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V/STOL TILT ROTOR AIRCRAFT STUDY PILOTED SIMULATOR EVALUATION OF THE BOEING VERTOL MODEL 222 TILT ROTOR AIRCRAFT

VOLUME IX

FEBRUARY 1973

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Prepared Under Contract No. NAS2-6598 by
BOEING VERTOL COMPANY
A Division of the Boeing Company
P. O. Box 16858
Philadelphia, Pennsylvania 19142
for
Ames Research Center
National Aeronautics and Space Administration
and
United States Army Air Mobility Research & Development Laboratory
Ames Directorate

Boeing D222-10068-1

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V/STOL TILT ROTOR AIRCRAFT STUDY
PILOTED SIMULATOR EVALUATION OF THE
BOEING VERTOL MODEL 222 TILT ROTOR AIPCRAFT

VOLUME IX

By: H. Rosenstein
M. A. McVeigh
P. A. Mollenkof

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FOREWORD

This report is one of a series prepared by The Boeing Vertol Company, Philadelphia, Pennsylvania for the National Aeronautics and Space Administration, Ames Research Center, Moffett Field, California under contract NAS2-6598. The studies reported under Volumes I through IV and VIII through X were jointly funded by NASA and the U. S. Army Air Mobility Research and Development Laboratory, Ames Directorate. Volumes V through VII were funded by the U. S. Air Force Flight Dynamics Laboratory, Wright Patterson Air Force Base, Ohio.

This contract was administered by the National Aeronautics and Space Administration. Mr. Richard J. Abbott was the Contract Administrator, Mr. Gary B. Churchill, Tilt Rotor Research Aircraft Project Office, was the Technical Monitor, and coordination and liaison with the U. S. Air Force Flight Dynamics Laboratory was through Mr. D. Fraga. The Boeing Vertol Company Project Engineer for the work presented in this report was Mr. H. Rosenstein.

The complete list of reports published under this contract is as follows:

Volume I	--	Conceptual Design of Useful Military and/or Commercial Aircraft, NASA CR-114437
Volume II	--	Preliminary Design of Research Aircraft, NASA CR-114438
Volume III	--	Overall Research Aircraft Project Plan, Schedules, and Estimated Cost, NASA CR-114439
Volume IV	--	Wind Tunnel Investigation Plan for a Full Scale Tilt Rotor Research Aircraft, CR-114440
Volume V	--	Definition of Stowed Rotor Research Aircraft, NASA CR-114598
Volume VI	--	Preliminary Design of a Composite Wing for Tilt Rotor Aircraft, NASA CR-114599
Volume VII	--	Tilt Rotor Flight Control Program Feedback Studies, NASA CR-114600

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Volume VIII -- Mathematical Model for a Real Time Simulation of a Tilt Rotor Aircraft (Boeing Vertol Model 222), NASA CR-114601

Volume IX -- Piloted Simulator Evaluation of The Boeing Vertol Model 222 Tilt Rotor Aircraft, NASA CR-114602

Volume X -- Performance and Stability Test of a 1/4.622 Froude Scaled Boeing Vertol Model 222 Tilt Rotor Aircraft (Phase I), NASA CR-114603

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NOMENCLATURE

Symbol	Definition	Units
h	Aircraft altitude	Ft.
$\dot{h}$	Aircraft rate of climb	Ft/sec
i_N	Nacelle angle	Rad.
p	Aircraft roll rate, positive when rolling clockwise (right wing down)	Rad/sec
q	Aircraft pitch rate, positive when pitching nose up	Rad/sec
r	Aircraft yaw rate, positive when yawing nose right	Rad/sec
u	Aircraft longitudinal component of velocity	Ft/sec
v	Aircraft lateral component of velocity	Ft/sec
α_F	Fuselage angle of attack	Deg.
β_F	Fuselage sideslip angle	Deg.
δ_B	Longitudinal stick position, positive aft	Inches
$\delta_{B_{SAS}}$	Longitudinal SAS link position	Inches
δ_{TH}	Power lever/collective control position	Inches
δ_e	Elevator angle, positive trailing edge down	Rad.
δ_f	Flap angle, positive wing trailing edge down	Deg.
δ_r	Rudder pedal position, right rudder positive	Inches
$\delta_{r_{SAS}}$	Rudder pedal SAS link position	Inches

NOMENCLATURE

Symbol	Definition	Units
δ_s	Lateral stick position, positive to the right	Inches
$\delta_{s_{SAS}}$	Lateral SAS link position	Inches
θ	Aircraft pitch attitude, positive nose up	Deg.
$\theta_{0.75}$	Rotor collective pitch at three quarters radius station	Deg.
ϕ	Aircraft roll attitude, positive right wing down	Deg.
ψ	Aircraft yaw attitude, positive nose right	Deg.
$\Delta\Omega$	Change in rotor rotational speed	Rad/sec

1.0 SUMMARY

This document presents the results of a real time piloted simulation conducted to investigate the handling qualities and performance of the Boeing Model 222 tilt rotor aircraft design as described in Reference (1). This piloted evaluation was conducted during the period from September 25, 1972 through October 28, 1972. Since this was the first piloted simulation of the Model 222, the run program (which is shown and described in Section 8 of this document) was set up to broadly cover all regimes of flight (hover, transition, cruise, climbs, descents, etc.) and to identify potential problem areas. During the above mentioned time period approximately 34 hours of piloted simulations were conducted.

The aircraft represented in this simulation was the Model 222 as described in Boeing Vertol's preliminary design study of March 1972 (Reference 1). It differs from the aircraft of Boeing Vertol's January 1973 proposal in several respects, the most important being: -

(a) The simulation model had outboard flaperons and spoilers only, whereas the January 1973 aircraft has full span flaperons and spoilers.

(b) The simulation model had .6 rad/sec^2 control power in pitch and 1.0 rad/sec^2 in roll, compared to 1.2 rad/sec^2 and 2.0 rad/sec^2 respectively for the January 1973 proposal.

(c) The load alleviation system on the model senses nacelle pitching and yawing moments to feed back into cyclic pitch. The January 1973 aircraft senses pitch and yaw angle and dynamic pressure.

(d) The longitudinal stability augmentation system in this simulation model incorporated a pitch attitude feedback loop. In addition, the SAS moved the elevator and longitudinal cyclic pitch actuators. In the January 1973 proposal the pitch attitude feedback was removed from the stability augmentation system and incorporated into the autopilot, and the longitudinal SAS moves only the longitudinal cyclic pitch actuator. These changes were made in order to simplify the design of the aircraft.

An eleven degree-of-freedom mathematical model i.e., 6 airframe, rotor RPM, first wing vertical bending and torsion and 2 nacelle degrees of freedom was formulated and is described

in Volume VIII of this series of reports. The mathematical model was mechanized and used to drive the Boeing Small Motion Base Flight Simulator (SMBFS). The SMBFS provides initial motion cues only and was modified to represent the Model 222. These modifications included the addition of power lever/collective pitch control mounted on the left arm rest with a nacelle incidence switch located on the grip, an instrument panel designed to represent the tilt rotor, and an appropriate force feel system. Other elements of the pilot's control system i.e., beep trim, mag. brake, stick and pedals were satisfactory and required no modification. The command pilot in the Model 222 is in the right seat.

Visual displays were computer-generated and projected onto a screen in front of the pilot. Two displays were used for this evaluation; a ship deck for hover and a mountainous scene with a road and telephone poles for the cruise mode. The majority of the piloted simulation was however, conducted using the road only.

The Model 222 tilt rotor aircraft was evaluated at the design gross weight of 12,000 lbs. with the nacelle-horizontal center of gravity located at 28% chord (most aft center of gravity at this weight).

The run program consisted of pilot familiarization, hover mode studies, transition mode studies, cruise mode studies, evaluation of maximum nacelle rates in transition and helicopter flight mode studies. Salient findings and conclusions are as follows:

1. An efficient cockpit design (instrument panel layout and placement of primary controls) is required to minimize pilot workload during transition.

2. There is no "best way" of trimming the Model 222 in transition and reconversion. Since the pilot has a nacelle tilt control, it is possible to trim the aircraft at many different combinations of tilt angle, and body attitude.

3. The Model 222 was flown from hover to maximum speed and back to a hover with the stability augmentation system off.

4. The aircraft is docile and easy to control through transition and reconversion. The changes made in the longitudinal SAS in the January 1973 proposal

and described in item (d) above could impact on the docile transition and reconversion characteristics on the 100 to 140 knot speed range. These should be re-evaluated by piloted simulation.

5. Relatively low rotor inertia requires careful design and tailoring of the thrust and power management system to insure precise altitude hold capability in hover low speed flight modes.

6. The Model 222's longitudinal handling characteristics in the cruise mode (nacelle horizontal and SAS off) are satisfactory. The cruise mode lateral directional evaluation showed a coupled roll/spiral mode from the end of transition to maximum speed, and high dihedral effect. These were annoying to the pilot but easily controllable. These can be completely eliminated by SAS feeding back roll rate into rudder, and sideslip angle into aileron.

7. The descent/deceleration/wing stall boundary in the helicopter mode was investigated. These preliminary evaluations indicate that if the wing is allowed to stall during steep approaches, the rate of descent builds up rapidly and recovery close to the ground may be difficult. It is felt that insufficient cues in the nudge base simulator (such as changes in noise level and no buffet onset indication) and relative pilot unfamiliarity with the vehicle are complicating factors and additional pilot training and familiarization would obviate any problem in this area.

   With the wing leading edge umbrellas or with spoilers open, descent capability is improved. It should be noted that descent rates up to 1500 ft/min at low speed have been achieved.

8. A preliminary evaluation of maximum nacelle til rates in rapid acceleration transitions and reconversions was conducted. One rapid transition and reconversion run was conducted with the nacelle tilt rate limited to 5°/sec (nominal maximum value is 10°/sec). The pilot indicated that lower maximum rates might be desirable in the high speed end of transition (100 KT → 140 KTS) to minimize pitch attitude changes at these conditions, while higher nacelle rates are acceptable at lower speeds. Additional work is required in this area to evaluate the desirability of establishing a schedule of maximum nacelle tilt rates, and to optimize control scheduling.

2.0 INTRODUCTION

Piloted simulation is a useful and important tool in the design, development and test of new flight vehicles. Figure 1 shows a summary of some of these uses as they could be applied to the Model 222 Tilt Rotor.

As a part of Contract NAS2-6598 Boeing Vertol developed a mathematical model of the Model 222 Tilt Rotor aircraft, intended primarily for use with the FSAA at Ames. As a further addition to the same contract Boeing Vertol programmed this math model on its hybrid computer and used it to drive the Small Motion Base Flight Simulator for preliminary pilot evaluation of a tilt rotor aircraft. The results of this simulation are presented in this report.

- Evaluation of Tilt Rotor Handling Qualities
  - o Stability and Control
  - o Control System Optimization
  - o Evaluation of Man-in-the-Loop System Compatibility
  - o Evaluation of Malfunction Effects
- Evaluation of Tilt Rotor Performance
  - o Maneuver Capability
  - o VTOL and STOL Takeoff and Landing Capability
- As a Tool to Evaluate Configuration Changes
  - o Changes in Cockpit Layout
  - o Changes in Tail Size
  - o Changes in Geometry
  - o Changes in SAS Configuration
  - o Changes in Elastic Characteristics
- As a Flight Test Support Tool
  - o Development of Emergency Techniques
  - o Familiarization of Flight Crews with Aircraft Characteristics Prior to Flight
  - o Correlation Studies
  - o Exploration of Flight-Discovered Phenomena

FIGURE 1. SUMMARY OF USES FOR PILOTED FLIGHT SIMULATION

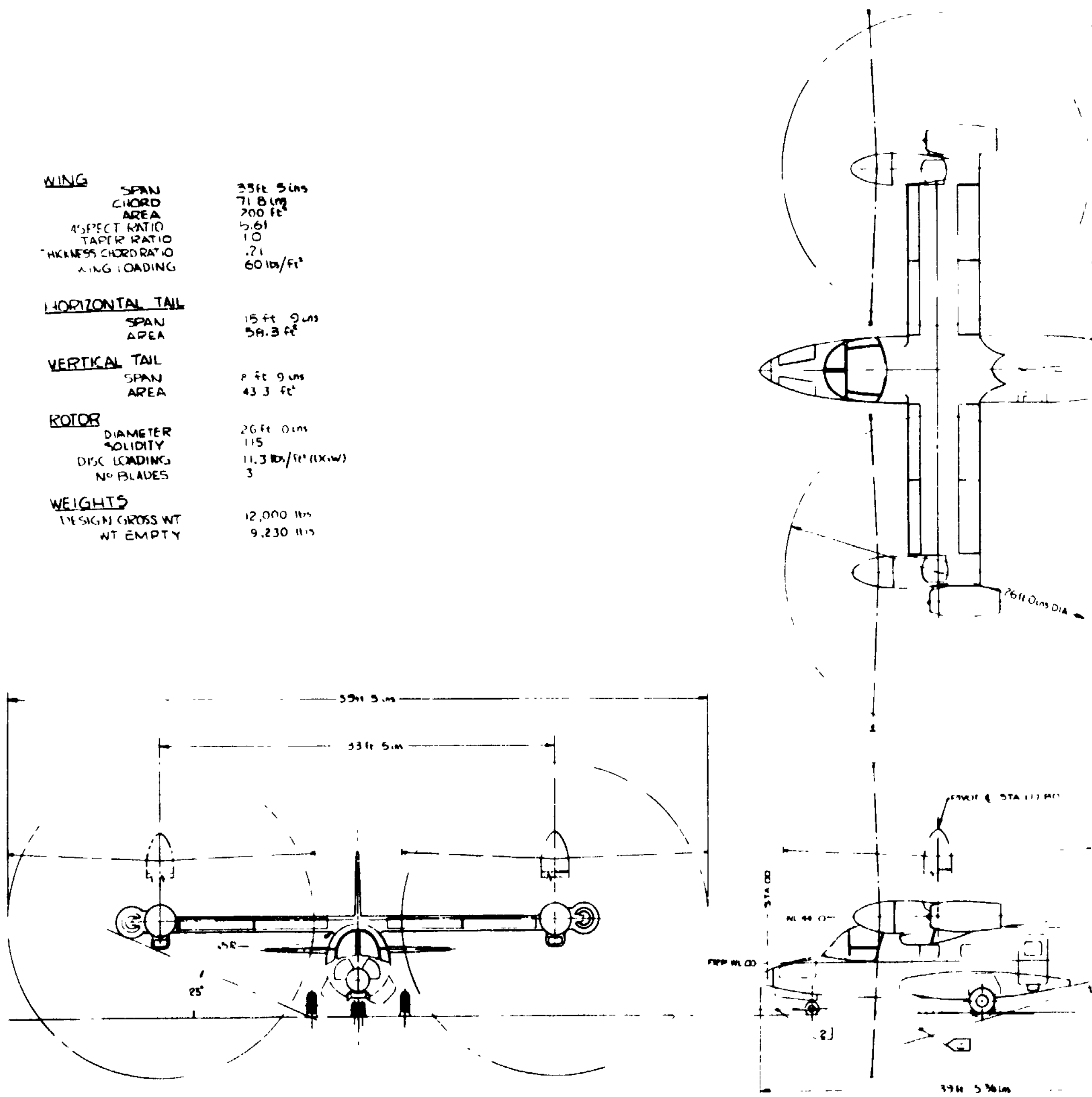
3.0 AIRCRAFT DESCRIPTION

The Boeing Model 222 Tilt Rotor Research Aircraft is a three place, twin turbine engine aircraft, with two rotors displaced laterally and is designed to demonstrate "Proof of Concept" for follow-on military or commercial tilt rotor airplanes. Figure 2 is a 3-view of the aircraft and provides the general arrangement and salient dimensional data. It should be noted that the aircraft simulated is the March 1972 version of the model, as described in Reference 1. The aircraft incorporates two 1550 horsepower Lycoming T53-L-13B engines (modified), each driving a three-bladed, soft-in-plane hingeless rotor. The rotors are interconnected by cross shafts, which transfer single engine power to both rotors in the event of an engine failure. Wing leading edge umbrellas, coupled with 30% chord single-slotted flaps capable of 70° deflection, are used at hover and low forward speed to minimize vertical drag or download on the wing. These have been programmed to open or close at a dynamic pressure corresponding to 50 KIAS, and a nacelle angle of 75°.

Control of the Model 222 is accomplished utilizing rotor longitudinal cyclic, differential cyclic, rotor thrust, and differential collective control in conjunction with airplane control surfaces. The airplane control surfaces consist of elevator, rudder and aileron/spoiler controls. The rotor controls provide the major portion of the control power at low speeds but are phased out as a function of decreasing nacelle incidence angle as speed increases and the airplane controls become relatively more effective. Figure 3 presents a summary of the primary moment-producing controls for each of the three flight modes.

In the version of the Model 222 used for this simulation, the thrust vectoring effect of longitudinal cyclic is amplified by providing a soft mounting for the nacelle in pitch so that the hub moment generated by cyclic tilts the nacelles simultaneously for longitudinal control and differentially for directional control. Note that in later versions of the aircraft the same effect is obtained by positive actuation of the nacelle. An artificial feel system is provided which varies the control feel forces about all three axes as a function of dynamic pressure to improve control force harmony and provide desirable levels of feel forces for handling qualities and flight safety considerations.

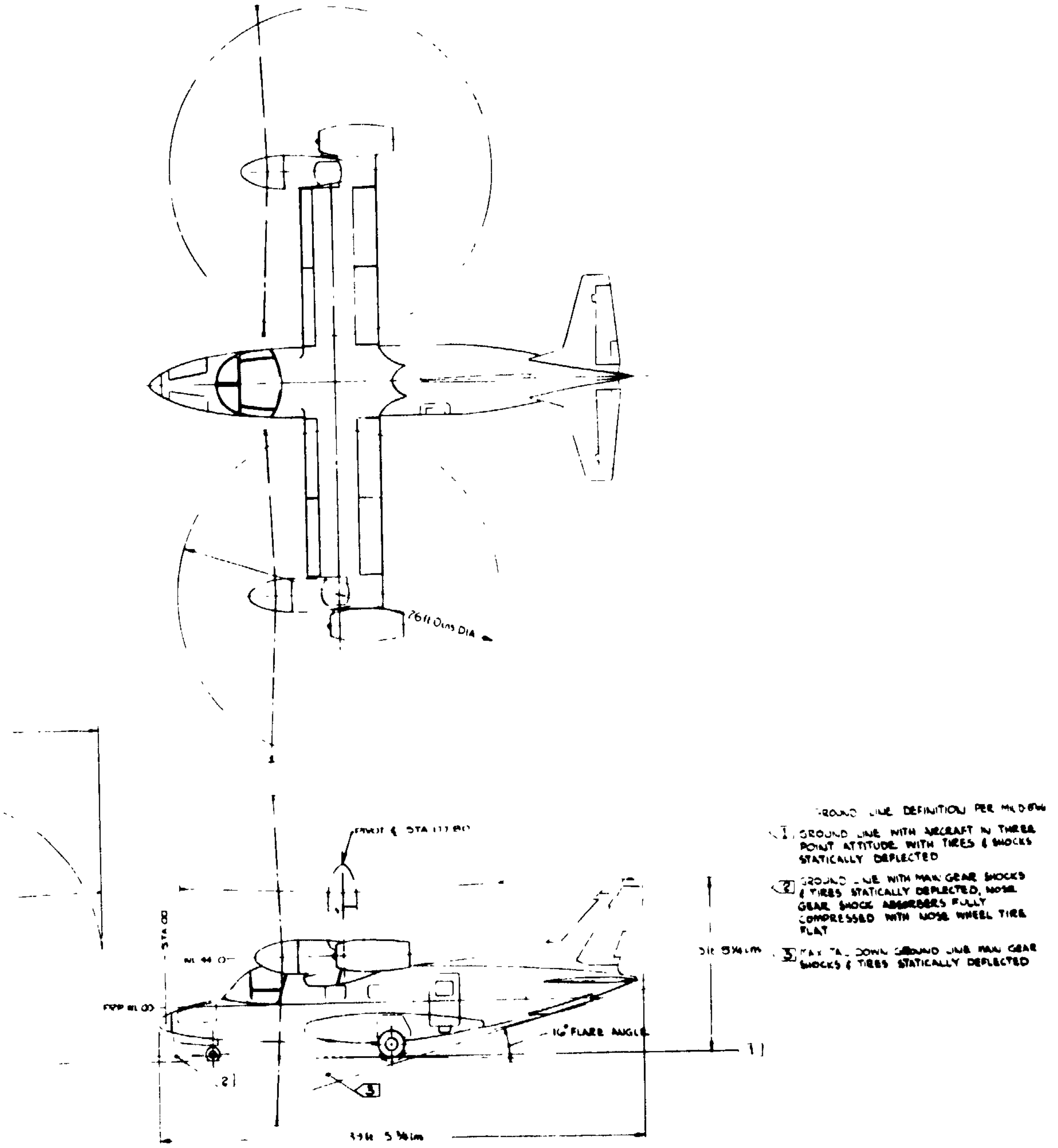
On the Model 222, longitudinal cyclic is connected to the stick for longitudinal control and to the pedals for directional control. Both longitudinal and lateral cyclic are programmed with nacelle tilt to minimize pivot moments as part of the load



WING	
SPAN	35 ft 5 ins
CHORD	71.8 ins
AREA	200 ft^2
ASPECT RATIO	5.61
TAPER RATIO	1.0
THICKNESS CHORD RATIO	.21
WING LOADING	60 lbs/ft^2
HORIZONTAL TAIL	
SPAN	15 ft 9 ins
AREA	58.3 ft^2
VERTICAL TAIL	
SPAN	8 ft 9 ins
AREA	43.3 ft^2
ROTOR	
DIAMETER	26 ft 0 ins
SOLIDITY	.115
DISC LOADING	11.3 lbs/ft^2 (DGW)
No BLADES	3
WEIGHTS	
DESIGN GROSS WT	12,000 lbs
WT EMPTY	9,230 lbs

FIGURE 2 MODEL 222-1 TILT ROTOR RESEARCH AI

FOLDOUT FRAME



)DEL 222-1 TILT ROTOR RESEARCH AIRCRAFT

FOLDOUT FRAME 2

FLIGHT MODE	PRIMARY CONTROLS
Helicopter (Hover)	
- Pitch	Longitudinal Cyclic
- Roll	Differential Collective
- Yaw	Differential Longitudinal Cyclic
Transition	
- Pitch	Longitudinal Cyclic and Elevator
- Roll	Differential Collective, Differential Longitudinal Cyclic, Aileron and Spoiler
- Yaw	Differential Longitudinal Cyclic, Differential Collective and Rudder
Airplane	
- Pitch	Elevator
- Roll	Aileron and Spoiler
- Yaw	Rudder

NOTE: Airplane control surfaces are operative at all times.

FIGURE 3. FLIGHT CONTROL MIXING

alleviation system (LAS). Roll control in hover is achieved by differential collective pitch. Roll control in transition utilizes phased differential collective pitch, differential longitudinal cyclic and differential nacelle tilt in conjunction with the spoilers and flaperons.

The rudder and elevator control surfaces are conventional. Roll control surfaces in this simulation consist of upward-operating semi-span spoilers, and downward-operation of the outboard flaps. This permits use of more efficient single-slotted flaps for low speed loiter in the cruise configuration and permits reduction of yaw due to roll control input because of the favorable yaw due to spoiler combined with the adverse yaw due to aileron control.

The stability augmentation system (SAS), used for this piloted simulation study consists of a pitch, roll and yaw SAS. The pitch SAS incorporates pitch rate, pitch attitude and longitudinal stick pickoff feedback loops. The SAS moves the elevator and longitudinal cyclic pitch actuators. Longitudinal SAS is used in hover and transition and is phased out in the cruise mode. The roll SAS consists of roll rate, roll attitude and a lateral stick pickoff. These are phased out in the cruise mode. A roll attitude hold mode is included to be used in the cruise configuration. The yaw SAS consists of roll rate, yaw rate and yaw attitude hold. These are phased out in cruise. The roll and yaw SAS's move both rotor and aerodynamic control surfaces.

The load alleviation system (LAS) utilizes longitudinal and lateral cyclic pitch feedback loops to zero out the rotor hub moments.

The thrust/collective pitch is controlled by throttle type levers in the cockpit, which, in hover, command directly both engine power and collective pitch. The governor adjusts the collective pitch to maintain constant rpm. Overtravel of the cockpit levers is provided beyond the normal maximum power position. The overtravel is entered by passing through a gate which shuts off the governor, so that in the overtravel position the lever directly controls collective pitch only and can be used just like a helicopter collective pitch lever to perform a collective flare. The mechanical interconnect from thrust/collective lever to collective pitch is phased out during transition so that in cruise the pilot demands power only, and pitch is governed to maintain rpm like a conventional propeller airplane.

It should be noted that the aircraft simulated during this program is not the same as described in Boeing Document D222-10050, Volumes I to XII (Study of V/STOL Tilt Rotor Research Aircraft Program - Phase I). The aircraft geometry is essentially the same. Weights, inertias, aerodynamic data, load alleviation and SAS configuration have been revised. While future piloted simulation studies may yield small differences in quantitative results, the qualitative results and trends should be similar.

4.0 MATHEMATICAL MODEL DESCRIPTION

The mathematical model of the Model 222 Tilt Rotor aircraft used to drive the Boeing Small Motion Flight Simulator (SMBFS) is described in Volume VIII of this series of reports, and is an eleven degree of freedom total force model. This model includes the basic six degree of freedom rigid body outer loop equations written about the instantaneous center of gravity with the inertial and aerodynamic terms included. The rotor is treated as a point source of forces and moments with appropriate response time lags and actuator dynamics. The wing has one vertical bending and one wing torsion degree of freedom. These structural degrees of freedom are treated on a "quasistatic" basis; i.e., the natural frequencies of vibration of the structure are much higher than the frequencies of the rigid body motion, and the coupling is in the aerodynamic terms. Each nacelle has an independent pitch degree of freedom about the wing pivot. The aerodynamics of the wing, tail, rotors, landing gear and fuselage are included. Wing and tail mutual interference effects and turbine engine performance and dynamic responses are represented.

The control system elements represented include pilot command (longitudinal and lateral stick, pedals, nacelle position and rate, power), three-axis stability augmentation systems (SAS), thrust management system (includes rotor constant speed governor) and a load alleviation system (LAS). The LAS system incorporates feedback to rotor cyclic and collective pitch for purposes of improving stability, blade load reduction, gust alleviation and increased damping of aeroelastic modes. Control system actuator dynamics are represented by appropriate second order systems. Figure 4 is a summary of the salient features of the mathematical model used for this study.

(1) Full Flight Envelope Capability with Total Force Representation

(2) 6 Rigid Body Degrees of Freedom

(3) Independent Nacelle Pitch Degree of Freedom

(4) 2 Elastic Degrees of Freedom

(5) 1 Rotor Rotational Degree of Freedom

(6) Includes the Aerodynamics of:

- Rotors
- Wings
- Rotor/Wing & Wing/Rotor Interference
- Fuselage
- Landing Gear
- Tail Surfaces
- Engines

(7) Control System Elements:

- Pilot Command
- SAS
- Load Alleviation System (LAS)
- Thrust and Power Management System

(8) Aeroelastic Representation

- Wing Vertical Bending
- Wing Torsion
- Nacelle Pitching Degree of Freedom

FIGURE 4. SALIENT FEATURES OF MATH MODEL

5.0 DATA BASIS

The Model 222 aircraft used in this simulation study is described in Reference 1. The data basis for this aircraft was, for the most part, obtained using analytical methods. These methods have been generally substantiated by test data obtained from wind tunnel tests on similar tilt rotor configurations. At the time input data for the simulation was being prepared (June 1972), there existed only a limited quantity of wind tunnel test data on the actual Model 222 configuration. Although a comparison of these limited test results with the corresponding analytical data indicates favorable agreement, it must be emphasized that the data base utilized for the simulation is subject to modification pending the outcome of further wind tunnel tests. In view of this, and the differences in aircraft characteristics previously noted, it should be borne in mind that pilot comments on handling characteristics, flying qualities, and performance of the Model 222, in future piloted simulation studies that incorporate a more complete data base may yield small differences in quantitative results although the qualitative results and trends should be similar.

