-Wire (Electrical flight controls)
F.C.	-	Flight Condition
FCF	-	Functional Check Flight
MPB	-	Manual Pitch Bias
FNA	-	Forward-Mounted Normal Accelerometer
GSE	-	Ground Support Equipment
IFR	-	Instrument Flight Rules
IMN	-	Indicated Mach Number
M	-	Mach Number
PCV	-	Probability Control Voltage
PFIC	-	Panel and Flight Instrumentation Controls
PRG	-	Pitch-Rate Gyro
PSV	-	Probability State Variable
SLU	-	SOC Logic Unit
SPT	-	Stabilator Position Transmitter
SOC	-	Self-Organizing Control
STAB	-	Stabilator Parallel Servo Power Amplifier and Actuator
TSG	-	Test Signal Generator

1. INTRODUCTION AND SUMMARY

An elementary self-organizing controller (SOC) for the F-101B pitch axis has been successfully designed, fabricated, installed, and flight tested. This controller was flown in a pseudo-fly-by-wire configuration, that is, as a fly-by-wire (FBW) flight control system with a normally disengaged mechanical backup. 32 test flights were conducted with the elementary SOC during July through November 1969, constituting a total flying time of approximately 40 hours. These flights encompassed nearly the entire performance envelope of the F-101B and included piloting tasks representative of the various missions flown with modern fighter aircraft. The test flights were divided about equally between two Air Force pilots, who rated the SOC between A1 and A2 on the Cornell Aeronautical Laboratory (CAL) Revised Pilot Rating Scale.

1.1 Background

The elementary SOC (References 1 and 2) is a single-axis controller derived from the general purpose self-organizing controller (References 1-16). The theory of self-organizing control having been adequately treated in the references, this report will emphasize design and installation characteristics of the elementary SOC and data from its qualifying tests on the ground and flight tests in the F-101B.

In this flight test program, the primary objective was to demonstrate ability of the elementary SOC to cope with the wide range (5.2:1) in stabilator control effectiveness, as well as variations in other airframe static and dynamic characteristics, produced by operation at different Mach numbers and altitudes within the

F-101B envelope. The success of this demonstration proves that gain scheduling is not required to meet the pitch-axis control requirements of a supersonic fighter aircraft of this type. It is hoped that future flight programs will provide an opportunity to demonstrate the multivariable decoupling control capabilities of the general purpose self-organizing controller.

The elementary SOC offers no inherent decoupling of multiple-axis response variables of a flight vehicle or other plant. Some designers (Reference 11) have attempted to use the elementary SOC for decoupling control by adding parameter-scheduled, linear crossover networks that generate the SOC error signals. This is much less effective in our judgment than use of a general purpose SOC. As shown in a number of references (2, 8, 9, 10, 12, 13, and 14), decoupling of nonlinear multivariable plants is achieved very effectively with proper application of general purpose self-organizing controllers. We caution the reader not to expect miracles from the elementary SOC by applying it outside of the problem area for which it was designed. That area, in summary, is control of essentially one-dimensional objects, either linear or nonlinear, in the presence or absence of sensor noise, and for which the ratio of maximum to minimum plant gains is no greater than approximately 5:1, if reasonably uniform response is desired throughout the gain range.

An additional caveat is offered. Some investigators have, in preparing analytical or computer models of the elementary SOC, either eliminated the noise source (Figure 1) or replaced it with a coherent high-frequency dither-signal generator. While these simplifications are admissible for control of low-order plants when the sensors are noise free, the result can be unsatisfactory in more demanding applications. With regard to the F-101B, hysteresis in the parallel servo valve of the stabilator can result in a pitch-axis limit cycle oscillation at about 3 Hz in the absence of the elementary SOC internal noise signal; restoring this signal stops the oscillation without reducing the bandwidth of the control system.

1.2 Objectives of the Program

Paragraph 2 of the contract Statement of Work (2 May 1966) reads as follows:

"Objective--Control of high-performance aircraft and aerospace vehicles through widely varying flight regimes poses severe flight control design problems to provide satisfactory vehicle flying qualities for effective and reliable mission accomplishment. The objective of this effort is to demonstrate, through a comprehensive flight test evaluation, the capability of a self-organizing controller (SOC) to achieve superior self-adaptive and reliability characteristics."

As the work progressed, the following cognate goals were tacitly established:

(1) develop design information and criteria for fly-by-wire flight control systems

(2) demonstrate performance and reliability of FBW systems

The principal FBW design information and criteria sought during the program were in the following areas:

(a) time constant of pre-filter model

(b) C* specifications (the questions of (i) relative weight between load factor and pitch rate and (ii) the time-response envelopes for C*)

(c) significance of positive vs. neutral speed stability for fighter aircraft

(d) controller requirements imposed by actuator rate limits, hysteresis, transport delay, and temperature restrictions

(e) controller test (BITE) and diagnosis (GSE) procedures

(f) component selection and burn-in requirements for FBW circuits

The performance and reliability goals became:

(a) demonstrate improved flying qualities for the system in comparison with conventional controls at all flight conditions and for all missions and maneuvers

(b) demonstrate failure-free operation in all flights

1.3 Attainment of Objectives

The contract objective and all related goals have been attained.

1.4 Organization of Report and Other Data

This report presents a discussion of the elementary SOC, its design and installation characteristics, and data from the ground and flight tests. The following materials were provided in earlier volumes furnished to the Air Force by this Contractor:

(a) Flight Worthiness Test Procedures and Results (References 24 and 26)

(b) Partial Manual to Flight Manual, T.O. 1F-101B (Reference 25)

(c) Instruction Manual for Ground Support Equipment Model Mark IV GSE (References 27 and 28)

(d) Detailed Schematic Drawings for the Elementary SOC, its Cockpit Control Panel (PFIC), Ground Support Equipment (GSE), and System Wiring (Reference 29).

2. BASIC DESIGN

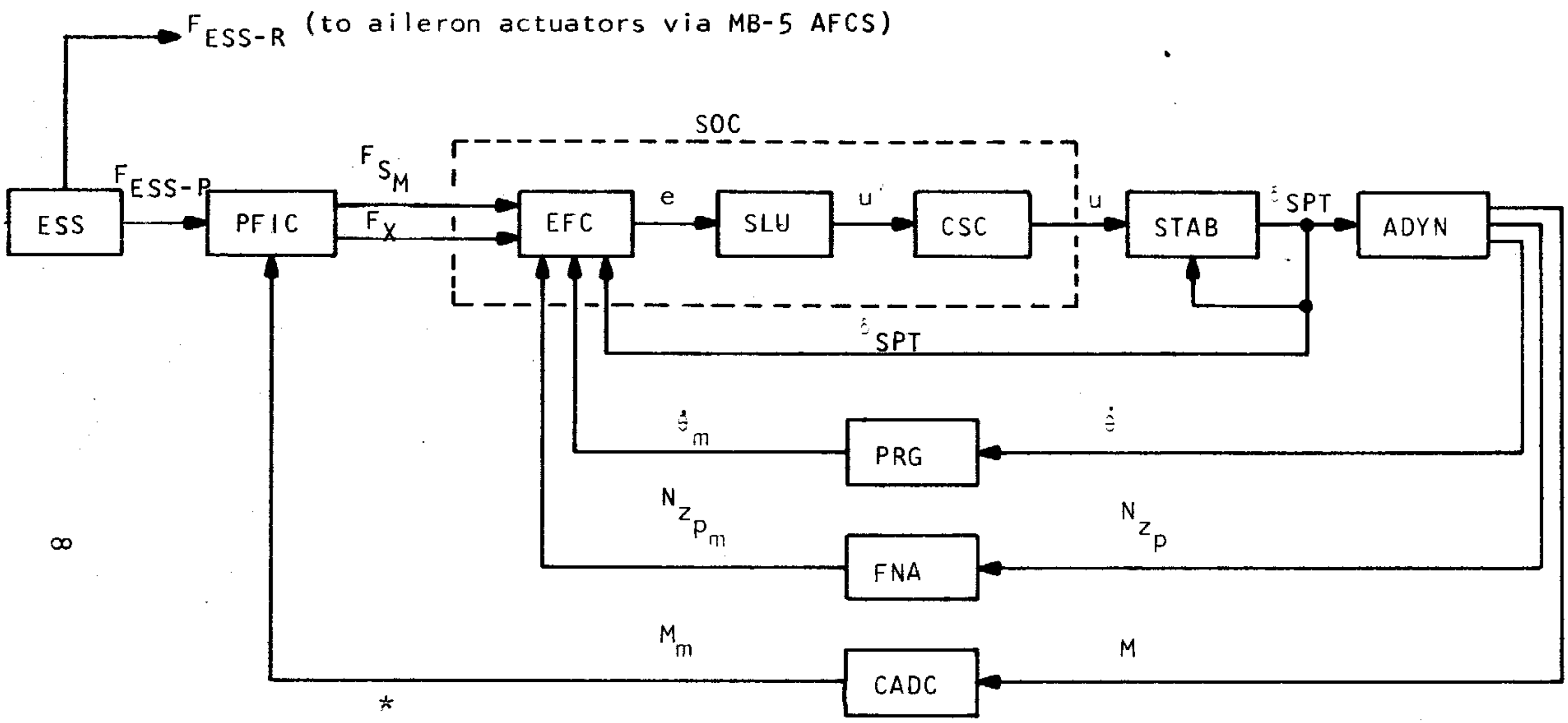
2.1 Elements in Systems

Figure 1 presents an overall block diagram of the elementary SOC system for the F-101B pitch axis. The following block symbols are used in the figure:

ESS	--	Electric Sidestick
PFIC	--	Panel and Flight Instrumentation Controls *
EFC	--	Error Function Coupler
SLU	--	SOC Logic Unit
CSC	--	Command Signal Coupler
STAB	--	Stabilator Parallel Servo Power Amplifier (in MB-5 AFCS) and Actuator
ADYN	--	Airframe Pitch-Axis Dynamics
PRG	--	Pitch-Rate Gyro
FNA	--	Forward-Mounted Normal Accelerometer
CADC	--	Central Air Data Computer

and the signals identified in Figure 1 are:

F_{ESS-P}	--	Force applied by pilot to ESS pitch axis, positive for pitch up
F_{S_M}	--	Smoothed (model) value of stick force, F_{ESS-P}
F_X	--	Composite input signal, positive for pitch up, consisting of smoothed sum of Manual Pitch Bias (F_{MPB}); calibrated Test Signal Generator voltage (F_{TSG}); scaled Mach Trim error, $K_M (M_{SET} - M_m)$; and scaled Mach Trim error rate, $K_{\dot{M}} \dot{M}_m$
e	--	Composite error signal (see below)
u'	-	Control signal upstream of CSC disconnect relays and smoothing



*Closed when Mach Trim function is engaged.

Figure 1: Pitch-Axis Elementary SOC System for F-101B

u	--	Control signal from SOC, nominally negative for pitch up
δ_{SPT}	--	STAB output displacement as measured by servo feedback potentiometer†
$\dot{\theta}$	--	Pitch rate, rad./sec., positive for pitch up
N_{z_p}	--	Incremental normal acceleration at pilot's station, g, positive for total acceleration exceeding one g
M	--	Mach number
$(\ )_m$	-	Denotes measured and/or computed value of ( )

Roll-axis control via the electric side stick was accomplished by means of direct connection between the ESS and the MB-5 AFCS aileron servo power amplifiers. No roll-rate sensing was employed and therefore roll-axis control was open loop.

The experimental airborne equipment consisted of the ESS (Government-furnished), the PFIC, and the SOC (comprised of the EFC, SLU, and CSC elements). In addition, special Ground Support Equipment (GSE) was furnished by the Contractor for pre-flight checkout of the system as well as ground demonstration and evaluation of the SOC.

The reliability objective of this program was a 50,000-hour MBTF in two-hour airborne missions (Reference 30). This objective was exceeded by use of triple redundancy of all SOC elements (including power converters). Figure 2 illustrates the basic approach employed in the redundant configuration.

Figure 3 shows the dominant transfer functions of the SOC system for the C_2* mode with Mach Trim off. For clarity, redundant branches are not shown in this figure.

† preferable signal source to Stabilator Position Transmitter

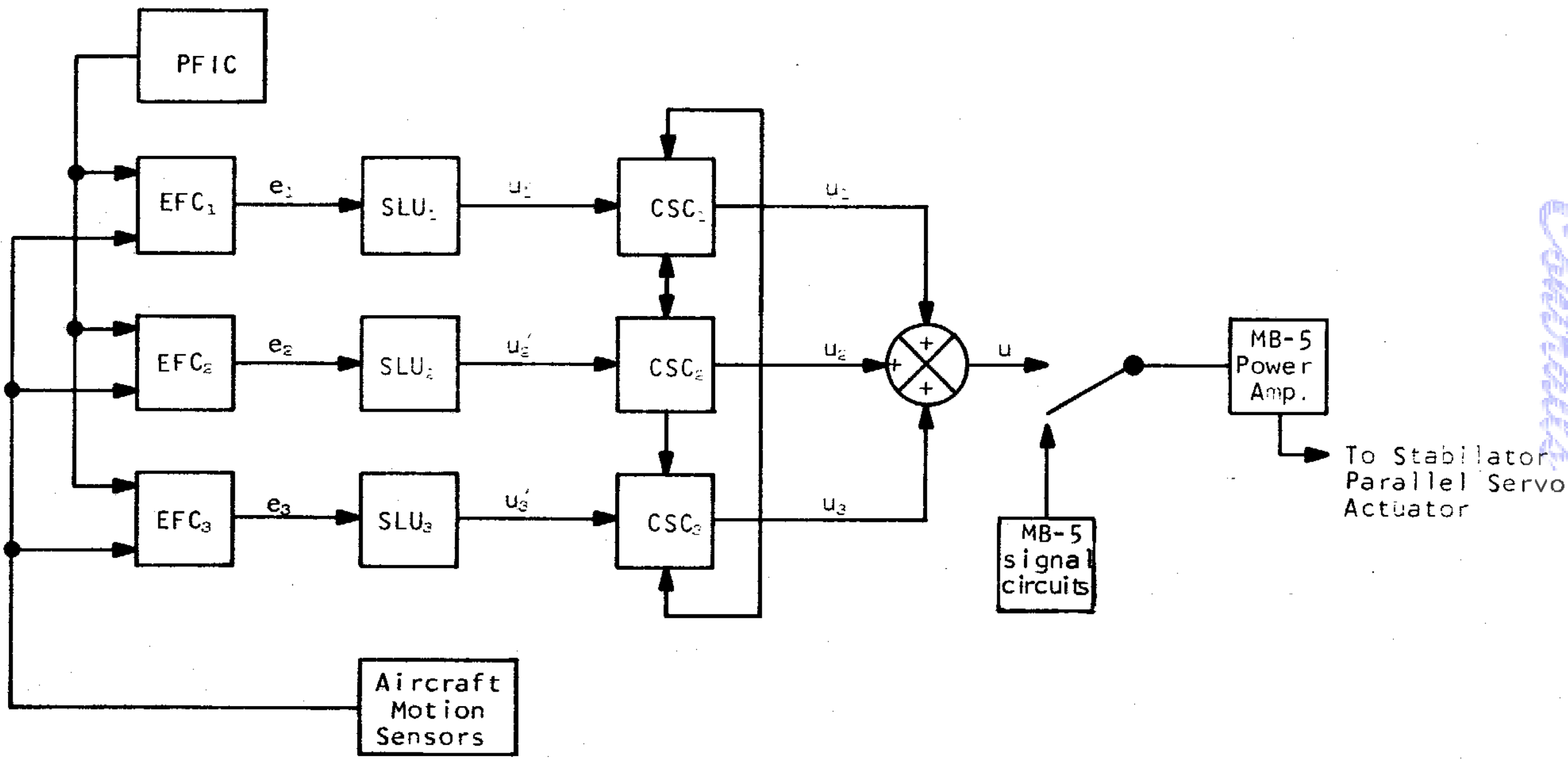
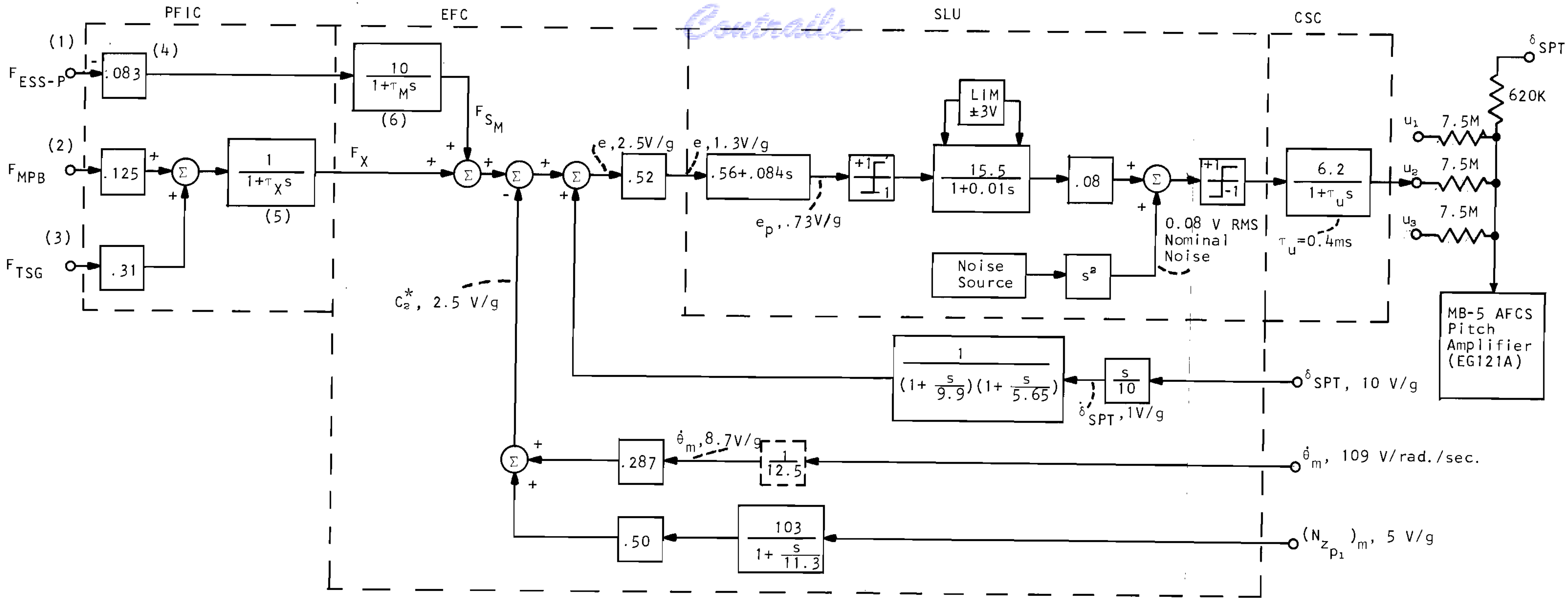


Figure 2: Approach Used in Triple Redundancy for SOC Elements. Redundant power converters not shown. The sensors and MB-5 are existing F-101B AFCS equipment.



(1) F_{ESS-P} = +6.0 (Nose Down), -12.0 (Nose Up) VDC Full Scale

(2) F_{MPB} = ±3.6 VDC Full Scale

(3) F_{TSG} = ± 4.0 VDC for ±0.5 g Test Commands

(4) Pitch Sensitivity Setting: 4

(5) τ_X = 0.4 sec. through Flight 16
= 0.2 sec. Flight 17 et seq.

(6) τ_M = 0.1, 0.2, 0.5 sec. (Pilot's Option)

Figure 3: Dominant Transfer Functions for Pitch Axis Controller, Showing One of Three Redundant Signal Branches, C_2^* Mode, Mach Trim Off, Flights 12 et seq.

Figure 4 shows the exterior of the PFIC. The SOC enclosure houses three identical removable modules, each of which is an independent controller consisting of one EFC, one SLU, one CSC, and one power converter. The summing circuit for u_1, u_2, and u_3 and the engage-disengage switching shown in Figure 2 were incorporated as modifications to the existing MB-5 AFCS equipment. The printed-circuit card being held in the photograph (Figure 4) implements the SLU for one of the three redundant controllers. Additional photographs of the system appear later in this report. Drawing 621-7 of Appendix I illustrates system interconnections.

2.2 PFIC Functions

The major functions implemented in the Panel and Flight Instrumentation Controls† (PFIC) were:

(1) power converter to energize the electric sidestick (pitch and roll axes) and PFIC circuits

(2) computation of F_{S_M}, where

$$F_{S_M} \equiv \frac{F_{ESS-P}}{1 + \tau_M s} \quad \ldots\ldots\ldots \quad 2:1$$

and τ_M, the model pitch-command lag, was selectable by the pilot to be 0.1, 0.2, or 0.5 sec.

(3) computation of F_X, where

$$F_X \equiv \frac{F_{TSG} + F_{MPB} + K_M(M_{SET}-M_m) + K_{\dot{M}}\dot{M}_m}{1+ \tau_X s}$$

†This name proved to be partly a misnomer, as it was found to be more suitable to use a standard remote control unit to activate the flight instrumentation (recorder).

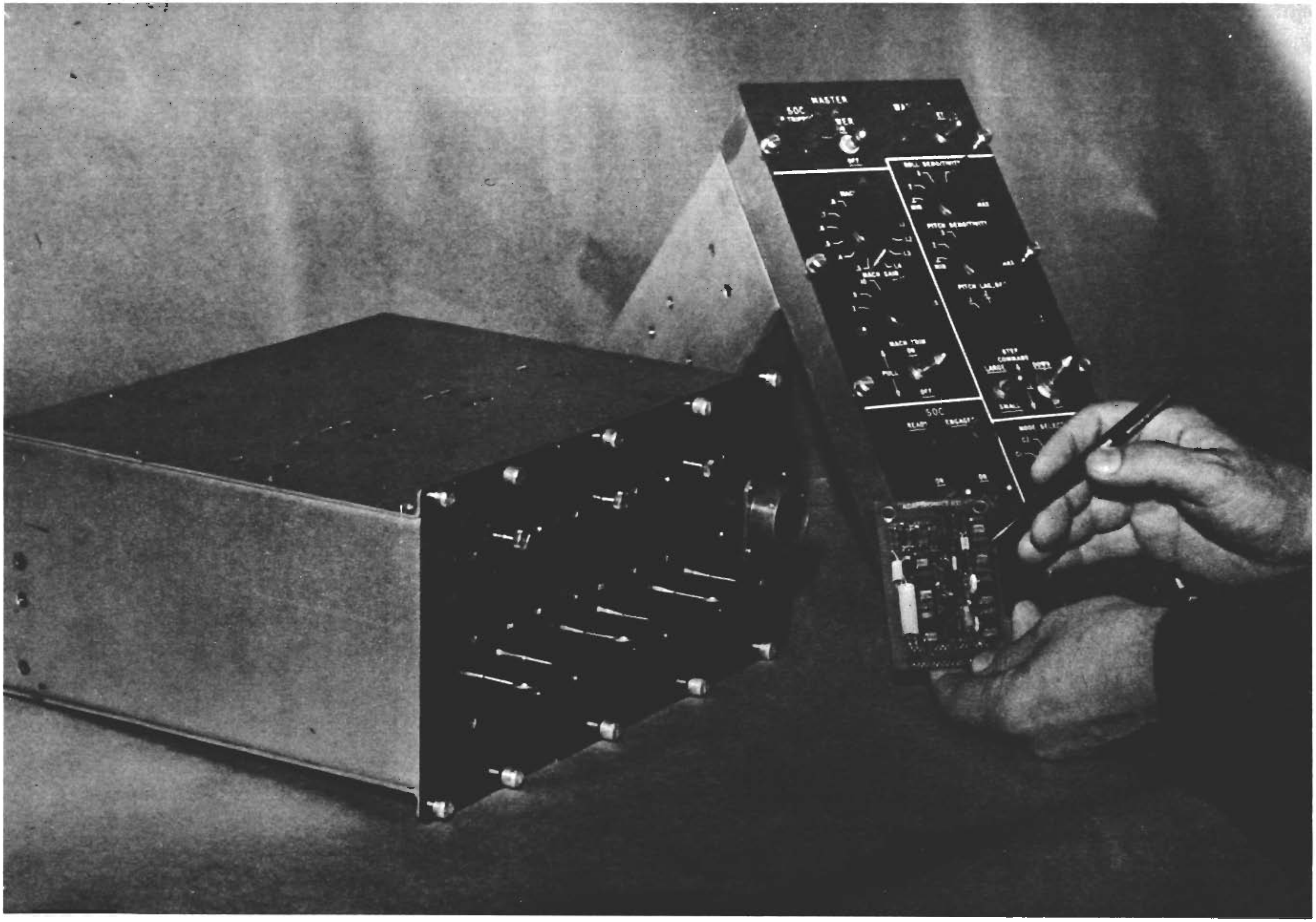


Figure 4: Exterior Photograph of SOC and PFIC. SLU printed circuit card also shown.

and F_{TSG} had the selectable values 0, ± 0.1, . . . 0.5g; F_{MPB} was obtained from a thumb-wheel potentiometer on the ESS handgrip;† K_M had the selectable values 0 (Mach Trim OFF), 0.049, 0.124, 0.247, 0.371, 0.494, and 0.618g (labelled MACH GAIN = 2, 5, 10, 15, 20, 25 on panel); $K_{\dot{M}}$ was zero (Mach Trim OFF) or 6.46 g-sec. (Mach Trim ON); M_{SET} had the selectable values 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4; and τ_X was 0.4 sec. (reduced to 0.2 sec. for Flight 17 et seq.)

(4) computation of C_R^* for monitoring via the airborne recording oscillograph, where

$$C_R^* = (N_{z_{p_1}})_m + 12.5\,\dot{\theta}_m \quad \text{.......................2:3‡}$$

(5) selectable roll-sensitivity and pitch-sensitivity ESS gains (the latter setting determined the system stick-force-per-g gradient in pitch)

(6) Roll Trim. Note: Roll axis control was open-loop, with the voltage sum of roll-axis stick force, F_{ESS-R}, and F_{MRB}, the Manual Roll Bias, applied directly to the aileron servo power amplifiers.

(7) Mode Select switching for C_1^* (V_{co}/g = 11.5 sec.), C_2^* (12.5 sec.), C_3^* (13.5 sec.), and $\dot{\theta}$ modes‡†

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†F_{MPB} served alternately as a vernier for C*, $\dot{\theta}$, or M, depending on mode selected by pilot for the system.

‡Aircraft had two forward-mounted normal accelerometers. The FNA used for computing C_R^* and for acceleration feedback in closed-loop control with the SOC in the C* mode is designated by the Subscript "1". The other FNA, denoted "2", was used only to trigger g-disconnect limiting circuits in the CSC's.

‡†For Flights 7 et seq., V_{co}/g values became 11.1, 12.1, 13.1 sec., respectively.

(8) Master Power switching and indicator light, SOC Ready switch and light, SOC Engage switch and light, and Branch Failure Warning light and reset switch.

Figure 5 illustrates the PFIC panel. Figure 6 shows the installation of the electric sidestick and the PFIC on the right-hand side of the F-101B forward cockpit. This location of the PFIC caused it to be partially obscured by the pilot's arm; however, there was insufficient space on the left side of the cockpit for mounting of the PFIC on that side.

An overall schematic of the PFIC is provided in Appendix 1 as Drawing No. 621-29-1.

2.3 EFC Functions

The SOC was designed to operate as either a C^* controller or a $\dot{\theta}$ controller, and in both of these modes the pilot had the option of using Mach Trim feedback. The C^* and $\dot{\theta}$ feedback error equations are summarized in Table I below. The SOC Error Function Coupler (EFC) implemented the e_{C^*}, $e_{\dot{\theta}}$, C^*, and H(s) functions listed in this table. Selection of the C^* mode (accomplished remotely via the PFIC) caused the EFC to compute control loop error in accordance with Equation 2:4 (see table); conversely, selection of the $\dot{\theta}$ mode caused the EFC to compute error in accordance with Equation 2:5.

Differentiated δ_{SPT} positive feedback† added in the error summation is an essential signal in the SOC system. The theory of this feedback was introduced in Reference 6. The low-pass filter, H(s), acts as a bandpass (with 3 db. frequencies of 5.65 and 9.9 rad./sec.) in terms of the position signal δ_{SPT}. The purpose is to cancel the airframe short-period limit-cycle oscillations which would otherwise occur (at approximately 1 to 1.5 Hz) due to the $\dot{\theta}_m$ phase lag produced by pitch rate gyro poles. When C^* feedback is used, the forward normal accelerometer output signal should partially compensate the gyro characteristics;

† $\dot{\delta}_{SPT} > 0$ results from stabilator downward travel (producing negative pitch acceleration) and vice versa for $\dot{\delta}_{SPT} < 0$.

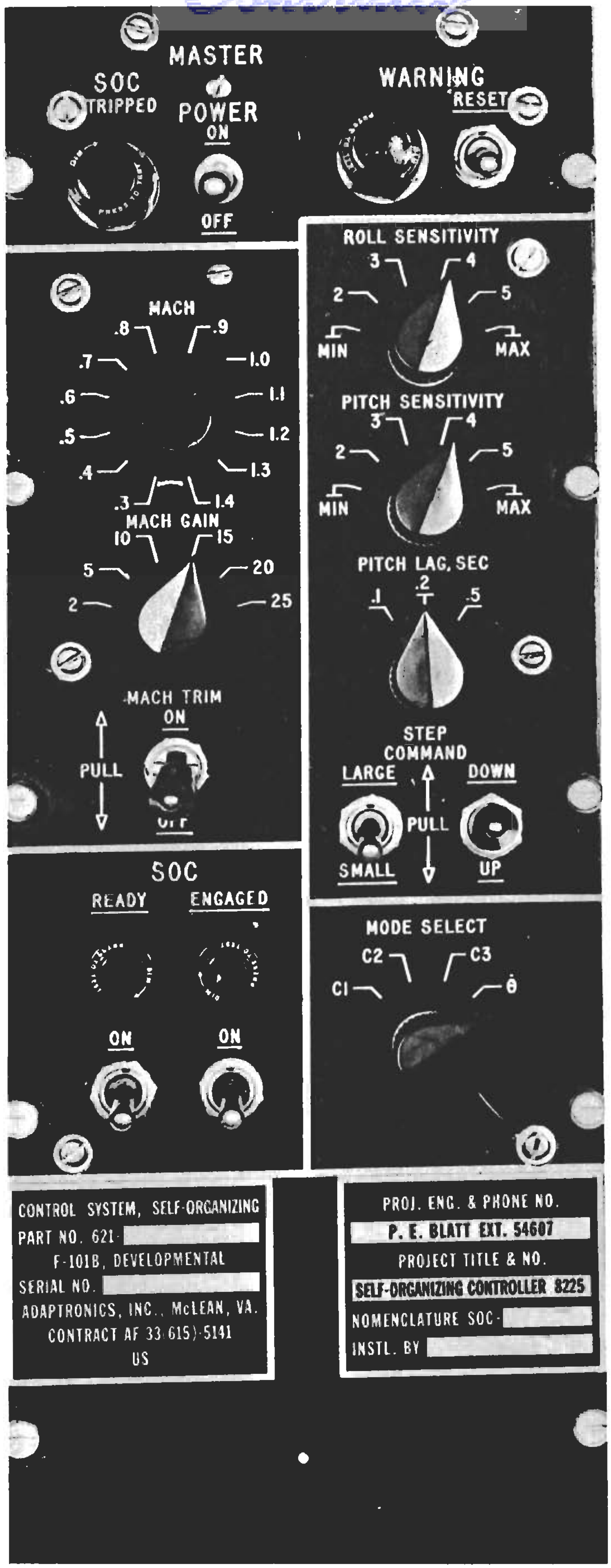


Figure 5: Photograph of PFIC Panel

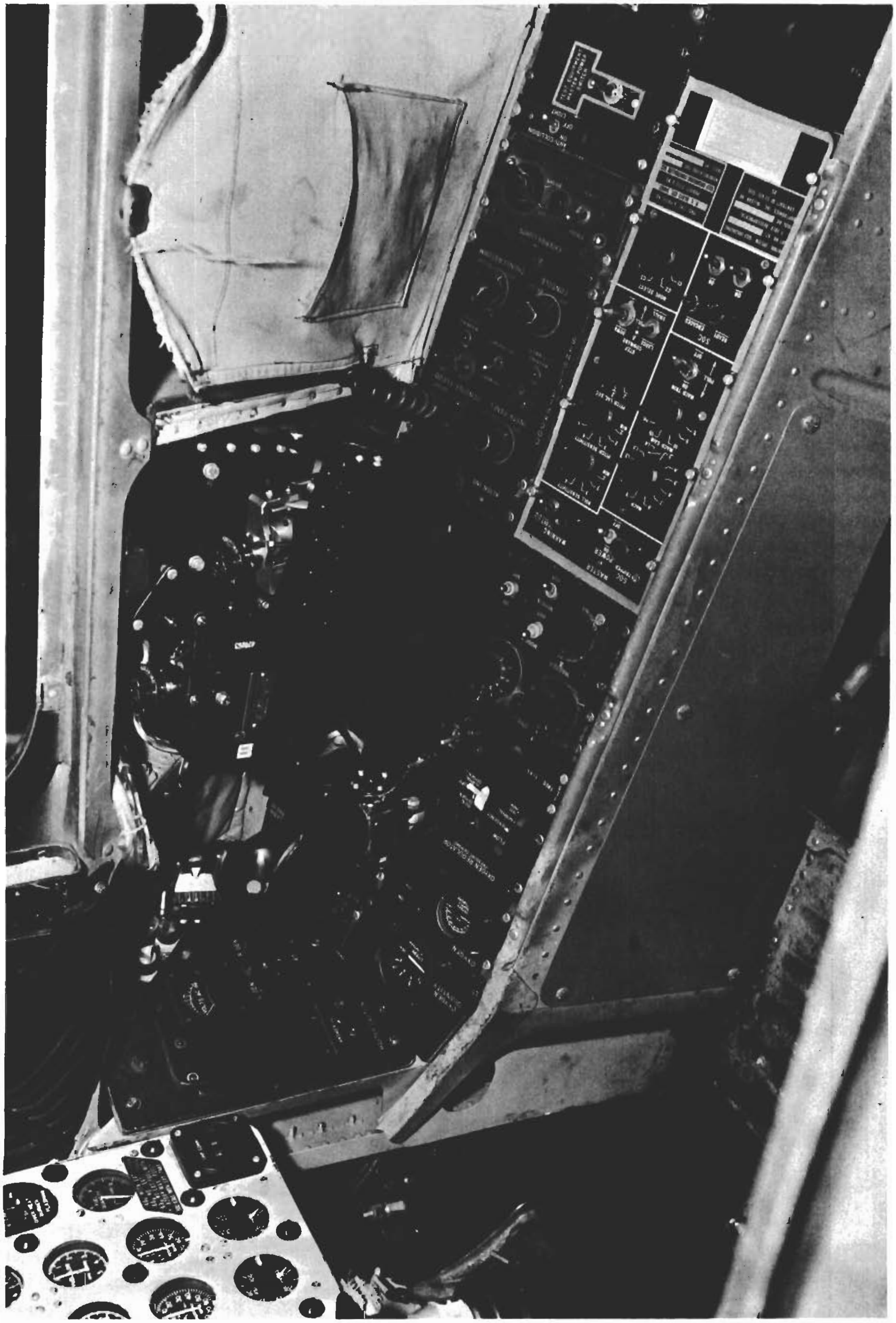


Figure 6: Photograph of Electric Sidestick and PFIC Installation in F-101B Forward Cockpit

Table I: Basic Error Equations

Units:

F_X, g

F_{S_M}, g

$\dot{\theta}_m$, rad./sec.

$(N_{z_{p_1}})_m$, g

$\dot{\delta}_{SPT}$, in./sec

$$e_{C^*} = K_1 F_X + K_2 F_{S_M} - K_3 C^* + K_4 {}_{C^*} \dot{\delta}_{SPT} H(s) \qquad \text{.......... } 2{:}4$$

$$e_{\dot{\theta}} = K_1 F_X + K_2 F_{S_M} - K_6 \dot{\theta}_m + K_4 {}_{\dot{\theta}} \dot{\delta}_{SPT} H(s) \qquad \text{.......... } 2{:}5$$

where:

$$F_X = \frac{F_{TSG} + F_{MPB} + K_M (M_{SET} - M_m) + K_{\dot{M}} \dot{M}_m}{1 + \tau_X s}$$

$$F_{S_M} = \frac{F_{ESS-P}}{1 + \tau_M s}$$

$$C^* = (N_{z_{p_1}})_m + \left(\frac{V_{co}}{g}\right) \dot{\theta}_m \qquad \text{.......................... } 2{:}6$$

$$H(s) = \frac{1}{(1+s/9.9)(1+s/5.65)} \qquad \text{.......................... } 2{:}7$$

Parameter	Flight Number 1	2	3-6	7-11	12-16	17-32
K_1, V/g	1.25	→	→	→	0.65	→
K_2, V/g	1.25	→	→	→	0.65	→
K_3, V/g	2.50	→	→	2.58	1.29	→
$K_{4_{C^*}}$, V/in./sec.	0.183	0.714	1.00	→	0.52	→
$K_{4_{\dot{\theta}}}$, V/in./sec.	0.733	2.87	1.00	→	0.52	→
K_5, V/rad./sec.	31.3	—	—	—	16.3	→
$K_M{}^{\dagger}$, g	0.618	→	→	→	0.322	→
$K_{\dot{M}}$, g-sec.	6.46	→	→	→	3.36	→
τ_X, sec.	0.4	→	→	→	→	0.2
τ_M, sec.	(0.1, 0.2, or 0.5 at pilot's option)					→
$\left(\frac{V_{co}}{g}\right)^{\ddagger}$, sec.	12.5	→	→	12.1	→	→

† "Mach Gain" = 25 on PFIC

‡ C2 Mode on PFIC

Table II: Parameter Values in Basic Error Equations vs. Flight Number therefore, the gain on $\dot{\delta}_{SPT}$ was originally specified to be smaller for the C^* mode than for the $\dot{\theta}$ mode (i.e., $K_{1_{C^*}} < K_{1_{\dot{\theta}}}$). But for Flights 3 et seq., these gains were made the same for both modes because of accelerometer anomalies (see below).

Table II lists the PFIC and EFC parameter values (C_2^* mode) used in the flight test evaluations. This table is discussed further in Sections 3 and 4.

Appendix I, Drawing 621-2 details the EFC design. Figures 7 and 8, below, diagram the basic signal circuits of the EFC for its two modes of operation. The low-pass filter consisting of the 36K resistor and 10μF capacitor was inserted in the accelerometer output path for Flights 7 et seq. Because this filter was loaded by three EFC's, each having an input resistor of R13′ = 43K, the filter transfer function was

$$\frac{1.03}{1 + s/11.3}$$

which had the secondary effect of reducing (V_{co}/g) by 3 percent. The 11.3 rad./sec. corner frequency was necessitated by an 80-Hz ripple component of approximately ± 0.1 g on the accelerometer output.†

†As a general comment, the accelerometer (and, to a lesser degree, the rate gyro) available in the F-101B were not of top instrument quality, having been originally provided in the aircraft for such purposes as g limiting rather than closed-loop control.

Table of Resistances, Kilohms

Resistor	Flight Nr. 1	2	3-6	7-11	12-32
R13	150	→	→	0	→
R13'	0	→	→	43	→
R41	75	→	→	→	39
R43	73	18.7	13.3	→	→

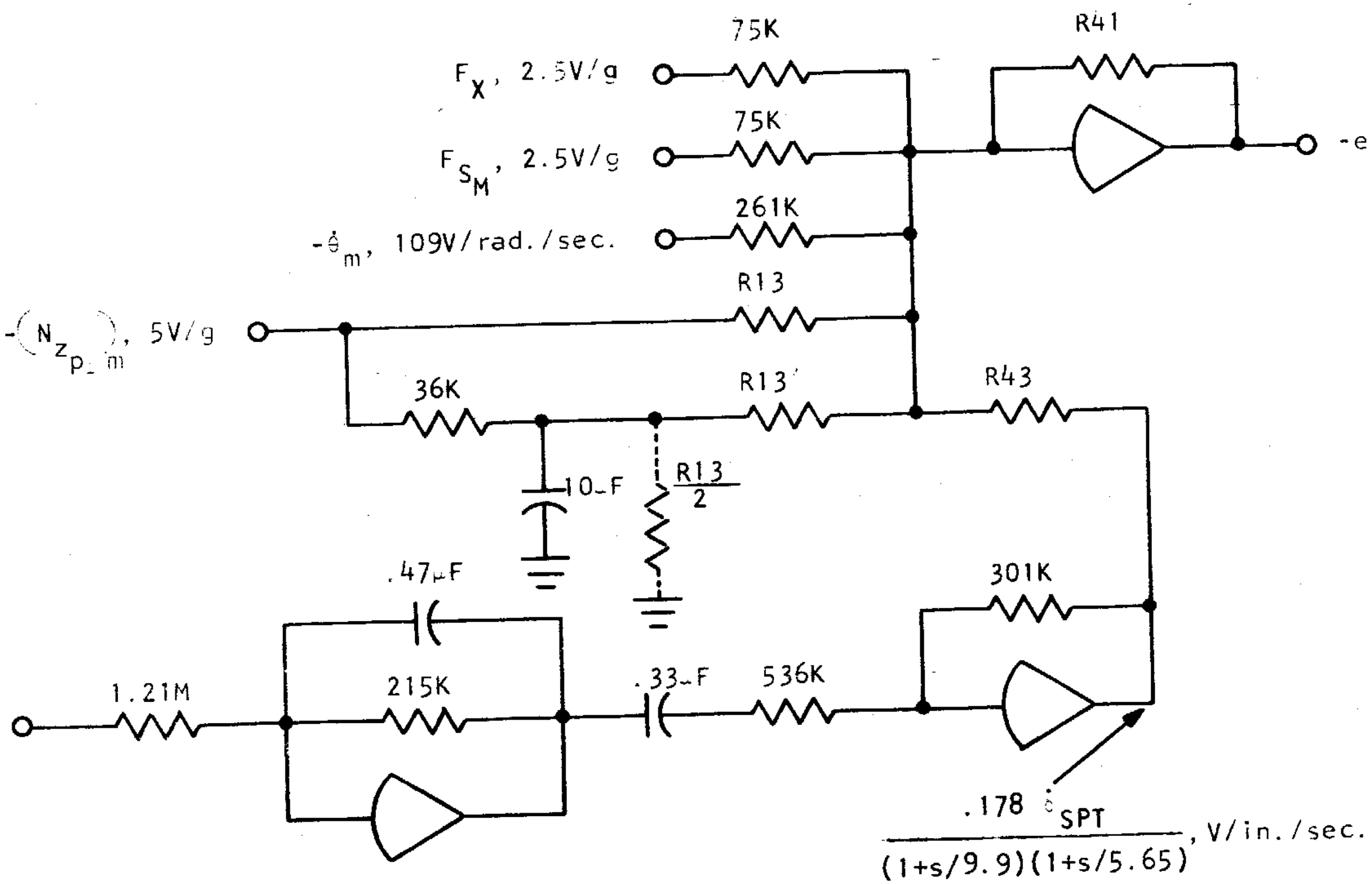


Table of Resistances, Kilohms

Resistor	Flight Nr. 1	2	3-6	7-11	12-32
R41	75	→	→	→	39
R43	18.2	4.65	13.3	→	→

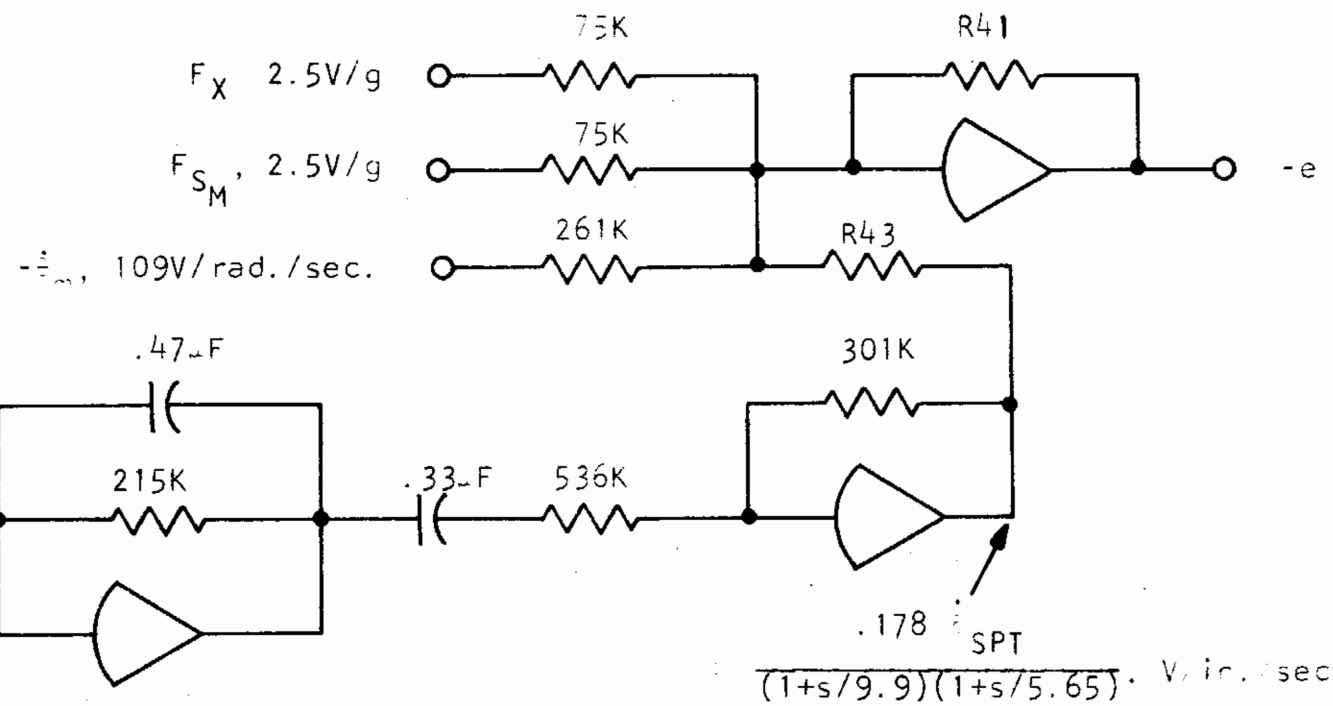


Figure 8 : EFC $\dot{\theta}$ Mode, Basic Circuit

2.4 SOC Logic Unit

The elementary SOC was unique in that it contained means for modulated-noise control signal generation. A functional block diagram of the SOC Logic Unit (SLU) which incorporated this feature is shown in Figure 9, and Figure 10 portrays the printed circuit board used to implement the SLU. The SLU received the error signal, e, from the EFC and computed an augmented derivative

$$e_p = e + 0.15\,\dot{e} \quad \text{.......} \quad 2{:}8$$

which was used to provide lead compensation. The sign of e_p was then determined by a zero-crossing detector (electronic relay). Up to this point, the SLU thus functioned as a relay controller with lead compensation. The novel portion of the unit was that which encoded sgn e_p, the output of this first zero-crossing detector, as sgn u, another binary control signal having the same low-frequency components as sgn e_p but with high-frequency components governed chiefly by the characteristics of the noise carrier used in a modulation process.

sgn u was a binary probability state variable (PSV), that is, the distribution function but not the instantaneous state of sgn u was controlled. A probability control voltage, PCV, established the binary probability distribution for sgn u: specifically, the probability of sgn u = + 1 increased for increasing PCV, while the probability of sgn u = - 1 decreased for increasing PCV, and the opposite relationships held for decreasing PCV. For its part, PCV was determined by a nonlinear lag operator acting on sgn e_p.

With the particular parameter values used in the lag operator for PCV, the latter was capable of moving from its midpoint to either of its limits (+ 3V or - 3V) in 0.003 sec., or from one of its limits to the opposite in 0.006 sec. Once at either of its

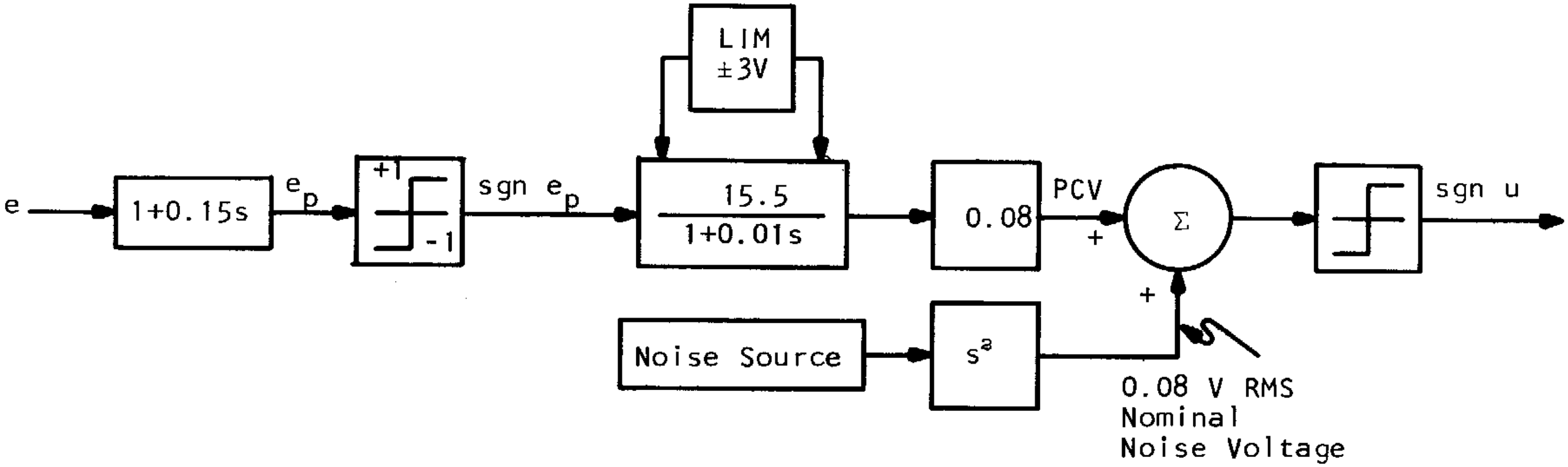


Figure 9: Functional Block Diagram of SOC Logic Unit (SLU)

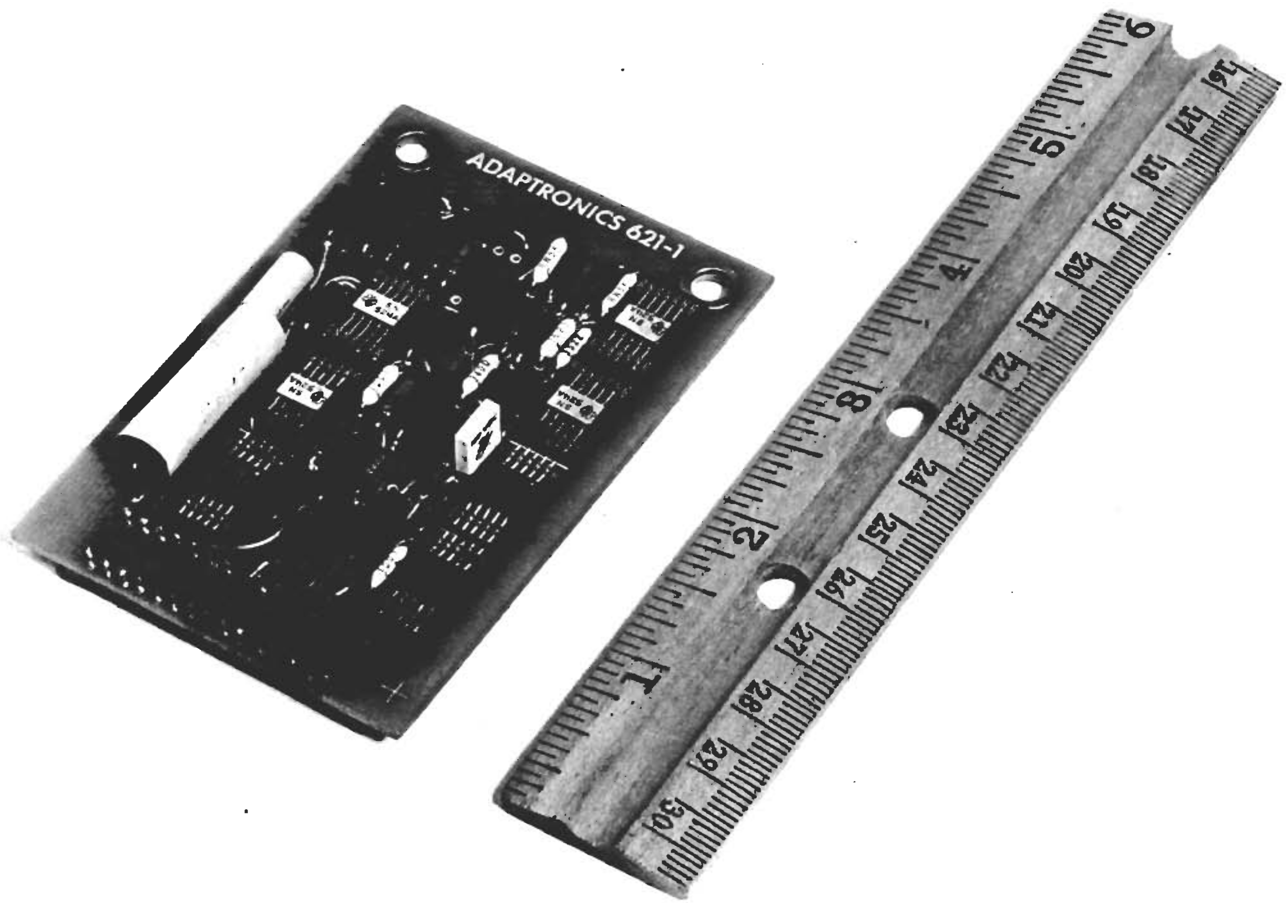


Figure 10: Photograph of Printed Circuit Board Used to Implement the SOC Logic Unit (SLU)

limits, PCV biased the noise source to approximately a 3σ level, i.e., sgn u became equal to sgn e_p with almost complete certainty. The minimum elapsed time interval of 0.006 sec. between the PCV limits prevented any coherent oscillation of sgn e_p from appearing in sgn u at frequencies above approximately $1/(0.012\pi) = 26.5$ Hz.

Although the phase shift of the nonlinear lag between sgn e_p and PCV was 180° at 26.5 Hz (the natural auto-oscillation frequency of the SLU encoder working in an otherwise lead-or-lag-free negative feedback loop), the phase shift of this element at basic control-mode frequencies (0-5 Hz) was negligible. Therefore, encoding of sgn e_p by the modulated-noise process to obtain sgn u had the effect of rejecting sharply any components of sgn e_p above the design cut-off frequency of approximately 26.5 Hz, while producing no substantial effect on basic control-mode signals.

The useful filtering properties of the PSV encoder were, in some respects, of secondary interest in this project compared with the capacities of this device to mitigate adverse control effects of hysteresis in actuators and in the airframe structure. Because the quantitative values of such hysteresis have not been precisely determined, and probably vary from one aircraft to the next, the following discussion considers only certain qualitative aspects.

Suppose some element within the actuator has a hysteresis loop of the type sketched in Figure 11. Suppose, further, that sgn e_p is oscillating in a limit cycle at a given frequency f_{LC}. Without the PSV encoder, the actuator input might then exhibit the waveform shown in Figure 11 below the actuator input-output hysteresis diagram. This input is not a rectangular wave (even though the sgn e_p waveform is rectangular) because of lags and rate limits between the controller and the actuator. For example, in the F-101B, the stabilator main power actuator is driven by a hydraulic servo (the parallel servo) which has a significant

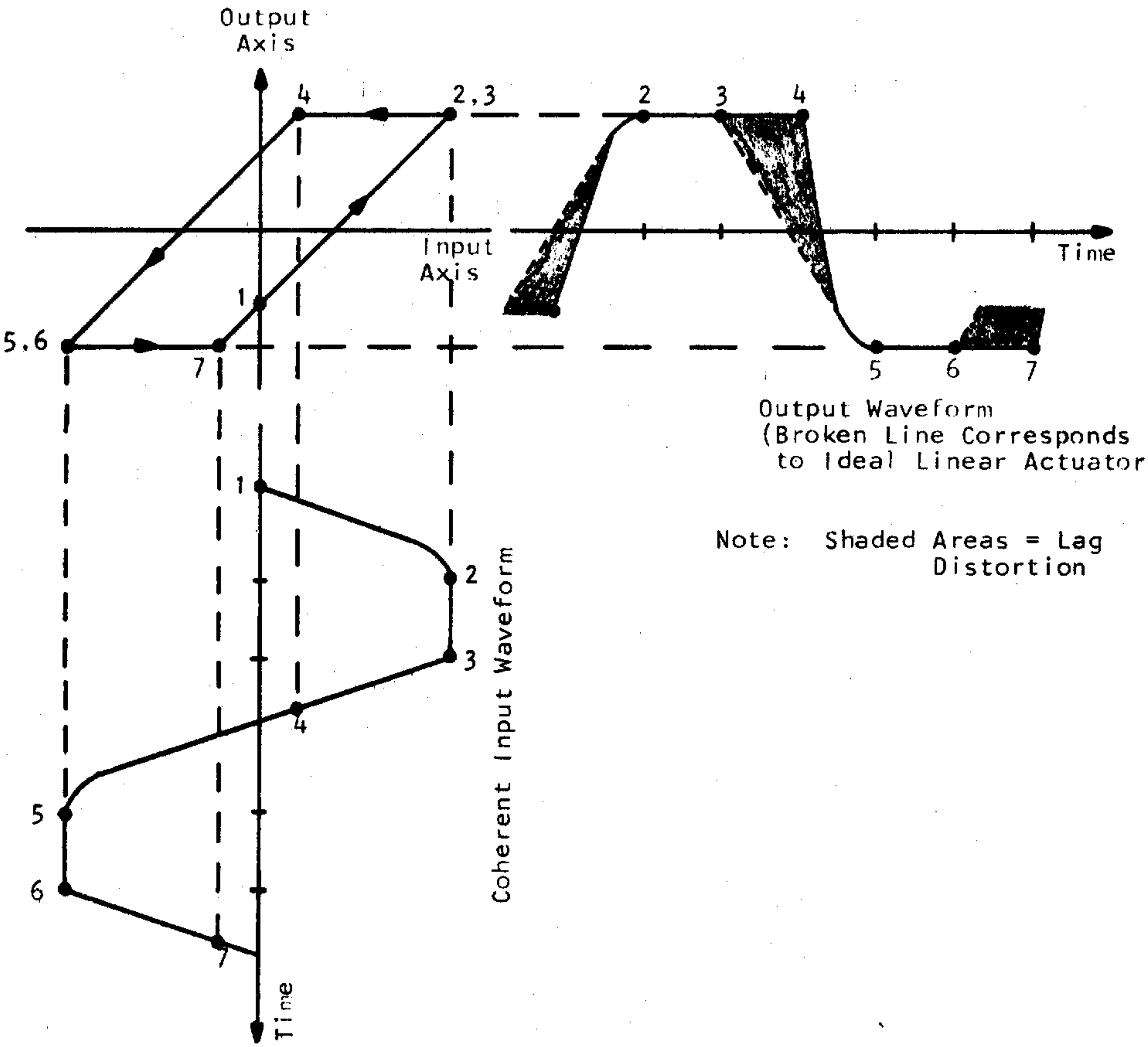


Figure 11: Sketch Illustrating Effect of Actuator Hysteresis on Waveform of Deterministic Control Signal

output-rate limit as well as first-order and higher-order dynamic lags. For the assumed coherent input, the output of the hypothetical actuator becomes the waveform shown at the top right of Figure 11. The shaded regions of the sketch represent the lag distortion imposed upon the driving waveform by the actuator hysteresis loop. Note that this distortion represents a substantial delay (essentially a dead time of one-sixth of the limit-cycle period).

Now contrast the above with the behavior of the actuator when sgn e_p has been encoded as a PSV signal. Provided the actuator input can assume the form shown in Figure 12, despite the presence of lags and rate limits between sgn u and the actuator, the new output waveform becomes another PSV signal, as shown in the figure, and this new output exhibits significantly less lag distortion than existed previously. In principle, then, and subject to the above proviso, the PSV encoder has reduced the effective dead time of the actuator. Theory says that this reduction in effective dead time should increase the control system limit-cycle frequency, f_{LC}. And with a raise in this frequency, the amplitude of the limit-cycle oscillation should be proportionately reduced (ignoring possible resonance effects). The designer's question, however, is whether the necessary rapid, random excursions about a mean dynamic input to the actuator are achievable in view of the natural upstream lags and rate limits. Based upon results of this project, the answer appears to be: "For the F-101B tested, yes." The matter seems to hinge on differences between the small-signal and large-signal characteristics of system elements between the controller and the final actuator. Indications are that the small-signal responses of these elements are not as severely rate-limited as are the large-signal (mean) responses.

