SIMULATION
+TRAINING
A Textron Company

Flight & Ground Vehicle Simulation Update - 2017
January 2017
Flight Control System Simulation

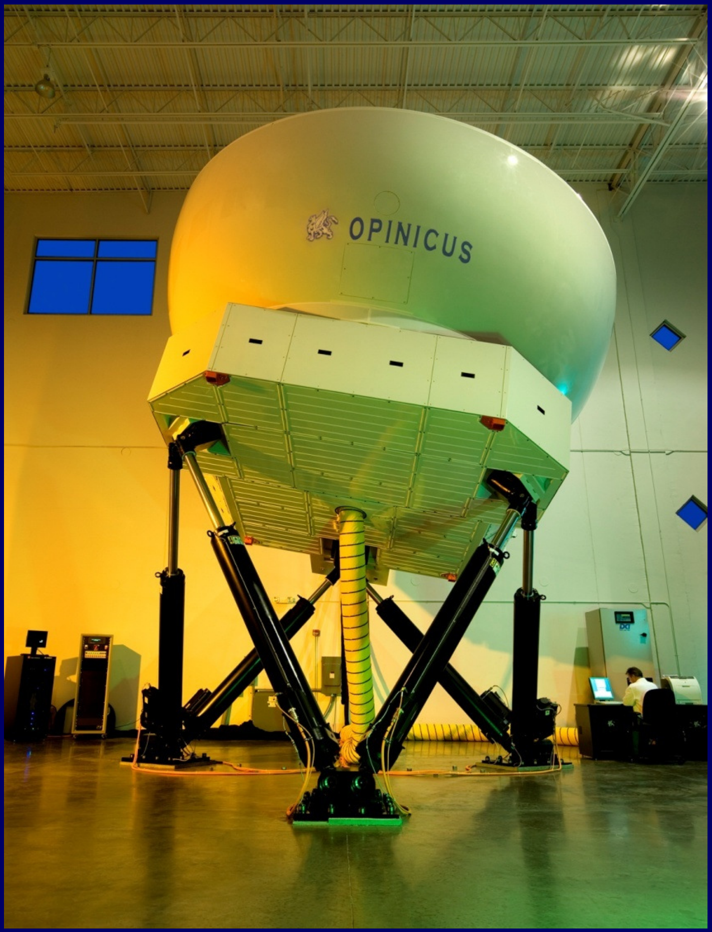
Flight Control System Simulation - 2017

James R. Takats

Sr. VP Global Strategy
Textron Inc.
Charleston, SC

www.TRUsimulation.com

TRU S+T… combines
OPINICUS, Mechtronix, AAI and ProFlight



FLIGHT & GROUND VEHICLE CONTROL SYSTEM SIMULATION

OUTLINE

- Introduction to Flight & Ground Control System
- Autopilot & Flight Guidance Control Systems
- Flight & Ground Vehicle Force Feedback Simulation
- Installation and Setup of Control Loading Systems
- Control Loading Performance Verification

INTRODUCTION TO FLIGHT CONTROL SYSTEMS

EVOLUTION OF FLIGHT CONTROL & AUTOPILOT SYSTEMS

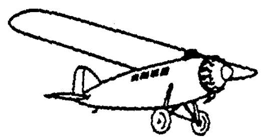
Pre-World War I

- Direct Mechanical Flight Control System

WRIGHT FLYER

WW I to WW II

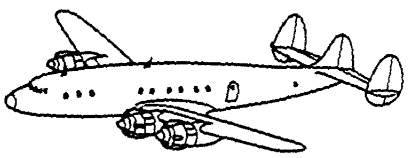
- Tab Driven Mechanical Flight Control Systems
- Autopilot Systems (Maintain Attitude)



LOCKHEED VEGA

1945 to 1965

- Autopilot Systems (Maintain Speed & Direction)
- Flight Augmentation Computers - Analog

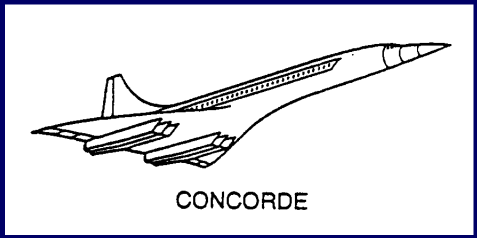


LOCKHEED CONSTELLATION

EVOLUTION OF FLIGHT CONTROL & AUTOPILOT SYSTEMS

1965 to 1985

- Hydraulically Boosted Flight Control Systems
- Flight Director Systems
- Automatic Landing Systems
- On-Board Digital Computers



1985 to 2000

- Fly-By-Wire or Fly-By-Light Flight Control Systems
- Fully Integrated Autopilot & Flight Management Computers/Mission Computer

EVOLUTION OF FLIGHT CONTROL & AUTOPILOT SYSTEMS

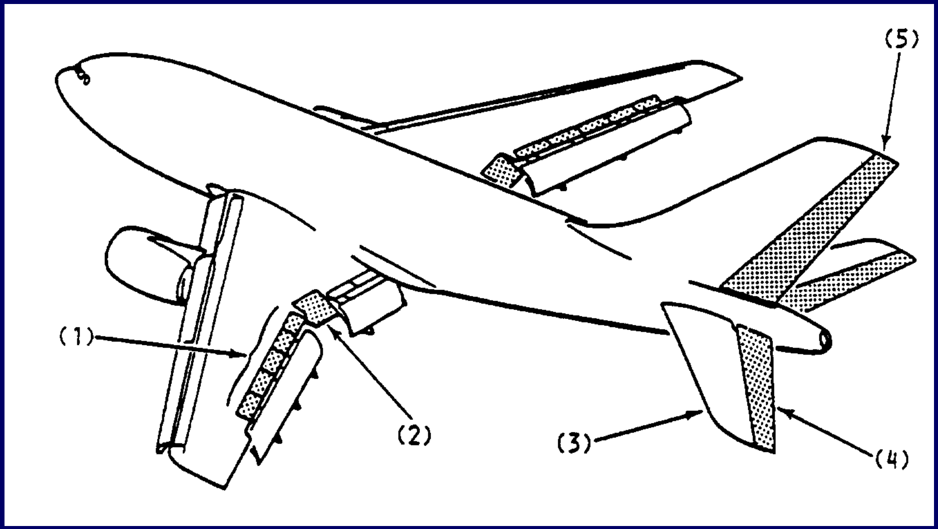
<u>2000 - present</u>

- More Sophisticated Fly-By-Wire or Fly-By-Light Flight Control Systems – including Vertical Takeoff and Landing systems
- Highly Optimized Fully Integrated Auto Flight Guidance and Auto SBAS capable Landing Systems (SBAS – Satellite Based Augmentation System) such as WAAS or EGNOS
- Unmanned Air Vehicles
- New systems such as "Gust Alleviation Systems" which uses wireless sensors

PRIMARY FLIGHT CONTROL SYSTEMS

Primary Controls

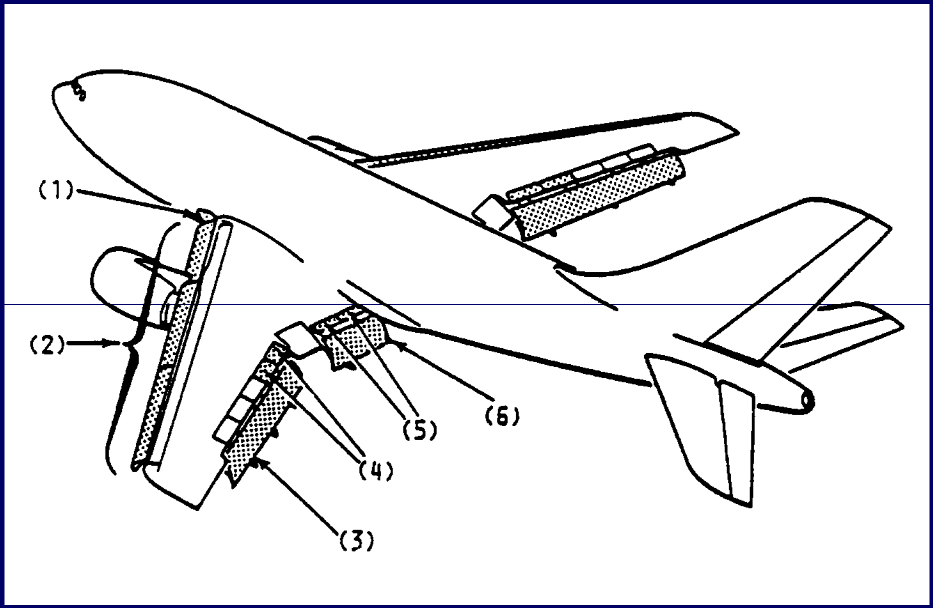
1. Roll Spoilers
2. Aileron
3. Trimmable Horizontal Stabilizer
4. Elevator
5. Rudder



SECONDARY FLIGHT CONTROL SYSTEMS

Secondary Controls

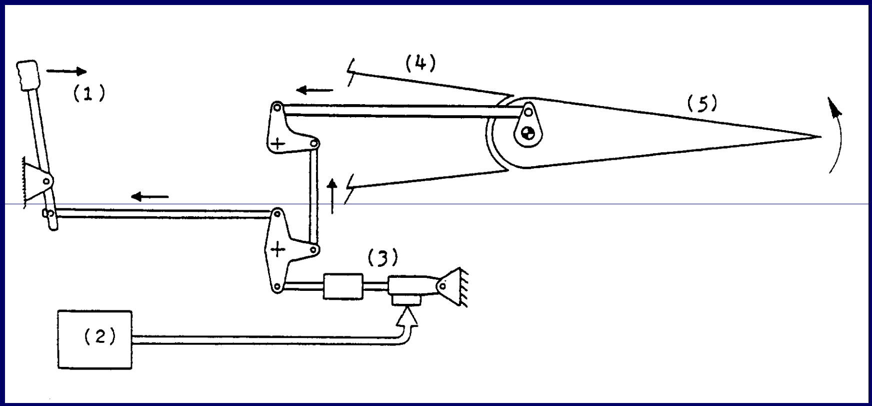
1. Kruger Flaps
2. Slats
3. Outer Flaps
4. Outer Speedbrakes
5. Inner Speedbrakes
6. Inner Flaps



REVERSIBLE FLIGHT CONTROL SYSTEMS

Direct Mechanical

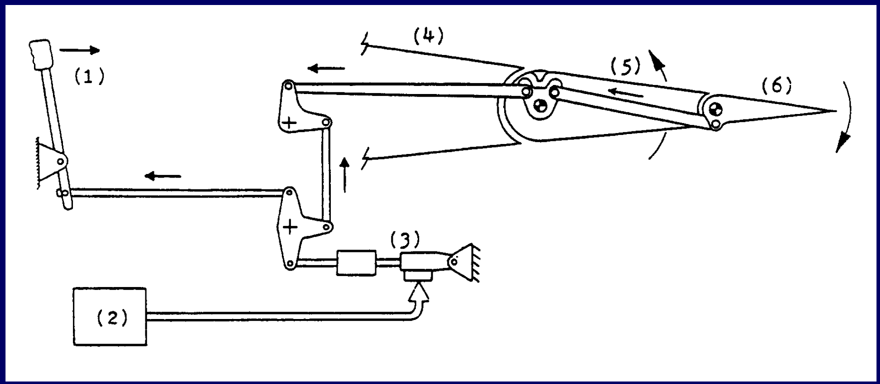
1. Control Stick
2. Autopilot Computer
3. Autopilot Actuator & Disconnect/Override Mechanism
4. Stabilizer
5. Control Surface