Rotor data used in the mathematical model were predicted from four Boeing-developed computer programs. Hover and cruise performance (thrust-power) were obtained using a propeller performance analysis computer program (B-92), which uses an explicit vortex influence technique theory (Reference 5). Transition performance data, in-plane forces and moments and cyclic pitch effects were estimated using computer program D88 (Reference 6). This program uses strip theory, combined with unsteady aerodynamic and non-uniform downwash to compute aeroelastic rotor loads. In-plane elastic rotor derivatives (both static and rate)in axial flow were estimated using computer program C41 (Reference 3). Elastic rotor rate derivatives in transition were estimated using computer program C-49 (Reference 4). Correlation with rotor test data is shown in Volume VIII, Section 7.0 of this series of reports. Wing, tail, fuselage and nacelle aerodynamics were estimated using DATCOM (Reference 2), combined with increments and trends derived from References 7 and 8. Rotor ground effects also were obtained from Reference 7. Aircraft geometry, weights and inertia are as specified in Reference 1.

6.0 FLIGHT SIMULATION FACILITIES DESCRIPTION

The Flight Simulation Facility is an integrated laboratory complex for performing unmanned and piloted real-time flight simulation studies of aircraft, control systems, and instrumentation concepts and configurations. It is comprised of two laboratories, the Flight Simulator Laboratory and the Hybrid Simulation Laboratory. These two laboratories are located in separate buildings and are interconnected by electrical cabling.

Flight Simulator Laboratory

The Flight Simulator Laboratory contains a six degree-of-freedom small motion base simulator, a pilot station equipped with an adaptable instrument panel and a wide-range variable flight control force-feel system, a cockpit-mounted out-of-the-window collimated visual-simulation display, a visual simulation scene generating system and associated interface, and control and readout hardware.

The variable flight control force-feel system incorporates actual aircraft flight controls modified to have load cells at the points of pilot applied forces, and to be positioned by hydraulic servo-actuators controlled by computer signals developed from the load cell force signals and control position feedback signals. Any desired relationship between pilot effort and control position can be simulated. The system offers high signal-to-noise ratios, and responds to forces ranging from an ounce to more than a hundred pounds. The visual display system presents the pilot with a bright collimated out-of-the-window symbolic visual scene. The visual scene is computer generated, offering both latitude in scene content and an unconstrained flight path and maneuver capability. The generated scene is reproduced by a 600 line black and white television system for viewing by the pilot through a large collimating lens. The pilot's field of view measures 38 degrees vertically by 53 degrees horizontally, and had a depression angle of zero (0) degrees.

Small Motion Base Flight Simulator

Facility Description: The small motion base simulator provides six-degree-of-freedom motion employing the relatively rigid strut actuator concept. The small travels of the actuators result in approximately uncoupled motion and deliver nudge-type acceleration cues to the pilot of satisfactory validity. Three of the six electro-hydraulic actuator struts are vertical and three are horizontal. The Moog valves of the struts respond to command signals generated from the mathematical model programmed on the hybrid computing system. The cockpit is equipped with a variable flight controls force-feel system and a cockpit-mounted out-of-the-window collimated visual display. Figure 5 shows the external structural details of the motion base and cab, and Figure 6 shows the internal arrangement of the simulator cab.

Testing Capabilities: This facility permits a wide variety of studies and pilot evaluations of aircraft handling and flying qualities, automatic and manual flight control systems, and design criteria definition for the praid, economical, manageable, and safe development of aircraft and aircraft systems. The facility is particularly adapted to the study of V/STOL aircraft because of its capability for providing cockpit motion in six-degrees-of-freedom.

Motion System Performance

Payload (including pilot) 770 lb

Travel Limits (stop-to-stop total):

Vertical	5 in.
Longitudinal	5 in.
Lateral	5 in.
Pitch	13 deg
Roll	19 deg
Yaw	19 deg
Pitch Tilt	26 deg

Rate Limits with Zero Acceleration:

Vertical	$\pm$ 26 in/sec
Longitudinal	$\pm$ 41 in/sec
Lateral	$\pm$ 26 in/sec
Pitch	$\pm$ 69 deg/sec
Roll	$\pm$ 97 deg/sec
Yaw	$\pm$155 deg/sec

Acceleration Limits for Zero Rates (incremental values):

Vertical	$\pm$ 64.4 ft/sec^2
Longitudinal	$\pm$ 35.4 ft/sec^2
Lateral	$\pm$ 28.9 ft/sec^2
Pitch	$\pm$ 248 deg/sec^2
Roll	$\pm$ 414 deg/sec^2
Yaw	$\pm$ 745 deg/sec^2

During the piloted simulation effort, it was necessary to tailor the motion system of the nudge base simulator. The motion system required tailoring for the tilt rotor in the vertical and longitudinal axes. The vertical acceleration capability of the tilt rotor aircraft in cruise flight was significantly higher than that of the other aircraft used to

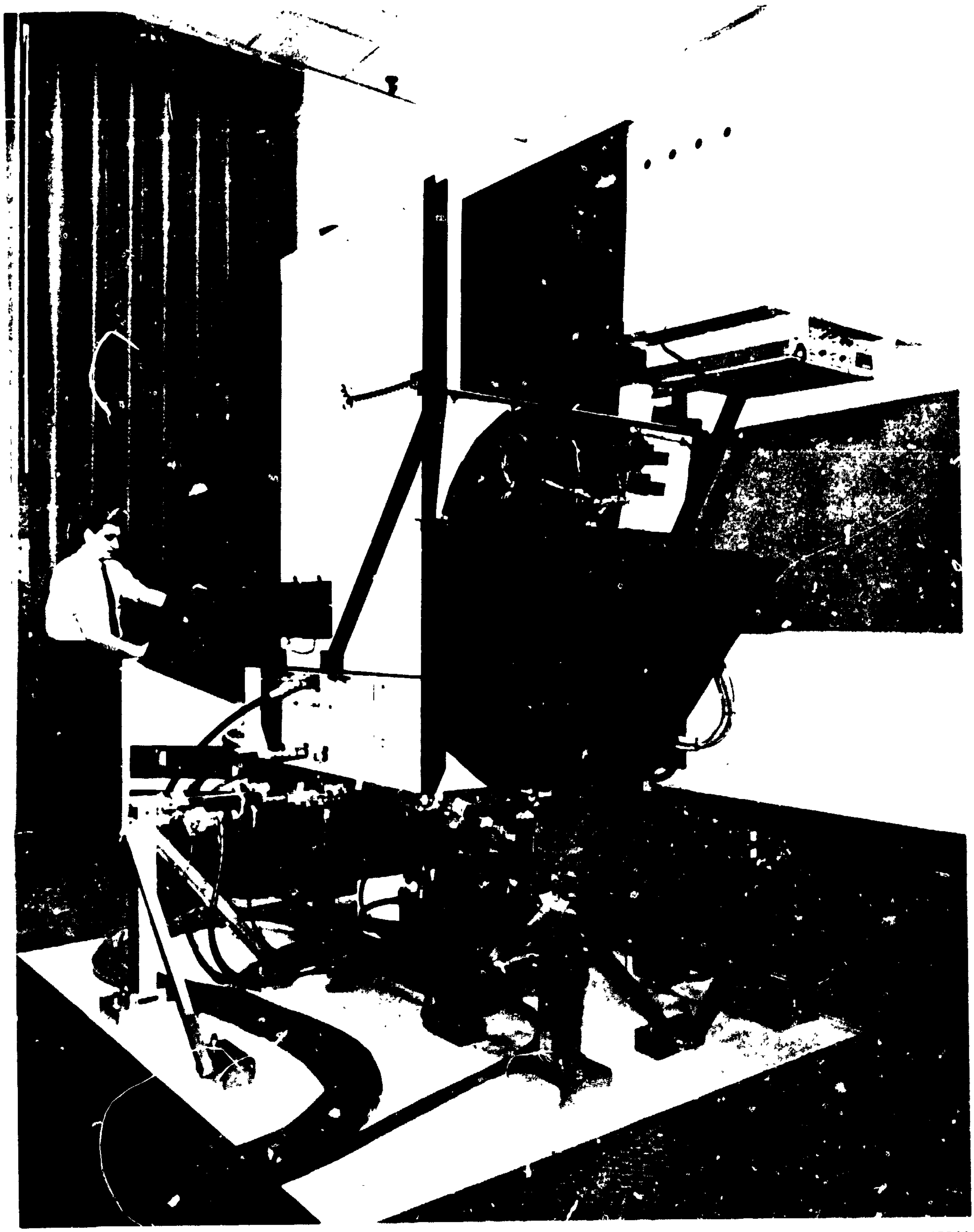


FIGURE 5. EXTERNAL VIEW OF BOEING SMALL MOTION BASE FLIGHT SIMULATOR

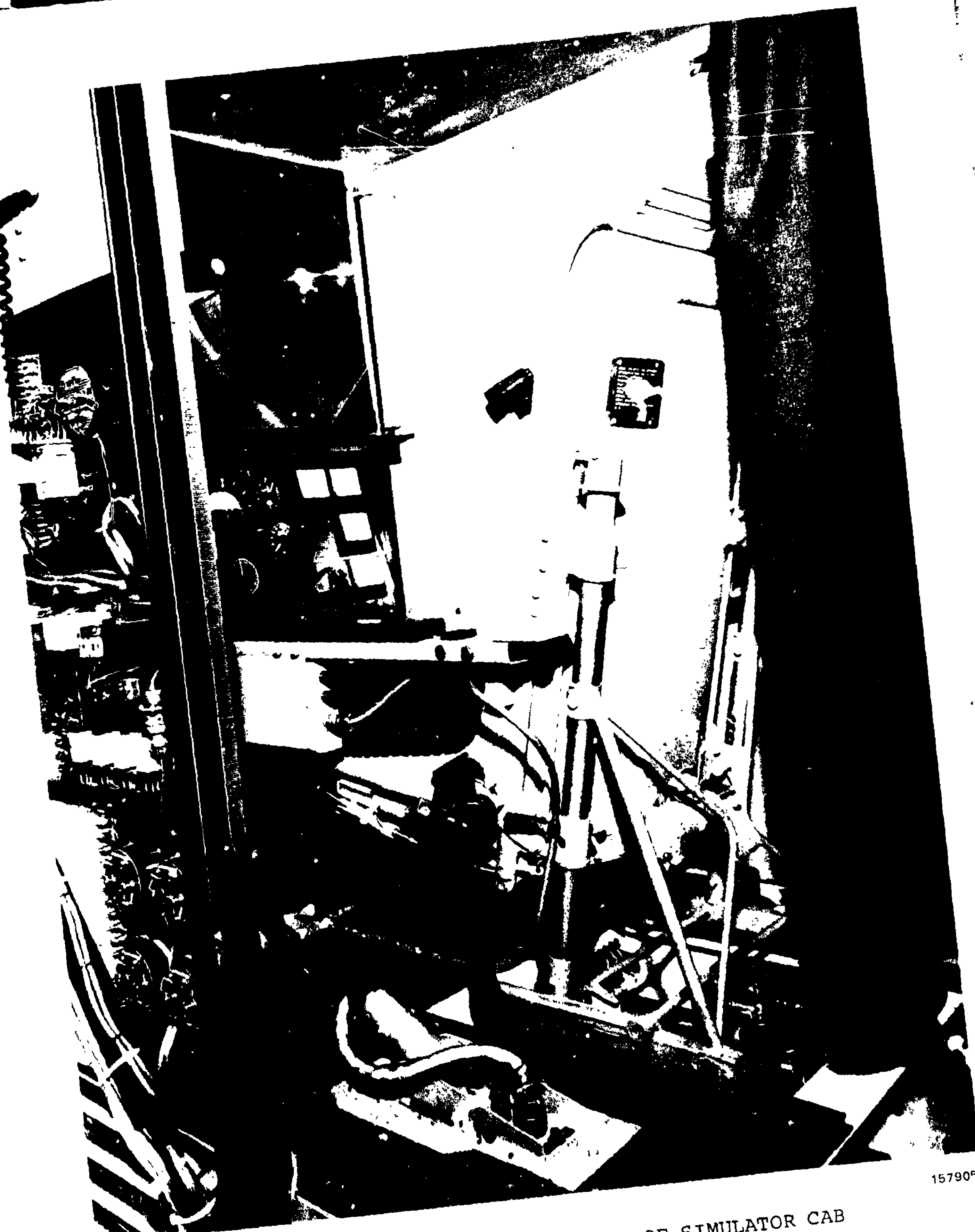


FIGURE 6. INTERNAL ARRANGEMENT OF SIMULATOR CAB

establish the motion system dynamic characteristics. In order to keep the simulator from hitting its motion limits, the vertical axis gain was reduced.

The longitudinal acceleration capability of the tilt rotor aircraft was also higher than the acceleration experiences in helicopters. It was found that the long term cockpit tilt used to represent longitudinal acceleration was very disorienting to the pilot. In order to eliminate this disorientation, the cockpit longitudinal tilt due to acceleration was attenuated by a factor of 4.

Visual Simulation System

The Visual Simulation System comprises two main subsystems: the Image Generating System and the Visual Display System. The image generation of a landing zone and horizon line are provided by a high-speed repetitive operating analog computer. This computer is part of the general purpose Hybrid Simulation laboratory. The capability, therefore, exists for expansion or adjustment of the visual scene to suit the customer's simulation task requirements. A number of different visual scenes have been used to date. One is the symbolic representation of a helicopter landing pad on a destroyer afterdeck. This particular display is capable of handling up to four surfaces (i.e. upper deck, lower deck, etc.) plus horizon line with perturbation of ship and aircraft motion.

The Visual Display Systems contains an Image Transfer Unit and a Visual Display Unit.

The Image Transfer Unit has a closed-circuit television camera looking at the face of a 5-inch oscilloscope through a beam splitter. The display computed by the Image Generating System as time-varying X and Y signals produces an animated pictograph on the scope which the camera converts into a video signal. The video drives an 9-inch monitor at the camera station for focusing and alinement reference, and a 14-inch monitor at the test observer station. It also works the Visual Display Unit consisting of a 23-inch television monitor attached to the Flight Simulator cab behind a 16-1/2 by 22-1/2 inch plastic collimating lens in the front window position. The pilot thus views a bright, enlarged, infinity-focused picture through a 38-degree by 53-degree sighting aperture. Head-position parallax is eliminated by the lens which lends an apperance of real-world depth to the scene. To assist the pilot in perceiving the picture as representing the outside world, a model of an aircraft nose boom is mounted between the collimating lens and the face of the 23-inch monitor. It appears in realistic 3-D outside his window. A beam-splitter permits the insertion of various instrument indications as a heads-up display presentation in the window. Lateral acceleration, velocity and position, and longitudinal velocity and position indications have been provided in this manner.

Hybrid Simulation Laboratory

The Hybrid Simulation Laboratory consists of an IBM 360/44 digital computer system connected to five Applied Dynamics, Inc. analog computers, providing capability for solving time-critical problems. The Hybrid system is connected to the limited-motion base flight simulator and includes a disc system, magnetic tape units, data adapter units, processing unit, card read/punch, printer, display stations and digital function generators.

The Hybrid system combines the best operational features of the analog and digital computers, thereby permitting system simulation involving the interaction of several technologies, such as flight control, aerodynamic performance, and vibratory analysis. Hybrid simulations have the ability to run in real time and include system parameters in a voltage analogy. This permits inclusion of flight hardware and actual loop-closure effects into system analysis. More sophisticated flight simulations are realized on the ground, materially reducing in-flight development programs and their attendant expenses.

7.0 PILOT STATION DEFINITION

The cab of the Small Motion Base Simulator was configured to represent the Model 222 aircraft. The configuration changes included instrument panel modifications, design and fabrication of the power lever/collective control and nacelle incidence control, modification of the pilots force feel system to provide the proper breakout forces and gradients as a function of dynamic pressure, and electro-mechanical limits placed on stick and pedal travel to properly simulate maximum control travels. Additional features include a magnetic brake on stick and pedals and "back drives" on the primary controls to provide initial control position trim in the cab. Although there is only one seat in the cab, instruments and primary controls were positioned such that the pilot flew as if from the right seat, as in conventional helicopters. A summary of Model 222 pilot station features are shown in Figure 7.

Instrument Panel Layout

The instrument panel of the simulator was modified to represent the Model 222 configuration. The standard "tee arrangement of the primary flight instrument was retained and the location of instruments unique to the Model 222 were defined after consultation with the project test pilot.

Figure 8 is a photograph of the simulator control panel. Instruments not labeled were not used for this simulation. Nacelle angle, sideward speed and "g" meter were located on the left side of the panel. Engine condition, rotor RPM, angle of attack and flap position were grouped on the right side of the panel. It should be noted, however, that as the test program progressed, it became evident that the engine torquemeters are more properly placed on the left side of the panel. Space constraints precluded making this change in the simulator.

Transmission limits and normal rotor RPM positions were marked on the appropriate instruments. Dual engine and single engine transmission limits are indicated by red index marks on the engine torquemeter dials. The dual engine transmission limit was placed at 74% torque and the single engine limits at 97% torque. Red index marks were placed at 100% and 70% rotor RPM, the normal hover and cruise values. Since rotor RPM is automatically scheduled as a function of nacelle angle, the index marks merely provide an indication that the automatic system is operational.

Primary Controls

The control stick and pedals in the simulator required no modification for the Model 222 simulation. Longitudinal stick

CAB INSTRUMENTATION:

Instrument	Range
Vertical Situation Indicator	±90° Pitch and Roll
Horizontal Situation Indicator	±120° Heading
Airspeed	0 → 520 KIAS
Pressure Altimeter	0 → 10,000 Ft
Radar Altimeter	0 → 1000 Ft
Rate of Climb	± 6000 FT/MIN
Turn and Bank	±3 Needle Widths ±1 1/2 Ball Widths
"g" Meter	-1, +3 "g"
Nacelle Angle	0 → 120°
Clock	
Sideward Velocity	± 40 Knots
Angle of Attack	± 20°
Wing Flap Position	0 → 100°
Rotor Speed	0 → 125%
Engine Torque Meters (2)	0 → 125%

PRIMARY FLIGHT CONTROLS

Stick (±6" Long.; ±5" Lateral)
Pedals (±2.5")
Power Lever (0→8" Normal; 0→10" Emergency)
Nacelle Position Thumb Switch

MISCELLANEOUS EQUIPMENT AND FEATURES

Back Drives to Trim Stick and Pedals while in Initial Condition (I.C.)
Landing Gear Up - Down Switch with Indicator Light
SAS ON-OFF Switch
Detent Switches on Spring Cartridges (Pedals & Lateral Stick)
Magnetic Brake on Pedals, Long. and Lateral Controls
Long. and Lateral Beep Force Trim on Stick
Power Lever Null Meter
Toe Brakes
Specified Force Feel System

FIGURE 7. MODEL 222 PILOT STATION FEATURE SUMMARY

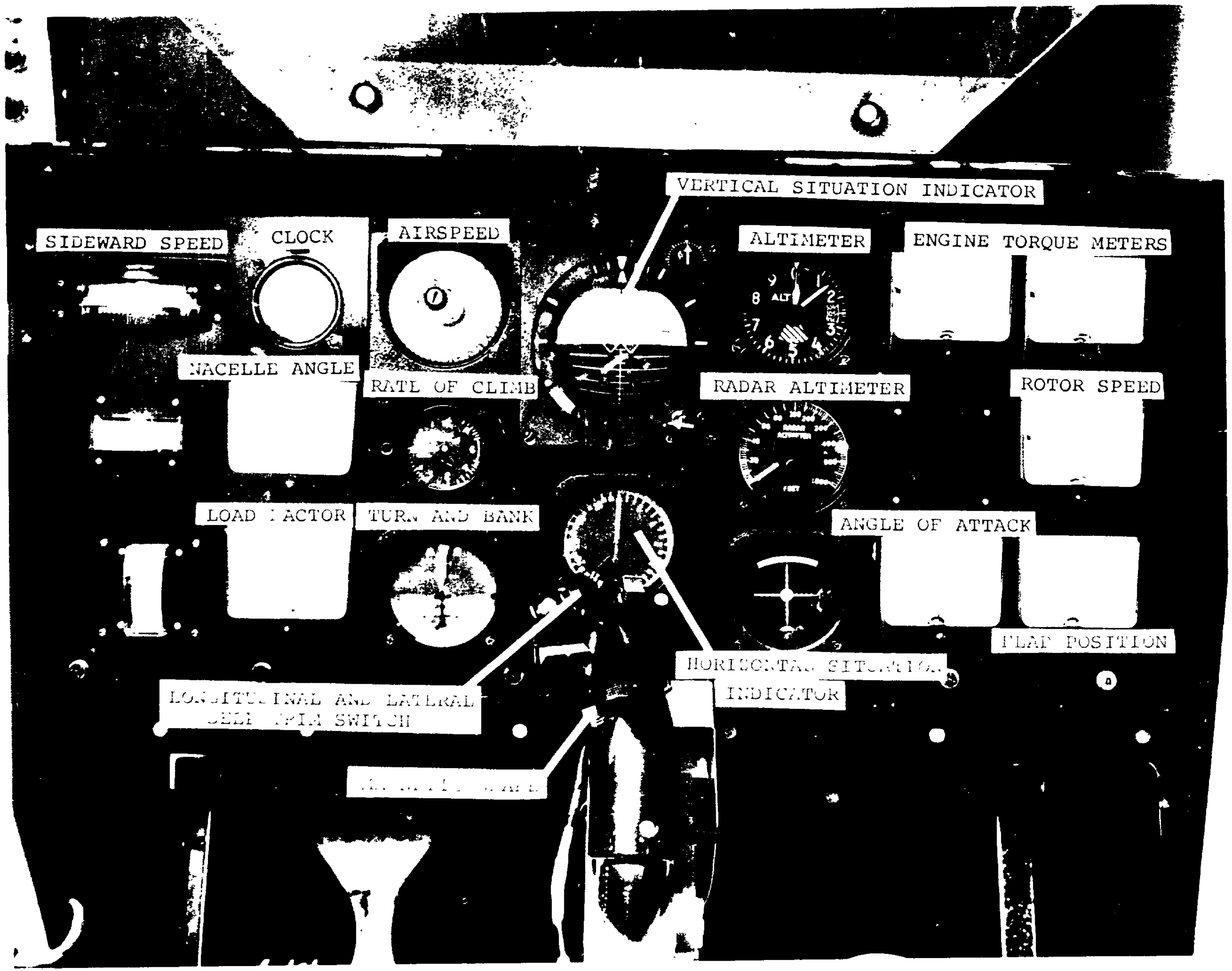


FIGURE 8. SIMULATOR INSTRUMENT PANEL ARRANGEMENT

travel was mechanically limited to 12 inches, lateral stick travel was mechanically limited to ±5 inches and pedal travel was mechanically limited to ±2.5 inches. A beep force trim "hat" switch was mounted on the stick. This enabled the pilot to zero out longitudinal and lateral stick forces and also was used for precise trimming of the aircraft at cruise speeds. A compromise beep trim rate of 1/2 inch/sec was used for most of the test program. A magnetic brake, operated by a button on the stick, was used to zero the stick and pedal forces simultaneously. This was used primarily in the low conversion speed range. Detents on the lateral stick and pedals were set at ±.050 inches.

The Model 222 Tilt Rotor uses a single lever to command the power of both engines, and to provide collective pitch lead in hover and transition with rotor speed controlled through a governor. Rotor speed is programmed as a function of nacelle incidence angle. Rotor speed is maintained at 551 RPM to a nacelle angle of 45°. From 45° to 0°, the rotor speed is linearly decreased to 386 RPM. A proportional thumb switch with detent, breakout and gradient, mounted in the hand grip, controls nacelle tilt. The power lever arrangement, shown in Figure 9, is mounted on the left arm rest. This can be rotated up for easier pilot entrance and exit. The power lever/collective control has a normal travel of eight inches (measured horizontally at approximately the center of the hand grip) and simulates the range of engine powers from flight idle to maximum power. For single or dual engine failures, direct pilot control of collective pitch for a flare is provided by sliding the power lever through a detent on the arm rest. This turns off the rotor governor and transforms the power lever into a collective lever. Two inches of overtravel (measured horizontally) were provided in the simulator. There was essentially no breakout or gradient (except that provided by friction) in the power lever.

Stick and pedal breakout forces and gradients were developed to meet the stick force per "g" requirements for satisfactory flying qualities as specified in MIL-F-8785B(ASG); and to improve control harmony among axes. Stick and pedal force gradients are specified as a function of dynamic pressure, with the breakout forces constant. The breakout forces and gradients used in the Model 222 simulation are shown in Figure 10 for the longitudinal and lateral sticks and rudder pedals.