Simulations (with appropriate actuator hysteresis) and ground tests of the F-101B/SOC system measured a closed-loop f_{LC} of

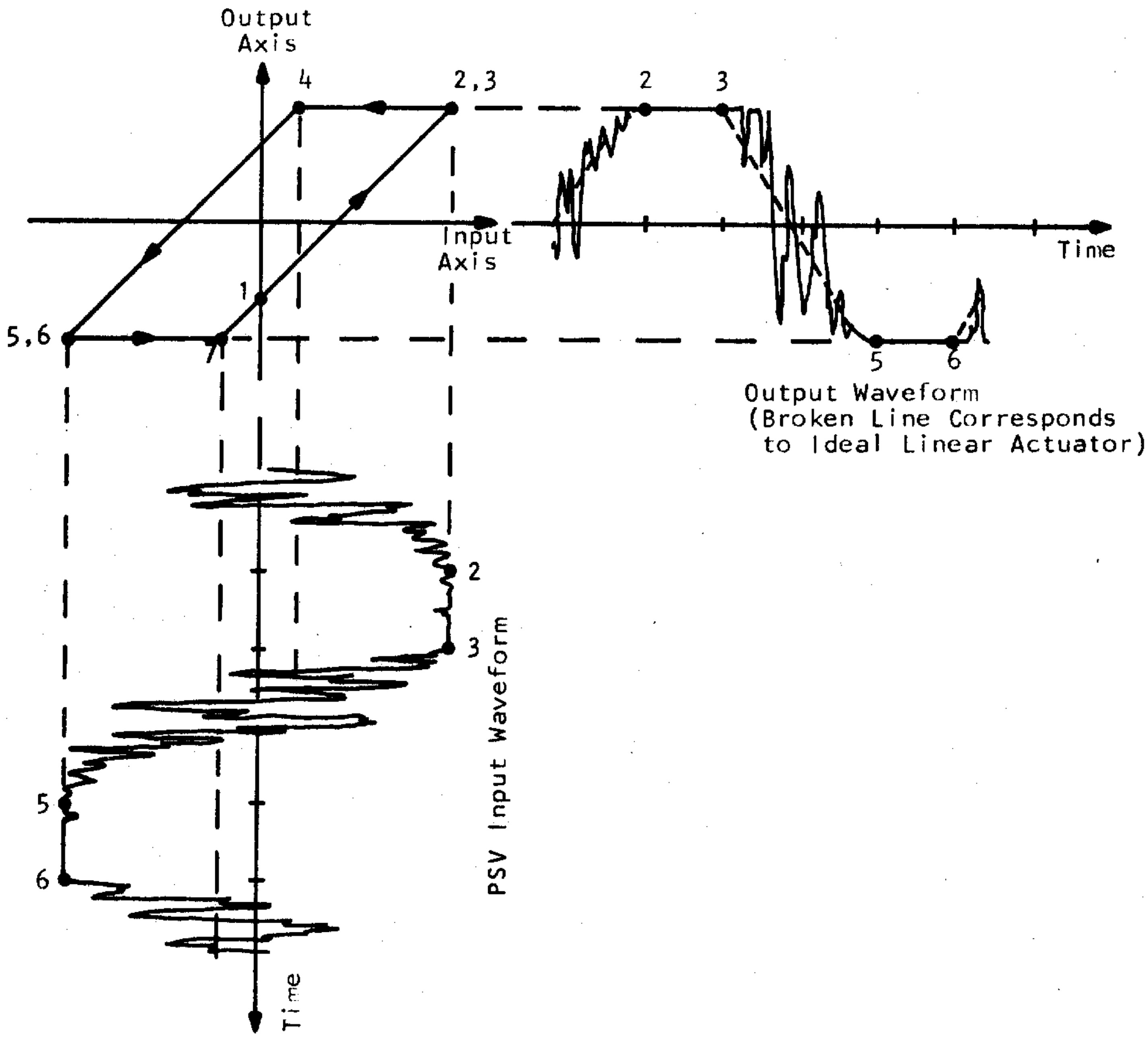


Figure 12: Sketch Illustrating Typical Effect of Actuator Hysteresis on Waveform of PSV Control Signal

20 Hz with the PSV encoders functioning.[†] Flight tests showed an intermittent oscillation to be present at approximately 16 Hz[‡] (the lower f_{LC} was possibly due to proximity in frequency of the airframe second bending mode), with no oscillations observed at frequencies higher than 16 Hz. No ground or flight tests were conducted with the PSV encoders disabled. Simulation experiments run without actuator hysteresis produced f_{LC} in the range 33-60 Hz (note that the encoder elevated its own nominal 26.5 Hz auto-oscillation frequency by a similar mechanism to that affecting the actuator behavior). A hysteresis magnitude just great enough to lower f_{LC} of the simulation to 20 Hz with the PSV encoders functioning was sufficient to introduce a substantial limit cycle at approximately 2.9 Hz (close to the airframe short-period mode) with these encoders disabled.

As shown in Figure 13, the SLU noise voltage varied with temperature, with the nominal peak occurring at 15 °C and voltage decreasing for either higher or lower temperatures. The SOC was designed to operate over an ambient temperature range of -54 °C to + 71 °C, for which the noise RMS amplitude varied as much as 2.4 to one. Although this range was acceptable from the standpoint of flight safety, it did produce some variation in SOC performance between cold and equilibrium temperature conditions. For future systems, noise-circuit temperature compensation is recommended, particularly if the range in ambient temperatures is substantially greater than was encountered in the experimental program. (The simplest procedure might be to mount the noise diode in a heat sink along with a heating resistor that has a positive resistance vs. temperature characteristic and is powered by a regulated voltage source.)

[†] Incremental δ_{SPT} amplitude of this oscillation was approximately 0.20 in. peak-to-peak.

[‡] Incremental δ_{SPT} amplitude (when oscillation was present) varied, but averaged approximately 0.25 in peak-to-peak.

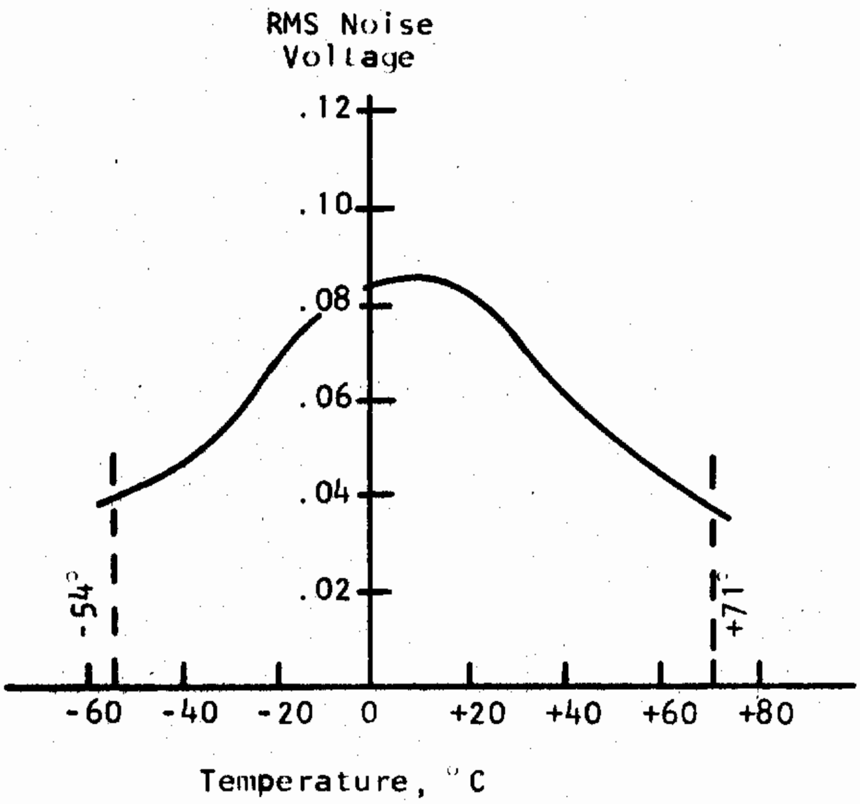


Figure 13: Measured Noise Voltage vs. Temperature Characteristic for Typical Noise Diode and Associated Circuitry

A detailed schematic of the SLU unit is presented in Appendix I as Drawing 621-1.

2.5 Command Signal Coupler

The Command Signal Coupler (CSC) provided the branch disconnect logic, as shown in Figure 14. Table III summarizes the SOC warning and disconnect logic implemented in the CSC elements.

The two disconnect conditions treated by the CSC units were:

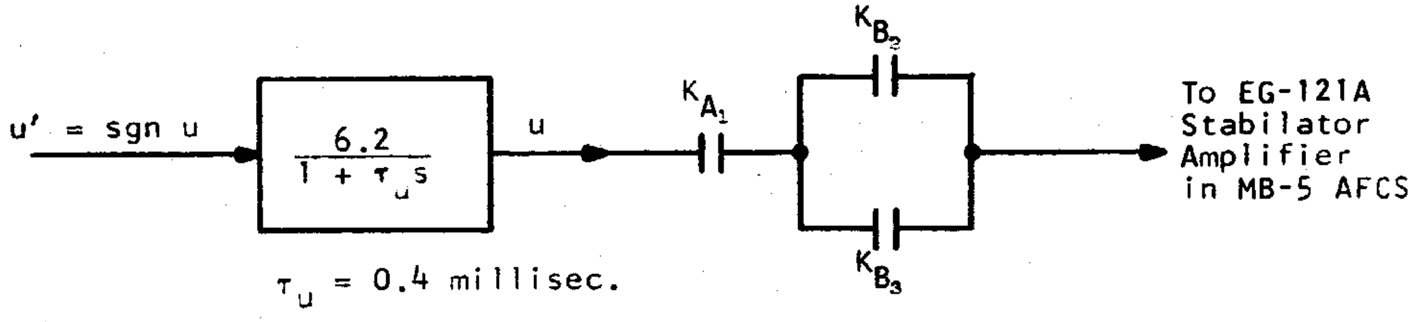
(1) g Disengage Limiting -- If the $\left(N_{z_{p_2}}\right)$ fell outside of an acceptable zone bounded by positive and negative g limits, the SOC was automatically disconnected.

(2) Value Signal Comparison Logic -- The Value Signal Comparison Logic, operating on a branch-by-branch basis, compared the phase of the sgn u signal of the branch with the phase of the sgn e_p signal of that branch. If the phase relationship was improper, as signified by the logical product of sgn e_p and sgn u being negative for a sufficient period of time to trigger a detector driven by an integrating circuit, a failure of the respective branch was assumed. In this event, the CSC disconnected the offending branch, and transmitted a warning signal to the PFIC.

The complete concept of the SOC failure detection, warning, and disconnect logic is presented in Reference 32. Table IV summarizes these concepts.

A reliability prediction for the triply redundant SOC was reported in Reference 30.† The predicted system reliability

†Although entitled "First Interim Reliability Prediction for Self-Organizing Flight Controller", the conclusions of this reference are essentially valid for the system as flown.



Relays: K_{A_1} is controlled by Branch 1 disconnect logic
K_{B_2} is controlled by Branch 2 disconnect logic
K_{B_3} is controlled by Branch 3 disconnect logic

Figure 14: Command Signal Coupler Functional Block Diagram for CSC_1

Table III: CSC Warning and Disconnect Logic

(1) $g_1 + g_2 + g_3 =$ #1 Warning

(2) $D_1 + D_2 + D_3 =$ #2 Warning and Branch Disconnect

(3) $g_1 \cdot g_3 + g_1 \cdot g_2 + g_2 \cdot g_3 + D_1 \cdot D_3 + D_1 \cdot D_2 + D_2 \cdot D_3 =$ Red-Light Failure Indication and System Disconnect

where

$$g_i = N_{z_p} > PGL_i \text{ or } < NGL_i$$

and the disconnect flip-flop set terms were:

$$D_{1_s} \equiv \overline{v_1} + D_2 \cdot D_3$$

$$D_{2_s} \equiv \overline{v_2} + D_1 \cdot D_3$$

$$D_{3_s} \equiv \overline{v_3} + D_1 \cdot D_2$$

in which

$$v_i \equiv \text{smoothed sgn } e_{p_i} \cdot \text{sgn } u_i$$

Table IV: Summary of CSC Failure Detection and Disconnect Concepts

Fault	Effect on SOC	Pilot's Indicator	Pilot Action
Single branch g-sensing failure or marginal g condition tripping g-sensing circuit in a single branch.	Reduction of redundant Σu paths, no loss of authority.	#1 Warning.	Attempt reset; if unsuccessful, disconnect manually after reaching flight conditions amenable to manual control.
1st branch failure.	Offending branch disconnected, "apparent" authority reduced to 2/3 of original value.	#2 Warning.	Attempt reset; if unsuccessful, disconnect manually after reaching flight conditions amenable to manual control.
Excessive g-level or 2nd branch failure.	System disconnected.	Failure light.	Manual control required

greatly surpassed the contract goal of an equivalent MTBF of 50,000 hours, based on a two-hour mission. The predicted probability of a mission-abort failure, defined as any system failure which would result in a warning to the pilot that the SOC had experienced a branch failure, was 0.00158 for two-hour airborne missions. The predicted probability of a safety-of-flight failure, defined as any system failure which would result in a loss of pilot ability to control the aircraft through the SOC, was 6.025×10^{-6} for the same type of mission. Thus a mission abort was expected about once in each 630 missions, and a controller failure about once in each 160,000 missions, the latter representing an equivalent MTBF of about 320,000 hours.

It should be noted that the estimated failure probability for the non-redundant PFIC was 3×10^{-6} failures per hour, giving a resulting probability of PFIC failure of 6×10^{-6} for a two-hour mission, which was by far the predominant factor in the calculation of system probability failure. If it were not for the non-redundant PFIC, the equivalent MTBF for the system would have been predicted to be on the order of 80 million hours.

Aside from the above predictions, it is noted that no SOC failures, either branch or system, occurred during the 32 flights of the test program, which accumulated approximately 40 hours of flight time with the SOC in operation.

2.6 Mach Trim Loop

The Mach Trim loop, implemented in the PFIC, was provided as an outer-loop function to permit evaluation of positive or neutral speed stability in control system design for high-performance fighter aircraft. The principles underlying the design of this loop are presented in Reference 17. Figure 15 presents an equivalent circuit diagram for the Mach Trim controller in the PFIC for the case of a "MACH GAIN" setting of 25 on the panel of this unit.

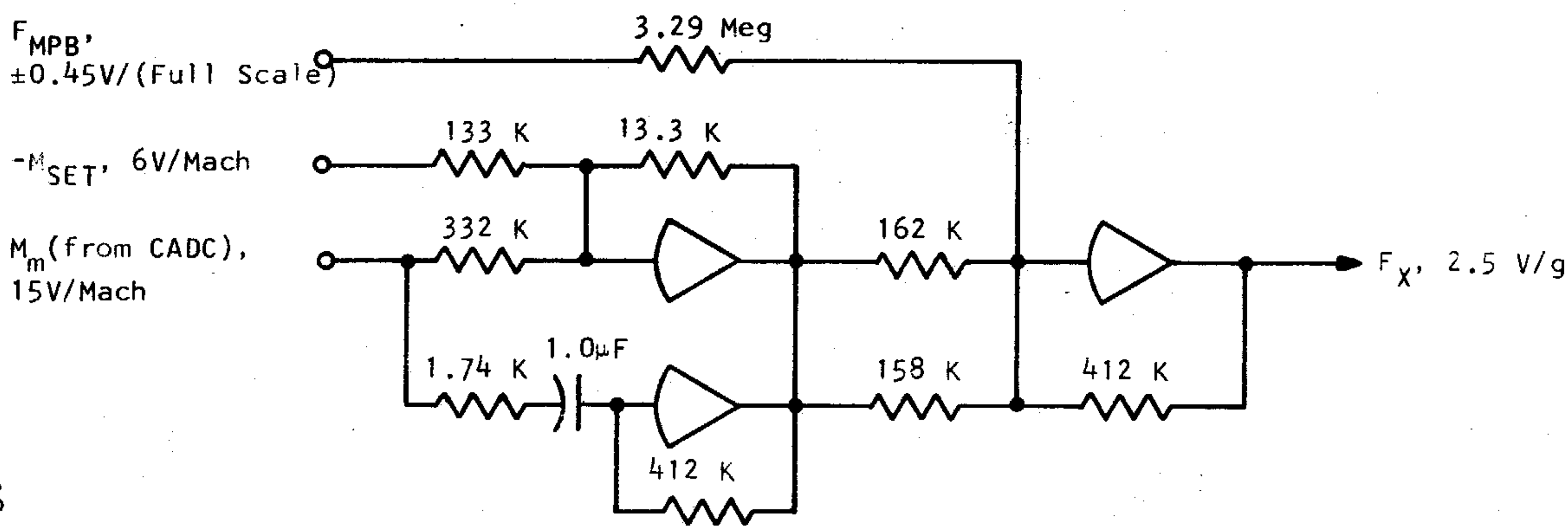


Figure 15: Mach Trim Controller, Basic Circuit†

† For PFIC "MACH GAIN" set at 25: $F_X = -0.618(M_{SET} + 0.033F_{MPB} - M_m) + 6.46\,\dot{M}_m$, g/Mach in which F_{MPB} = 0.033 Mach/(Full Scale).

Authors differ on the question of positive versus neutral speed stability for aircraft. In general, neutral stability is advantageous for highly-maneuverable fighter aircraft in combat situations, whereas some positive speed stability is needed for large bomber and transport aircraft, and is often desirable during ferry missions, takeoffs and landings, and under IFR conditions in fighter operations. The Mach Trim loop of the experimental system was, as can be seen from Figure 15, a low-gain control. As such, this loop did not produce particularly rapid settling to the commanded Mach number, but was intended to prevent aircraft speed divergence, or at least to reduce the level of pilot attention required to maintain a given cruise Mach number.

Drawing 621-29-1 in Appendix I contains the detailed PFIC circuit for the Mach Trim function.

2.7 Packaging

Packaging of the self-organizing controller is shown in Figures 16 - 18. The connector on the front of the enclosure provided for tie-in with the Ground Support Equipment, while those on the rear were for interfaces with the PFIC, the taper pin junction assembly, the MB-5 AFCS, and the flight recorder, as shown in Drawing 621-7 of Appendix I. The outer dimensions of the SOC enclosure were 10.750" deep by 5.781" high by 11.750" wide, and the all-up weight was approximately 12 pounds.

Figure 18 reveals the interior of one of the three removable modules with its individual power converter. Each module consisted of a motherboard on which were mounted connectors for the five removable printed circuit boards for the EFC (1), SLU(1), and CSC (3). The metal baffles between these removable boards and the module provided shielding, structural rigidity, and a pivot point for the extractor tool used in removal of the boards.

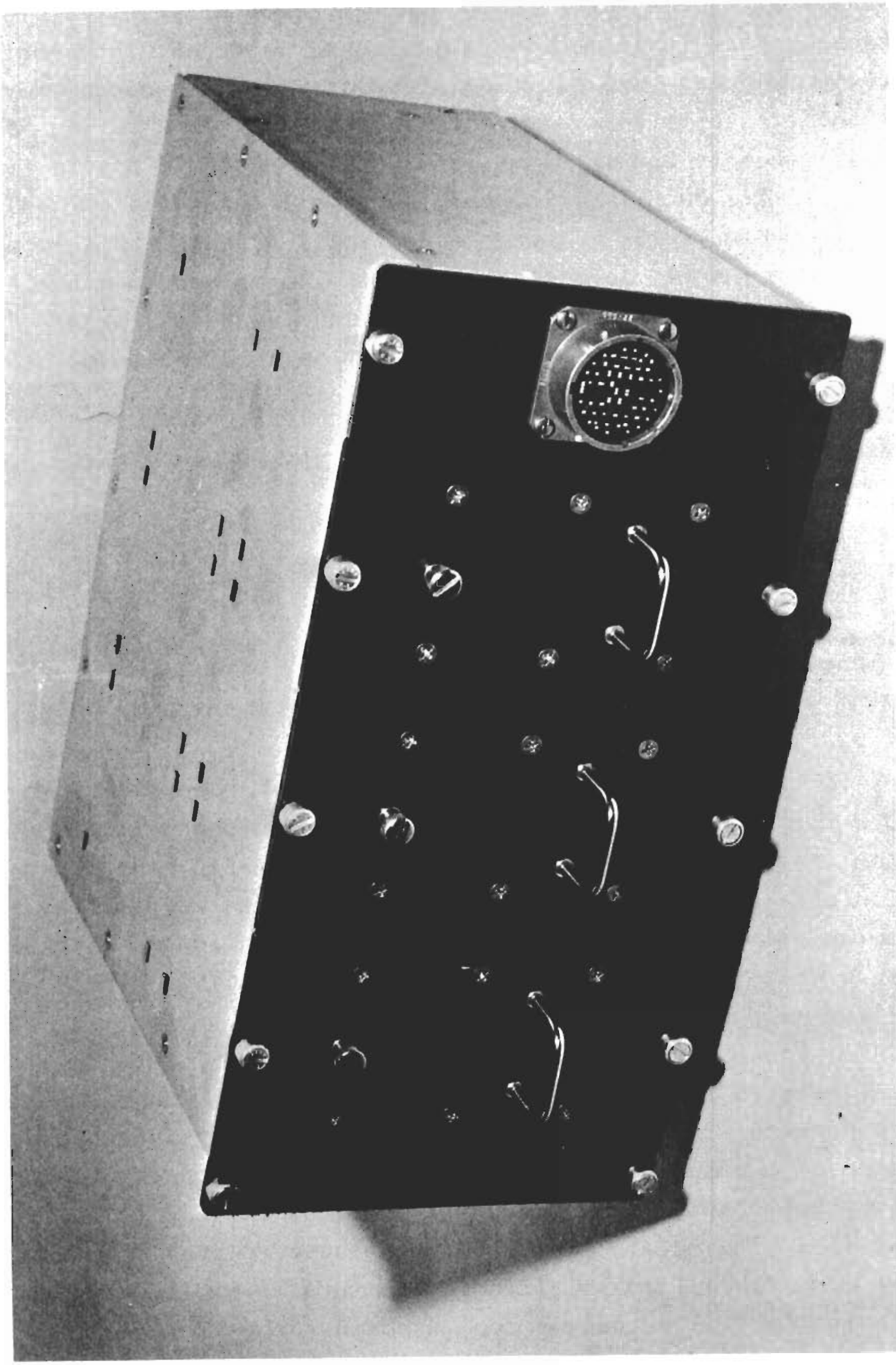


Figure 16: SOC Enclosure, Front Photograph

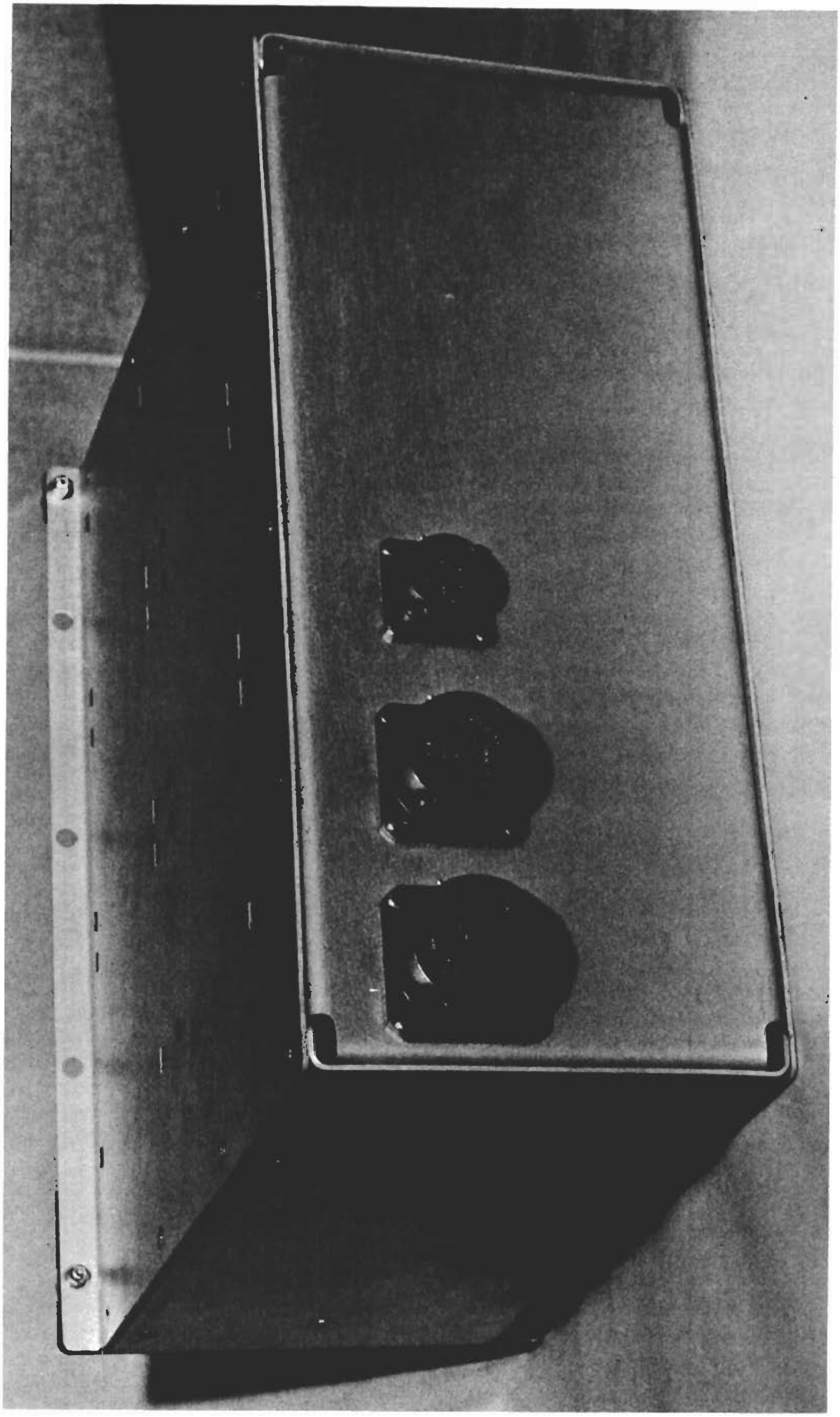


Figure.17: SOC Enclosure, Rear Photograph

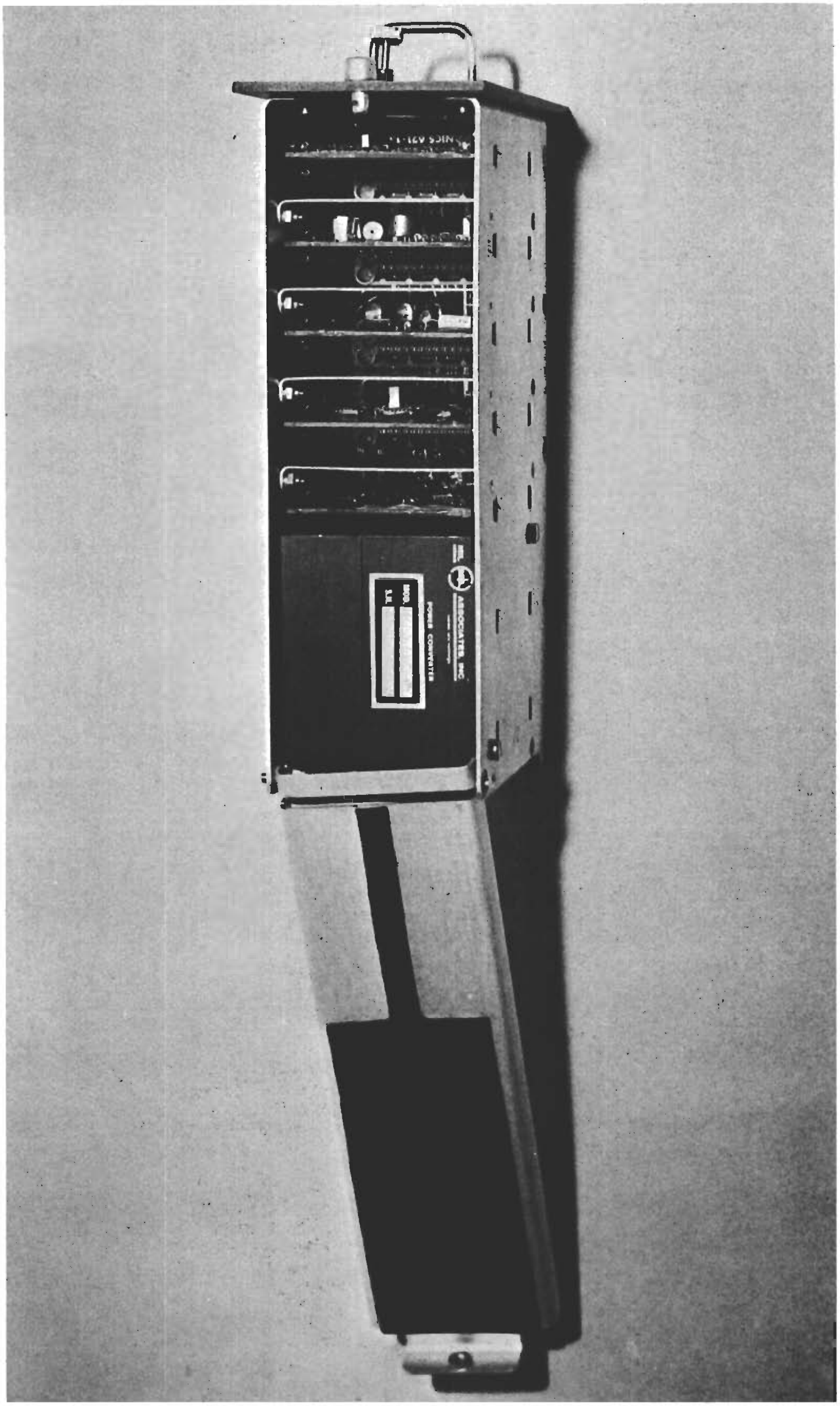


Figure.18: SOC Module, Top Photograph with Cover Plate Removed

2.8 Simulations

Because the SOC and the object it controlled were both highly nonlinear, computer simulations of closed-loop system operation were the primary tool for design analyses as well as system testing. Three simulations were employed:

(1) analog simulation (EAI TR-48 computer) of airframe short period pitch-axis dynamics and characteristics of the actuator, sensors, and SOC

(2) analog simulation (SD 10/20, a ±100 V computer) of combined short period and phugoid mode airframe dynamics, as well as actuator and sensors, for flight-worthiness testing and pre-flight checkout of SOC and PFIC (see Drawing 621-9 in Appendix I)

(3) digital simulation† (IBM 1130 computer), which included effects of first three body bending modes and, because it used exact dynamic and kinematic relationships for the F-101B, was valid for large perturbations in the aircraft response variables (Reference 17).

Table V presents a summary of the ten flight conditions used for design analyses and both ground and flight testing of the SOC. The table includes the M_δ (stabilator surface effectiveness) value for each flight condition and the ratio of M_δ to a weighted-average value of M_δ, denoted M_δ*. The weights in this average were calculated by estimating the relative frequency of each flight condition in typical operations of the F-101B. The M_δ values varied from a minimum of 0.45 M_δ* to a maximum of 2.35 M_δ*, or a range of 5.2 to 1.

†Performed by DODCO, Inc., Princeton, New Jersey.

Table V: Flight Conditions

Number	Altitude, ft.	Mach Number	M_δ	M_δ/M_δ*
1	10,000	0.45	8	0.45(Min)
2	10,000	0.80	31	1.73
3	10,000	0.95 (540 KIAS)	42	2.35(Max)
4	20,000	0.55	9	0.50
5†	20,000	0.90	22	1.23
6†	20,000	1.20 (580 KIAS)	39	2.18
7†	35,000	0.75	10	0.56
8	35,000	0.95	18	1.00
9	35,000	1.30	23	1.29
10	35,000	1.60 (or maximum safe Mach)	26	1.45

Note: M_δ* = Average M_δ calculated by considering relative frequency of each flight condition in typical operations of the F-101B
= 17.9

† Denotes one of three conditions extensively used in checkout of the SOC.

Flight conditions 5, 6 and 7 were used most extensively in checkout of the SOC. Subjectively speaking, condition 5 was the most representative, while conditions 6 and 7 appeared to be the hardest to control among those at each end of the M_h range.

Simulation results summarized in Figure 19 illustrate the way in which the δ_{SPT} limit cycle oscillations were studied on the TR-48 computer. This figure plots the peak-to-peak amplitudes and the frequencies of these oscillations vs. K_{4C*}, the error-function gain on δ_{SPT}. (See pp. 19-22.) System behavior is shown for three flight conditions. The broken-line portions of the curves in Figure 19 represent regions over which no steady-state oscillations were sustained, although damped transient oscillations of the indicated maximum amplitudes were observed in the simulation up to those values of K_{4C*} for which the amplitude curves cross the abscissa of this graph.

The simulation used to map relationships between the δ_{SPT} limit cycle and K_{4C*} did not contain actuator hysteresis, airframe bending modes, or the 11.3 rad./sec. smoothing later found necessary to eliminate a strong 80-Hz ripple component from the aircraft accelerometer output (see p. 21). This simulation therefore exhibited some disagreement with flight data, although the trends shown in Figure 19 were borne out well by flight measurements. Larger values of K_{4C*} were required in actual operation than are shown in this figure. Whether a value as large as that listed in Table II (i.e., K_{4C*} = 1.00) was needed remains a moot question.

Figures 20 - 22 present SD 10/20 simulation date obtained in verification of Mach Trim loop operation. As can be seen from Drawing 621-9 in Appendix I, the simulation used for the F-101B phugoid mode was linearized for the analog computer;† however, comparisons with results of the digital

† The linearization assumed the aircraft operation at constant thrust in the neighborhood of a trim point.

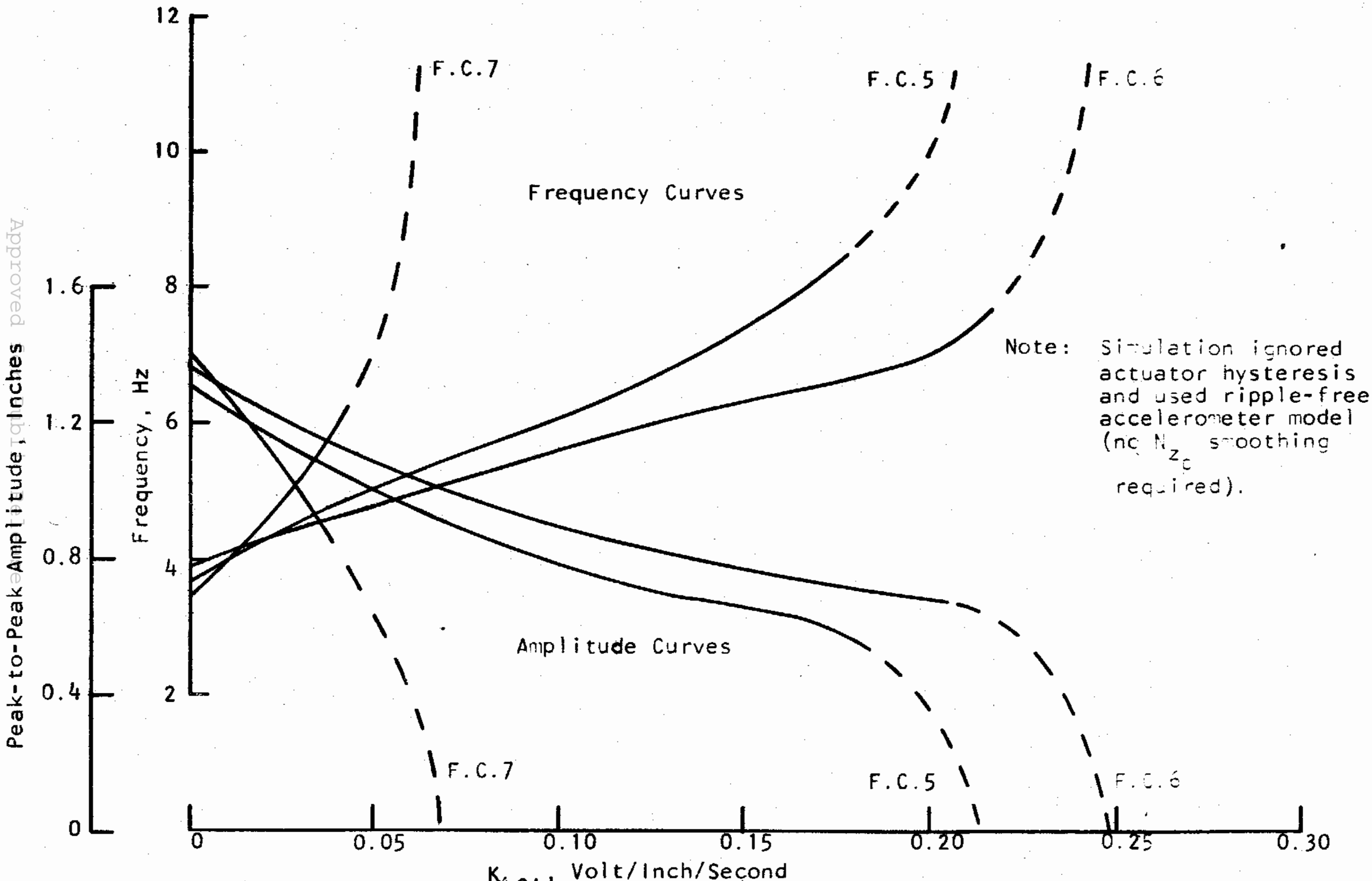
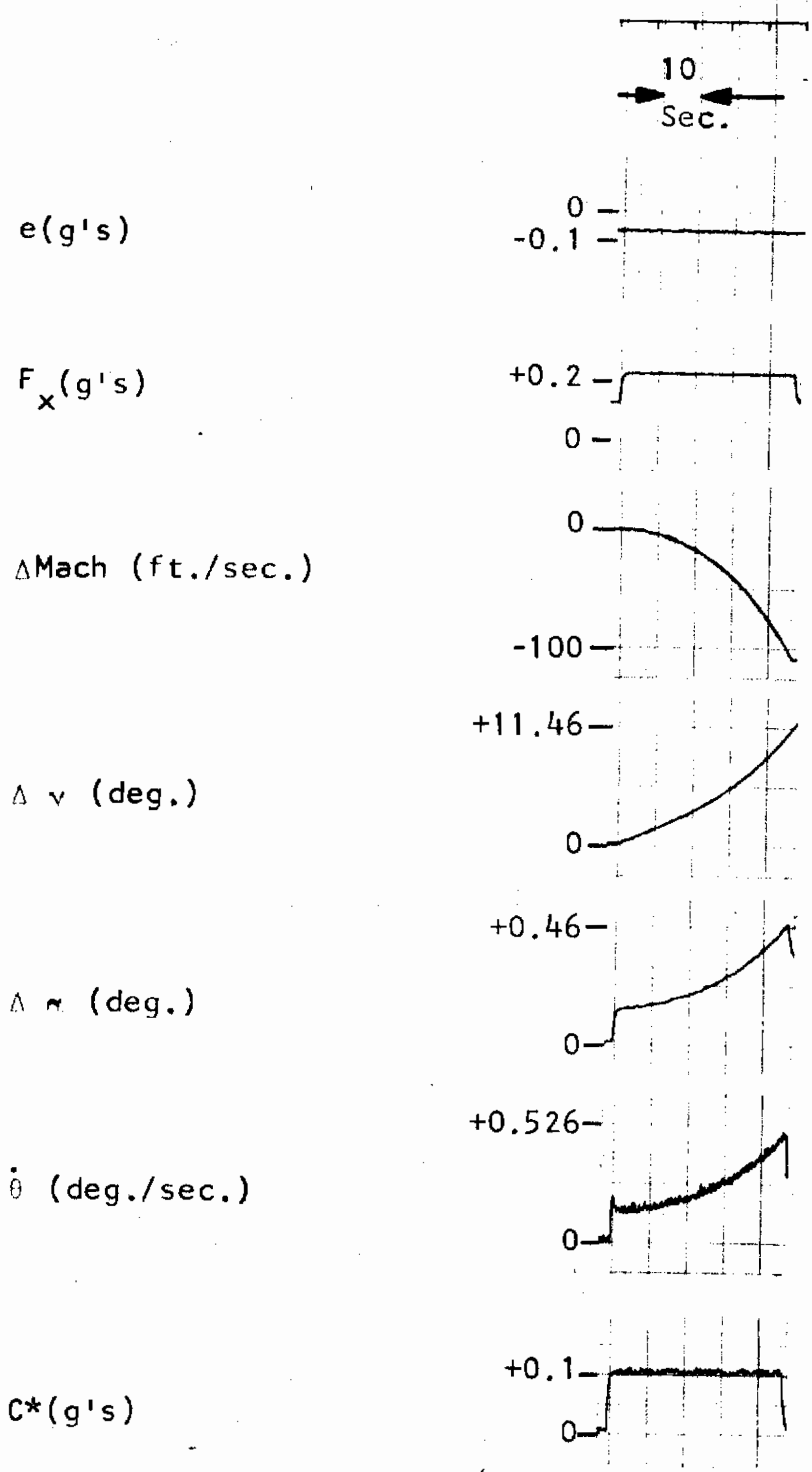
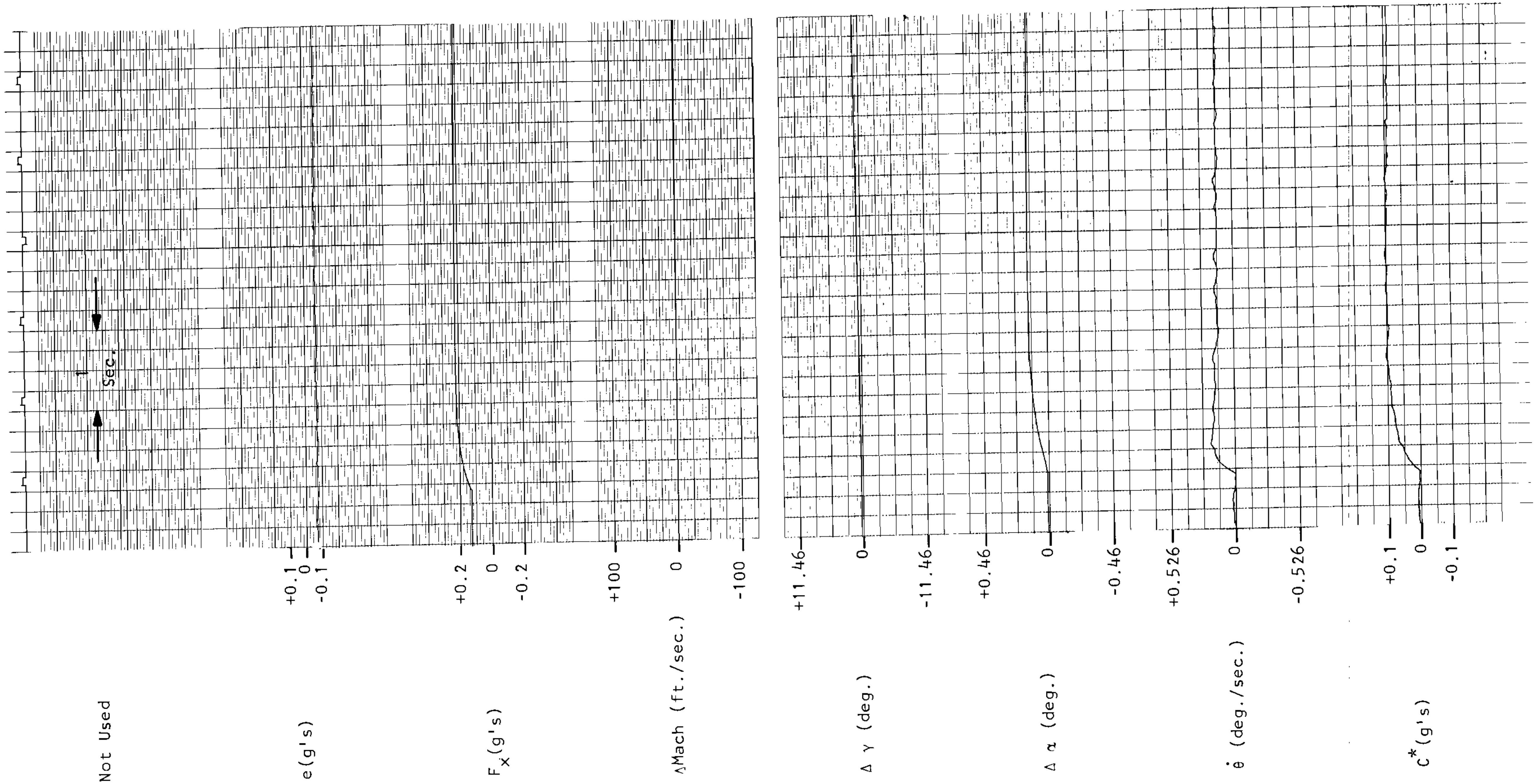


Figure 19: Simulation Data for ζ_{SPT} Limit Cycle



Command = +0.1g C*
Flight Condition No. 5

Figure 20: F-101B Response, Mach Trim Loop Out

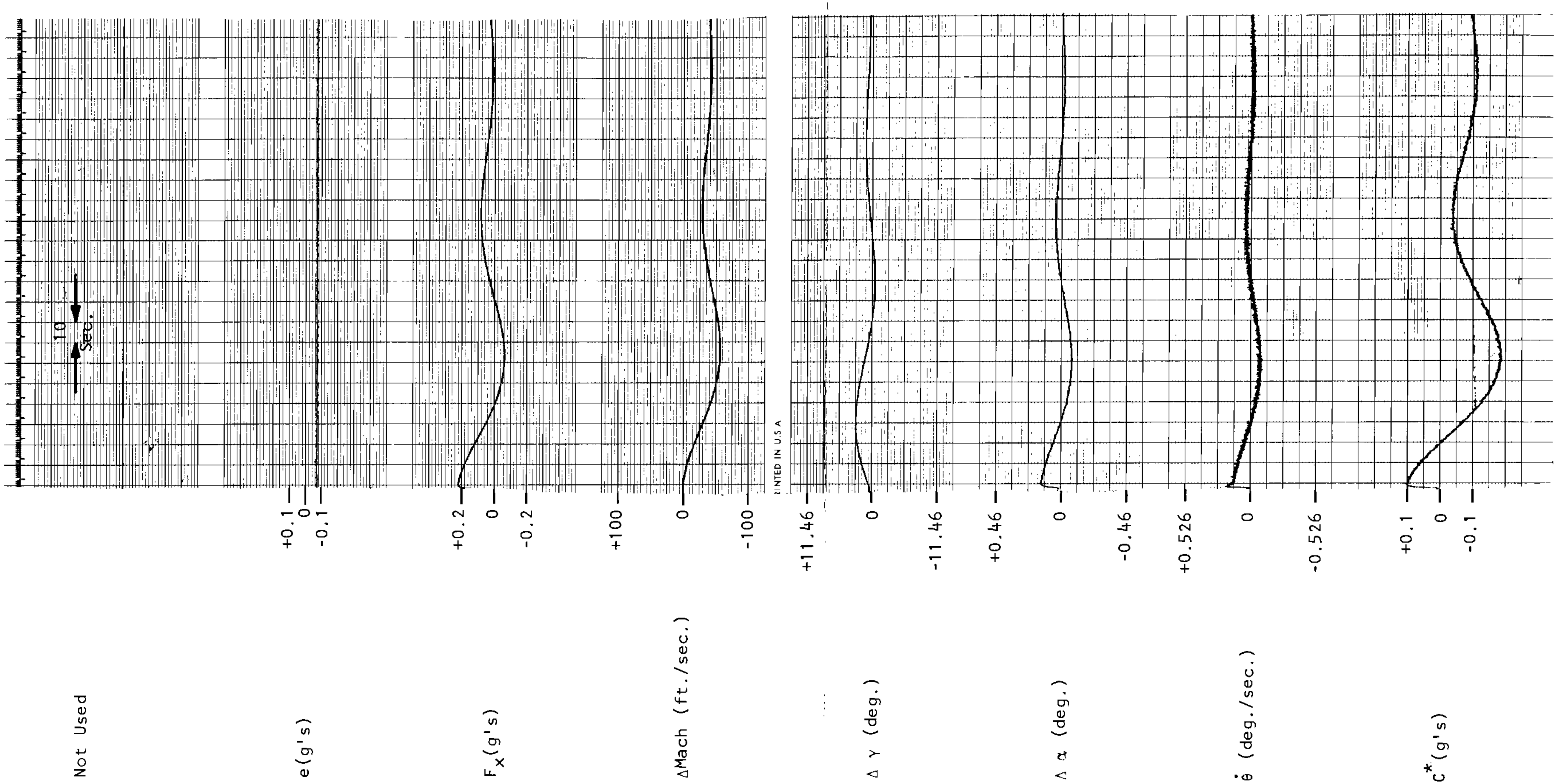


Command = +0.1g C*

K_M = 20

Flight Condition No. 5

Figure 21: F-101B Response, Mach Trim Loop In



Command = +0.1g C*

K_M = 20

Flight Condition No. 5

Figure 22: F-101B Response, Mach Trim Loop In

simulations showed good agreement as long as relatively small speed changes were involved. The simulations revealed the expected divergence of airspeed without Mach Trim (Figure 20), while with this function engaged, behavior of the phugoid mode was similar to that of the basic airframe, airspeed showing a damped oscillation that subsided in three or four minutes. As previously mentioned, the purpose of the Mach Trim loop, which was given very limited authority, was to eliminate airspeed divergence, not to provide tight control of Mach number.

Other analog computer simulations are presented in Section 3.1.

Figure 23 gives results obtained during that portion of the digital computer simulation work devoted to system short-period response characteristics. (The C* performance boundaries are discussed in Appendix IV.)

The digital simulations revealed no significant steady-state bending mode oscillations. First-mode transients were oscillatory but subsided within one or two seconds after application of a step-function stick signal. Second-mode oscillations disappeared in about 0.5 sec., and the third mode was non-oscillatory.

MIL-F-8785 specifies that any residual oscillations of the longitudinal control system must be less than ±0.020 g. Digital simulations showed a limit-cycle amplitude with the SOC of ±0.005 g under worst case conditions (F.C. 6). This oscillation was computed to be at 4.4 Hz.

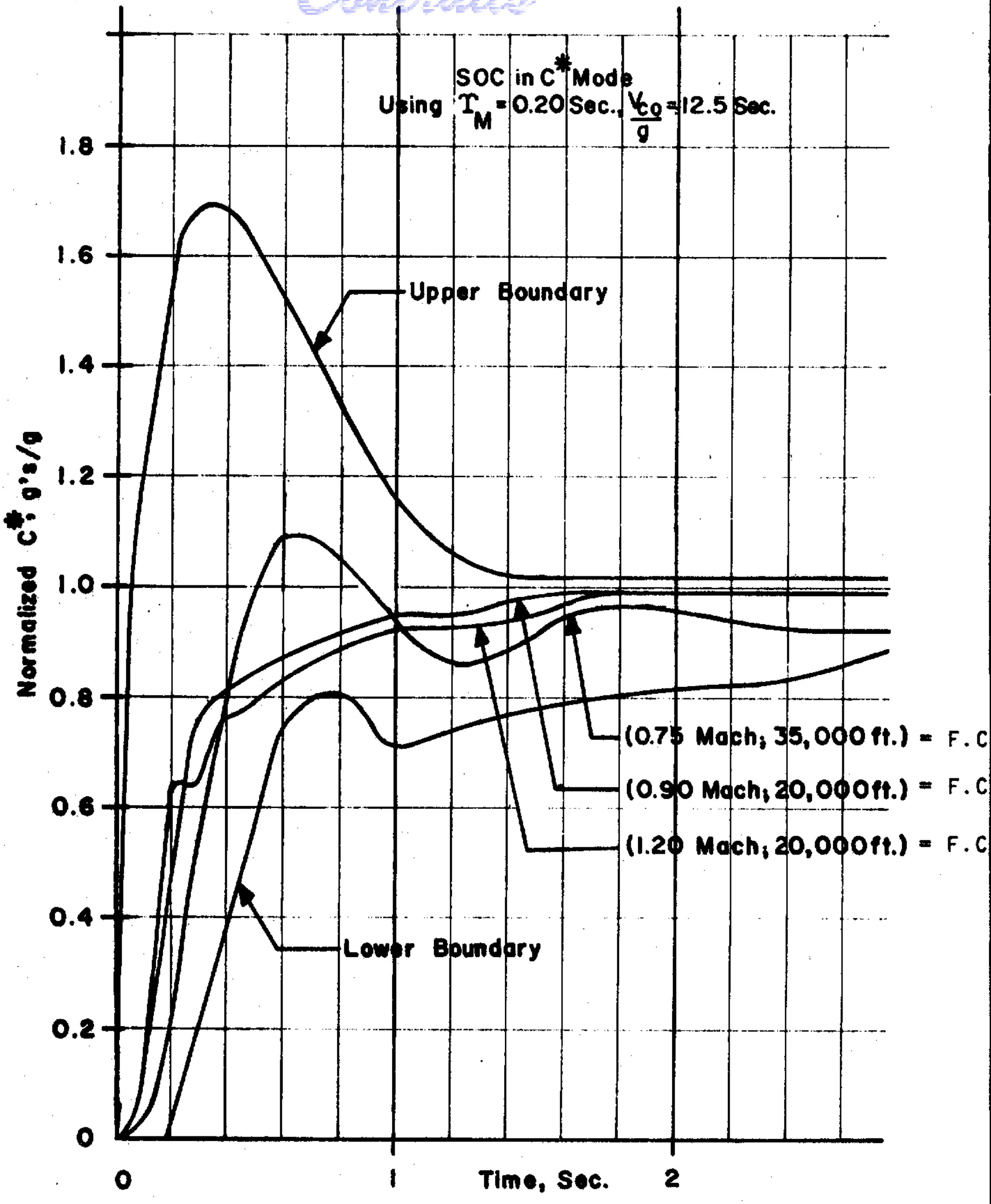


FIGURE 23: NORMALIZED C* PERFORMANCE BOUNDARIES AND SURVEY OF SOC RESPONSES

3. TEST RESULTS

3.1 System Bench Tests

As part of the flight worthiness test procedures (References 24 and 26), system bench tests were conducted using the following PFIC settings: Model = 0.2 Sec., C* Speed = 240 Knots. The primary power supply voltage was set at 28 Volts d.c., the environmental temperature was room ambient, and the system was not under vibration. Figures 24, 25, and 26 are representative of the $\dot{\theta}$ responses obtained. Figures 27, 28, and 29 are representative of the C* responses obtained. Designations of flight conditions are summarized in Table V.

3.2 Installation and Ground Checkout

The SOC equipment, including GSE and spares, was delivered to Wright-Patterson Air Force Base on 17 November 1967. The test aircraft, F-101B 59-462, arrived at Wright-Patterson on 26 July 1968. Extensive demodification work on the aircraft was required before installation of the SOC system could commence. The Air Force completed these demodifications by 10 October 1968, and the modifications for the SOC and its installation were accomplished by Air Force personnel between that time and 10 January 1969.

C. A. Crow, Jr. of Adaptronics, Inc. established residence at Wright-Patterson on 13 January 1969 to exercise local project responsibility for the Contractor during the ground checkout and flight test phases. Only minor interface problems arose during ground checkout of the SOC, although delays were encountered due to MB-5 AFCS malfunctions.