REVERSIBLE FLIGHT CONTROL SYSTEMS

Tab Driven

1. Control Stick
2. Autopilot Computer
3. Autopilot Actuator & Disconnect/Override Mechanism
4. Stabilizer
5. Control Surface
6. Control Tab



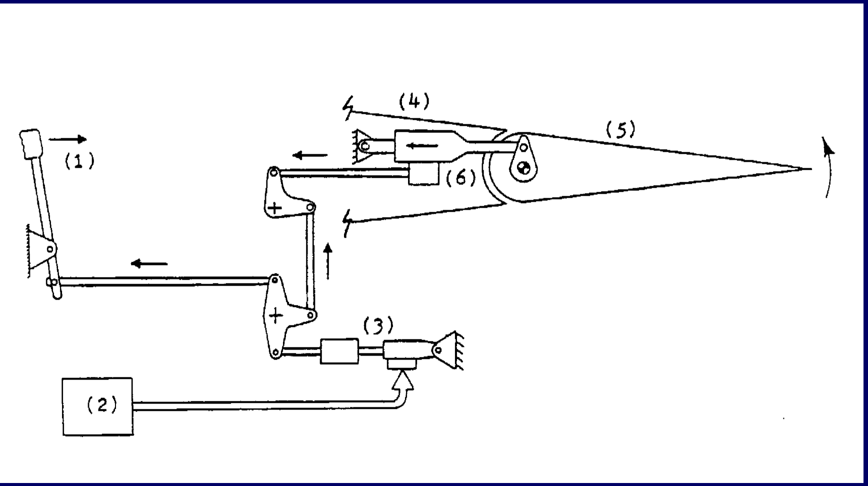
IRREVERSIBLE FLIGHT CONTROL SYSTEMS

<u>Mechanical,</u>

<u>Hydraulically</u>

<u>Boosted</u>

1. Control Stick
2. Autopilot Computer
3. Autopilot Actuator & Disconnect/Override Mechanism
4. Stabilizer
5. Control Surface
6. Hydraulic Actuator



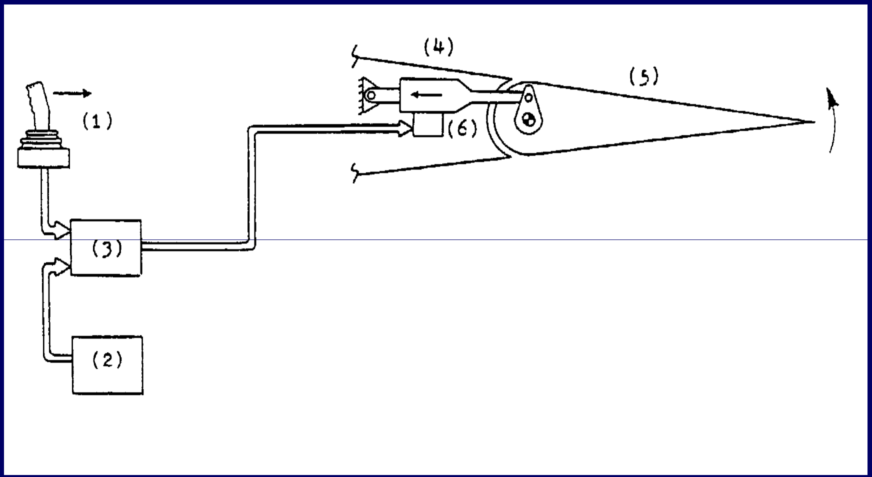
IRREVERSIBLE FLIGHT CONTROL SYSTEMS

Fly-By-Wire,

Hydraulically

Boosted

1. Side Stick
2. Autopilot Computer
3. Electronic Flight Control Computer
4. Stabilizer
5. Control Surface
6. Hydraulic Actuator



CONVENTIONAL ROTARY WINGED AIRCRAFT

<u>Conventional</u>

<u>Helicopter</u>

1. Mechanical Linkage
2. Hydraulically Powered
3. Simple or No Stability Augmentation System
4. Simple or No Autopilot System

SOPHISTICATED ROTARY WINGED AIRCRAFT

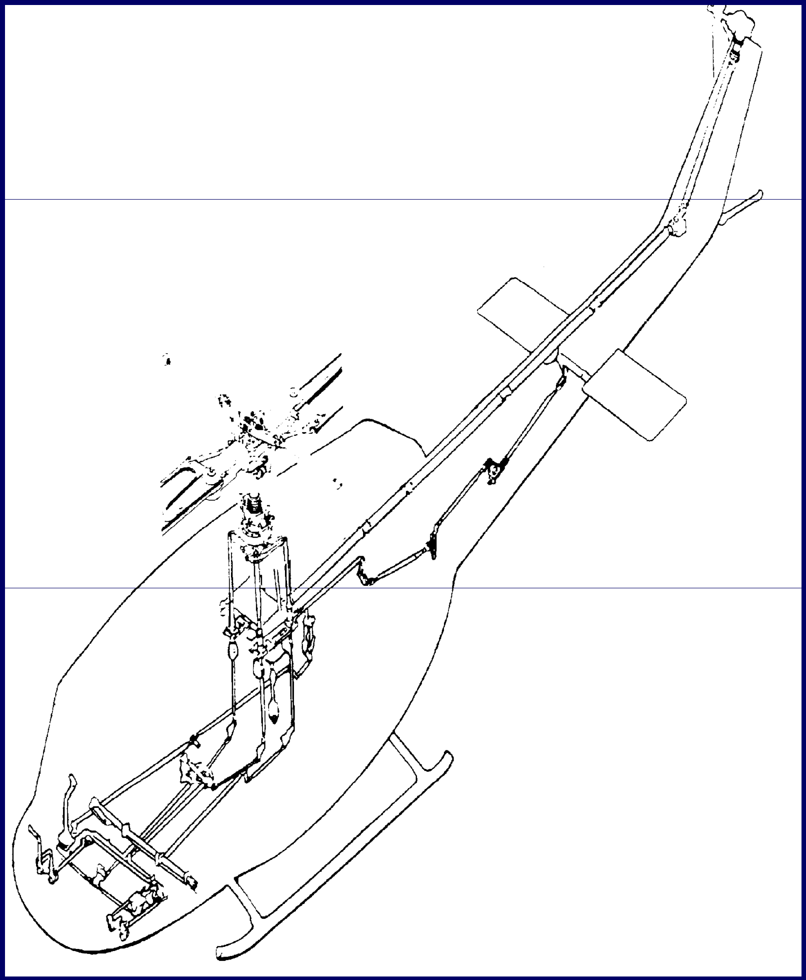
Sophisticated Helicopter

1. Mechanical Linkage
2. Hydraulically Powered and Boosted
3. Dual Stability Augmentation System (SAS)
4. Sophisticated Digital Autoflight Control System (DAFCS)

ROTARY WINGED AIRCRAFT CONTROL LINKAGE

Helicopter Control Linkage

1. Ridged Mechanical Linkage (Light and Responsive)
2. Hydraulically Powered
3. 4 channels (Lateral and Longitudinal Cyclic, Collective, & Pedals)

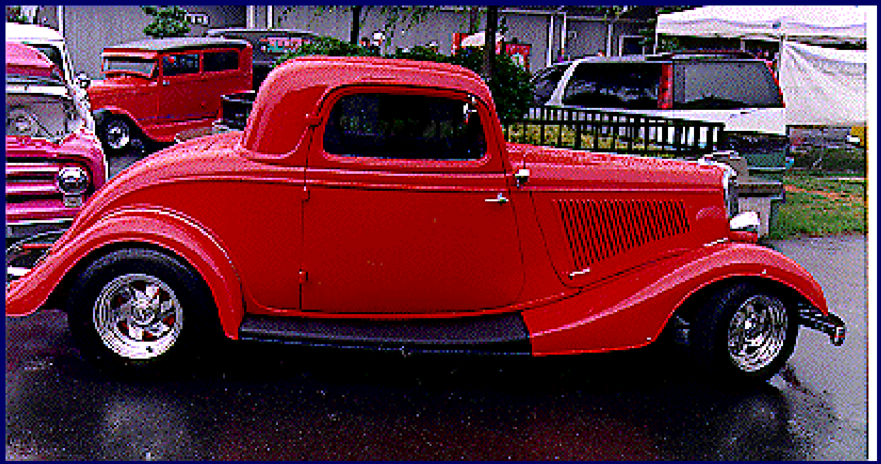


GROUND VEHICLE CONTROL SYSTEMS

Mechanical

Manual

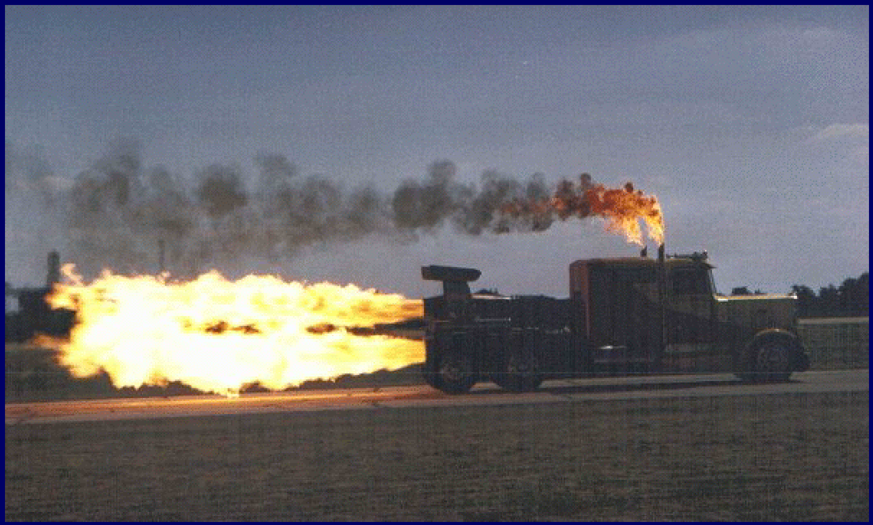
1. Mechanical Linkage
2. Manual Transmission
3. No Power Steering or Power Brakes