Two computer generated visual displays were available for use during the test program. One is a symbolic representation of a helicopter landing pad on a destroyer afterdeck. In this display the body axis geometry is transformed through an earth axis system to a point in the aircraft, with the result that ship and aircraft motion are independently possible. This can be used for the hover and near-hover mode. The other

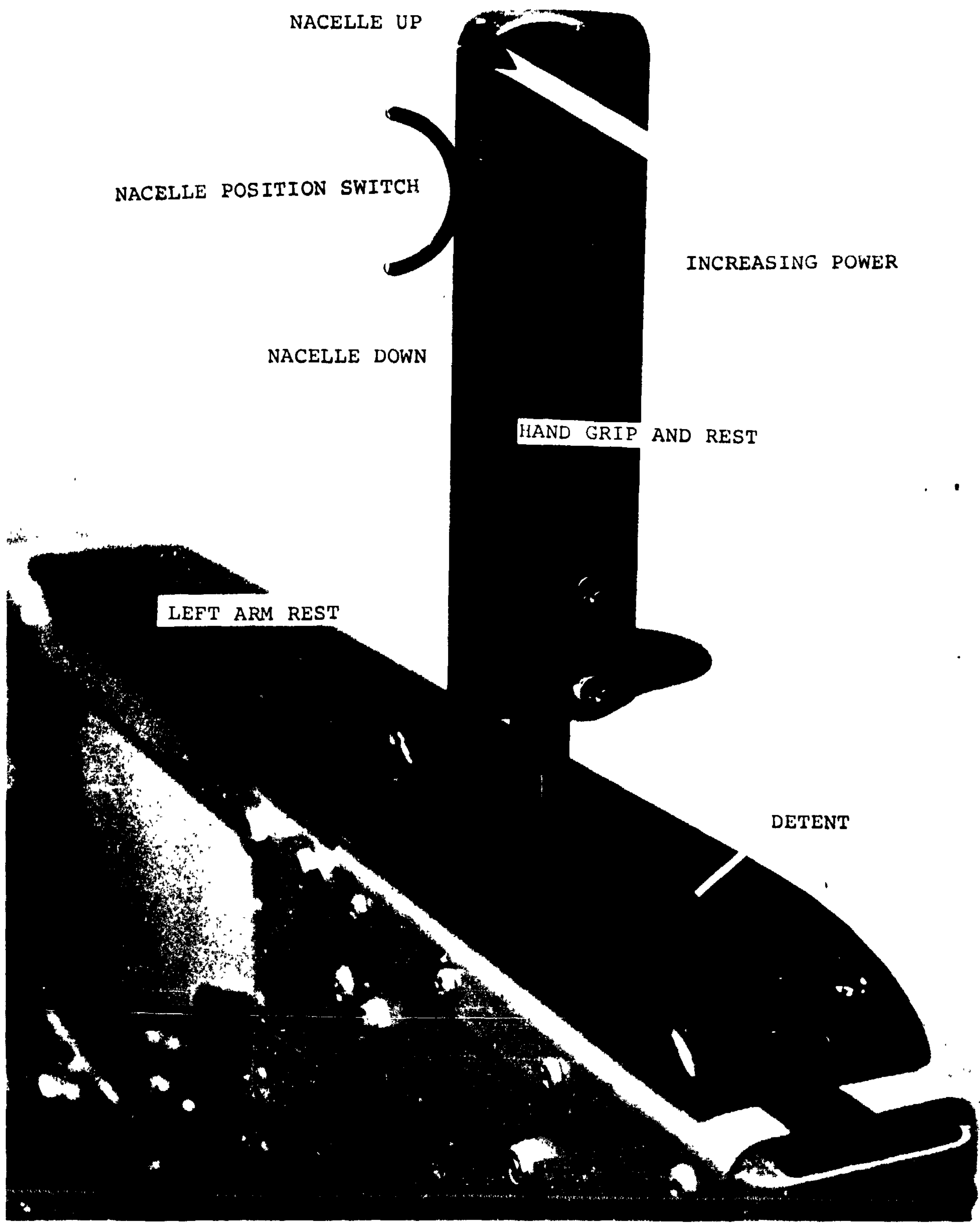


FIGURE 9. POWER LEVER/COLLECTIVE CONTROL FOR M222 SIMULATION

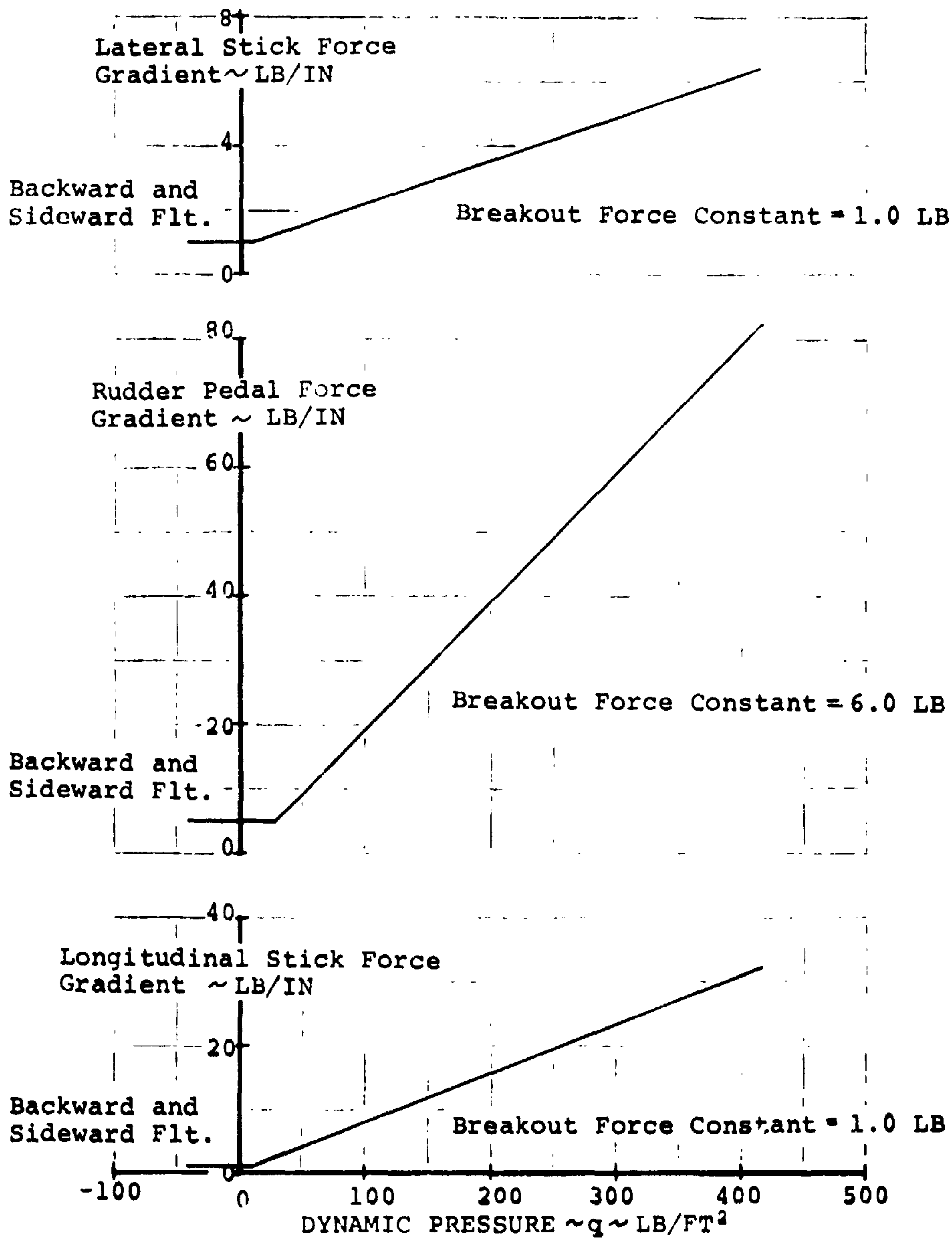


FIGURE 10. MODEL 222 CONTROL FORCE GRADIENTS AND BREAKOUT FORCES

display is a symbolic representation of a road with telephone poles on the side for reference. Mountains are provided in the background. This is used primarily for cruise mode studies, although it was used almost exclusively for the Model 222 simulator program.

Additional features of the cab included a landing gear up-down lever with indicator light, toe brakes on the directional pedals and SAS on-off switches. The simulator's primary controls i.e., stick and pedals are back driven to an initial trim position from signals computed in the mathematical model. Initial power lever/collective control trim is accomplished by the pilot by moving the lever until the power lever trim indicator (null meter) is zero. The simulator can then be "flown" by depressing the operate switch. While the simulator is in operate, the backdrives are inoperative.

8.0 SIMULATOR RUN PROGRAM

The run program developed for the Model 222 piloted simulation was predicated on evaluating the full flight envelope, with approximately equal emphasis on all flight modes. Since the scope of this program was large, and the objective was to evaluate the full flight envelope, there were some conditions that were not evaluated in depth. These areas are noted in Section 10 and are recommended as subjects for additional work. The simulator run plan was as follows.

1. Familiarization

   a) General comments on cockpit layout
   b) "Learn to fly"

2. Hover Mode Studies

   a) Height control capability
      - adequacy of control
      - precision of control

   b) Longitudinal and lateral stick and pedal pulses (from trimmed flight conditions)

   c) SAS evaluation (evaluate on, off; rate, attitude, LAS)

   d) Control sensitivity

   e) Control response to large inputs
      - adequacy of response
      - control coupling

   f) Response in gusts

   g) Engine out operation

3. Transition Mode Studies

   a) Slow acceleration and deceleration through transition

   b) Rapid acceleration and deceleration through transition

   c) Control sensitivity (roll, pitch and yaw)

   d) Longitudinal and lateral stick and pedal pulses (from trimmed flight conditions)

e) SAS evaluation (evaluate on, off; rate, attitude, LAS)

f) Control response to large inputs
   - adequacy of response
   - control coupling

g) Response in gusts

h) Flight path control (including low speed climbs and descents)
   - adequacy of control
   - precision of control

i) Control sensitivity

j) Engine out operation

4. Cruise Mode Studies

a) Longitudinal, lateral stick and pedal pulses (from trimmed flight conditions)

b) SAS evaluation (evaluate on, off; rate, attitude, LAS)

c) Maximum acceleration and deceleration

d) Control response to large inputs
   - adequacy
   - control coupling

e) Response to gusts

f) Climbs and descents

g) Engine out operation

5. Evaluation of Maximum Nacelle Rates in Transition

6. Evaluate Helicopter Flight Mode

Voice recorder, used part of the time, and 36 channels of brush recorder data were obtained for each maneuver except for the familiarization runs where only brush recorded data were obtained. These will be retained for future reference.

9.0 PILOTED RESULTS

This section contains the pilot comments that were obtained during the piloted simulation portion of this program. The primary experience of the Tilt Rotor project pilot is in flying helicopters. His experience in flight testing of V/STOL air craft is limited. Therefore, the comments presented herein should be interpreted accordingly. During discussions held prior to the start of this phase, the pilot was instructed to be as critical as possible to enable the Tilt Rotor project to define the significant problem areas. Although the Model 222 as simulated had generally acceptable stability and handling characteristics, the following modifications have been incorporated as the result of the pilots comments presented in this section.

- Hover control power and sensitivity have been increased as follows: -

Axis	Control Sensitivity Rad/Sec^2		Control Sensitivity Rad/Sec^2	
	This Simulation	Current	This Simulation	Current
Pitch	.6	1.2	.1	.2
Roll	1.0	2.0	.2	.4
Yaw	.5	.5	.2	.2

- Lateral control power in transition and cruise was increased by using full span ailerons and spoilers compared to partial span ailerons and spoilers used in this simulation
- Throttle sensitivity in the hover and low speed flight modes was reduced.
- The governor was modified for improved response
- Representation of engine dynamics was modified to more closely match actual engine response characteristics.
- Stability Augmentation System (SAS) refined. The hover and low speed SAS gains and shaping were modified to obtain improved response. Cruise mode roll and yaw SAS feedback loops were added to eliminate roll/spiral coupling and to reduce the high dihedral effect.

It should be noted that the above list is not all-inclusive, but is provided to illustrate the importance of early piloted simulation as an aid in the aircraft design. A further discussion of the piloted simulation results and pilot comments is in Section 10.

These piloted studies were all conducted for an aircraft gross weight of 12,000 lb with the center of gravity at 28% chord (most aft CG at this weight). Configuration details and aerodynamic characteristics are as described in Reference 1 and summarized in Section 3.0. It is to be emphasized that the aircraft simulated during this program is not the same as described in Boeing Document D222-10050, Volumes 1 to 11 (Study of V/STOL Tilt Rotor Research Aircraft Program - Phase I). The aircraft geometry is essentially the same. Weights, inertias, aerodynamic data, load alleviation, and SAS configurations have been revised.

The pilot comments are presented in the same order as shown in the run plan. Generally where the size of the control inputs is not noted, the pilot was attempting to put in 1-second pulses (1 inch of control at low speed and 1/2 inch in the cruise mode).

9.1 FAMILIARIZATION

9.1.1 General Comments on Cockpit Layout

The following items were noted concerning the cockpit layout.

a. Nacelle tilt indicator is a primary flight instrument and should be located near the basic Tee. Rate of climb, airspeed, torquemeter and nacelle tilt indicator should be located on the same side of the basic Tee.

b. Nacelle tilt switch arrangement needs further investigation. Switch position (cyclic stick or thrust lever), direction of travel, force gradient and breakout, proportional rate, fixed rate beep or two rate beep need evaluation.

9.1.2 "Learn to Fly"

Much time was spent in trying to determine the best way of flying through transition. The aircraft is very tolerant of a wide range of nacelle tilt angles and body attitudes. The most comfortable or convenient combination may be selected for the particular task to be performed. The operation of the aircraft in the cruise mode is conventional.

During this period the following items were noted.

a. Operation with nacelle incidence above zero at speeds above about 160 knots is undesirable. Positive prevention of such operation should be considered. An automatic up stop at 90 to 95° is desirable to facilitate reconversion. Positive pilot action should be required to go beyond this setting.

b. The mag. brake is too coarse to be used for trim in the cruise range and should be locked.

9.2 HOVER MODE STUDIES

9.2.1 Height Control Capability in Hover

The height control capability of the Model 222 was evaluated by performing a series of vertical climbs and descents to specified altitudes. Adequacy and precision of control were evaluated. The pilot comments for these maneuvers follow: -

Initial Condition	Maneuver	Pilot Comments
HOVER All SAS on (Roll, pitch, yaw). Load Alleviation System (LAS) on.	Perform rapid climbs to 50', 150', and 250' altitude. Then descend rapidly from 250' to 150' to 50'.	Difficult to control rate of climb with existing power lever sensitivity. The combination of high throttle sensitivity and poor external visual cues resulted in overshooting target altitudes by as much as 50'. A ±10% torque change in this maneuver typically resulted in ±1000 ft/min vertical rate.
	As above but at low vertical rates and 50' increments in altitude	This was a more natural altitude change and was much easier to control. 2 to 3% changes in torque gave 200 to 300 ft/min vertical rates. The maneuvers were fairly well controlled although the power lever was still quite sensitive. Pitch, roll, and yaw were flown hands off and these axes seemed well stabilized.
	Vertical control. Small height changes. Task was to hold altitude as closely as possible after small changes in altitude were made.	Small altitude corrections were difficult to achieve and the difficulty was compounded by poor visual cues. The slightest pressure on the power lever was sufficient to change altitude by a few feet. The power lever sensitivity was not adequate for a precision hover. Plus or minus 4 feet was the best the pilot could achieve.

Initial Condition	Maneuver	Pilot Comments
		Plus or minus 2 feet altitude could be held with a lot of work. Once trimmed, the aircraft held fairly well.

9.2.2 Control Pulses, SAS Evaluation and Control Sensitivity in Hover

Control pulses (longitudinal, lateral stick and pedal), evaluation of aircraft characteristics with various SAS and LAS feedback loops off, and control sensitivity were evaluated. Note that the SAS evaluation was not a malfunction analysis but an evaluation of aircraft handling qualities with various components inoperative. The pilot comments for these maneuvers follow: -

Initial Condition	Maneuver	Pilot Comments
HOVER- SAS and Load Alleviation System (LAS) On	Pitch Pulse	Aircraft behaves well, returns to trim attitude with no oscillation. Control sensitivity adequate.
	Roll Pulse	Well behaved response. Control sensitivity adequate.
	Yaw Pulse	Well behaved response. Control sensitivity adequate. The yaw axis was heavily damped and stopped immediately when the pedal input was removed.
HOVER-LAS On Roll Attitude SAS Off	Roll Pulses	Fairly long period, (20 sec), neutral, damped roll oscillation
All Roll SAS Off	Roll Pulses	Slow roll divergence

Initial Condition	Maneuver	Pilot Comments
Pitch Attitude SAS Off	Pitch Pulses - Nose Up	Pitch oscillation developed. Nose came up 10°, checked at zero, then pitched down to -5° attitude. Oscillation was neutrally damped.
	Pitch Pulses - Nose Down	Developed 3 degrees nose down attitude on input. A plus or minus 4 to 5 degree neutrally damped oscillation developed.
All Pitch SAS Off	Pitch Pulses	No significant change from SAS on. Pitch axis slowly divergent and oscillatory.
Yaw SAS Off	Yaw Pulses	Not much inherent damping in yaw although sensitivity was good. Yaw axis came back to trim and went divergent in the opposite direction. This effect was not repeatable and may be a function of not getting pedals back to trim. Feet off pedals gave a left yaw rate that required 1/8 inch right pedal to check. Yaw axis very lightly damped.
HOVER-LAS Off All SAS On	Pitch, Roll and Yaw Pulses	The pitch and roll axes looked about the same. The yaw axis again was heavily damped and stopped immediately when pedal input was removed. There were no apparent differences LAS on and LAS off.
HOVER - LAS Off Roll SAS off	Roll Pulses	Roll oscillations of shorter period than with LAS on, neutral to convergent. Control response was sluggish.

Initial Condition	Maneuver	Pilot Comments
Pitch SAS Off	Pitch Pulses	Power changes had quite an effect on pitch. The pitch axis response to pulse inputs was slowly divergent and not much different from that with LAS on. Response rather sluggish.
Yaw SAS Off	Yaw Pulses	Sensitivity and response was very similar to LAS on flight.
HOVER-All SAS and LAS Off	Pulses about all axes	The aircraft was manageable. There was some yaw-pitch coupling present; right pedal gave pitch down and left pedal gave pitch up.* The longitudinal stick trim position was more forward than with SAS on. In hands-off condition aircraft was unstable with a tendency to yaw left. SAS off control sensitivity was adequate.
HOVER-All SAS Off, LAS On	Pulses about all axes	No significant change from LAS off.

9.2.3 Response to Large Inputs in Hover

The response to large control inputs was evaluated. The pilot comments for these maneuvers are shown below:-

Initial Condition	Maneuver	Pilot Comments
HOVER-SAS and LAS On	Response to large inputs - Pitch - Roll - Yaw	A 2 inch longitudinal stick input produced a 5 degree attitude change. 2.5 inches of lateral stick resulted in 15 degrees of bank. Applied 2.5 inches of pedal; response was well damped. Adequacy of response difficult to evaluate because of motion cues.

*Note: This is the result of engine inertial coupling since both engines turn in the same direction.

Initial Condition	Maneuver	Pilot Comments
HOVER-LAS On Pitch SAS Off	Large inputs in pitch, roll and yaw	Except for larger excursions from trim pitch attitude, response was not very different from SAS on. Roll inputs resulted in a small amount of pitch up. Right pedal inputs caused pitch down, left pedal, pitch up.
Yaw SAS Off	Large Inputs	Yaw was more responsive than with SAS on. The response was very sensitive and inherent damping was low. Yaw axis was unstable in hover. Pitch inputs gave no coupling. Roll inputs gave some proverse transient coupling.
Roll SAS Off	Large Inputs	Aside from roll instability, roll response was not very different from SAS on. With full lateral input, initial response was the same as SAS on. Sensitivity was low for smaller inputs. Pitch inputs gave no coupling. Yaw inputs gave lateral velocity and roll due to dihedral effect.

9.2.4 Response to Gusts in Hover

The response of the Model 222 in random turbulence was studied during this piloted evaluation. Pilot comments are shown for 4 and 3ft/sec RMS turbulence. It should be noted that these are moderately severe random turbulence levels.

Initial Condition	Maneuver	Pilot Comments
HOVER-All SAS and LAS On	Evaluation of response in gusts. RMS gust velocity 3ft/sec	Attempted to hold altitude at 95 feet. Used rate of climb instrument to hold altitude.

Initial Condition	Maneuver	Pilot Comments
		Torque varied between 33% and 70% as commanded by the pilot. Started at 95 feet altitude and ended up at 195 feet. The task of changing altitude and trying to stabilize was difficult with this level of gust. Acceleration cues really needed to modulate power successfully.
HOVER-LAS, SAS On	Evaluation of response in gusts. RMS gust velocity 4 ft/sec	Flown with hands off on pitch, roll, and yaw. The vertical axis was very difficult to hold. In severe gusts pitch holds ± 5 degrees, roll holds ± 3 degrees, yaw was pretty much locked on. It was impossible to trim out at any particular altitude. Power was 50% for hover plus or minus 20% to hold altitude. Rate of climb went ± 300 feet per minute and occasionally to ± 1000 feet per minute. Rotor RPM held well.

9.2.5 Engine Out Operation in Hover

During this maneuver, one engine was failed with the aircraft in a steady hover, to evaluate the engine out landing capability. The pilot comments are noted below.

Initial Condition	Maneuver	Pilot Comments
HOVER-All SAS On and LAS On	Single engine failure from loo ft.	Develops 1000ft/min rate of descent in about 1 sec after failure. Starting at 80 ft of altitude, use of forward throttle into over-travel region, checked descent at 40 ft. 100 ft/min rate of climb obtained at full forward throttle.

Initial Condition	Maneuver	Pilot Comment
		Detent position on throttle checked rate of descent to 500 feet per minute. Transient following failure mild.

9.3 TRANSITION MODE STUDIES

9.3.1 Slow and Rapid Acceleration and Deceleration Through Transition

Slow and rapid accelerations and decelerations were evaluated. These were conducted with the stability augmentation and the load alleviation system on. During the pilot familiarization portion of this program, the pilot flew a slow acceleration through transition to 150 knots and back to hover with the SAS and LAS inoperative. He stated that it required considerable pilot effort and attention. It should be noted that this situation (all SAS and LAS off) would require several malfunctions in the automatic stabilization system because of the dual and/or triple redundancy. The pilot comments of the slow and rapid acceleration and deceleration characteristics of the Model 222 through transition with the SAS and LAS on, follow.

Initial Condition	Maneuver	Pilot Comments
HOVER-All SAS on LAS On	Slow acceleration from hover to airplane flight	Difficult to control altitude. The motion-base postural tilt gave deceptive motion cues. Otherwise docile.
	Rapid acceleration from hover to airplane flight	Strong pitch-down motion aggravated by postural tilt makes this maneuver difficult. Full aft stick was required to hold altitude near zero.
	Rapid deceleration from cruise	Requires considerable technique. With a fixed-rate nacelle tilt control there was a tendency to overshoot on required nacelle angle. As minimum power speed was approached rate of climb was controlled with pitch attitude. Upon reaching minimum power speed prompt use of throttle was required to prevent a sharp increase in descent rate.
	Slow deceleration from cruise	No difficulty encountered. Close control of altitude required.

9.3.2 Control Sensitivity and Aircraft Response to Longitudinal Stick, Lateral Stick and Pedal Pulses in Transition

Control sensitivity and aircraft response to longitudinal stick, lateral stick and pedal pulses in transition were evaluated for 20 knot intervals through transition. 20, 80 and 120 knots have been selected as the conditions to show the pilot comments. The stability augmentation system (SAS) and load alleviation system were in operation. The pilot comments for these maneuvers follow.

Initial Condition	Maneuver	Pilot Comments
V=20 Knots Nacelle Angle -85° All SAS & LAS On	Pitch Pulses Pitch Up	3° attitude change and a return to trim following a 5° overshoot
	Pitch Down	Same as pitch up pulse
	Roll Pulses	Same as the response in hover
	Pedal Pulses	Same as the response in hover
V=80 Knots Nacelle Angle =60° Pitch Attitude =4° All SAS & LAS On	Pitch Pulses	Pitch - less apparent pitch response, due to higher stick forces. There was more damping than at 20 knots. Sensitivity of the response a bit sluggish with the higher damping.
	Roll Pulses	Aircraft rolls to a bank angle and holds well. Some small sideslip angle develops.
	Pedal Pulses	Aircraft is highly damped.
V=120 Knots Nacelle Angle =20° All SAS & LAS On	Pitch Pulses	Response well damped and sluggish, similar to 80 kts Control response was adequate.
	Roll Pulses	Roll response seems better with good bank angle hold.
	Pedal Pulses	Response was a little weak, with high dihedral effect.

9.3.3 SAS Evaluation in Transition

The response of the Model 222 to various SAS configurations in transition was evaluated at 80 knots. The pilot comments are presented below.

Initial Condition	Maneuver	Pilot Comment
V=80 Knots LAS On Roll & Yaw SAS On Pitch rate and longitudinal stick pickoff on, pitch attitude off	Pitch Pulses	Trimmed at 60° nacelle incidence, 5° pitch attitude, and 40% torque. The pitch axis was convergent and returns to trim in about 2 seconds with a 1.5 degree overshoot. Pitch damping was high.
Same as above with pitch rate feedback off LAS On	Pitch Pulses	Pitch response only slightly less stable but still convergent.
Same as above All pitch SAS Off, LAS On	Pitch Pulses	There was an apparent degradation of sensitivity without the pickoff. Pitch response had a small overshoot and developed a convergent long period oscillation.
Same as above, LAS Off	Pitch Pulses	Longitudinal stick trim moved 1/2 to 3/4 of an inch more forward. One inch pitch pulse generated 3-4 degrees of attitude. Long period oscillation developed with longer period than LAS on case. The pitch response generally very similar to LAS on case.
V=80 Knots LAS On Pitch & Yaw SAS On, Roll attitude hold Off	Roll Pulses	Input generated 7-8 degrees of bank angle with a very slow return to trim. Roll control sensitivity seemed low.
Same as above with rate and attitude roll SAS Off, LAS On	Roll Pulses	The basic aircraft had good roll response. Roll rate damped out reasonably well with a very slow return to trim.

Initial Condition	Maneuver	Pilot Comment
LAS On Roll SAS Off	Roll Pulses	Roll response was highly damped and similar to SAS on i.e., sluggish
Same as above LAS Off	Roll Pulses	Roll response similar to LAS on case above. Slight roll angle overshoot and a slow return to trim.
80 Knots LAS On Roll and pitch SAS On Yaw attitude hold off	Pedal Pulses	Response was stiff and highly damped to pedal inputs and also very sluggish. Pedal forces were unexplainably high for this case. (Force feel system malfunction)
Same as above Yaw SAS Off Roll into Yaw SAS Function On	Pedal Pulses	Pedal pulses generated 2 cycles of fishtailing with high pedal forces again. (Force feel system malfunction)
Same as above all Yaw SAS Off	Pedal Pulses	Same response as above
Same as above LAS Off	Pedal Pulses	Similar to LAS on case above. No apparent change in yaw response occurred with LAS off.

9.3.4 Control Response to Large Inputs in Transition

Aircraft response characteristics to large inputs were evaluated and found to be similar to small input responses except for amplitude.

9.3.5 Aircraft Response to Gusts in Transition

The response of the Model 222 to random turbulence at 80 knots in transition was evaluated. An RMS gust value of 4 ft/sec was used. The pilots comments are noted below.

Initial Condition	Maneuver	Pilot Comments
V=80 Knots All SAS On LAS On	Response to a RMS gust	Holding vertical airspeed was the only problem. Held rate of climb with pitch attitude.

Initial Condition	Maneuver	Pilot Comments
	Same as above, hands off	Pitch and roll attitude disturbances averaged about ±1 degree from trim. Airspeed varied about ±5 knots from trim. Rate of climb varied ±500 ft/min about trim.

9.3.6 Flight Path Control Evaluation in Transition

Flight path control capability of the Model 222 was evaluated for several conditions. The pilots comments for these maneuvers is noted below.

Initial Condition	Maneuver	Pilot Comments
V=230 Knots 3000 ft altitude All SAS On LAS On	Decelerate to 160 knots, 2500 ft of altitude after a 90° heading change, then stabilize on a 500 ft/min rate of descent, and decelerate through transition to hover at 1000 ft altitude.	Decelerated to 150 knots with no difficulty and brought nacelles up to 25 degrees incidence. At 100 knots altitude or rate of climb required pilot attention. Stabilized on a 500 ft/min rate of descent at 120 knots and continued to beep nacelles up reaching 80 knots without difficulty. Failed to apply power and lost control at approximately 80 degrees nacelle incidence.
Same as above but with maximum nacelle beep rate set at 5°/sec for transition	Same as above	Decelerationthrough transition accomplished with a gain in altitude of 100 to 200 ft. Lower maximum nacelle rates would be desirable at the high speed end of transition.
V=60 knots SAS On LAS On 70° Nacelle incidence	Investigate rates of descent and maneuverability	Set up a rate of descent of 500 ft/min at 35% torque (40% required for level flight). Banked aircraft to 15° and obtained 700ft/min rate of descent. Banked aircraft to 20° and obtained 1000 ft/min rate of descent.