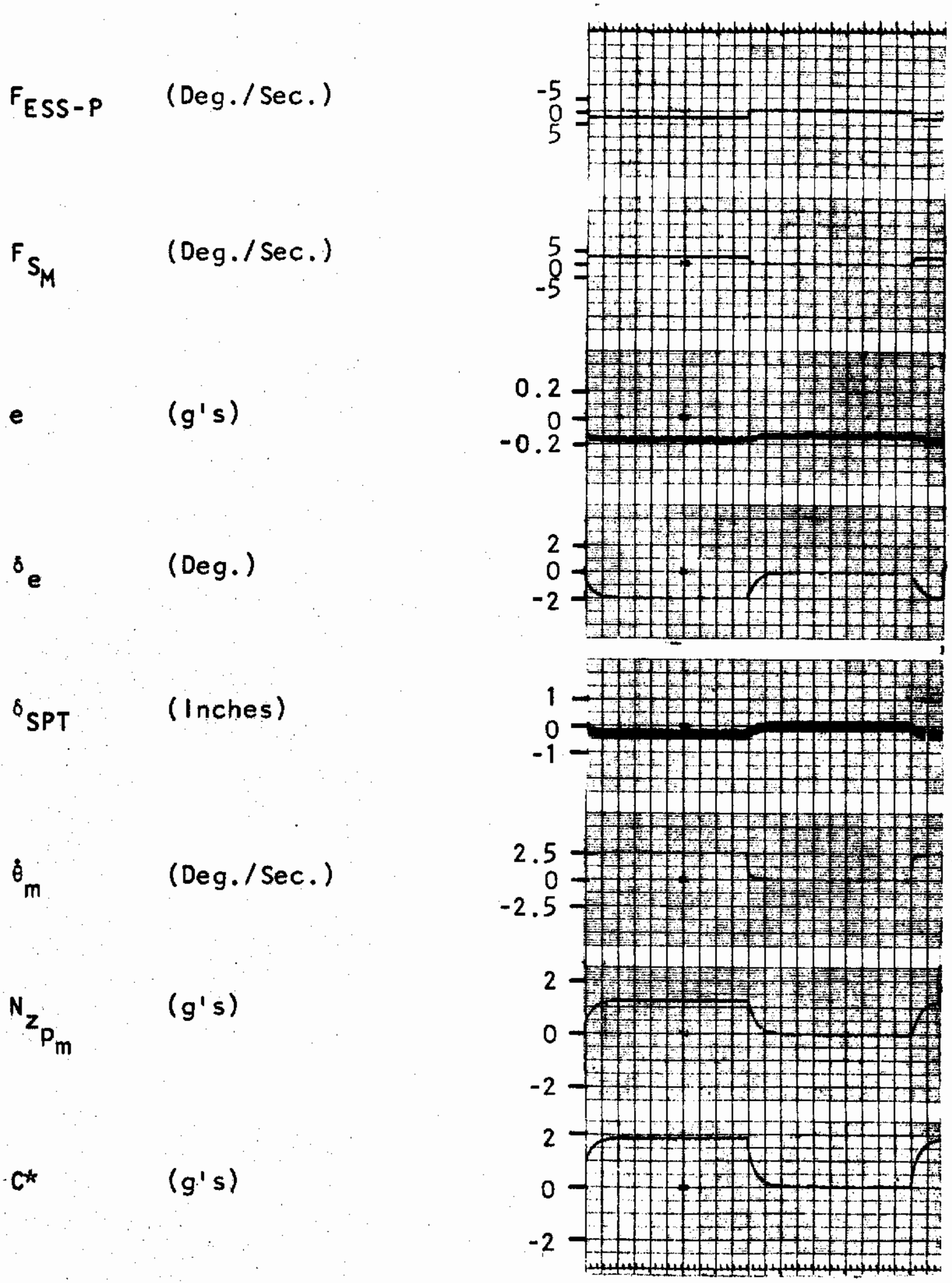


Figure 24: Flight Condition Nr. 5, +2.5 Deg./Sec. $\dot{\theta}$

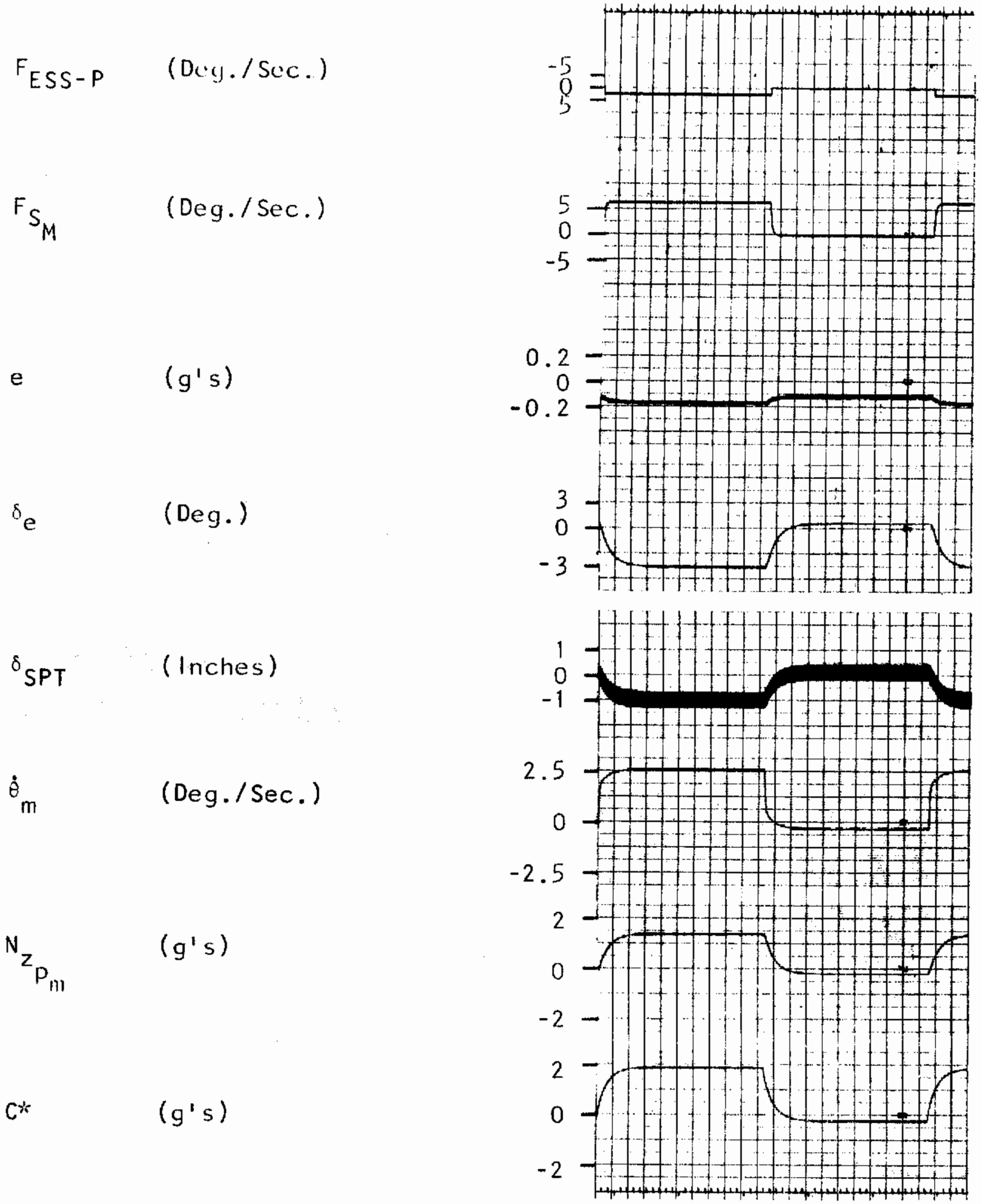


Figure 25: Flight Condition Nr. 6, +2.5 Deg./Sec. $\dot{\theta}$

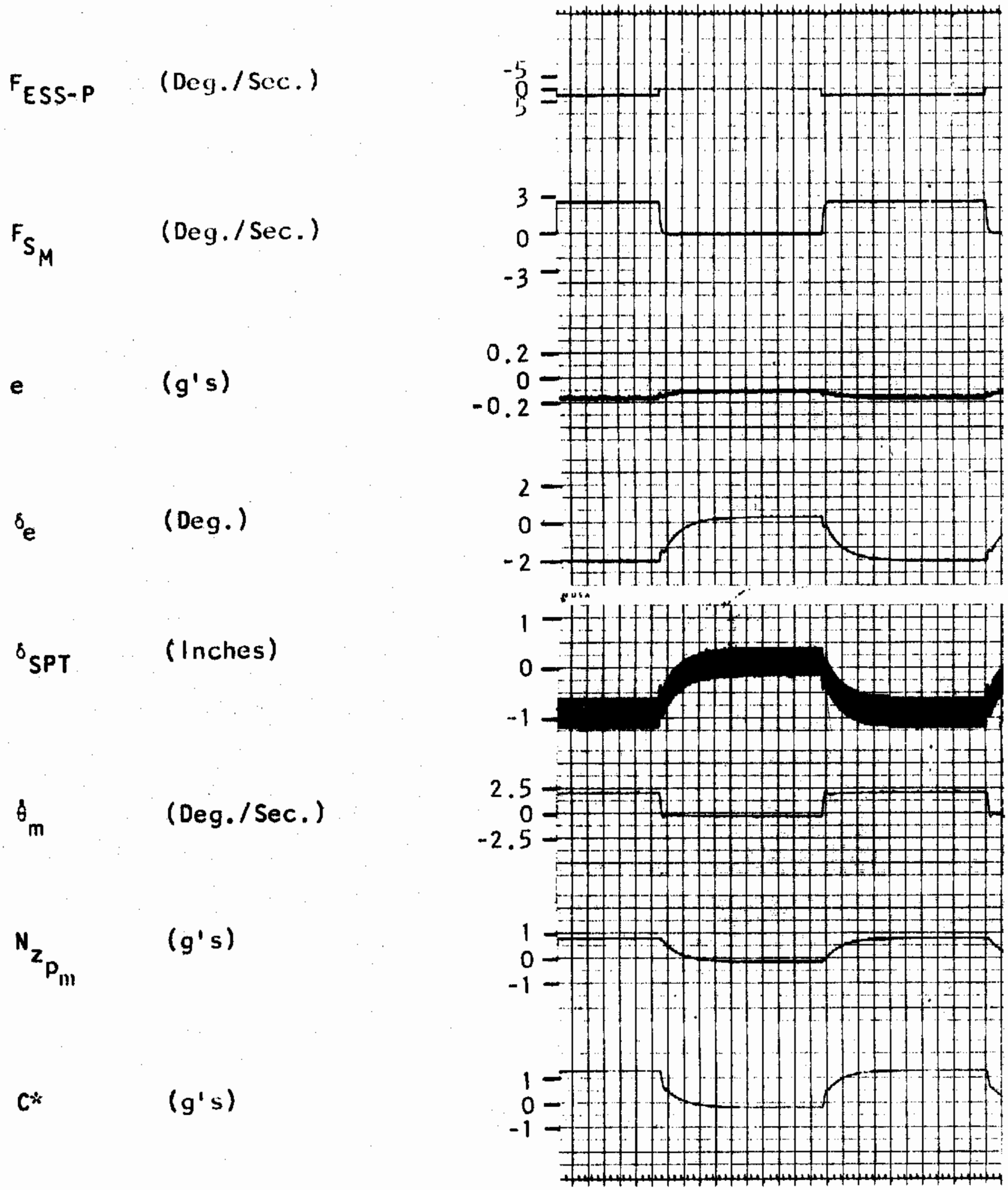


Figure 26: Flight Condition Nr. 7, +2.5 Deg./Sec. $\dot{\theta}$

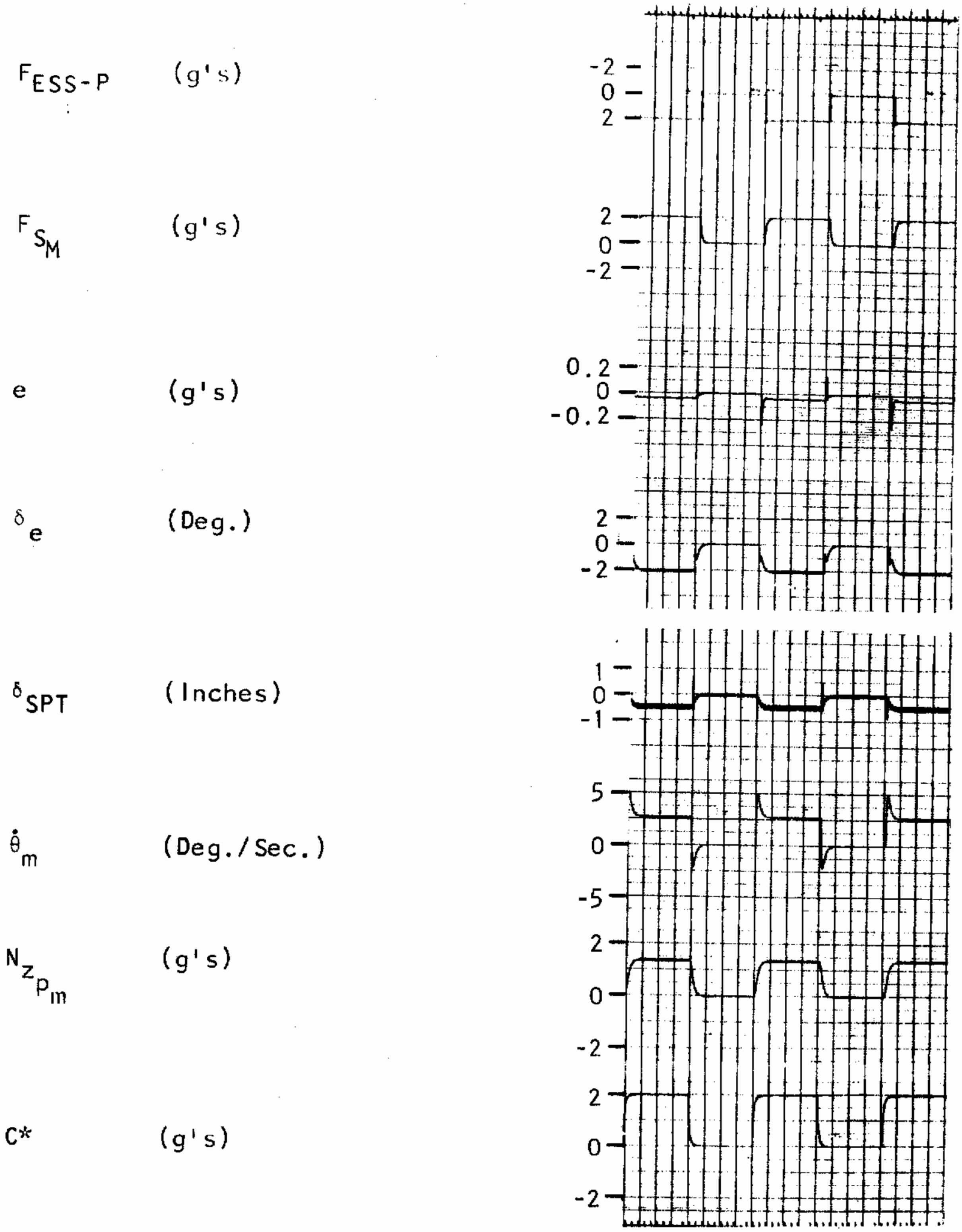


Figure 27: Flight Condition Nr. 5, +2g C*

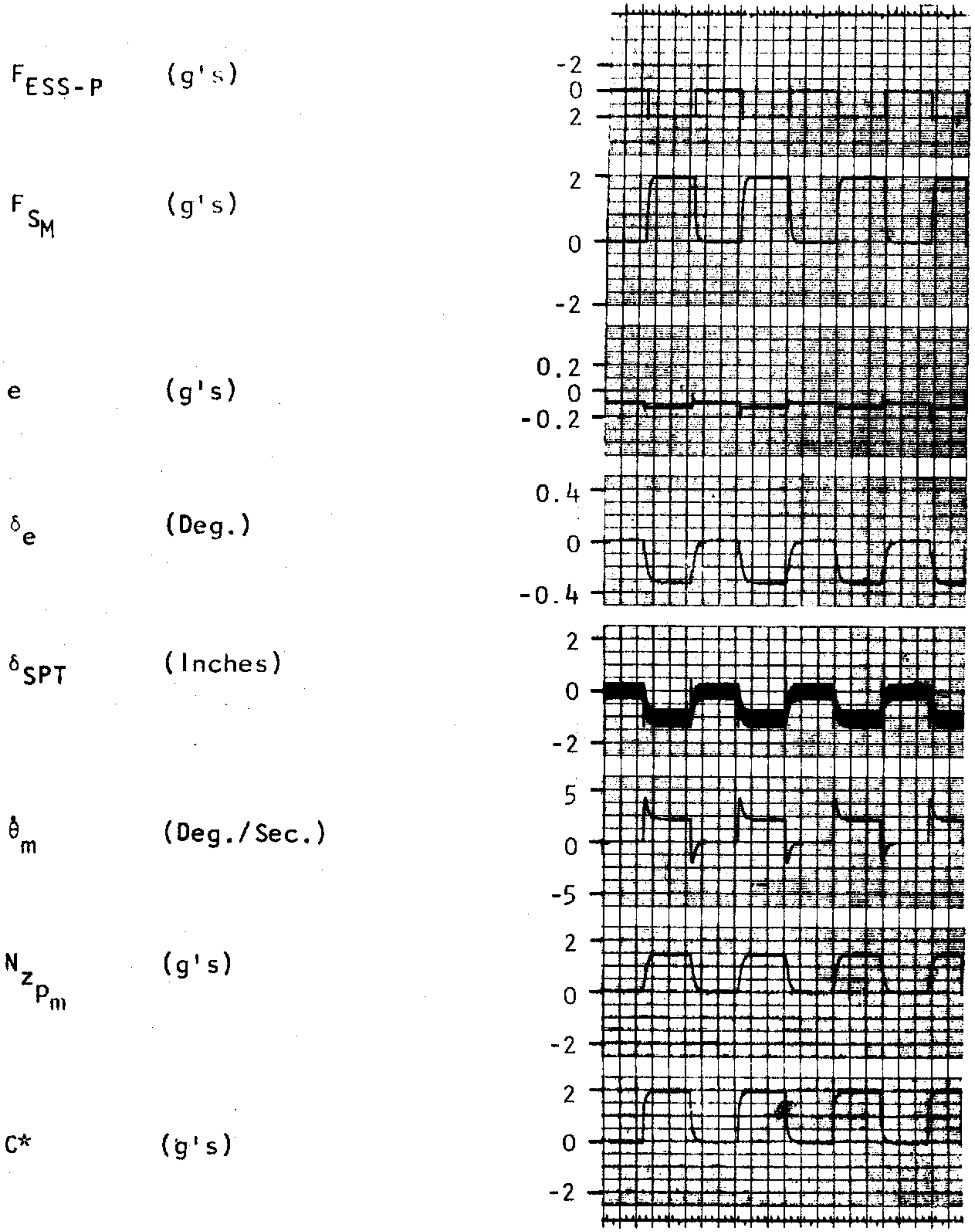


Figure 28: Flight Condition Nr. 6, +2g C*

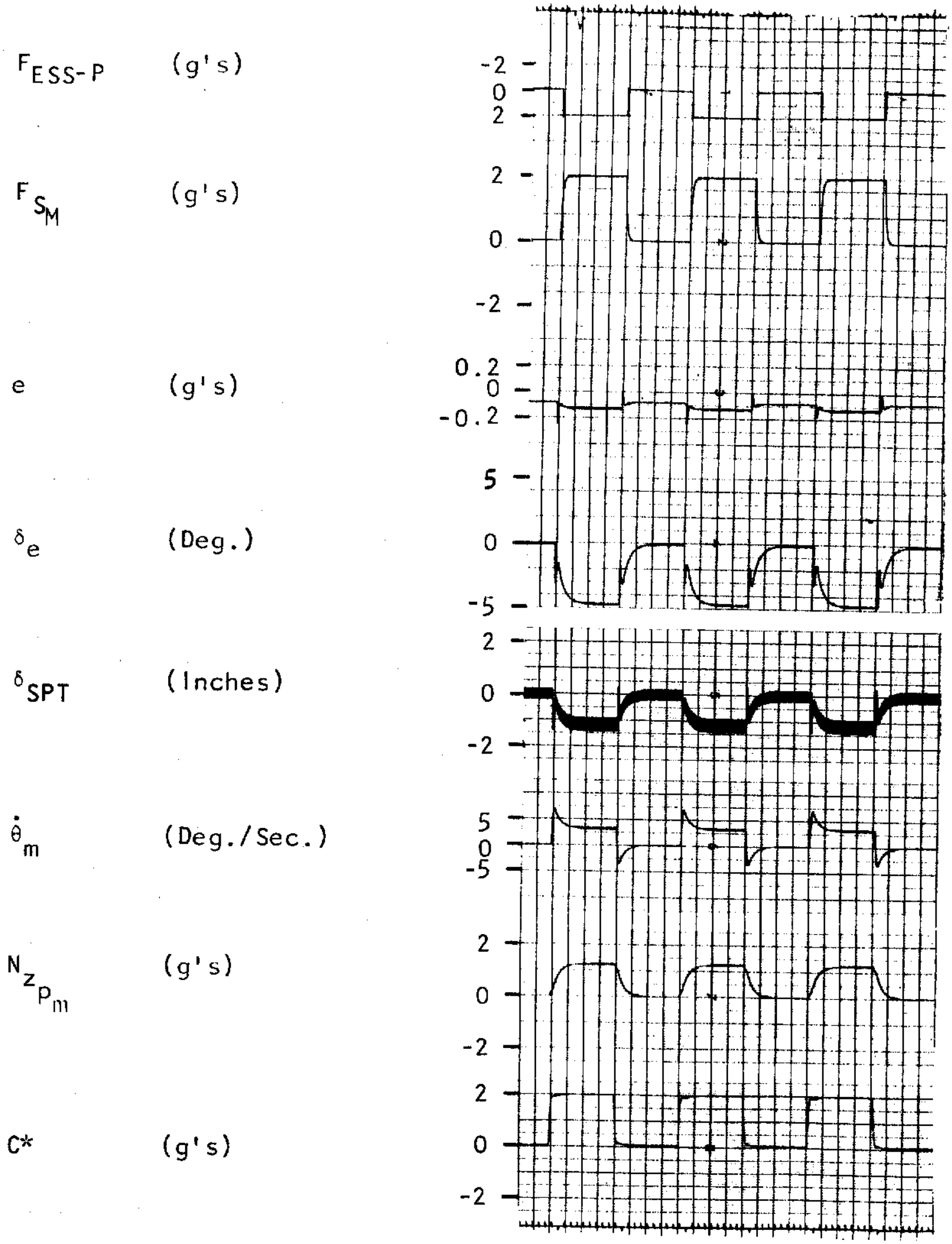


Figure 29: Flight Condition Nr. 7, +2g C*

During ground checkout, all functions of the SOC were completely checked utilizing the aircraft electrical system. A complete survey of the ten flight conditions was run. At each flight condition every combination of pitch lag and mode select was checked, as well as representative settings of roll and pitch sensitivity. Results of this survey were completely satisfactory.

Mach Trim loop operation was checked at flight conditions 5, 6, and 7 with satisfactory results. The Mach Set switch was calibrated with the following results:

Mach Set	Desired VDC	Actual VDC
0.5	+ 4.65	+ 4.7
0.6	+ 6.15	+ 6.4
0.7	+ 7.65	+ 7.8
0.8	+ 9.15	+ 9.2
0.9	+ 10.65	+ 10.9
1.0	+ 12.15	+ 11.5

The g-limit disengage settings were measured. Negative limits were in the range +4.8 VDC to +5.1 VDC. Positive limits varied from -20.5 VDC to -22.0 VDC. Satisfactory operation of g-limit disengage circuits and of failure detection and warning functions was verified.

The pitch trim thumbwheel authority was measured. Maximum nose-up trim authority was +0.42 VDC. Maximum nose-down trim authority was -0.49 VDC.

The test signal generator UP-DOWN switch was calibrated with the following results:

Small Step (0.1g)

Up Command	+ 0.26 VDC
Down Command	- 0.23 VDC

Large Step (0.5g)

Up Command	+ 1.25 VDC
Down Command	- 1.23 VDC

The pitch sensitivity switch was calibrated and the following readings obtained:

Stick Full Back

Sensitivity Setting	VDC
Min	- 0.61
2	- 0.74
3	- 0.88
4	- 1.02
5	- 1.17
Max	- 1.13

Stick Full Forward

Sensitivity Setting	VDC
Min	+ 0.41
2	+ 0.43
3	+ 0.47
4	+ 0.52
5	+ 0.56
Max	+ 0.61

Although the roll sensitivity switch was also calibrated during the ground checkout, it became necessary early in the flight test program to reduce roll sensitivity. Following are final roll sensitivity readings:

Full Right Roll

Sensitivity Setting	VDC
Min	+ 0.135
2	+ 0.195
3	+ 0.305
4	+ 0.307
5	+ 0.420
Max	+ 0.485

Full Left Roll

Sensitivity Setting	VDC
Min	- 0.055
2	- 0.120
3	- 0.240
4	- 0.310
5	- 0.360
Max	- 0.432

Upon completion of the electrical checkout, hydraulic pressure was applied to the aircraft and a full survey of three representative flight conditions was run. Although results were within limits, system response to a square-wave input showed a slight ripple on C*, N_{zp}, and $\dot{\theta}$. This was corrected by changing the δ_{SPT} pickoff from the stabilator position transducer to the servo feedback pot. System operation was entirely satisfactory and the aircraft was released to Maintenance on 16 May 1969.

Several pre-flight tests were conducted with aircraft hydraulics on to determine the effects of the actual parallel-servo characteristics on closed-loop performance of the SOC system. For these tests, the aircraft δ_{SPT} signal (from the servo feedback pot) was fed to both the SOC and the appropriate point in the GSE analog computer. In other words, the simulated parallel servo was by-passed in favor of the actual device in the aircraft, while keeping the remaining elements of the GSE computer model in the simulation. The tests produced reasonably close agreement between results obtained by simulating the parallel servo. The aircraft unit exhibited essentially the same low-frequency, small-signal properties as the simulation; however, there was greater attenuation of high-frequency signals and some additional nonlinearities (such as more than one set of rate limits) appeared to be present.

Figures 30 - 33 present the comparative results for flight condition 7 with simulated and actual parallel-servo dynamics. Figures 30(a) and 31 present data obtained with the GSE computer simulation of the servo, while Figures 30(b), 32, and 33 present results obtained with the aircraft hardware. Note that the C_2* response is somewhat slower with the actual servo. Also, the high-frequency "buzz" decreased from approximately 47 Hz to approximately 20 Hz in going from the simulated to the actual servo (possibly due to lower rate limits than those which were simulated) and the amplitude of this oscillation increased when using the aircraft parallel servo. These recordings were made prior to the second and third flights using the SOC parameters of those flights.

The first Functional Check Flight (FCF) of the aircraft was flown on 6 June 1969. Aircraft discrepancies noted during this flight were corrected by the Air Force, and the second FCF, flown on 30 June, was satisfactory. Accordingly, the first SOC Test flight was conducted on 3 July 1969.

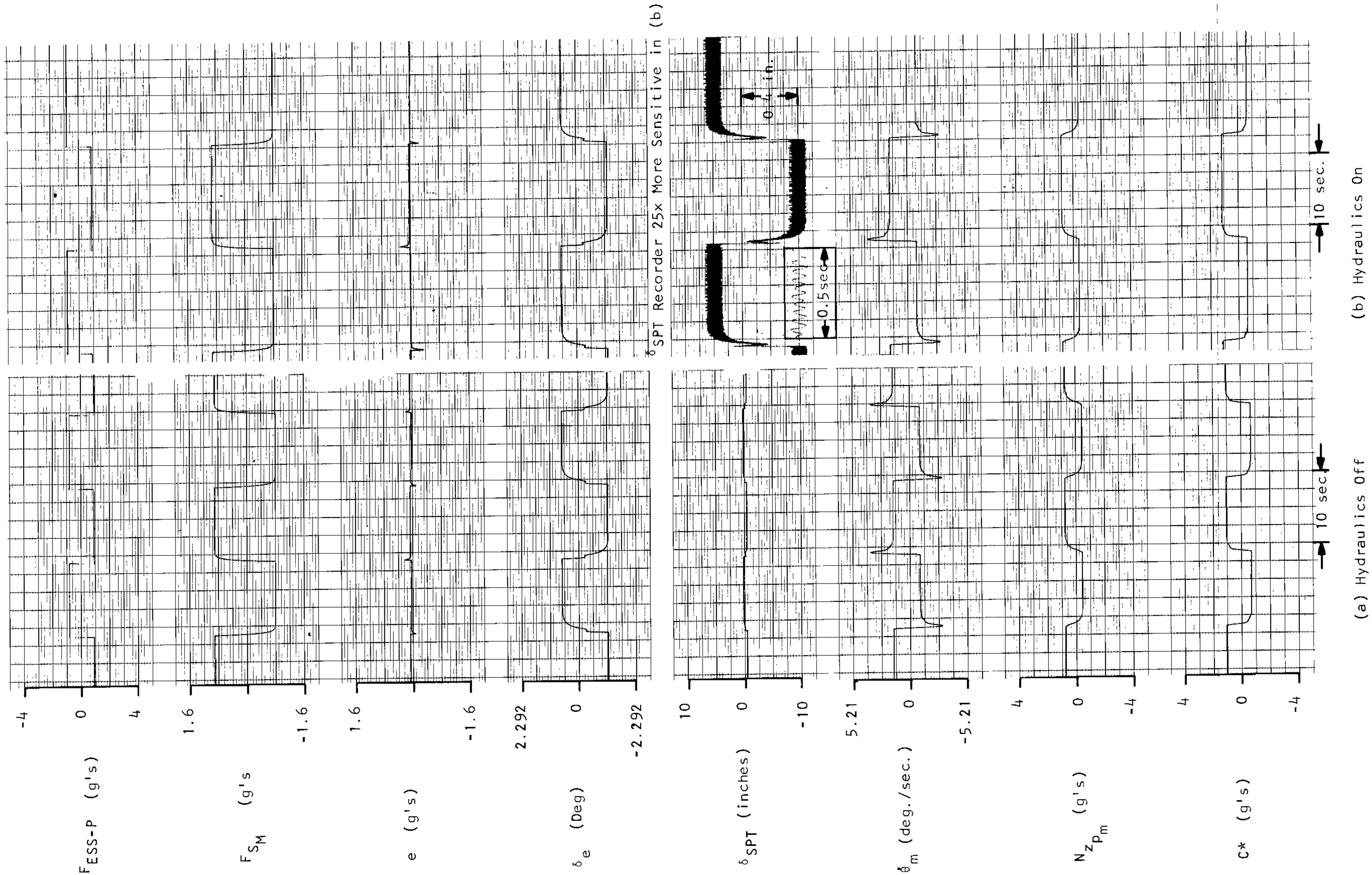


Figure 30: Pre-Flight Checkout Recording for Flight 3, F.C. 5, July 22, 1969. (a) Simulated Parallel Servo (Hydraulics Off), (b) Aircraft Parallel Servo (Hydraulics On)

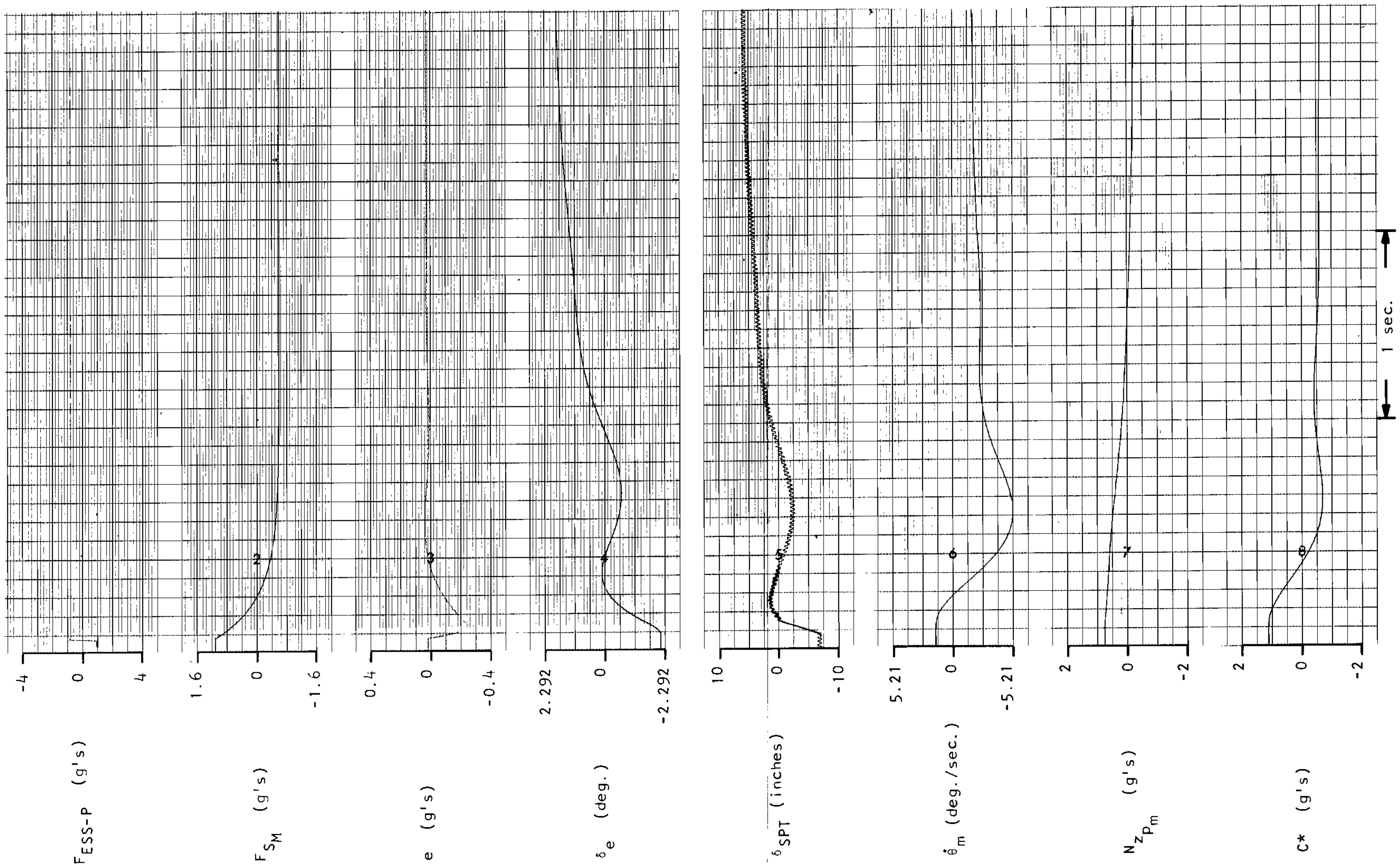


Figure 31: Pre-Flight Checkout Recording for Flight 2, F.C. 7, July 17, 1969. Simulated Parallel Servo, Hydraulics Off, Negative g Command

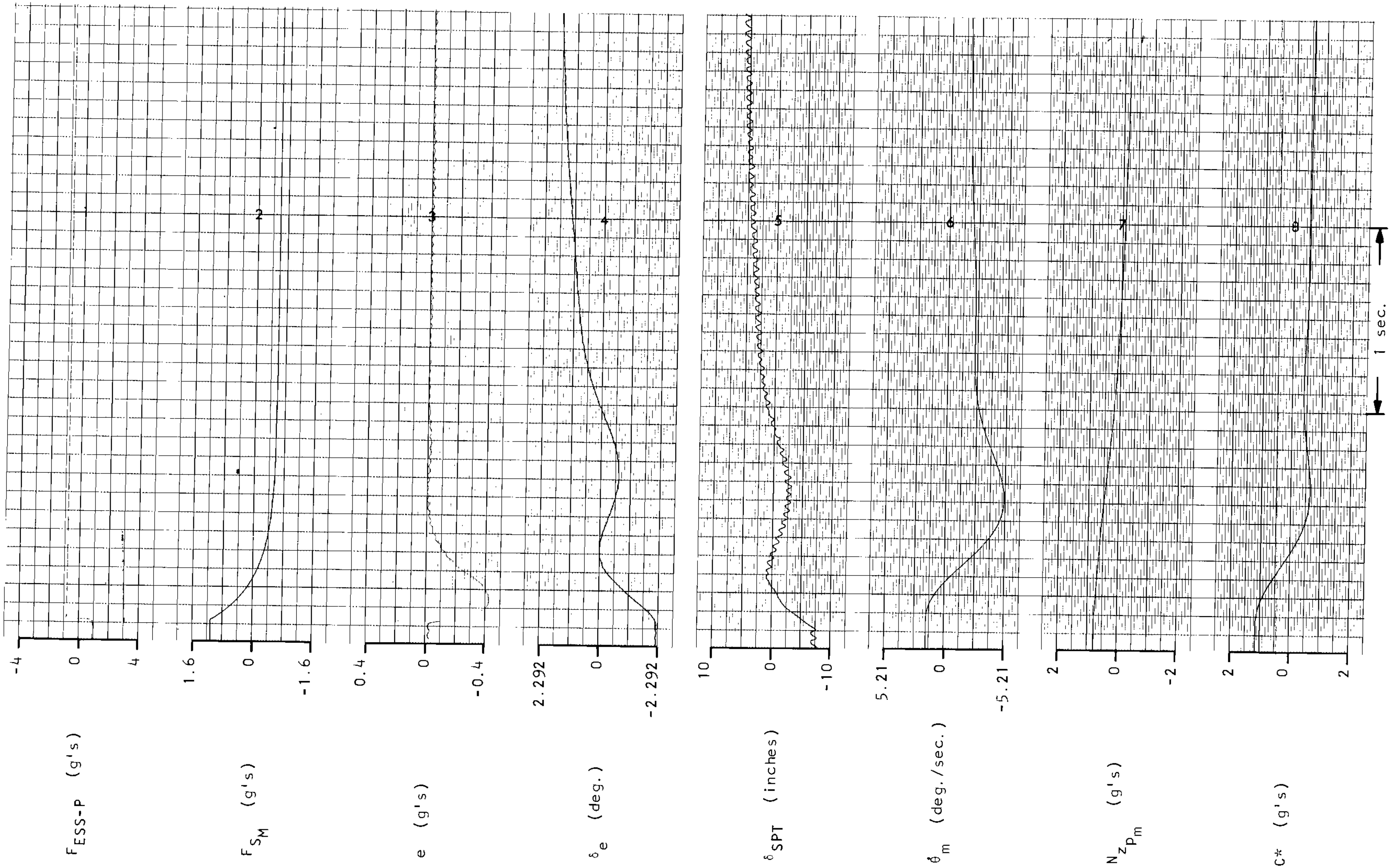


Figure 32: Pre-Flight Checkout Recording for Flight 2, F.C. 7, July 17, 1969. Aircraft Parallel Servo, Hydraulics On, Negative g Command.

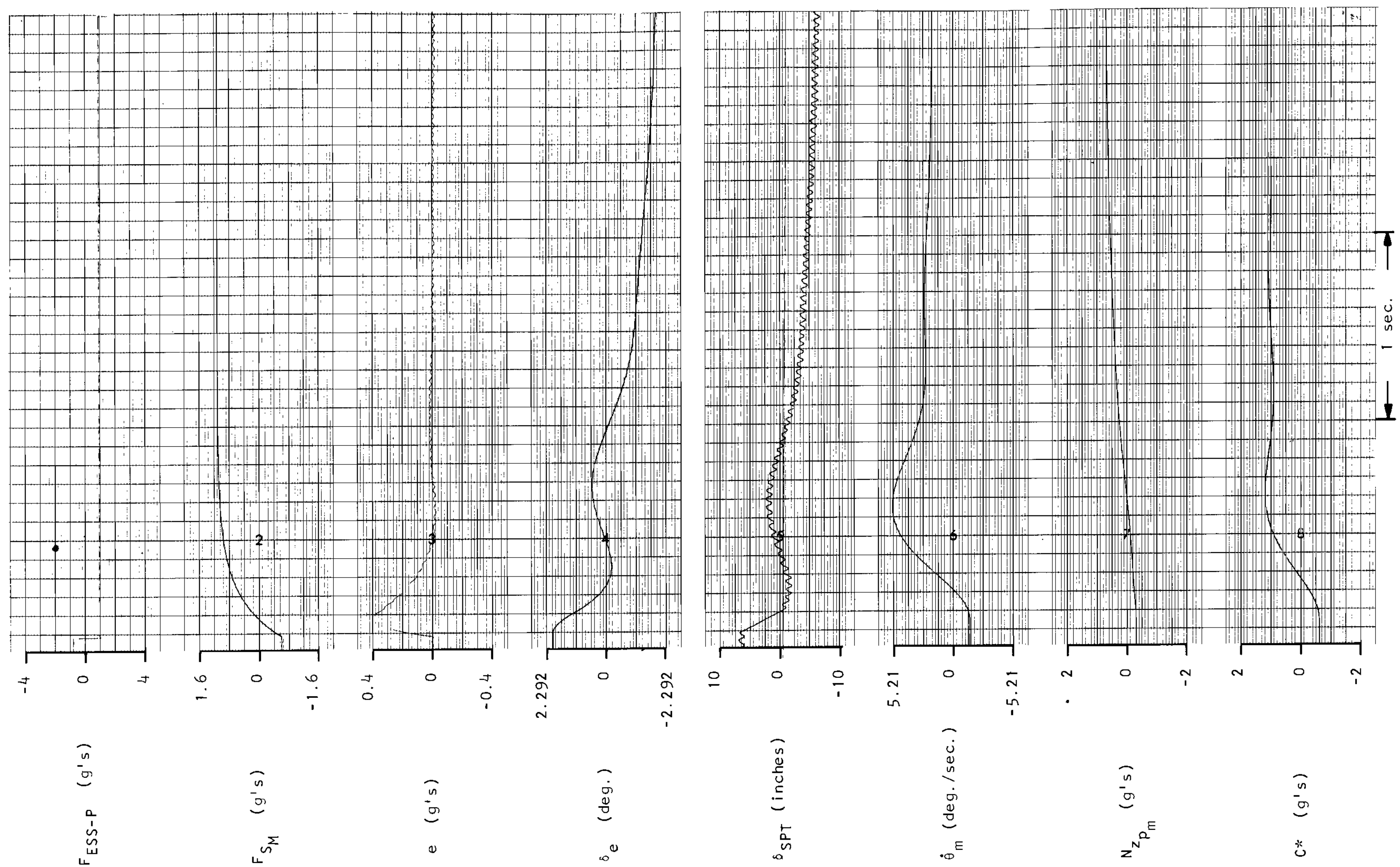


Figure 33: Pre-Flight Checkout Recording for Flight 2, F.C. 7, July 17, 1969.
Aircraft Parallel Servo, Hydraulics On, Positive g Command.

Figure 34 shows the SOC enclosure as it was installed in an Avionics bay of the aircraft (behind door 213R). Figure 35 is an overall view of the aircraft, showning the Avionics bay and ground support equipment for the MB-5 AFCS and the SOC.

3.3 Flight Evaluations

40.9 hours of flight test time with the SOC were accumulated during 32 test missions between 3 July 1969 and 18 November 1969. The major objectives of the flight test program were (Reference 34):

(1) verify proper engage/disengage switching of SOC, increase pilot familiarization with the electric side stick and SOC control panel (PFIC), determine preferred PCIC sensitivity settings for the side stick, and establish confidence in the SOC equipment (8 missions);

(2) obtain recordings of system response to the calibrated test input command at each of the ten flight conditions for comparison with results of prior simulations (13 missions);

(3) obtain qualitative (pilot opinion) evaluations of system performance in both prescribed and arbitrary maneuvers (11 missions).

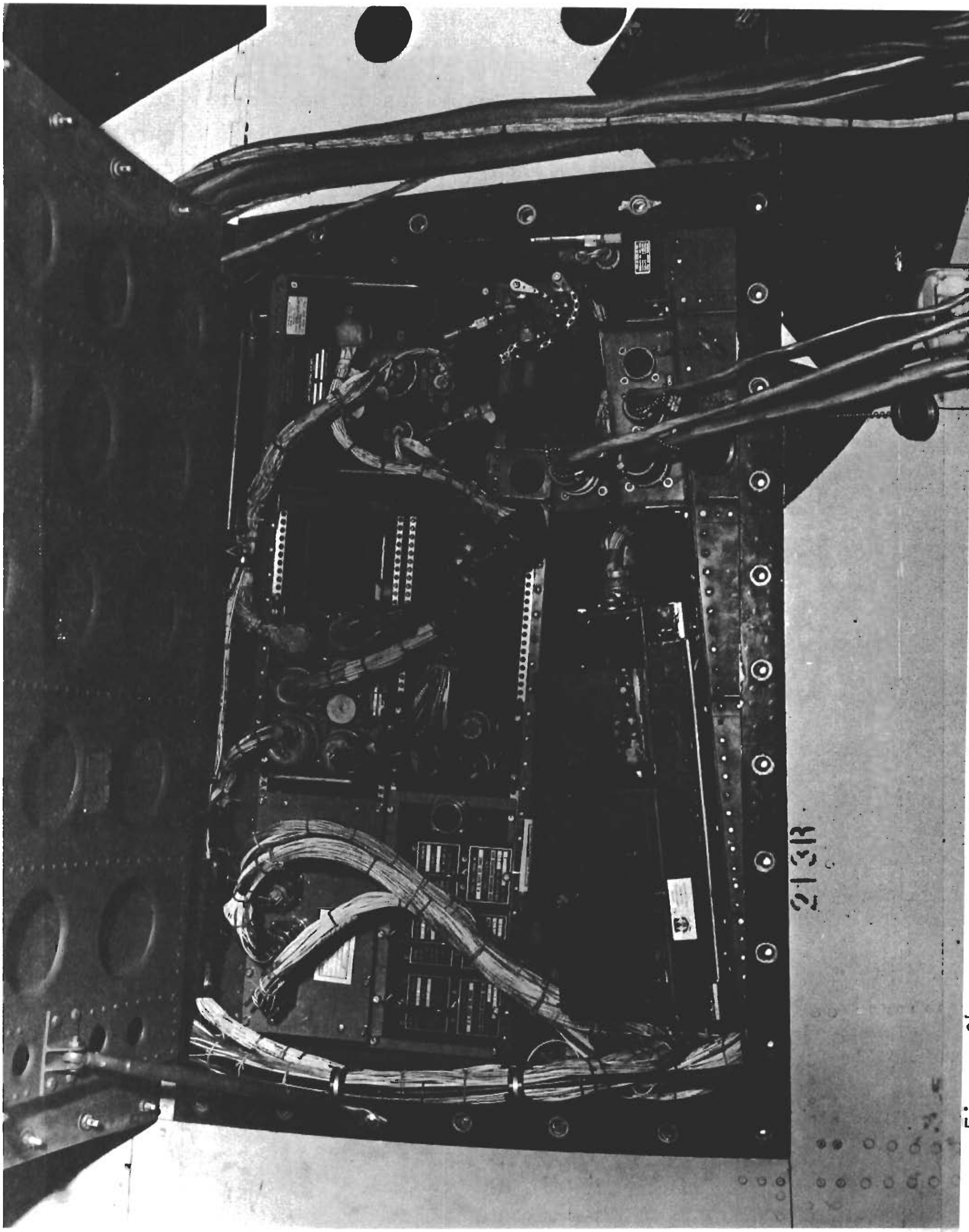


Figure 34: Photograph Showing SOC Mounted in F-101B Avionics Bay

Figure 35: Photograph of F-101B 59-462 during MB-5 AFCS Checkout. SOC GSE is visible at right of picture.

A multichannel Consolidated recording oscillograph (CEC Model 5-114-P7-5) was used to record 27 aircraft and SOC parameters (Reference 33). In part (2) of the evaluations, the aircraft was brought to straight and level flight at the specified altitude and indicated Mach number (IMN). With the Large-Small switch on the PFIC in its Large position, an incremental pitch acceleration of +0.5 g† was commanded (using the test signal generator in the PFIC) when the pilot moved the Up-Down switch to Up from its spring-loaded center position. With Mach Trim off, first in the C_a* mode and then in the $\dot{\theta}$ mode, this command was applied for approximately five seconds, after which the switch was allowed to return to its center position. However, with Mach Trim on, the test input was held on for several minutes so that both the short-period response and the response of the system in settling to a new steady-state Mach number could be recorded.

Figures 36 - 45 provide the reduced flight data obtained in C_a* mode with Mach Trim off. These figures are presented in the sequence of increasing M_δ/M_δ* (not in the sequence of flight condition number). Thus, Figure 36 relates to the case of minimum stabilator effectiveness, while 45 relates to maximum effectiveness.

Figures 46 - 55 present reduced flight data obtained in $\dot{\theta}$ mode, again with Mach Trim off.

The performance boundaries shown in Figures 36 - 45 are discussed in Appendix IV. The test inputs are also drawn on these figures. For Flights 17 et seq., the test signal lag (τ_X, p. 12) was reduced from 0.4 sec. to 0.2 sec., as the latter corresponded more nearly to pilot preferences regarding τ_M, the model time constant. Thus, Figures 40 and 44 pertain to the case in which τ_X = 0.2 sec., while the test signals

[Cont'd. on p. 93]

† 1.15 deg./sec. in $\dot{\theta}$ mode

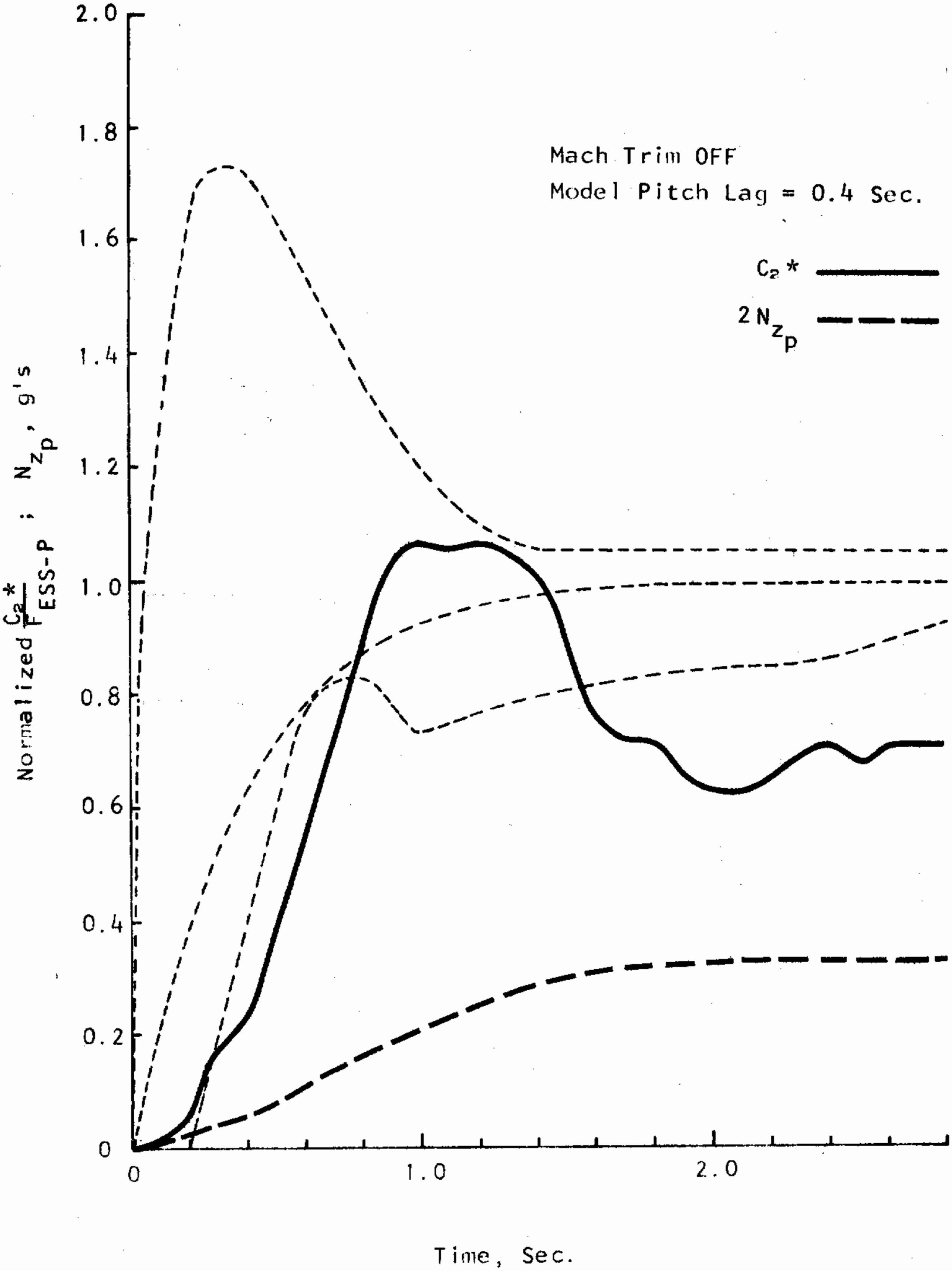


Figure 36: C_2* Mode -- SOC Flight Test #10; F.C. 1; 10,000 Ft., Mach 0.45 ($M_\delta/M_\delta* = 0.45$ = Min.)

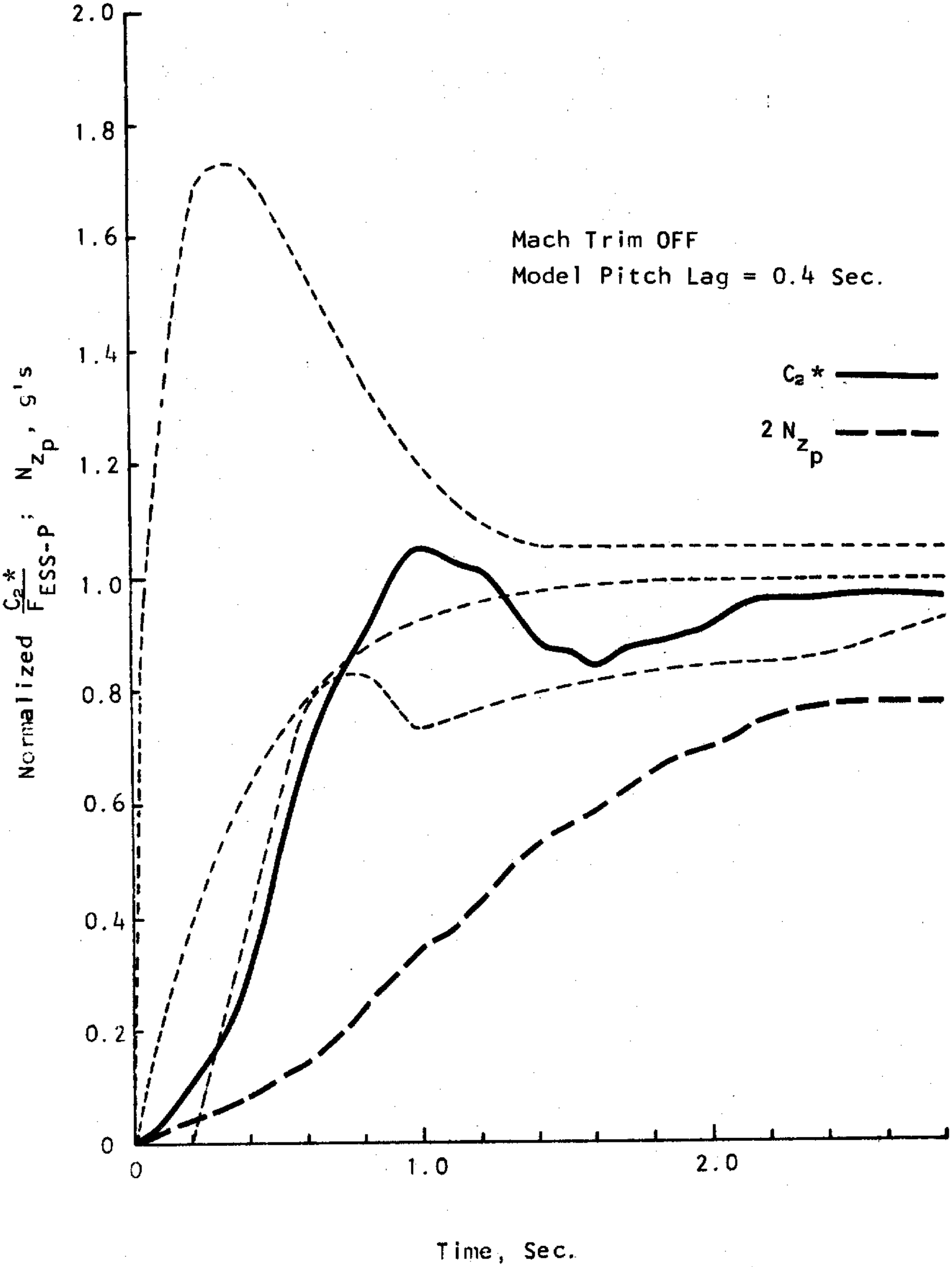


Figure 37: C_a* Mode -- SOC Flight Test #7; F.C. 4, 20,000 Ft., Mach 0.55 ($M_\delta / M_\delta* = 0.50$)

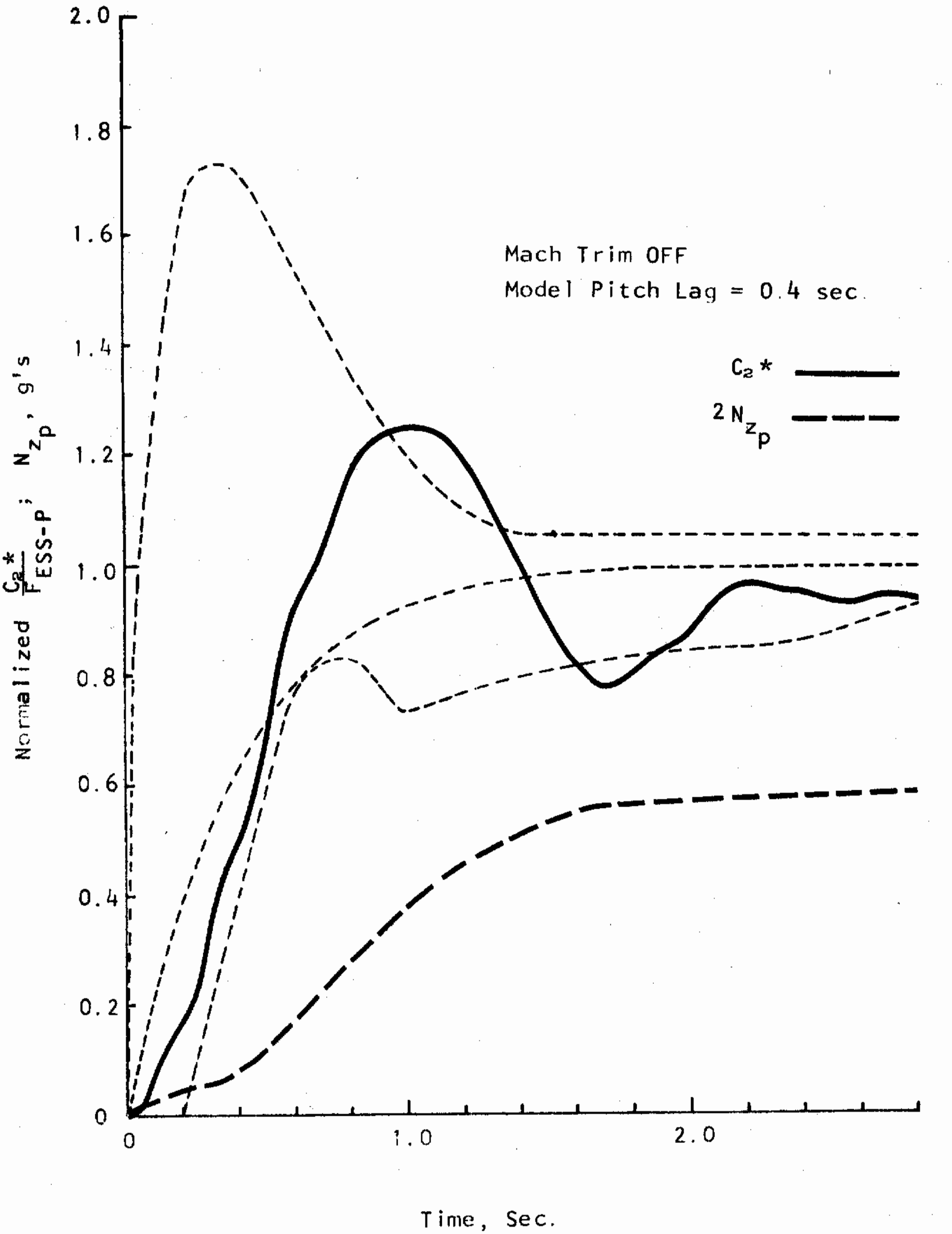


Figure 38: C_a* Mode -- SOC Flight Test #8 F.C. 7; 35,000 Ft., Mach 0.75 ($M_\delta/M_\delta* = 0.56$)

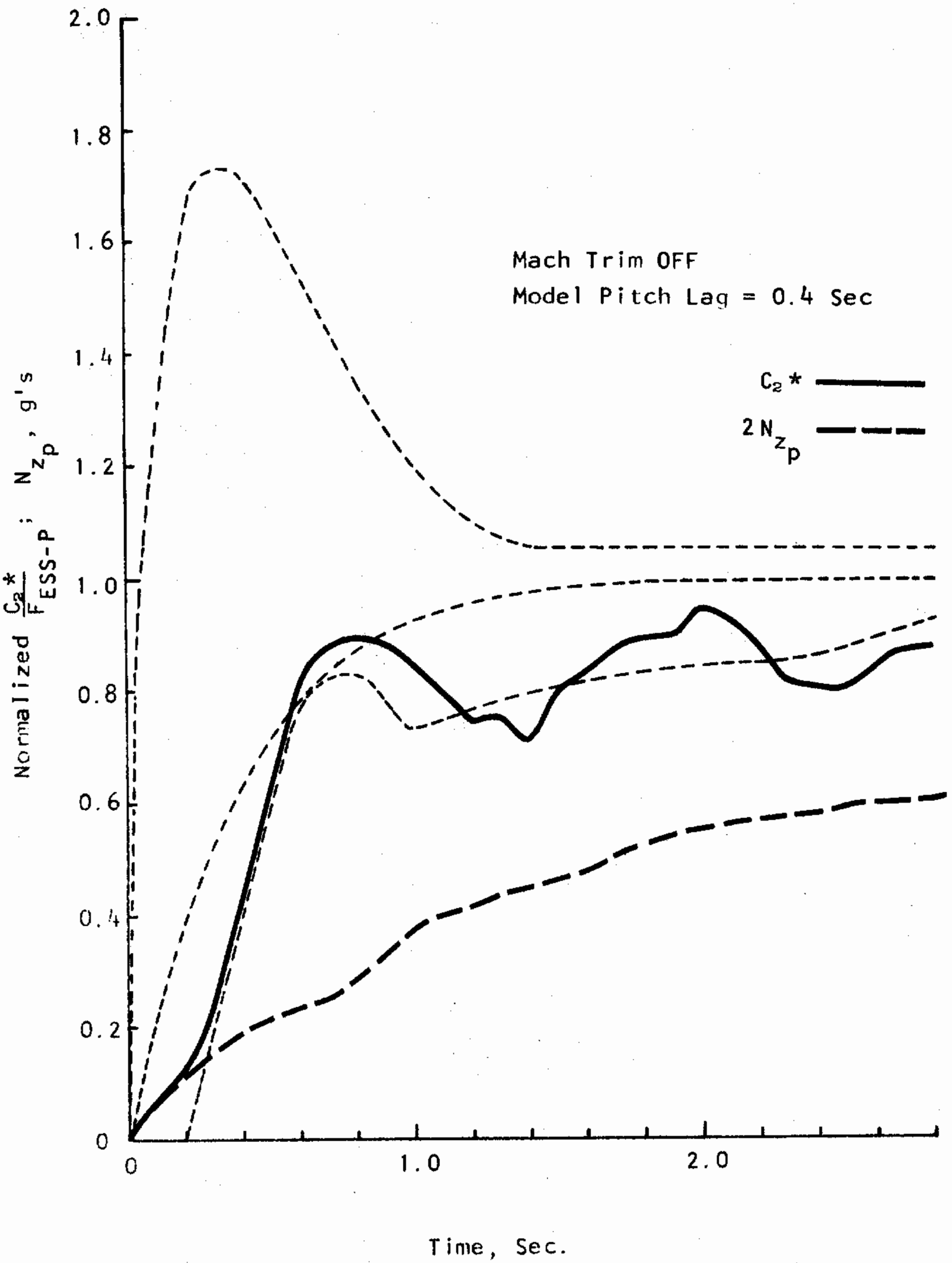


Figure 39: C_2* Mode -- SOC Flight Test #13; F.C. 8; 35,000 Ft., 0.95 Mach (M_δ/M_δ* = 1.00)

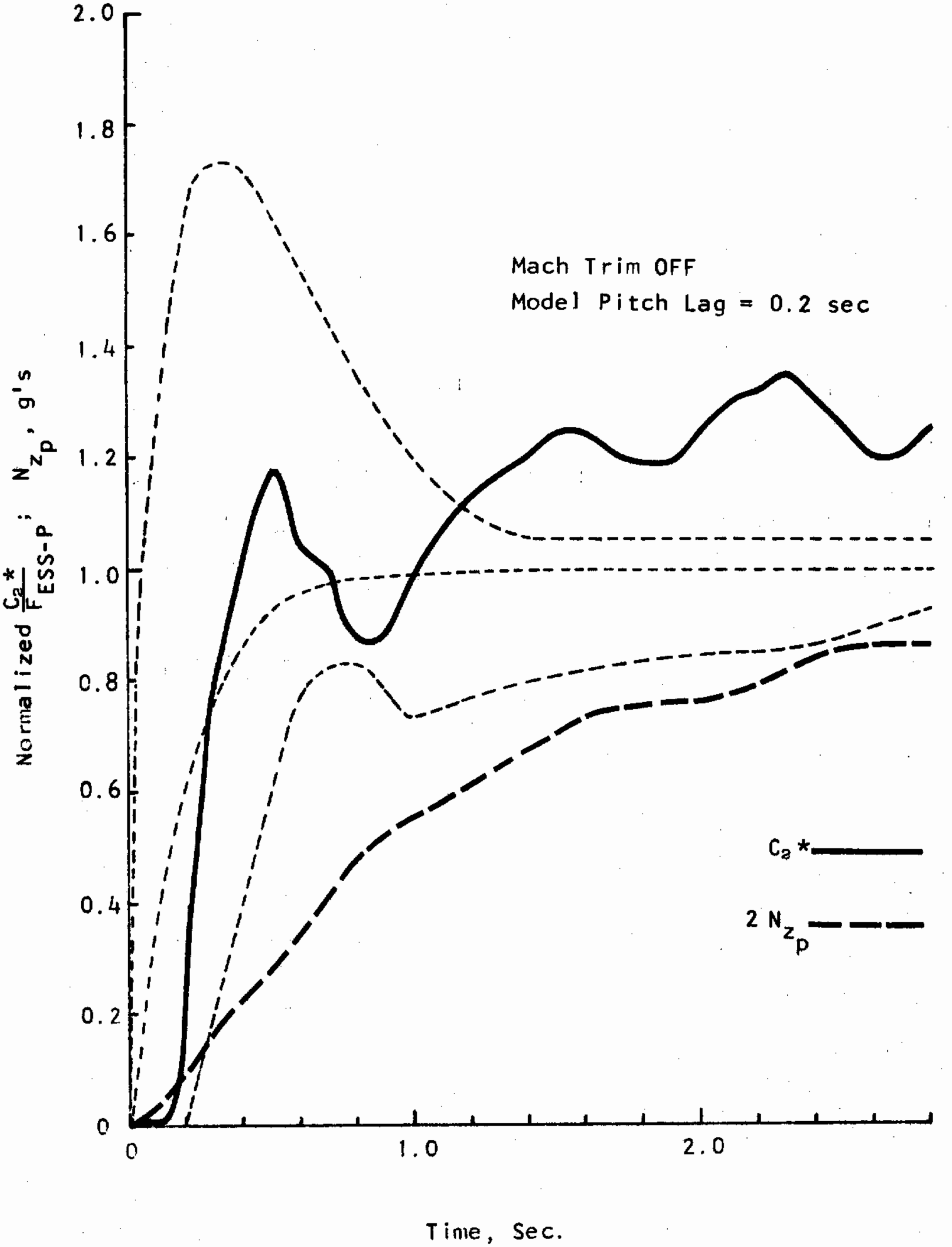


Figure 40: C_2* Mode -- SOC Flight Test #19; F.C. 10; 35,000 Ft., Mach 1.4 ($M_\delta/M_\delta* = 1.11$)

Note: Responses are shown in this figure for two test maneuvers performed at the given flight condition during Flight #8.