GROUND VEHICLE CONTROL SYSTEMS

Customized

1. Custom Heavy Duty Linkage
2. Custom Transmission
3. Custom Steering & Custom Brakes



GROUND VEHICLE CONTROL SYSTEMS

Precision Controls

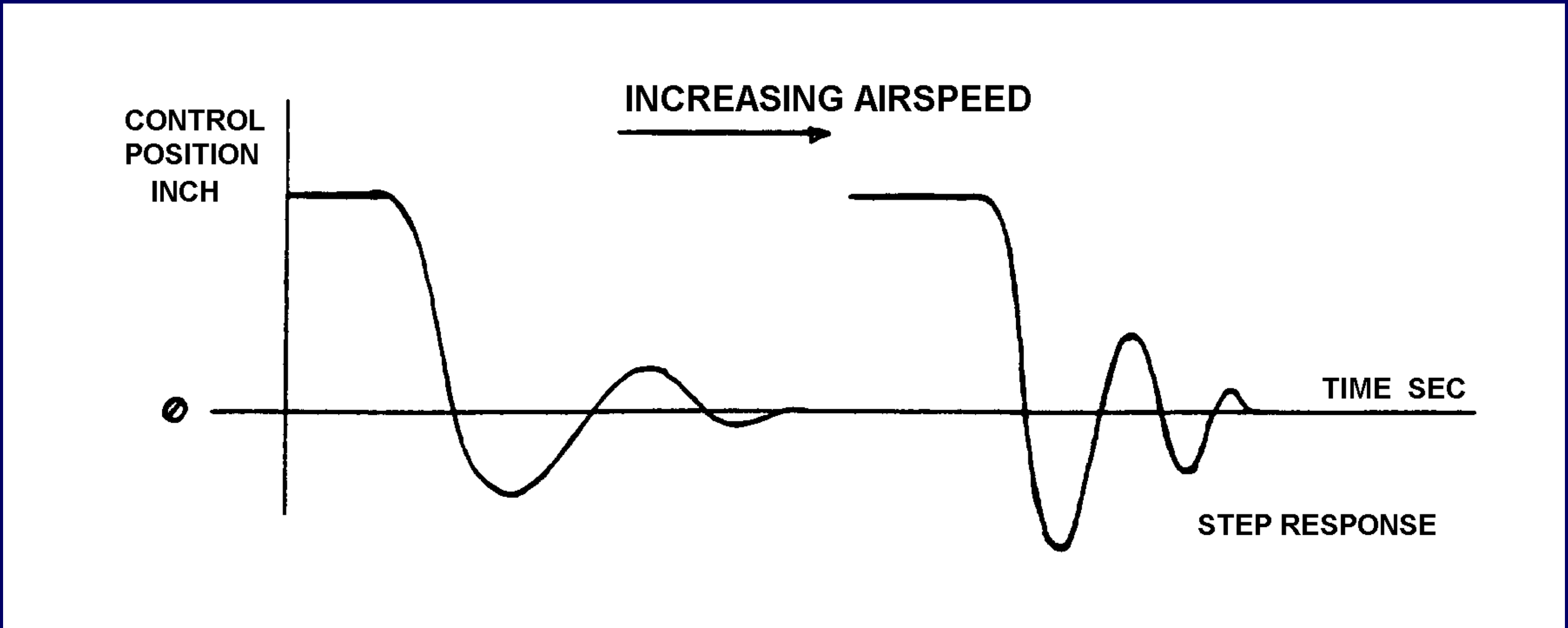
1. **Precision Mechanical Linkage**
2. **Precision Transmission**
3. **Precision Steering & Precision Brakes**

Simulation of Mechanical Flight Control System & Ground Vehicle Control System

- Static Simulation (lower level devices)
- Dynamic Simulation (focus)

SIMULATION OF MECHANICAL FLIGHT CONTROL SYSTEMS

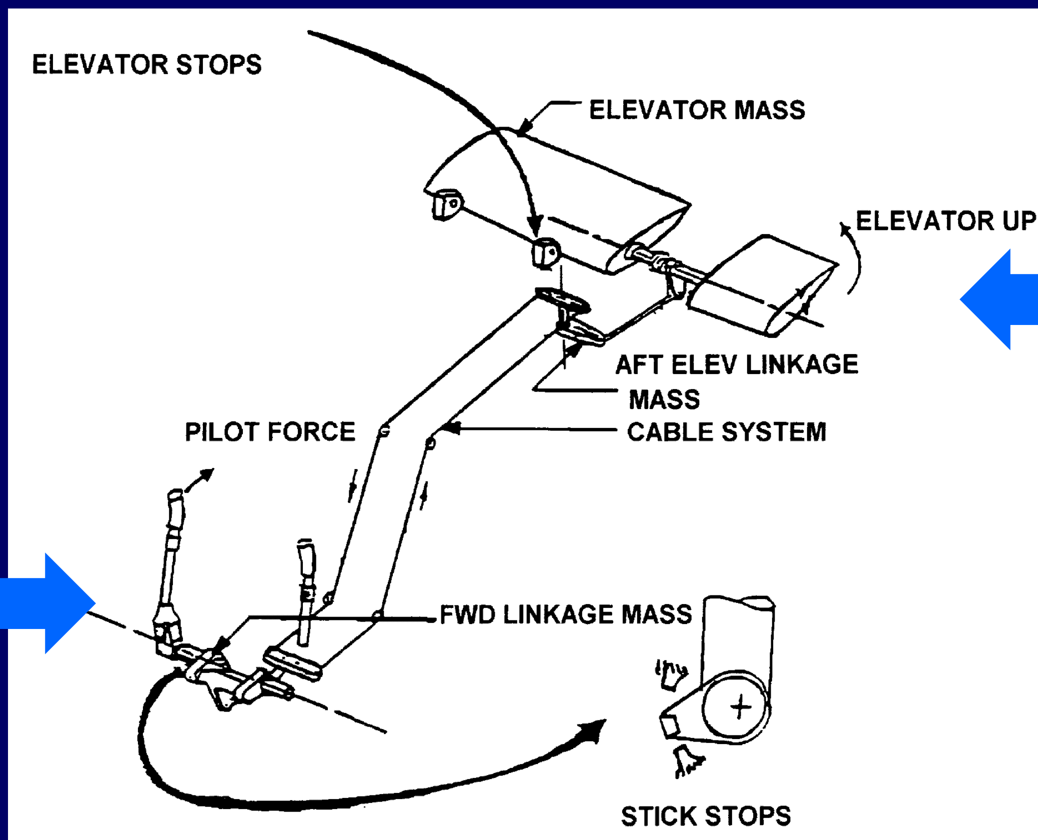
Dynamic Simulation



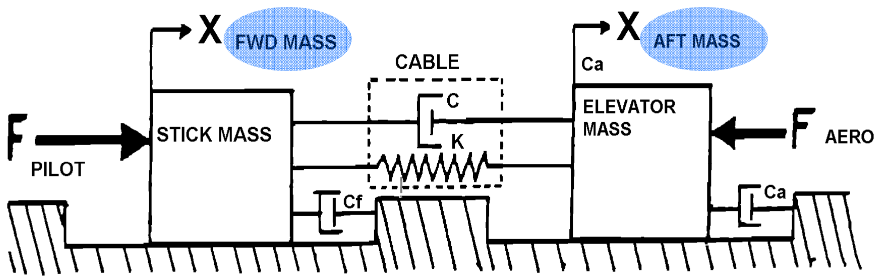
SIMULATION OF MECHANICAL FLIGHT CONTROL SYSTEMS

Reversible Pitch Flight Control System

FORWARD MASS

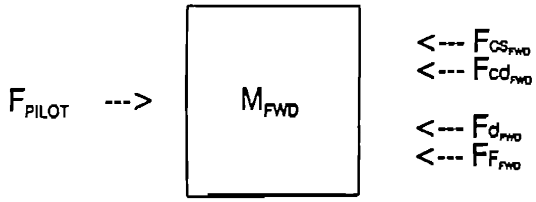


AFT MASS



FORWARD MASS

STICK FREE BODY DIAGRAM



$$F_{CS_{FWD}} = F_{CABLE\ SPRING} = K * (X_{FWD} - X_{AFT})$$

$$F_{Cd_{FWD}} = F_{CABLE\ DAMPING} = C * (\dot{X}_{FWD} - \dot{X}_{AFT})$$

$$F_{d_{FWD}} = F_{FWD\ MASS\ DAMPING} = C_F * \dot{X}_{FWD}$$

$$F_{F_{FWD}} = F_{FWD\ MASS\ FRICTION} = f(\dot{X}_{FWD})$$

$$\Sigma F_{FWD} = F_{PILOT} - F_{CS_{FWD}} - F_{CD_{FWD}} - F_{D_{FWD}} - F_F$$

$$\Sigma F_{FWD} = M_{FWD} * \ddot{X}_{FWD}$$

$$\ddot{X}_{FWD} = \Sigma F_{FWD} / M_{FWD}$$

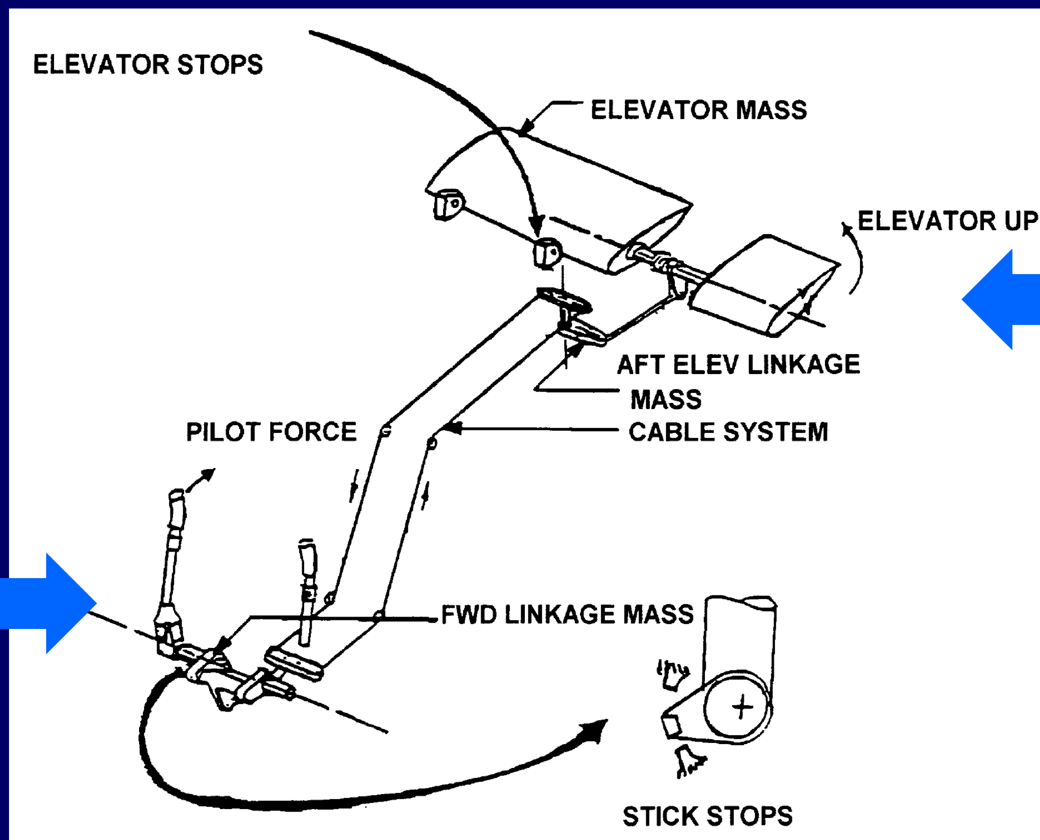
$$\dot{X}_{FWD} = \int_0^t \ddot{X}_{FWD}\, dt$$