Initial Condition	Maneuver	Pilot Comments
		Aircraft was well behaved. Leveled off and reduced power to maintain 1000 ft/min descent. ± 2 degree long period pitch oscillation developed. Attempted a 1500 ft/min rate of descent unsatisfactorily. Lost control after pitch down, due to wing stall and failure to apply power.
Same as above at 65 Knots	Wings-level, partial power rates of descent	Trimmed at zero rate of climb, 65 knots, 5 deg. angle of attack, 2600 ft altitude. Recorded angle of attack vs rate of descent as follows: Decreasing Power 10 deg @ 500 ft/min 15 deg @ 1200 ft/min 18 deg @ 1500 ft/min Lost control after pitch-down due to wing stall.
90 Knots, SAS On, LAS On, 45° nacelle incidence 37% torque and 6.5° pitch attitude at zero rate of climb	Achieve rates of descent in 500 ft/min increments by reducing power	Reached 500 ft/min descent at 90 knots, 4° pitch attitude 7.5 degrees angle of attack and 30% torque with no difficulty. A descent of 1000 ft/min was obtained at 27% torque, 7 degrees angle of attack, and 1 degree pitch attitude. A 1500 ft/min yielded 10 degrees angle of attack and -2 degrees pitch attitude (nose down). A 2000 ft/min rate of descent required an angle of attack of 12 degrees. Pilot elected to go to 4000 ft/min rate of descent and noted increased nose down attitude required to maintain airspeed.

Initial Condition	Maneuver	Pilot Comments
80 Knots, SAS On, LAS On, 5° Pitch attitude 6° angle of attack, and 37% torque 60 degree nacelle incidence	Same as above	The following trim rates of descent were flown: 500 ft/min @ 2° pitch attitude and 6 degrees angle of attack 1000 ft/min @1° pitch attitude and 10 degrees angle of attack 1500 ft/min @ 0° (level) pitch attitude and 14 degrees angle of attack A 2000 ft/min point was flown.
40 Knots SAS On, LAS On, 80 degrees nacelle incidence, 5 degrees pitch attitude, and zero rate of climb	Same as above	The following trim rates of descent were flown at the listed conditions: 500 ft/min @ 4° angle of attack 1000 ft/min at 4° angle of attack 1500 ft/min at 18° angle of attack and 50 knots. A slight pitch oscillation developed at 1500 ft/min and 50 knots airspeed.

9.3.7 Engine Out Operation in Transition

Engine failures in transition were not evaluated per se. The effect of reducing power is adequately covered in Section 9.3.6. Powers used were less than available with a single engine. The engine out transients and the ability to control altitude precisely at low speed (near hover) with single engine power were not evaluated. These should be evaluated at a later date.

9.4 CRUISE MODE STUDIES

9.4.1 Longitudinal Stick, Lateral Stick and Pedal Pulses in Cruise

This section presents the pilot comments obtained from control pulses in the cruise mode. Responses to longitudinal stick, lateral stick and pedal pulses were examined over a range of speeds from 140 knots to 260 knots. The simulated aircraft does not have cruise SAS. These studies were all conducted with the load alleviation system (LAS) on. The pulses in cruise were generally 1/2 inch for 1 second. Pilot comments for these studies are presented below.

Initial Condition	Maneuver	Pilot Comments
Control response characteristics at 140 knots. Pitch attitude=6.5° Torque = 35%	Trim	Difficult to trim in roll - tends to fall off
	Pitch Pulses	
	Nose Up	Reasonably well damped and returns to trim
	Nose Down	Well damped and returns to trim
	Roll Pulses	
	Left Roll	Rolled 5 or 6 degrees with a very slow return to trim
	Right Roll	Rolled 5 degrees with a very slow return to trim
	Pedal Pulses	Yaw rate reasonably well damped. Dihedral effect apparent and symmetrical.
Control response characteristics at 160 knots. Pitch attitude =5° Torque =40%	Pitch Pulses	
	Nose Up	Pitched up 5°, overshot to 2° below trim attitude. Developed a very slow convergent pitch oscillation indicates poor trimability. Pitch oscillation not noticed at 140 knots.
	Nose Down	Same characteristics i.e. reasonably symmetrical.
	Roll Pulses	
	Left Roll	Reached 10° bank angle and developed slight sideslip and slowly returned to zero bank angle with very long period.

Initial Condition	Maneuver	Pilot Comments
	Roll Pulses Right Roll	Symmetrical roll response. Inputs essentially h ands off i.e. no pitch inputs.
	Pedal Pulses	Input generated a 3 needle width yaw rate. Aircraft rolled 20 degrees after input. The yaw axis was well damped with a slight overshoot and slightly oscillatory.
Control response characteristics at 180 knots. Pitch attitude = 3.5° Torque = 42% LAS On	Trim	Difficulty in attaining trim. Aircraft was sensitive to rate of climb with pitch attitude.
	Pitch Pulses	Very slight oscillation that was more noticeable for nose down inputs. There was a very slowly divergent long period oscillation.
	Roll Pulses Left Roll	Reached 10° bank angle and generated a little bit of sideslip that returned to zero slip.
	Right Roll	Symmetrical response.
	Pedal Pulses	Inputs generated 2 needle width yaw rates. Dihedral effect drove bank angle to 15° right for right inputs and 10° left for left inputs.
Control response characteristics at 200 knots. Trim pitch attitude = 1.5° Torque = 50% LAS On	Pitch Pulse Nose Up	Input excited a pitching oscillation of long period, plus or minus a couple of degrees attitude, plus or minus 5 knots airspeed, plus or minus 500 to 800 ft/min rate of climb. Long period seemed neutrally damped.
	Nose Down	Input gave .4g's, response similar to nose up input.
	Roll Pulses Left Roll	Achieves bank angle and slowly returns to zero bank

Initial Condition	Maneuver	Pilot Comment
	Roll Pulses Right Roll	Similar to left input. Heavily damped oscillatory response with first peak nose left.
	Yaw Pulses	Similar to response at 180 kts. single needle width rate generated 10 degrees of bank angle.
	Beep Trim	Vernier beep response was too slow for roll beep inputs. Because of the difficuly of trimming in roll there was a tendency to overcontrol. The tendency to overcontrol existed when the stick wasused for vernier control.
Control response characteristics at 255 knots. Trim pitch attitude =1° Torque = 58% LAS On	Pitch Pulses Nose Up	Input generated .4g's and pitch attitude of 4 degrees
	Nose Down	Input generated at 2 to 3 degrees attitude change with a 4 degree trim overshoot. Phugoid slowly damped out.
	Roll Pulses	Initial response was non-oscillatory and damped out and returned to trim slowly.
	Yaw Pulses	A 1 needle width rate banked aircraft 10 degrees and was symmetrical.
Control response characteristics at 260 knots. Trim pitch attitude = 0.0° Torque = 75% LAS On	Pitch Pulses Nose Up	Input generated .4g's, 3 to 3.5 degrees pitch attitude chanc and returned to trim, slight undershoot in rate of descent to 300 ft/min. Airspeed changed about 5 knots. Total airspeed variation was plus 2 kts to minus 4 kts.
	Nose Down	Input was .5g's, 3 degree attitude generated 1000 ft/min rate of descent. Returned to trim and overshot to 500 ft/min rate of climb. Long term phugoid of ±2 knots and ±1 degree pitch attitude.

Initial Condition	Maneuver	Pilot Comments
	Roll Pulses	
	Left	Input generated 10° bank angle that came back to 5 degrees rather quickly, followed by slow return to 4 degrees, the aircraft remained at 4 degrees.
	Pedal Pulses	
	Right Pedal	Generated a 1 needle width yaw rate, 10 degree right bank, then a 10 degree left bank which was well coordinated and drifted to 13 or 14 degrees left bank
	Left Pedal	Developed 5° left roll angle. Asymmetric response attributed to being out of trim.
	Repeat Inputs	
	Right	Generated 2 needle width rate and 15 degrees of bank, then returned.
	Left	Generated 1 needle width rate and 8 degrees of bank, then returned.

9.4.2 SAS Evaluation in Cruise

Since the simulated aircraft does not have a cruise stability augmentation system, aircraft response to longitudinal stick, lateral stick and pedal pulses were evaluated with the load alleviation system (LAS) off. These runs were conducted at 140, 180, and 260 knots. The load alleviation system simulated zeros out the rotor hub moments. The pulses in cruise were generally 1/2 inch for 1 second, except where noted. Pilot comments are shown below for these maneuvers.

Initial Condition	Maneuver	Pilot Comments
Control response characteristics at 140 knots. LAS off - Trimmed at 5.5° pitch attitude, Torque = 35%	Pitch Pulses Nose Up	Pitched up 2 to 3 degrees, returned to trim and undershot. No tendency to diverge and returns to trim airspeed and pitch attitude well.

Initial Condition	Maneuver	Pilot Comments
	Pitch Pulses Nose Down	Pitched down 2.5 degrees, nose up overshoot with a very slight airspeed change and returns to trim well.
	Roll Pulses	Very sluggish in roll for 1 inch inputs with a slight tendency for long period roll oscillation.
	Pedal Pulses	Sluggish response with strong dihedral effect. A 1 needle width rate generates 8 degrees of bank angle.
Control response characteristics at 180 knots. LAS off Trimmed at 3° pitch attitude Torque 43%	Pitch Pulses Nose Up	Generated 3 degree attitude change with slow return. Airspeed fell to 160 knots. Neutrally damped long period between 180 and 160 kts. Attitude excursion reached max. nose up 7 deg. possibly due to mistrim.
	Nose Down	Pitched down 3 deg. from trim and gained 10 kts airspeed, pitch attitude returned through trim and reached 5° nose up, airspeed dropped to 170 knots ±10 knot oscillation about trim.
	Roll Pulses Left Roll	Aircraft continued to roll after removal of input. Tendency to spiral instability.
	Right Roll	Response was symmetrical. Roll response was sluggish and difficult to trim. Required large and long inputs to maneuver.
Control response characteristics at 260 knots. LAS Off Trimmed at 0° pitch attitude and 75% torque	Pedal Pulses	Response similar to lower speeds, with high dihedral effect.

Initial Condition	Maneuver	Pilot Comments
	Pitch Pulses Nose Up	Response was fairly well damped initially. Aircraft came back to trim and overshot airspeed by 10 kts. Long term oscillation was about the same as lower airspeeds, i.e., $\pm$10 knots.
	Nose Down	Response reached .5g's initially and was well damped. Low amplitude long period oscillation was apparent.
	Roll Pulses Left Roll	Aircraft was difficult to trim in roll with LAS off. Initially rolled to 10° left with a slow, very slow, return to wings level. Response was slightly unsymmetrical, probably due to mistrim. Roll axis tended to fall off one way or the other at random.
	Pedal Pulses	Similar dihedral effect characteristics as lower speeds.

9.4.3 Maximum Acceleration and Deceleration in Cruise

Maximum acceleration and deceleration characteristics of the Model 222 were investigated. The aircraft was accelerated from 140 knots to 250 knots and then decelerated to 140 knots. The pilot comments for this maneuver is shown below.

Initial Condition	Maneuver	Pilot Comments
Level flight at 140 knots LAS On	Acceleration at maximum power to 250 knots, then decelerate back to 140 knots	The aircraft accelerated slower than anticipated developing 500 foot per minute rate of climb. Rate of climb was sensitive to pitch attitude changes. The roll axis was unsteady but controllable. The control harmony between roll and pitch was not very good. The force feel system did not have a positive feel around zero force. Transients easily controllable.

9.4.4 Control Response to Large Inputs

Aircraft response to large control inputs in the cruise mode were investigated at 140 knots. The load alleviation system was on. Pilot comments are shown below.

Initial Condition	Maneuver	Pilot Comments
Level flight at 140 kts. LAS On	2" pitch pulse 2" roll pulse 2.5" pedal pulse	Control response was adequate in all axes. There was no undesirable coupling except for the high dihedral effect. Trimmability was quite poor, particularly in roll.

9.4.5 Response to Gusts in the Cruise Mode

The response of the Model 222 to random turbulence in the cruise mode was investigated at 140, 180, 225 and 250 knots. The load alleviation system was on. Pilot comments for these maneuvers are as follows.

Initial Condition	Maneuver	Pilot Comments
Level Flight at V=140 Kts LAS On	4 ft/sec RMS gust	Most active in pitch axis with very little yaw disturbance. Trimmability was poor, however, the aircraft returned to trim after upsets.
Level Flight at V=180 Kts. LAS On		Gust response similar to 140 knots.
Level Flight at V=225 Kts LAS On		Response similar to 140 knots, but the vertical upsets became more abrupt. Aircraft returned to trim after gust upsets.
Level Flight at V=250 Kts LAS On		Response similar to 225 knots. Aircraft did not diverge due to gusts, and airspeed drifted ± 15 knots.

9.4.6 Climbs and Descents in the Cruise Mode

Aircraft response during steady state climb and descents in the cruise mode were evaluated. The pilot started from sea level and climbed to 10,000 feet holding airspeed at 150 knots.

Initial Condition	Maneuver	Pilot Comments
Level Flight @ V=150 Knots LAS On	Climb to 10,000 ft at 150 Kts.	Aircraft climbed at 1700 ft/min, no problem in holding airspeed.
Level Flight @ V=150 Knots LAS On	Descend to Sea Level	Pulled off power and descended at 1000 ft/min. Pitch attitude between 2 and 3 degrees. Aircraft well behaved.

9.4.7 Engine Out Operation in Cruise Mode

Aircraft response to engine failure in the cruise mode was evaluated. At 250 knots one engine was failed, with the response noted. This was repeated at 250 kts with two engines failed. Pilot comments are noted.

Initial Condition	Maneuver	Pilot Comments
Level Flight @ 250 Knots LAS On	Fail one engine	With one engine failed and hands off, the aircraft is well behaved. The roll axis is unstable but aircraft is easily controllable. Transients mild. The aircraft stabilized at 150 knots.
Level Flight @ 250 Knots LAS On	Fail two engines	Same as with single engine failure except pilot applied power to stabilize at 150 knots.

9.5 EVALUATION OF MAXIMUM NACELLE RATES IN TRANSITION

This was evaluated in Section 9.3.6. The maximum nacelle rate capability was reduced to 5 deg/sec (from a nominal 10 deg/sec). The pilot indicated that lower maximum rates might be desirable in the high speed end of transition (100 to 140 knots) to minimize pitch attitude changes at these conditions, while higher nacelle rates are acceptable at lower speeds. Additional work is required in this area to evaluate the desirability of establishing a schedule of maximum nacelle tilt rates.

9.6 EVALUATION OF HELICOPTER FLIGHT MODE

Evaluation of the helicopter flight mode was conducted for several incidence angles. The procedure was to establish a nacelle incidence angle and then accelerate at that incidence angle. The pilots comments are shown below. It should be noted that this type of operation results in extreme nose down pitch attitudes at the higher speeds and some negative speed stability.

Initial Condition	Maneuver	Pilot Comments
All SAS and LAS On Nacelle incidence =90°	Accelerate to 160 knots at constant altitude	10 deg nose down @ 80 knots 15 deg nose down @ 100 knots
Nacelle incidence = 80°	Same	Longitudinal stick trim aft with increasing airspeed between 50 knots and 80 knots (reversal). The stick moves forward between 80 and 100 knots.
Nacelle incidence = 70°	Same	Longitudinal stick reversal at about 80 knots starts forward at 90 knots. 100 knots 5° nose down, stick is moving fwd. 160 knots 10° nose down nacelles keep down automatically.
Nacelle incidence = 45°	Same	Accelerated to 160 knots. Trimmed at a 4° nose down altitude at that speed.

10.0 CONCLUSIONS AND RECOMMENDATIONS

1. The math model was successfully programmed for the hybrid computer and checked out on the Small Motion Base Flight Simulator.

2. Nacelle tilt indicator is a primary flight instrument and should be located near the basic Tee. Rate of climb, airspeed, torquemeter and nacelle tilt indicator should be located on the same side of the basic Tee.

3. Nacelle tilt switch arrangement needs further investigation. Switch position (cyclic stick or thrust lever), direction of travel, force gradient and breakout, proportional rate, fixed rate beep or two rate beep need evaluation.

4. Operation with nacelle incidence above zero at speeds above about 160 knots is undesirable. Positive prevention of such operation should be considered. An automatic up stop at 90 to 95° is desirable to facilitate reconversion. Positive pilot action should be required to go beyond this setting.

5. The mag. brake is too coarse to be used for trim in the cruise range and should be locked.

6. Governor characteristics and thrust/collective pitch lever sensitivity need to be carefully tailored to facilitate accurate altitude control in hover.

7. Hover and transition characteristics are acceptable SAS off and good SAS on. They can be further improved by increasing control sensitivity in pitch and roll. The aircraft was successfully flown through transition SAS off.

8. Overtravel of the thrust/collective lever to provide position control of pitch for a collective flare is highly desirable for use in event of engine failure.

9. Descent rates of 1500 ft/min achievable without problem. Higher descent rates at speeds around 60 kts may result in wing stall and rapid further increase in descent rate if power is not applied rapidly. Further investigation is needed in this area.

10. Longitudinal characteristics in cruise satisfactory. The aircraft modelled had a roll/spiral coupling in cruise making it hard to trim in roll. It also showed very large dihedral effect. A cruise SAS should be provided in the lateral/directional axes.

11. Tilt rates around 10°/sec appeared quite acceptable at high nacelle angles, but lower rates are preferred at the high speed end of transition.

12. The aircraft can be flown in the helicopter mode up to about 100 kts but this results in large nose down attitudes. Early initiation of nacelle tilt provides a more comfortable and easily controlled transition.

11.0 REFERENCES

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8. Smith M.C., "University of Maryland Wind Tunnel Test 489, Force, Moment and Downwash Measurements on a Rigid Rotor and Semispan Wing", (4 volumes), Boeing Document D8-1062-1, The Boeing Company, Vertol Division, Philadelphia, Pa., March 1968.

APPENDIX A - TIME HISTORIES OF SELECTED PILOTED MANEUVERS

Aircraft time histories of the Boeing Vertol Model 222 Tilt Rotor for selected piloted maneuvers are presented in this appendix. They were selected to illustrate some of the pertinent pilot comments described in Section 9.0. These piloted studies were all conducted for an aircraft gross weight of 12,000 lb with the nacelles down (i_N=0) center of gravity at 28% mean aerodynamic chord (most aft C.G. at this weight). Configuration details and aerodynamic characteristics are as described in Reference 1 and summarized in Section 3.0.

Figure A.1(a) through A.1(c) show a slow transition from hover to cruise (approximately 80 seconds) and a reconversion to the hover mode (approximately 140 seconds). All pertinent information concerning the longitudinal and lateral directional axes are shown. In addition, information on the SAS motions, power/collective lever travel, rotor collective pitch, flap angle, nacelle angle, and governor behavior are shown. Figures A.(a) through A.2(c) show the same information for a rapid transition from the hover mode to the cruise mode (approximately 13 seconds) and a reconversion to the hover mode (approximately 15 seconds). For slow transitions, the aircraft is docile. As can be noted for the rapid transitions, holding altitude would require considerable pilot effort, although it is anticipated it would become easier with additional pilot experience with this vehicle. All stability augmentation (SAS) and load alleviation systems (LAS) were operating for these runs.

Figures A.3 and A.4 show the Model 222's response to longitudinal and lateral directional control pulses in hover with all SAS and LAS systems functioning. Figures A.5 and A.6 show this information with the SAS and LAS off. The pitch and yaw axes exhibit inherent damping provided by the hingeless rotors. The yaw axis is unstable. This is attributed to the lack of inherent damping in this axis. All tilt rotor aircraft, however, regardless of the type of rotor system would have this characteristic. It should be noted that fuselage angle of attack and sideslip are undefined for the hover mode in the mathematical model, and therefore those traces should be disregarded for these runs.

Figures A.7 and A.8 show aircraft response to longitudinal and lateral directional control pulses in the transition mode at 80 knots. The nacelle angle is 70 degrees. Figures A.9(a) and A.9(b) show helicopter mode maneuvers. With the nacelles at 90 degrees, the Model 222 is at a 15 degree nose down attitude at 100 knots, and the longitudinal stick is approximately 3 inches forward. Figure A.10 shows a series of partial power descents at 70 knots with the nacelle angle at 70 degrees.

Descent rates in excess of approximately 1500 ft/min could be achieved before wing stall occurred. Figures A.7 through A.10 were obtained with the SAS and LAS systems operating.

Figures A.11 through A.14 show longitudinal and lateral directional pulses at 140 knots in the cruise mode (i_N=0) with the load alleviation system on and off. It should be noted that at this time, the Model 222 did not have a cruise SAS. There is virtually no difference in response LAS on or off. The aircraft is heavily damped in the longitudinal axis. In the lateral directional axes there is roll/spiral coupling which makes it difficult to trim and a large dihedral effect. Both of these characteristics were eliminated in Boeing Vertol's January 1973 proposal with a cruise mode stability augmentation system. Figures A.15 through A.18 show the same information for the cruise mode at 260 knots.

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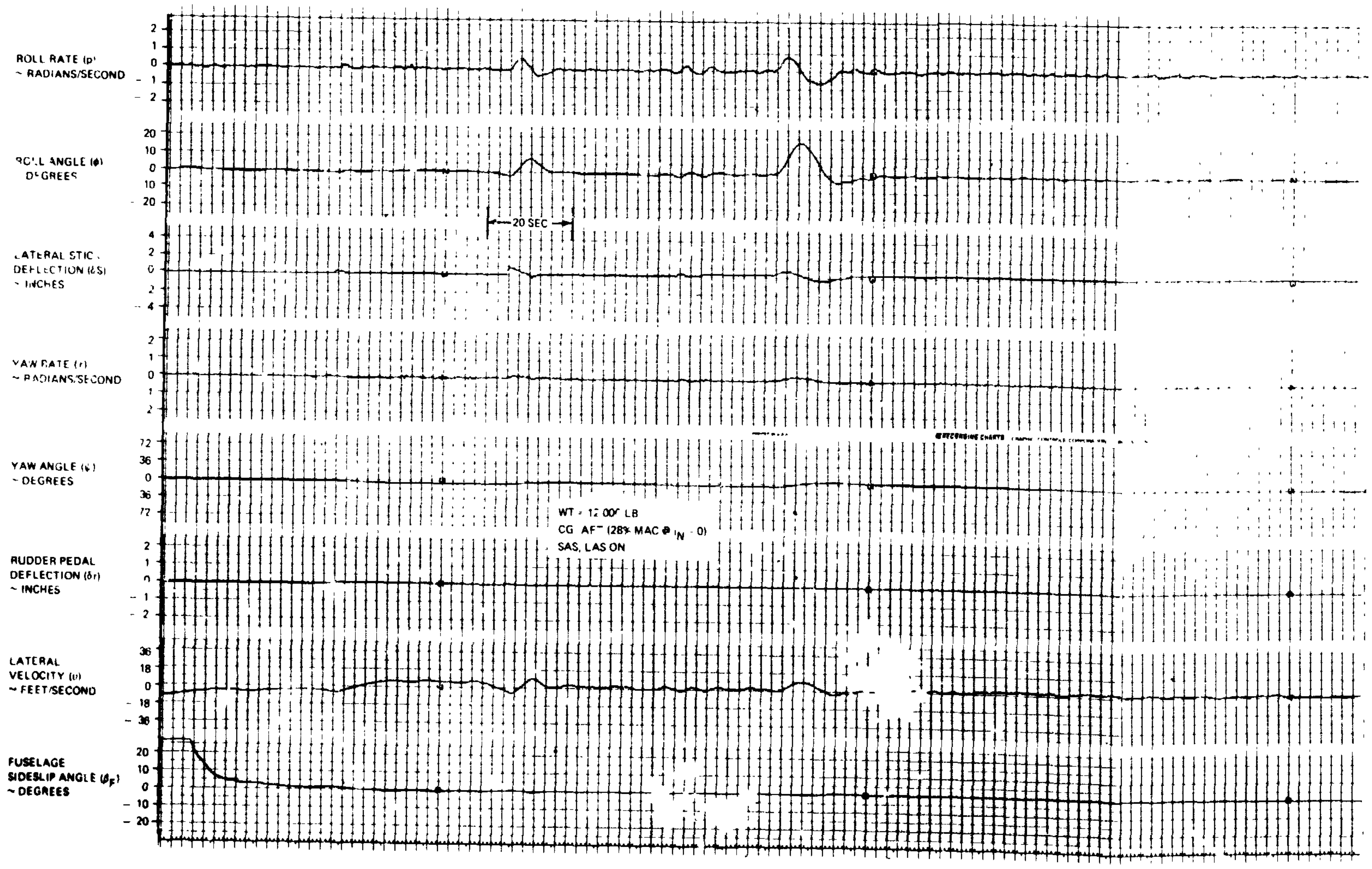

Figure A.1(a). Slow Piloted Transition and Reconversion SAS and LAS On

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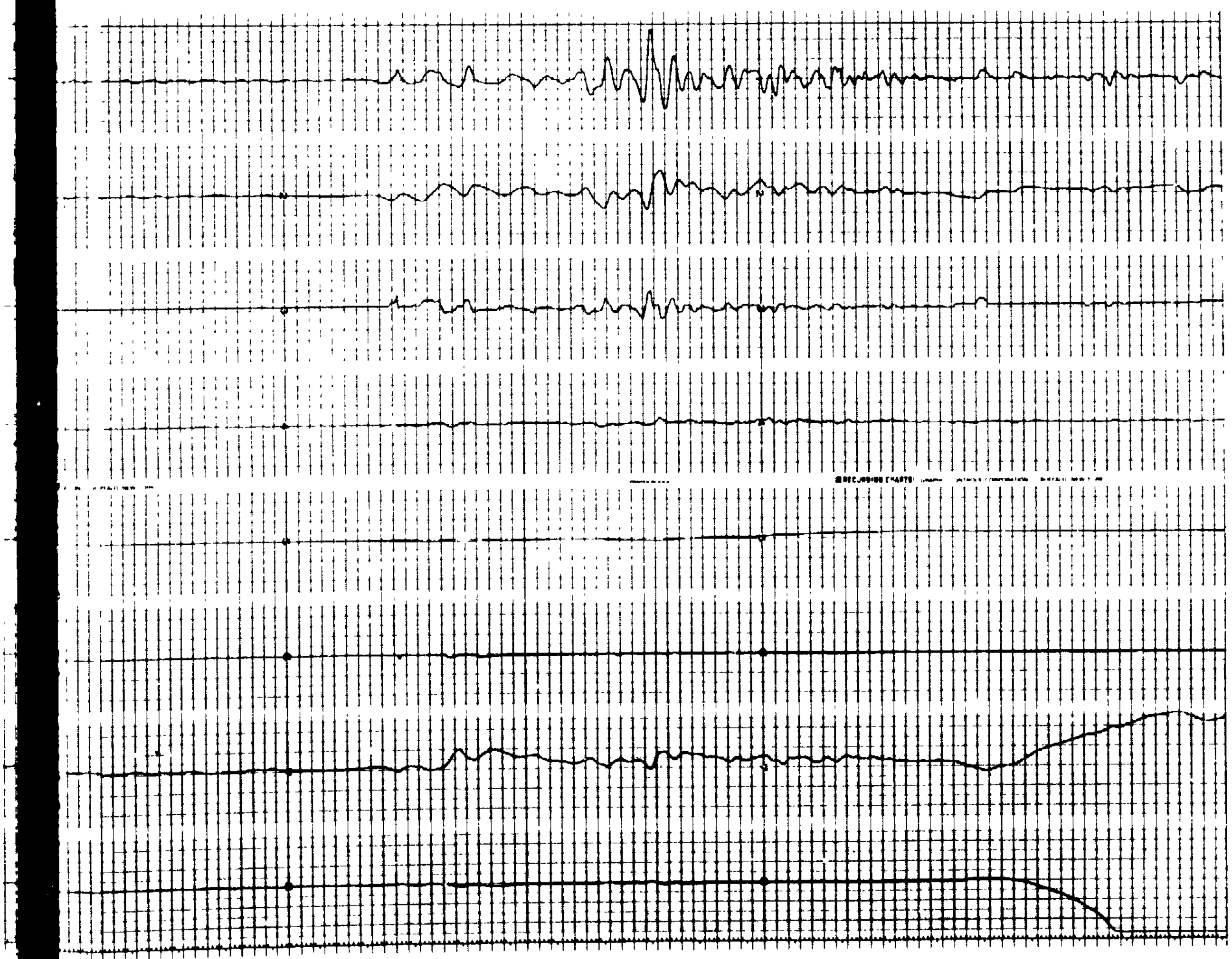