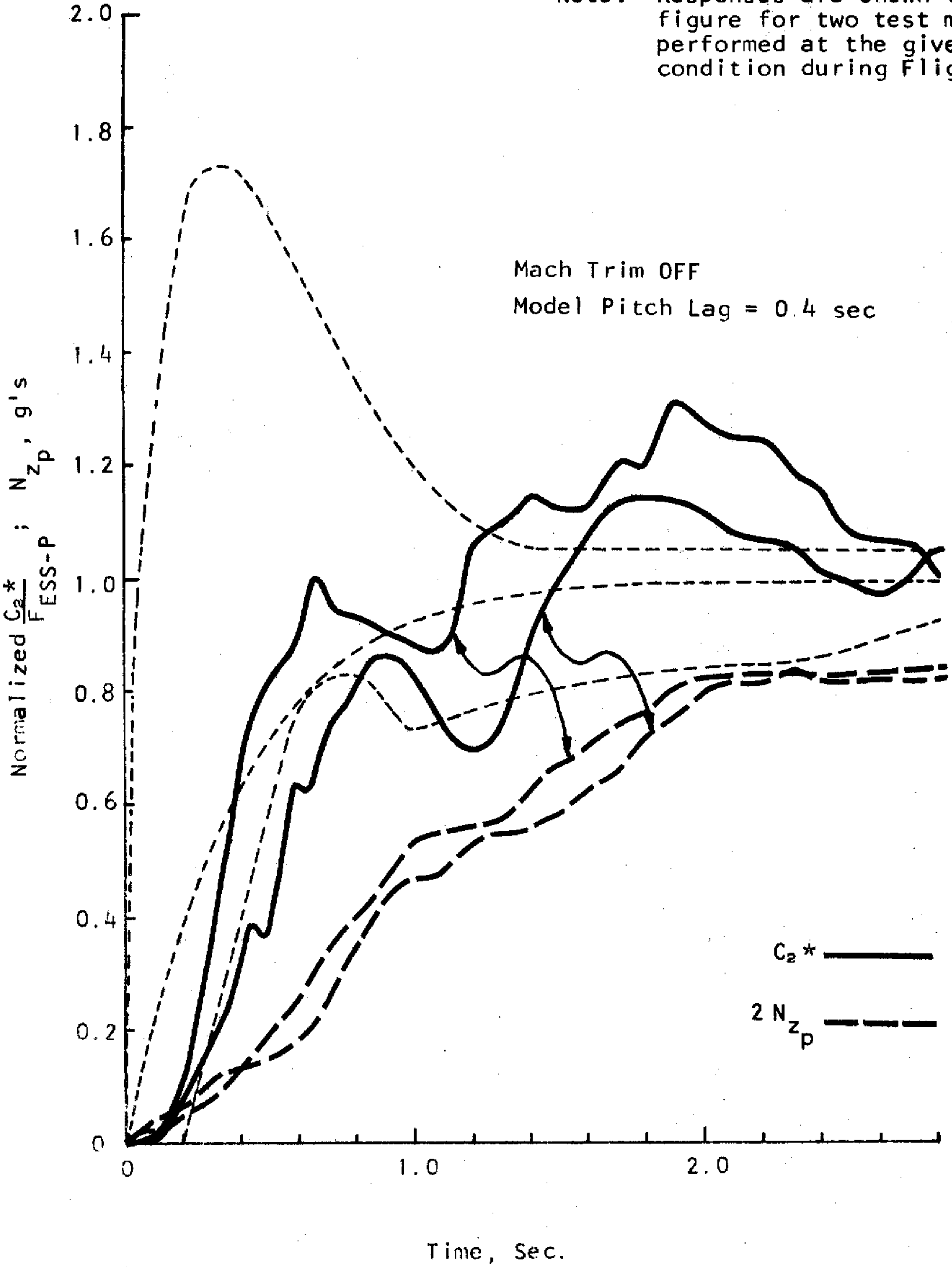


Figure 41: C_2* Mode -- SOC Flight Test #8; F.C. 5; 20,000 Ft., Mach 0.90 ($M_\delta/M_\delta* = 1.23$)

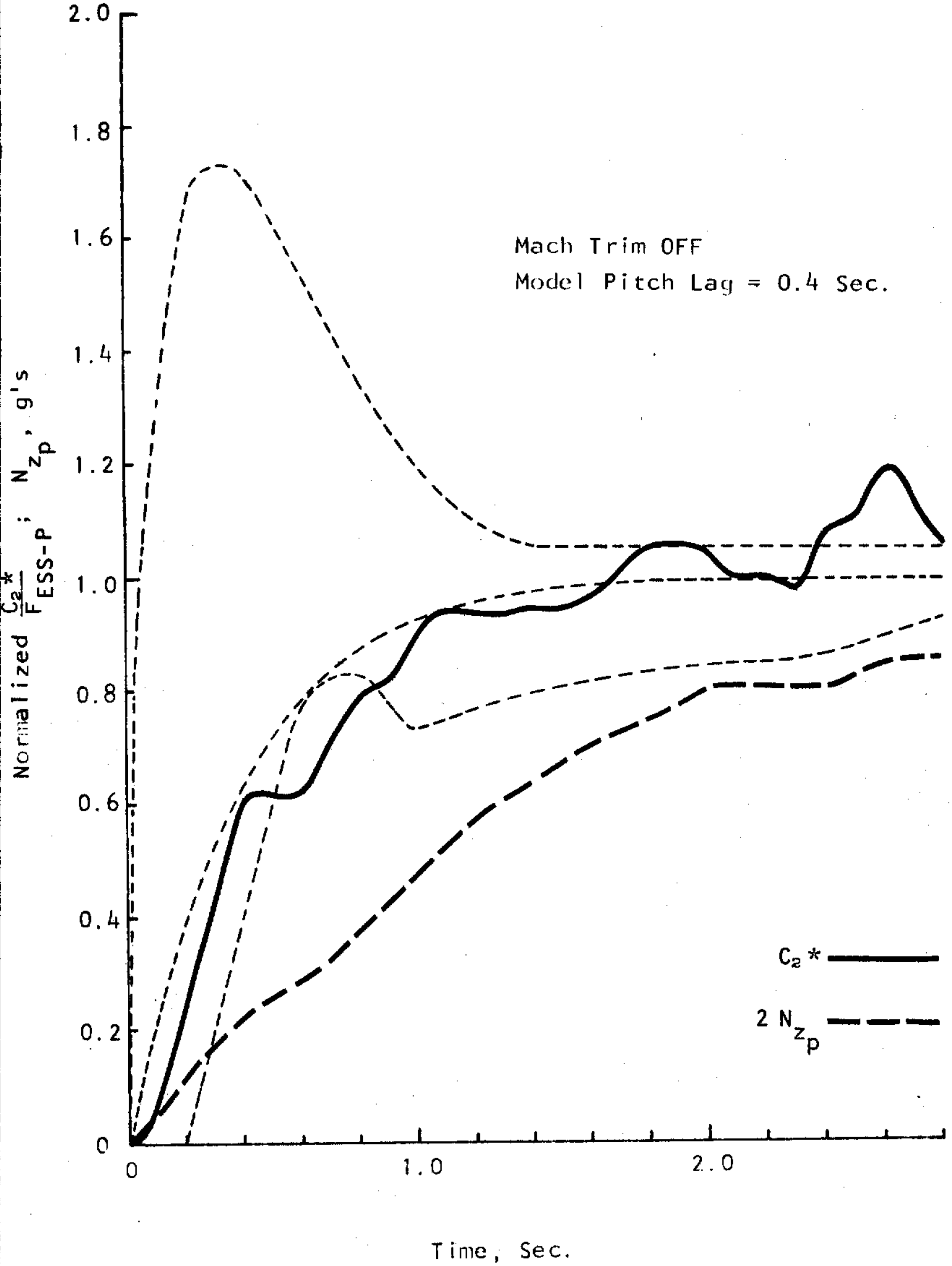


Figure 42: C_2* Mode -- SOC Flight Test #13; F.C. 9: 35,000 Ft., Mach 1.3 ($M_\delta/M_\delta* = 1.29$)

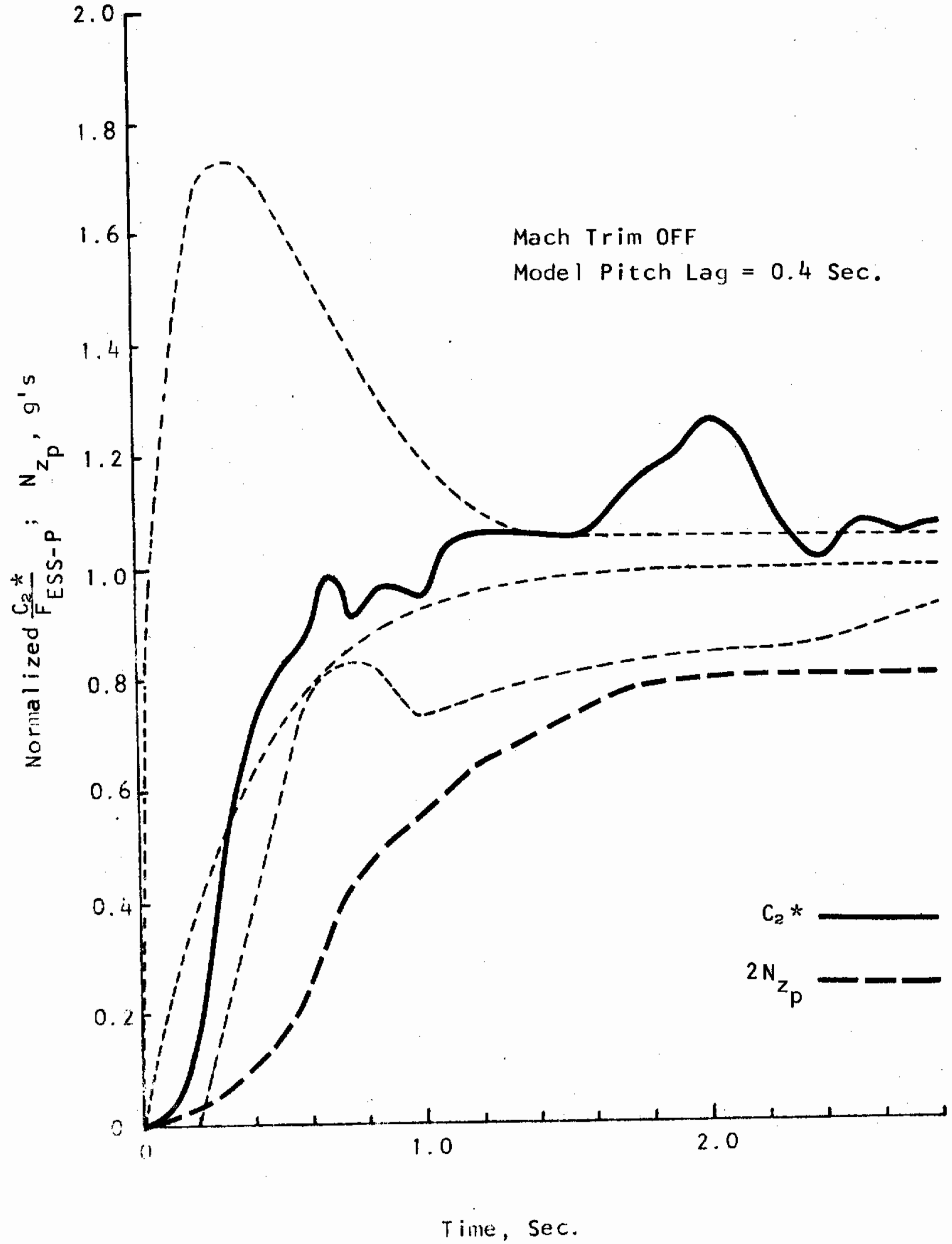


Figure 43: C_2* Mode -- SOC Flight Test #10; F.C. 2; 10,000 Ft., Mach 0.80 ($M_\delta/M_\delta* = 1.73$)

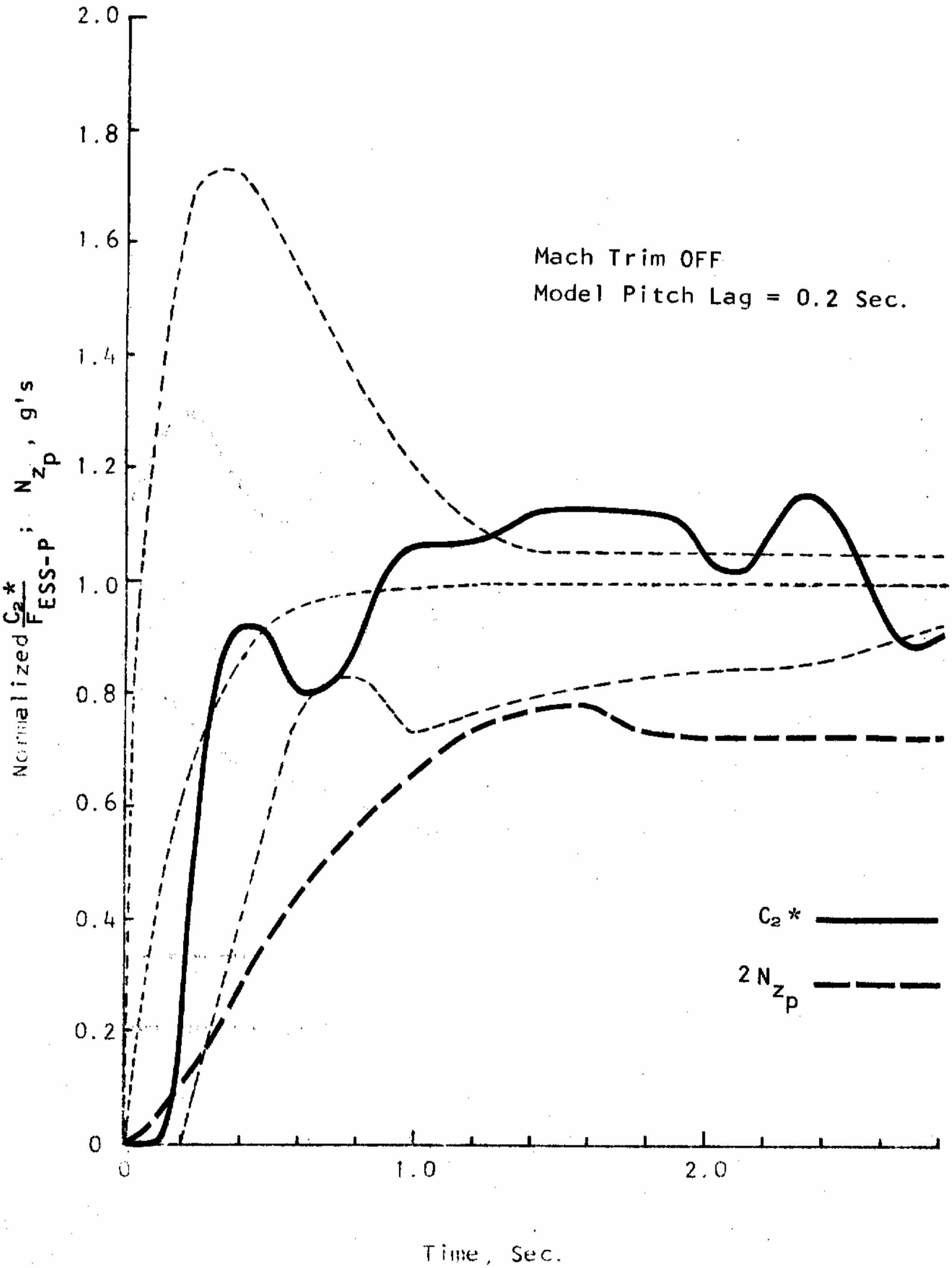


Figure 44: C_2* Mode -- SOC Flight Test #26; F.C. 6
20,000 Ft., Mach 1.20 ($M_\delta/M_\delta* = 2.18$)

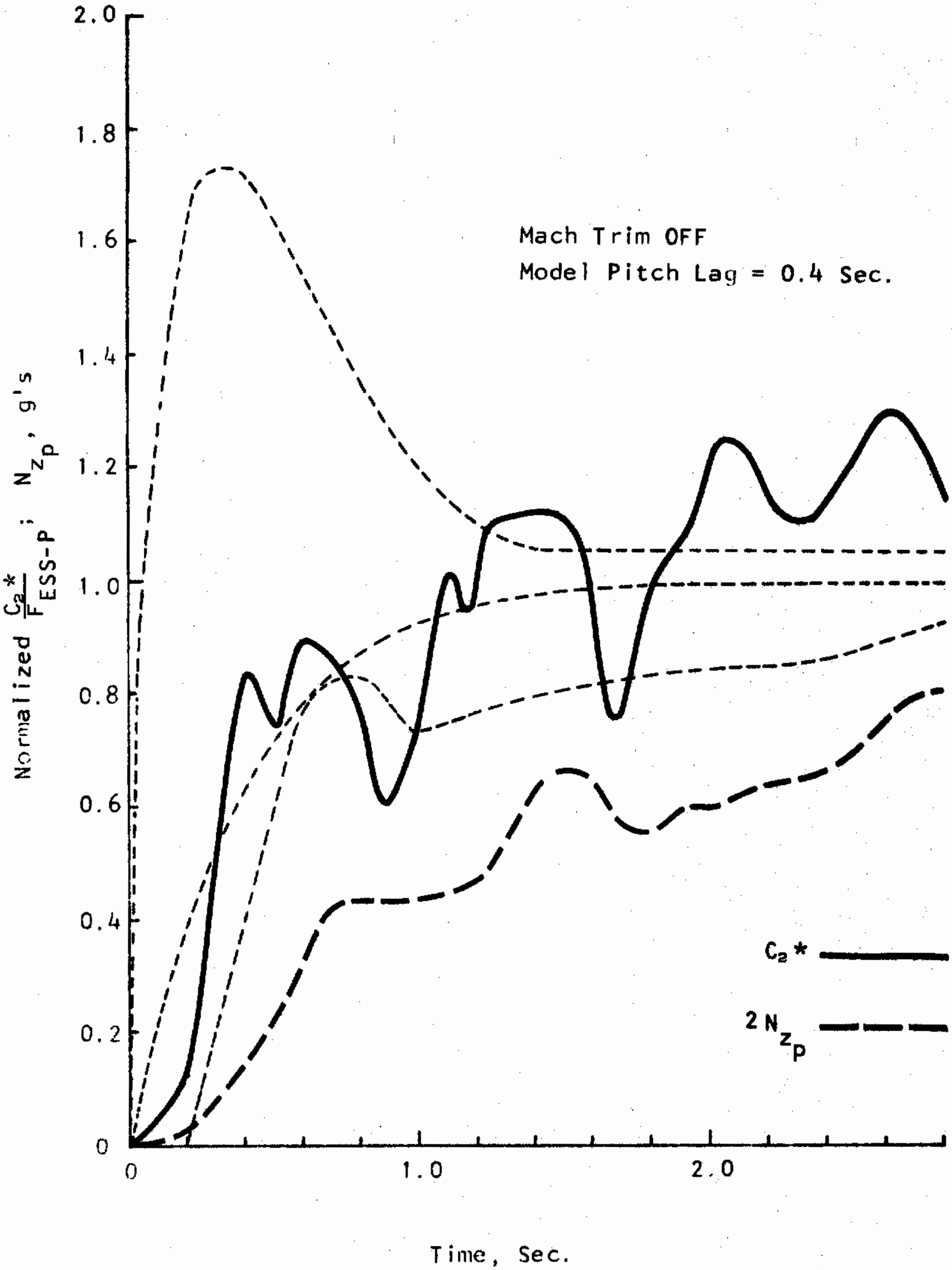


Figure 45: C_2* Mode -- SOC Flight Test #15; F.C. 3; 10,000 Ft., Mach 0.95 ($M_\delta/M_\delta* = 2.35$ = Max.)

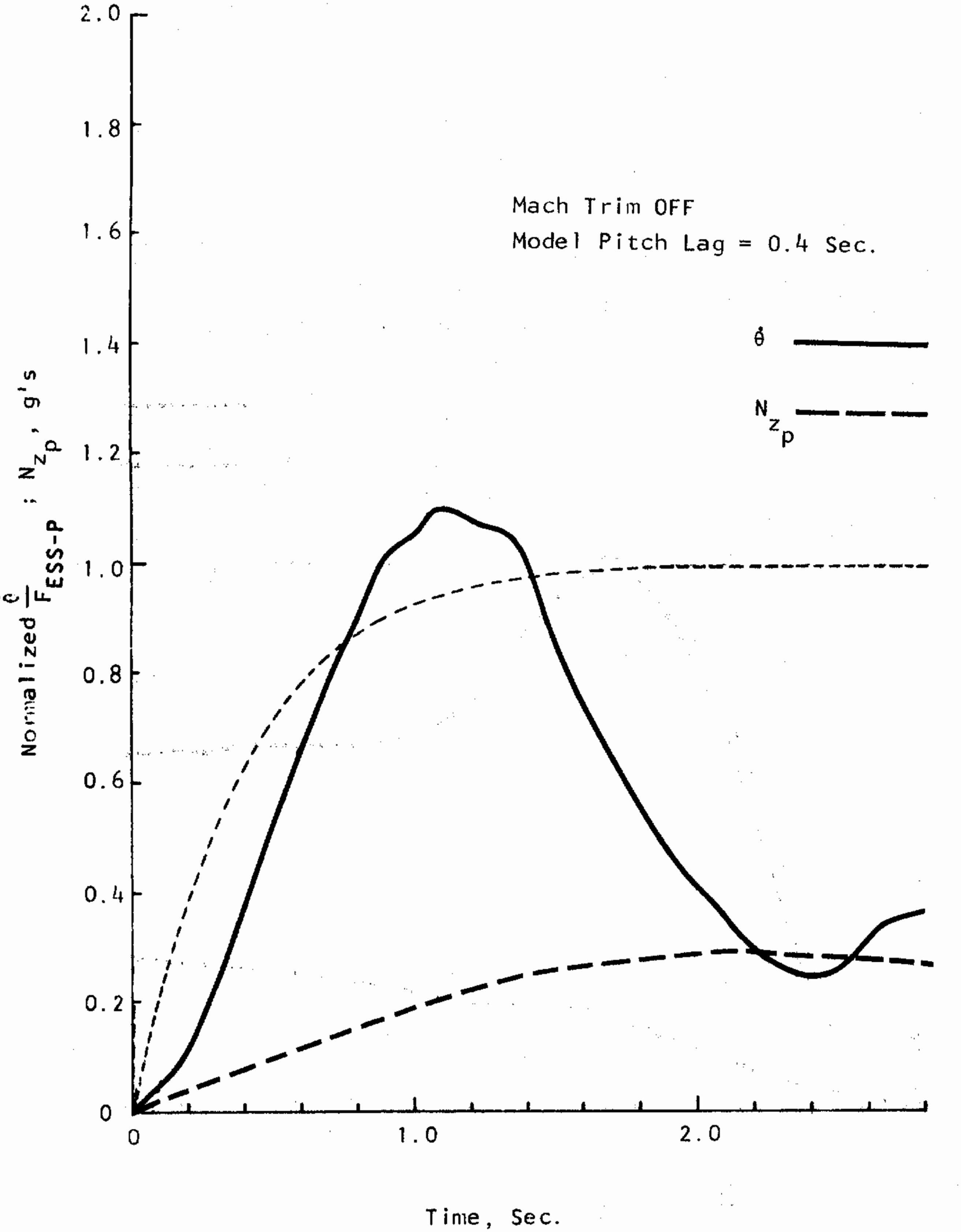


Figure 46: $\dot{\theta}$ Mode -- SOC Flight Test #10; F.C. 1; 10,000 Ft., Mach 0.45 ($M_\delta/M_\delta{*}$ = 0.45 = Min.)

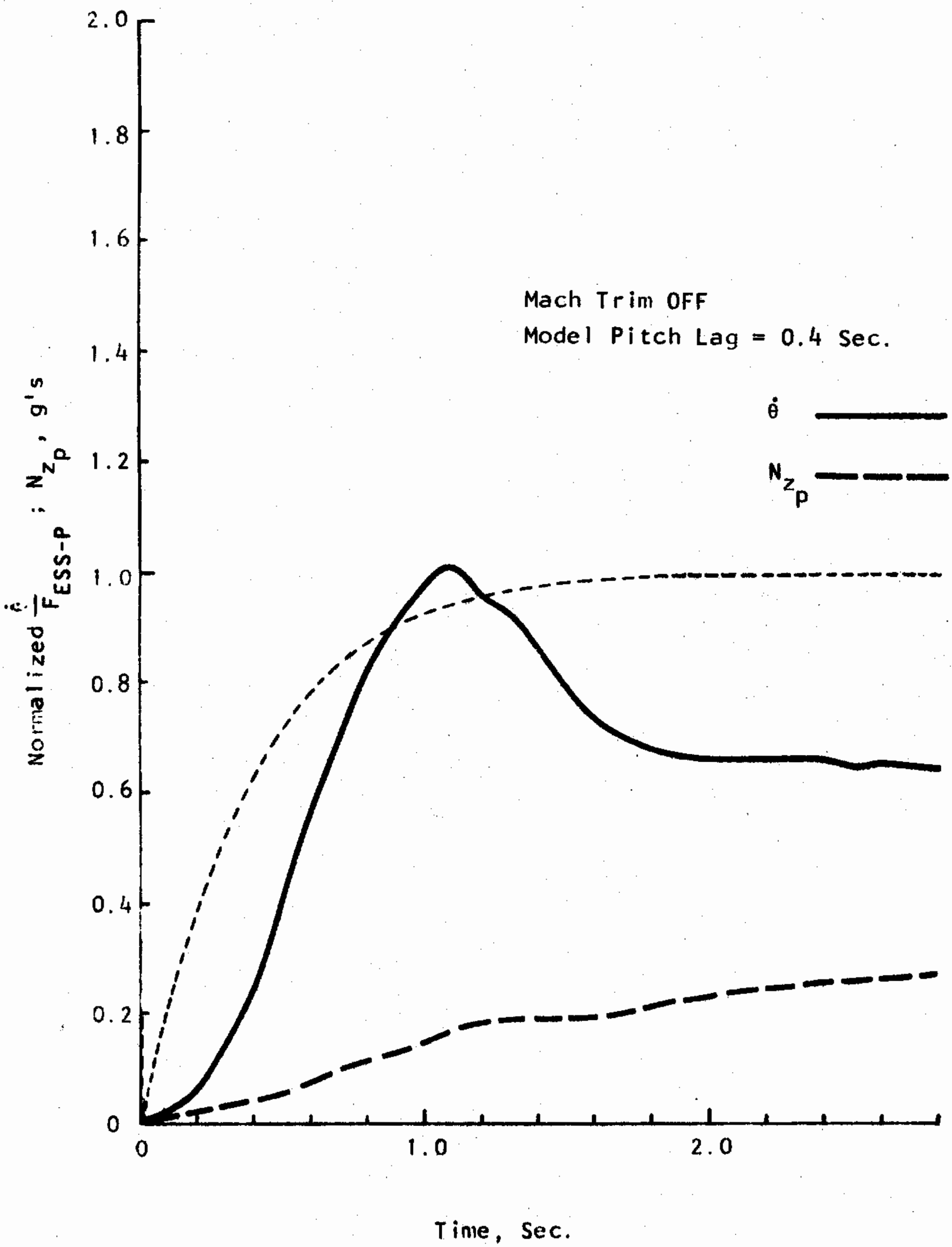


Figure 47: $\dot{\theta}$ Mode -- SOC Flight Test #7; F.C. 4; 20,000 Ft., Mach 0.55 (M_δ / M_δ^* = 0.50)

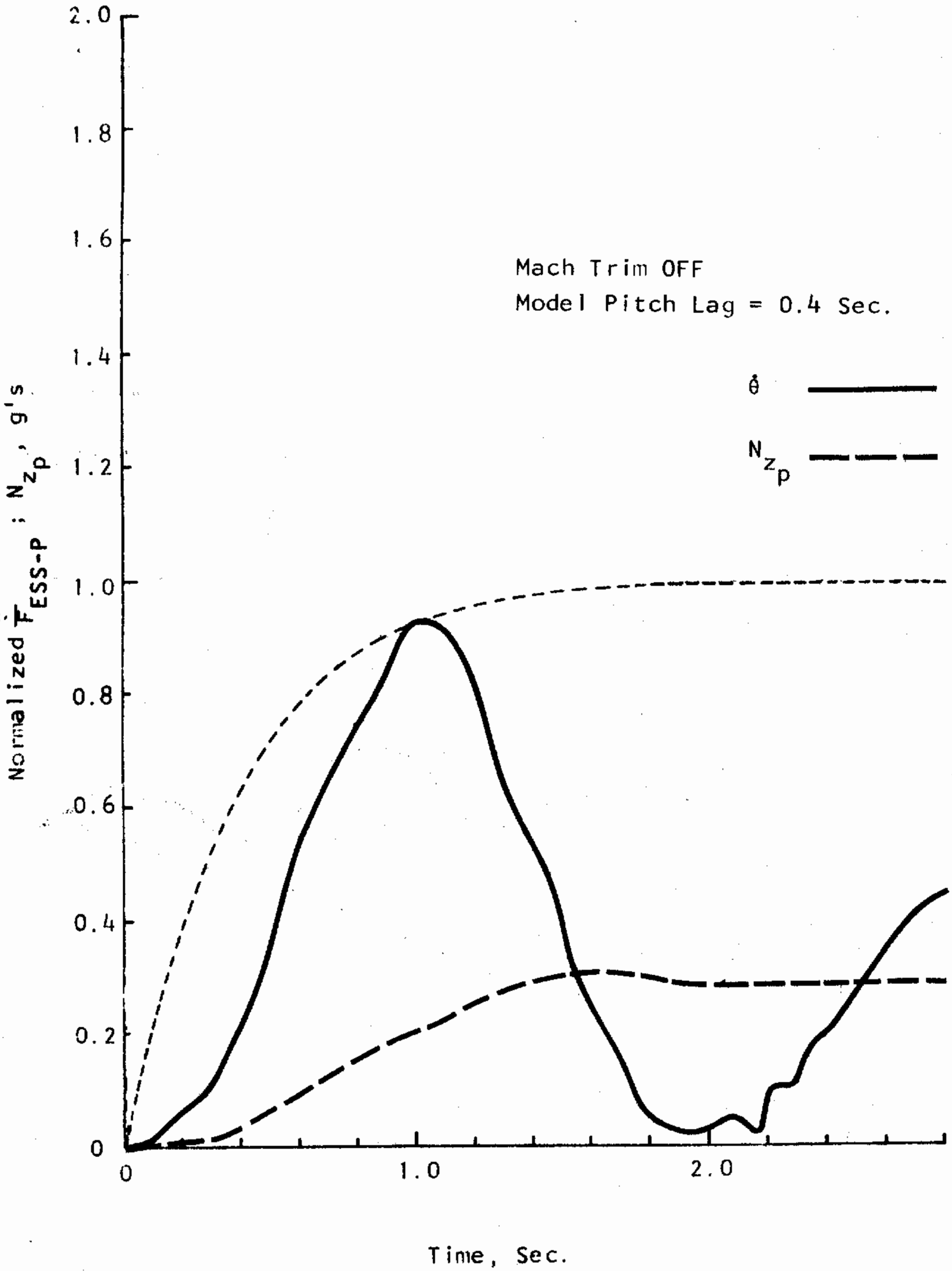


Figure 48: $\dot{\theta}$ Mode -- SOC Flight Test #8; F.C. 7; 35,000 Ft., Mach 0.75 ($M_\delta/M_\delta{*}$ = 0.56)

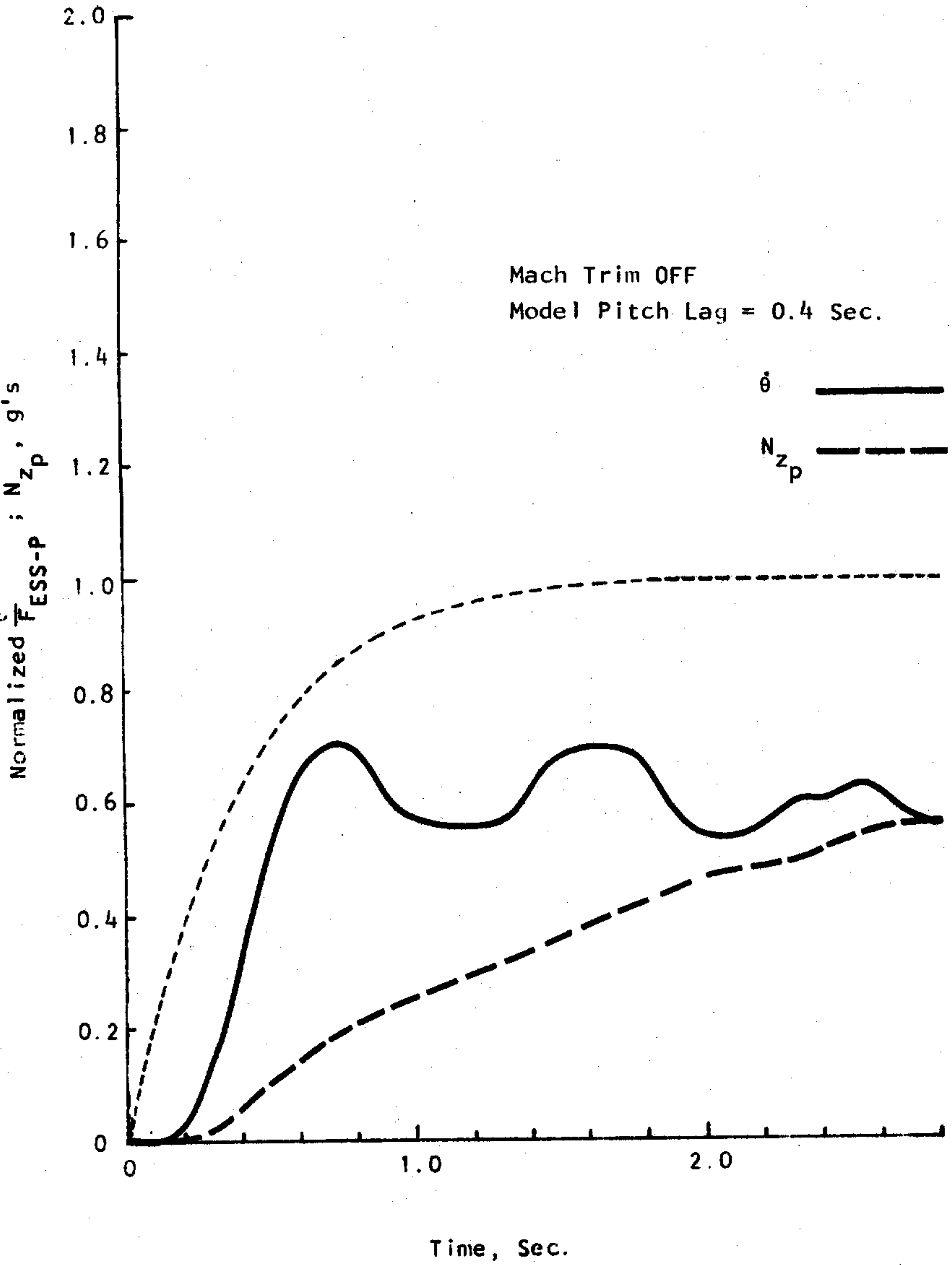


Figure 49: $\dot{\theta}$ Mode -- SOC Flight Test #13: F.C. 8
35,000 Ft., Mach 0.95 ($M_\delta/M_\delta{}^* = 1.00$)

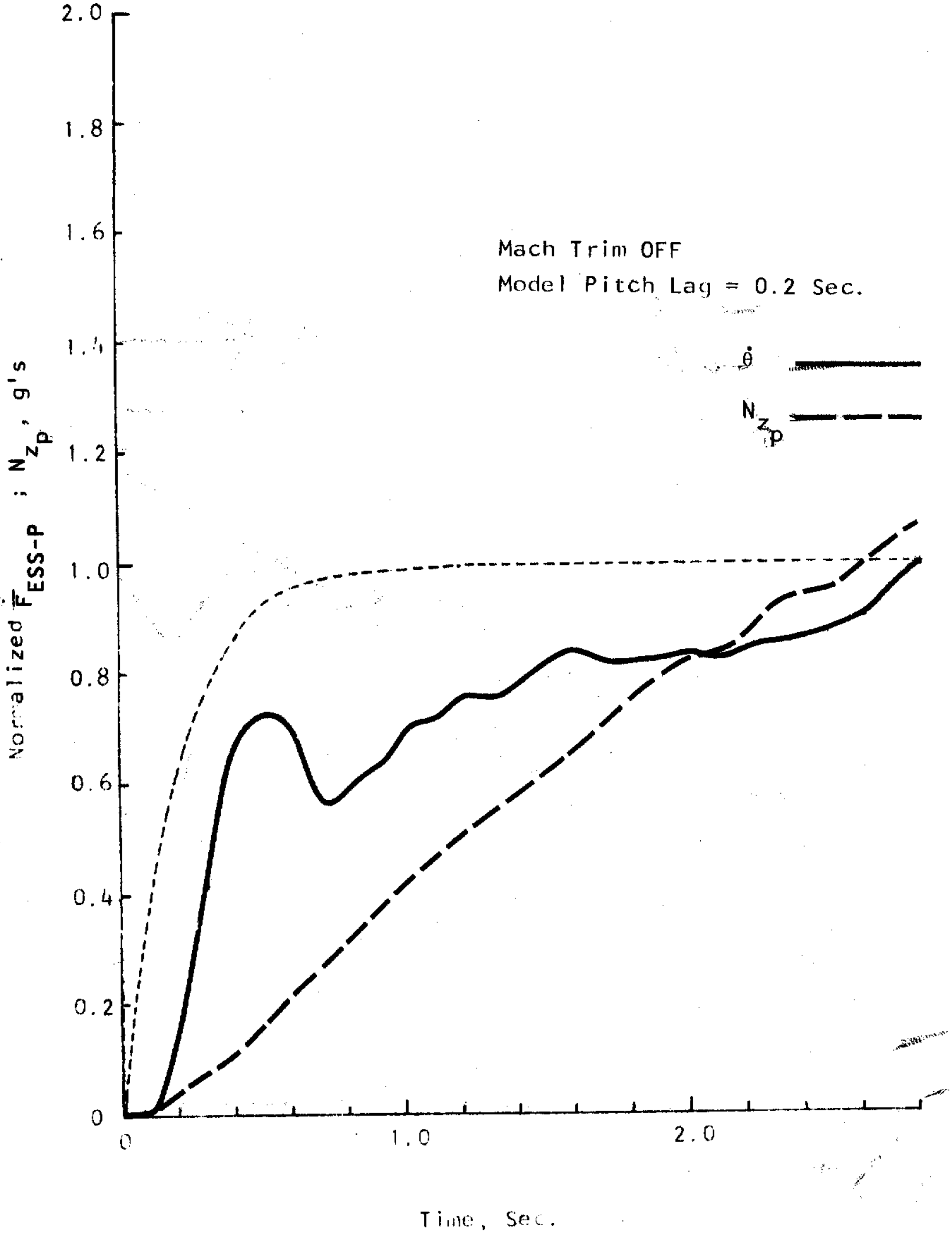


Figure 50: $\dot\theta$ Mode -- SOC Flight Test #19; F.C. 10; 35,000 Ft., Mach 1.4 ($M_\delta/M_\delta* = 1.11$)

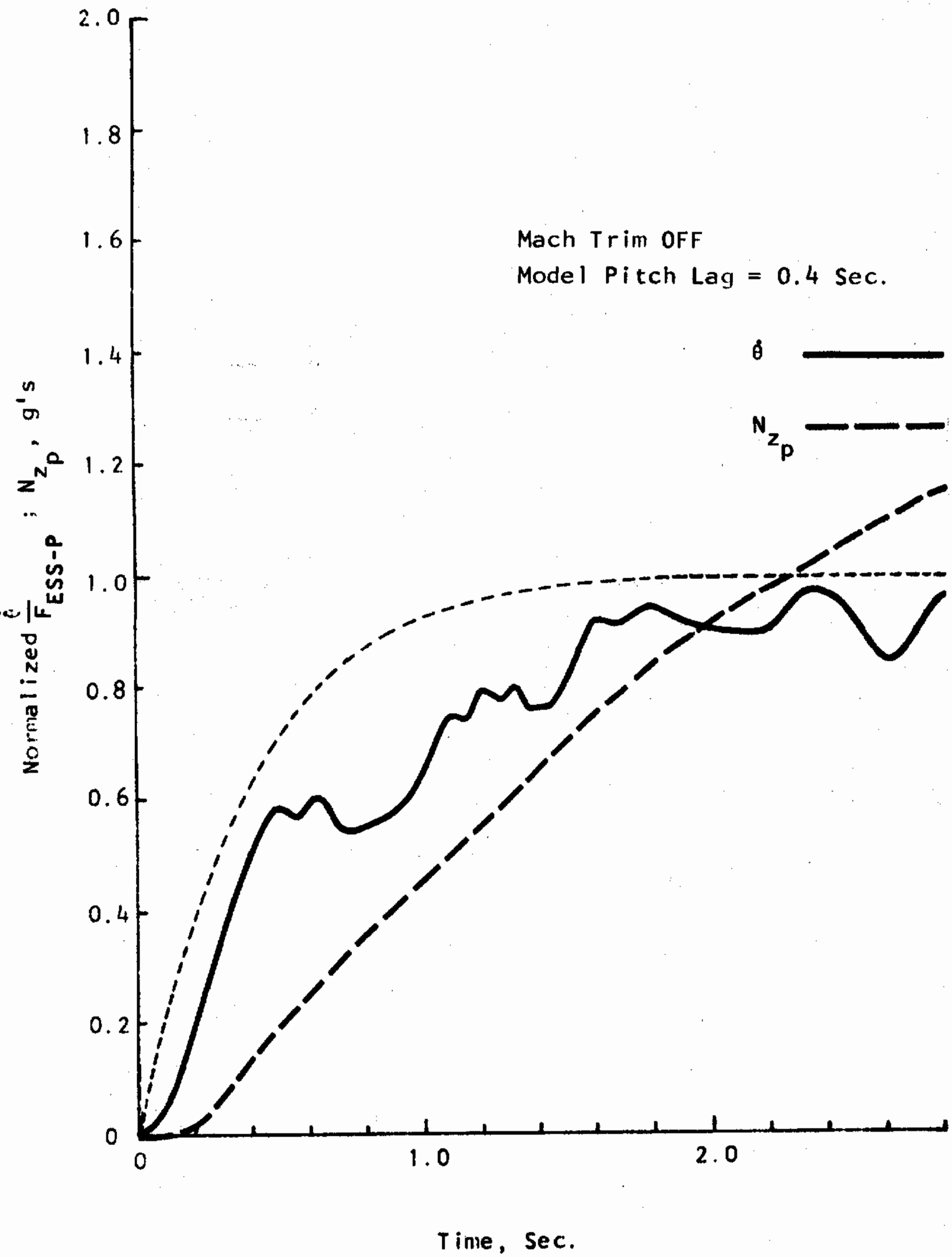


Figure 51: $\dot{\theta}$ Mode -- SOC Flight Test #8: F.C. 5
20,000 Ft., Mach 0.90 ($M_\delta/M_\delta{}^* = 1.23$)

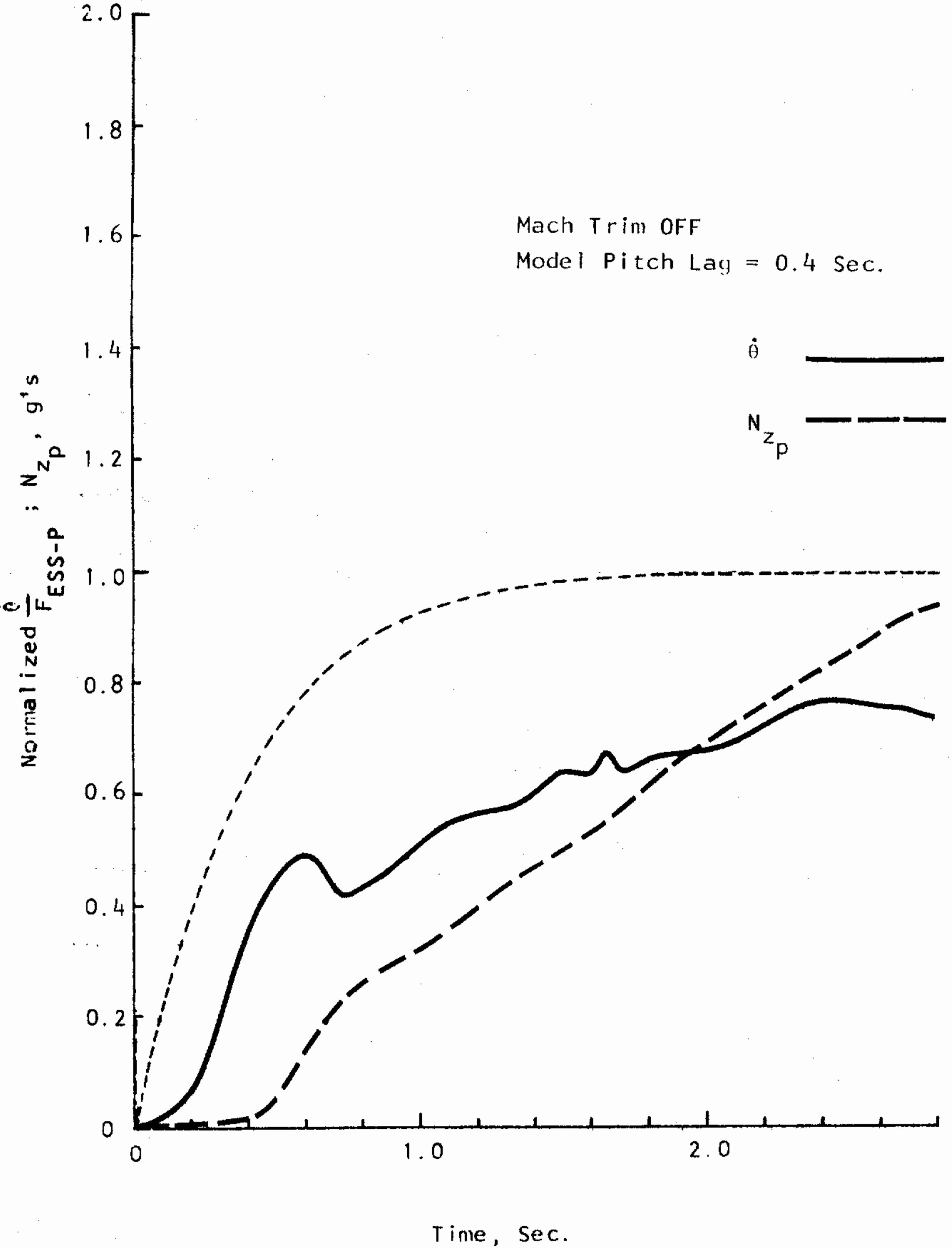


Figure 52: $\dot{\theta}$ Mode -- SOC Flight Test #13; F.C. 9; 35,000 Ft., Mach 1.3 $(M_\delta/M_\delta* = 1.29)$

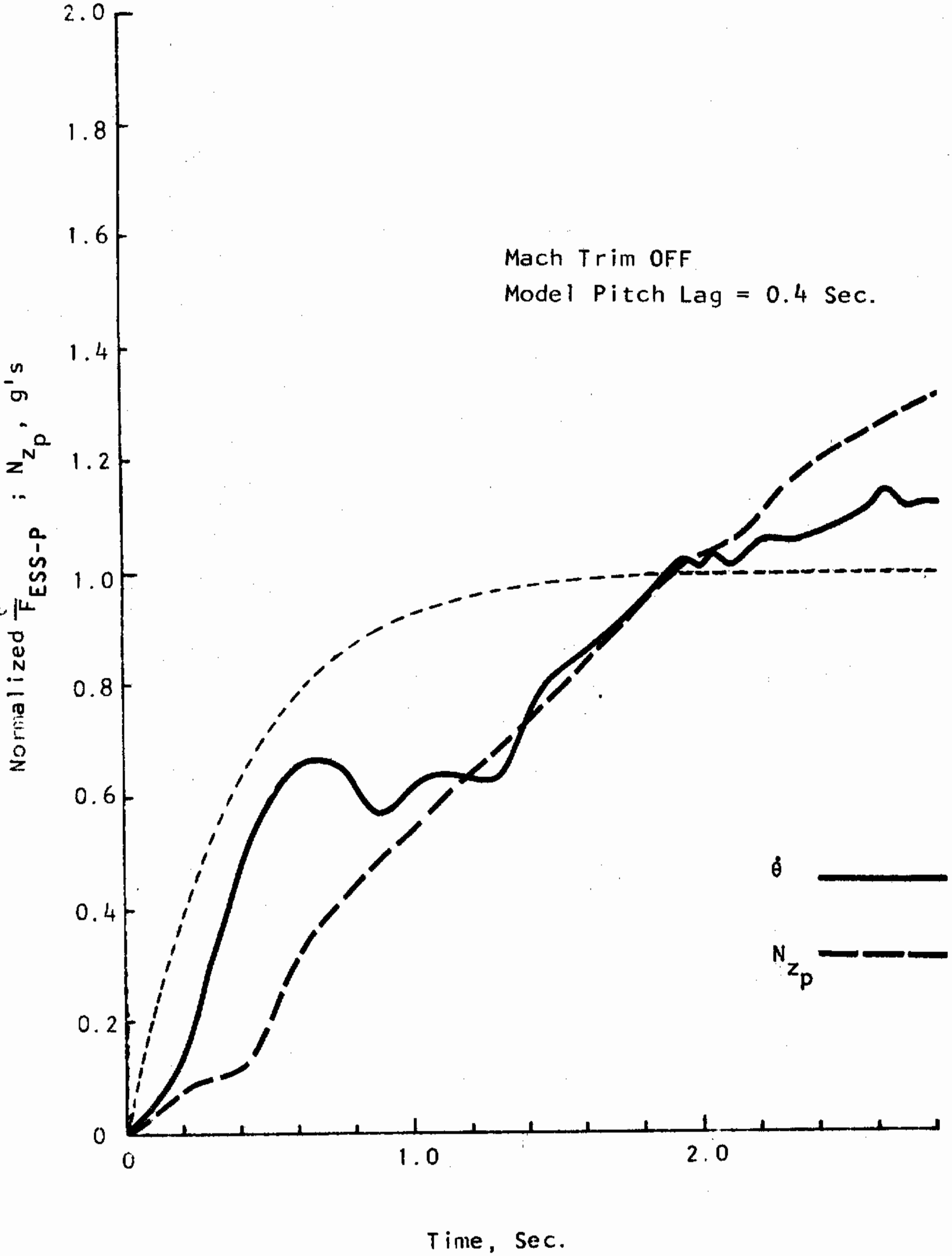


Figure 53: $\dot{\theta}$ Mode -- SOC Flight Test #10; F.C. 2; 10,000 Ft., Mach 0.80($M_\delta/M_\delta* = 1.73$)

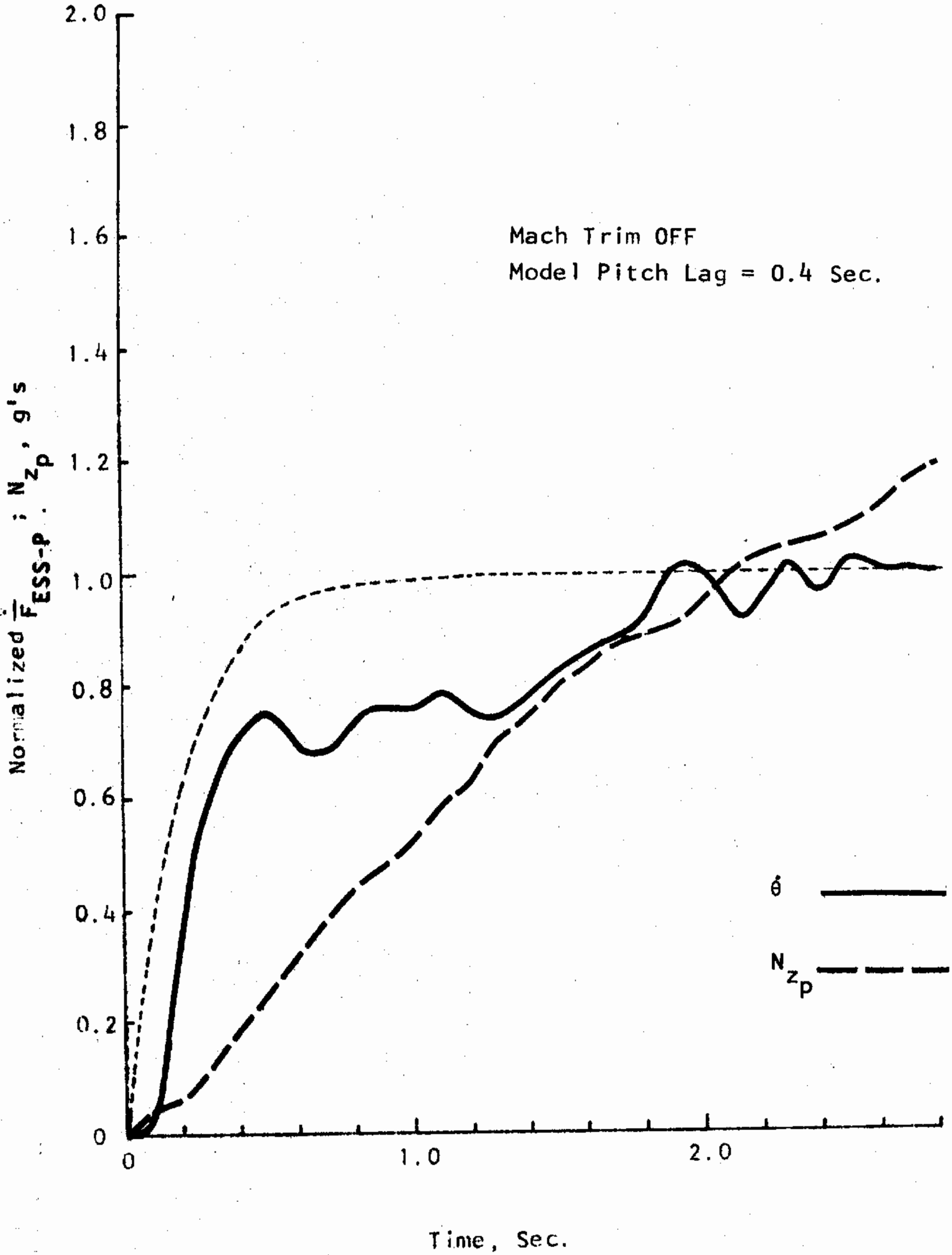


Figure 54: $\dot{\theta}$ Mode -- SOC Flight Test #29; F.C. 6; 20,000 Ft., Mach 1.20 ($M_\delta/M_\delta* = 2.18$)

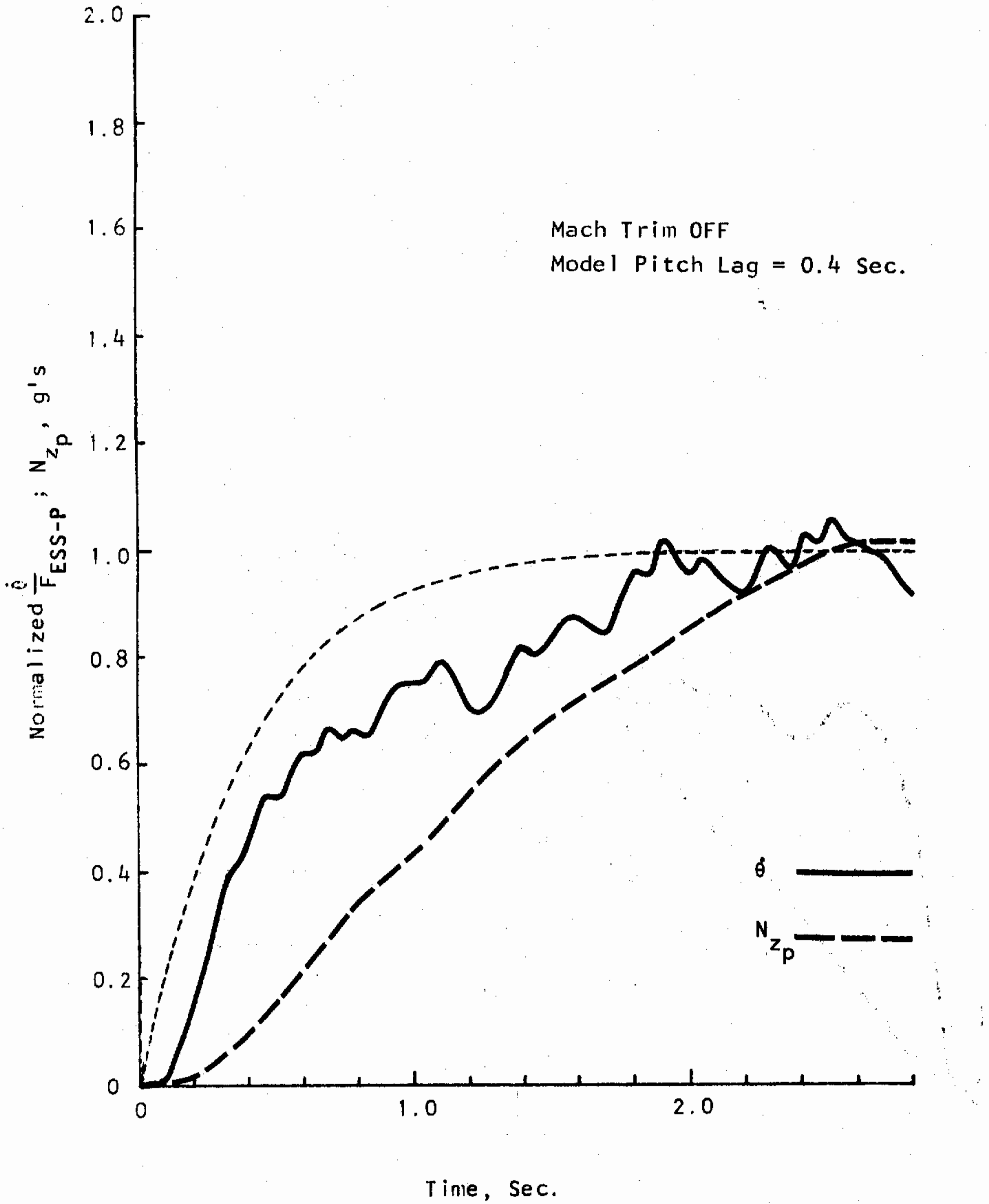


Figure 55: $\dot{\theta}$ Mode -- SOC Flight Test #15; F.C. 3; 10,000 Ft., Mach 0.95 ($M_\delta/M_\delta{}^*$ = 2.35 = Max.)

and responses shown in the other figures were obtained using a time constant of 0.4 sec. The test signals, generated within the PFIC, were smoothed by a first-order lag so as to make them representative of manual step inputs applied through the model pre-filter.