$$X_{FWD} = \int_0^t \dot{X}_{FWD}\, dt$$

SIMULATION OF MECHANICAL FLIGHT CONTROL SYSTEMS

Reversible Pitch Flight Control System

FORWARD MASS



AFT MASS

AFT MASS

AFT MASS FREE BODY DIAGRAM

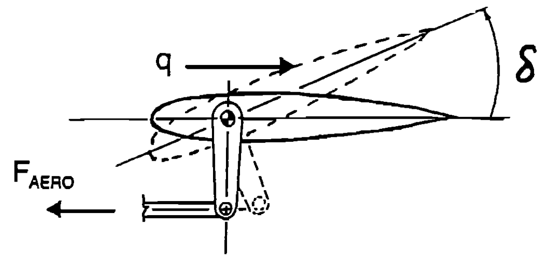
Fcs_{AFT} <--- , Fcd_{AFT} <--- [M_{AFT}] <--- F_{AERO} , <--- Fd_{AFT} , <--- FF_{AFT}

$$Fcs_{AFT} = F_{CABLE\ SPRING} = K * (X_{AFT} - X_{FWD})$$

$$Fcd_{AFT} = F_{CABLE\ DAMPING} = C * (\dot{X}_{AFT} - \dot{X}_{FWD})$$

$$Fd_{AFT} = F_{AFT\ MASS\ DAMPING} = C_A * \dot{X}_{AFT}$$

$$FF_{AFT} = F_{AFT\ MASS\ FRICTION} = f(\dot{X}_{AFT})$$



$$F_{AERO} = (H_k + H_o) * G_H$$

Hinge Moment due to Aerodynamic Force Gradient

$$H_k = \underbrace{q S \bar{c} * C_{H_\delta}}_{\text{Force Gradient (K)}} * \underbrace{\delta}_{\text{Surface Deflection}}$$

Hinge moment due to Aerodynamic offsets

$$H_o = q S \bar{c} \, (C_{H_o} + C_{H_\alpha} * \alpha)$$

$$\Sigma F_{AFT} = -F_{AERO} - Fcs_{AFT} - Fcd_{AFT} - Fd_{AFT} - FF_{AFT}$$

$$\Sigma F_{AFT} = M_{AFT} * \ddot{X}_{AFT}$$

$$\ddot{X}_{AFT} = \Sigma F_{AFT} / M_{AFT}$$

$$\dot{X}_{AFT} = \int_0^t \ddot{X}_{AFT} \, dt$$

$$X_{AFT} = \int_0^t \dot{X}_{AFT} \, dt$$

M_{FWD}	FWD MASS
$\ddot{X}_{FWD}$	FWD MASS ACCELERATION
$\dot{X}_{FWD}$	FWD MASS VELOCITY
X_{FWD}	FWD MASS POSITION
C_F	FWD MASS DAMPING COEFFICIENT
Fd_{FWD}	FWD MASS DAMPING FORCE
FF_{FWD}	FWD MASS FRICTION FORCE
M_{AFT}	AFT MASS
$\ddot{X}_{AFT}$	AFT MASS ACCELERATION
$\dot{X}_{AFT}$	AFT MASS VELOCITY
X_{AFT}	AFT MASS POSITION
C_A	AFT MASS DAMPING COEFFICIENT
Fd_{AFT}	AFT MASS DAMPING FORCE
FF_{AFT}	AFT MASS FRICTION FORCE
K	CABLE SPRING RATE
C	CABLE DAMPING COEFFICIENT
Fcs_{FWD}	CABLE SPRING FORCE ON FWD MASS
Fcd_{FWD}	CABLE DAMPING FORCE ON FWD MASS
Fcs_{AFT}	CABLE SPRING FORCE ON AFT MASS
Fcd_{AFT}	CABLE DAMPING FORCE ON AFT MASS

F_{PILOT}	PILOT APPLIED FORCE
F_{AERO}	TOTAL AERODYNAMIC FORCE
G_H	GEAR RATIO, SURFACE HINGE to AFT MASS
H_k	HINGE MOMENT DUE TO AERODYNAMIC FORCE GRADIENT
H_o	HINGE MOMENT DUE TO AERODYNAMIC OFFSETS
C_{H_δ}	VARIATION OF HINGE MOMENT COEFF. WITH SURFACE DEFLECTION
C_{Ho}	HINGE MOMENT COEFF. FOR ZERO ANGLE OF ATTACK
C_{H_α}	VARIATION OF HINGE MOMENT COEFF. WITH ANGLE OF ATTACK
δ	SURFACE DEFLECTION
α	ANGLE OF ATTACK
q	DYNAMIC PRESSURE
S	SURFACE AREA
$\bar{c}$	MEAN AERODYNAMIC CORD

MODULAR MODELING APPROACH
Component Groups Usually Simulated

Cockpit Control, Forward Linkage & Cable Quadrant Mass

- Inertia
- Bobweight (or Mass Imbalance)
- Damping
- Centering Spring Force (if applicable)
- Friction (static & kinetic)
- Position Stops

Cable System

- Cable Spring Rate (or Stretch)
- Deadband (or Backlash)
- Damping

MODULAR MODELING APPROACH
Component Groups Usually Simulated

AFT Linkage System & Cable Quadrant Mass

- Inertia
- Bobweight (or Mass Imbalance)
- Damping
- Centering Spring or Q-feel Device (if applicable)
- Friction (static & kinetic)
- Position Stops

Load Limiters (or Interconnect Bungees)

- Breakout Force
- Force Profile Beyond Breakout
- Compression/extension limits
- Damping

MODULAR MODELING APPROACH
Component Groups Usually Simulated

Surface Hydraulic Actuators

- Actuator Dynamics
- Control Valve Stops and Spring Forces
- Override Forces
- Maximum Actuator Rates

Control Surfaces

- Inertia
- Mass Imbalance
- Mechanical Damper (if applicable)
- Friction
- Aerodynamic Hinge Moments
  - Offsets, Gradients, Damping

MODULAR MODELING APPROACH
Component Groups Usually Simulated

Trim Actuators

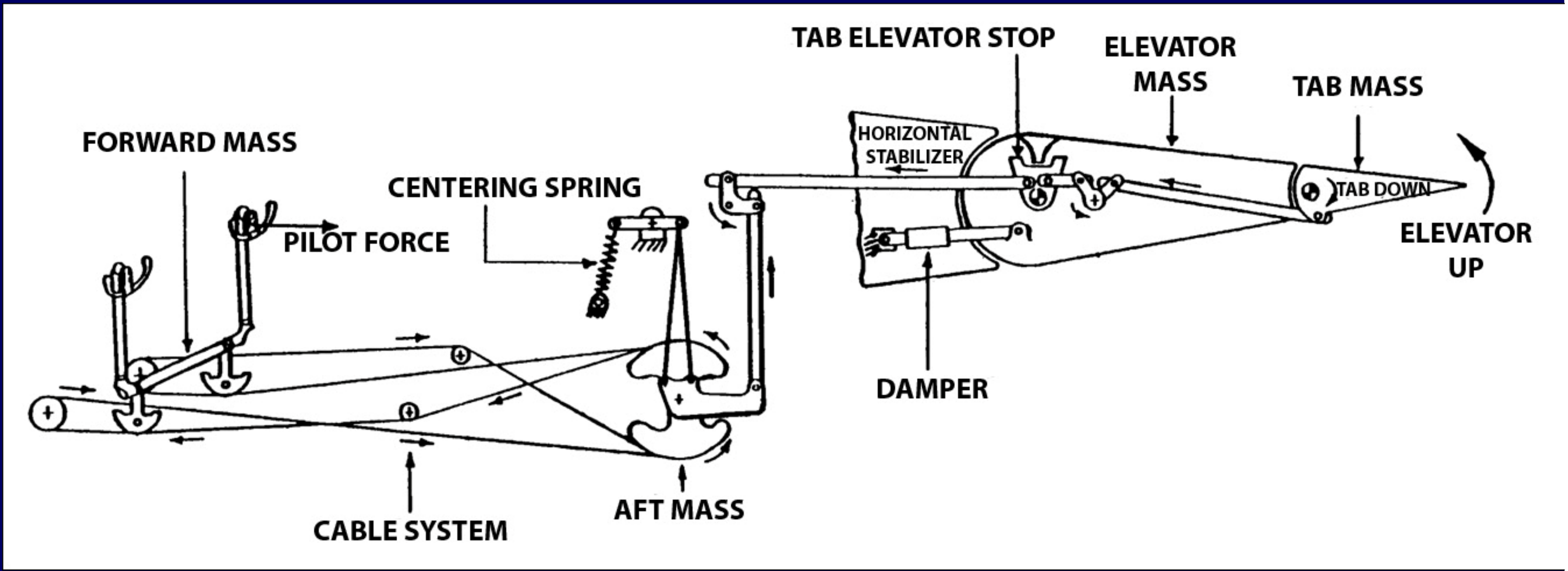
- Actuator Dynamics (Characteristic Lag)
- Loading Effects on Trim Rates
- Maximum Trim Rates

Autopilot Actuators

- Actuator Dynamics
- Loading Effects on Autopilot Authority
- Override Force
- Maximum Actuator Rates