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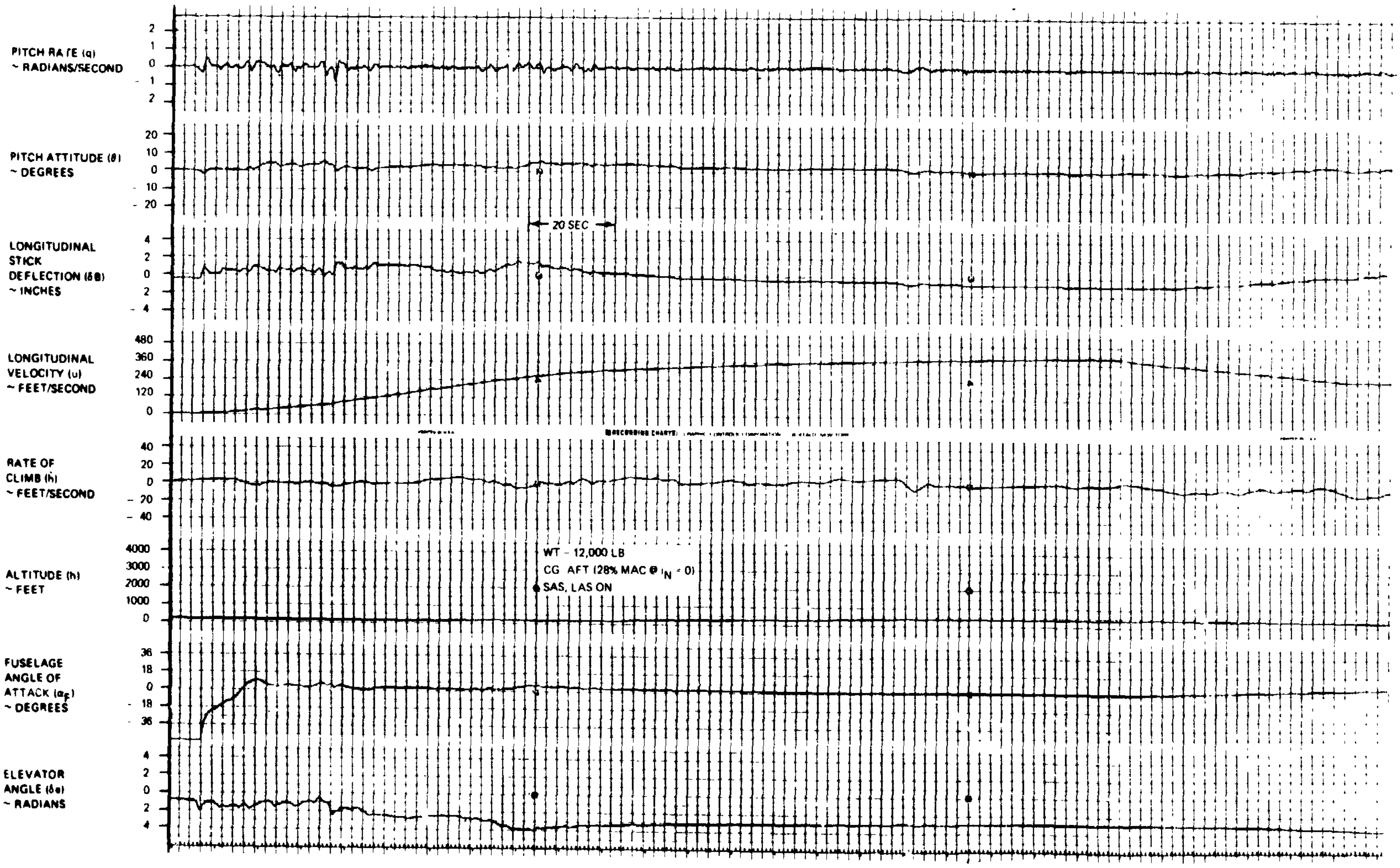

Figure A.1(b). Slow Piloted Transition and Reconversion SAS and LAS On

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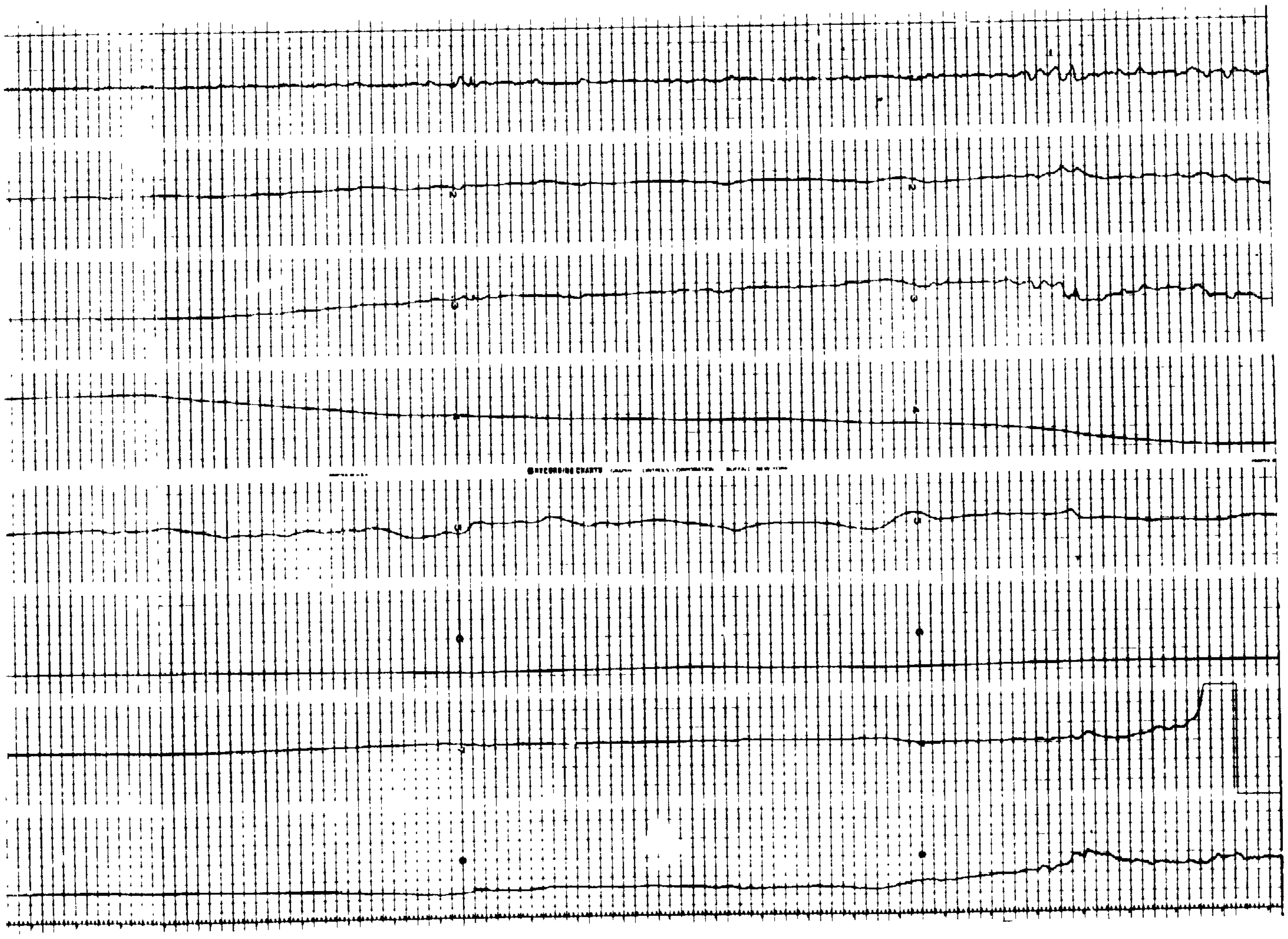

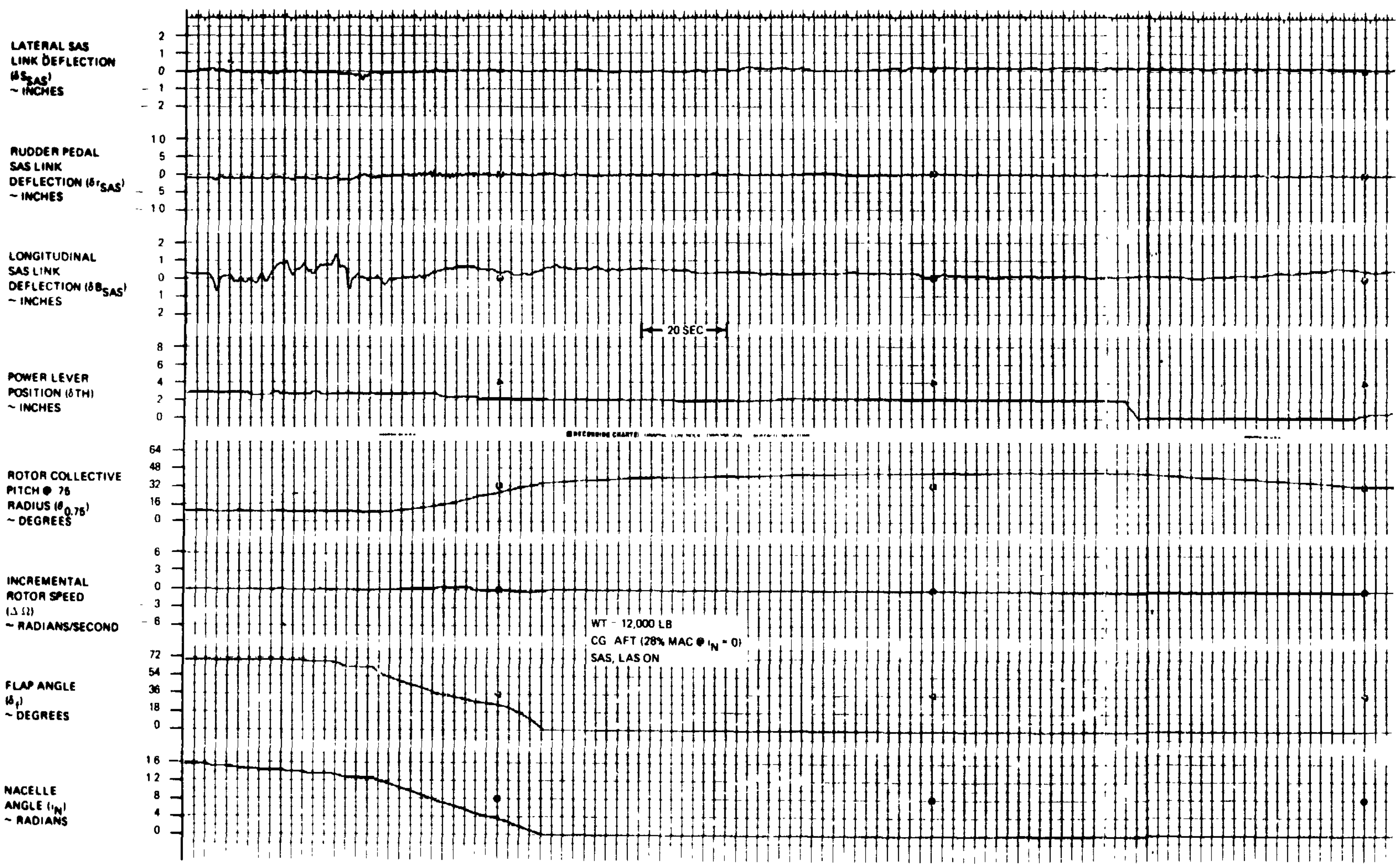

Figure A.1(c). Slow Piloted Transition and Reconversion SAS and LAS On

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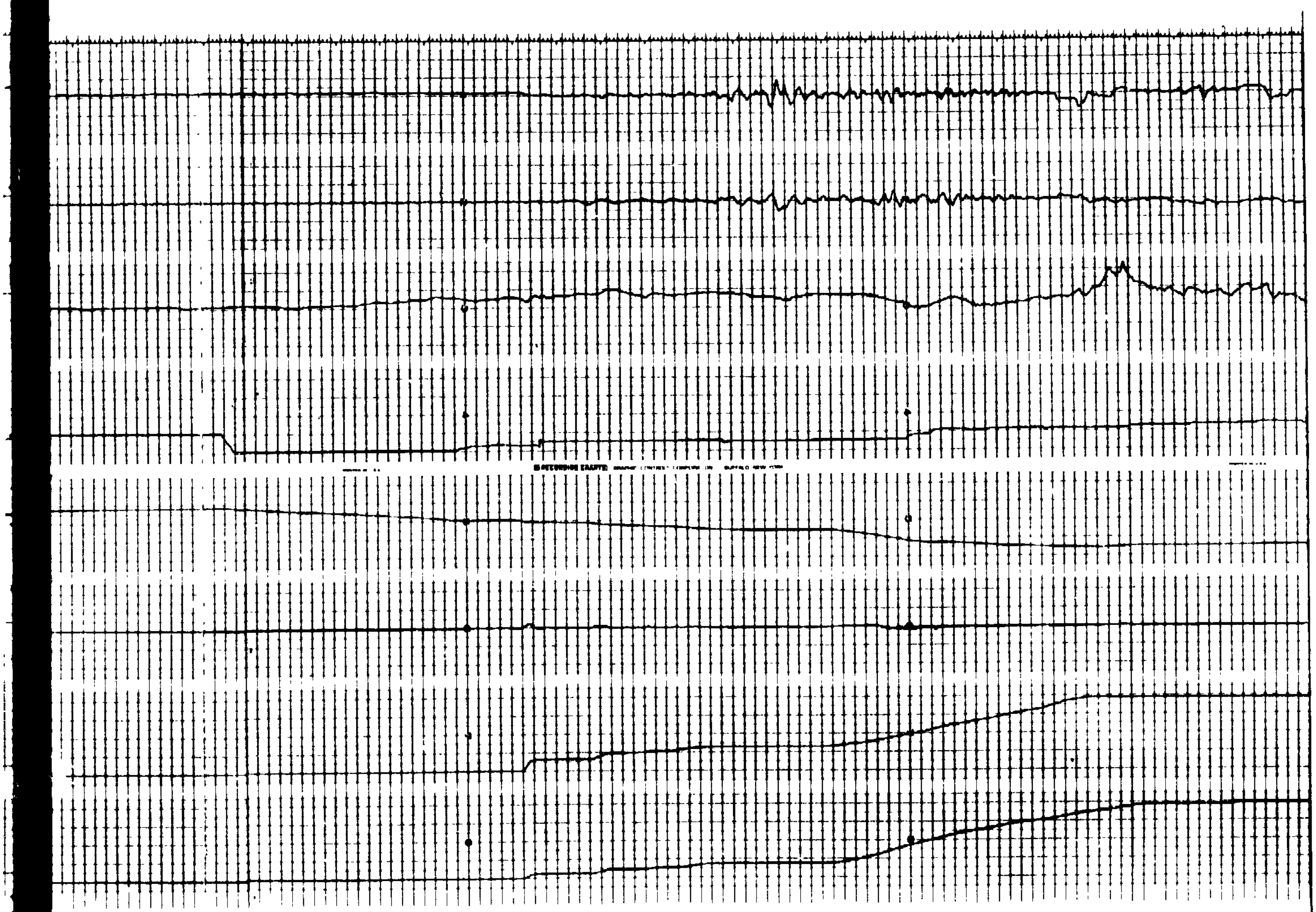