Because flight data are seldom entirely repeatable, Figures 36 - 55 should be viewed as indicative of trends, as they are not average or precise (calm air) responses. Figure 41 illustrates the variance between test results at one flight condition. Note that these responses were measured during the same flight, the difference presumably being due chiefly to atmospheric turbulence factors.

Generally speaking, the C_2* mode responses showed adequately small rise times and acceptable levels of overshoot. Steady-state errors were reasonably small, except at the minimum M_δ flight condition (Figure 36). Although the figures indicate that C_2* settling times may have been longer than specified, the full evidence suggests that normal air turbulence was responsible for much of the apparent activity after 1.5 or 2.0 sec. Because a steady-state command of +0.5 incremental g was applied, $C_2{}^*/F_{ESS-P} = 1$ corresponded to a like level. Ten percent of this command was only 0.05 g, or 1.6 ft./sec.^{2}, an incremental acceleration consistent with typical air turbulence effects, particularly at high q flight conditions.

The $\dot{\theta}$ mode responses were, on the other hand, poor compared to both desired performance and prior simulation results. The steady-state errors for this mode were undesirably large (from the control system designer's standpoint) for all median or low M_δ conditions. Pilot comment (presented later in this section and in Appendix III) was that the $\dot{\theta}$ mode felt "uncomfortable because of a tendency to overcontrol (i.e., a Pitch input commands a more rapid 'g' build-up than is expected, especially noticeable at high 'q')." This criticism appears to be directed principally at the familiar tendence of an FCS to produce excessive g's per unit stick force at high q, a characteristic usually found in

$\dot{\theta}$ systems having no input scaling for different q conditions. The C* modes, because N_{z_p} was blended with the $\dot{\theta}$ feedback, overcome this problem. In other words, the basic deficiency of the $\dot{\theta}$ mode reported by the pilots was anticipated, even though the sizable $\dot{\theta}$ steady-state errors at low M_δ conditions came as a surprise. In retrospect, the SOC might have benefitted from use of higher gain for all $\dot{\theta}$ work.

The recorded C* flight responses do not appear to correlate well with simulation results, pre-flight tests (Figures 30-33), and pilot comments. Several possible explanations which have been advanced are:

(a) inadvertent pilot inputs or dynamic responses of the electric sidestick (which was not dynamically balanced)

(b) air turbulence and gusts

(c) non-ideal characteristics of the parallel servo and primary hydraulic actuator

(d) aeroelastic characteristics of the aircraft

(e) non-ideal pitch rate gyro and forward normal accelerometer dynamics, including presence of the 11.3 rad./sec. pole in the accelerometer feedback path (required to smooth accelerometer ripple components)

(f) use of TSG 0.4 sec. filter time constant rather than preferred 0.2 sec. in many of the test manuevers

(g) insufficient SOC gain working into the MB-5 AFCS

(h) variation of SLU noise voltage due to temperature changes

(i) recorder deflections too small for accurate reading, leading to errors in reduction of recorded data.

Each of these possible factors has been considered, and, while it is felt that many may have contributed to the discrepancies between simulated and flight data, the principal cause is believed to be that of non-ideal actuator, airframe, and (particularly) sensor characteristics, with atmospheric turbulence probably being the next most important factor.

Flight #7 seemed to produce results which correlated best with prior simulations, as may be seen by comparison of Figure 37 with Figure IV.4 in Appendix IV.

Figures 56 - 61 are reproductions of flight recordings for several key variables. Figure 56 documents the first in-flight SOC engage sequence, performed at an average M_δ condition. Note that approximately 1.5 sec. after engaging the SOC in C_2* mode, δ_{SPT} began a 5-Hz limit-cycle oscillation with a peak-to-peak amplitude of approximately 1.0 in. When the sidestick was pulled back slightly (Figure 56, second sheet), the oscillation partly disappeared. $\dot{\theta}$ mode was not used in the first flight. (Appendix III should be consulted for the pilot's comments on this and subsequent missions.)

For the second flight, $K_{4_{C*}}$ and $K_{4_{\dot{\theta}}}$ were quadrupled (Table II). The pilot reported that the pitch oscillation was now considerably smaller in amplitude, and this can be seen in Figure 57. The first use of $\dot{\theta}$ mode occurred in the second flight, and it was observed that no oscillation was present in this mode, although a small center stick chatter was reported at a frequency of about 20-30 Hz. (Note: The SOC worked into the parallel servo actuator, so actuator motions were mechanically transmitted to the center stick during SOC operations.)

The third mission was flown with slightly greater $K_{4_{C*}}$ and reduced $K_{4_{\dot{\theta}}}$ (see Table II), these coefficients now being equal to

[Cont'd. on page 114]

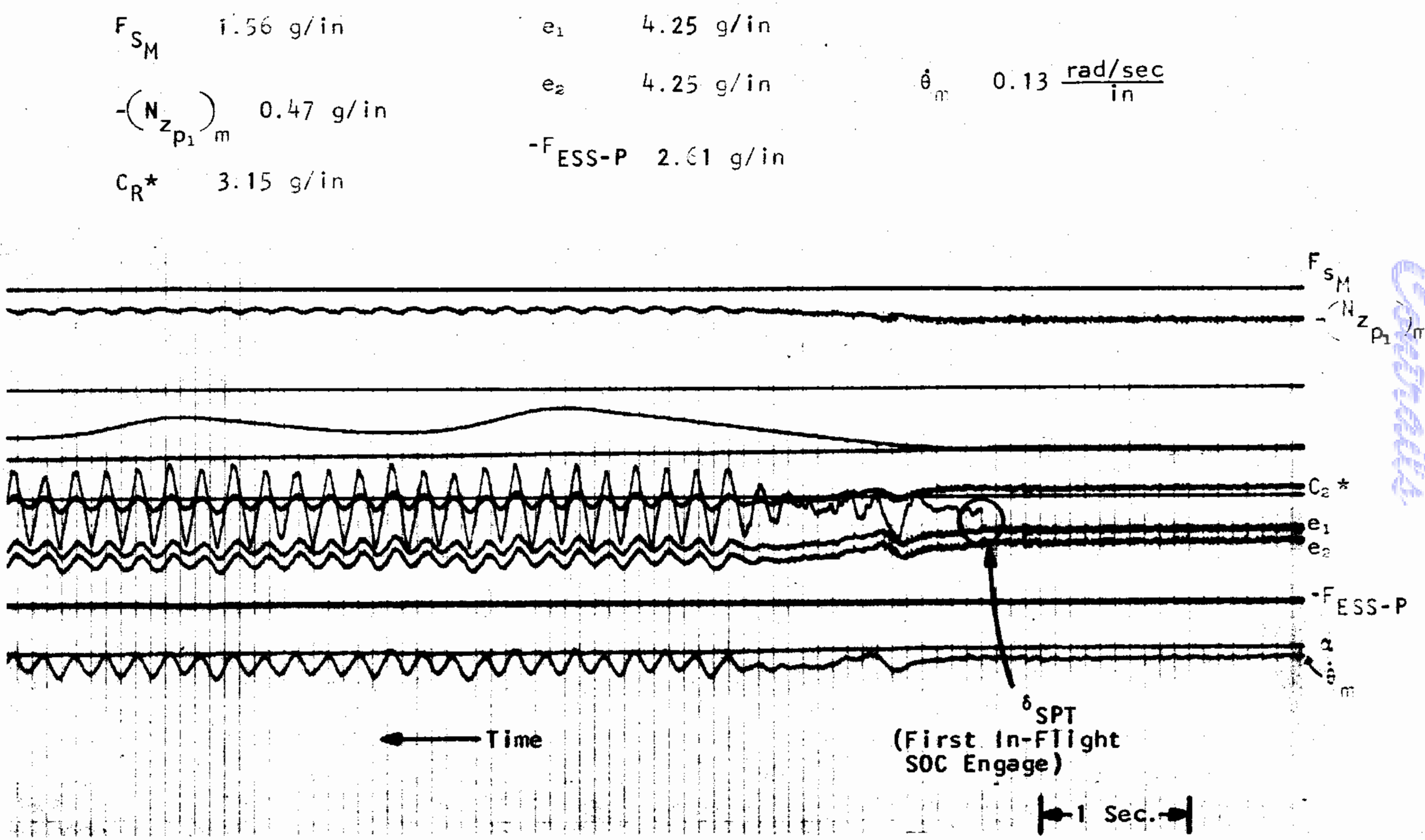


Figure 56: Flight Recording Flight #1; 20,000 Ft., Mach 0.75; C_a* Mode, Mach Trim OFF (Figure Cont'd.)

F_{s_M} 1.56 g/in e_1 4.25 g/in C_R^* 3.15 g/in

e_2 4.25 g/in $\dot{\theta}_m$ 0.13 $\frac{\text{rad/sec}}{\text{in}}$

$-(N_{z_{p_1}})_m$ 0.47 g/in

$-F_{ESS-P}$ 2.61 g/in

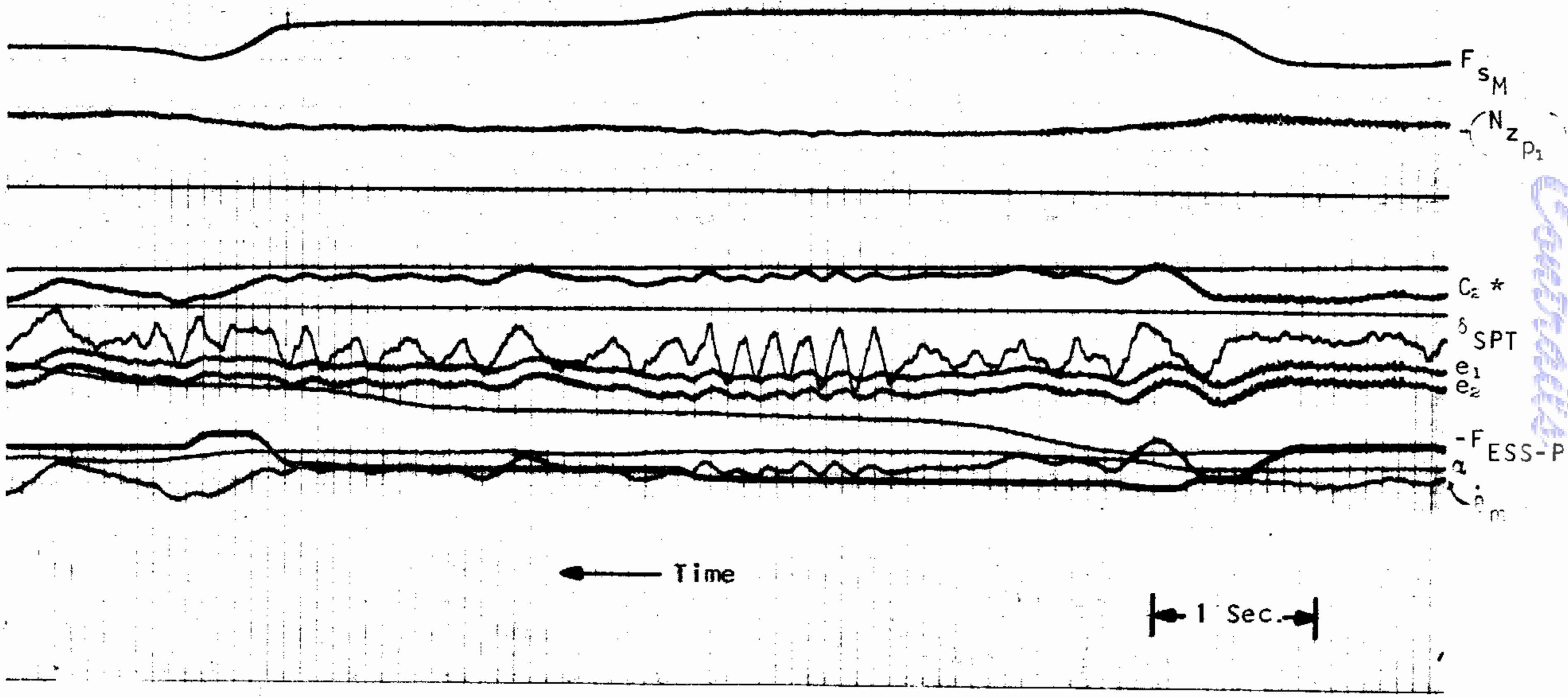


Figure 56: Flight Recording; Flight #1; 20,000 Ft., Mach 0.75
C_a* Mode, Mach Trim OFF (Concluded)

$-(N_{z_{p_1}})_m$	0.47 g/in	e_1	4.25 g/in	$-F_{ESS-P}$	2.61 g/in
δ_{SPT}	2.30 in/in	e_2	4.25 g/in	$\dot{\theta}_m$	0.13 $\frac{rad/sec}{in}$

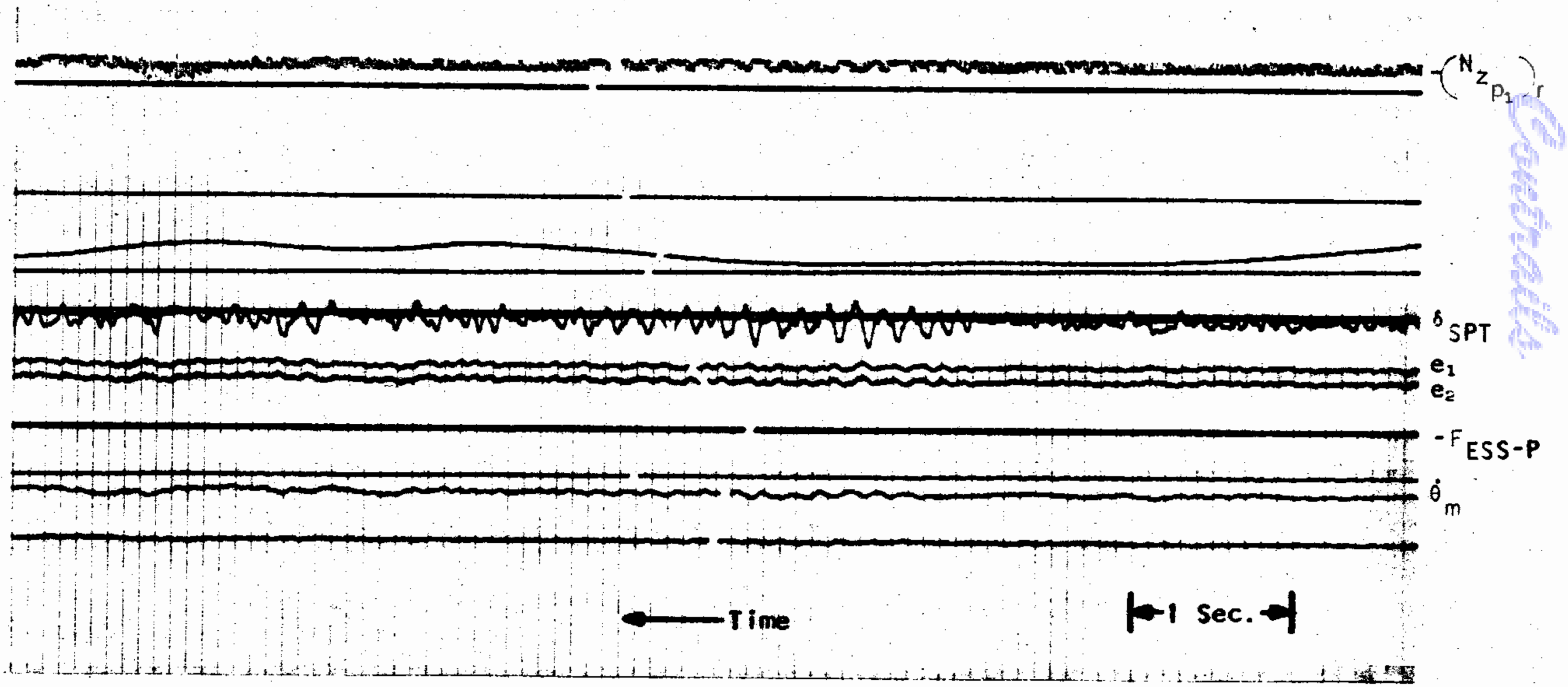


Figure 57: Flight Recording Flight #2; 20,000 Ft., Mach 0.75; C_2* Mode, Mach Trim OFF

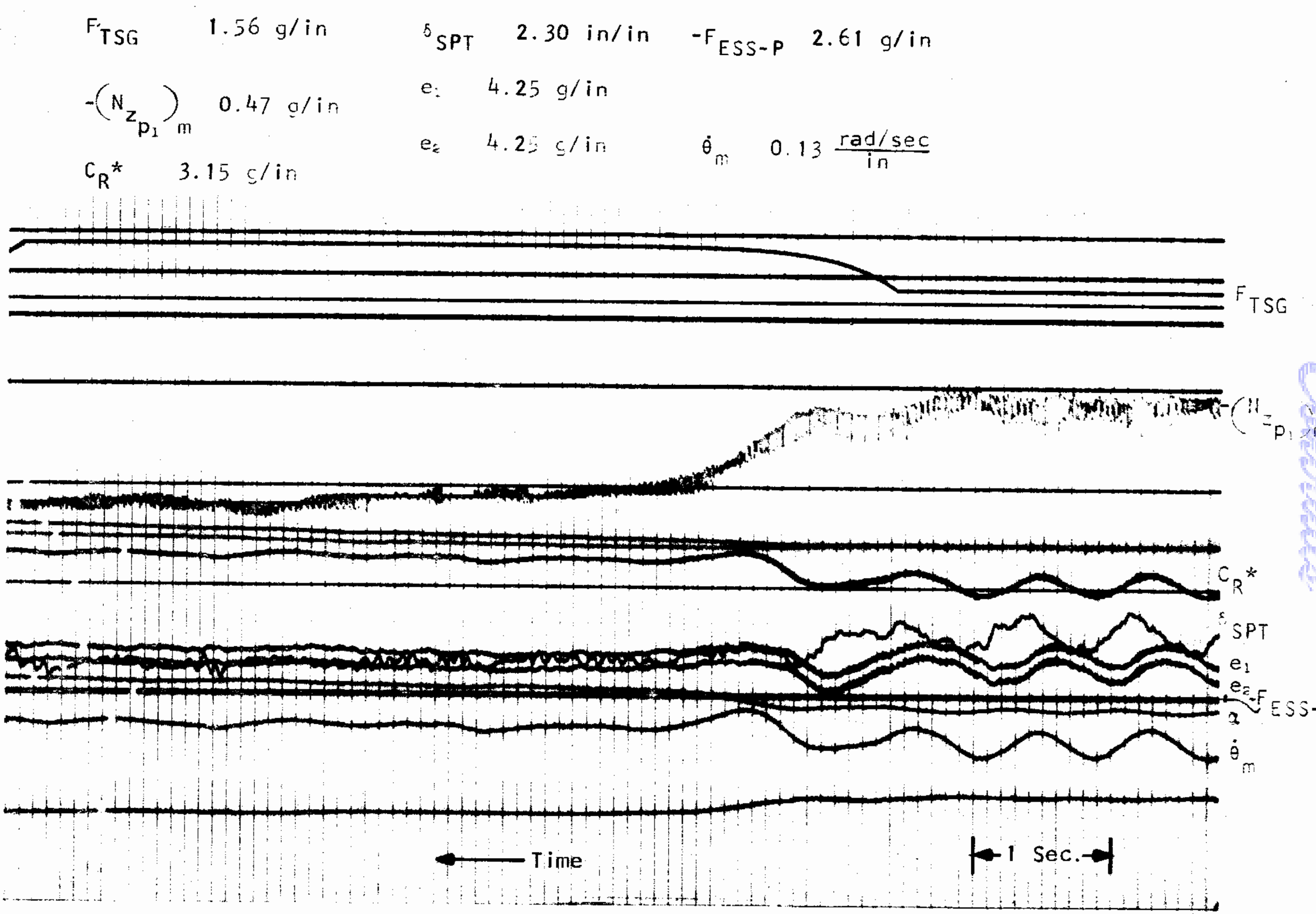


Figure 58: Flight Recording; Flight #3 20,000 Ft., Mach 0.75: θ Mode, Mach Trim OFF; +0.5g TSG Step Command

F_{TSG} 1.56 g/in C_R* 3.15 g/in $-F_{ESS-P}$ 2.61 g/in

$-(N_{z_{p_1}})_m$ 0.47 g/in $\dot{\theta}_m$ 0.13 $\frac{rad/sec}{in}$

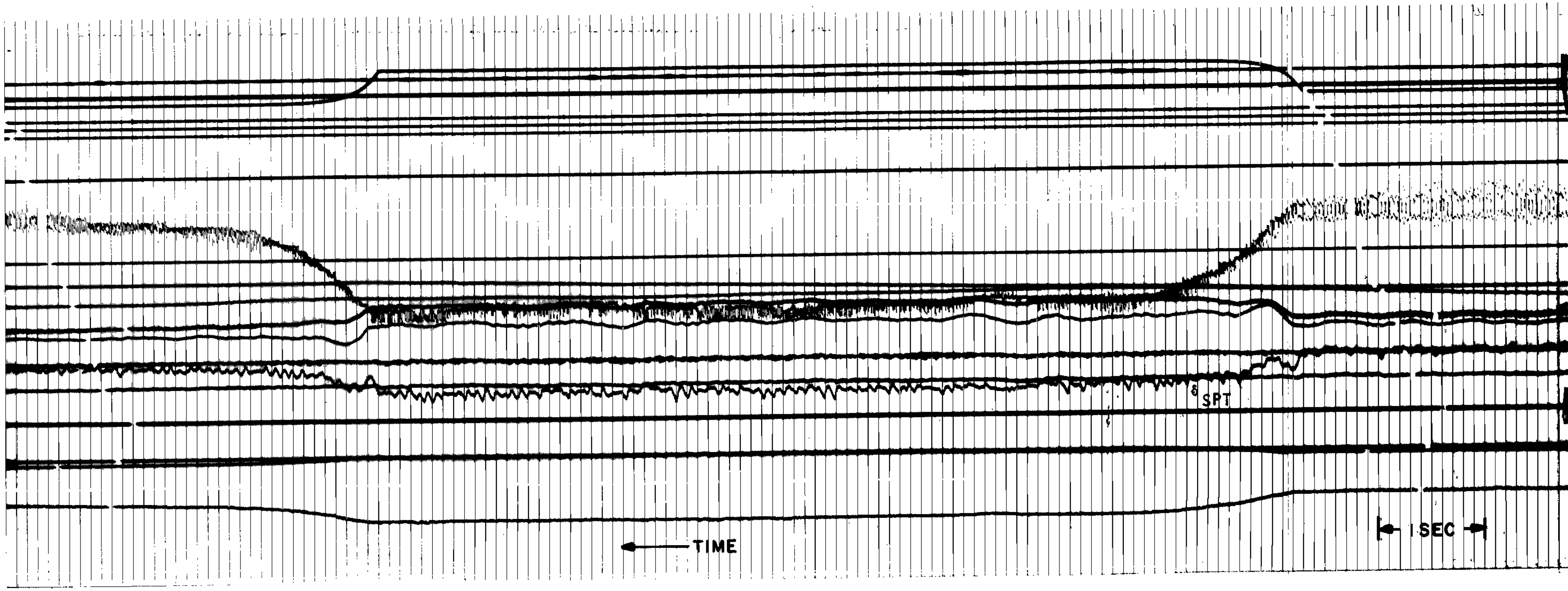


Figure 59: Flight Recording; Flight #26 F.C. 6; 20,000 Ft., Mach 1.20; C* Mode, Mach Trim OFF +0.5 g TSG Step Command

$-\left(N_{z_{p_1}}\right)_m$ 0.47 g/in F_{ESS-P} 2.61 g/in

C_R^* 3.15 g/in

$\dot{\theta}_m$ 0.13 $\frac{rad/sec}{in}$

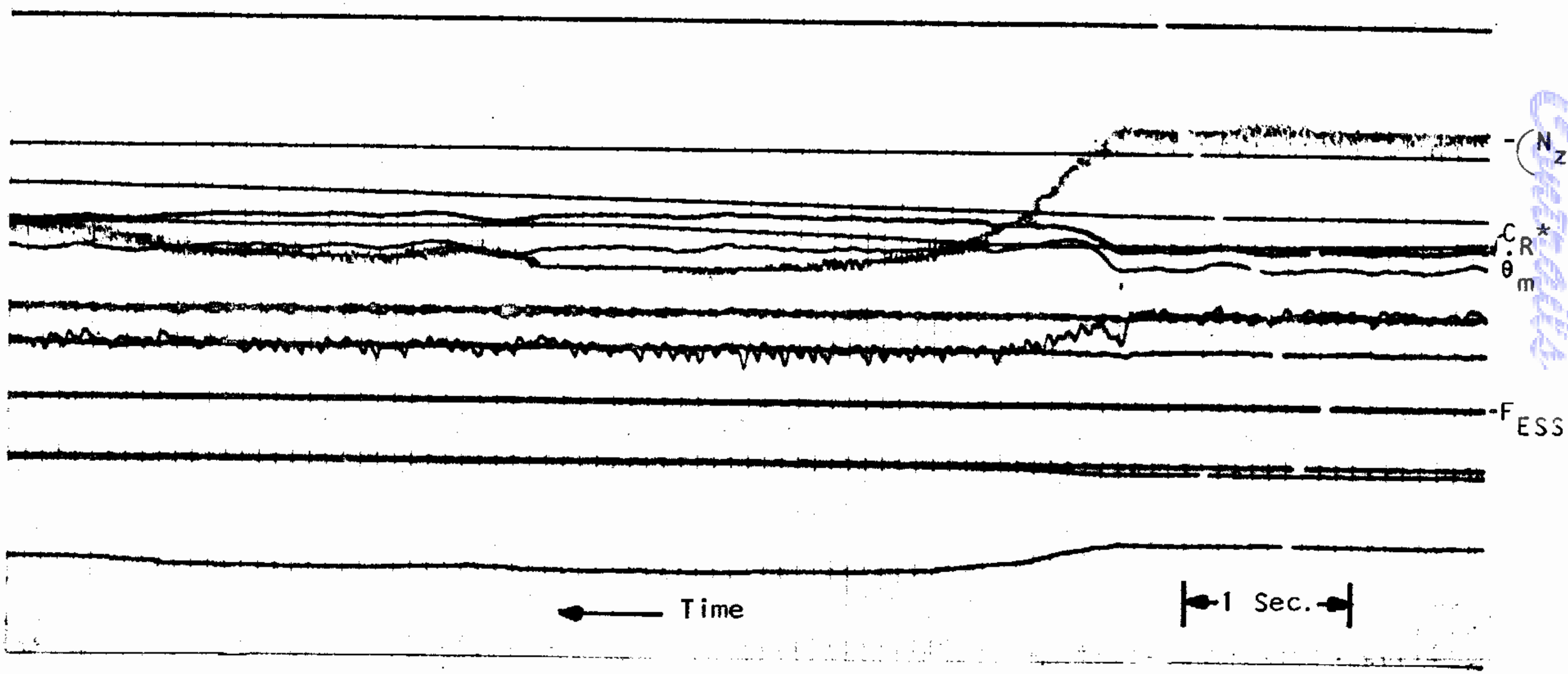


Figure 60: Flight Recording: Flight #28; F.C. 6, 20,000 Ft., Mach 1.20: C_** Mode, Mach Trim ON; +0.5 g TSG Step Command

F_X 1.56 g/in

$-(N_{z_{p_1}})_m$ 0.47 g/in

C_R^* 3.15 g/in

e_1 4.25 g/in

e_2 4.25 g/in

δ_{SPT} 2.30 in/in

$-F_{ESS-P}$ 2.61 g/in

$\dot{\theta}_m$ 0.13 $\frac{rad/sec}{in}$

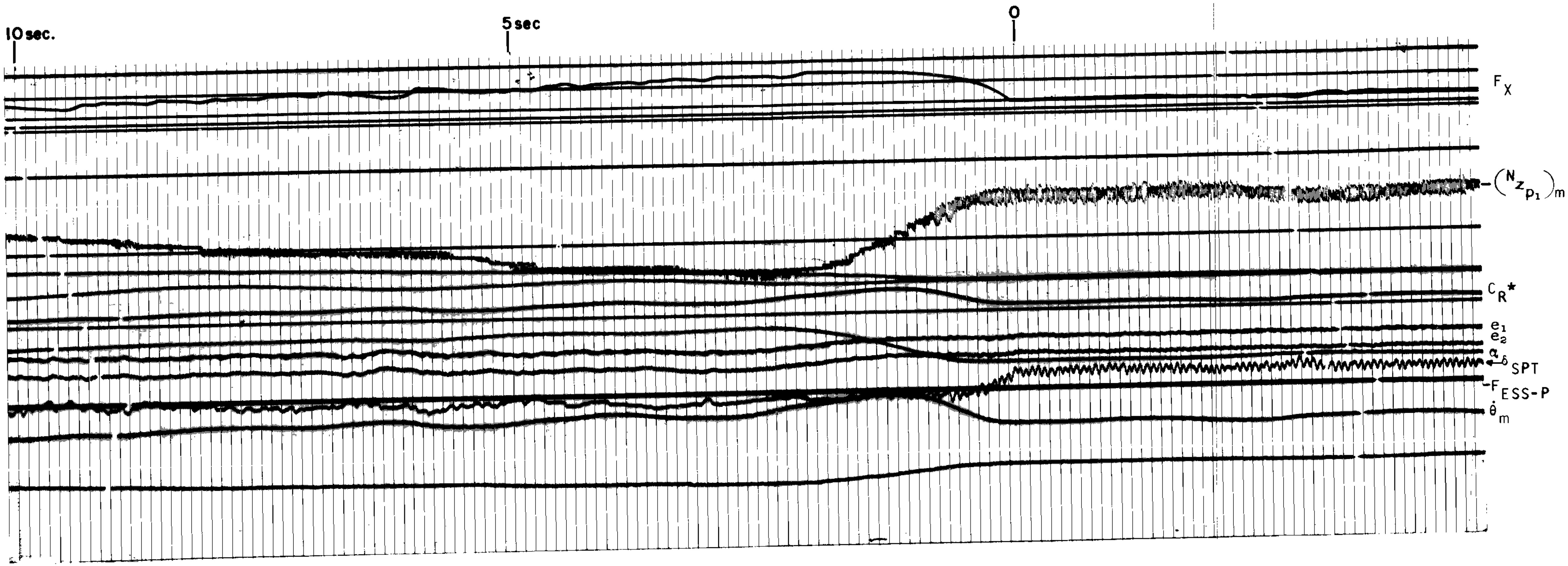


Figure 61: Flight Recording; Flight #7; F.C. 4; 20,000 Ft., Mach 0.55; $\dot{\theta}$ Mode, Mach Trim ON; +0.5 g TSG Step Command (Cont'd.)

F_X 1.56 g/in

$-(N_{z_{p_1}})$ 0.47 g/in

C_R^* 3.15 g/in

e_1 4.25 g/in

e_2 4.25 g/in

δ_{SPT} 2.30 in/in

$-F_{ESS-P}$ 2.61 g/in

$\dot{\theta}_m$ 0.13 $\frac{\text{rad/sec}}{\text{in}}$

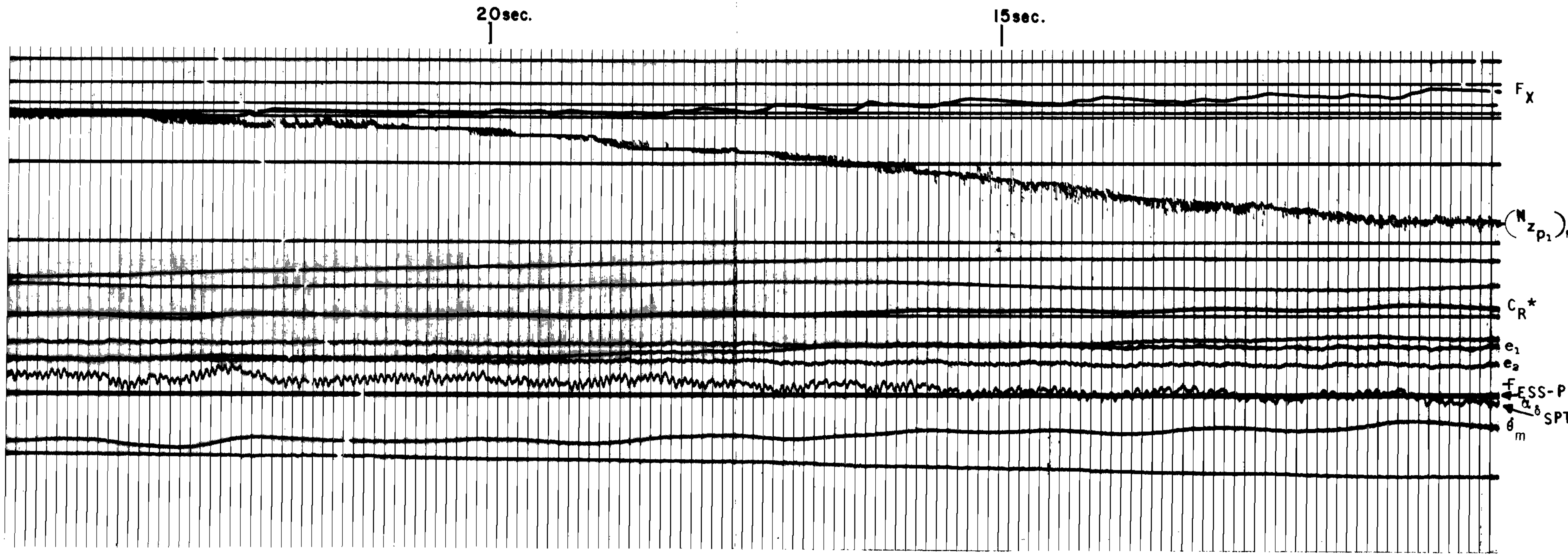


Figure 61: Flight Recording; Flight #7; F.C. 4; 20,000 Ft., Mach 0.55; $\dot{\theta}$ Mode, Mach Trim ON; +0.5 g TSG Step Command (Cont'd.)

F_X 1.56 g/in

$-(N_{z_{p_1}})_m$ 0.47 g/in

C_R* 3.15 g/in

e_1 4.25 g/in

e_2 4.25 g/in

δ_{SPT} 2.30 in/in

$-F_{ESS-P}$ 2.61 g/in

$\dot{\theta}_m$ 0.13 $\frac{rad/sec}{in}$

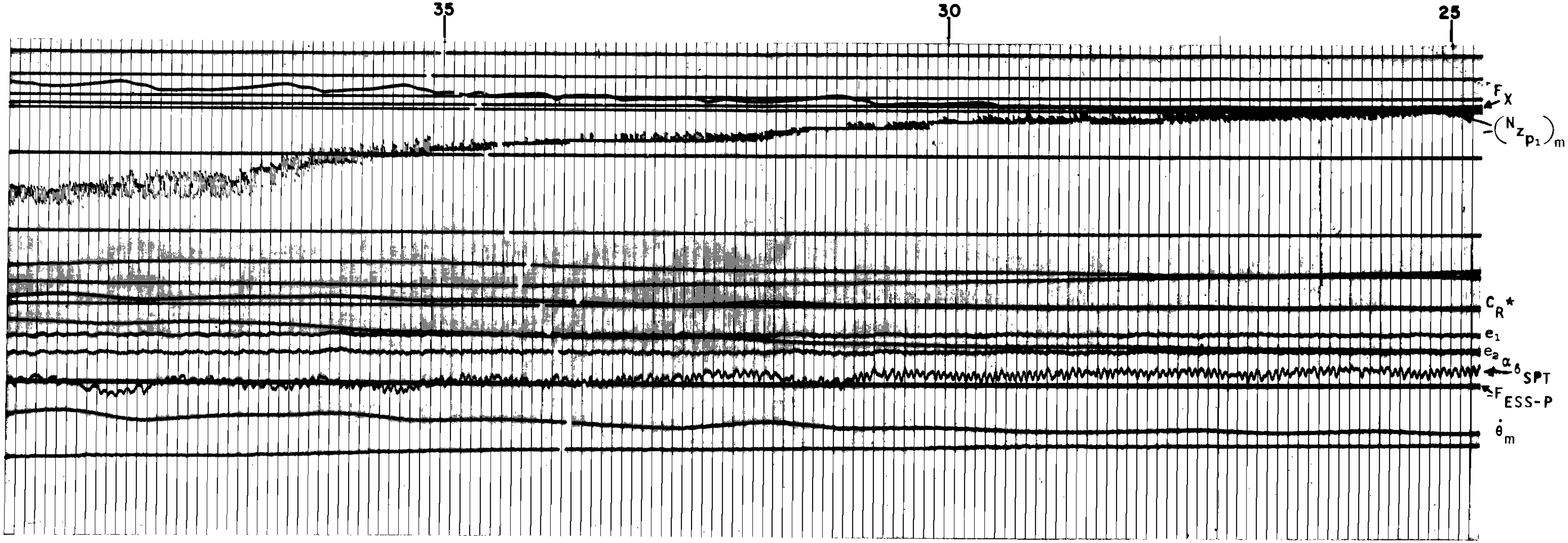


Figure 61: Flight Recording Flight #7; C.C. 4; 20,000 Ft., Mach 0.55; $\dot{\theta}$ Mode, Mach Trim ON; +0.5 g TSG Step Command (Cont'd.)

F_X 1.56 g/in

$-(N_{z_{p1}})_m$ 0.47 g/in

C_R^* 3.15 g/in

e_1 4.25 g/in

e_2 4.25 g/in

δ_{SPT} 2.30 in/in

$-F_{ESS-P}$ 2.61 g/in

$\dot{\theta}_m$ 0.13 $\frac{rad/sec}{in}$

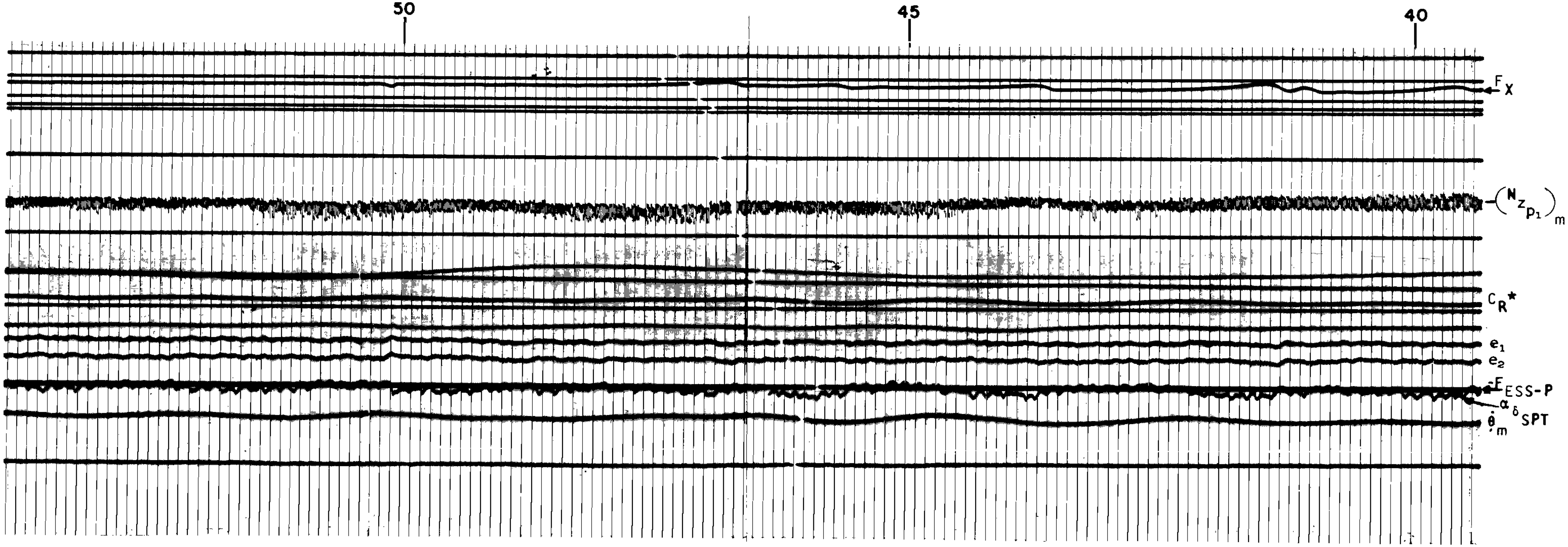


Figure 61 : Flight Recording; Flight #7 F.C. 4, 20,000 Ft., Mach 0.55, $\dot{\theta}$ Mode, Mach Trim ON; +0.5 g TSG Step Command (Cont'd.)

F_X 1.56 g/in

$-(N_{z_{p_1}})_m$ 0.47 g/in

C_R^* 3.15 g/in

e_1 4.25 g/in

e_2 4.25 g/in

δ_{SPT} 2.30 in/in

$-F_{ESS-P}$ 2.61 g/in

$\dot{\theta}_m$ 0.13 $\frac{rad/sec}{in}$

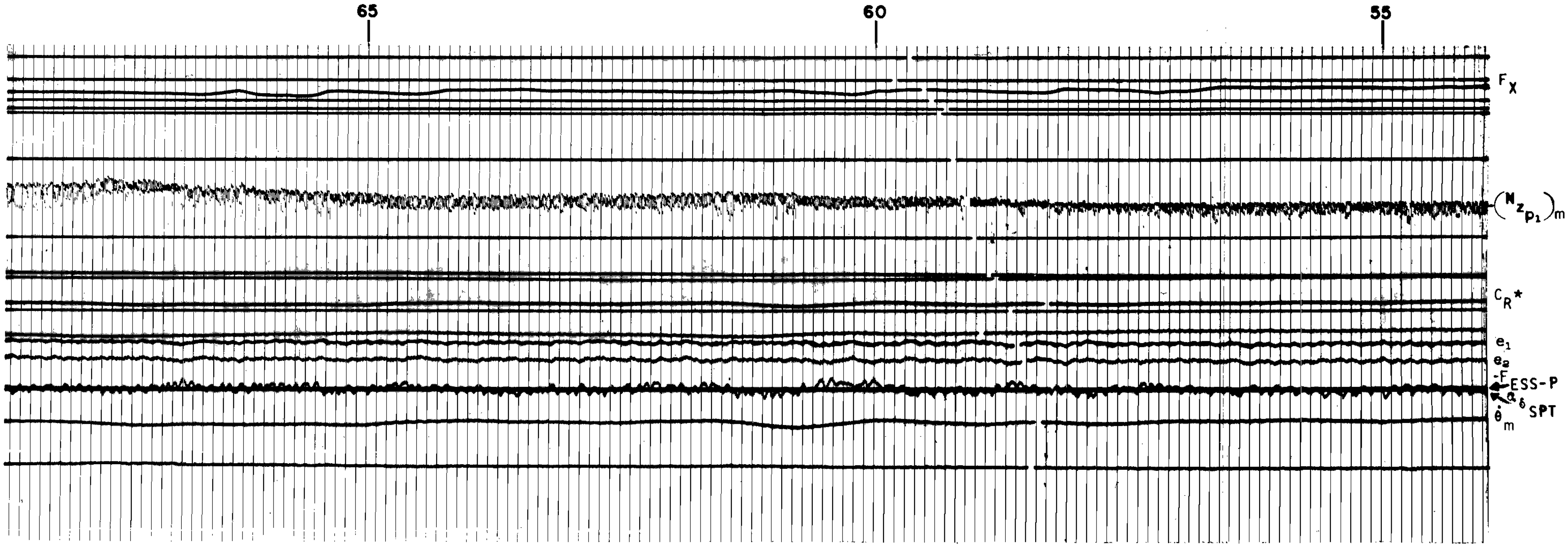


Figure 61: Flight Recording; Flight #7; F.C. 4; 20,000 Ft., Mach 0.55, $\dot{\theta}$ Mode, Mach Trim ON; +0.5 g TSG Step Command (Cont'd.)

F_X 1.56 g/in

$-(N_{z_{p_1}})_m$ 0.47 g/in

C_R^* 3.15 g/in

e_1 4.25 g/in

e_2 4.25 g/in

δ_{SPT} 2.30 in/in

$-F_{ESS-P}$ 2.61 g/in

$\dot{\theta}_m$ 0.13 $\frac{\text{rad/sec}}{\text{in}}$

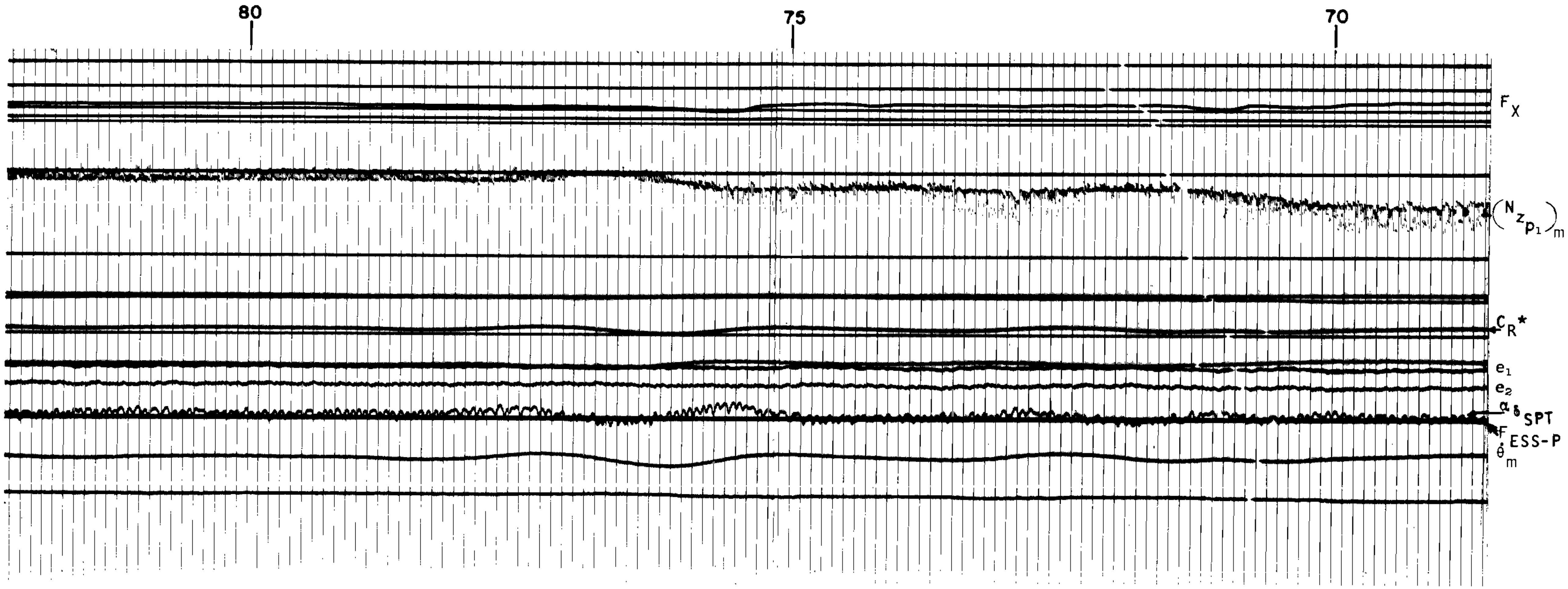


Figure 61: Flight Recording; Flight #7; F.C. 4; 20,000 Ft., Mach 0.55, $\dot{\theta}$ Mode, Mach Trim ON; +0.5 g TSG Step Command (Cont'd.)

F_X 1.56 g/in

$-\left(N_{z_{p_1}}\right)_m$ 0.47 g/in

$C_R{}^*$ 3.15 g/in

e_1 4.25 g/in

e_2 4.25 g/in

δ_{SPT} 2.30 in/in

$-F_{ESS-P}$ 2.61 g/in

$\dot\theta_m$ 0.13 $\frac{\text{rad/sec}}{\text{in}}$

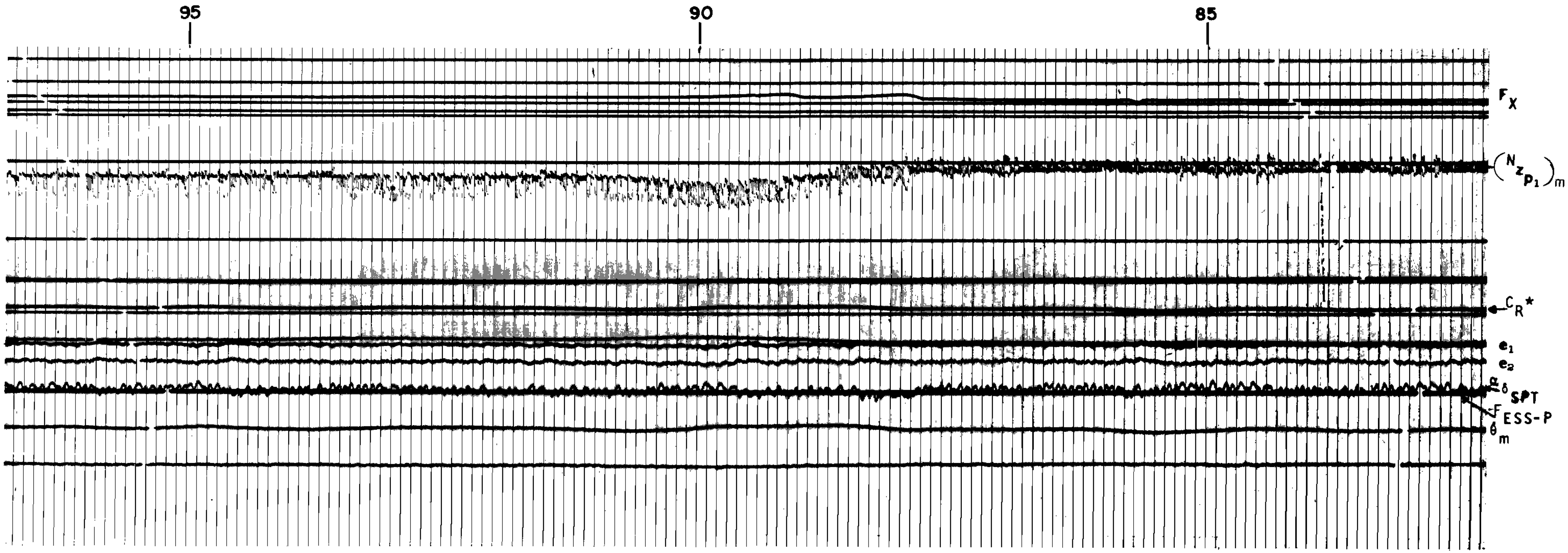


Figure 61: Flight Recording; Flight #7; F.C. 4; 20,000 Ft., Mach 0.55; $\dot\theta$ Mode, Mach Trim ON; +0.5 g TSG Step Command (Cont'd.)

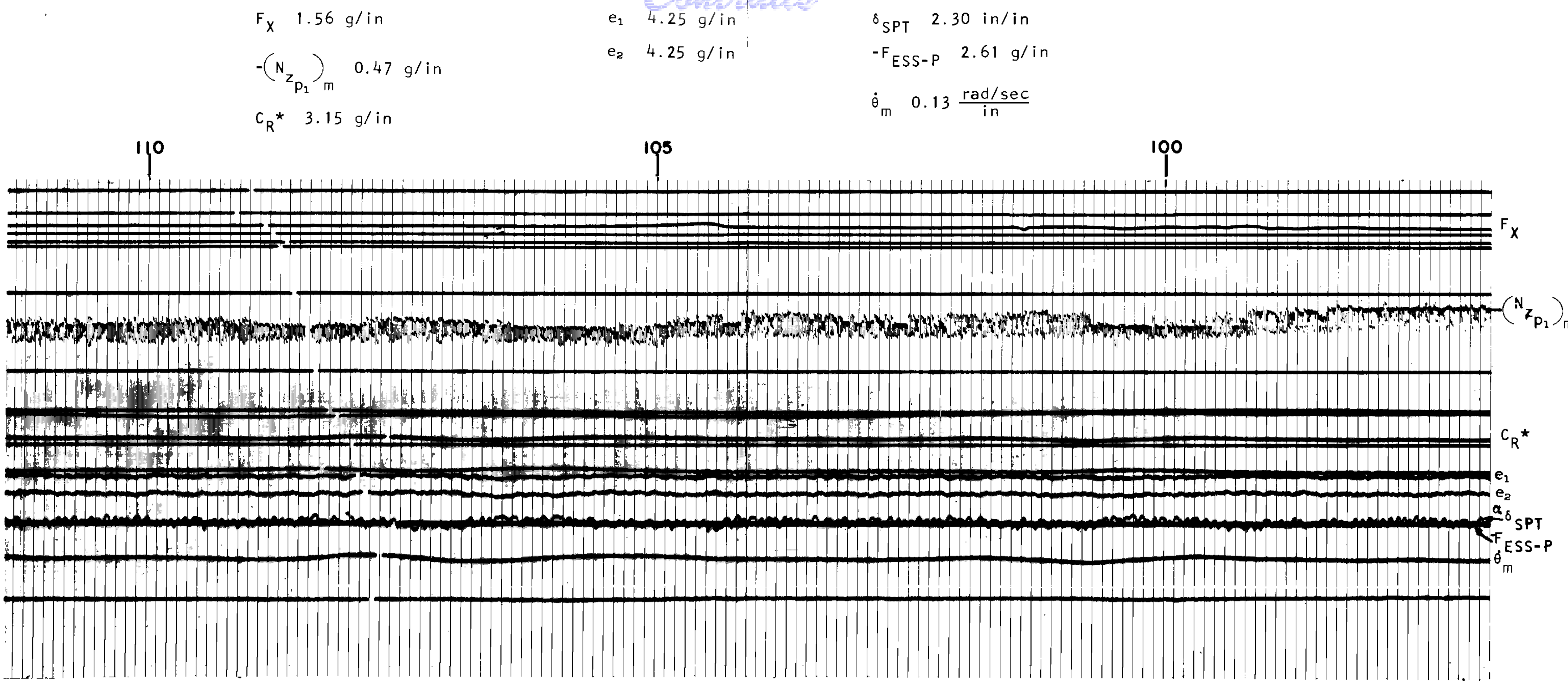


Figure 61: Flight Recording; Flight #7; F.C. 4; 20,000 Ft., Mach 0.55; $\dot{\theta}$ Mode, Mach Trim ON; +0.5 g TSG Step Command (Cont'd.)

F_X 1.56 g/in

$-(N_{z_{p_1}})_m$ 0.47 g/in

$C_R{}^*$ 3.15 g/in

e_1 4.25 g/in

e_2 4.25 g/in

δ_{SPT} 2.30 in/in

$-F_{ESS-P}$ 2.61 g/in

$\dot{\theta}_m$ 0.13 $\frac{\text{rad/sec}}{\text{in}}$

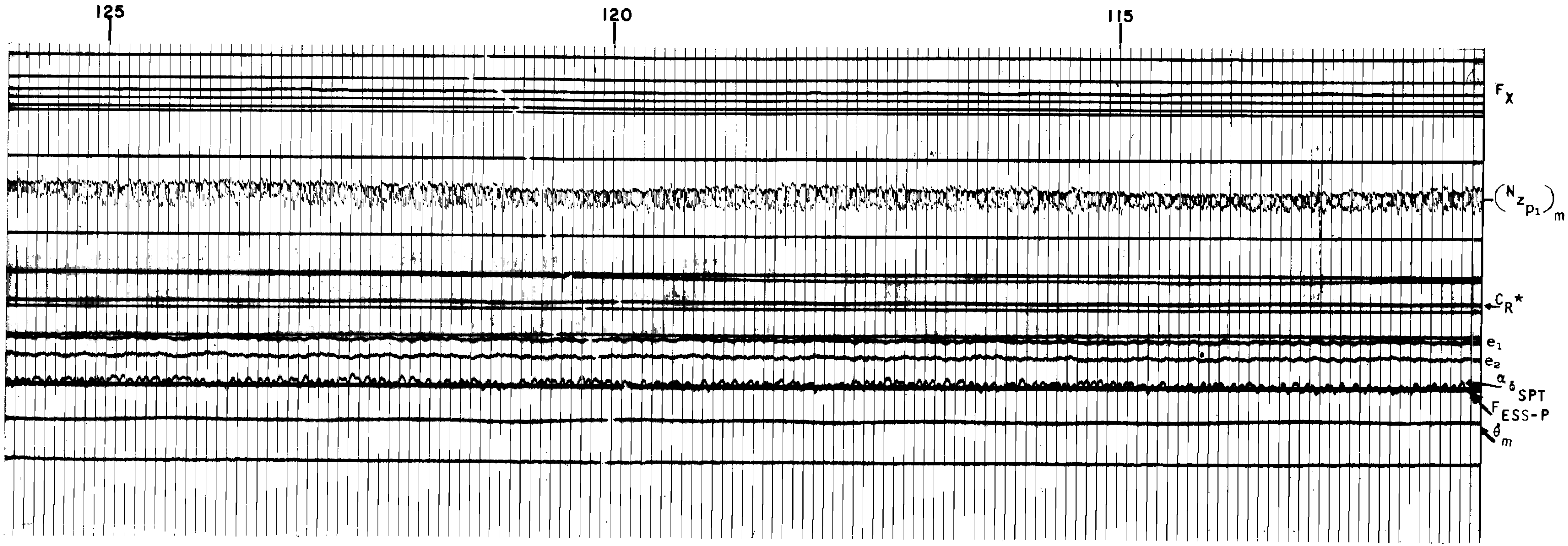


Figure 61 : Flight Recording; Flight #7; F.C. 4; 20,000 Ft., Mach 0.55; $\dot{\theta}$ Mode, Mach Trim ON; +0.5 g TSG Step Command (Concluded)

one another. The earlier δ_{SPT} limit-cycle oscillation was now gone, but in its place was an airframe short-period oscillation at about 1.2 Hz when the aircraft was not pulling incremental g's. Examination of the oscillograph traces, of which Figure 58 reproduces a sample, revealed a wide blur on the $\left(N_{z_{p_1}}\right)_m$ signal, and this blur was its widest for $\left(N_{z_{p_1}}\right)_m = 0$, i.e., whenever the short-period oscillation occurred.

The accelerometer output trace was found to contain a strong 80-Hz ripple component; when the mean output of the accelerometer went to zero, the amplitude of this ripple voltage rose to a level equivalent to ±0.1 g. Bench experiments with SOC circuits showed that this ripple voltage and frequency were sufficient to cause almost continuous saturation of the e_p stage in the SLU (because of its differentiating action). The need was thus evidenced for elimination of the ripple voltage carried on the accelerometer signal. A first-order low-pass filter (11.3 rad./sec. corner frequency) was therefore installed in the accelerometer output line for flights 7 et seq. For flights 12 et seq., the EFC gain was lowered twofold, further reducing signal levels into the e_p stage of the SLU. Although the use of accelerometer output smoothing introduced a pole in the N_{z_p} feedback path which tended to degrade overall performance of the SOC system in C* modes, removal of the ripple voltage completely solved the saturation problem and rid the system response of nearly all airframe oscillations in the short-period frequency range.