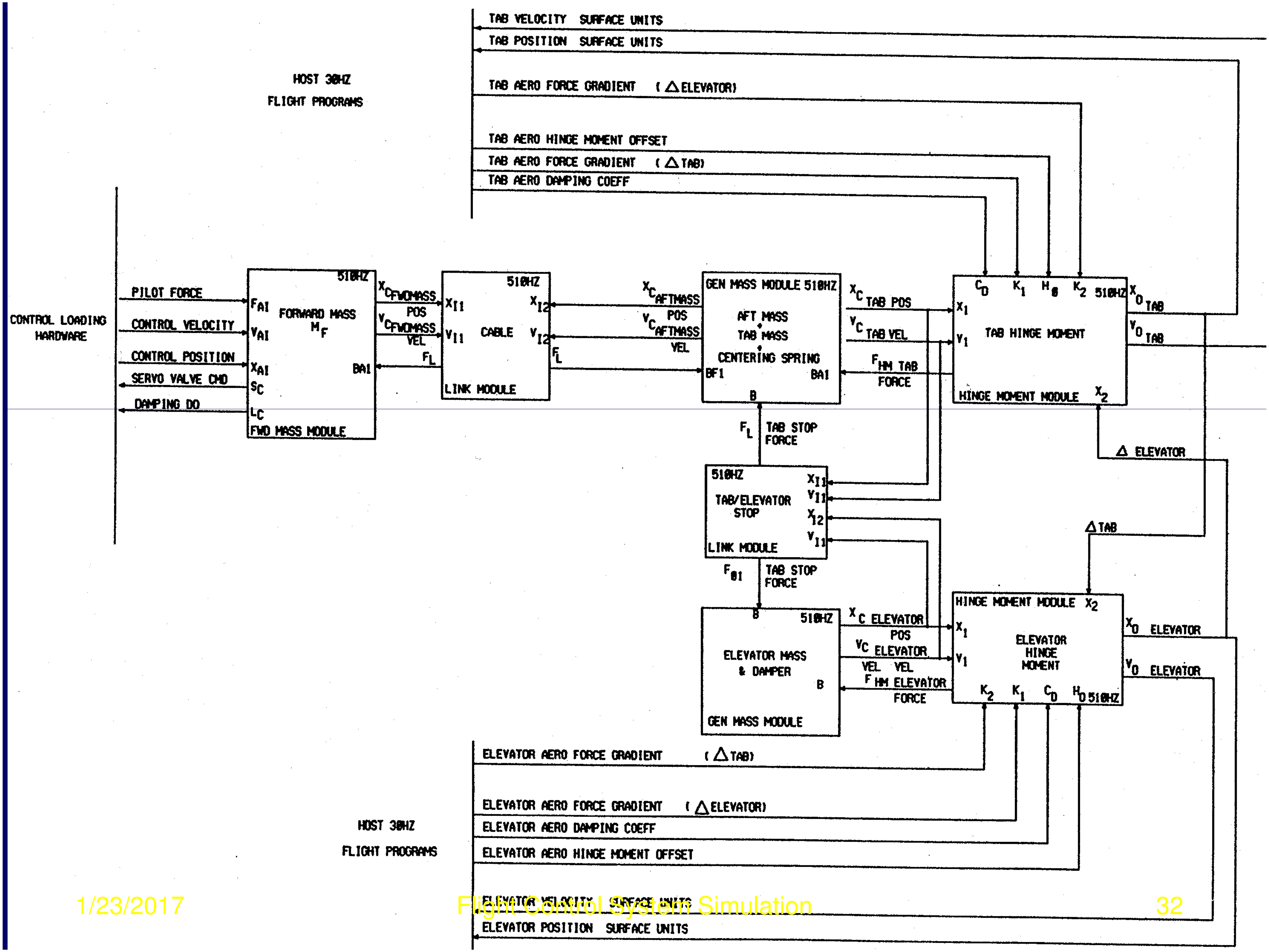
REVERSIBLE FLIGHT CONTROL SYSTEM

Typical Reversible Tab Driven Elevator Flight Control Systems



Digital Model of Reversible Flight Control System

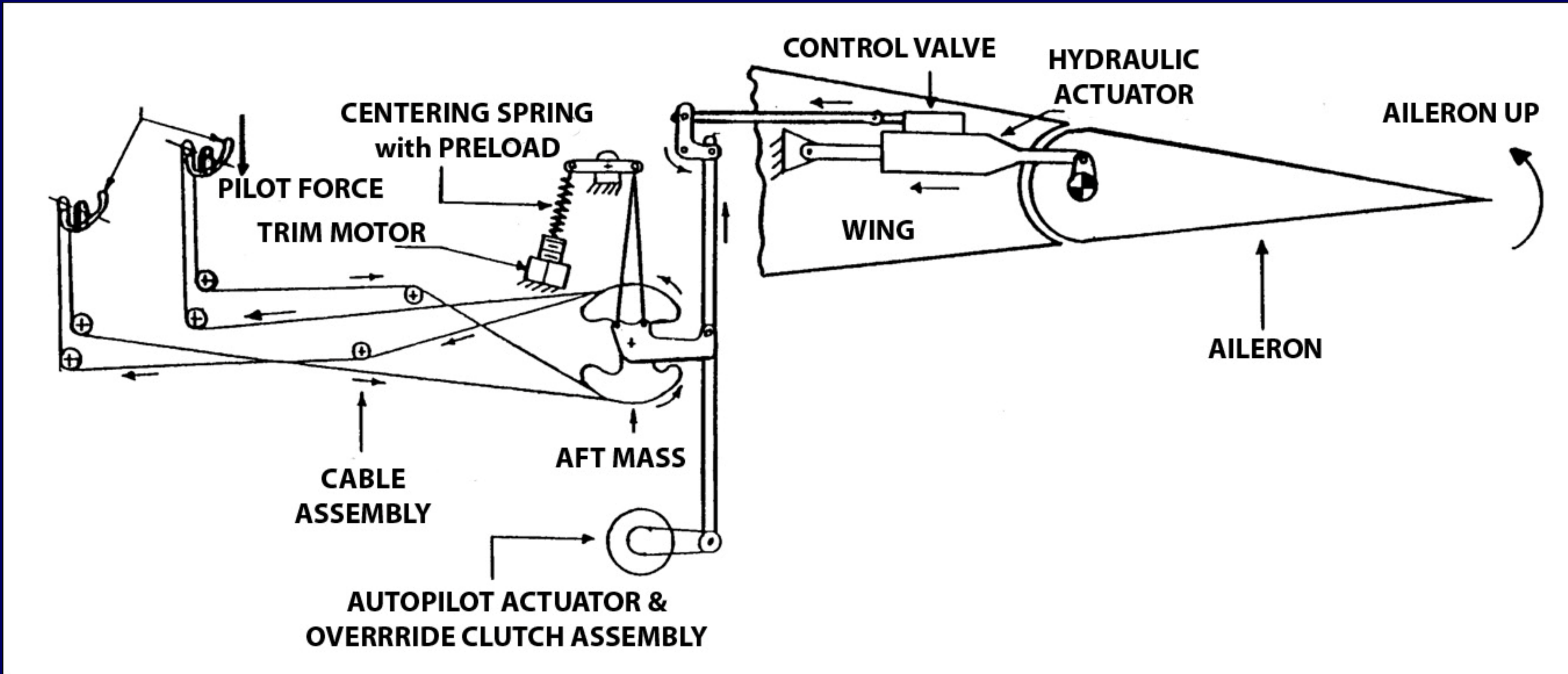
- See Next Slide -



TAB VELOCITY SURFACE UNITS
TAB POSITION SURFACE UNITS
HOST 30HZ
FLIGHT PROGRAMS
TAB AERO FORCE GRADIENT (△ELEVATOR)
TAB AERO HINGE MOMENT OFFSET
TAB AERO FORCE GRADIENT (△TAB)
TAB AERO DAMPING COEFF
CONTROL LOADING HARDWARE
PILOT FORCE
CONTROL VELOCITY
CONTROL POSITION
SERVO VALVE CMD
DAMPING DO
510HZ
FORWARD MASS
FWD MASS MODULE
CABLE
LINK MODULE
GEN MASS MODULE 510HZ
AFT MASS
TAB MASS
CENTERING SPRING
TAB POS
TAB VEL
HM TAB FORCE
TAB HINGE MOMENT
HINGE MOMENT MODULE
△ ELEVATOR
TAB STOP FORCE
TAB/ELEVATOR STOP
LINK MODULE
△TAB
TAB STOP FORCE
ELEVATOR MASS & DAMPER
GEN MASS MODULE
C ELEVATOR POS
ELEVATOR VEL
HM ELEVATOR FORCE
HINGE MOMENT MODULE
ELEVATOR HINGE MOMENT
ELEVATOR
ELEVATOR AERO FORCE GRADIENT (△TAB)
ELEVATOR AERO FORCE GRADIENT (△ELEVATOR)
ELEVATOR AERO DAMPING COEFF
ELEVATOR AERO HINGE MOMENT OFFSET
ELEVATOR VELOCITY SURFACE UNITS
ELEVATOR POSITION SURFACE UNITS
HOST 30HZ
FLIGHT PROGRAMS