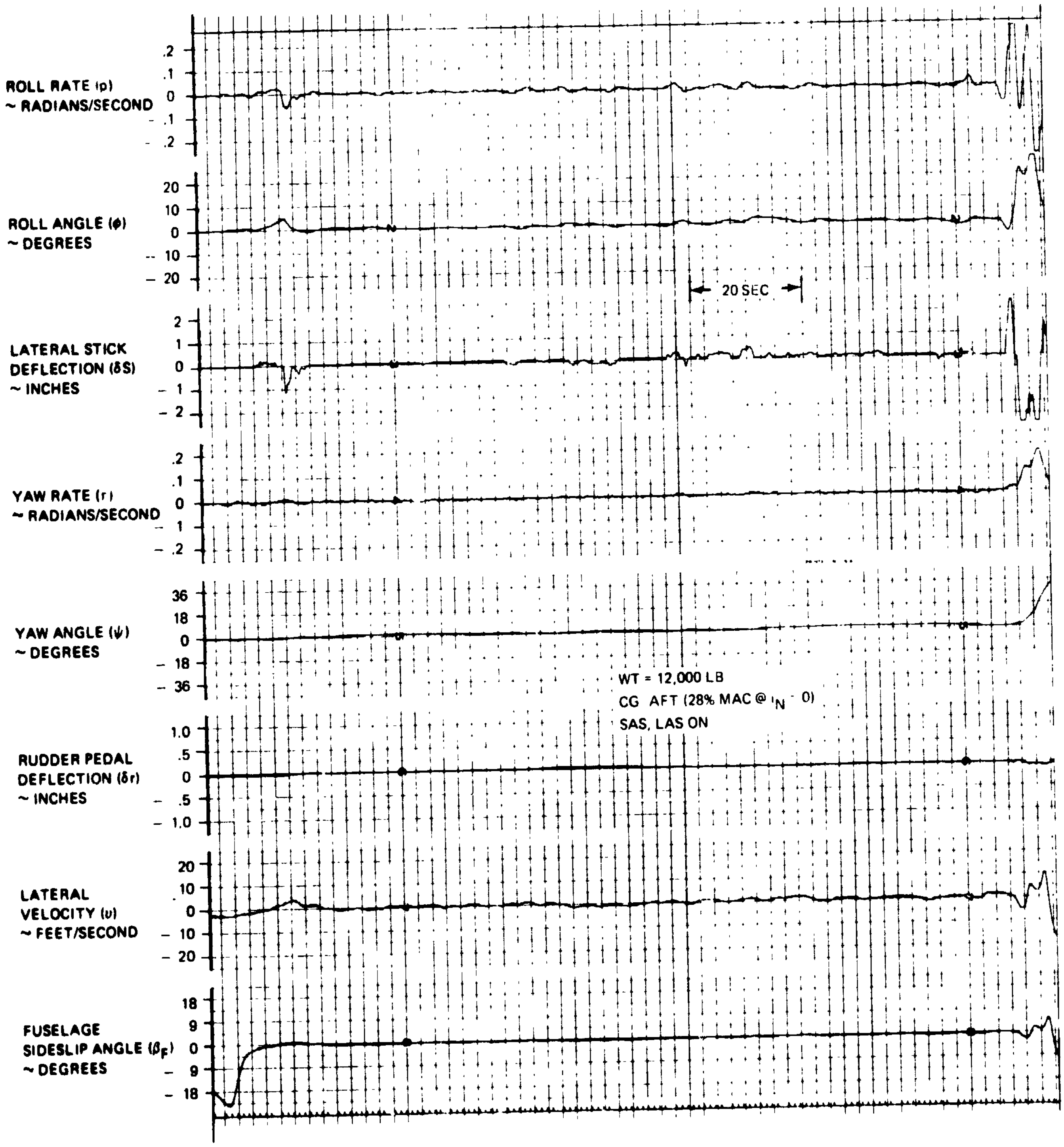

Figure A.2(a). Rapid Piloted Transition and Reconversion SAS and LAS On

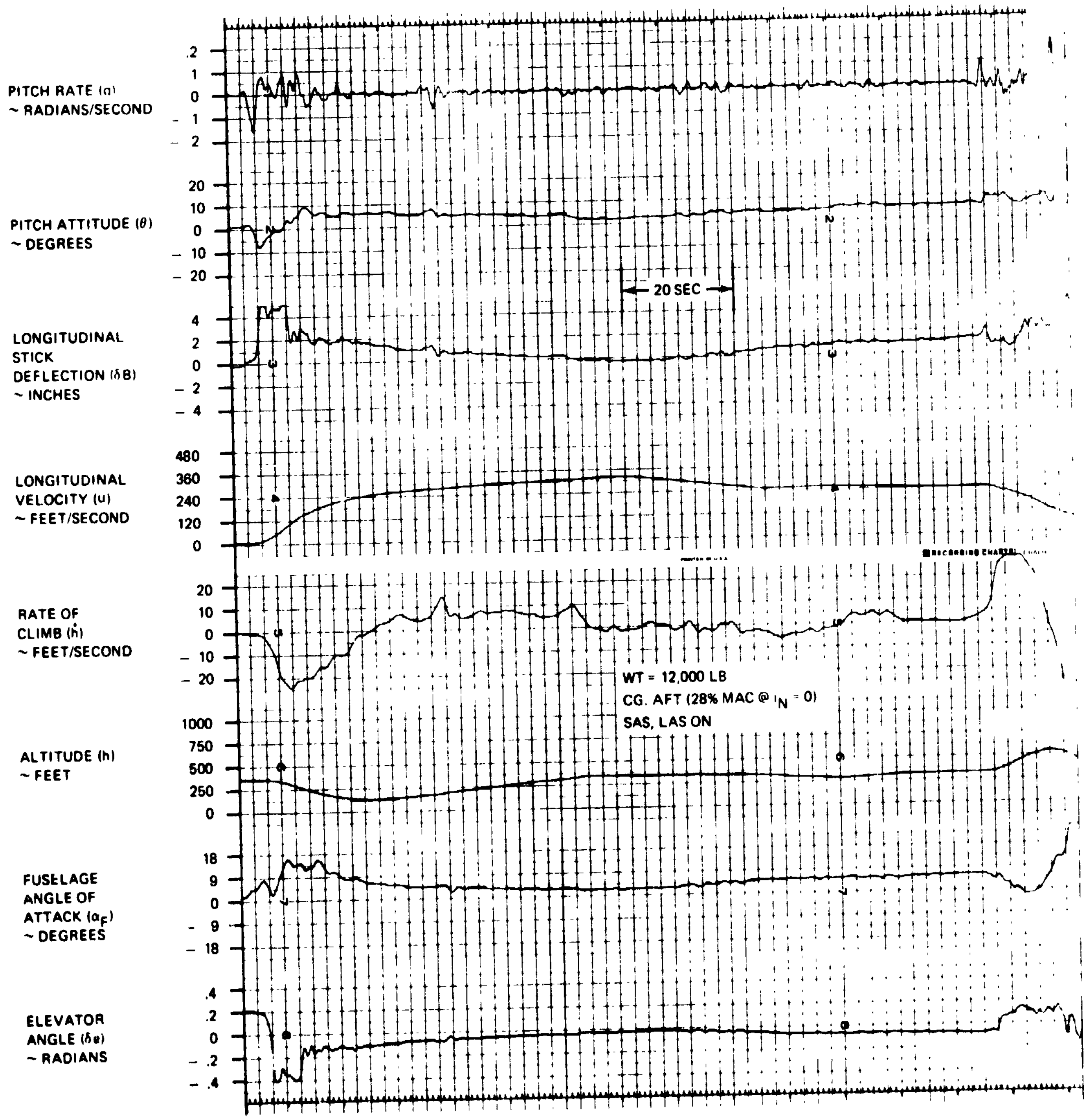

Figure A.2(b). Rapid Piloted Transition and Reconversion SAS and LAS On

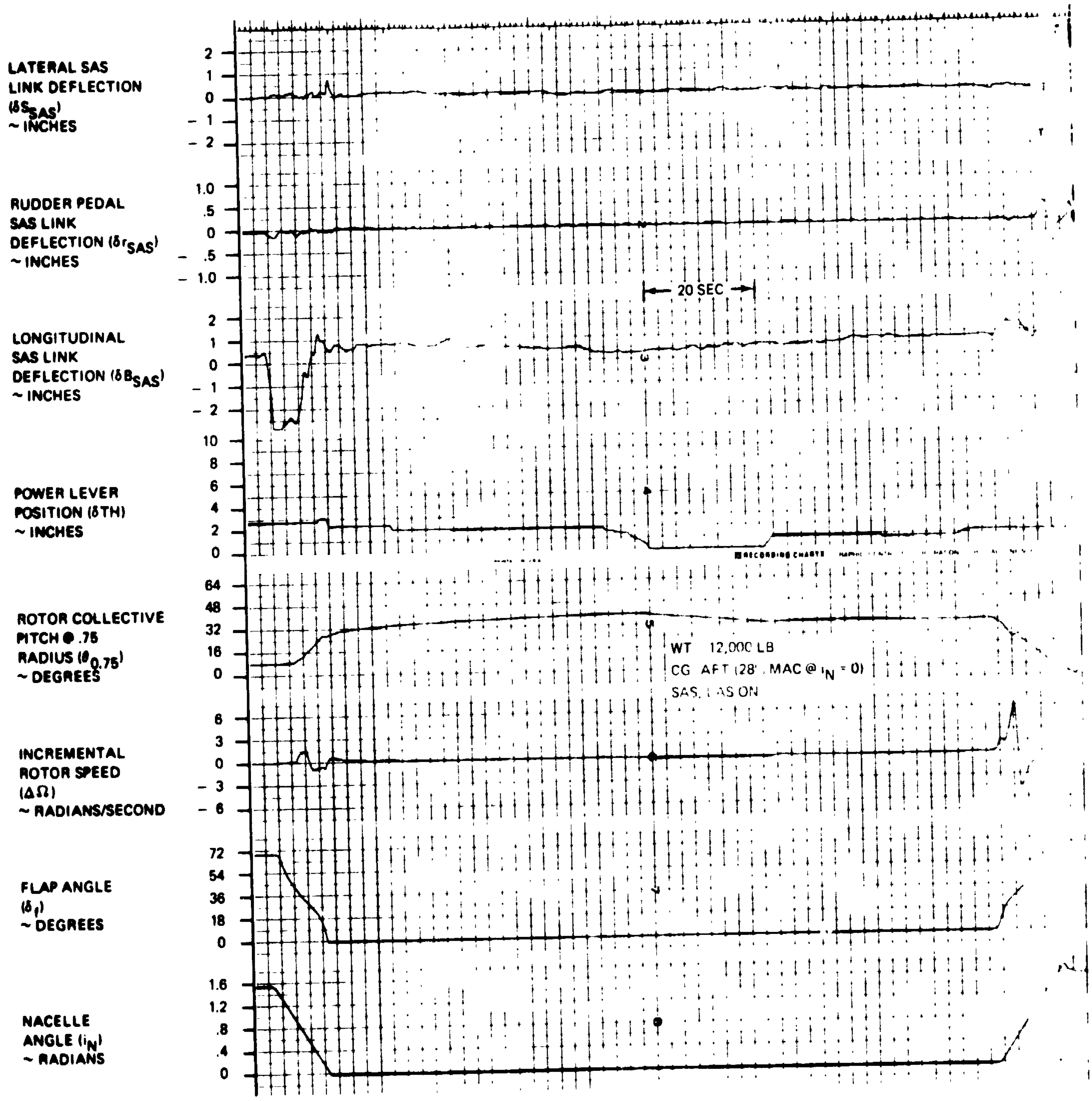

Figure A.2(c). Rapid Piloted Transition and Reconversion SAS and LAS On

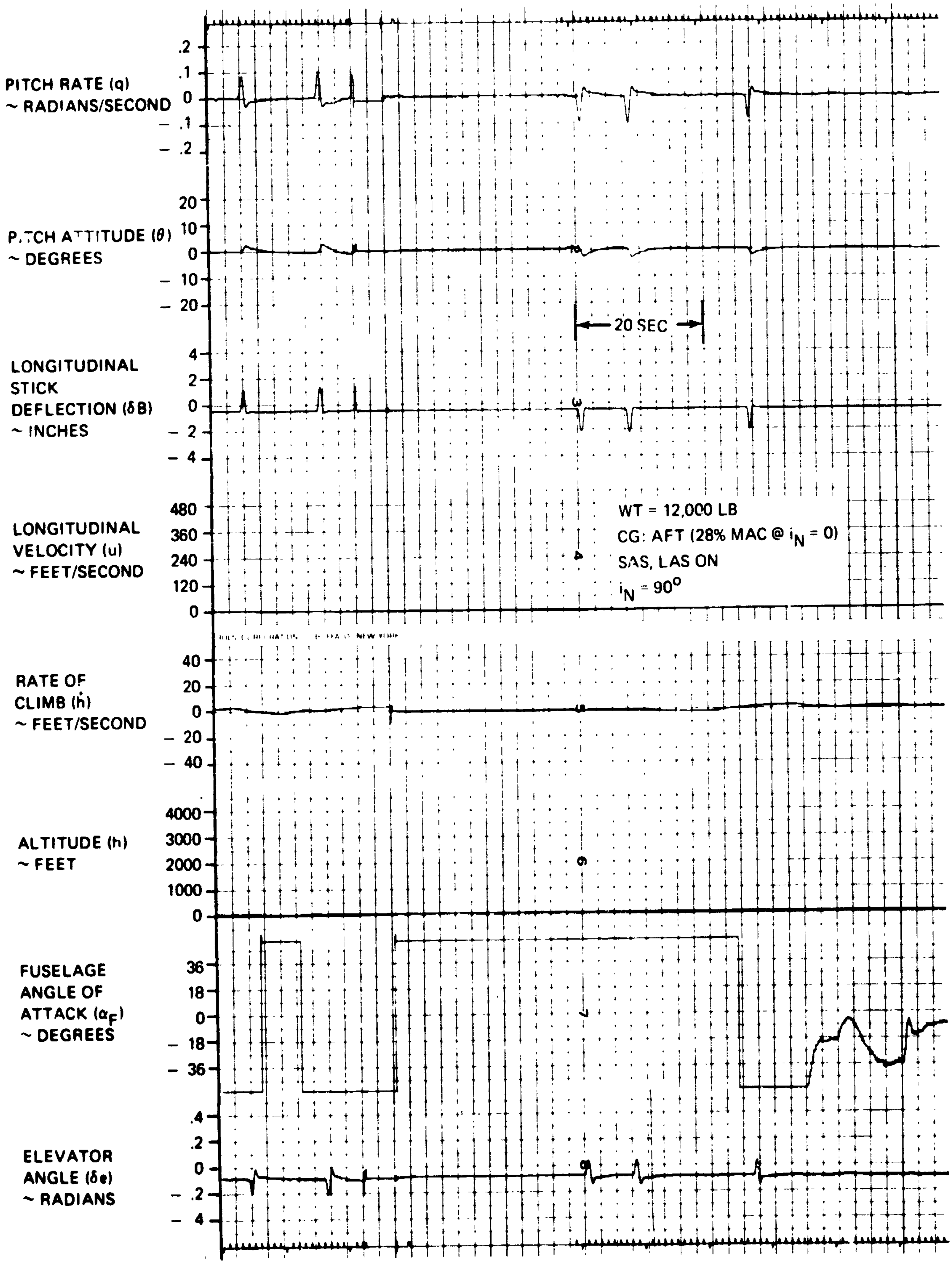

Figure A.3. Piloted Time History – Response to Longitudinal Stick Pulses in Hover, SAS and LAS On, $i_N = 90^{\circ}$

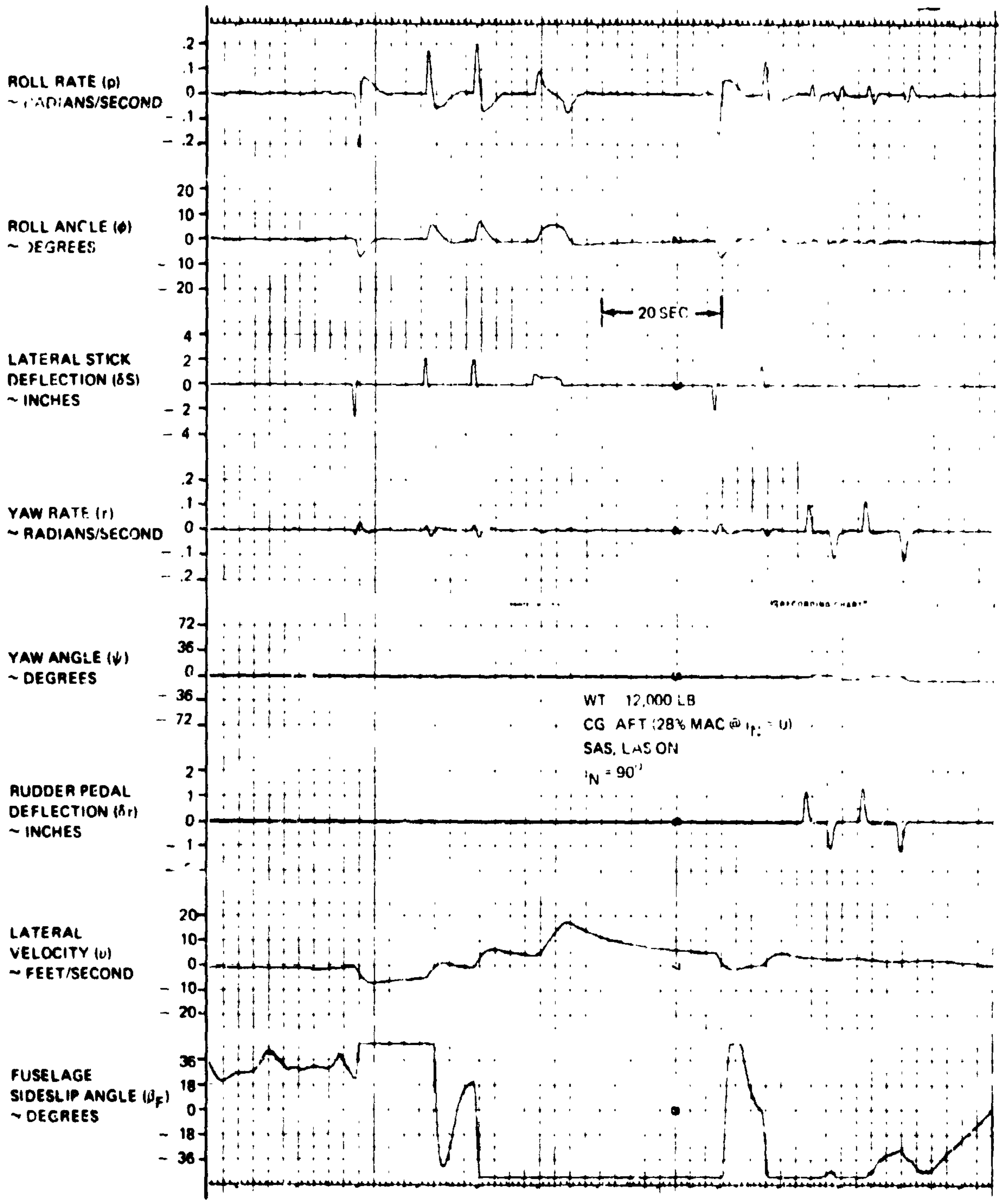

Figure A 4 Piloted Time History – Response to Lateral Stick and Rudder Pedal Pulses in Hover SAS and LAS On, $i_N = 90^o$

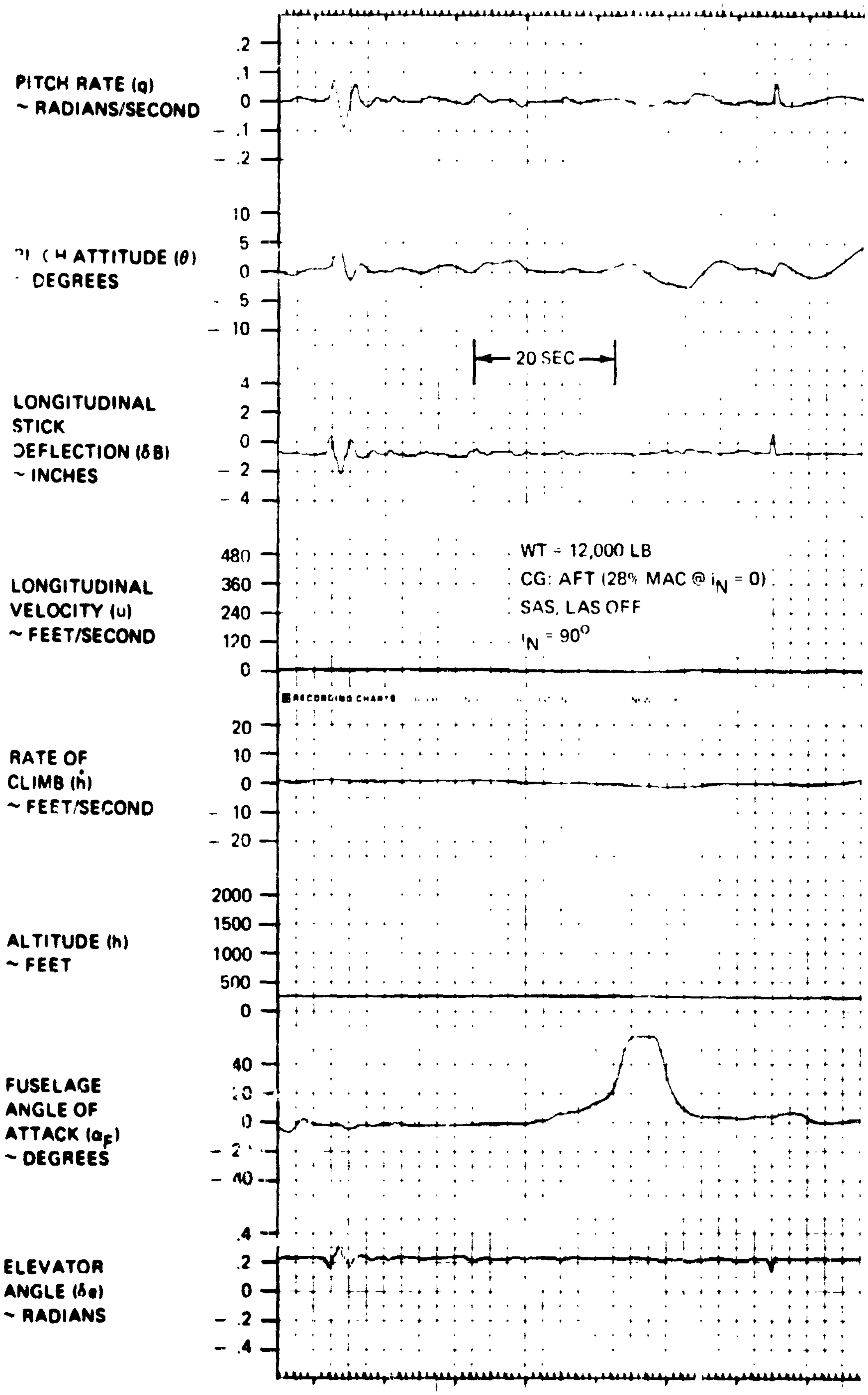

Figure A.5. Piloted Time History – Response to Longitudinal Stick Pulses in Hove., SAS and LAS Off, $i_N = 90^\circ$

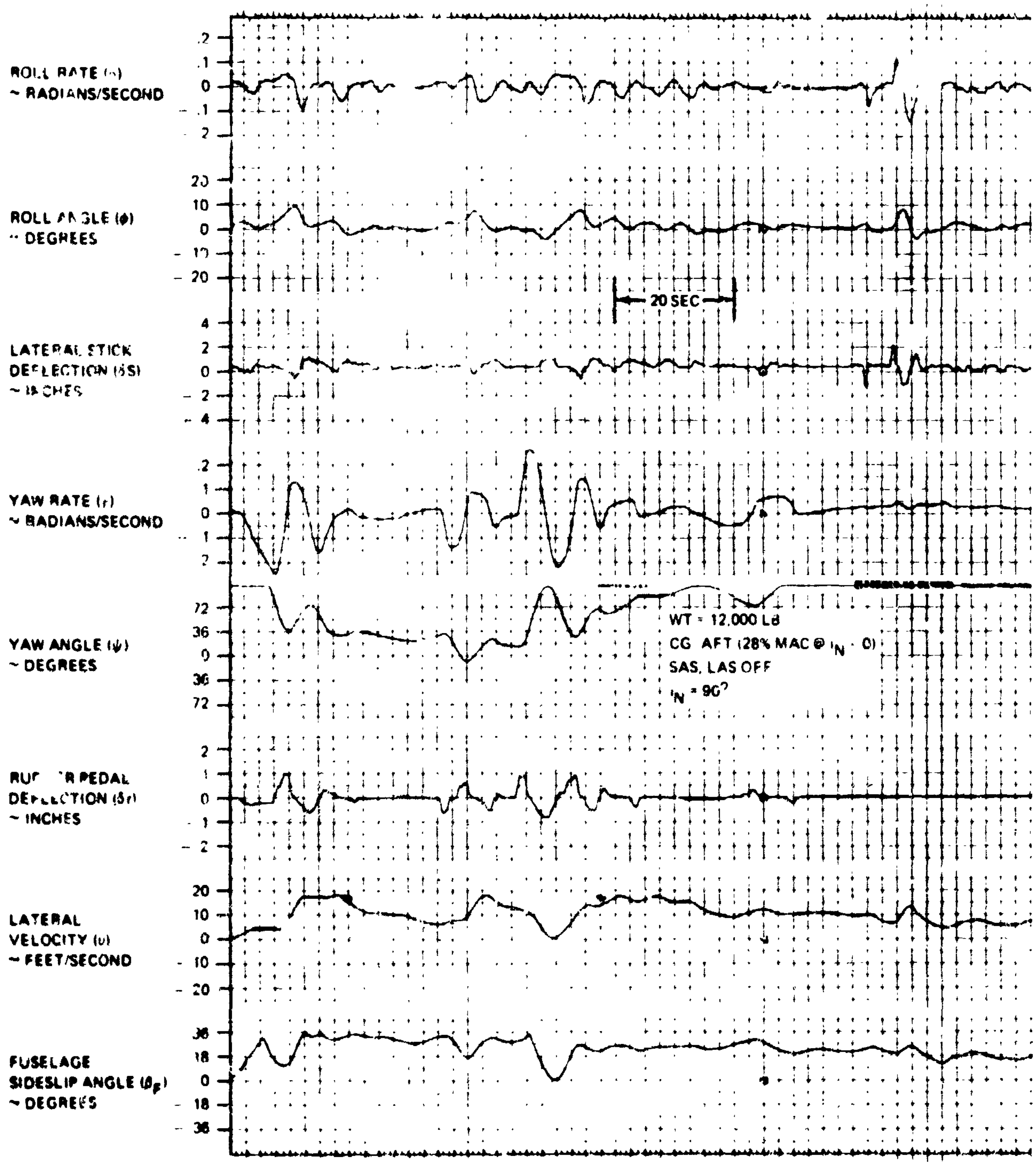

Figure A 6 Piloted Time History Response to Lateral Stick and Rudder Pedal Pulses in Hover SAS and LAS Off, $i_N = 90°$

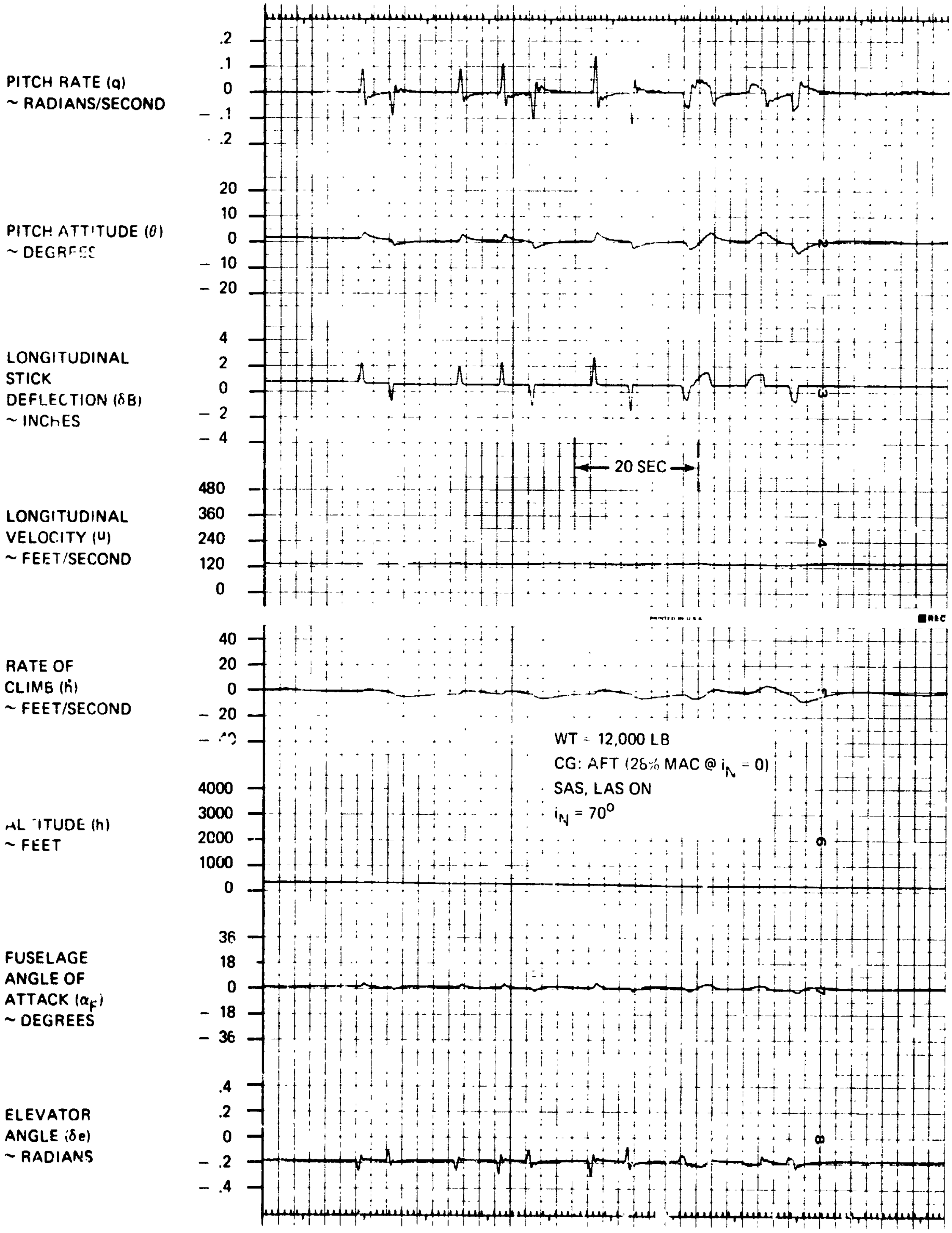

Figure A.7. Piloted Time History – Response to Longitudinal Stick Pulses in Transition, SAS and LAS On, $i_N = 70^{o}$, V = 80 Knots

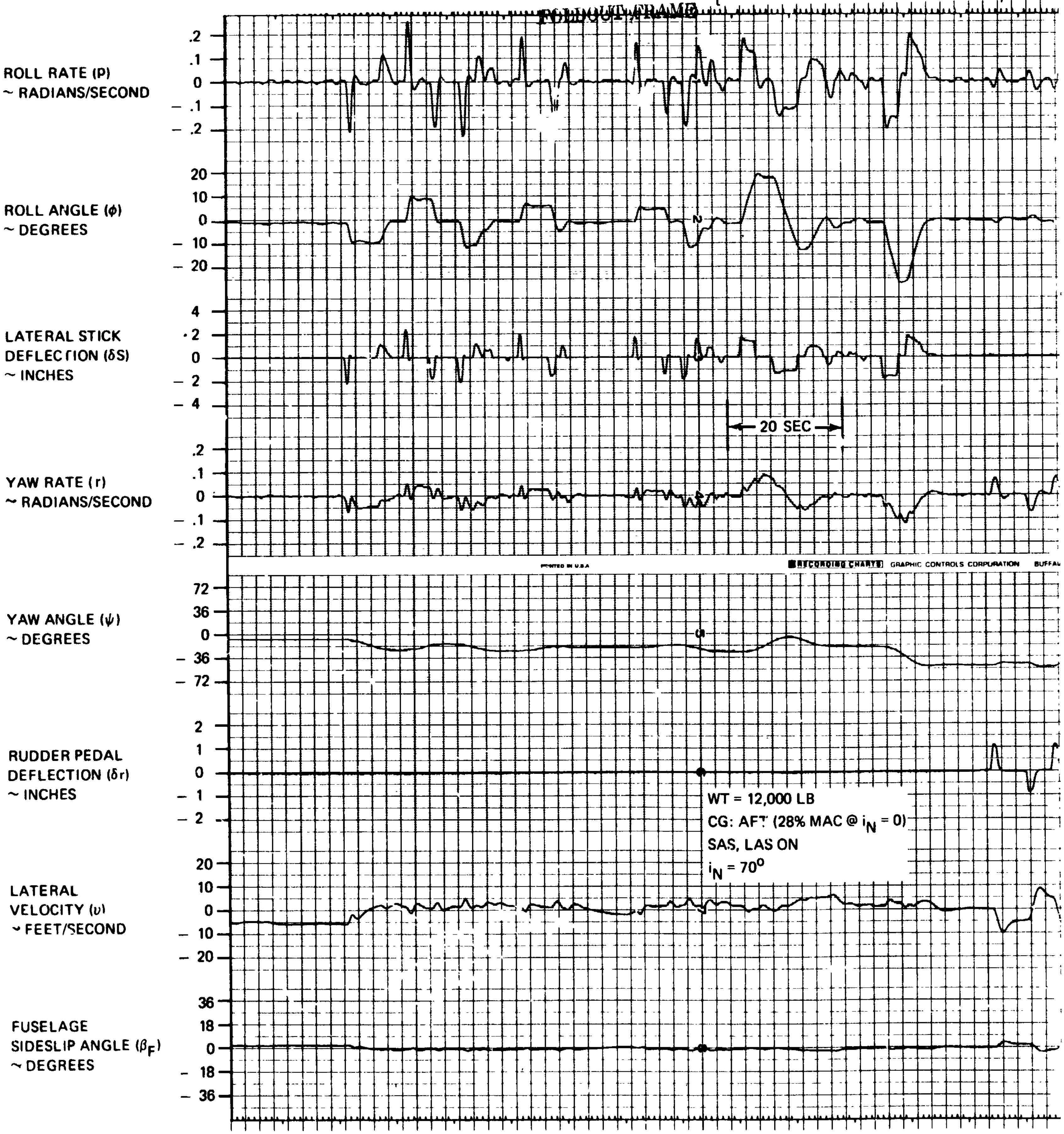

Figure A.8. Piloted Time History – Response to Lateral Stick and Rudder Pedal Pulses in Transition, SAS and LAS On, $i_N = 70^\circ$ V = 80 Knots

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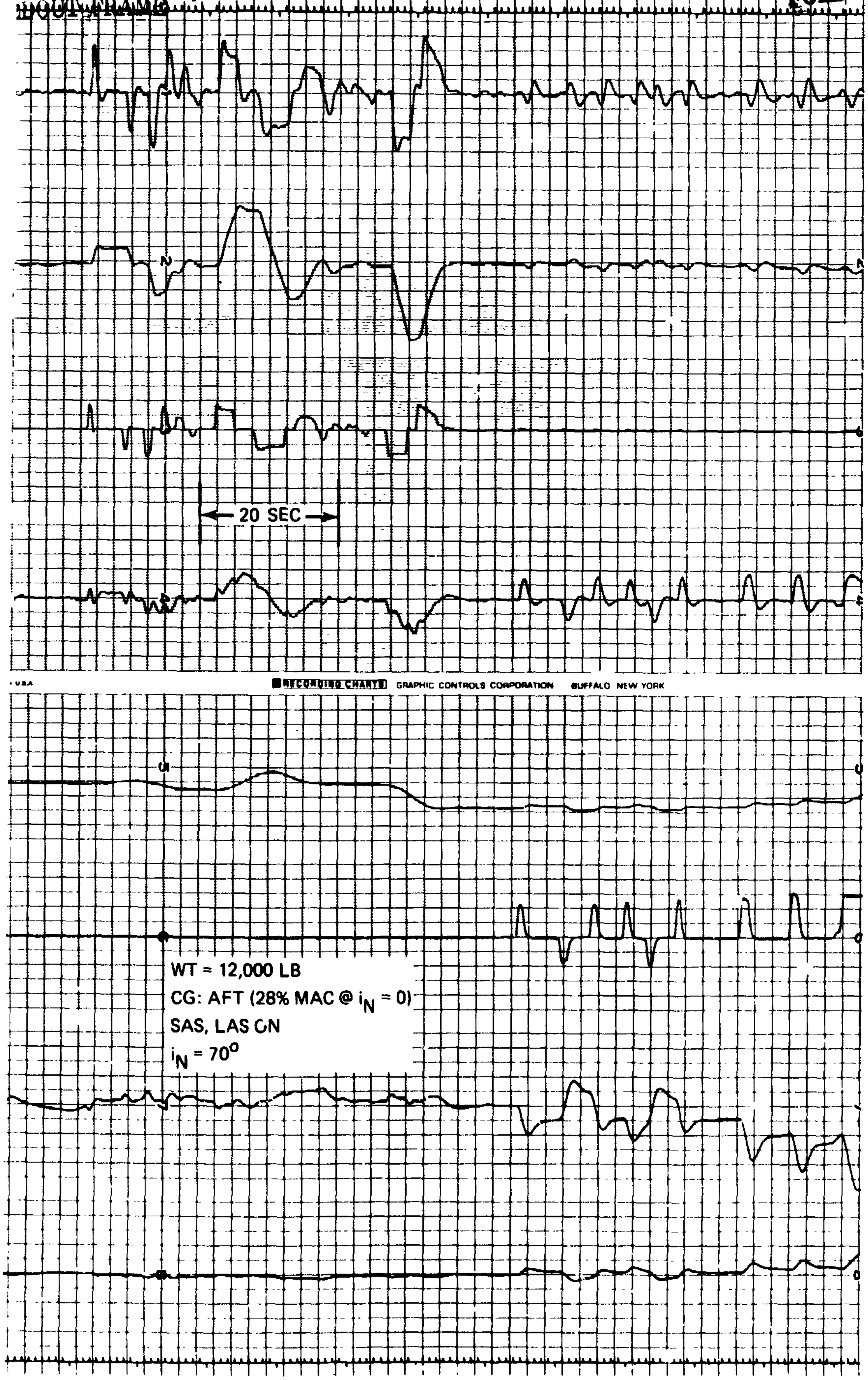