Although the accelerometer output smoothing was able to eliminate nearly all traces of ripple voltage from the sensor signal, it could not, of course, compensate for nonlinear response characteristics of the accelerometer. These nonlinearities are seen in Figures 49 and 50, but are especially evident in Figure 51, which reveals a tendency of the sensor to jump between discrete levels of output voltage rather than producing a smoothly varying output signal.

Figure 59 shows the improvement obtained with accelerometer output smoothing. (The accelerometer trace on the recorder is taken from a point ahead of the low-pass filter, and therefore does not show the effects of smoothing.) This recording was obtained at F.C. 6 (generally, the worst case in terms of short-period mode excitation, if any).

Figure 60 shows the short-term behavior of the SOC in C_2* mode at low M_δ with Mach Trim on. Lastly, Figure 61 (nine sheets), presents an entire Mach Trim transient in $\dot{\theta}$ mode at low M_δ and details behavior of the system as it seeks equilibrium at a new Mach number. The rather jerky changes in F_X are due to discrete changes in CADC readout of IMN. Note the evidence of nonlinearity in accelerometer response. The small δ_{SPT} chatter seen in these traces had a frequency of approximately 16 Hz. Mach Trim performance has been shown here for low M_δ cases because these best represent subsonic cruise conditions, the Mach Trim function being useful chiefly during cruise and IFR conditions to avoid airspeed divergence in the event the pilot is occupied with navigation or other tasks.

Table VI summarizes procedures followed by the pilots in their qualitative evaluations of the SOC system. Table VII presents the completed questionnaires of the two pilots who flew the aircraft with the self-organizing controller.

Table VI: Self-Organizing Controller Qualitative Evaluation

Task 1 - SIMULATED LANDING

a. 10,000 ft., C_2 mode, pitch lag .2, Mach Trim off, fly simulated overhead traffic approach, final approach, flare-out, and go-around

b. Repeat a. in $\dot{\theta}$ mode.

c. Repeat a. and b. with Mach Trim on and Mach Set at .5.

Task 2 - GUST RESPONSE

a. C_2 mode, pitch lag .2, Mach Trim off, fly through turbulent air at varying airspeeds. Note controllability, damping, etc.

b. Repeat a. in $\dot{\theta}$ mode.

c. Repeat a. and b. with Mach Trim on and Mach Set corresponding to speed flown.

d. Repeat a. with SOC off and AFCS engaged.

e. Repeat a. with SOC off and AFCS off.

Task 3 - AIR-TO-AIR COMBAT MANEUVERING

a. Beginning at 35,000 ft., supersonic speed, C_2 mode, pitch lag .2, Mach Trim off, execute a series of high "g" turns and rolls while rapidly varying airspeed and altitude.

b. Repeat a. with Mach Trim engaged.

c. Beginning at 35,000 ft., C_2 mode, pitch lag .2, Mach Trim off, track another aircraft through a series of simulated combat maneuvers.

d. Repeat c. with Mach Trim engaged.

e. While flying a relatively loose formation on another aircraft, evaluate C_2 and $\dot{\theta}$ modes with the Mach Trim off and SOC engaged.

(Continued)

Table VI: Self-Organizing Controller Qualitative Evaluation (Continued)

Task 4 - SIMULATED AIR-TO-GROUND ATTACKS

a. At ______ ft., C_a mode, pitch lag .2, Mach Trim off execute dive bombing passes.

b. Repeat a. with Mach Trim engaged.

c. Repeat a. without SOC or AFCS engaged.

d. At 3,000 ft., maximum safe speed, C_a mode, pitch lag .2, Mach Trim off, follow a power line or road for a sufficient time to permit SOC evaluation.

e. Repeat d. with Mach Trim engaged.

f. Repeat d. without SOC or AFCS engaged.

NOTE: FOR DIVE BOMBING PASSES ASSUME GROUND LEVEL IS 5,000 FT.

Task 5 - INSTRUMENT FLYING

a. At 20,000 ft., C_a mode, pitch lag .2, Mach Trim off, enter and fly holding pattern.

b. Make a TACAN penetration to a low approach.

c. Fly a GCA/ILS.

d. Repeat a. thru c. in $\dot{\theta}$ mode.

e. Repeat a. thru d. with Mach Trim on, Mach Set at .5.

NOTE: EXCEPT IN SMOOTH AIR THIS TASK SHOULD NOT BE PURSUED BELOW 1,000 FT.

Task 6 - LEVEL ACCELERATION-DECELERATION

a. Attain 35,000 ft., 0.75 Mach, using C_a mode, pitch lag .2, Mach Trim off.

b. While maintaining level flight, accelerate to maximum speed (approximately 1.35 Mach).

c. Decelerate to Mach 0.7.

Table VI: Self-Organizing Controller Qualitative Evaluation (Concluded)

Task 6 - LEVEL ACCELERATION-DECELERATION (Continued)

d. Repeat a. thru c. with Mach Trim on and Mach Set at 0.9.

e. Attain 20,000 ft., 230 knots IAS, using C_a mode, pitch lag .2, Mach Trim off.

f. While maintaining level flight accelerate to 0.95 Mach (1.20 Mach if at Wurtsmith R-4207).

g. Decelerate to 230 knots IAS.

h. Repeat f. and g. with Mach Trim on and Mach Set at .7.

i. Repeat f. and g. with SOC off and AFCS engaged.

Task 7 - MACH TRIM CLIMB

a. Attain 10,000 ft., 0.8 Mach, using C_a mode, and .2 pitch lag.

b. With Mach Set at 0.8, engage Mach Trim.

c. Increase to Military power and observe if SOC maintains 0.8 Mach during climb.

d. Vary power to control rate of climb.

e. Repeat a. thru d. in $\dot{\theta}$ mode.

Task 8 - MACH TRIM DESCENT

a. Attain 35,000 ft., 0.75 Mach, using C_a mode and .2 pitch lag.

b. Engage Mach Trim with Mach Set at .8.

c. Increase Mach Set to .9.

d. Vary power to control rate of descent.

e. Repeat a. thru d. in $\dot{\theta}$ mode.

Task 9 - FORMATION FLYING

(Concluded)

Table VII: PILOT OVERALL FLIGHT EVALUATION OF SELF-ORGANIZING CONTROLLER, MARK IV

1. Date:	2 October 1969	17 December 1969
2. Pilot's name:	(Pilot A)	(Pilot B)
3. Pilot's rank:	Major	Lt. Colonel
4. Total flight hours:	3500	8330
5. F-101 flight hours:	700	682
6. Previous experience with Electric Side Stick:	None in an aircraft; several types in spacecraft simulators.	Same controller in an F-101A at Minneapolis-Honeywell (M-H). Pencil type in an F-102A.
7. Flight hours using SOC:	About 20 hours.	Approximately 18 hours.
8. Preferred Pitch Sensitivity setting:	4	4
9. Preferred Roll Sensitivity setting:	3 or 4	4
10. Preferred Pitch Lag setting:	.2 (or .1, I cannot see a difference).	.1 or .2 -- cannot differentiate.
11. If you had to select one mode of control for all tasks, which would you select? C1, C2, C3, $\dot{\theta}$	C2 C1 or C3 are equally desirable, as I cannot see a difference in C* modes.	Cannot differentiate between C1, C2, C3. No $\dot{\theta}$.
12. Would you desire the ability to select between C* mode and $\dot{\theta}$ mode? Comment.	Yes This is not a strong desire, however. I see little need for the $\dot{\theta}$ mode. (See Item 13.)	No I feel there is little need for the $\dot{\theta}$ mode. Mach Trim is a little better in this mode (better aircraft response).

(Continued)

PILOT OVERALL FLIGHT EVALUATION OF SELF-ORGANIZING CONTROLLER, MARK IV, Continued:

	(Pilot A)	(Pilot B)
13. For which tasks do you prefer:		
C^* mode?	All tasks involving high "g" forces. All tasks involving maneuvering flights.	Tasks involving maneuvering flight using higher scale "g" forces.
$\dot{\theta}$ mode?	The only time I prefer $\dot{\theta}$ mode is for straight and level flight (as in Cross-country navigation) with Mach Trim engaged. The aircraft response to Mach Trim is freer and quicker in $\dot{\theta}$ mode.	Do not like $\dot{\theta}$ mode; however, Mach Trim is more responsive in $\dot{\theta}$.
Comment:	$\dot{\theta}$ mode generally is uncomfortable because of a tendency to over-control (i.e., a Pitch input commands a more rapid "g" build-up than is expected, especially noticeable at high "q").	$\dot{\theta}$ mode in maneuvering flight -- there is a tendency to over-control the aircraft. Under some higher "q" applications it is difficult to keep from over-controlling.
14. For which tasks do you prefer to have the Mach Trim engaged?	Straight and level cross country flying. Precision instrument flying.	None. I found the Mach Trim to be sluggish and to exhibit too much lag. There was really no useful application in this aircraft.
Disengaged?	Any maneuvering flight involving large speed changes, such as air-to-ground attacks, air-to-air combat maneuvers, simulated landing patterns, etc.	All maneuvering flight and actually all the time.
Comment:	The Mach Trim does not add very much to ease of flight control. The more I fly with the Mach Trim off (neutral speed stability), the better I like it.	I prefer Mach Trim OFF.

(Continued)

PILOT OVERALL FLIGHT EVALUATION OF SELF-ORGANIZING CONTROLLER, MARK IV, Continued:

	(Pilot A)	(Pilot B)
15. Preferred Mach Gain setting:	25	25
16. Do you feel you would like higher Mach Gain than present maximum?	No	No
17. Is the airplane difficult to trim (Pitch Trim only)?	No	No
Comment:	Not over small speed changes with Mach Trim on; large speed changes require resetting the Mach Set knob. With Mach Trim off, Pitch Trim is no problem.	Aircraft is easy to Pitch Trim with Mach Trim OFF. Difficult to trim with Mach Trim ON; larger speed changes -- harder to trim.
18. Is Pitch Trim a problem during rapid accelerations, decelerations, high "g" turns, etc.?	No	No
Comment:	Not a problem, but a minor nuisance with Mach Trim on. With Mach Trim off, very little Pitch Trim is required.	No problem with Mach Trim off.
19. Is attitude control satisfactory?	Yes	Yes
Comment:	It is exceptionally good. It is a pleasure to put the aircraft smoothly in a desired attitude and have it stay.	Attitude control is smooth and holds attitude well. As good as any I have ever seen.
20. Are there any difficulties in flight path control during climbing and descending turns?	No	No
Comment:	No difficulties due to SOC. The hand control causes some difficulty when making nose-down Pitch inputs. The motion required is unnatural and jerky.	Side Stick is poor in Pitch. Pivot point is poorly placed -- really nothing new concerning this particular Side Stick.

(Continued)

PILOT OVERALL FLIGHT EVALUATION OF SELF-ORGANIZING CONTROLLER, MARK IV, Continued:

	(Pilot A)	(Pilot B)
21. Are there any problems associated with the tracking task? Comment:	No No problem with SOC. Same problem with hand control as stated in Item 20. Best method to acquire target is to place pipper below target and slowly move up to target with a nose-up input.	No Other than Side Stick.
22. Comment on the following specific items:		
a. Airplane response to pilot inputs:	C* very nice; rapid, well-damped, well-managed. $\dot{\theta}$ rapid and smooth, but "g" onset is too rapid.	$\dot{\theta}$ "g" build-up is too rapid - - it is hard to apply smooth inputs. C* is smooth, easily regulated, and appears well damped.
b. Control in presence of random disturbances:	Very good. Aircraft stability and control in turbulence is slightly better with SOC than basic flight control.	Response in turbulence (stability and control) is improved in the F-101 with SOC on.
c. Precision of control:	C* is very good; I could track an airborne target with greater precision and smoothness than with center stick.	In all C modes, control is better than with center stick, excluding Side Stick itself.
d. Demands on pilot:	No greater than normal flight controls. In fact, the Side Stick makes for more relaxing flying than the center stick.	SOC reduces demand on pilot; however, the M-H Side Stick is very tiring to the wrist and arm in maneuvering flight.

(Continued)

PILOT OVERALL FLIGHT EVALUATION OF SELF-ORGANIZING CONTROLLER, MARK IV, Continued:

(Item 22 continued)	(Pilot A)	(Pilot B)
e. Instrument flying, including instrument approach:	I liked it very much. It was as easy to fly as the normal system and was better in the following ways: (1) smoothed out turbulence better than basic system; (2) held aircraft steadier during configuration changes, especially speed-break actuations, than could be done with center stick.	Excellent for instrument flight. All prior comments apply.
f. Formation flying:	No problem with SOC. Some problem with Side Stick when making nose-down Pitch inputs.	Same as e., above.
g. Aircraft response in the landing configuration:	It handled well; however, it is severely limited by the command signal limiter (CSL). It was unable to hold a level attitude below 175-180 knots, depending on fuel load.	CSL limited; however, did make several low approaches - 190 KIAS or above. Lower speeds were impossible due to lack of authority with CSL.
h. PIO tendency:	No problem at all in C* modes. Minor tendency in $\dot{\theta}$ mode at high "q".	None.
i. Special piloting techniques:	Side Stick requires some "getting used to".	Side Stick is poor in Pitch.
j. Reliability:	Not a single failure in 21 flights.	No failures.
23. What are the good features of the SOC?	1. Rapid and well-managed response (not necessarily better than basic flight control system but as good).	1. Excellent damping. 2. Good controllability in C* modes.

(Continued)

PILOT OVERALL FLIGHT EVALUATION OF SELF-ORGANIZING CONTROLLER, MARK IV, Continued:

(Item 23 continued)	(Pilot A)	(Pilot B)
	2. Allows smoother tracking of an airborne target than with center stick. 3. Provides excellent damping in turbulent air. 4. Provides inflight selection of modes and gain settings.	3. Good Response - rapid and easily regulated.
24. What are the objectionable features of the SOC?	1. C* mode, Mach Trim off: no objections. 2. Mach Trim on: must keep changing Mach settings. 3. $\dot{\theta}$ mode: objectionable control response at high "q" (see previous comments). See Item 27.	1. $\dot{\theta}$ - Difficult to obtain smooth control - higher "g"s. 2. Mach Trim too sluggish - hard to hold trim.
25. Using the attached Pilot Rating Scale, assign a rating based on your entire experience with the SOC.	A2	A2
26. What is the primary reason for this rating?	I think basic C* Mach Trim off could be rated even A-1. Considering all aspects of the SOC in the flight regimes I evaluated, I would rate it a little less than optimum. (See Item 24.)	It is difficult to define other than A-2 with the Side Stick controller installed in #462. The undesirable feature of having to lift and push down the stick for respective inputs did, in reality, mask some of the good features of the SOC. I feel the overall rating of the SOC is equal to and better in damping and attitude hold than the basic airplane. The SOC should be evaluated with a force stick or an optimized Side Stick.

(Continued)

PILOT OVERALL FLIGHT EVALUATION OF SELF-ORGANIZING CONTROLLER, MARK IV, Concluded:

	(Pilot A)	(Pilot B)
27. Additional Comments:	A couple of limitations prevented as thorough an evaluation as I would have liked: (1) the hand control (ESS) was considerably less than optimum. Pitch input motions were more of a lifting motion for nose-up, and a pushing-down motion for nose-down. This caused considerable problem in making precise nose-down inputs. (2) the SOC, working through the MB-5 autopilot, was restricted by the Command Signal Limiter. This severely limited pitch authority at low "q" flight conditions. I would very much like to evaluate the system on a maneuverable airplane with a decent Side Stick. I think it would be very good.	(None)

CONTROLLABLE CAPABLE OF BEING CONTROLLED OR MANAGED IN CONTEXT OF MISSION, WITH AVAILABLE PILOT ATTENTION	**ACCEPTABLE** MAY HAVE DEFICIENCIES WHICH WARRANT IMPROVEMENT, BUT ADEQUATE FOR MISSION. PILOT COMPENSATION, IF REQUIRED TO ACHIEVE ACCEPTABLE PERFORMANCE, IS FEASIBLE.	**SATISFACTORY** MEETS ALL REQUIREMENTS AND EXPECTATIONS, GOOD ENOUGH WITHOUT IMPROVEMENT. CLEARLY ADEQUATE FOR MISSION.	EXCELLENT, HIGHLY DESIRABLE	A1
			GOOD, PLEASANT, WELL BEHAVED	A2
			FAIR. SOME MILDLY UNPLEASANT CHARACTERISTICS. GOOD ENOUGH FOR MISSION WITHOUT IMPROVEMENT.	A3
		UNSATISFACTORY RELUCTANTLY ACCEPTABLE. DEFICIENCIES WHICH WARRANT IMPROVEMENT. PERFORMANCE ADEQUATE FOR MISSION WITH FEASIBLE PILOT COMPENSATION.	SOME MINOR BUT ANNOYING DEFICIENCIES. IMPROVEMENT IS REQUESTED. EFFECT ON PERFORMANCE IS EASILY COMPENSATED FOR BY PILOT.	A4
			MODERATELY OBJECTIONABLE DEFICIENCIES. IMPROVEMENT IS NEEDED. REASONABLE PERFORMANCE REQUIRES CONSIDERABLE PILOT COMPENSATION.	A5
			VERY OBJECTIONABLE DEFICIENCIES. MAJOR IMPROVEMENTS ARE NEEDED. REQUIRES BEST AVAILABLE PILOT COMPENSATION TO ACHIEVE ACCEPTABLE PERFORMANCE.	A6
	UNACCEPTABLE DEFICIENCIES WHICH REQUIRE MANDATORY IMPROVEMENT. INADEQUATE PERFORMANCE FOR MISSION EVEN WITH MAXIMUM FEASIBLE PILOT COMPENSATION.		MAJOR DEFICIENCIES WHICH REQUIRE MANDATORY IMPROVEMENT FOR ACCEPTANCE. CONTROLLABLE. PERFORMANCE INADEQUATE FOR MISSION, OR PILOT COMPENSATION REQUIRED FOR MINIMUM ACCEPTABLE PERFORMANCE IN MISSION IS TOO HIGH.	U7
			CONTROLLABLE WITH DIFFICULTY. REQUIRES SUBSTANTIAL PILOT SKILL AND ATTENTION TO RETAIN CONTROL AND CONTINUE MISSION.	U8
			MARGINALLY CONTROLLABLE IN MISSION. REQUIRES MAXIMUM AVAILABLE PILOT SKILL AND ATTENTION TO RETAIN CONTROL.	U9
UNCONTROLLABLE CONTROL WILL BE LOST DURING SOME PORTION OF MISSION.			UNCONTROLLABLE IN MISSION.	10

COOPER-HARPER PILOT RATING SCALE

4. CONCLUSIONS AND RECOMMENDATIONS

An elementary self-organizing controller (SOC) for the pitch axis of the F-101B aircraft has been successfully demonstrated in piloted flight tests. The SOC provided good to excellent[†] transient and steady-state performance in the C* feedback mode over the 5.2:1 range in stabilator effectiveness values (and comparable variations in other aerodynamic parameters) encountered within the operational envelope of the test aircraft. A simple modulated-noise control generation technique was employed to obtain effective high-authority control at all flight conditions. No malfunctions of the SOC occurred during the 32 flights conducted with this equipment.

The tests indicated two areas in which design improvements of the SOC should be sought:

(1) In $\dot{\theta}$ mode under flight conditions of low stabilator aerodynamic effectiveness, steady-state response errors were excessive. Means should be incorporated in future SOC systems to reduce steady-state errors, without a significant increase in controller maximum authority levels used during transients.

(2) In both modes (C* and $\dot{\theta}$), the stabilator parallel servo was subjected to high-frequency chatter (a δ_{SPT} oscillation of approximately ±0.05 in. at 16 Hz). Although this chatter produced no vibration of the aircraft noticeable to the pilot, it presumably led

[†]The two pilots who performed the system evaluations rated overall SOC performance "A2" on the Cooper-Harper Pilot Rating Scale. (See Table VII.) Pilot A commented that the SOC in C* control with Mach Trim off "could be rated even A1." Certain features of the M-H electric side stick, furnished by USAF, were reflected in lowering of the overall SOC performance rating. (Reference 34)

to some accelerated wear on the hydraulic seals. In an integrated hydraulic actuator package (as might be used in fly-by-wire systems) this chatter could also contribute to unwanted temperature rise of the actuator. Means should be provided for eliminating steady-state actuator oscillations in future SOC systems.

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15. ________________, Self-Organizing Control of Advanced Turbine Engines, Adaptronics, Inc. Final Technical Report under Contract F33615-68-C-1606, AFAPL-TR-69-73, Air Force Aero Propulsion Laboratory, August 1969, AD #857616.

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30. Bird Engineering-Research Associates, Inc., First Interim Reliability Prediction for Self-Organizing Flight Controller, prepared under subcontract 621-1 to prime contract AF 33(615)-5141, 27 March 1967.

31. Gouge, J. R., Jr., "Reliability Prediction for Networks of Probability State Variable Devices", in Cybernetic Problems in Bionics, H. L. Oestreicher and D. R. Moore, Eds., Gordon and Breach, London, 1968, pp. 655-672.

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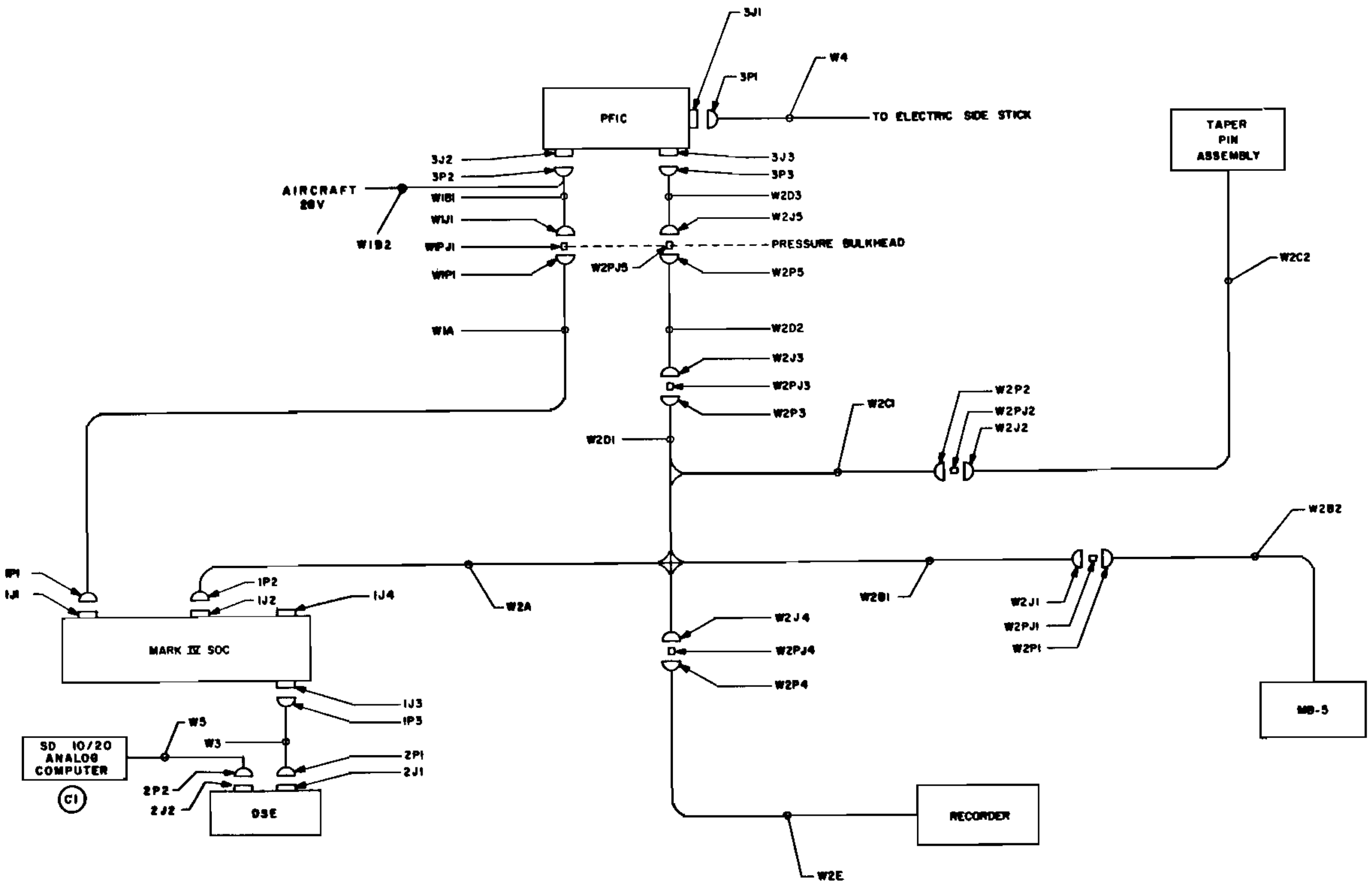
APPENDIX I

DIAGRAMS REFERRED TO IN TEXT

This Appendix includes the following:

REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	APPROVED
	A	GENERAL REVISION	12 APR 67	R. L. Barron
C-1	B	3116F-14-5P CHANGED TO 3116F-14-5S 3112E-14-5S CHANGED TO 3112E-14-5P	11 MAY '67	R. L. Barron
	C	(1) ADDED SD 10/20 ANALOG COMPUTER, W3, 2P2, AND 2J2 (2) ADDED W5 (3) ADDED NO. 22cu - 5 AMPS (4) ADDED 2P2, 2J2	22 JUNE 1967	R. L. Barron



NOTES:

1. CURRENT CARRYING CAPACITY OF WIRE AND CABLE TO BE IN ACCORDANCE WITH THE REQUIREMENTS OF MIL-W-5088, AS SHOWN BELOW:
   - NO. 16cu — 13 AMPS.
   - NO. 20cu — 7.5 AMPS.
   - (C3) NO. 22cu — 5 AMPS

CABLE ASSEMBLY SCHEDULE

CABLE DESIGNATION	NUMBER AND SIZE OF CONDUCTORS	
(C2) W5	10-NO 22 SHIELDED	TO SD 10/20 ANALOG COMPUTER
W1B2	2-NO16	
W2E	2 - NO 16 4 - NO 22 SHIELDED 26 - NO 20	TO RECORDER
W4	1 - NO. 16 5 - NO 22 SHIELDED 8 - NO 20	TO ELECTRIC SIDE STICK
W3	55 - NO. 20	TO GSE
W2D3	2 - NO. 16	TO PFIC
W2D2	5 - NO 22 SHIELDED	
W2D1	18 - NO 20	
W2C2	19 - NO. 20	TO TAPER PIN ASSEMBLY
W2C1	19 - NO. 20	
W2B2	10 - NO 20	TO MB-5
W2B1	10 - NO 20	
W2A	9-NO 22 SHIELDED 34-NO. 20	TO SOC
W1B	3 - NO 16	
W1A	5 - NO 16	

BENDIX SCINTILLA CONNECTOR SCHEDULE

CONN DES	MS NUMBER
(C4) 2P2	3116F-20-39P
2J2	3112E-20-39S
3J2	3112E-14-5P
3J3	3112E-20-39S
3P3	3116F-20-39P
3P2	3116F-14-5S
3P1	3116F-16-26P
3J1	3112E-16-26S
W2PJ5	3119 -20-39
W2PJ4	-20-39
W2PJ3	-20-39
W2PJ2	-14-19
W2PJ1	-12-10
W1PJ1	3119 -14-5
W2P5	3116F-20-39P
W2P4	-20-39P
W2P3	-20-39P
W2P2	-14-19P
W2P1	-12-10P
W2J5	-20-39S
W2J4	-20-39S
W2J3	-20-39S
W2J2	-14-19S
W2J1	-12-10S
W1J1	-14-5S
W1P1	-14-5P
2P1	3115F-22-55P
2J1	3112E-22-55S
1P3	3115F-22-55P
1P2	3115F-20-41P
1P1	3116F-14-5S
1J3, 1J4	3112E-22-55S
1J2	3112E-20-41S
1J1	3112E-14-5P

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ON FRACTIONS ± DECIMALS ± ANGLES ±

MATERIAL:

CONTRACT NO. AF 33(615)-5141

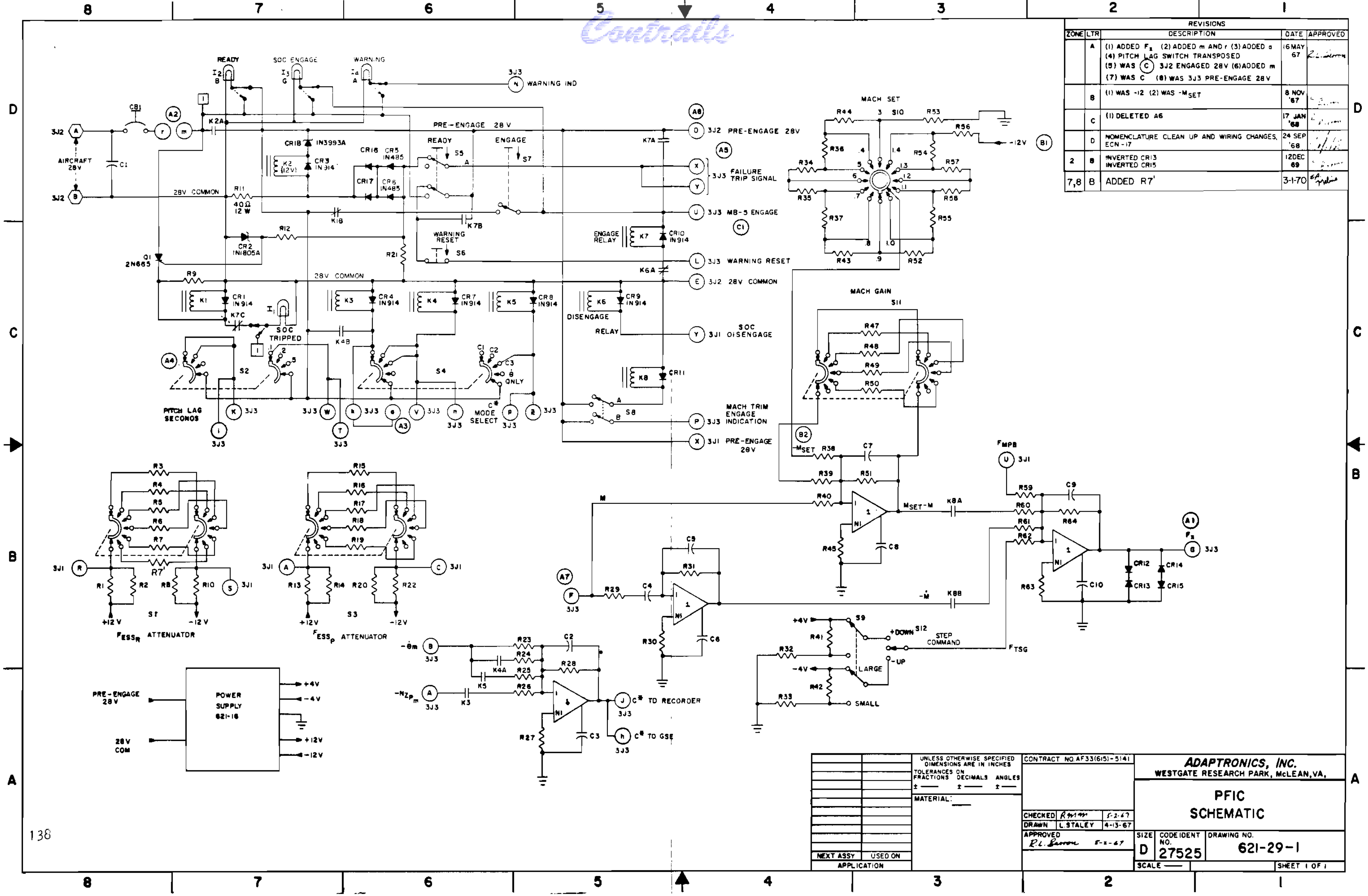
CHECKED	G.C.V.	6/21/67
DRAWN	R.P.L.	2/27/67
APPROVED	R L Barron	APR 14 1967

ADAPTRONICS, INC.
WESTGATE RESEARCH PARK, McLEAN, VA.

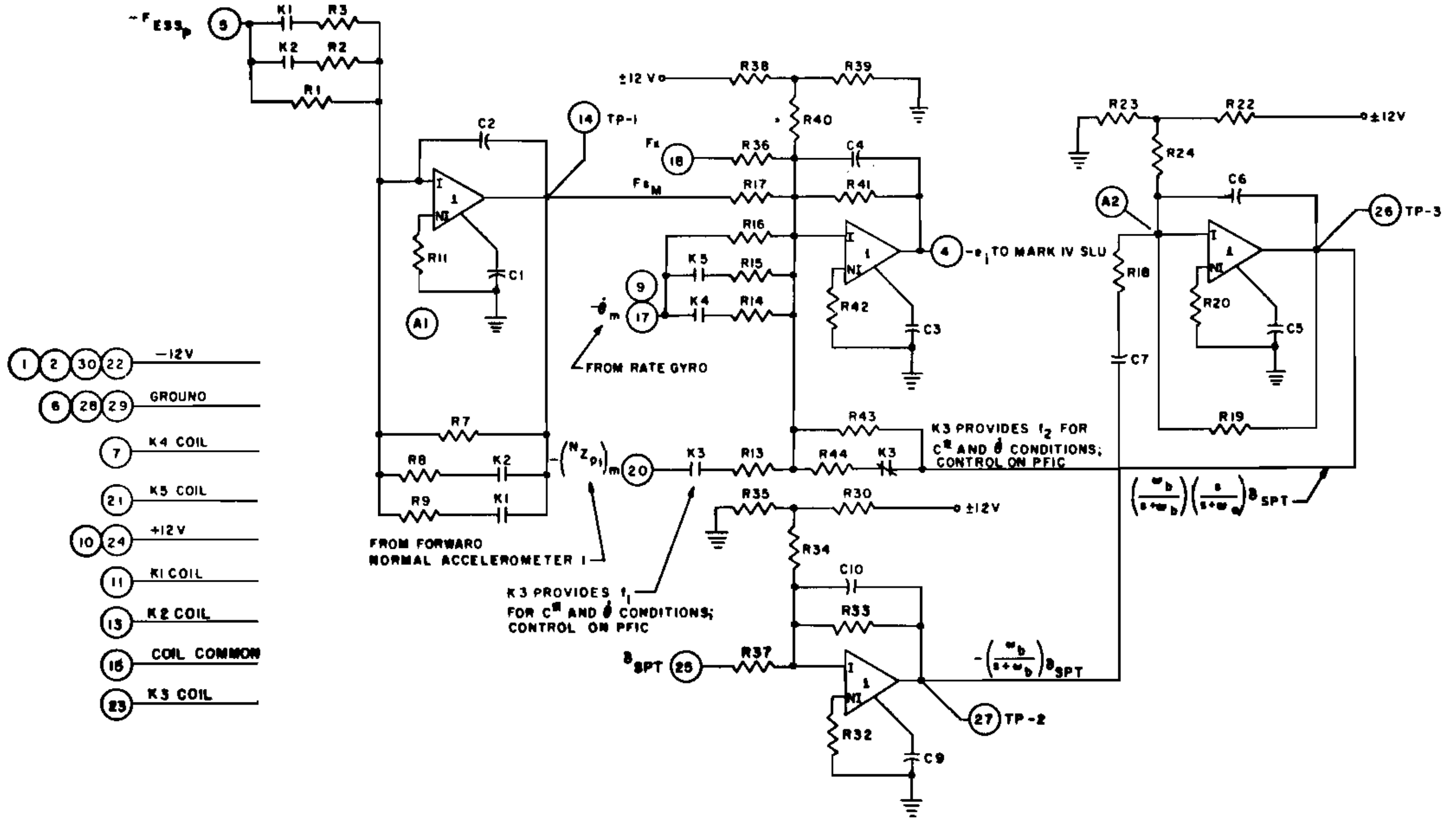
WIRING DIAGRAM, SINGLE LINE INTERCONNECTION SIMPLIFIED SYSTEM

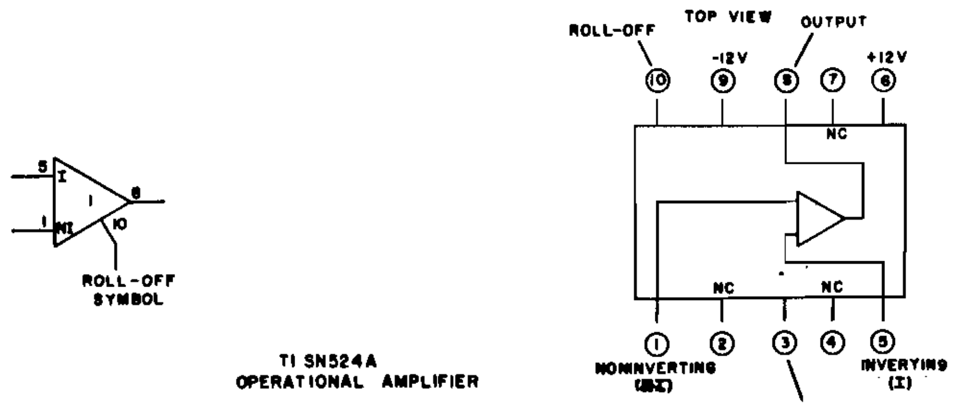
137

SIZE D | CODE IDENT NO. 27525 | DRAWING NO. 621-7
SCALE NONE | SHEET 1 OF 1


REVISIONS
ZONE | LTR | DESCRIPTION | DATE | APPROVED
A | (1) ADDED F_2 (2) ADDED m AND r (3) ADDED a (4) PITCH LAG SWITCH TRANSPOSED (5) WAS (C) 3J2 ENGAGED 28V (6) ADDED m (7) WAS C (8) WAS 3J3 PRE-ENGAGE 28V | 16 MAY 67
B | (1) WAS -12 (2) WAS -M_SET | 8 NOV '67
C | (1) DELETED A6 | 17 JAN '68
D | NOMENCLATURE CLEAN UP AND WIRING CHANGES, ECN-17 | 24 SEP '68
2 | B | INVERTED CR13 INVERTED CR15 | 12 DEC 69
7,8 | B | ADDED R7' | 3-1-70
READY
SOC ENGAGE
WARNING
WARNING IND
AIRCRAFT 28V
PRE-ENGAGE 28V
28V COMMON
FAILURE TRIP SIGNAL
MB-5 ENGAGE
ENGAGE RELAY
WARNING RESET
SOC TRIPPED
DISENGAGE RELAY
SOC DISENGAGE
MACH TRIM ENGAGE INDICATION
MACH SET
MACH GAIN
PITCH LAG SECONDS
MODE SELECT
θ ONLY
STEP COMMAND
LARGE
SMALL
ATTENUATOR
POWER SUPPLY 621-16
C* TO RECORDER
C* TO GSE
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ON FRACTIONS DECIMALS ANGLES
MATERIAL:
NEXT ASSY | USED ON
APPLICATION
CONTRACT NO. AF33(615)-5141
CHECKED 5-2-67
DRAWN L. STALEY 4-13-67
APPROVED R.L. Sarron 5-2-67
ADAPTRONICS, INC.
WESTGATE RESEARCH PARK, McLEAN, VA.
PFIC SCHEMATIC
SIZE D
CODE IDENT NO. 27525
DRAWING NO. 621-29-1
SCALE
SHEET 1 OF 1

ZONE	LTR	DESCRIPTION	DATE	APPROVED
	A	(1) WAS R10, R12, ±12V (2) ADDED CONNECTION	22 JUNE 1967	R.L. Barron





TI SN524A OPERATIONAL AMPLIFIER

TYPICAL FLAT PACK CONNECTIONS

NOTES

1. FOR COMPONENT IDENTIFICATION SEE PARTS LIST, PL 621-2.
2. ○ DENOTES CONNECTOR PIN NUMBER.
3. ABBREVIATIONS:
   - I = AMPLIFIER INVERTING INPUT.
   - NI = AMPLIFIER NONINVERTING INPUT.
   - TP = TEST POINT.
   - 1 = TI SN524A OPERATIONAL AMPLIFIER.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES. TOLERANCES ON FRACTIONS, DECIMALS, ANGLES

MATERIAL:

NEXT ASSY | USED ON — APPLICATION

CONTRACT NO. AF 33(615)-5141

CHECKED — DRAWN M D BLASC 4/5/67 — APPROVED R.L. Barron

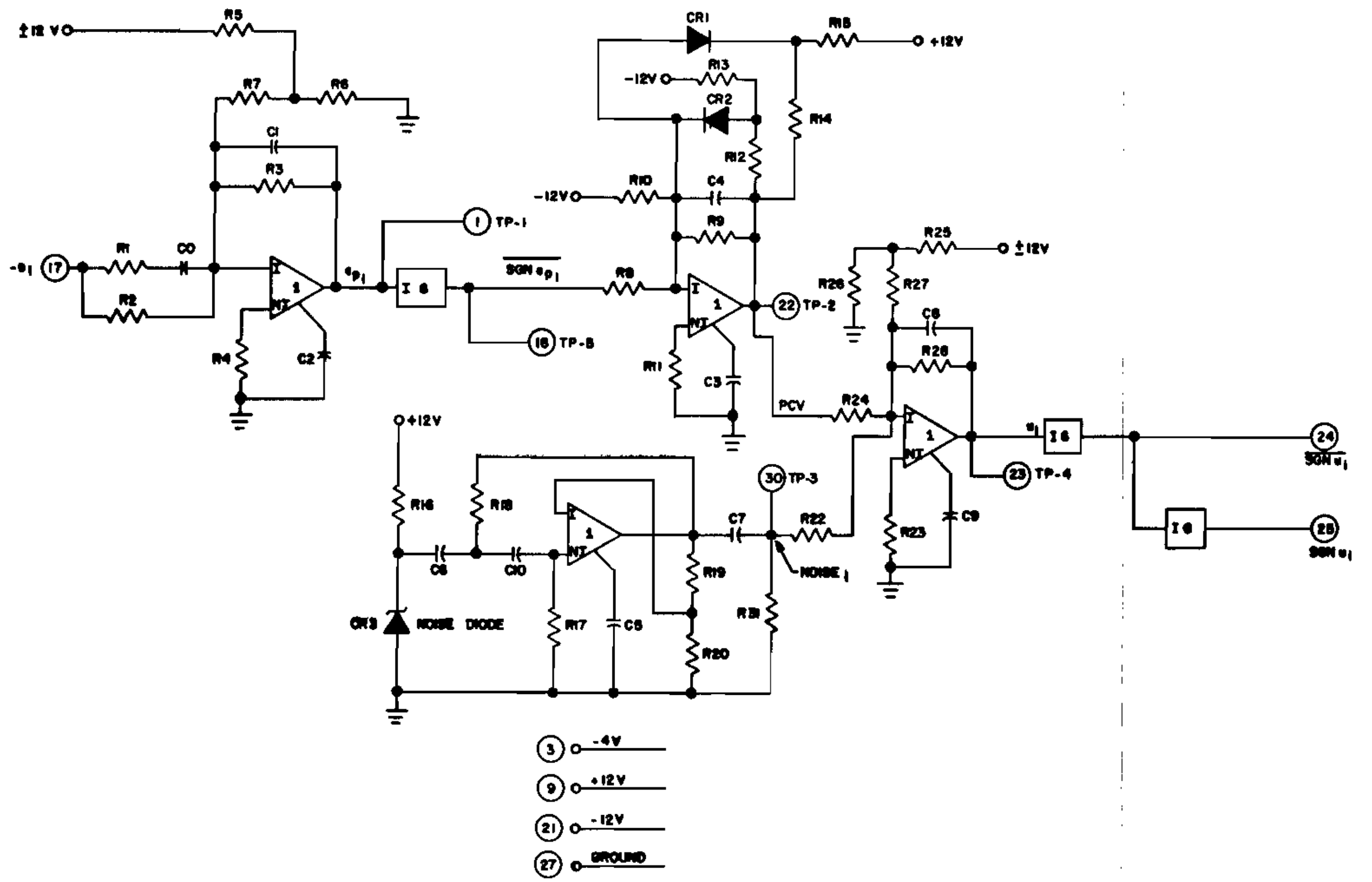
ADAPTRONICS, INC.
WESTGATE RESEARCH PARK, McLEAN, VA.

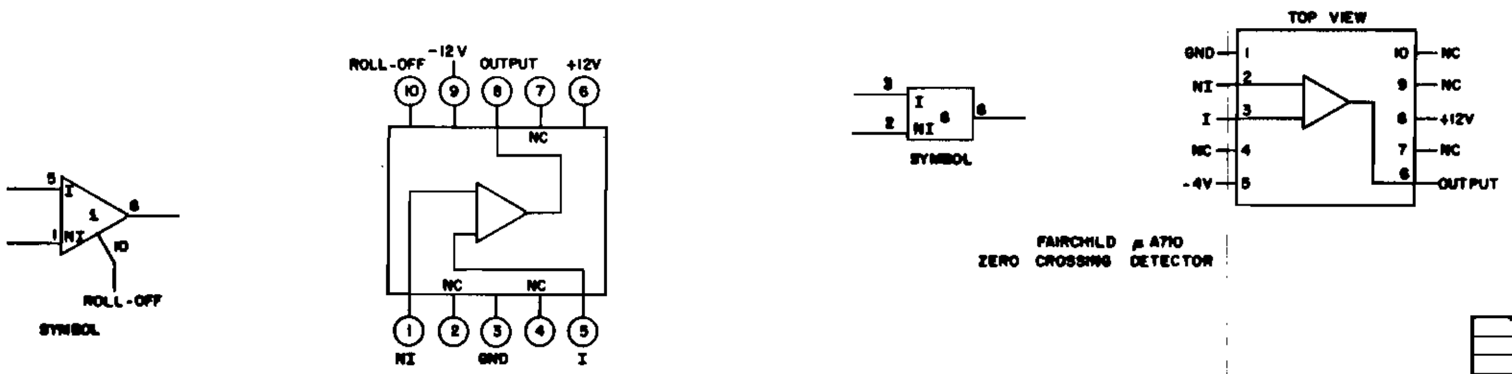
ERROR FUNCTION COUPLER MARK IV SOC

139

SIZE D — CODE IDENT NO. 27525 — DRAWING NO. 621-2

SCALE NONE — SHEET 1 OF 1





TI SN524A OPERATIONAL AMPLIFIER

TYPICAL FLAT PACK CONNECTIONS

FAIRCHILD μ A710 ZERO CROSSING DETECTOR

NOTES:

1. FOR COMPONENT IDENTIFICATION SEE PARTS LIST, PL 6D-1.
2. ◯ DENOTES CONNECTOR PIN NUMBER.
3. ABBREVIATIONS:
   - TP = TEST POINT.
   - I = AMPLIFIER INVERTING INPUT.
   - NI = AMPLIFIER NONINVERTING INPUT.
   - PCV = PROBABILITY CONTROL VOLTAGE.
   - 1 = TI SN524A OPERATIONAL AMPLIFIER.
   - CR3 = SOLITRON NOISE DIODE, SDI-W12
   - 6 = FAIRCHILD μA710 ZERO-CROSSING DETECTOR.
   - SGN = BINARY SIGNAL: -0.5V (TYP) LOGICAL ZERO, +3.0V (TYP) LOGICAL ONE (NAND LOGIC).

REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	APPROVED

NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ON FRACTIONS ± DECIMALS ± ANGLES ±
MATERIAL:

CONTRACT NO. AF 33(615)-5141
CHECKED WLS
DRAWN R.P.L. 2/10/67
APPROVED R. L. Barron APR

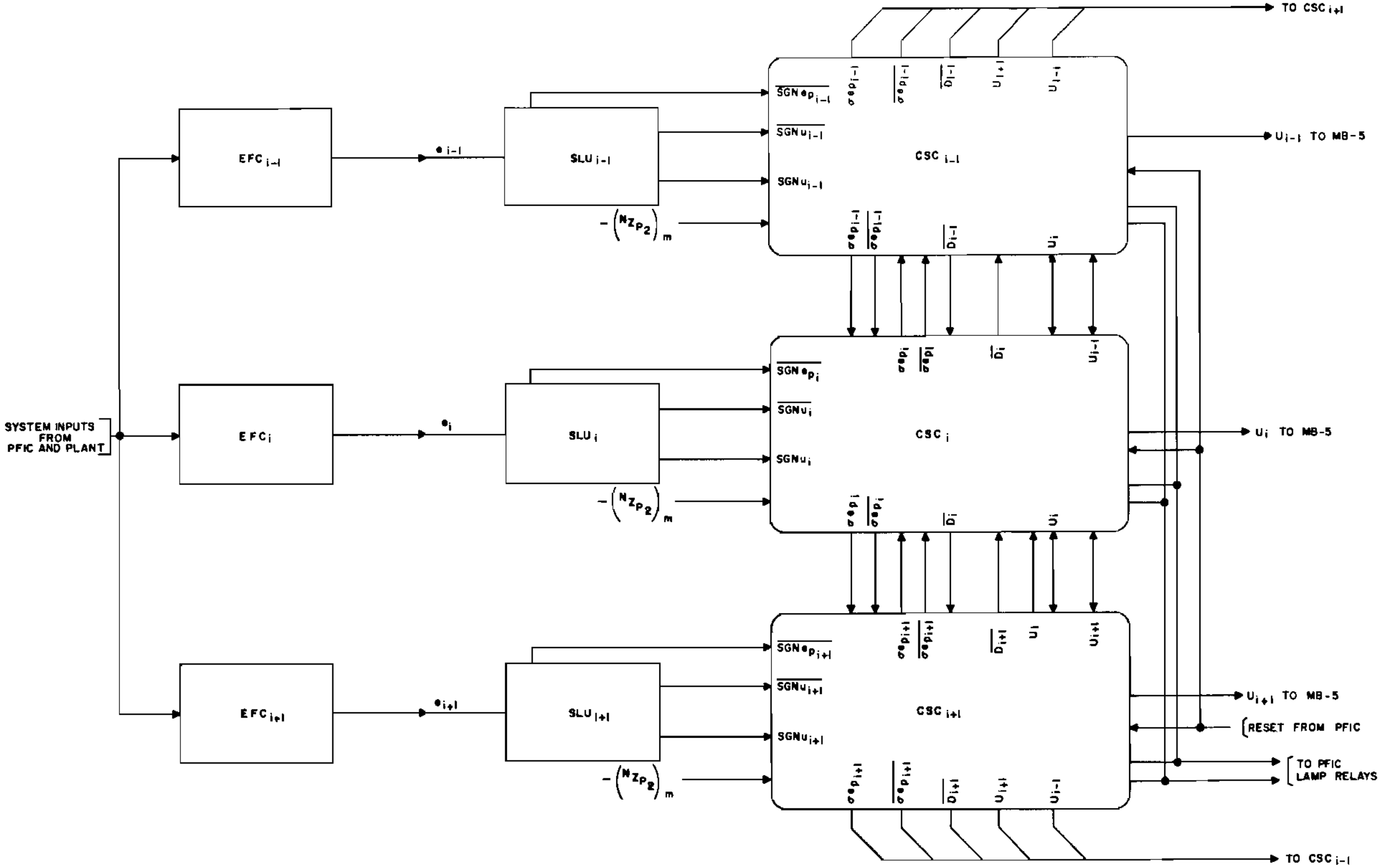
ADAPTRONICS, INC.
WESTGATE RESEARCH PARK, McLEAN, VA.

SOC LOGIC UNIT
MARK IV SOC

SIZE D | CODE IDENT NO. 27525 | DRAWING NO. 621-1
SCALE NONE | SHEET 1 OF

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APPROVED



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ON
FRACTIONS ± — DECIMALS ± — ANGLES ± —

MATERIAL:

CONTRACT NO. AF 33(615)-5141

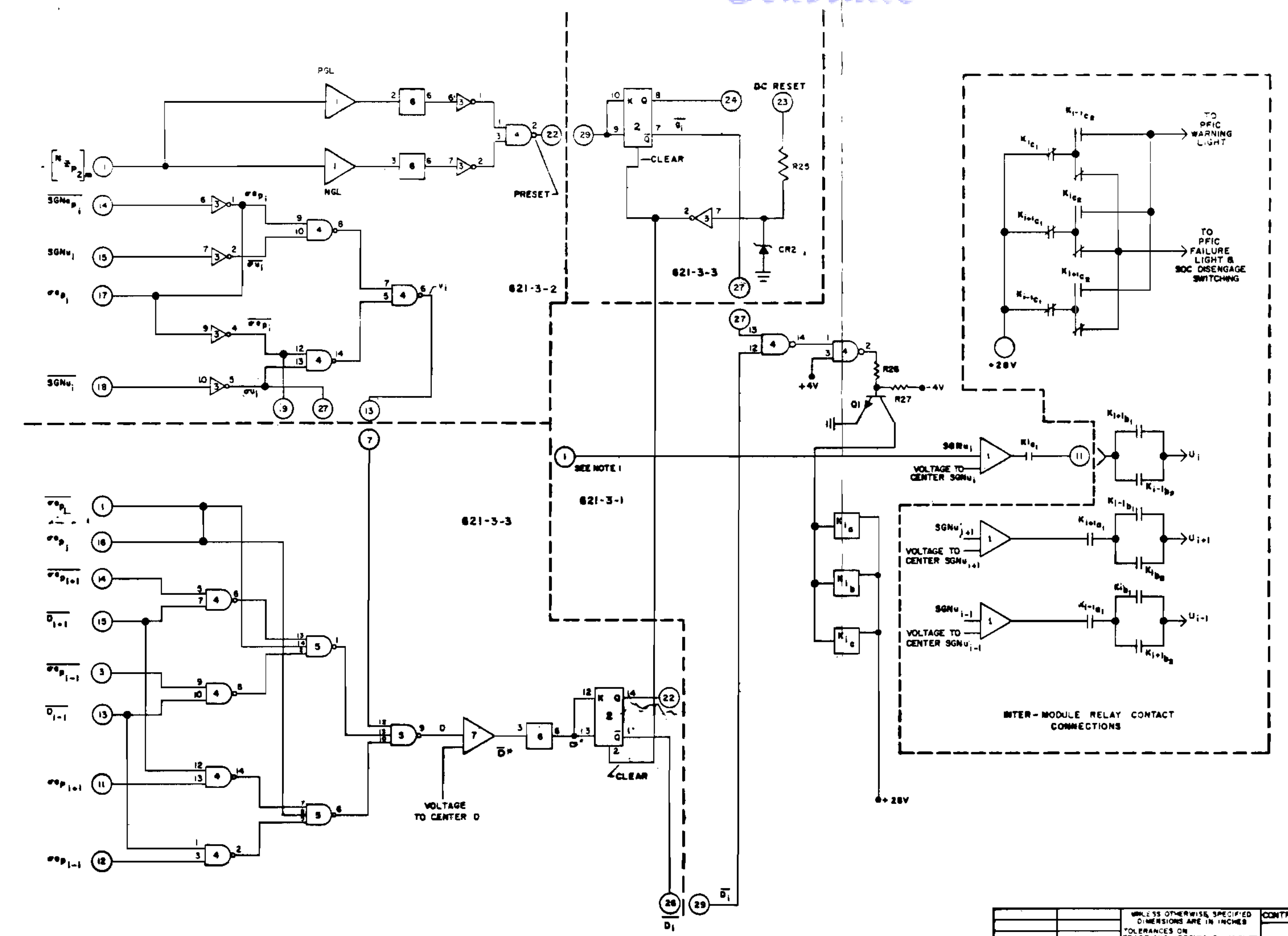
CHECKED		
DRAWN	R.P.L.	2/10/67
APPROVED	K. L.	

ADAPTRONICS, INC.
WESTGATE RESEARCH PARK, McLEAN, VA.

FUNCTIONAL BLOCK DIAGRAM
MARK IV SOC 141

SIZE	CODE IDENT NO.	DRAWING NO.
D	27525	621-6

SCALE NONE — SHEET 1 OF 1

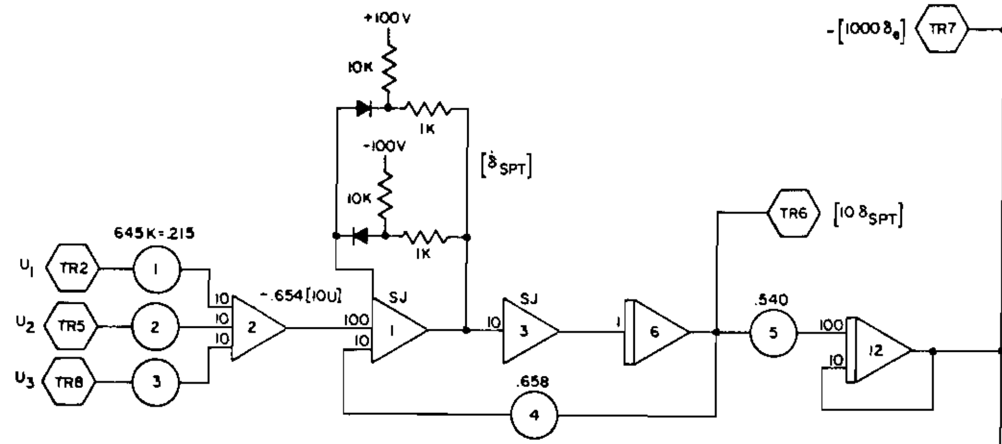


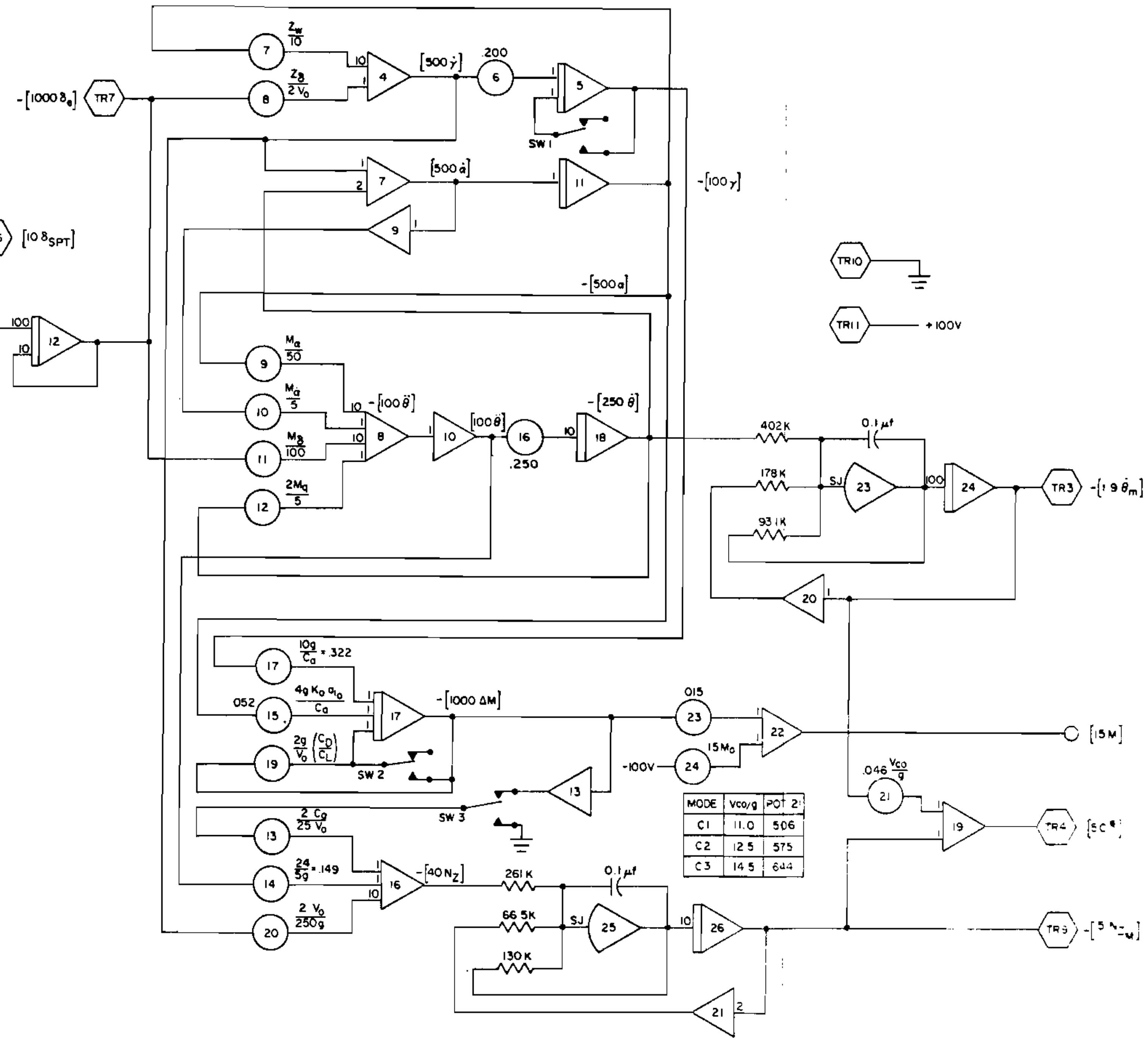
NOTES:

1. CONNECTION TO $SGNu_i$ OR $\overline{SGNu_i}$ TO BE DETERMINED-
2. ABBREVIATIONS:
   - 1 = TI SN524A OPERATIONAL AMPLIFIER.
   - 2 = TI SN5304 DUAL JK FLIP-FLOP.
   - 3 = TI SN535 QUAD INVERTER.
   - 4 = TI SN5360 QUAD TWO-INPUT NAND/NOR GATE.
   - 5 = TI SN5331 TRIPLE THREE-INPUT NAND/NOR GATE.
   - 6 = SGN FAIRCHILD μA710 ZERO CROSSING DETECTOR.
   - 7 = 10 RAD/SEC LOWPASS
   - SGN = BINARY SIGNAL -0.5 V (TYP) LOGICAL ZERO. +3.0 V (TYP) LOGICAL ONE (NAND LOGIC).
   - σ = BINARY SIGNAL: 0V (TYP) LOGICAL ZERO, +4.0 V (TYP) LOGICAL ONE (NAND LOGIC).
   - Q1 = 2N2221A SILICON SWITCHING TRANSISTOR

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES	CONTRACT NO. AF 33(618)-5141	ADAPTRONICS, INC. WESTGATE RESEARCH PARK, McLEAN, VA.
TOLERANCES ON FRACTIONS ± — DECIMALS ± — ANGLES ± —	CHECKED	COMMAND SIGNAL COUPLER MARK IV SOC FUNCTIONAL BLOCK DIAGRAM
MATERIAL: —	DRAWN 10 JAN 67	
NEXT ASSY / USED ON / APPLICATION	APPROVED K. L. Barron	SIZE D · CODE IDENT NO. 27525 · DRAWING NO. 621-5
		SCALE — · SHEET 1 OF 1

REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	APPROVED
	C	REVISED AND REDRAWN TO INCLUDE BOTH LONG AND SHORT PERIOD DYNAMICS. ECN 15	JULY 11 '68	[illegible]





MODE	Vco/g	POT 21
C1	11.0	.506
C2	12.5	.575
C3	14.5	.644

POTENTIOMETER SCHEDULE													
POTS	1	2	3	4	5	6	14	15	16	17	21	23	24
VARIABLE	.645K	.645K	.645K	—	—	—	$\frac{24}{5g}$	$\frac{4gK_0 a_{10}}{C_a}$	—	$\frac{10g}{C_a}$	.046 $\frac{V_{co}}{g}$	—	.15 M_0
SETTING	(K=1/3) .215	(K=1/3) .215	(K=1/3) .215	.658	.540	.200	.149	.052	.250	.322	SEE TABLE	.015	15 PER MACH

FLIGHT CONDITION POTENTIOMETER SCHEDULE										
	POTS	7	8	9	10	11	12	13	19	20
F.C.	ALT / MACH	$\frac{Z_w}{10}$	$\frac{Z_\delta}{2V_0}$	$\frac{M_a}{50}$	$\frac{M_{\dot{a}}}{5}$	$\frac{M_\delta}{100}$	$\frac{2M_q}{5}$	$\frac{2C_a}{25V_0}$	$\frac{2g}{V_0}\left(\frac{C_D}{C_L}\right)$	$\frac{2V_0}{250g}$
1	10K / 0.45	.0611	.0423	.1120	.0328	.0970	.3580	.164	.01	.1158
2	10K / 0.80	.1162	.0824	.3616	.0636	.3305	.6904	.092	.007	.2059
3	10K / 0.95	.1517	.0903	.8070	.0638	.430	.9228	.046	.010	.2445
4	20K / 0.55	.0524	.0372	.1112	.0396	.0990	.3108	.140	.010	.1363
5	20K / 0.90	.1097	.0688	.4220	.0604	.2995	.5768	.086	.006	.2232
6	20K / 1.20	.1064	.0669	.9992	.0324	.4035	.6544	.064	.015	.2975
7	35K / 0.75	.0436	.0305	.1122	.0250	.1035	.2512	.110	.007	.1748
8	35K / 0.95	.0661	.0385	.3218	.0300	.1655	.3396	.066	.011	.2213
9	35K / 1.30	.0667	.0391	.6340	.0144	.2385	.3672	.061	.010	.3030
10	35K / 1.60	.0681	.0370	.8384	.0020	.2740	.3328	.052	.011	.3729

NOTES.