IRREVERSIBLE FLIGHT CONTROL SYSTEM

Typical Irreversible Aileron Flight Control Systems



IRREVERSIBLE FLIGHT CONTROL SYSTEM

Digital Model of Irreversible Flight Control System

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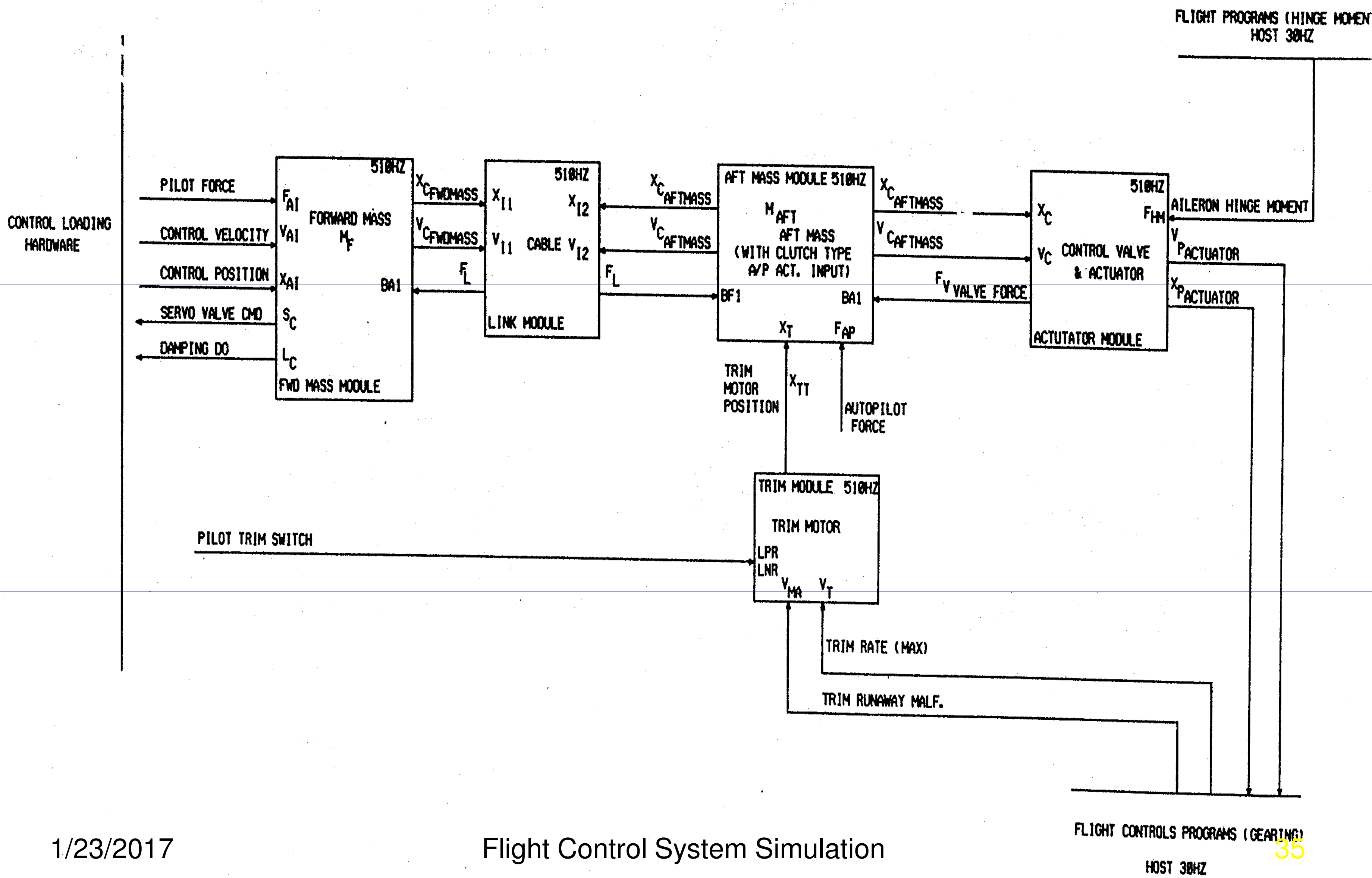
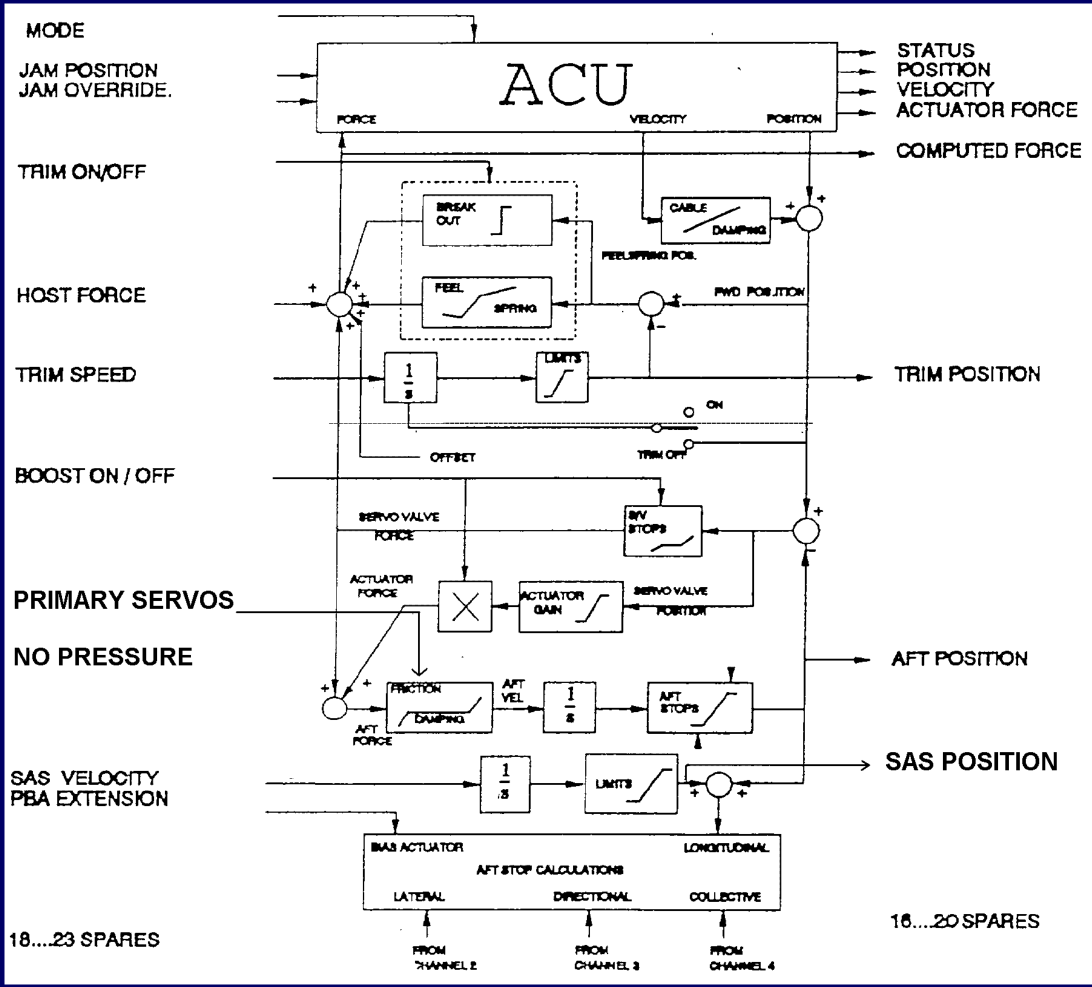
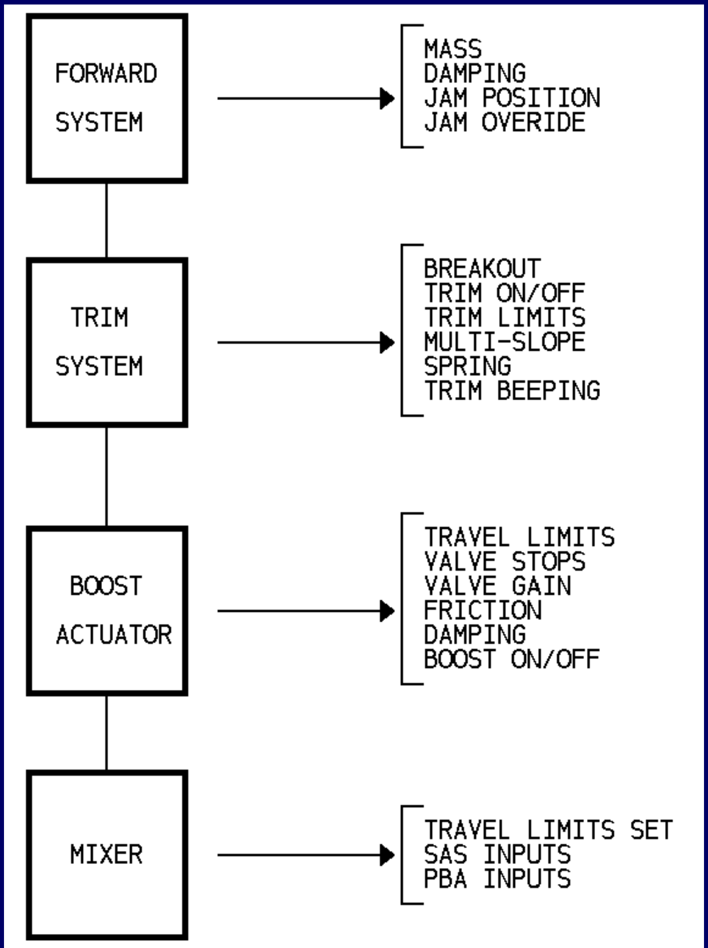

FLIGHT PROGRAMS (HINGE MOMENT
HOST 30HZ
CONTROL LOADING HARDWARE
PILOT FORCE
CONTROL VELOCITY
CONTROL POSITION
SERVO VALVE CMD
DAMPING DO
510HZ
FORWARD MASS
FWD MASS MODULE
LINK MODULE
CABLE
AFT MASS MODULE 510HZ
AFT MASS
(WITH CLUTCH TYPE
A/P ACT. INPUT)
CONTROL VALVE
& ACTUATOR
ACTUTATOR MODULE
AILERON HINGE MOMENT
VALVE FORCE
TRIM MOTOR POSITION
AUTOPILOT FORCE
TRIM MODULE 510HZ
TRIM MOTOR
PILOT TRIM SWITCH
LPR
LNR
TRIM RATE (MAX)
TRIM RUNAWAY MALF.
FLIGHT CONTROLS PROGRAMS (GEARING)
HOST 30HZ

HELICOPTER FLIGHT CONTROL SYSTEM (Specific)

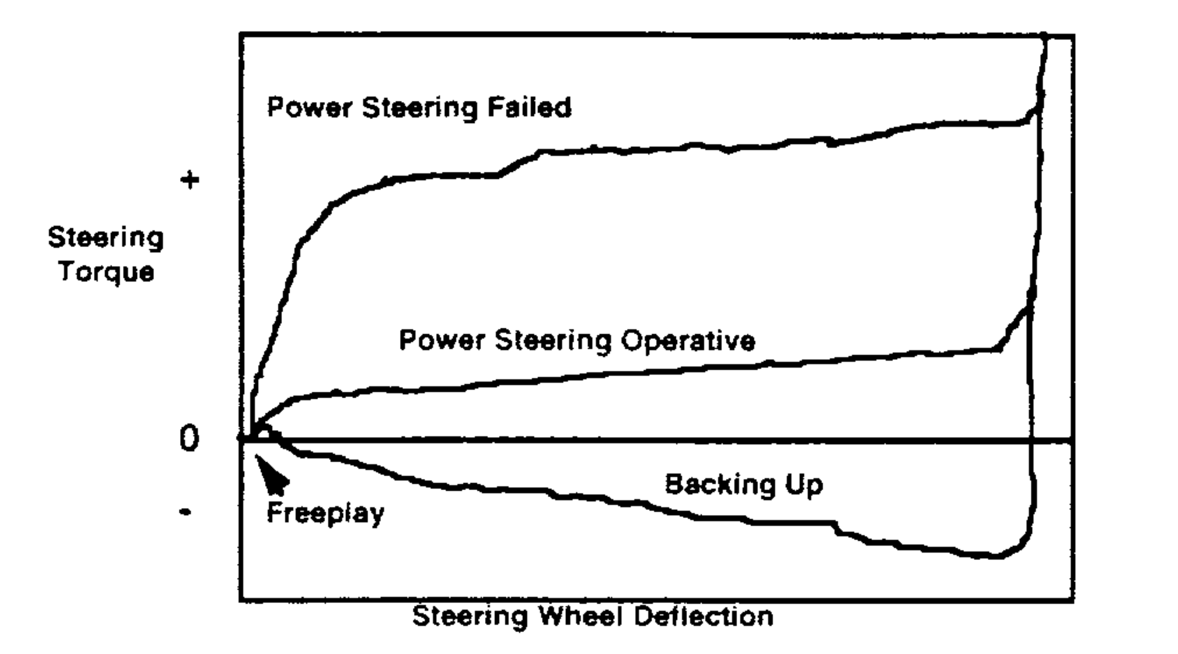


HELICOPTER FLIGHT CONTROL SYSTEM (Generic)



Challenges - Steering Control System

- High Dynamic Range
- Low Force Gradients
- Unstable when Vehicle Backing Up



Challenges - Pedals

- Accelerator (especially)
  - Low Mass
  - High Force when Simulating Stops
  - High return speeds

AUTOPILOT AND FLIGHT GUIDANCE CONTROL SYSTEMS

ELECTRONIC AUTOPILOT & FLIGHT CONTROL SYSTEMS CONSIDERATIONS

Fly-By-Wire & Autopilot Guidance Systems Common Considerations

SIMULATION vs. STIMULATION

- System Complexity ?
- Specified Performance (Requirements) ?
- Life Cycle Costs ?
- Availability of Data ?
- Cost of Data ?
- Cost of Avionics (Black Boxes) ?

SIMULATION vs. STIMULATION

PROS & CONS

Simulation

PROS

- Special Simulator Function
- Malfunctions
- Hardware Costs

CONS

- Performance
- Updates
- Development Costs

Stimulation

PROS

- Performance
- Ease of Updates
- Costs (initial?)

CONS

- Special Simulator Function
- Malfunctions
- Hardware Complexity
- Hardware Costs (repeats?)