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V = 80 Knots

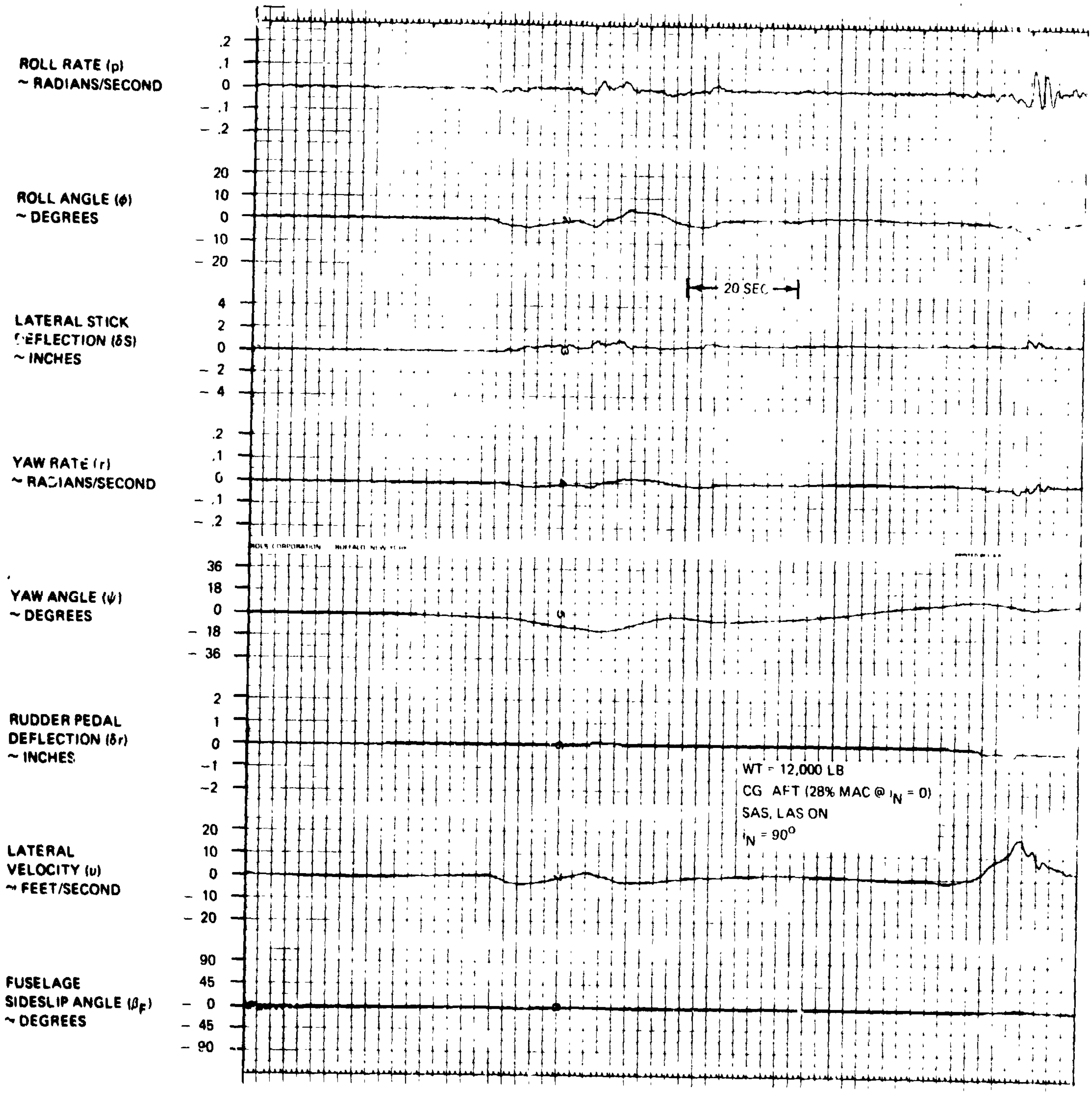


Figure A.9(a). Piloted Time History – Helicopter Mode Maneuvers, SAS and LAS On, $i_N = 90^o$

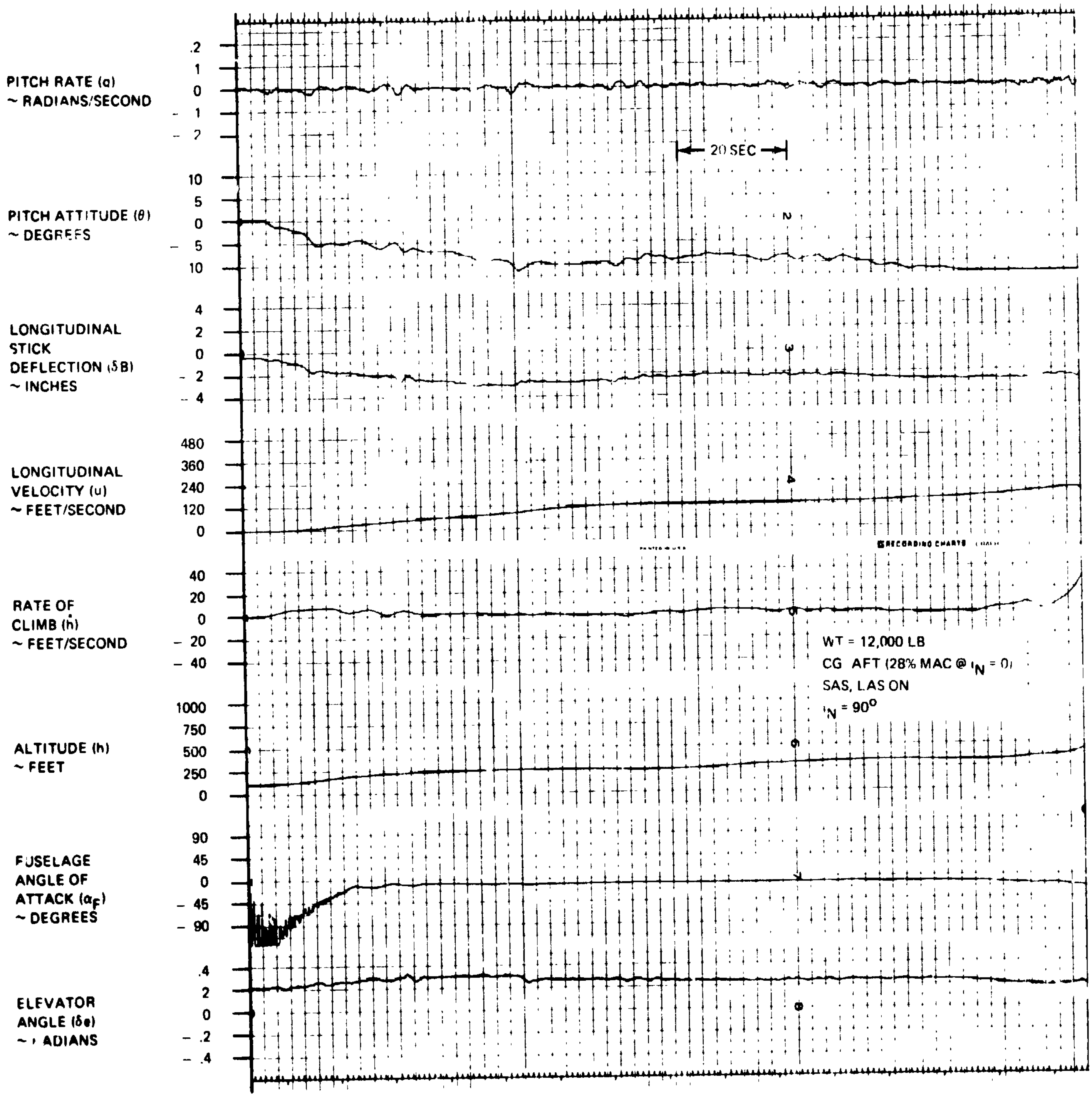


Figure A.9(b). Piloted Time History Helicopter Mode Maneuvers, SAS and LAS On, $i_N = 90^{o}$

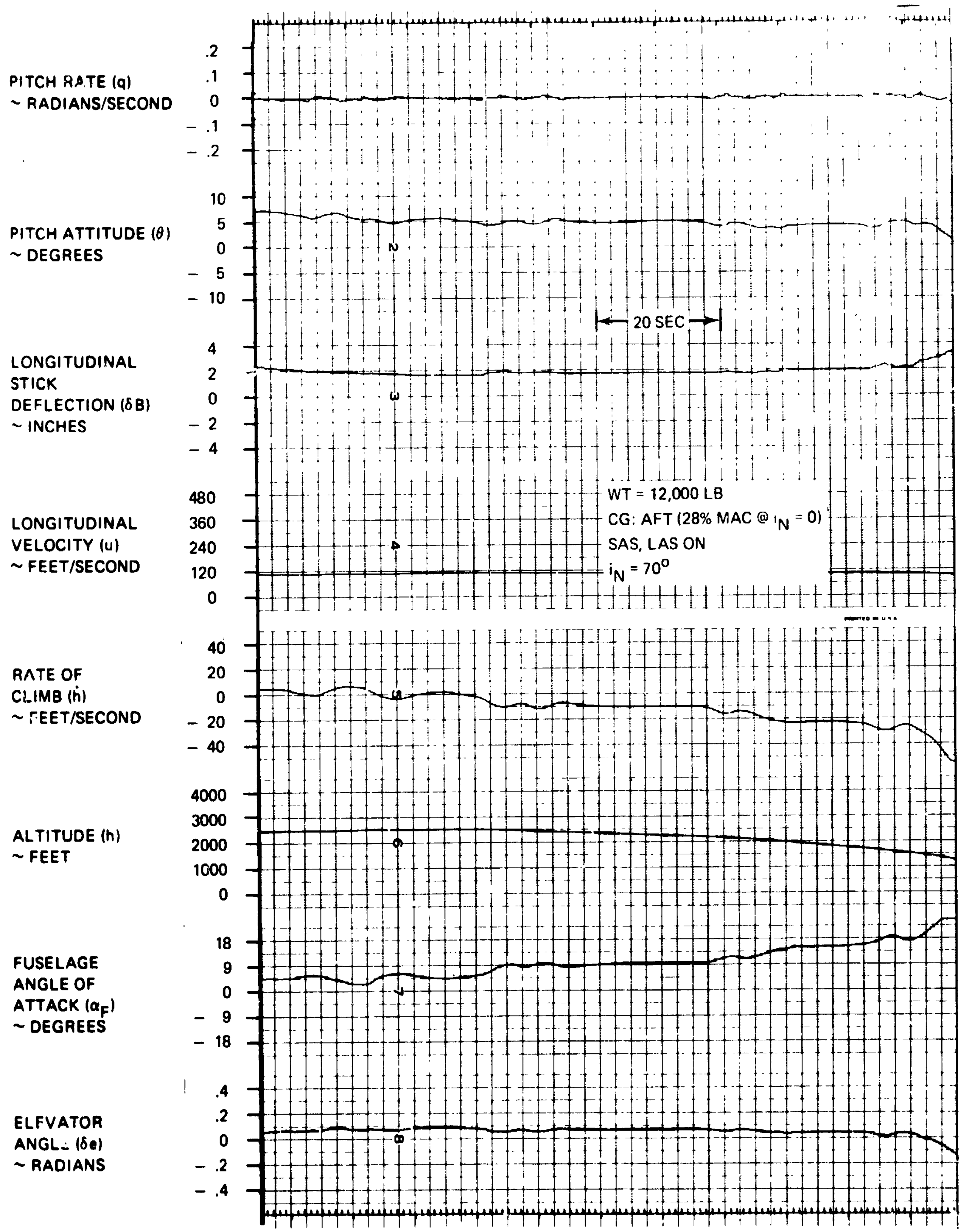


Figure A.10. Piloted Time History – Partial Power Descents in Transition, SAS and LAS On, $i_N = 70^0$, V = 70 Knots

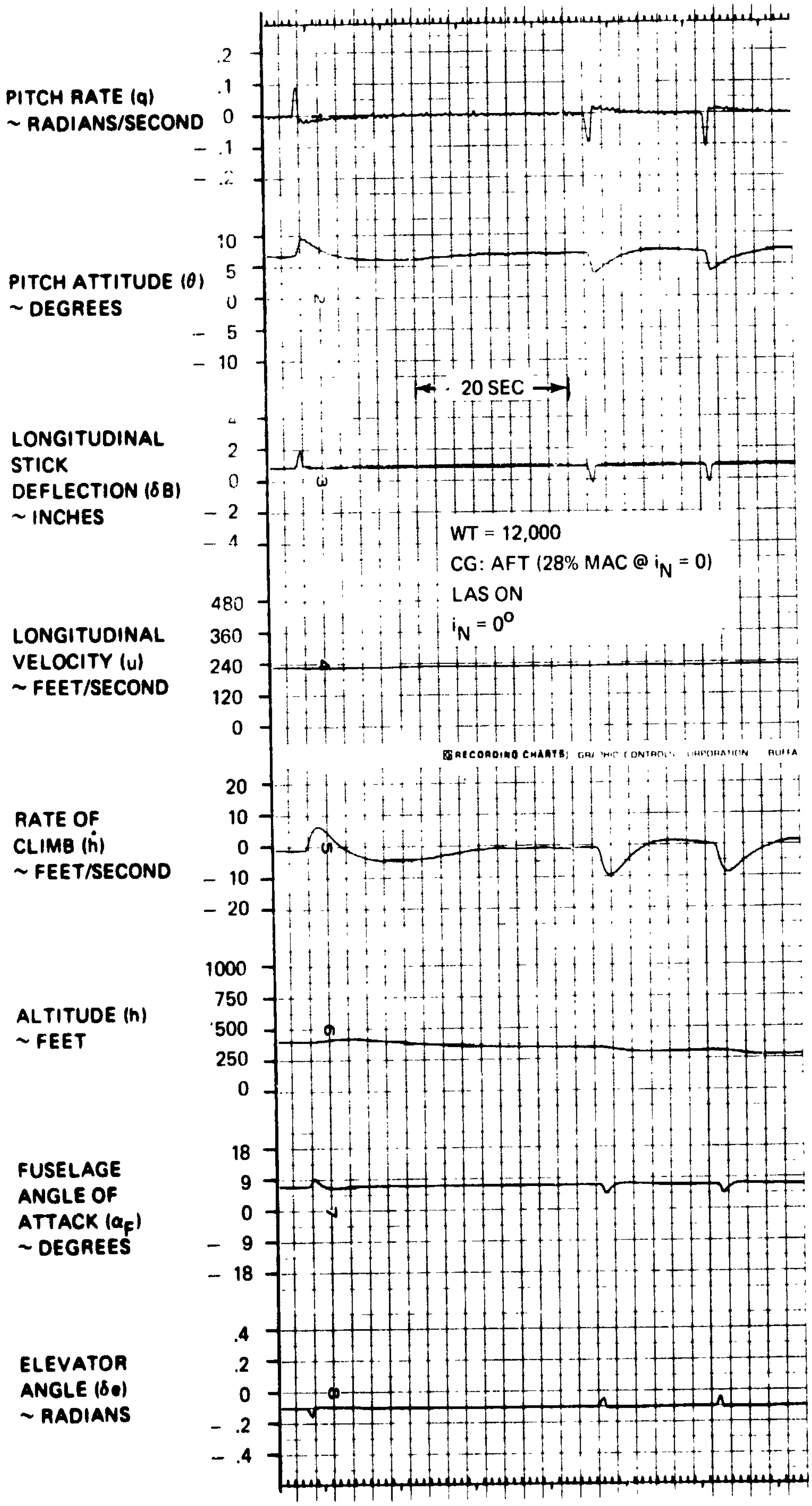


Figure A.11. Piloted Time History – Response to Longitudinal Stick Pulses at 140 Knots, LAS On, $i_N = 0^o$

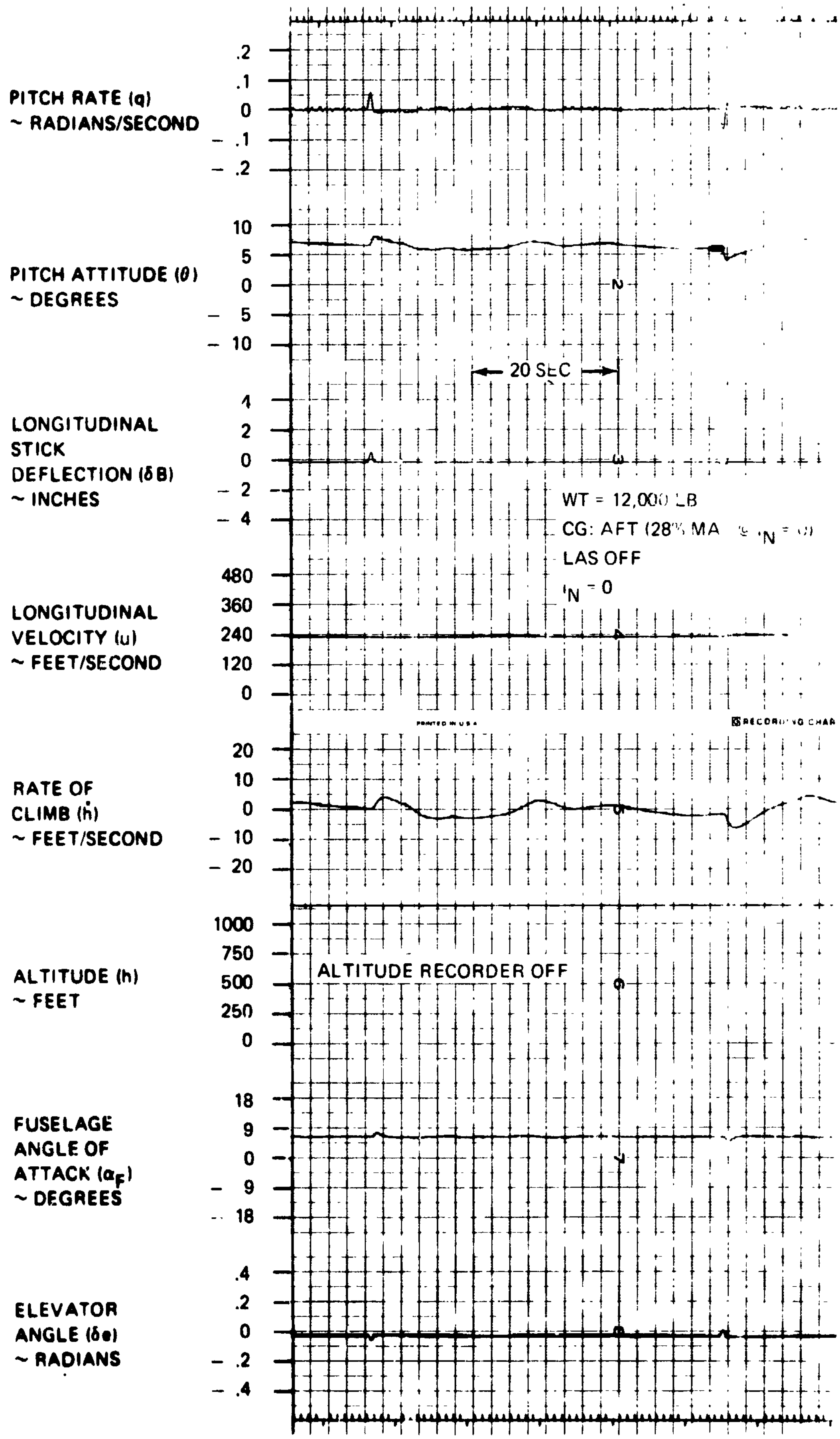


Figure A.12. Piloted Time History – Response to Longitudinal Stick Pulses at 140 Knots, LAS Off, i_N

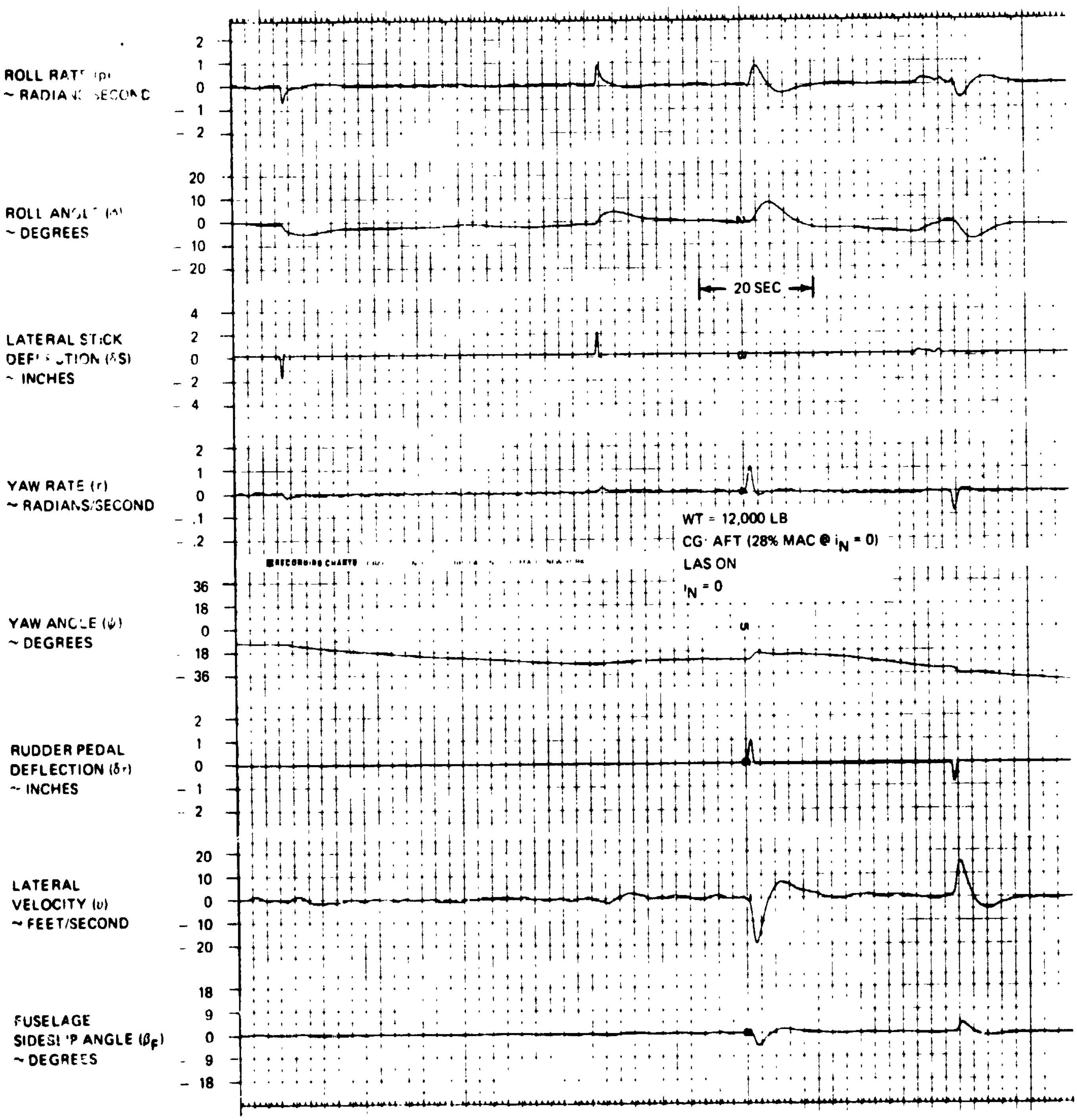


Figure A.13. Piloted Time History – Response to Lateral Stick and Rudder Pedal Pulses at 140 Knots, LAS On, $i_N = 0^{\circ}$

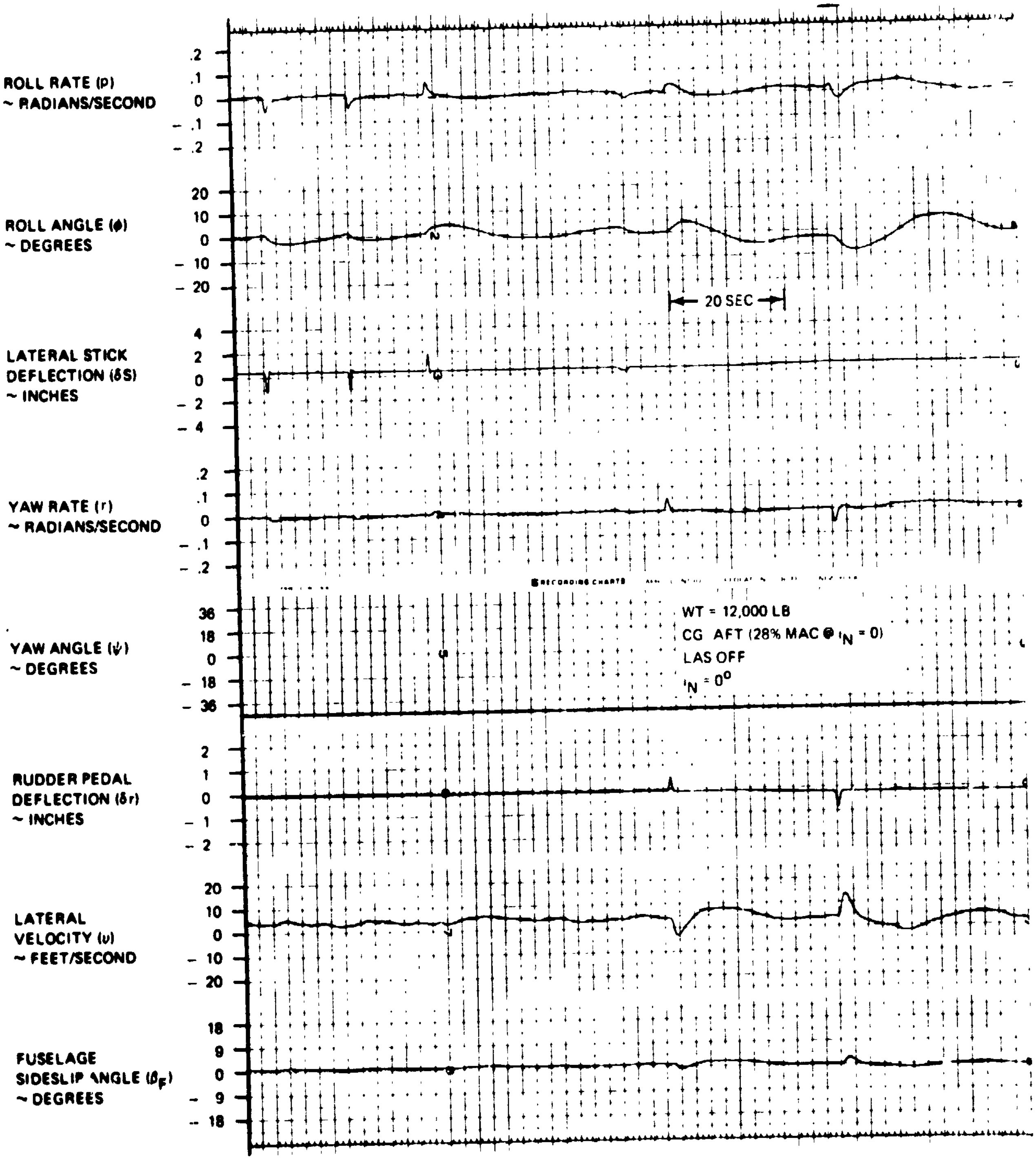


Figure A.14. Piloted Time History – Response to Lateral Stick and Rudder Pedal Pulses at 140 Knots, LAS Off, $i_N = 0^{o}$