1. FUNCTION SWITCHES UP: LONG AND SHORT PERIOD DYNAMICS
   FUNCTION SWITCHES DOWN: SHORT PERIOD DYNAMICS ONLY
2. UNSCALED EQUATIONS:

ACTUATOR DYNAMICS

$$U = K(U_1 + U_2 + U_3),\ K = 1/3$$

$$\delta_{SPT} = \frac{9.8U}{1 + 0.0152S} \text{ INCHES, } \dot{\delta}_{SPT} \leq 10 \text{ IN/SEC}$$

$$\delta_e = \frac{0.054\,\delta_{SPT}}{1 + 0.1S} \text{ RADIANS}$$

AIRCRAFT DYNAMICS

$$\dot{\gamma} = Z_w a + \frac{Z_\delta}{V_0}\delta_e \text{ RADIANS/SEC}$$

$$\dot{a} = \dot{\theta} - \dot{\gamma} \text{ RADIANS/SEC}$$

$$\ddot{\theta} = -M_a a - M_{\dot{a}}\dot{a} - M_\delta \delta_e - M_q \dot{\theta} \text{ RADIANS/SEC}^2$$

$$\Delta M = \left(-\frac{2g}{V_0}\frac{C_D}{C_L}\Delta M - \frac{2gK_0 a_{10}}{C_a}a - \frac{g}{C_a}\gamma\right)/S \text{ MACH}$$

$$M = M_0 + \Delta M \text{ MACH}$$

$$N_Z = \frac{2K\,C_a}{V_0}\Delta M + \frac{V_0}{g}\gamma + \frac{12}{g}\dot{\theta} \text{ g's}$$

SENSOR DYNAMICS

$$\dot{\theta}_M = \frac{(75)^2\,57.3\,\dot{\theta}}{S^2 + 107S + (75)^2} \text{ DEG/SEC}$$

$$N_{Z_M} = \frac{(55)^2 N_Z}{S^2 + 77S + (55)^2} \text{ g's}$$

$$C^* = N_{Z_M} + \frac{1}{57.3}\frac{V_{co}}{g}\dot{\theta}_M \text{ g's}$$

NEXT ASSY	USED ON	UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES. TOLERANCES ON FRACTIONS ± DECIMALS ± ANGLES ±
APPLICATION		MATERIAL:

CHECKED:
DRAWN: J.M. Lewis 7/11/68
APPROVED: [illegible]

ADAPTRONICS, INC.
WESTGATE RESEARCH PARK, McLEAN, VA.

F-101B SIMULATION, 143
ANALOG COMPUTER,
SYSTRON DONNER SD10/20

SIZE	CODE IDENT NO.	DRAWING NO.
D	27525	621-9

SCALE — SHEET 1 OF 1

APPENDIX II

DESIGN PRINCIPLES FOR SELF-ORGANIZING CONTROL SYSTEM FLIGHT HARDWARE

Paper delivered at 1967
National Aerospace Electronics Conference
Dayton, Ohio
May 15-16-17, 1967

Note: Design changes incorporated in the SOC system subsequent to this paper are described in the body of this report.

DESIGN PRINCIPLES FOR SELF-ORGANIZING CONTROL SYSTEM FLIGHT HARDWARE*

By: Robert M. McKechnie, III, Design Engineer,
and Roger L. Barron, President, Adaptronics, Inc.

Introduction

This paper presents basic design principles for self-organizing control system flight hardware. These principles are illustrated by reference to current work that will culminate in early FY '68 flight testing of the Mark IV self-organizing system for F-101B pitch-axis control augmentation. A unique feature of this self-organizing controller (SOC) is the use of noise injection to aid accomplishment of high-gain control. Because of its stability with high loop gains, the SOC can provide essentially uniform response characteristics throughout the aircraft altitude and Mach-number envelope. This is achieved without air-data sensing or gain scheduling and produces no objectionable limit-cycle oscillations or structural excitation.

Prior applications work with self-organizing control systems progressed through the breadboard stage by mid FY '66, with investigations of spacecraft attitude control[1,2,3,4] and control of high-performance aircraft.[5,6] The ongoing program† for design, fabrication, and flight testing of a single-axis SOC "brassboard" is contributing greatly to the body of SOC theory and applications experience.

Except for the work described in References 7 and 8, SOC development has thus far stressed single-goal, single-actuator applications. Up to this time this emphasis has been good because it has forced SOC systems to compete from the outset with conventional controller designs on the latter's terms, e.g., in problems where optimum deterministic solutions exist and can be implemented.

Looking beyond these efforts, advanced SOC techniques are being developed for multiple-goal, multiple-actuator flight control systems.[7,8] In these advanced applications, the SOC noise-injection process is instrumental in accomplishing high-speed parameter space search to identify the effectiveness of system actuators (including actuator polarities) and the interactions between coupled response variables.

SOC Description

The Mark IV self-organizing control system will be flight tested in an F-101B aircraft. The Mark IV is a pitch-axis

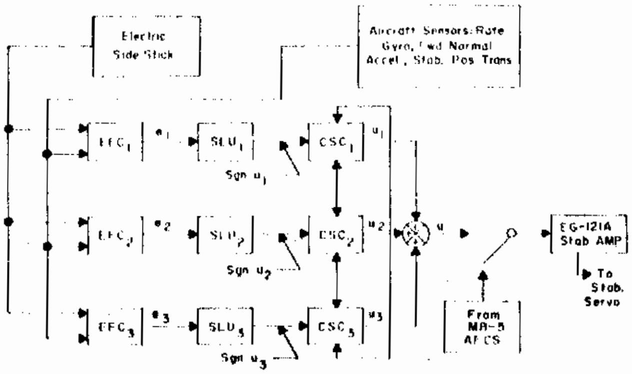


FIGURE 1: F-101B MARK IV SOC/MB-5 FUNCTIONAL BLOCK DIAGRAM

controller and will drive the stabilator parallel servo. Roll and yaw axes will be controlled by the existing MB-5 AFCS. In this program, the Air Force is installing an Electric Side Stick" for pilot pitch and roll commands. The existing F-101B pitch-rate gyro, forward normal accelerometer, and stabilator position transmitter will be used by the SOC.

The Mark IV SOC system consists of a network of three independent operational modules, housed in a receptacle located behind door 214R in an unpressurized area of the F-101B. The Panel and Flight Instrumentation Controls unit (PFIC) is located in the cockpit.

The system uses high forward-loop gain with either rate-gyro feedback or C* feedback, the latter being a weighted sum of rate-gyro and forward-normal-accelerometer outputs.[10] The stabilator position transmitter signal, δ_{SPT}, is used to compensate the rate-gyro dynamics.[11] Positive δ_{SPT} feedback is proportional to negative $\ddot{\theta}$ at high frequencies and acts to equalize effects of the rate-gyro poles, which are near the $j\omega$ axis at high loop gain.

The SOC module interconnections are shown in Figure 1. Each SOC module consists of one Error Function Coupler (EFC), Figure 2; one SOC Logic Unit (SLU), Figure 3; and one Command Signal Coupler (CSC), Figure 4. The EFC receives signals from the Electric Side Stick and the sensors; this unit provides the proper scaling and computes the error signal for the SLU. The SLU contains the circuits which operate on the error signal from the EFC to provide the pulse-density-coded control signal, sgn u, or its inverse, $\overline{\text{sgn u}}$. The CSC smooths the SLU output to obtain an analog control signal. The CSC also provides the logic

*Work supported under Contract No. AF 33 (615)-5141 by Flight Dynamics and Avionics Laboratories (RTD), Air Force Systems Command, Wright-Patterson Air Force Base, Ohio.
†Ibid.

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circuits (not shown) for failure detection, warning, and disconnect. The three SOC modules have interconnected CSC logic so as to warn the pilot if one SOC module fails and automatically disconnect the system if two modules fail.

The PFIC contains the controls for selecting various EFC parameters as well as the warning and failure lights. Provisions have been made to select three pre-filter (model) lag time constants, (τ_M = 0.1, 0.2, or 0.5 sec.) from the PFIC. Also, a switch is provided for choice of the accelerometer weighting factor in C* (V_{co}/g = 11, 12.5, or 14.5 sec.), and choice between pure rate-gyro or C* feedback. Finally, PFIC circuitry is included for a Mach trim follow-up loop, used to achieve both long-period speed stability of the aircraft and a stick force per velocity change gradient acceptable to the pilot.[11]

$$e = \left(F_{ESS_p}\right)\left(\frac{1}{1+\tau_M s}\right) - \left(\frac{V_{co}}{57.3g}\right)\dot{\theta}_m \quad f_1\left(N_{z_{p_m}}\right) + f_2\, H(s)\,\delta_{SPT}$$

$$f_1 = \begin{cases} 1 \ (C^* \text{ Mode}) \\ 0 \ (\dot{\theta} \text{ Mode}) \end{cases} \qquad f_2 = \begin{cases} 0.25 \ (C^* \text{ Mode}) \\ 0.70 \ (\dot{\theta} \text{ Mode}) \end{cases}$$

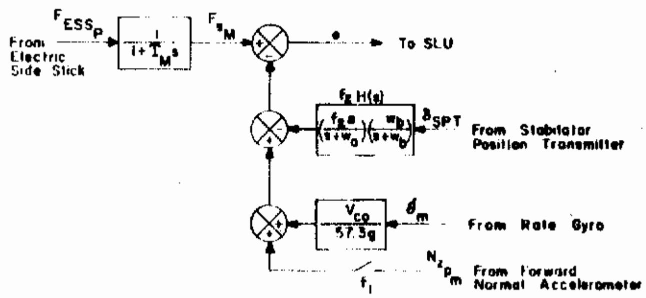


FIGURE 2: ERROR FUNCTION COUPLER (EFC) FUNCTIONAL BLOCK DIAGRAM

Electrical Design

General

The Mark IV SOC consists of three independent modular subsystems, as shown in Figure 1. Each subsystem is composed of one Error Function Coupler (EFC), one SOC Logic Unit (SLU), and one Command Signal Coupler (CSC). The outputs of the three subsystems are summed at the input of the EG-121A stabilator amplifier in the existing MB-5 AFCS.[12] (A switch on the PFIC allows the pilot to change from the MB-5 to the SOC once he has completed a pre-engage procedure.) Each SOC subsystem has five printed-circuit (PC) cards, one 28 Volt d.c. input power supply,

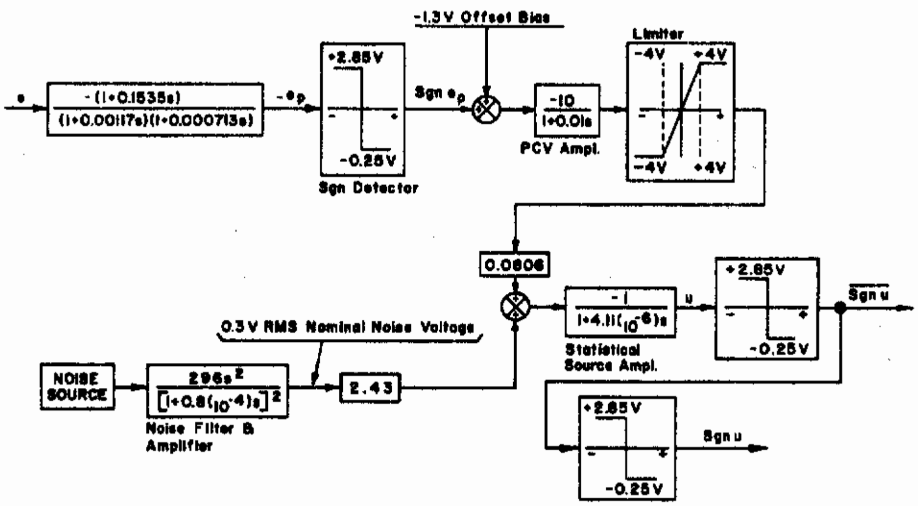


FIGURE 3: SOC LOGIC UNIT (SLU) FUNCTIONAL BLOCK DIAGRAM

and a mother board.

The SOC system uses MIL-rated components (-54°C to +85°C) which have been individually burned in and tested under environmental conditions to insure proper component performance. The resistors used have ± 1% tolerance, with ± 50 ppm temperature coefficients. The capacitors have ±5% tolerances with temperature coefficients of less than ± 2.5%. Texas Instruments SN524A operational amplifier flatpacks, Fairchild μA710 zero-crossing detector flatpacks, and Texas Instruments Series 53 digital logic flatpacks have been mounted on Amp Crimp-Pacs before being mounted on the PC cards. The PC cards (manufactured by Electro-Circuits, Inc.) were designed and fabricated according to appropriate MIL specifications, using plated-through holes and conductor patterns on both sides of the cards. After assembly and check out, the cards were cleaned ultrasonically and conformally coated.

Error Function Coupler

The Error Function Coupler (EFC) is a single 2.3-inch by 3.45-inch PC card which provides the error signal to the SLU using the signals from the rate gyro, forward normal accelerometer, and the stabilator position transmitter (see Figure 2). The EFC consists of three stages which are: (1) the prefilter Model (first-order lag) for shaping the Electric Side Stick signal, (2) the H(s) filter which operates on the signal from the stabilator position transmitter, and (3) the error summing amplifier for forming the error signal, e. The values for ω_a and ω_b in the H(s) transfer function were selected from computer simulation studies to be 5.7 rad./sec. and 10 rad./sec., respectively. The EFC circuits scale all incoming signals to prevent any saturation of the operational amplifiers. Active components are used in all EFC stages. Teledyne miniature Type 412 28-Volt relays are used for remote selection (from the PFIC) of τ_M and V_{cc}/g values as well as for selection between $\dot{\theta}$ and C* modes.

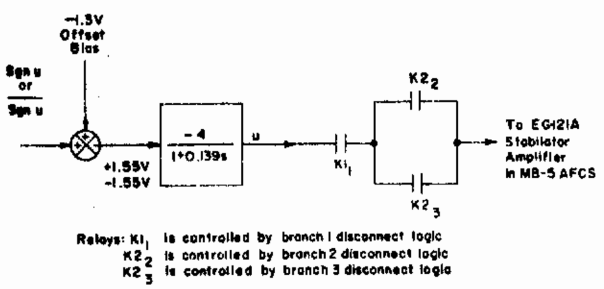


FIGURE 4: COMMAND SIGNAL COUPLER (CSC) FUNCTIONAL BLOCK DIAGRAM

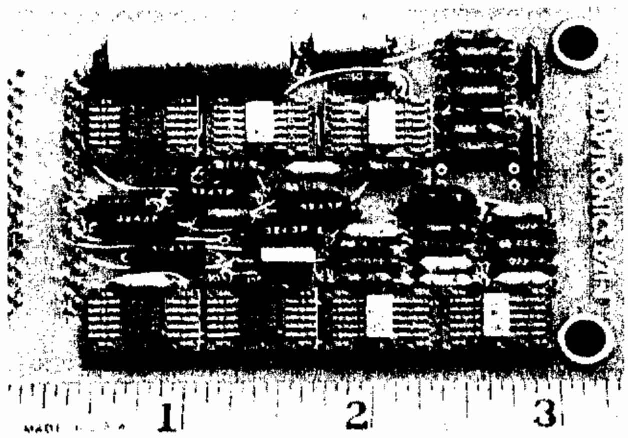


FIGURE 5: MARK IV SOC LOGIC UNIT (SLU)

SOC Logic Unit

The SOC Logic Unit (SLU) is the heart of the Mark IV System. The SLU is a single 2.3-inch by 3.45-inch PC card, as shown in Figure 5. This unit has three major circuits:

(1) sgn e_p

(2) statistical filter

(3) sgn u

The sgn e_p circuit is an augmented differentiator, which provides a lead time constant of 0.15 sec., followed by a zero-crossing detector. The proper choice of component values for this circuit is dependent on the location of the control loop natural frequencies. The F-101B has structural bending modes at approximately 8, 12, and 20 Hz. The actuator natural frequency is at 4.5 Hz, while the accelerometer has a natural frequency at 8.75 Hz and the rate gyro has a natural frequency at 11.9 Hz. The first pole in the circuit should therefore be at a frequency approximately five times greater than 20 Hz. The 1 + Ts operation is performed by a Texas Instruments SN524A operational amplifier. To provide sgn e_p, a Fairchild μA710 flatpack zero-crossing detector is connected to the output of the e_p operational amplifier. This detector has a switching window of ± 10 millivolts. The high output of the typical μA710 is +2.85 Volts, while the low output is -0.25 Volt.

The statistical filter[8] is a section of the SLU which has three subparts:

(1) PCV amplifier

(2) Noise Generator

(3) Statistical Source amplifier

The PCV (probability control voltage) amplifier is a low-gain closed-loop operational amplifier with centering, smoothing, and limiting. The first approach for

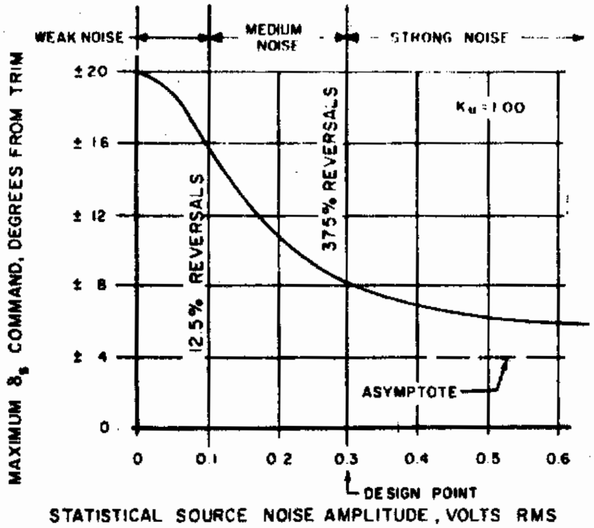


FIGURE 6: RELATIONSHIP BETWEEN STATISTICAL SOURCE NOISE AMPLITUDE AND SOC AUTHORITY

this amplifier was to use an integrator with limiting, but a digital computer analysis showed that the same response could be obtained with smoothing and limiting, while the pure integrator approach has severe drift problems. The closed-loop corner frequency of the PCV amplifier is 15.9 Hz, and limiting is provided by a diode network in the amplifier feedback set to limit at +4 Volts or -4 Volts. One other important function of the PCV amplifier is to center the output of the sgn e_p zero-crossing detector. This centering is designed for ambient conditions and holds well at extreme temperatures.

Noise Generator Design

As pointed out by Boskovich and Kaufmann, "... if the bandwidth of the inner loop exceeds the model bandwidth by a factor of three or more, the over-all response of θ/θ_c essentially will be that of the model."[12] For a model time constant, τ_M, of 0.2 sec., it would follow that the inner loop bandwidth should be not less than 2.4 Hz.

The purpose of the Noise Generator in single-actuator SOC applications is to aid the realization of high bandwidth in the control system. In design of conventional controllers, the bandwidth is often severely compromised to avoid excessive limit-cycle amplitudes and excitation of structural modes, both of which can result if loop gain is increased to the levels required by the bandwidth criterion. Furthermore, when conventional filtering is used in these systems in an effort to attenuate high frequencies, such filtering tends to introduce unacceptable phase shifts within the passband for control inputs.

In the SLU, the statistical filter section acts as a low-pass filter which produces no additional phase shift at any frequency. It is therefore possible to suppress unwanted high-frequency modes at virtually no penalty to system low-frequency response. The procedure is to design the Noise Generator circuit for maximum output at frequencies above the passband for control inputs. When the noise signal is added to the PCV signal, the sum will be predominantly incoherent at frequencies where the noise has large amplitudes. Putting it in different terms, an SOC input signal at a frequency where the injected noise is strong will undergo many more reversals of polarity than will a signal at a frequency where the injected noise is weak.

The statistical filter produces no alteration of its input phase because noise cannot convey phase information, although it can attenuate as a function of its own frequency distribution. The same cannot be said of periodic (dither) signals in view of the coherence of such signals.

The Noise Generator circuit includes a high-pass filter which produces a noise signal of large amplitude over the frequency range where it is desired to have the SOC reject coherent inputs and produce an output uncorrelated with either coherent or random inputs. Basic design criteria that have been established for the high-pass filter are:

(1) The noise signal should be attenuated 100 db or more at the upper edge of the SOC input passband.

(2) At frequencies above the SOC input passband, the noise amplitude should increase with frequency, and the slope of the amplitude vs. frequency curve should be as steep as possible.

(3) The noise signal must be centered (readily achieved via capacitive coupling).

It is helpful to bear in mind that the SOC closed-loop gain-phase roll-off frequency and slope are affected in a manner inverse to the Noise Generator frequency distribution, but are unaffected by phase shift within the noise high-pass filter.

The Mark IV SOC/F-101B system has a bandwidth of 3 Hz at minimum dynamic pressure (q) and 5 Hz at maximum q, this range being due to the inherent change in stabilator effectiveness with q. The Noise Generator is designed with approximately 100 db attenuation at 4.4 Hz, and the slope of the amplitude vs. frequency curve for the noise high-pass filter is +40 db/decade. This filter characteristic is obtained with one flatpack; for more demanding applications it would be desirable to use a two-stage filter (+80 db/decade).

With the +40 db/decade slope, and using a Noise Generator output of 0.3 Volt RMS as shown in Figure 3, the parallel servo has a negligible "buzz" in both $\dot{\theta}$ and C* modes. Under worst-case conditions (peak q), the "buzz", as seen on δ_{SPT}, is

±0.08 inch with a frequency of approximately 20 Hz. However, if the Noise Generator output is arbitrarily reduced from 0.3 Volt RMS to 0.15 Volt RMS, the δ_{SPT} "buzz" increases to ±0.12 inch, still at 20 Hz.

No adverse excitation of structural bending modes has been observed under any of the conditions simulated.

The Statistical Source noise amplitude of 0.3 Volts RMS causes 37.5 percent reversals of sgn u within an SOC branch when the PCV voltage of that branch is at one of its limits (±4 Volts). As shown in Figure 6, the resulting maximum stabilator command from the SOC is approximately ±8 deg. from trim. This would be sufficient controller authority to produce ±6.5 deg./sec. pitch rate or ±3.3 g's of C* response at a low dynamic pressure condition (0.75 Mach at 35,000 ft.), if the aircraft could undergo such maneuvers without stalling, which it cannot.

The Noise Generator uses a Sounvister Solitron noise diode, type SD1-W12, as its basic noise source. This diode has a Gaussian distribution of frequencies and an output of 500 microvolts RMS. The noise is filtered by a high-pass filter chosen because of its suitability for use with low-gain (60 db. open-loop) amplifiers. The output of the Noise Generator circuit varies between 0.4 Volts RMS at -55°C and 0.2 Volts RMS at +100°C.

The outputs of the PCV amplifier and the Noise Generator are summed by the Statistical Source amplifier to produce the u signal. The noise signal is biased by the PCV amplifier output and the amplitude relationship between these variables must be such that the Statistical Source amplifier is not driven into saturation when the PCV fully biases the noise signal.

The output of the Statistical Source amplifier, u, is connected to the sgn u circuit, which is a zero-crossing detector (Fairchild μA 710). This detector is followed by another to provide $\overline{\text{sgn u}}$. The allowance for both sgn u and $\overline{\text{sgn u}}$ provides latitude in application of the SLU.

Command Signal Coupler

The Command Signal Coupler (CSC) is a set of three 2.3-inch by 3.45-inch PC cards which provide the output interface between the SLU and the F-101B parallel-servo amplifier. The CSC output, u, is connected to the EG-121A stabilator amplifier in the MB-5. The CSC has two functions:

(i) Smooth, center, and scale the SLU sgn u or $\overline{\text{sgn u}}$ output
(ii) provide failure warning and disconnect logic functions

The u amplifier centers the sgn u or $\overline{\text{sgn u}}$ signal; provides smoothing, using a lag time constant, τ_u, of 0.139 sec.; and scales the u signal to the range ±6.2 Volts, nominal. Analog computer studies were performed to determine a value of τ_u which would allow good control response and limit the amount of wear on the servo valve which might result if τ_u were too small. The centering signal is required because the zero-crossing detector output is not symmetrical, as noted previously.

The failure detection, warning, and disconnect is accomplished by cross-connecting the CSC units of the three SOC branches. The failure detection and disconnect concepts are summarized in Table 1.

The CSC circuitry is implemented using Texas Instruments SN524A operational amplifiers and Series 53 digital logic. Teledyne 412 relays are also employed.

SOC Performance

The F-101B Mark IV SOC system has been extensively simulated on digital and analog computers, the latter work conducted with a bench prototype of the flight equipment. The digital simulations, performed by DODCO, Inc.,[10] included three-degree-of-freedom longitudinal dynamics of the airframe and the effects of the first three body bending modes.

The basic parameters of the Mark IV SOC system and the final design values selected for them are:

(1) K_u = 1.0 Volts/Volt (0.33 Volts/Volt per branch)
(2) τ_u = 0.139 sec.
(3) $f_2(C^*)$ = 0.25 Volts/in./sec.
(4) $f_2(\dot{\theta})$ = 0.70 Volts/in./sec.
(5) Slope of noise generator gain curve below cut-on frequency = +40 db/decade
(6) Statistical Source noise amplitude = 0.3 Volt RMS

The above values were used in obtaining the simulation data presented here.

Figure 7 shows upper and lower boundaries on C* time responses as specified by the Air Force for the F-101B SOC system. These boundaries relate to the case in which a step input (F_{ESS_P}) is applied at time zero. The boundaries and other curves in Figure 7 have been normalized by dividing the magnitude of F_{ESS_P} into C*. The upper boundary corresponds to that for "Category I" control requirements[14] and the lower boundary stems from the slightly less stringent "Category II" requirements.[14]

Table 1: Summary of SOC Failure Detection and Disconnect Concepts

Fault	Effect on SOC	Pilot's Indicator	Pilot Action
Single branch g-sensing failure or marginal g condition tripping g-sensing circuit in a single branch or 1st branch failure	Offending branch disconnected, "apparent" authority reduced to 2/3 of original value.	Warning.	Attempt reset, if unsuccessful disconnect manually after reaching flight conditions amenable to manual control.
Excessive g-level or 2nd branch failure	System disconnected.	Failure light.	Manual Control required.

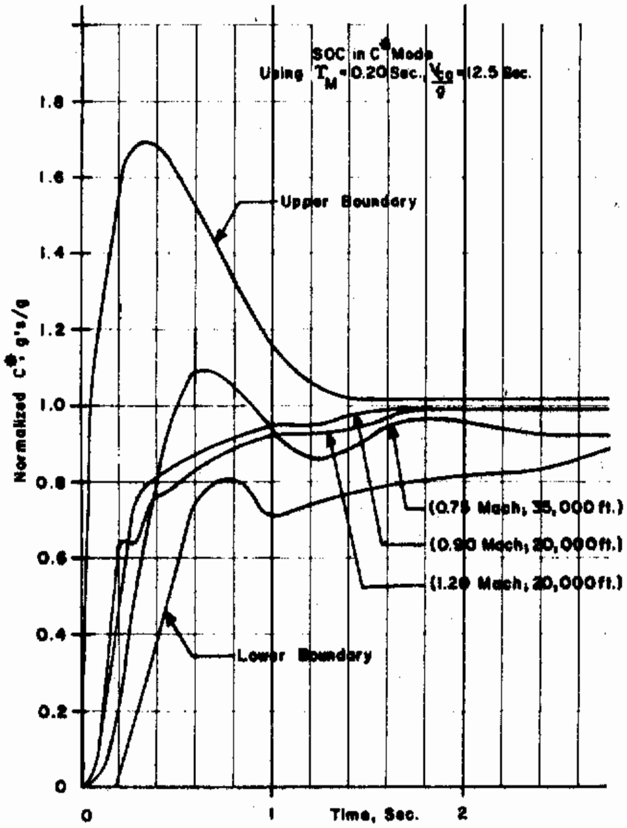


FIGURE 7: NORMALIZED C* PERFORMANCE BOUNDARIES AND SURVEY OF SOC RESPONSES

Digital Simulations

Digital computer simulations were performed to analyze structural mode behavior and limit-cycle characteristics, to evaluate effects of aerodynamic nonlinearities, and to investigate Mach stability and related long-term handling qualities of the system.

Ten flight conditions have been designated by the Air Force for the SOC flight evaluations. For this set of conditions, minimum q occurs at 0.75 Mach - 35,000 ft., while maximum q is met at 1.20 Mach - 20,000 ft. Figure 7 plots responses of the SOC obtained via digital simulations for both of these flight conditions as well as for an average q condition (0.90 Mach - 20,000 ft.). Not only these three responses but those for all ten flight conditions are within the specified performance envelope. Most of the ten responses have the general character of the one shown for average q.

It is believed that use of a model time constant, τ_M, of 0.1 sec. would cause all of the SOC responses to lie within the "Category I" envelope presented in Reference 14. However, simulations were conducted using τ_M = 0.2 sec. in the belief that this value will be preferred by the pilot.

The digital simulations have revealed no significant steady-state bending mode oscillations. First-mode transients are oscillatory but subside between one and two seconds after application of a step-function stick signal. Second-mode oscillations disappear in about 0.5 sec., while the third mode exhibits no oscillation whatever.

N_{z_p}, the normal acceleration sensed near the cockpit, varies smoothly in all the conditions simulated. MIL-F-8786 specifies that any residual oscillations must be less than ±0.020 g: the limit-cycle amplitude with the SOC is ±0.005 g under worst case (peak q) conditions. This oscillation occurs at 4.4 Hz for this case.

The SOC responses shown in Figure 7 were obtained with the Mach trim follow-up disengaged. Although this loop interacts very little with the initial C* transient, it causes a long-term C* decay, because with the Mach follow-up the aircraft always seeks to regain its trim condition.

Analog Simulations

Analog simulations have verified proper operation of the SOC hardware. The results below were recorded at bench ambient temperatures, but have been confirmed in tests at temperatures throughout the range -55°C to +71°C. One SOC branch was used alone to obtain the runs shown, but K_u was scaled to give this branch comparable authority to that available when three branches are connected normally.

The figures present recordings of the Model output, F_{s_M}; C*; $\dot{\theta}$; stabilator surface position (relative to trim), δ_s; and normal acceleration at the cockpit station, N_{z_p}. The analog simulation used a linearized, two-degree-of-freedom representation for the F-101B longitudinal dynamics.[6] Structural modes, aerodynamic nonlinearities, and long-period dynamics were ignored.

C* command responses of one-g and two-g magnitude are shown for the same minimum-q, average, and maximum-q flight conditions used to prepare Figure 7. In addition, $\dot{\theta}$ command responses of 2.5 and 5 deg./sec. are shown for the average-q case.

Effects of sensor noise, sensor stiction, air turbulence, and wind gusts have also been simulated (results not shown); the SOC has not been found particularly sensitive to any of these phenomena.

Reliability Prediction

The Mark IV SOC functions with little apparent degradation of performance in the event of a branch failure. The failure detection, warning, and disconnect circuitry of the Mark IV has been designed to detect the first branch failure, disconnect the offending branch from the system, and notify the pilot that such a failure has occurred. The recommended course of action in the event of such warning is for the pilot to attempt a "reset" of the disconnected branch. Failing in this attempt, the pilot should then disengage the SOC and employ manual control as soon as this is practicable. After two branch failures it is possible but not certain that the SOC can continue to control the aircraft in response to the pilot's commands. Therefore, in the event that two branch failures occur, the Mark IV SOC disengages itself automatically.

A reliability prediction for the Mark IV SOC has been calculated by Bird Engineering-Research Associates, Inc.[15] The system elements which were considered to comprise the SOC were the three SOC branches (each consisting of one EFC, one SLU, one CSC, and one multi-voltage power supply) and the PFIC. The prediction procedures used were the part-stress analysis procedures of Paragraph 5.0 of MIL-HDBK-217A[16] and techniques previously developed by Bird Associates for probability state variable systems.[17]

The estimated probability that <u>one</u> branch failure will occur in a two-hour airborne mission is 0.00158 (one failure in each 630 missions). The estimated probability that <u>two</u> branch failures will occur in a two-hour airborne mission is 0.721×10^{-6} (one failure in each 1.4 million missions).

In the Mark IV system, the PFIC is a non-redundant element and has a predicted failure probability for a two-hour mission of 6×10^{-6}. The probability of a Mark IV system failure has been calculated as the probability of PFIC failure plus the probability that an undetected failure in the SOC will be accompanied by an additional branch failure of any sort. The latter probability is extremely small (0.025×10^{-6} for a two-hour mission), and, therefore, the probability of system failure is comparable to the PFIC figure of 6×10^{-6} (one failure in each 160,000 missions, approximately). This represents an equivalent predicted MTBF for the system of 320,000 hours. If it were not for the PFIC, the system predicted MTBF would be 80 million hours.

Concluding Remarks

The success of the SOC in aircraft single-actuator applications is being built on fast, well-damped response to commands and disturbances, smooth steady-state behavior, minimum excitation of high-frequency modes, and low sensitivity to changes in flight conditions.

This paper has described the design characteristics and performance of the Mark IV F-101B SOC system. The noise-injection process used in the SOC statistical filter is shown to be compatible with stringent control-augmentation requirements. We believe the SOC design presented here provides a major link in the formulation of flight control systems for multiple-goal, multiple-actuator tasks.

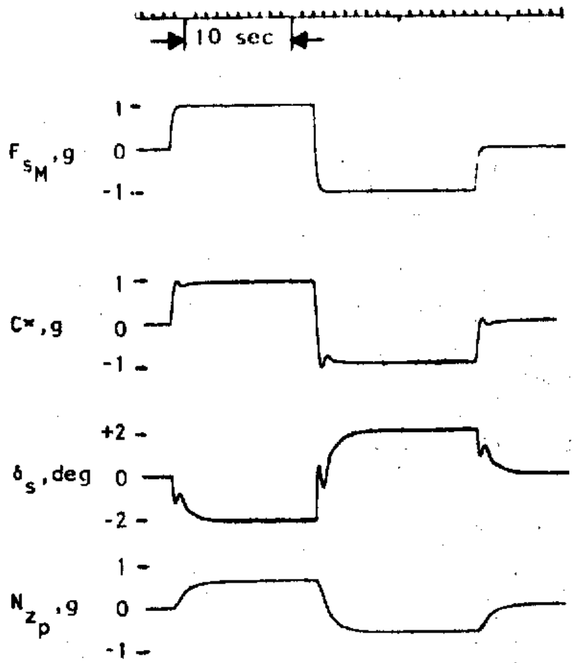
Acknowledgments

The authors are indebted to Mr. P. E. Blatt, AF Flight Dynamics Laboratory, who has guided the Air Force SOC program since 1965 and has contributed immeasurably to the understanding and application of SOC techniques. Messrs. M. A. Ostgaard and R. P. Johannes, likewise with the AF Flight Dynamics Laboratory, and Mr. C. W. Gwinn, AF Avionics Laboratory, have also made important contributions. Messrs. Ostgaard and Gwinn have given vital encouragement and support to this work since its inception in 1960.

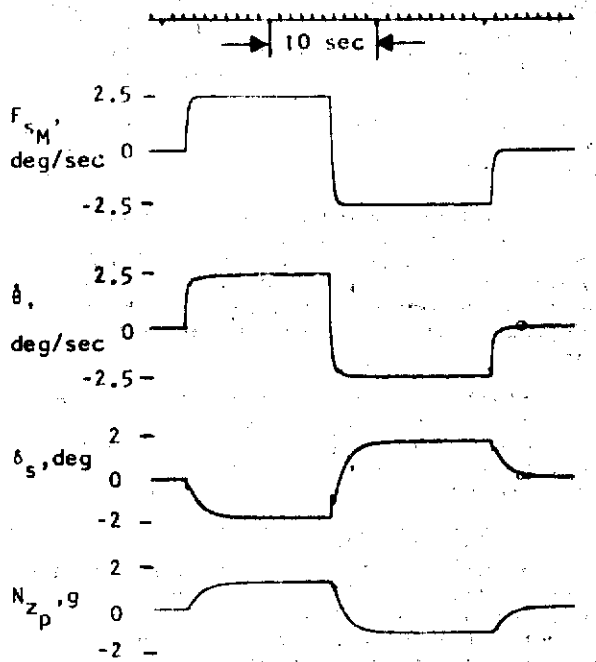
Senior Adaptronics, Inc. staff members who have participated in the Mark IV SOC development program include Messrs. G. C. Vieth, N. E. Wilson, C. W. Armstrong, R. F. Snyder, and L. O. Gilstrap, Jr.

Mr. J. R. Gouge, Jr., of Bird Engineering-Research Associates, Inc. and

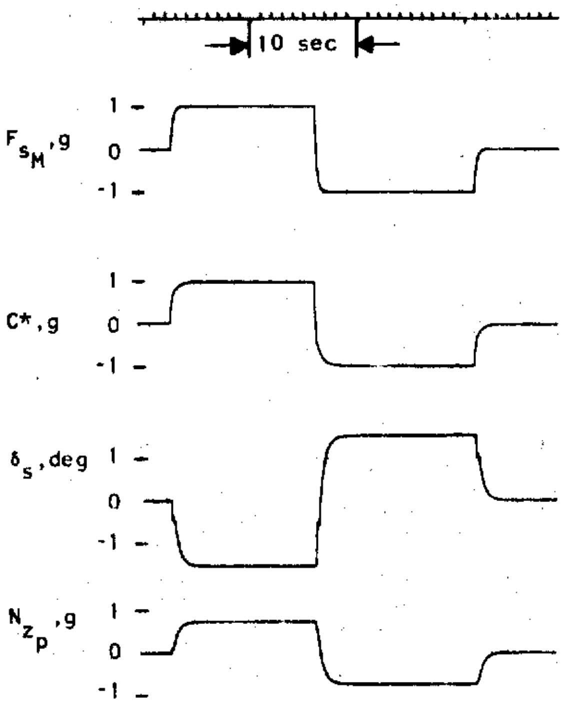
C* Mode: SOC Command Response at 0.75 Mach - 35,000 ft. (Minimum q)



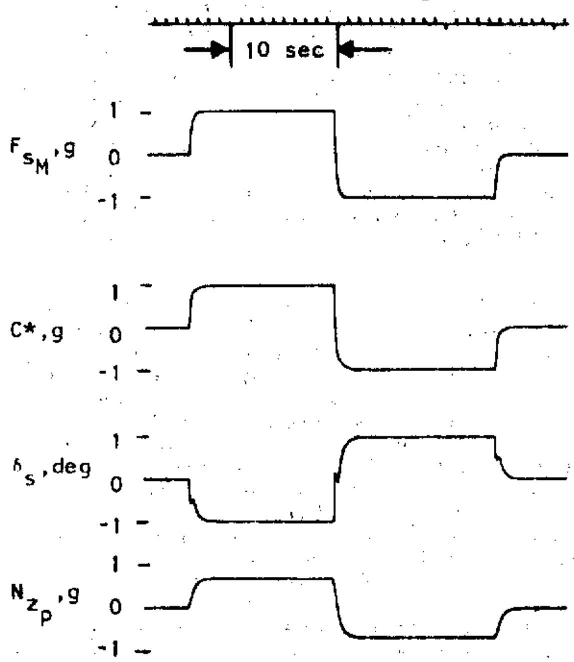
Ḣ Mode: SOC Command Response at 0.90 Mach - 20,000 ft. (Average q)



C* Mode: SOC Command Response at 1.20 Mach - 20,000 ft. (Maximum q)



C* Mode: SOC Command Response at 0.90 Mach - 20,000 ft. (Average q)



Messrs. D. O. Dommasch and C. W. Laudeman of DODCO, Inc. have also made valuable contributions.

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APPENDIX III

FLIGHT EVALUATIONS OF MARK IV SELF-ORGANIZING CONTROLLER

The following pages contain the flight test records, by number, through Flight Number 22. On-site support of the flight test program by Adaptronics, Inc. ceased on 9 October 1969. Ten more flights were made after that date, but no recorded events or debriefings are available, although oscillographic data are included in Section 3.3 of this report along with data from the earlier flights. The overall evaluations of the SOC by the two test pilots are presented at the end of Section 3.3.

SUMMARY OF PILOT DEBRIEFING AFTER FIRST SOC TEST FLIGHT
3 July 1969

PILOT: Major John Taylor, USAF

TAKE-OFF: 1330 EDST

LANDING: 1430 EDST

SOC ENGAGED FIRST TIME: 1340 EDST

The first SOC engagement was performed at 19,300 ft. indicated, 0.86 IMN, and with the ESS Pitch thumb-trim wheel set at -2. No engage transient was noted. The pilot stated that he engaged the SOC at least 15 times with the Pitch Trim wheel on the ESS set at various positions between its extremes. No engage transient was noticed at any time. However, a disengage transient was present but was not uncomfortable.

The pilot stated that Pitch thumb-trim action was sluggish, but that this function did not seem to be needed. The SOC maintained constant aircraft attitude regardless of Pitch Trim setting. There was no need to hold constant stick force to maintain constant aircraft attitude.

ESS Roll sensitivity and Roll Trim sensitivity were excessive and almost uncomfortable.

The pilot preferred the maximum Pitch sensitivity setting.

Speed during flight was varied between 0.75 and 0.87 IMN. Good response and stick force gradients were experienced at all speeds. Maximum g's pulled were 3.2 at 0.86 IMN, 20,000 ft. The g rise was smooth and the pilot was able to fly at the MB-5 CSL limit with ease, there being no fade. Pilot stated he was pleased with this capability.

The entire flight was flown in the C* mode.

All three Pitch Lag settings were tried. Pilot stated he could tell no difference between settings of 0.2 and 0.5, but that 0.1 seemed more sluggish than other settings.

No warning or trip lights were observed except one time, when the SOC tripped when pilot switched from a Pitch Lag setting of 0.2 to 0.5. No trouble was experienced re-engaging the SOC.

Gust response was good.

Mach Trim loop was not used during this flight. The pilot stated that he reacted somewhat negatively to the resulting neutral speed stability, but thinks his opinion may change when he becomes more used to the characteristic. In response to the explanation of reasons for providing neutral speed stability (tracking tasks), pilot stated that this characteristic would probably be well suited for its intended uses.

Pilot reported an objectionable steady-state oscillation at or near ESS neutral position (but not away from neutral). Frequency was estimated to be 3 Hz, with center stick movement of ±0.5 in. The oscillation would appear and disappear spontaneously for no apparent reason. The oscillation produced some aircraft rocking which bordered on the discomfort level. The oscillation was not present when any significant ESS command was applied, but would sometimes appear when going through the neutral ESS position.

In his summation, pilot expressed enthusiasm for system tested and his desire to gain further experience with it.

Note: No voice recording made on first flight.

Flight # 2

PILOT DEBRIEFING

Date: 18 July 1969

Pilot: Major J. Taylor   Observer: Chas. Rowles

1. Roll sensitivity 3 is "right where I want it". Maximum roll sensitivity is too much. Roll and Pitch sensitivity blend well.

2. Pitch sensitivity 4 is preferred (P. L. = .2, C2 mode). Maximum Pitch sensitivity is too much.

3. Initial turn-on transient is very small.

4. C* mode Pitch oscillation is about the same in frequency as in Flight #1, but has considerably smaller amplitude. Oscillation is "just a little annoying." Amplitude varies: oscillation goes away when pull g's.

5. In $\dot{\theta}$ mode have smooth flight, no oscillation. Get small stick chatter, frequency about 20-30 Hz, but no aircraft response to same.

6. First 15 minutes of this flight spent on ESS gains, C mode comparisons, and P. L.'s. Sequence was C1, C2, C3; for each C mode, P. L. = .5, .2, .1; for each P. L., minimum ESS-P sensitivity to maximum ESS-P sensitivity. "Can't tell difference between different C modes".

7. Flight conducted in 0.7 - 0.8 IMN range primarily. Some 0.85 IMN work. Pulled 2 g's at 0.8 IMN, 20,000 ft. (CSL limit.)

8. "Flys pretty nice; I like it."

9. Not enough nose-up trim in C* modes. Nose drops slightly lower with each oscillation. If goes to nose-down trim, gets trim response, so trim signal is there.

10. Roll Trim adequate.

11. Didn't change airspeed very much. Used climbing and descending turns.

12. Did not engage Mach Trim loop.

13. 40-45 minutes SOC operation. No warning lights, drop-offs, or blinks.

14. Disengaged SOC prior to switching into $\dot{\theta}$ mode. Engaged SOC in θ mode at 19,000 ft., 0.8 IMN. Engaged with P. L. = .5. Most $\dot{\theta}$ work with .5, but some .2.

15. Noticed a tendency for "drift" in $\dot{\theta}$ in terminal phase of transient (not steady-state).

16. Could fly up to CSL limit in $\dot{\theta}$ mode, but some g fading (as in basic F-101 autopilot) at CSL limit in $\dot{\theta}$ mode. C* mode is therefore preferable for flight at CSL limit.

17. Smooth air during flight. IFR conditions. Many radio interruptions. Lost radio contact several times.

Flight #2

REPORT OF EVENTS
(From Pilot's Voice Recorder)

Date: 18 July 1969

Pilot: Major J. Taylor Observer: Chas.Rowles

Event No:

1 Ground Test

2 Recorder on in air

C2, Pitch Lag .2

Pitch sensitivity 3, Roll sensitivity 3.

Ready - Engage

Slight Pitch oscillations.

Roll control is good. (Real nice)

Little stick nibbling - not nearly so bad as 1st flight.

Maximum Roll sensitivity - too much.

Minimum Roll sensitivity - not bad at this speed, would probably be inadequate of low speeds, like 3 best.

Maximum input, 2 g's, holding against CSL.

Pitch oscillations only when no input command.

Like 4 Pitch sensitivity.

3 C1, Pitch Lag .5, minimum Pitch sensitivity roll sensitivity 3.

Aircraft response somewhat sluggish.

4 C2, Pitch sensitivity 2, Pitch Lag .5. Pitch oscillations a little worse.

5 Pitch sensitivity 3 - somewhat sluggish.

6 Pitch sensitivity 4 - somewhat sluggish

Flight #2(Continued)

7 Pitch sensitivity 5 - somewhat sluggish.

8 Pitch sensitivity maximum.

SOC working much better.

Still slight oscillations but much reduced in amplitude.

9 Pitch Lag .2, minimum pitch sensitivity.

Quicker response.

10 Pitch sensitivity 2.

Not enough nose up trim.

Not quite holding altitude as well as 1st flight.

11 Pitch sensitivity 3.

Feels good. Mach .7, 1 1/2 g.

12 Pitch sensitivity 4.

Good response.

Roll control very good.

SOC is smooth as can be with input. Aircraft and center stick steady.

13 Pitch sensitivity 2.

Move sensitive - not bad.

14 Pitch sensitivity maximum.

C1, mininum Pitch sensitivity, Pitch Lag .1.

Not great deal of difference between Pitch Lag .1 and.2.

15 Pitch sensitivity 2.

16 Pitch sensitivity 3.

17 Pitch sensitivity 4. Pretty good response still.

18 Pitch sensitivity 5.

19 Pitch sensitivity maximum.

Lost about 5 minutes of recording

Flight #2 (Continued)

20 C3, Pitch Lag .2, minimum Pitch sensitivity still has slight Pitch oscillations. About same as C1 and C2.

21 Pitch sensitivity 2.

Pitch sensitivity 4.

.7 IMN, 20,000 ft.

22 Maximum Pitch sensitivity.

No difference in C1, C2, C3.

23 Pitch Lag .1, minimum Pitch sensitivity.

24 Pitch sensitivity 3.

25 Pitch sensitivity maximum.

All C* modes felt good. Real good response.

Pitch oscillations a little annoying but not really that bad.

SOC off.

26 $\dot{\theta}$, Pitch Lag .2, minimum Pitch sensitivity.

.73 IMN, 19,000 ft.

Slight nose up transient.

Little higher frequency stick shake. No aircraft oscillation.

Seems little more sluggish.

Very smooth.

27 Pitch sensitivity 4.

Aircraft responds faster in $\dot{\theta}$. Tendency to overshoot.

28 Pitch Lag .5.

Responds very quickly.

Like initial response but get feeling am going to overshoot. Aircraft definitely smoother. No oscillations.

Flight # 3

PILOT DEBRIEFING

Date: 24 July 1969

Pilot: Major J. Taylor Observer: Chas. Rowles

1. There was a noticeable improvement over Flight #2.

   Oscillation is still there but would not call it an oscillation. It is more of a "hunting". Doesn't bother the pilot too much. Response is good enough to proceed with calibration flights if we feel we can get the data we want.

2. $\dot{\theta}$ is very smooth. The vibration on the center stick is not noticeable unless one is looking for it.

3. The center stick vibration is still present in all C* modes. Less stick shaking than Flight #2. Frequency is $\approx$ 2 CPS.

4. Response to step commands in $\dot{\theta}$ is more rapid. You get more g's.

5. Pitch Trim is still the same, i.e., not enough nose-up trim.

6. Mach Trim was engaged at .8 IMN, Mach gain = 15. In C* the speed varied between .75 IMN to .85 IMN when step command (small) was introduced. SOC responds faster in the $\dot{\theta}$ mode. Speed varies between .78 IMN and .82 IMN.

7. When introducing a large up step command the nose of the aircraft would go up approximately 15° above the horizon and aircraft would run out of airspeed before the nose would start to drop. Response to the small step command felt the same as pilot had seen in the simulations. (Note: This with Mach Trim engaged.)

8. There was no noticeable difference in aircraft response (feel) with Mach Trim engaged except that the SOC wants to hold airspeed.

9. Pilot suggests a higher gain on Mach Trim.

10. The SOC was turned on at beginning of the flight and was not turned off until starting return to base. No disengages or warning lights.

Flight #3

REPORT ON EVENTS
(From Pilot's Voice Recorder)

Date: 24 July 1969

Pilot: Major J. Taylor   Observer: Chas. Rowles

Event No.

2 — SOC Engage. C1 Mode - Pitch Lag .2 - 20,000 ft. - .75 IMN.

Pilot comment after approximately 15 seconds: - "Just a little bit of oscillation there yet - Not oscillation but hunting - less than last flight - Approximately 1 CPS, 0.1g acceleration".

3 — C1, Pitch Lag .1, large up step command.

Pilot maneuvering with ESS.

Pilot comment: "Flies smoothly against CSL".

4 — C1, Pitch Lag .2, large up step followed by pilot maneuvering with ESS.

5 — C1, Pitch Lag .5, large up step followed by large down step.

ESS maneuvering.

6 — C2, Pitch Lag .1, large up step .

ESS maneuvering.

Pilot comment: "Can pull 1.1 incremental g's against CSL - smooth."

7 — C2, Pitch Lag .2, large up step followed by large down step and ESS maneuvering.

8 — C2, Pitch Lag .5, large up step followed by large down step. Then small up step.

Pilot comment: "Not noticeable".

ESS maneuvering.

Pilot comment - at .8 IMN, 20,000 ft can pull 1.6 incremental g's against CSL.

Flight #3(Continued)

9 C3, Pitch Lag .1, large up step followed by large down step.

ESS maneuvering.

Pilot comment: "Flies real nice - I like the way it feels. Oscillation today is different from first flight - slowed down considerably - less than 2 CPS."

10 C3, Pitch Lag .2, large up step followed by large down step.

ESS maneuvering.

11 C3, Pitch Lag .5, large up step followed by large down step.

ESS maneuvering.

Pilot Comment: "Doesn't seem to want to hold altitude. Nose drops with full nose-up trim".

12 $\dot{\theta}$, Pitch Lag .1, large up step followed by large down step.

ESS maneuvering.

Pilot Comment: "Aircraft is smooth as glass - still a little quiver on the center stick but not as much as last time - real nice. Better trim in $\dot{\theta}$ - enough to hold altitude. Step commands get faster response than in C* modes - g's rise rapidly - aircraft feels real good. Wouldn't notice stick quiver if not looking for it".

13 $\dot{\theta}$, Pitch Lag .2, large up step followed by large down step.

ESS maneuvering.

Pilot comment: "Rapid response but not excessive".

14 $\dot{\theta}$, Pitch Lag .5, large up step followed by large down step. Small down step followed by small up step.

Pilot comment on small steps: "Very little response. Not noticeable on the down command".

15 C2, Pitch Lag .2, M_{SET} = .8, M = .8

Mach Trim engaged. Power was reduced and speed fell off. At .75 IMN nose dropped, speed increased to .8 IMN and nose started up. Speed was .83 IMN when aircraft nose continued up to 7° above horizon. (Note: Mach gain = 15).

16 Mach gain = 25. 20,000 ft., M = .8. Power off - speed fell to .75 then nose started down. Power on - airspeed builds up and nose starts up. It takes a change in Mach of .05 to start nose moving.

17 $\dot{\theta}$, .8 IMN Mach Trim engaged. Power off. Nose falls - passing .78 IMN nose starts up.

Pilot comment: "Mach Trim seems more sensitive in $\dot{\theta}$. Airspeed only went down to .78 IMN".

Large up step - Intend to hold for about 4 minutes. Ran out of airspace before nose started down. (Note: Pilot was operating in a 2,000 ft. altitude block).

Aircraft recorder out of paper. May have been out for a few minutes.

Pilot continued Mach Trim loop but no further significant observations.

Flight #3
(Observer's Record)

Date: 24 July 1969

Pilot: Major J. Taylor   Observer: Chas. Rowles

2. SOC on
3. C1, .1 Large up
4. C2, Large up
5. .5 Large up
6. C2, .1 Large up
7. .2 Large up
8. .5 Large up
9. C3, .1 Large up
10. .2 Large up
11. .5 Large up
12. $\dot{\theta}$, .1 Large up
13. .2 Large up
14. .5 Large up
15. C2, .2, Mach Trim on.
16. M. G. 25, .8
17. $\dot{\theta}$, M. G. 25, .8
18. C2, Large up ≈ 4 minutes
19. Out of paper.

Flight # 4

PILOT DEBRIEFING

Date: 25 July 1969

Pilot: Major J. Taylor

1. He is very pleased with the system. It is working well. The SOC seems to improve with age. There was very little oscillation in the C* modes toward the end of the flight, however at slow flight the oscillation is still present. The pilot feels that the oscillation is definitely aircraft short-period dynamics.

2. A thorough investigation of the Mach Trim loop was made. The pilot made several large speed changes and the Mach Trim loop worked very well. Aircraft response seemed to feel like that of the basic aircraft (almost). Pilot feels there is no need for a change in Mach Trim gain.

3. There was plenty of Pitch Trim authority today.

4. When the SOC is engaged with the Mach Trim on there is always a noseup transient of .5 to .8g. There is also a disengage transient. There is still no engage or disengage transient when Mach Trim is off.

4. Pilot prefers C* modes at higher speeds. The $\dot{\theta}$ response is too fast (too small a stick force/g?).

5. At end of flight pilot selected 17,000 ft., .4 IMN. C* response was very good - there was no oscillation.

6. The pilot reported that aircraft response was much better at the end of the flight. He suggested that the reason may be that the accelerometers had not been performing properly since it had been a long time since they had been exercised thoroughly. Speed on this flight was varied between .4 IMN and .9 IMN. G forces were as high as 4g. Altitude varied from 30,000 ft to 17,000 ft.

7. Pilot recommends no changes to system, at least until he has another flight in same configuration.

8. Pilot remarked that so far in the flight test program he has had no disengages nor even a warning light. It is too early (5 hours of flight test) to remark on reliability but at least we have a good start.

Flight #4

REPORT ON EVENTS
(From Pilot's In-Flight Notes)

Date: 25 July 1969

Pilot: Major J. Taylor

Event No.

1 — 21,000 ft., .7 Mach, C2, .2, Mach Trim on when engaged. Slight nose-up transient ≈ .5g. Oscillations started about 10 seconds after engage. Definitely aircraft short period. Not as bad as on Flight #3.

Mach Trim operated as expected. Mach = .7, set M_{SET} to .8. Aircraft nosed down and eventually settled down at .8.

Feels natural.

3 — Mach Trim Loop Tests.

4 — Step commands with Mach Trim Loop engaged.

5 — $\dot{\theta}$ mode experiments.

Note: Pilot later returned to C* mode but did not event it.