SIMULATION vs. STIMULATION

Design Considerations
Stimulation

- Simulation Architecture
  - System Transport Delays
  - I/O Iteration Rates
  - Program Sequencing
  - Program Iteration Rates
- Sensor Simulation
  - Signal Waveform
  - Signal Phase
  - Signal Transducer Offsets
- Servo Actuator Simulation
  - Static Characteristics
  - Dynamic Characteristics
  - Feedback Monitoring
- Limitation on Special Simulator Functions
  - Freezes
  - Repositions
  - Record/Playback
  - Etc.

SIMULATION vs. STIMULATION

Design Considerations
Simulation

- **Simulation Architecture**
  - Program Sequencing
  - Program Iteration Rates

- **Limitation on Simulation**
  - Filter Cutoff Frequencies
  - Signal Distortion

SIMULATION vs. STIMULATION

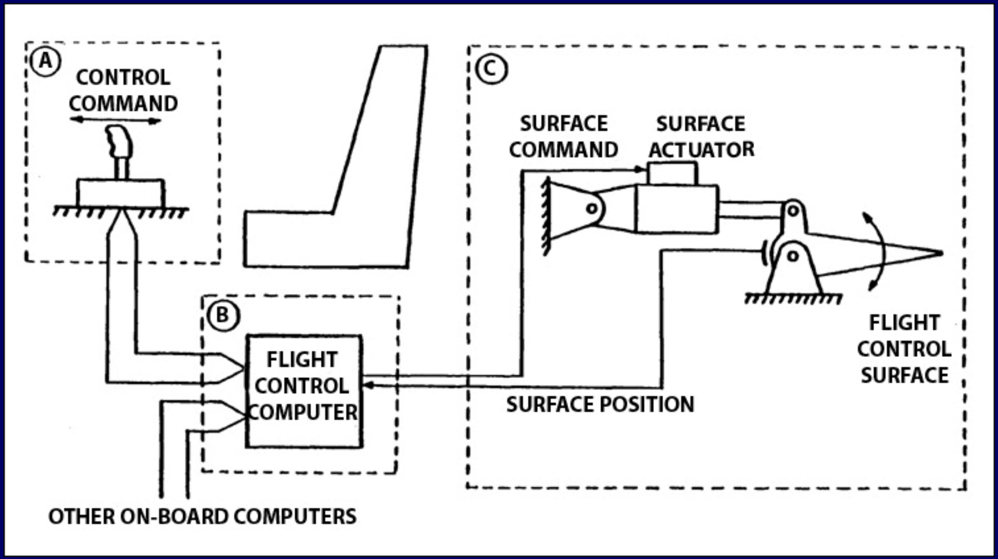
Data Considerations

DETAILED DATA DESCRIBING	SIMULATION	STIMULATION
System Performance	X	X
Internal Control Laws	X	X*
Internal Logic	X	X*
Internal Fault Monitoring	X	X*
Fault Detection Circuits (sniffers)		X
Electrical Characteristics of Computer Inputs & Outputs		X
Sensor Output Characteristics (waveform, phase, offsets)		X
Servo Actuator Transfer Functions		X

* Used to expedite hardware/software integration and assist with debugging

SIMULATION vs. STIMULATION

Simplified Fly-By-Wire System



Simulation

A. Control Loading Device or Aircraft Stick
B. Simulated Flight Control Computer
C. Simulated Actuator & Control Surface

Stimulation

A. Aircraft Stick
B. Aircraft Flight Control Computer
C. Simulated Actuator & Control Surface

SIMULATION of FLY-BY-WIRE & AUTOPILOT FLIGHT CONTROL SYSTEMS

Common Features

- Inner & Outer System Feedback Control Loops
- Onboard Computer “Black Boxes”
  - Complex Control Laws
  - Signal Conditioners
  - Filters
  - Switch Logic
  - Fault Monitoring & Detection Systems (SNIFFERS)

AUTOMATIC FLIGHT CONTROL SYSTEMS

Autopilot System

- Pitch Control
- Roll Control
- Yaw Control

Flight Augmentation System

- Yaw Damper
- Pitch Trim
- Flight Envelope Protection

Thrust Control System

- Autothrottle
- Autothrust
- Engine Parameter Management

Flight Director System

- Pitch Direction
- Roll Direction
- Yaw Direction

AUTOPILOT SYSTEMS
Typical Modes/Functions

Longitudinal Modes

- Vertical Speed Hold/Acquire
- Altitude Hold/Acquire
- Profile/VNAV
- Glideslope

Lateral Modes

- Heading Hold/Acquire
- NAV or LNAV (FMS or GPS)
- VOR/LOC

Integrated Modes

- Takeoff
- Land (LOC & G/S)
- Land SBAS (WAAS, EGNOS
- Go-around
- Control Wheel Steering

FLIGHT AUGMENTATION AND THRUST CONTROL
Typical Modes/Functions

Flight Augmentation System

- Dutch Roll Damping
- Turn Coordination
- Assist Autopilot During Engine Failure
- Auto Trim
- Mach Trim
- Alpha Trim

Thrust Control System

- Thrust Mode
- Speed/Mach Hold/Acquire
- Retard Mode

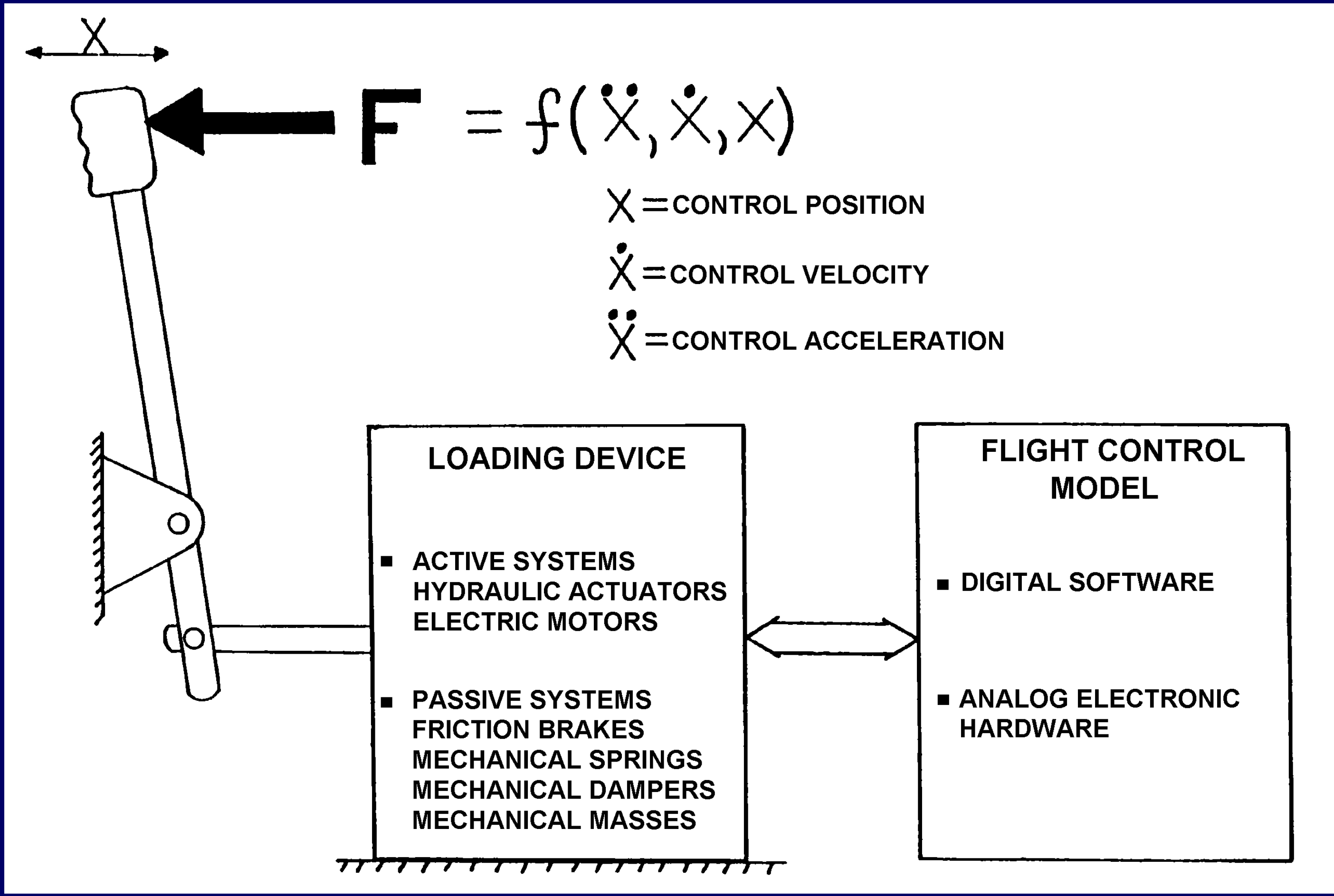
OTHER INNOVATIVE Modes/Functions

Active Gust Alleviation System

- Many of the sensors in the B787 Dreamliner are connected wirelessly to a central data processor.
- Some are used for the "active gust alleviation" system which uses sensors to measure turbulence at the nose, then instantly adjusts wing flaps to counter it.

FLIGHT AND GROUND VEHICLE FORCE FEEDBACK SIMULATION

SIMULATION of COCKPIT CONTROL "FEEL" aka - CONTROL LOADING



SIMULATION OF COCKPIT CONTROL "FEEL" (aka CONTROL LOADING)

ACTIVE vs. PASSIVE Loaders

ACTIVE Loading Devices are Used When:

- Control Forces VARY with Flight Conditions *and/or*
- Accurate Dynamic Performance IS Required *and/or*
- Back Driving of the Cockpit Control IS Required

PASSIVE Loading Devices are Used When:

- Control Forces DO NOT VARY with Flight Conditions *and*
- Accurate Dynamic Performance IS NOT Required *and*
- Back Driving of the Cockpit Control IS NOT Required

HISTORIC OVERVIEW

- Analog Hydraulic Control Loading – ACL (60's - 80's)
  - Position Loop Servo (60's and 70's) – low fidelity
  - Force Loop Servo (80's) – high fidelity
- Digital Hydraulic Control Loading – DCL (mid 80's – 90's)
  - Force Loop Servo
  - Servo Compensation Techniques – stability
  - Enhanced Modeling – higher order
  - Calibration and Tuning Software

HISTORIC OVERVIEW (cont.)

- **Digital Electric Control Loading – DECL (90's – present)**
  - Force Loop Servo
  - Enhanced Servo Compensation Techniques – improved stability, increased frequency response
  - Better performance, higher fidelity, better handling qualities
  - Improved Modeling due to very powerful, cost effective, commercial of-the-shelf PCs
  - Enhanced Calibration and Tuning Software
  - Lower Maintenance

ELECTRIC vs. HYDRAULIC

Electric Systems

(advantages)

- No Hydraulic Power Unit or Distribution System
- No Mess from Hydraulic Oil Leaks
- Improved Reliability
- Less Maintenance
- Lower Acquisition and Life Cycle Costs

Hydraulic Systems

(advantages)

- Proven Long Term Performance
- High Force/High Sustained Force Capability
- Small Package

ELECTRIC vs. HYDRAULIC (cont.)