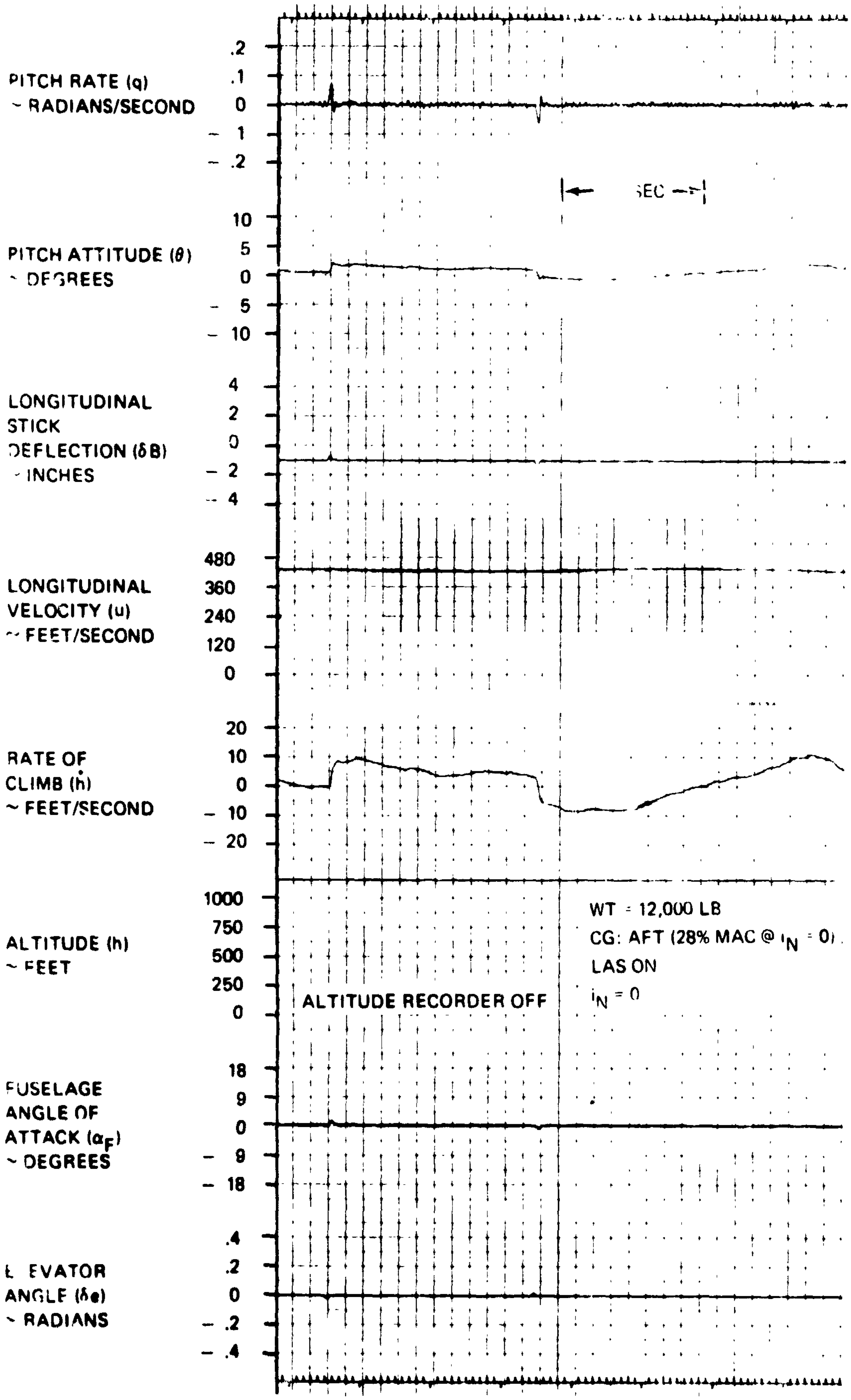


Figure A.15 Piloted Time History – Response to Longitudinal Stick Pulses at 260 Knots, LAS On, $i_N = 0^0$

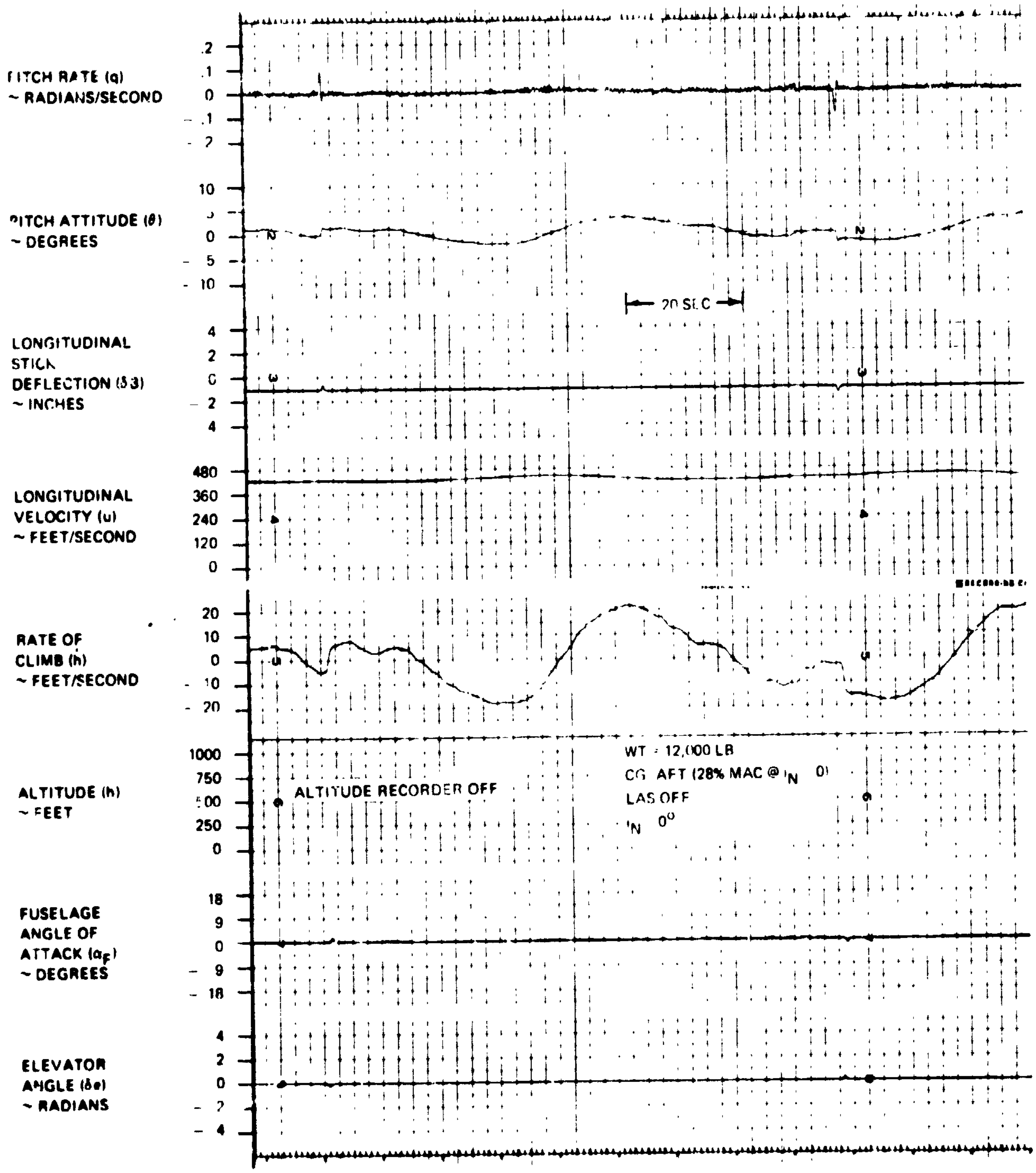


Figure A 16 Piloted Time History – Response to Longitudinal Stick Pulses at 260 Knots, LAS Off, $i_N = 0^o$

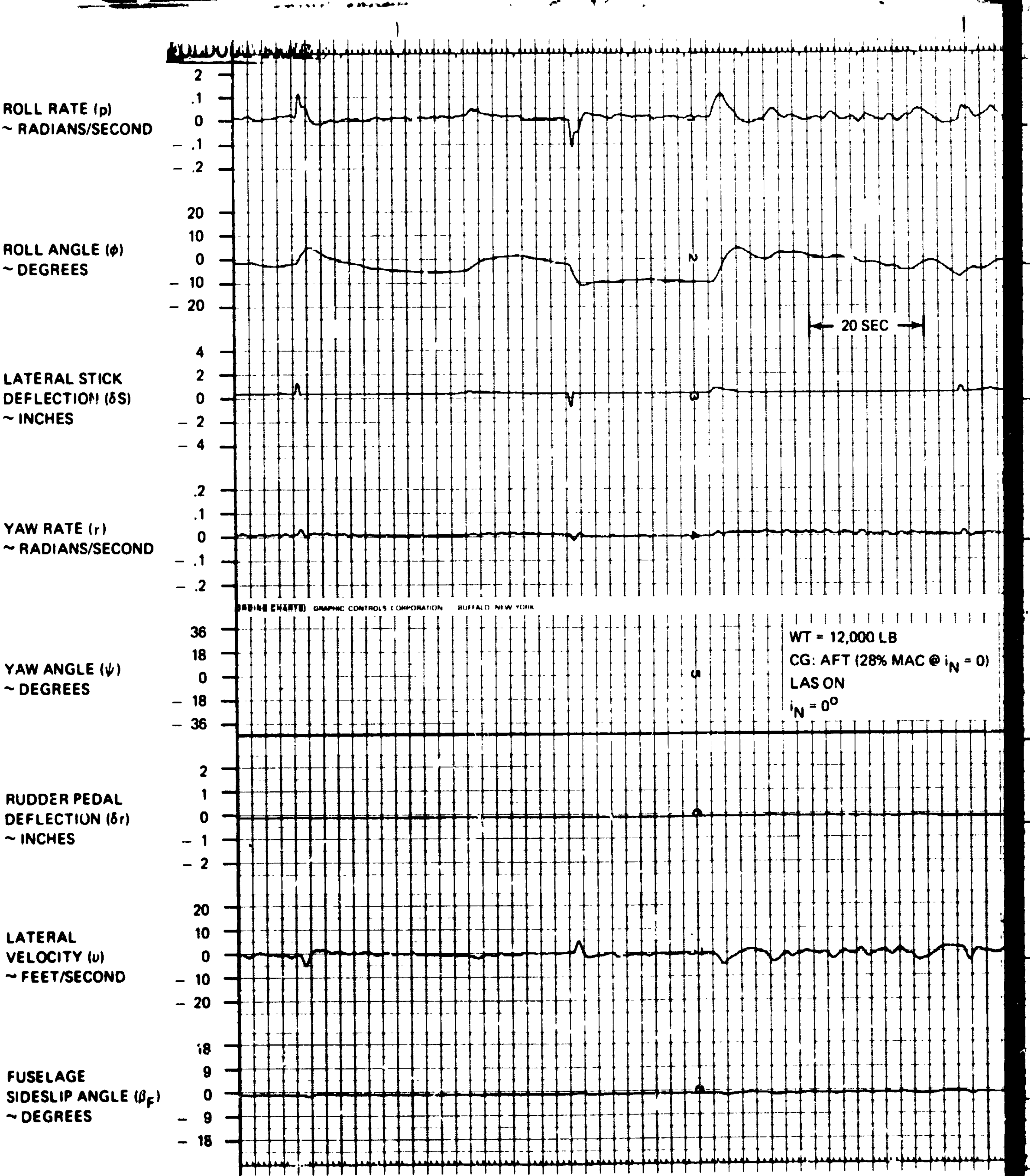
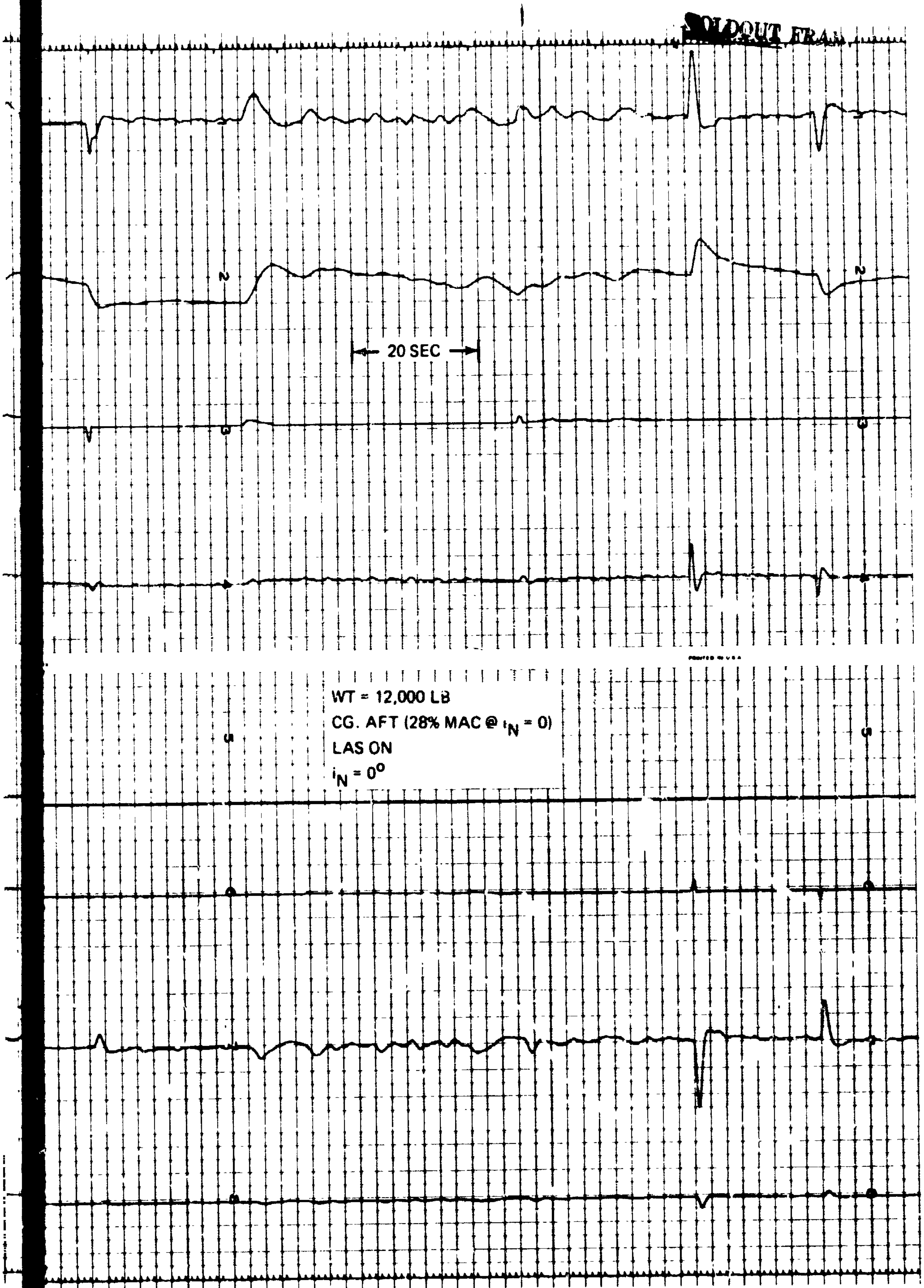


Figure A.17. Piloted Time History – Response to Lateral Stick and Rudder Pedal Pulses at 260 Knots, LAS On, $i_N = 0^\circ$



tory – Response to Lateral Stick and Rudder Pedal Pulses at 260 Knots,

FOLDOUT FRAME

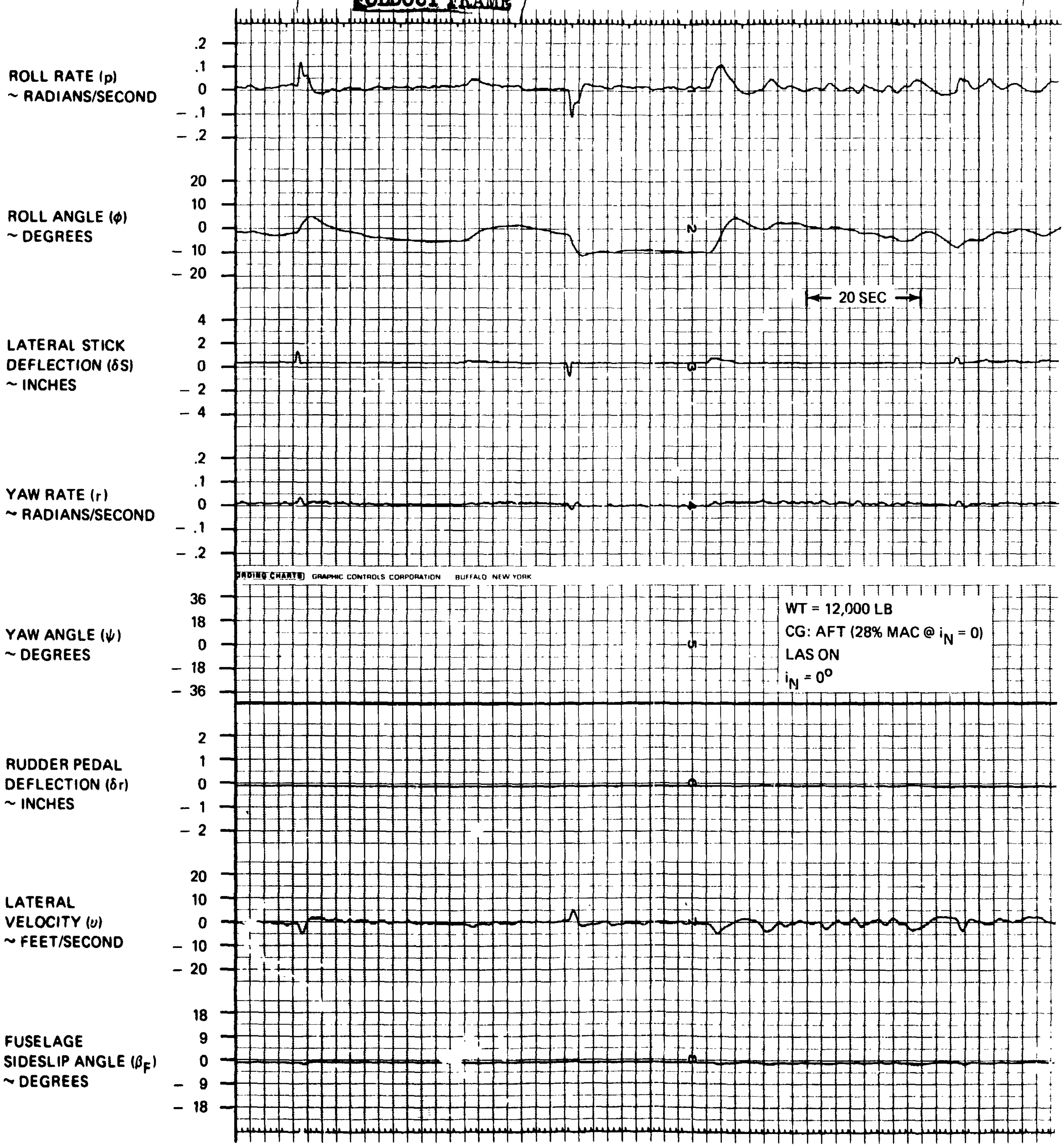
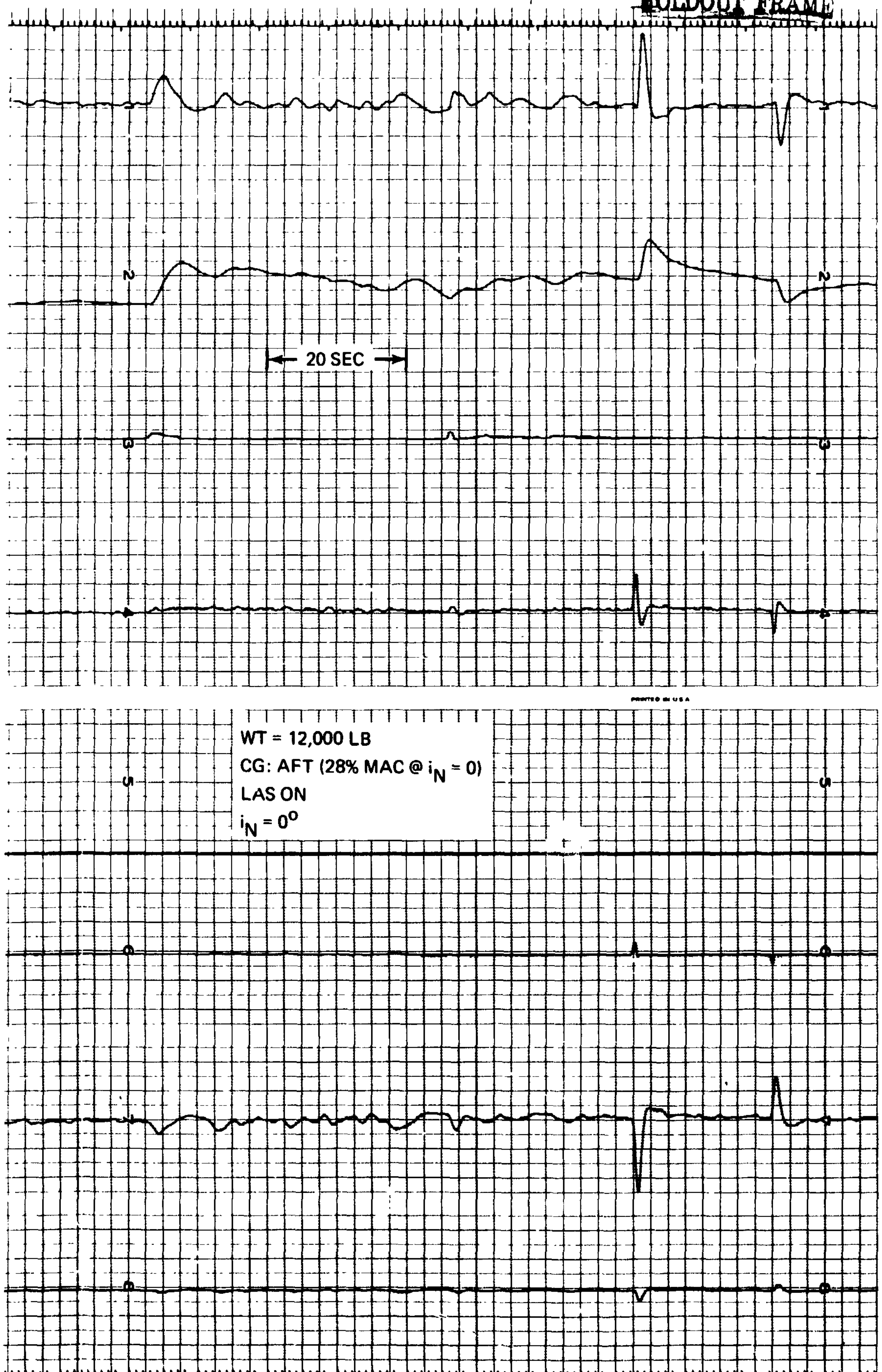


Figure A.17. Piloted Time History – Response to Lateral Stick and Rudder Pedal Pulses at 260 Knots, LAS On, $i_N = 0^o$

FOLDOUT FRAME



sponse to Lateral Stick and Rudder Pedal Pulses at 260 Knots,

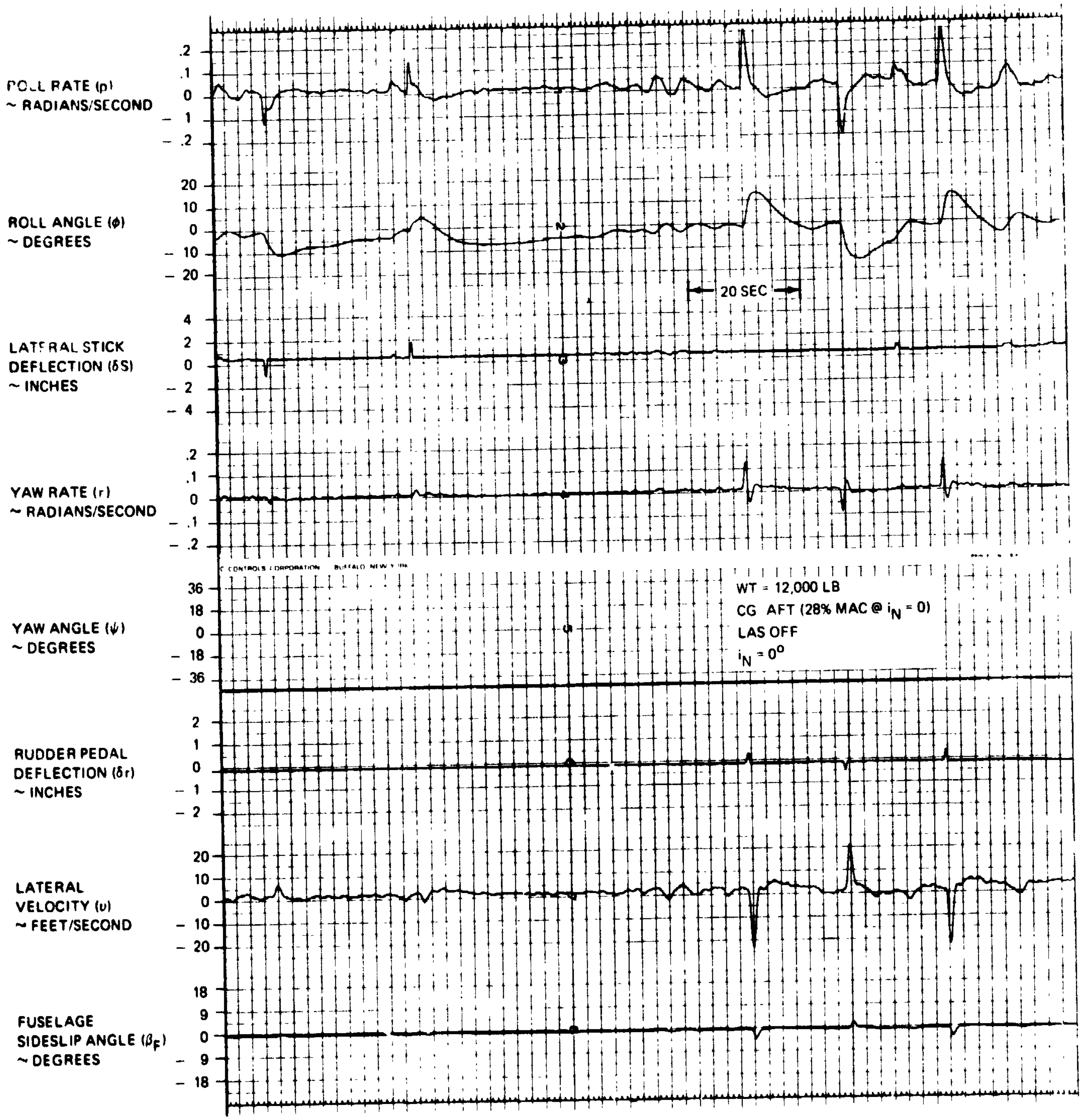


Figure A.18. Piloted Time History – Response to Lateral Stick and Rudder Pedal Pulses at 260 Knots, LAS Off, $i_N = 0^o$