Note: Practically no information on the voice recording. Pilot was continually cut out by UHF radio transmissions from other aircraft and Flight Test Radar.

Flight #5

REPORT ON EVENTS

(From Pilot's Voice Recorder)

Date: 30 July 1969

Pilot: Major J. Taylor

Event No.

10 This is the response of the basic aircraft, no MB-5, no SOC. (Pilot excited aircraft short period in order to give us a basis for comparison.)

Recorder Off.

Note: Since the oscillations had virtually disappeared after severe maneuvering on Flight #4, it was agreed that the pilot would give the aircraft a good work-out prior to engaging the SOC.

11 Recorder On.

23,000 ft, Mach = .7

Mach Trim Off.

Roll Sensitivity = 3, Pitch Sensitivity = 4

C2 mode, Pitch Lag = .2

12 SOC Engage.

Pilot Comments: "With full left wing down Roll Trim, the aircraft still wants to roll to the right. There is a little bit of Pitch oscillation, same as at the beginning of the last flight".

22,000 ft, Mach = .7

Large up step command

Followed by large down step command

Recorder Off.

Pilot went through maneuvers with SOC engaged.

Pilot Comments: "Oscillations are still there - not too large - not too abrupt - slightly annoying. In

C* modes, and aircraft oscillating, switching to $\dot{\theta}$ immediately stops the oscillations. When switching back to C* mode, the oscillations start immediately. Also in $\dot{\theta}$ mode, Pitch Trim is good - have to reset Pitch Trim to neutral. Roll Trim is barely sufficient to keep aircraft level in $\dot{\theta}$. Switching back to C*, both Roll Trim and Pitch Trim are insufficient."

13 Recorder On.

C2 Mode, Pitch Lag = .2

Mach Trim On.

22,000 ft, M_{SET} = .7, Mach = .7

14 Small up step command.

Pilot Comment: "Cannot feel response - switching to large step command."

15 Large up step command.

Pilot Comments: "Oscillations get larger in magnitude as airspeed decreases. Oscillations at slow speeds cause 1.5° peak-to-peak oscillation on angle of attack indicator - not observable on g meter."

Pilot Question: "Can the shift in c.g. cause a change in oscillations?"

Recorder Off.

16 Recorder On.

$\dot{\theta}$ mode.

Mach Trim On.

Large up step command.

Pilot Comment: "Much more responsive reaction in $\dot{\theta}$."

Recorder Off.

Recorder On.

C2 mode, 35,000 ft, 6500 lbs fuel.

Pilot Comment during maneuvers: "Still have small oscillations - not as large as earlier in the flight - oscillations almost gone."

Flight # 5

PILOT DEBRIEFING

Date: 30 July 1969

Pilot: Major J. Taylor

1. The aircraft responded the same way as in Flight #4. There is still not enough nose-up Pitch Trim. Also, with full left wing down Roll Trim, the right wing tends to go down. Pilot had to hold left wing down roll command on ESS to maintain level flight.

2. Pitch Trim in $\dot{\theta}$ mode is O.K. Roll Trim is barely sufficient with full left wing down trim.

3. Pilot likes $\dot{\theta}$ very much. It is very smooth and there are no oscillations.

   Note: At higher and lower speeds, the pilot has experienced a preference for C*.

4. The Mach Trim operates better in $\dot{\theta}$ mode; gives faster response. There is no need to change the gain on Mach Trim.

   Note: Pilot uses maximum setting on Mach Gain.

Flight # 6

PILOT DEBRIEFING

Date: 5 August 1969

Pilot: Lt. Col. Zimmerman Observer: Mr. Wm. Ahrendt

This was the first familiarization flight for Col. Zimmerman. He seemed to be favorably impressed with the SOC. The 1.2 Hz oscillations were present, but only mildly annoying. The pilot commented several times on the center stick "chatter". Col. Zimmerman and Mr. Ahrendt determined that this chatter was not present on the airframe.

Voice and oscillograph recordings were obtained. (Voice recording has not yet been transcribed.)

Flight # 7

PILOT DEBRIEFING

Date: 7 August 1969

Pilot: Major J. Taylor   Observer: Mr. Wm. Ahrendt

1. The pilot reported that the oscillations previously noted in C* modes had completely disappeared. Chatter on the center stick is now present in all modes.

2. A preference for C* modes at high q was noted. At medium q there appears to be little difference between C* and $\dot{\theta}$.

3. Data for one flight condition, 10,000 Mach .55, was recorded.

4. While returning to the field the pilot lowered the landing gear and flaps with the SOC engaged. The landing configuration was flown down to 4000 ft. and 160 KIAS. Control was very good.

Flight #7

REPORT ON EVENTS
(From Pilot's Voice Recorder)

Date: 7 August 1969

Pilot: Major J. Taylor

Event No.

2 Basic autopilot.

C2, Pitch Lag .2, 20,000 ft., Mach = .7.

SOC engaged.

Pilot Comment: "No oscillations. Looks better than before. Looks like we have a winner."

C3.

Pilot Comment: "No oscillations. Looks real good. Still has chatter on stick."

$\dot{\theta}$.

Pilot Comment: "Chatter on the stick is the same in all modes - like it was in $\dot{\theta}$ before."

C2.

Recorder off.

Pilot Comment: "It's really nice - I'm glad we got it fixed."

Pitch lag to .5 then to .1.

Pilot Comment: "I can see a difference today. It seems more sluggish at .5."

3 Recorder on.

Mach = .7, M_{SET} = .7, Mach gain = Max.

14,000 ft., Mach Trim on.

Pilot Comment: "It settled down right on .7."

Flight #7 (Continued)

4 Recorder on.

Engage and disengage with Mach Trim on.

Pilot Comment: "Still get transient with Mach Trim on. Not with Mach Trim off."

Autopilot kicked off.

Autopilot on.

SOC engaged.

$\dot{\theta}$, Mach Trim off.

11,000 ft, 7800 lbs. fuel. High speed, pulled 3.8 g's.

Pilot Comment: "In C* the damping is faster, very positive. At higher q, C* feels better. $\dot{\theta}$ feels like the aircraft will overshoot. Can tell no difference at medium q."

5 10,000 ft.

Deceleration and acceleration.

Trimmed for level flight.

6 275 Kts. 11,000 ft.

Decelerate - "Aircraft holds altitude."

Accelerate - "Works as advertised."

Recorder on.

20,000 ft., Mach = .55.

C2, Pitch Lag = .2

7 Large up step command.

8 $\dot{\theta}$, large up step command.

Fuel = 5000 lbs.

9 M_{SET} = .5, Mach = .55.

C2, 20,000 ft., Fuel = 4500 lbs.

Mach Trim on.

Large up step command.

Recorder off.

10 Recorder on.

$\dot{\theta}$.

Large up step command with Mach Trim on.

Pilot Comment: "Quicker, better damped response in $\dot{\theta}$. It flys so good I hate to turn it off."

Recorder off.

Recorder on.

Pilot Comment: "I like the SOC better with Mach Trim on."

Gear and flaps down. 4000 ft.

Pilot Comment: "Nice handling - better than the center stick."

SOC off.

Pilot Comment: "It seems strange to go back to the center stick."

Flight # 8

PILOT DEBRIEFING

Date: 8 August 1969

Pilot: Major J. Taylor

1. Very good flight. Two flight conditions were completed.

2. The SOC feels very good. Pilot reaction to the SOC is becoming more favorable with each flight.

3. Outline of the flight is as recorded on the voice recorder.

Flight #8

REPORT ON EVENTS
(From Pilot's Voice Recorder)

Date: 8 August 1969

Pilot: Major J. Taylor

SOC engaged - C2, Pitch Lag = .2
Pilot Comment: "Feels good, real smooth."

Event No.

5 — 20,000 ft., Mach = .9.
Large step command up.

6 — C2, Pitch Lag = .2.
Large up step command.
Switch to $\dot{\theta}$.

7 — Large step command up.
Mach Trim on. $M_{SET} = .9$.

8 — C2, Pitch Lag = .2.
Large up step command.
Recorder off.
Switch to $\dot{\theta}$.
Recorder on.

9 — Large up step command.
Recorder off.
Switch to C2.

10 — 35,000 ft., Mach = .75, C2, Pitch Lag = .2.
Large up step command.
Recorder off.

Flight #8 (Continued)

Switch to $\dot{\theta}$.

Recorder on.

11 Large up step command.

Step command probably distorted as it pulled aircraft into CSL. Definitely faster response in $\dot{\theta}$.

Recorder off.

Mach Trim on.

Switch to C2.

Recorder on.

12 Large up step command.

Disregard event 12. Pilot had to break off before response was completed.

13 Large up step command.

Airspeed dropped to .71.
Airspeed up to .76.
Airspeed stabilized at .75.

Recorder off.

Switch to $\dot{\theta}$.

Recorder on.

14 Large up step command.

Jerky response. Up against CSL.

15 Small up step command.

Recorder off.

C2, Mach Trim on.

Recorder on.

16 Small up step command.

Recorder off.

End of flight.

Flight # 9

PILOT DEBRIEFING

Date: 8 August 1969

Pilot: Major J. Taylor Observer: Mr. Wm. Ahrendt

1. The oscillograph failed during take-off so there are no recordings for this flight.

2. The pilot found moderately rough air and evaluated SOC gust response. The SOC seemed to damp out what little aircraft reaction that occurred.

3. Flight through the transonic range was up to 1.2 IMN at 35,000 ft., was evaluated. There was good control throughout. (C2, Pitch Lag = .2). It was found that Roll sensitivity at supersonic speeds is reduced. The pilot had to increase Roll sensitivity to position #5.

4. The SOC feels good at supersonic speeds. $\dot{\theta}$ control is too sensitive at these speeds. The pilot expressed the opinion that he would probably choose the C* modes for all flight conditions, but that $\dot{\theta}$ was also very good at the intermediate conditions.

Flight #9

REPORT ON EVENTS

(From Pilot's Voice Recorder)

Note: Oscillograph went out on take-off. No record obtained.

Pilot Comments:

1. Trying gust response. Not really rough air but SOC seems to be damping out what there is.

2. Supersonic. Mach = 1.2 at 35,000 ft. SOC feels good. No noticeable effect in transonic range. (C2, Pitch Lag = .2).

3. Trying Pitch Lag = .5. No noticeable difference. Roll sensitivity at 1.2 is reduced. Needs position 5.

4. Feels good at supersonic speeds. Like C* modes at these speeds.

Flight # 10

PILOT DEBRIEFING

Date: 11 August 1969

Pilot: Major J. Taylor

1. The pilot experienced trouble with the MB-5 from the beginning of the flight. Whenever the AFCS was engaged the aircraft would go into a steady nose up position. He was quite pleased that, in this condition, he could engage the SOC and control the aircraft normally.

2. The true airspeed computer was faulty during the first part of the flight but appeared to be working normally during calibration runs. Pilot was able to complete the Mach Trim part of the runs.

3. The aircraft was grounded for faulty vertical gyro and faulty CADC at the end of the flight.

Flight #10

REPORT ON EVENTS

(From Pilot's Voice Recorder)

Date: 11 August 1969

Pilot: Major J. Taylor

Event No. (Voice Recording begins here).

10,000 ft., Mach = .45.
CADC True Airspeed Computer not functioning.

Recorder on.

9 Engage SOC and disengage SOC to see if autopilot still bad. SOC on.

10 C2, Pitch Lag = .2, 10,000 ft., Mach = .45.

Large up step command.

Switch to $\dot{\theta}$.

11 Large up step command.

Recorder off.

Switch to C2.

Mach Trim on. M_{SET} = .45. M = .45.

Recorder on.

12 Large up step command.

Recorder off.

Switch to $\dot{\theta}$.

13 Large up step command.

Pilot Comment: "It really goes after it in $\dot{\theta}$."

Recorder off.

Mach Trim off.

Switch to C2, Pitch Lag = .2.

10,000 ft., Mach = .8.

14 Recorder on.

15 Large up step command.

Switch to $\dot{\theta}$.

16 Large up step command.

Recorder off.

Switch to C2.

Mach Trim on. $M_{SET} = .8$.

Recorder on.

17 Large up step command.

Recorder off.

Switch to $\dot{\theta}$.

Flight aborted due to faulty MB-5.

Flight # 11

PILOT DEBRIEFING

Date: 20 August 1969

Pilot: Lt. Col. Zimmerman   Observer: Mr. Wm. Ahrendt

Colonel Zimmerman appeared quite pleased with the SOC operation. He flew from .88 IMN down to landing configuration and landing speed. He stated the SOC was particularly good in the landing configuration.

The pilot noted two "problems" -

1. He usually got a transient when he engaged Mach Trim. He assumed that the Mach Set switch settings were IMN. When it was explained that these settings were for true Mach, and when the function of the Pitch Trim wheel with Mach Trim engaged was explained, he agreed that the reason for the Mach Trim engage transient was that Mach Set was appreciably different from true Mach when Mach Trim was engaged.

2. He stated that "the center of Roll Trim appeared to be shifting". With any significant change in airspeed he had to re-trim in Roll. It was explained to him that the Roll axis control was not a part of present tests but that the problem would be investigated.

At the conclusion of the debriefing Colonel Zimmerman stated that he had now gained confidence in the SOC and was looking forward to future flights. He brought up the subject of landing with the SOC engaged. It was explained to him that actual landings with the SOC engaged were not intended to be part of the test program.

Flight #11

REPORT ON EVENTS
(From Pilot's Voice Recorder)

Date: 20 August 1969

Pilot: Lt. Col. Zimmerman Observer: Mr. Wm. Ahrendt

Event No.

SOC Engage. 20,000 Ft., Mach = .6, C2, Pitch Lag = .2, Pitch sensitivity = .4, Roll sensitivity = .4.

Pilot Comments: "Much better than last time." "Feels pretty good."

Recorder on.

1 Mach Trim off. Large up step command.

Recorder off.

2 Recorder On. Mach Trim off. Large up step command.

Recorder off.

Recorder on.

Mach Trim on. $\dot{\theta}$.

3 Large up step command.

Recorder off. SOC off.

Recorder on. SOC on. $\dot{\theta}$. Mach Trim on.

4 Large up step command.

Mach Gain maximum.

Recorder off.

Recorder on.

5 Large up step command.

Recorder off.

Recorder on. C2 mode. Pitch Lag = .2.

6 Large up step command. Mach Trim on.

Pilot comment: "Seems to be better response in C2."

Recorder on. Mach = .88 IMN, C2. Mach Trim on.

7 Large up step command.

Recorder off.

Recorder on. Mach = .88 IMN, $\dot{\theta}$. Mach Trim on.

8 Large up step command.

Recorder off.

Flight # 12

PILOT DEBRIEFING

Date: 22 August 1969

Pilot: Lt. Col. Zimmerman Observer: Mr. Wm. Ahrendt

1. Calibration runs at 20,000 ft., .6 IMN were run in C2 and $\dot{\theta}$, both with Mach Trim off and on.

2. Pilot was well satisfied with the way the SOC responds and feels. He is eager to get the calibration runs completed so that the qualitative evaluation can be started.

3. The authority of the Pitch Trim wheel with Mach Trim engaged was investigated. It was confirmed that this authority is at least .1 Mach on either side of Mach set.

Flight #12

REPORT ON EVENTS

(From Pilot's Voice Recorder)

Date: 22 August 1969

Pilot: Lt. Col. Zimmerman   Observer: Mr. Wm. Ahrendt

Event No.	
1	20,000 ft. Mach = .6.
	SOC on. Mach Trim off.
	Recorder off.
	C2, Pitch Lag = .2.
2	Recorder on.
	Large up step command.
	Recorder off.
	Switch to $\dot{\theta}$.
	Stick chatter seems to be reduced.
	[Note: New cards (621-2) being used.]
	Recorder on.
3	Large up step command.
	Recorder off.
	Recorder on.
4	C2, Large up step command.
	Recorder off.
5	$\dot{\theta}$. Mach Trim on.
	Large up step command.
	Recorder off.
	Switch to C2.
	Recorder on.

Flight #12 (Continued)

6 C2, Large up step command.

Mach Trim on.

Recorder off.

Trim for level flight.

Pitch Trim wheel reads -6.

Recorder on.

7 Mach Trim on. Mach = .7, M_{SET} = .7.

Recorder off.

Mach Trim off. M_{SET} = .7, Mach = .7.

Pitch Trim wheel reads -6.
Recorder on.

8 Mach Trim on.

Retrim aircraft. Pitch Trim wheel reads -9.5.

Full up on Pitch Trim wheel.

Aircraft slowed to Mach = .6 IMN.

Recorder off.

Full nose down on Pitch Trim wheel.

Aircraft increased to Mach = .82 IMN.

Mach Trim on.

Mach = .7 IMN.

Full nose up on Trim wheel.

Recorder on.

SOC on.

Mach Trim off.

Mach Trim on.

Recorder off.

Flight # 13

PILOT DEBRIEFING

Date: 5 September 1969

Pilot: Major J. Taylor Observer: Mr. Wm. Ahrendt

The entire flight went off without a hitch. SOC power was left on from the first turn-on, on the ground, until return to base. The SOC was engaged at 4000 ft. and the pilot attempted a climb at .7 IMN, Mach Trim on, using power to control the rate of climb. Mach Trim is too sluggish with present parameters for precise speed holding, with the aircraft "hunting" approximately ± .05 IMN around Mach set. A Mach Trim descent was tried at the end of the flight with the same results.

All test points were flown for 35,000 ft., Mach .95. In addition, two points were obtained at 35,000 ft., Mach 1.3. SOC response was very smooth throughout the flight.

One rather severe transient in Roll was encountered toward the end of the flight. In trying to counter this transient there appeared to be no Roll control on the ESS. The pilot disengaged the SOC and AFCS and recovered using normal control.

Flight #13

REPORT ON EVENTS

(From Pilot's Voice Recorder)

Date: 5 September 1969

Pilot: Major J. Taylor   Observer: Mr. Wm. Ahrendt

C2, Pitch Lag .2, Mach Trim off, 35,000 ft., .95 Mach.

Event No.

2 — Recorder on.

Recorder off.

3 — Recorder on.

Large up step command.

4 — $\dot{\theta}$. Large up step command.

Recorder off.

Switch to C2, Mach Trim on.

5 — Recorder on.

Large up step command.

Pilot comment: "At .95 slight changes in speed requires change in Roll Trim."

Recorder off.

Switch to $\dot{\theta}$, Mach Trim on.

Recorder on.

6 — Large up step command.

Recorder off.

Switch to C2.

35,000 ft., Mach 1.3.

Recorder on.

7 Large up step command.

Switch to $\dot{\theta}$.

8 Large up step command.

Recorder off.

Flight # 14

PILOT DEBRIEFING

Date: 8 September 1969

Pilot: Major J. Taylor Observer: Mr. C. Rowles

Flight condition 35,000 ft., Mach 1.3 was completed. The SOC operation was very smooth. The pilot noted that the "chatter" on the center stick was considerably reduced.

(Note: This was Maj. Taylor's first flight with the modified 621-2 cards.)

Due to extensive afterburner operation no further check points could be flown. However, during return to base the pilot made a few shallow simulated bombing runs with Mach Trim off. He was extremely pleased with the ease of acquiring the target and the lack of pilot effort required to maintain his point of aim. He also commented favorably upon the fact that no trim changes were required during the bombing runs.

Flight #14

REPORT ON EVENTS
(From Pilot's Voice Recorder)

Date: 8 September 1969

Pilot: Major J. Taylor Observer: Mr. C. Rowles

35,000 ft., Mach = 1.3, C2, Pitch Lag .2, Mach Trim on.

Recorder on.

Event No.

2 Large up step command.

Recorder off.

Switch to $\dot{\theta}$.

Recorder on.

3 Large up step command.

Recorder off.

Switch to C2, Mach Trim off.

10,000 ft., Mach = 0.95.

Recorder on.

4 Small up step command.

5 Large up step command.

Recorder off.

Flight # 15

PILOT DEBRIEFING

Date: 8 September 1969

Pilot: Major J. Taylor Observer: Mr. Wm. Ahrendt

Flight condition 10,000 ft., Mach 0.95 was flown. Flight condition 35,000 ft., maximum Mach was attempted but the pilot elected to abort the flight when the fire warning light came on upon selection of afterburner.

Turbulance at 10,000 ft. was noticeable but not severe. SOC response in the turbulence appeared to be quite good.

Flight # 15

REPORT ON EVENTS

(From Pilot's Voice Recorder)

Date: 8 September 1969

Pilot: Major J. Taylor Observer: Mr. Wm. Ahrendt

C2, Pitch Lag = .2, Mach Trim off. 10,000 ft., Mach = 0.95.

Event No.

2 Recorder on.

Large up step command.

Pilot comment: "We have some turbulence."

Switch to $\dot{\theta}$

3 Large up step command.

Recorder off.

C2, Mach Trim on, Mach set = 0.9.

Pilot comment: (1) "Seems to handle that turbulence pretty good." (2) "It's handling that turbulence pretty good."

4 Large up step command.

Recorder off.

Switch to $\dot{\theta}$.

Recorder on.

5 Large up step command.

Recorder off.

Pilot comment: "May have to do those points over at 10,000 ft. There was a reasonable amount of turbulence there."

35,000 ft. V_{MAX}, C2, Pitch Lag = .2, Mach Trim off.

Recorder on.

Note: Flight aborted due to fire warning light.

Flight # 16

PILOT DEBRIEFING

Date: 9 September 1969

Pilot: Major J. Taylor

Observer: Mr. C. Rowles

One point flown at 35,000 ft, V_{MAX}, C2, Pitch Lag .2, Mach Trim on. SOC operation was normal.

The flight was aborted due to a fire warning light.

Flight // 16

REPORT ON EVENTS

(From Pilot's Voice Recorder)

Date: 9 September 1969

Pilot: Major J. Taylor

Observer: Mr. C. Rowles

Event No.

1 Ground shot.

Recorder off.

Recorder on.

V_{MAX} = 1.4, C2, Pitch Lag = .2.

35,000 ft., Mach Trim on.

2 Large up step command.

Flight aborted due to fire warning light.

Flight #17

PILOT DEBRIEFING

Date: 29 September 1969

Pilot: Major J. Taylor Observer: Mr. Wm. Ahrendt

The pilot reported that the oscillations noted during the first few flights were back again. They seemed to be exactly the same as before.

He attempted to obtain data at 35,000, V_{max}, but doubts if it will be useable.

Note: Upon checking immediately after the flight, it was discovered that the resistor in the filter network, which had been placed on the accelerometer output, was on the wrong pin in the junction box. Correction was made and the SOC operated normally on the following flight on 29 September.

Flight # 17

REPORT ON EVENTS

(From Pilot's Voice Recorder)

Date: 29 September 1969

Pilot: Major J. Taylor   Observer: Mr. Wm. Ahrendt

"There are the old oscillations back."

Recorder on.

"Don't want to take it supersonic today. Data probably wouldn't be any good anyway."

Switch to $\dot{\theta}$.

"Oscillations disappear. Must be something associated with the accelerometer output."

"Seems just like the first flights."

SOC off.

Basic autopilot. "Seems O.K."

Recorder on.

Event No.

3   SOC on. C2.

Pilot Comment: Oscillation with just little nose up input is almost like PIO. It seems as if the filter put on the accelerometer output is missing."

Note: This was actually the problem. See note to pilot debriefing.

Flight # 18

PILOT DEBRIEFING

Date: 29 September 1969

Pilot: Major J. Taylor Observer: Mr. C. Rowles

The oscillations noted on Flight #17 were no longer present. The SOC operated normally.

This was the first of the flights for qualitative evaluation of the SOC. Formation flying and ILS approaches were evaluated. Formation flying without Mach Trim and with Mach Trim was conducted. The pilot remarked favorably on the ease of aircraft control. The C2 mode was preferred. θ mode was too sensitive for smooth control. The pilot preferred the Mach Trim off for formation flying.

ILS approaches with Mach Trim off, Mach Trim on, and in basic aircraft were flown. There were no problems. Aircraft is easy to control both with Mach Trim on and off. Both were easier than basic aircraft.

There was moderate turbulence at low altitude but SOC handled it very well.

Flight # 18

REPORT ON EVENTS

(From Pilot's Voice Recorder)

Date: 29 September 1969

Pilot: Major J. Taylor Observer: Mr. C. Rowles

"Oscillations not there now. It's flying like it used to."

Formation Flying

"ESS feels unnatural for formation flying. Putting in a nose down command feels strange."

"Feels good after you get used to the ESS."

"I think I prefer the Mach Trim off for formation flying."

"θ mode is a little sensitive. Prefer C* mode."

"Feels good in formation. Only problem is that the side stick feels unnatural."

Event No.

3 Recorder on for ILS Approach.

Pilot Comment: "Feels real nice in approach. At low speeds we have to fly against CSL limits and can't quite hold attitude."

Second ILS with Mach Trim on.

Third ILS with SOC off - basic airplane.

Pilot Comment: "There is mild turbulence on all these low altitude passes. It gave the SOC a pretty good workout."

Flight # 19

PILOT DEBRIEFING

Date: 30 September 1969

Pilot: Major J. Taylor Observer: Mr. C. Rowles

Obtained all check points at 35,000 ft., V_{max}. IMN was 1.4 to 1.5.

SOC operated normally.

At the end of the flight when power was reduced, Mach Trim on, the nose dropped and negative g limit was exceeded. The SOC disengaged but was re-engaged normally.

This was a short flight, .6 hrs., due to extensive after-burner operation.

Flight # 19

REPORT ON EVENTS

(From Pilot's Voice Recorder)

Date: 30 September 1969

Pilot: Major J. Taylor

Observer: Mr. C. Rowles

35,000 ft., V_{max}

C2 mode, Pitch Lag = .2

Event No.

3 Recorder on.

Mach Trim on.

1.4 IMN.

Large up step command.

Mach Trim off.

4 Large up step command.

Switch to $\dot{\theta}$.

Mach Trim on.

1.4 IMN.

Large up step command.

Mach Trim off.

1.5 IMN.

Large up step command.

Mach Trim on.

5 1.45 IMN.

Large up step command.

Switch to C2

Negative g limit disengage.

Flight # 19 (continued)

Event No.

5(cont) Mach Trim off.

SOC engage.

Flight # 20

PILOT DEBRIEFING

Date: 30 September 1969

Pilot: Major J. Taylor   Observer: Capt. D. Ghertson

Acceleration and deceleration tests were run at 20,000 ft. SOC maintained attitude during large changes in airspeed. Also maintained attitude when speed brakes were extended and retracted. (Mach Trim off)

Simulated bombing attacks, 30° dive angle from 20,000 ft. to 5,000 ft. were conducted. Very easy to stay on target in basic SOC (Mach Trim off). Pilot stated he is beginning to appreciate neutral speed stability for certain tasks. He would like the capability to switch on and off as desired.

Low altitude (3,000 ft.), high speed (450 KIAS) tracking. C2, Mach Trim off is preferred. Very easy to follow road used as target. $\dot{\theta}$ mode is too sensitive for this task. With Mach Trim on, considerable retrimming is required. Moderate turbulencce but SOC handles very well.

Flight // 20

REPORT ON EVENTS

(From Pilot's Voice Recorder)

Date: 30 September 1969

Pilot: Major J. Taylor

Observer: Capt. D. Ghertson

Recorder on. C2, Pitch Lag = .2
20,000 ft., 230 KIAS, Mach Trim on.

Event No.

2 Acceleration from 230 Knots to .7 IMN, followed by deceleration. Mach Trim on.

Pilot Comment: "It is more difficult to put in smooth commands with Mach Trim on."

Recorder off.

Mach Trim off.

SOC off.

3 Acceleration and deceleration with basic aircraft.

Simulated bombing attack. 20,000 ft. to 8,000 ft., 230 KIAS to 450 KIAS. 30° dive angle.

Simulated bombing attack in CSS mode. Same conditions.

SOC on, C2, Mach Trim off. Same conditions.

Recorder on.

4 Roll in at 20,000 ft., 240 KIAS, 32° dive angle.

Pilot Comment: "Hard to put in nose down command using ESS. Pipper stays on target once it is there. If pipper is below target, it is easy to bring it up."

5 Mach Trim on, roll-in at 20,000 ft., IMN = .7, 28° dive angle.

6 C2, Mach Trim off, roll-in at 20,000 ft., about 30° dive angle.

7 Simulated landing pattern at 9,000 ft. Speed brakes out. Speed brakes in. Flaps down. Landing gear down.

"Holding up against CSL. Hard to hold nose up."

Simulated flare-out. Gear up.

8 Mach Trim on, M_{SET} = .5. Simulated landing pattern.

Gear down.

Flaps down.

Pilot Comment: "CSL limits control authority below 180 KIAS."

Recorder off.

Low altitude, 3,000 ft., high-speed tracking. Mach Trim off, C2 mode.

Switch to $\dot{\theta}$.

Pilot Comment: "Uncomfortable. Hard to turn without pulling too much 'g'".

Switch to C2. Mach Trim on. 0.7 IMN.

Flight // 21

PILOT DEBRIEFING

Date: 1 October 1969

Pilot: Major J. Taylor Observer: Mr. C. Rowles

Simulated air-to-air combat, simulated in-flight refueling, air-to-air tracking (tail chase), and TACAN approaches to go around were evaluated during this flight. All maneuvers were evaluated in both C2 and $\dot{\theta}$ modes and with the Mach Trim off and on. They were also flown in the basic aircraft mode.

The pilot feels that the $\dot{\theta}$ mode is not suitable for these tasks. The C2 mode was very good, with the Mach Trim on or off; however, he prefers the Mach Trim off. In either case, the C2 mode is better than basic aircraft only. Very little pilot effort is required over the wide change of rapidly changing flight conditions.

The pilot again expressed some dissatisfaction with the ESS, especially when making nose down inputs. He likes the idea of a side stick controller, but feels that this particular model needs improvement.

The pilot stated that he likes the SOC, especially in the C2 mode with Mach Trim off.

Note: The canopy seal sprang a leak early in the flight creating so much cockpit noise that the voice recording could not be read.

Flight // 22

PILOT DEBRIEFING

Date: 3 October 1969

Pilot: Lt. Col. R. C. Zimmerman Observer: Capt. Ghertson

This was a familiarization flight for the pilot. He feels he is now ready to commence qualitative evaluation flights. He feels comfortable flying the SOC.

Flight // 22

REPORT ON EVENTS

(From Pilot's Voice Recorder)

Date: 3 October 1969

Pilot: Lt. Col. R. C. Zimmerman Observer: Capt. Ghertson

"Working out pretty well again as usual."
This after trying C1, C2, and C3.

"Can't tell much difference in C* modes."
Made actual TACAN penetration.

APPENDIX IV

SOC SYSTEM CLOSED-LOOP C* PERFORMANCE SPECIFICATION

The SOC system closed-loop C* performance specification is given by the two curves in Figure IV.1, labeled "SOC SPECIFICATION UPPER BOUNDARY, C*", and "SOC SPECIFICATION LOWER BOUNDARY, C*". These curves are functions of normalized F_{ESS-P}, it being assumed that a step change from 0 to 1 in normalized F_{ESS-P} occurs at time 0.

The specification upper and lower boundaries apply for the ten simulated flight conditions given in the main text of this report. System response falling on or lying between the specification boundaries is acceptable provided that the response is smooth, i.e., does not contain high-frequency modes of excessive amplitude superimposed on the dominant response.

The broken curve labeled "MODEL (EXPECTED SOC RESPONSE)" is the nominal response of the SOC system for a model time constant of 0.2 Sec.

Category I, II, and III envelopes shown on Figure IV.1 are based on several independent studies of aircraft short-period handling qualities requirements and appear as Figure 3 in Boeing Document D6-17841 T/N, New Short Period Handling Quality Criterion for Fighter Aircraft, L. G. Malcolm and H. N. Tobie, Nov. 10, 1965.

> "The Category I envelope is considered the requirement where optimum response is required. Flight conditions where this envelope may be applicable are: ground attack, penetration, aerial combat, etc.
>
> The Category II envelope is considered the requirement for satisfactory response where the piloting task is not as critical as for Category 1. Flight conditions

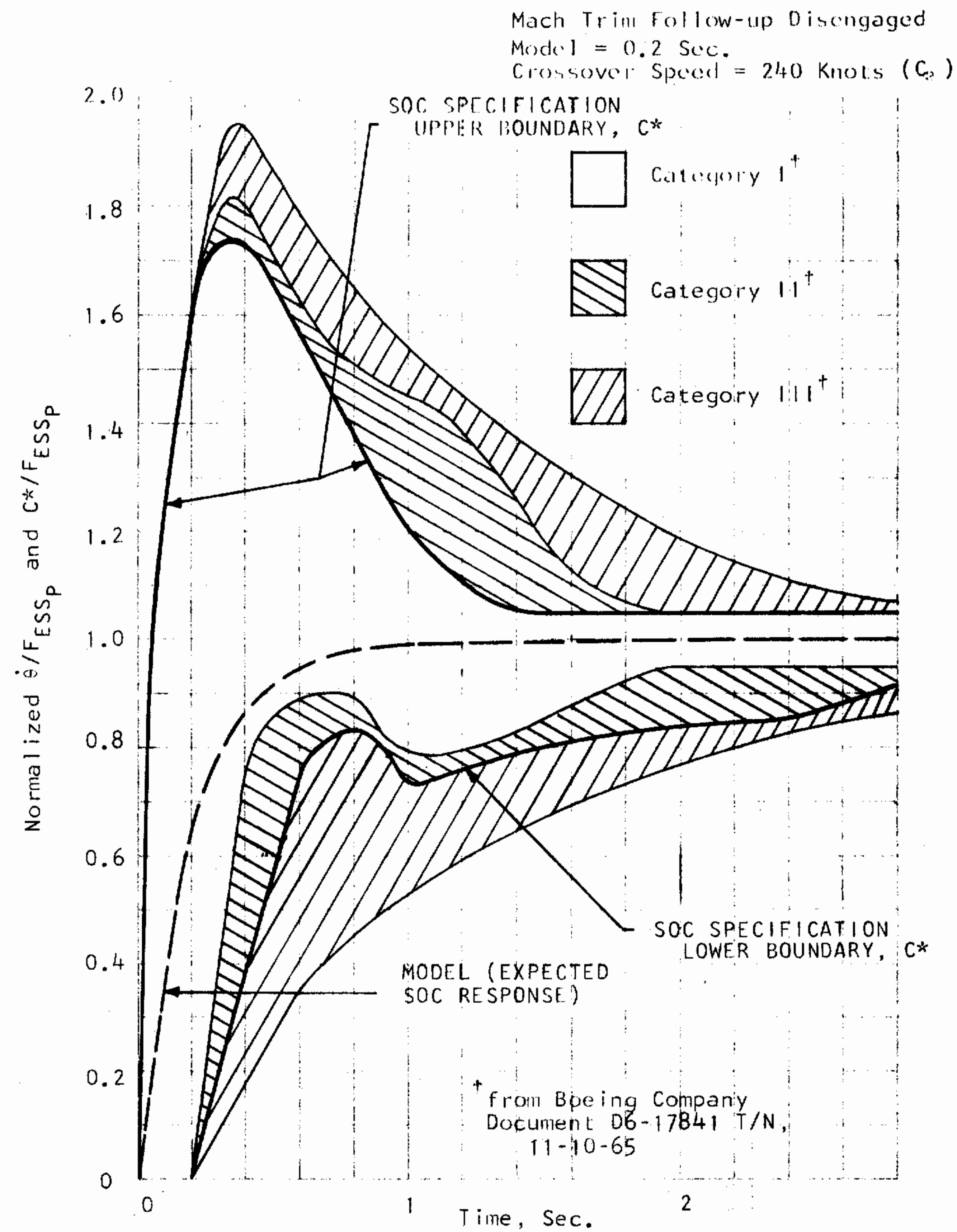

Figure IV.1: SOC System Closed-Loop C* Performance Specification where this envelope may be applicable are: refueling, cruise, etc. This envelope is the proposed envelope presented in NADC-ED-6282, where a detailed discussion is given." (Malcolm and Tobie, p. 8)

The specification upper boundary is identical with the Category I upper boundary, while the lower boundary is identical with the Category II lower boundary.

Figures IV.2 through IV.7 are representative of responses obtained during flightworthiness testing. Flight Conditions 5, 6, and 7 were chosen as being representative of the ten flight conditions tested. Flight Condition 6 produces the highest "q", Flight Condition 7 the lowest, and Flight Condition 5 produces an intermediate "q".

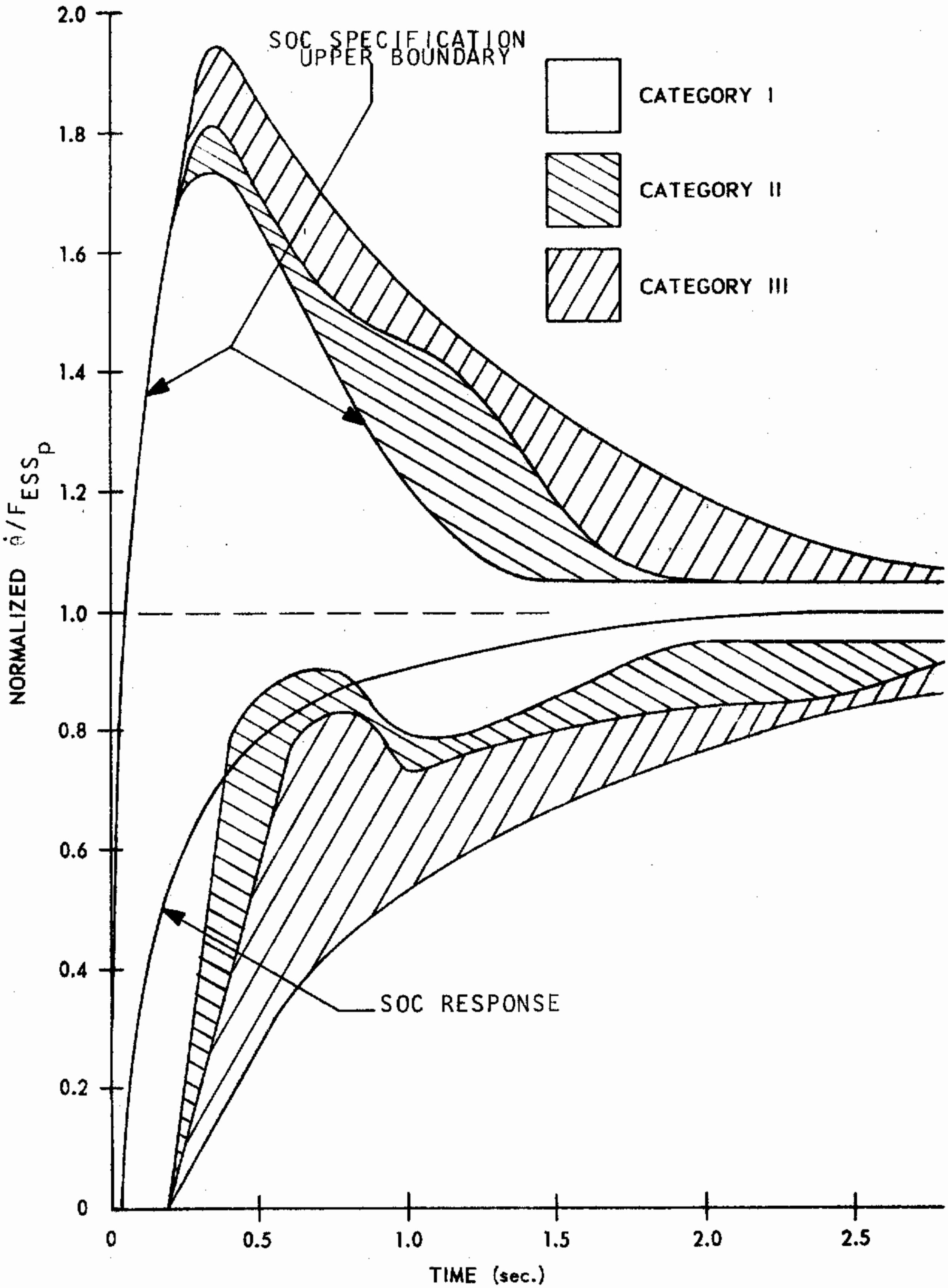

Figure IV.2: Flight Condition Nr. 5, $\dot{\theta}$ Command = +2.5 Deg./Sec., Model = 0.2 Sec.

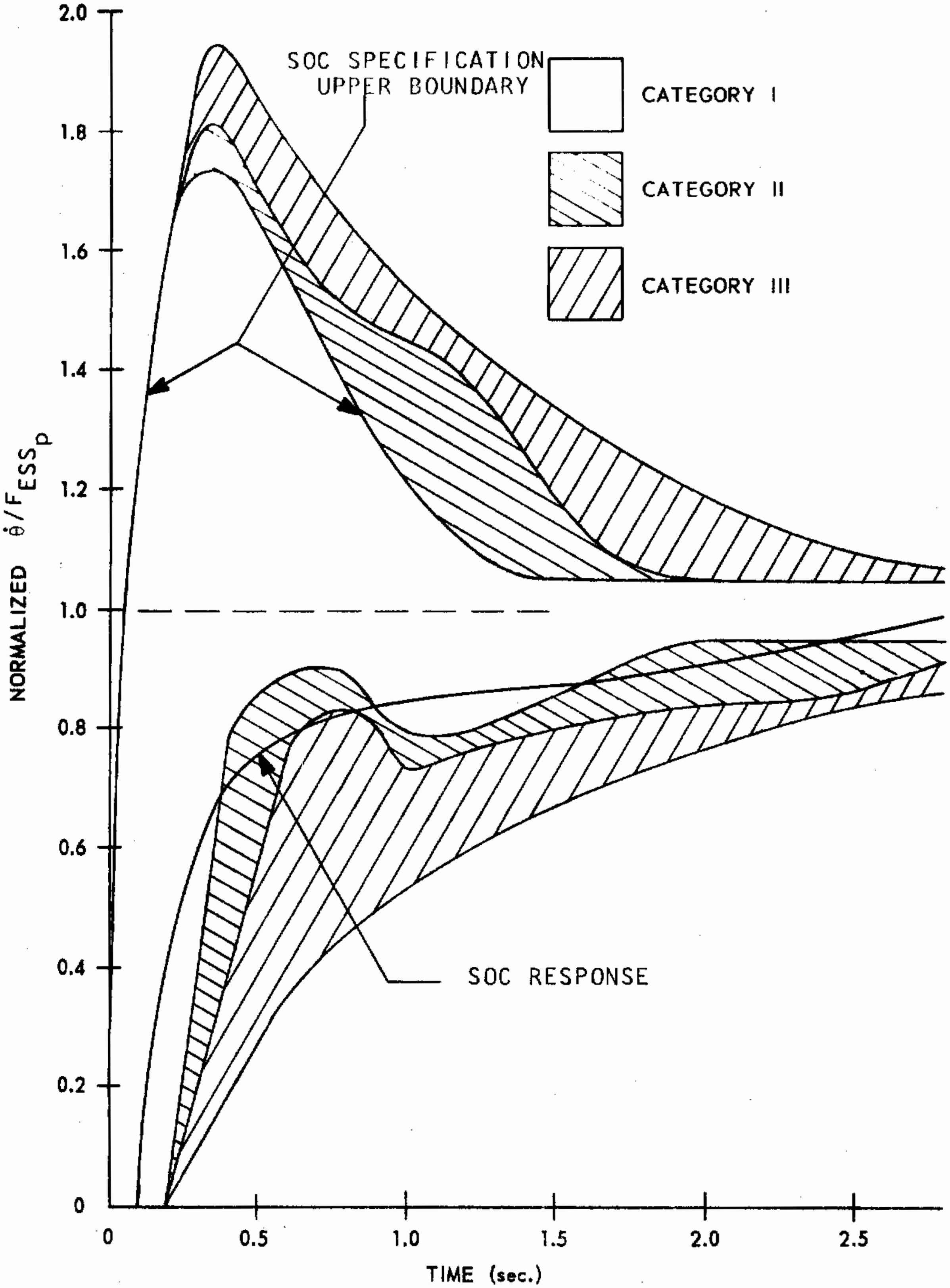

Figure IV.3: Flight Condition Nr. 6, $\dot{\theta}$ Command = +2.5 Deg./Sec., Model = 0.2 Sec.

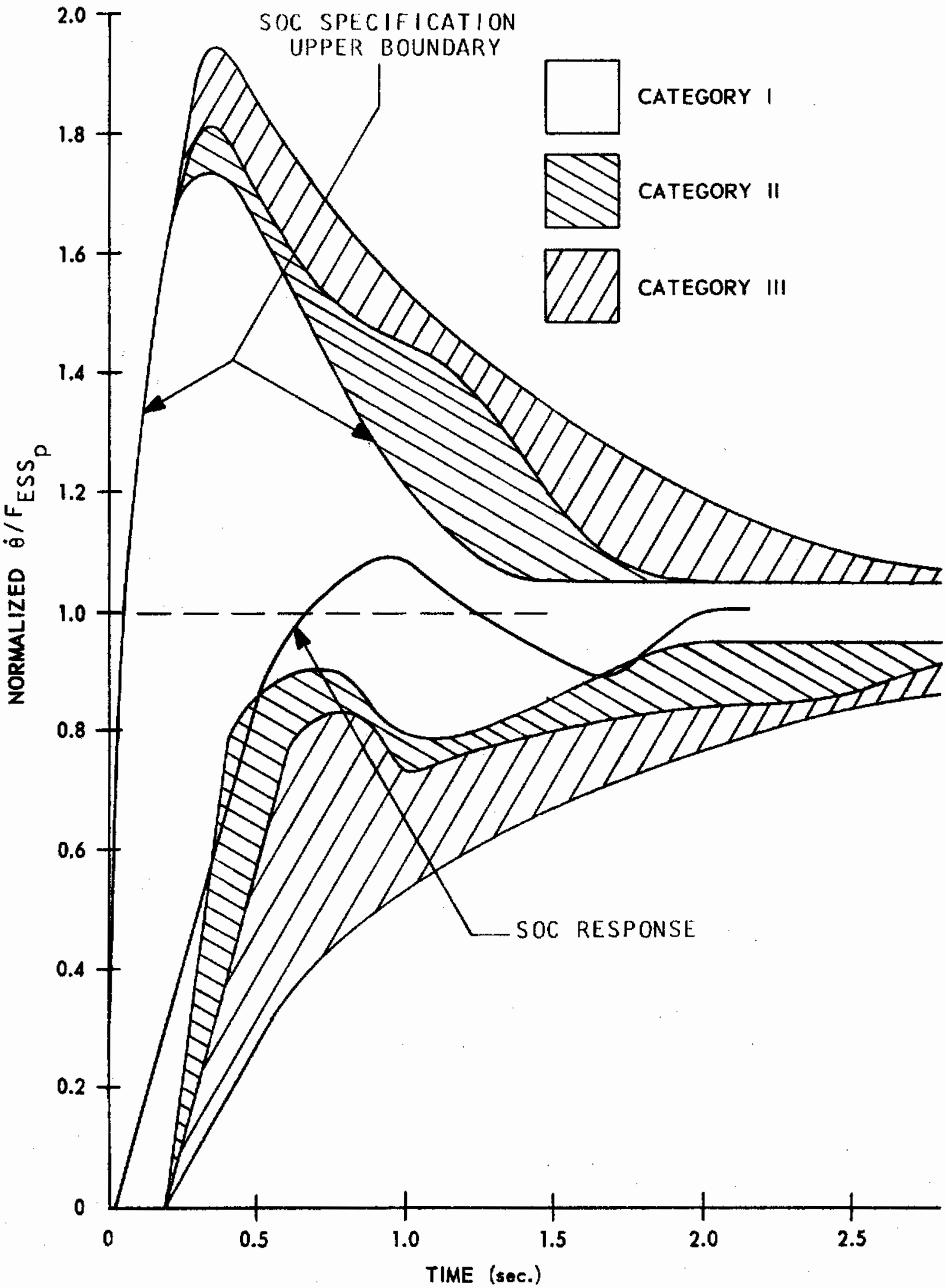

Figure IV.4: Flight Condition Nr. 7, $\dot{\theta}$ Command = +2.5 Deg./Sec., Model = 0.2 Sec.

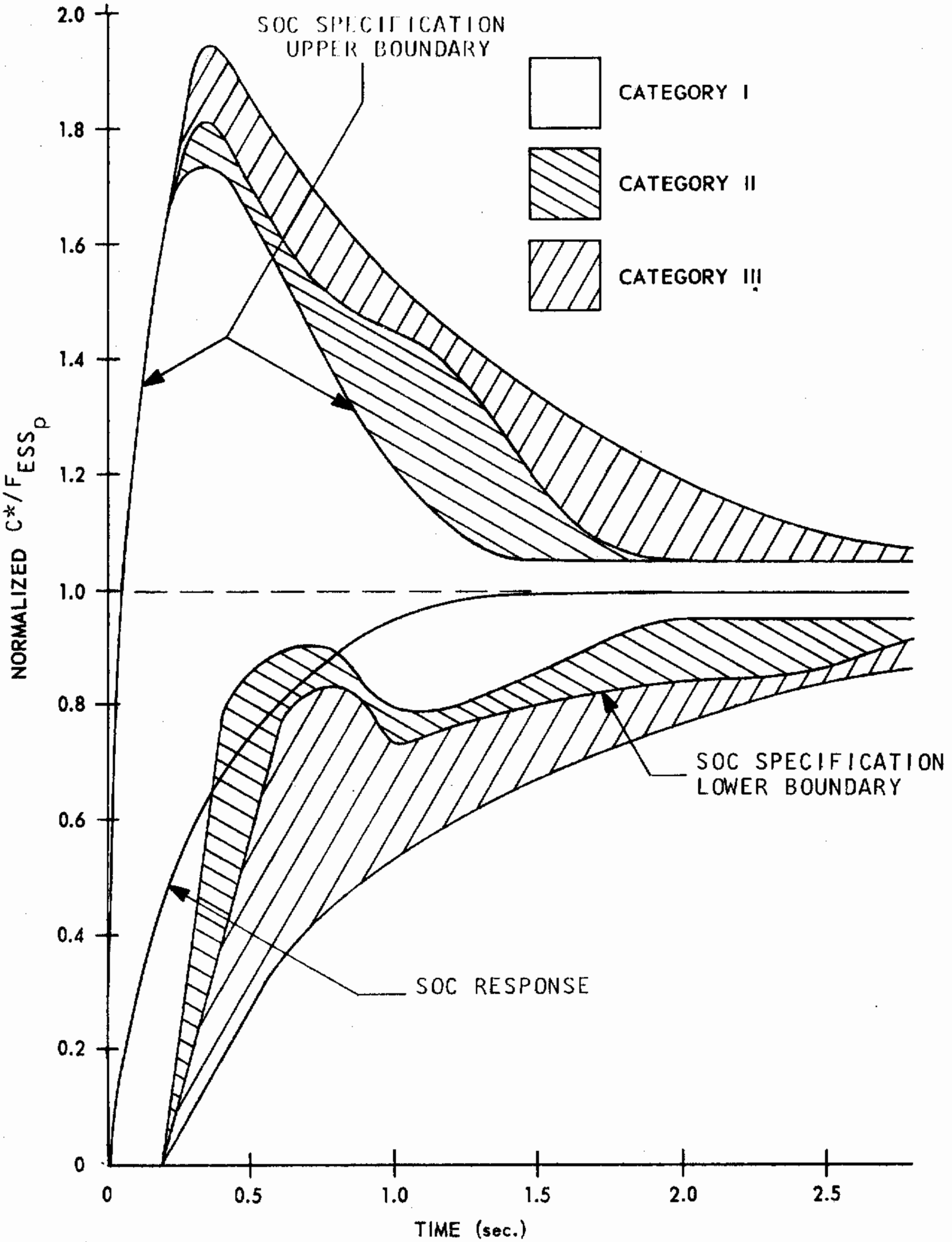

Figure IV.5: Flight Condition Nr. 5, C* Command = +2 g,
Model = 0.2 Sec.

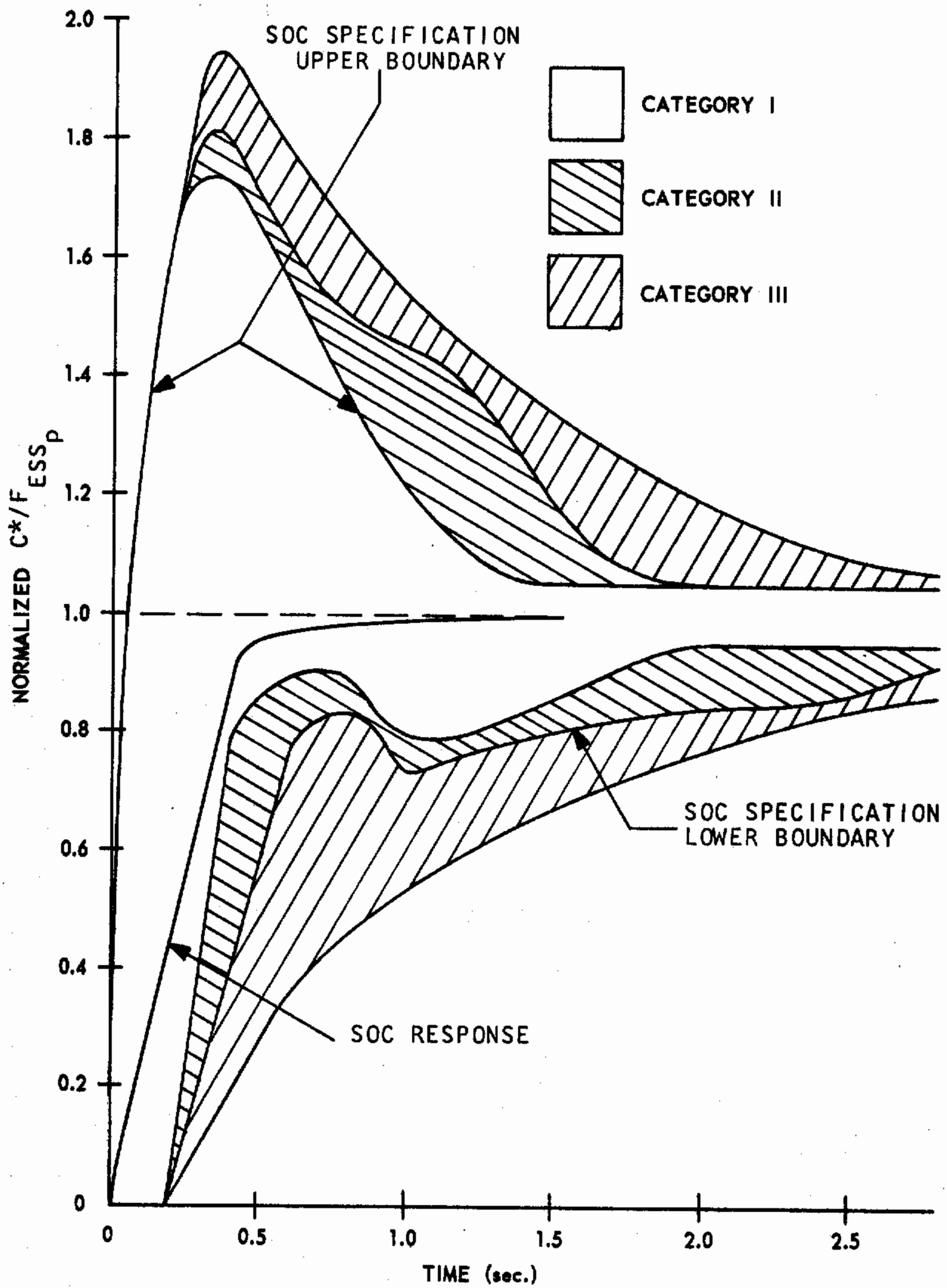

Figure IV.6: Flight Condition Nr. 6, C* Command = +2 g, Model = 0.2 Sec.

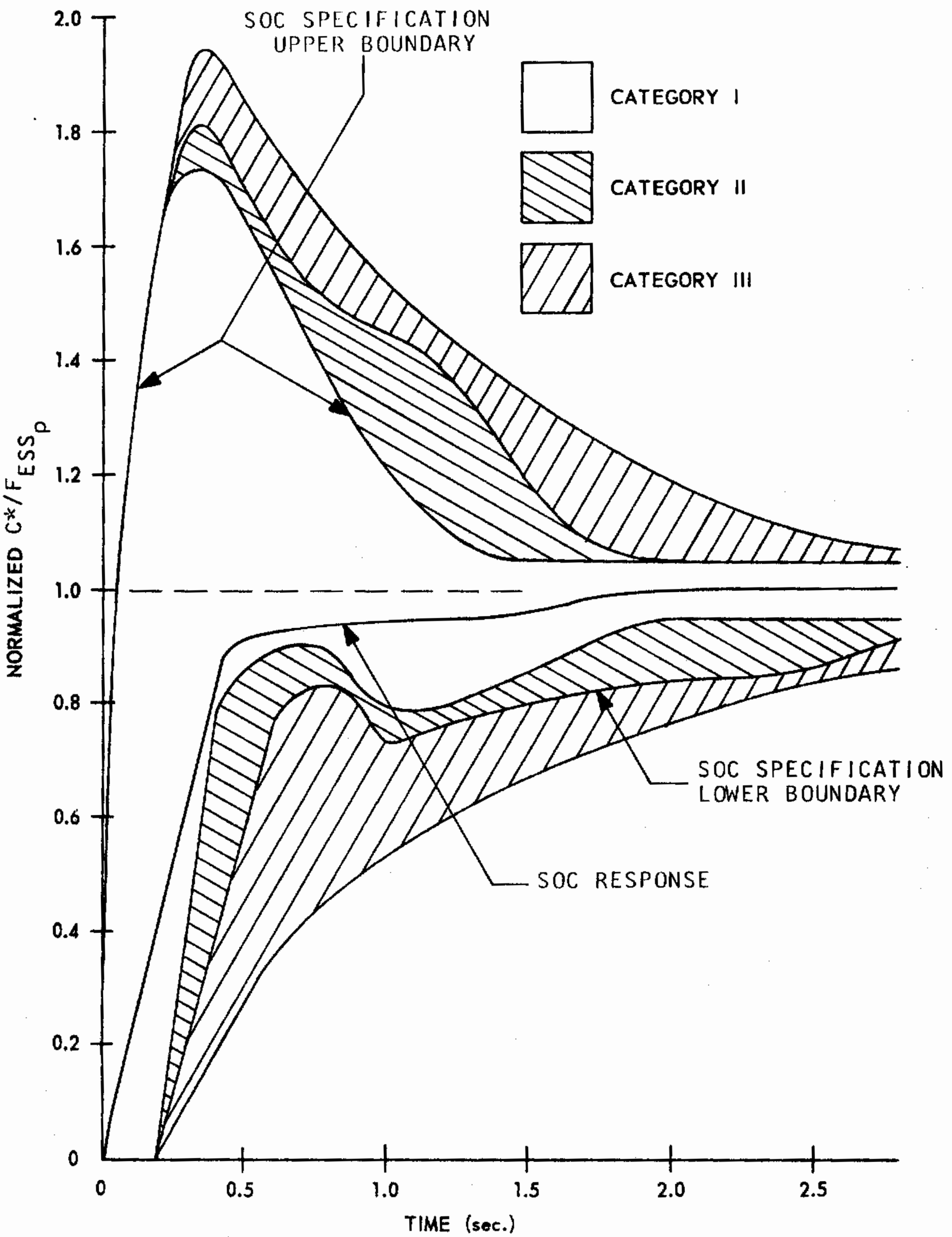

Figure IV:7: Flight Condition Nr. 7, C* Command = +2 g, Model = 0.2 Sec.

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13. ABSTRACT This report summarizes design characteristics, simulations, bench tests, and flight tests of an elementary self-organizing controller (SOC) for the pitch axis of the F-101B aircraft. This controller was flown with a cockpit electric side stick in a pseudo-fly-by-wire configuration, that is, as a fly-by-wire system with a normally disengaged mechanical backup. Blended pitch-rate and forward normal acceleration feedback (C*) and stabilator position feedback were the primary return signals used by the SOC. An optional Mach Trim loop was also investigated. The SOC, which incorporated unique modulated-noise circuits to minimize adverse effects of control-loop nonlinearities, had full authority over the aircraft stabilator within the inherent rate and position limits of the actuator. 32 test flights were conducted with the SOC, constituting a total flying time of approximately 40 hours. These flights encompassed nearly the entire performance envelope of the F-101B and included piloting tasks representative of missions flown with current fighter aircraft. The Air Force pilots rated the SOC between A1 and A2 on the CAL Revised Pilot Rating Scale. There were no in-flight malfunctions of the SOC equipment.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
flight control systems self-organizing control self-adaptive control fly-by-wire control probability state variable systems						

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