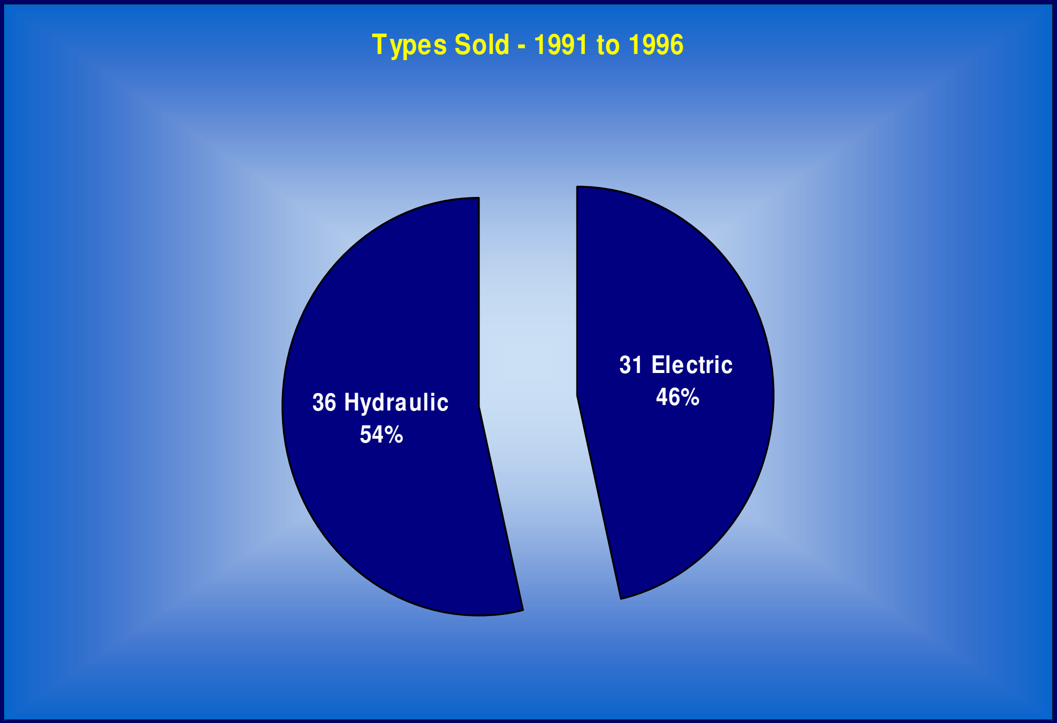
Control Loading Hardware Component Requirements

Component	Requirement	Component	Requirement
❖ ELECTRIC		❖ HYDRAULIC	
◆ Electric Motor	- High Torque	◆ Hydraulic Actuator	- Low Friction
	- High Accuracy		
	- Low Inertia	◆ Servo Valve	- Near Zero Hysteresis
	- Low Friction		- Near Zero Drift
	- Smooth	❖ BOTH	
		◆ Linkage	- Low Inertia
◆ Power Amplifier	- High Power		- Low Friction
	- Low Noise		- High Stiffness
			- Zero Free Play
◆ Gear Reduction	- Zero Backlash	◆ Transducers	- High Accuracy
	- Low Friction		- High Signal-to-Noise
	- Low Inertia		- Low Friction
	- Low Vibration		

ELECTRIC vs. HYDRAULIC CONTROL LOADING RELIABILITY

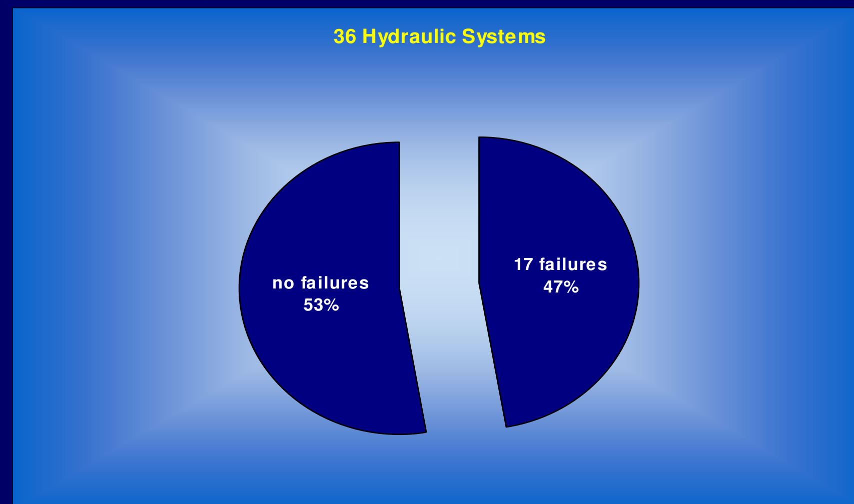
- ***REALFeel®***
  System theoretical
  MTBF: **15,800 hrs.**

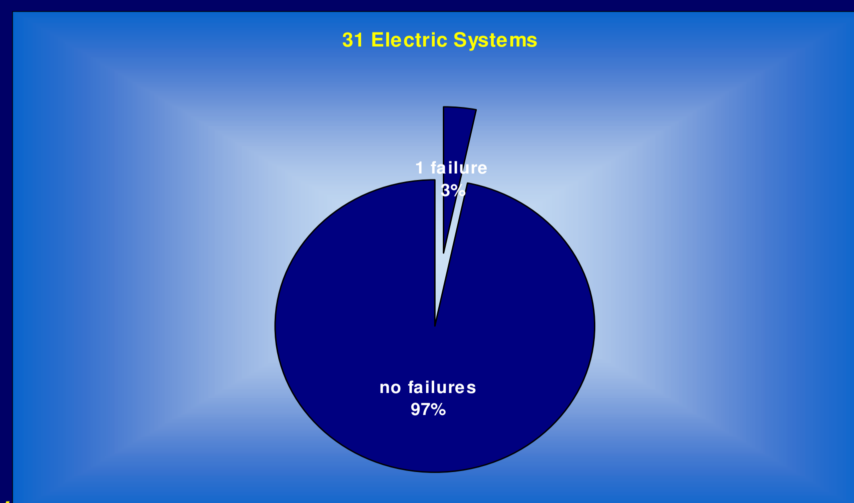
- From FSEMC '96
  - BAE/Reflectone: Electric vs. Hydraulic system sales over a five year period
  - Performed a reliability study



ELECTRIC vs. HYDRAULIC CONTROL LOADING RELIABILITY

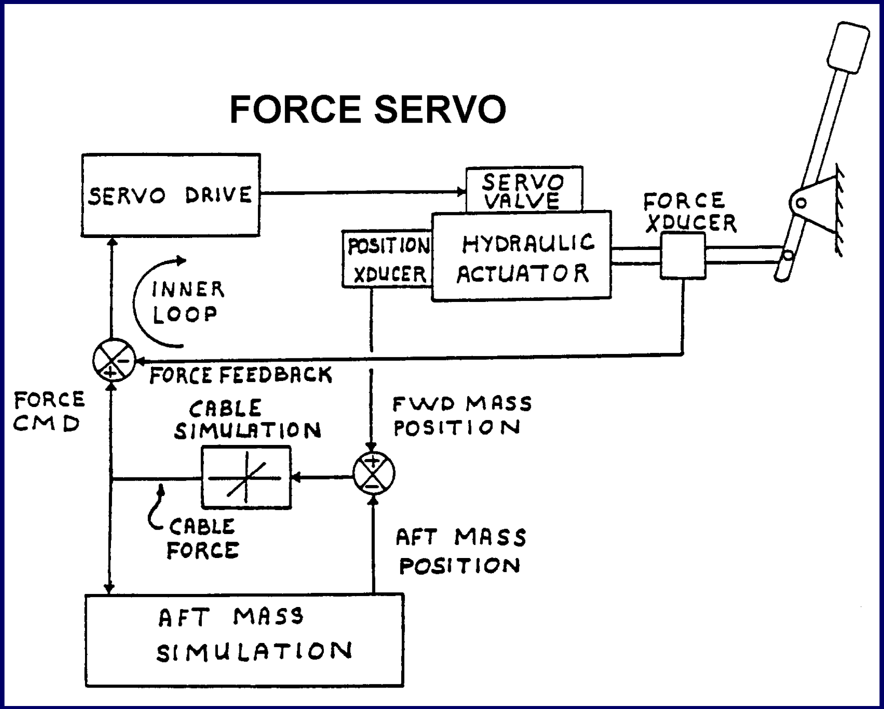
- 36 Hydraulic:
  - 17 failures
  - Cost $13,164.
- 31 Electric:
  - 1 failure
  - Cost $500.
- Cost factor:
  - 26:1 in favor of Electric

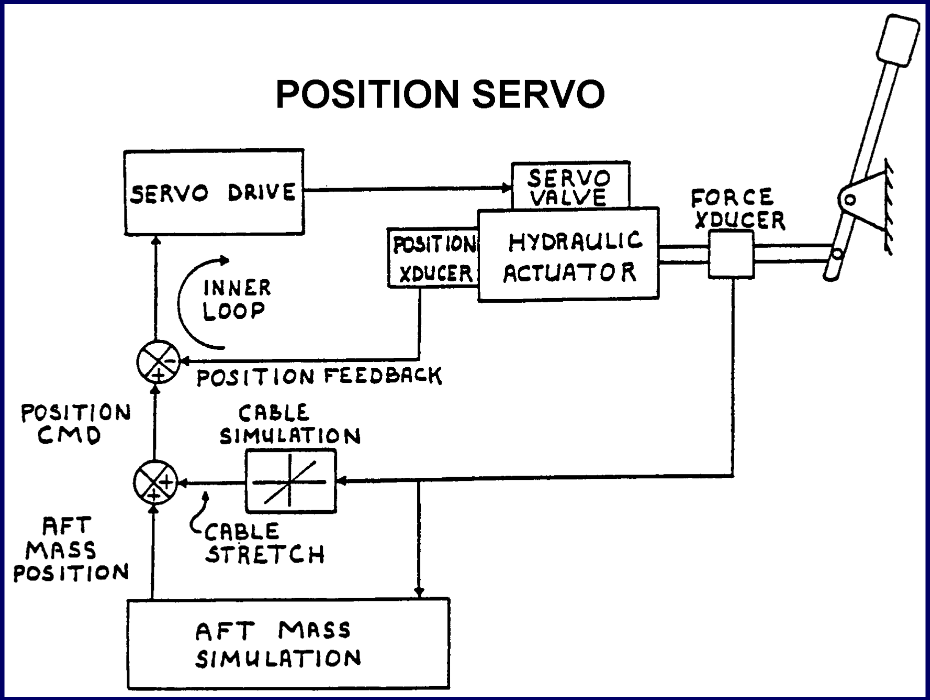




INTEGRATION OF CONTROL LOADING SYSTEMS

Servo Configuration - Force & Position Servo





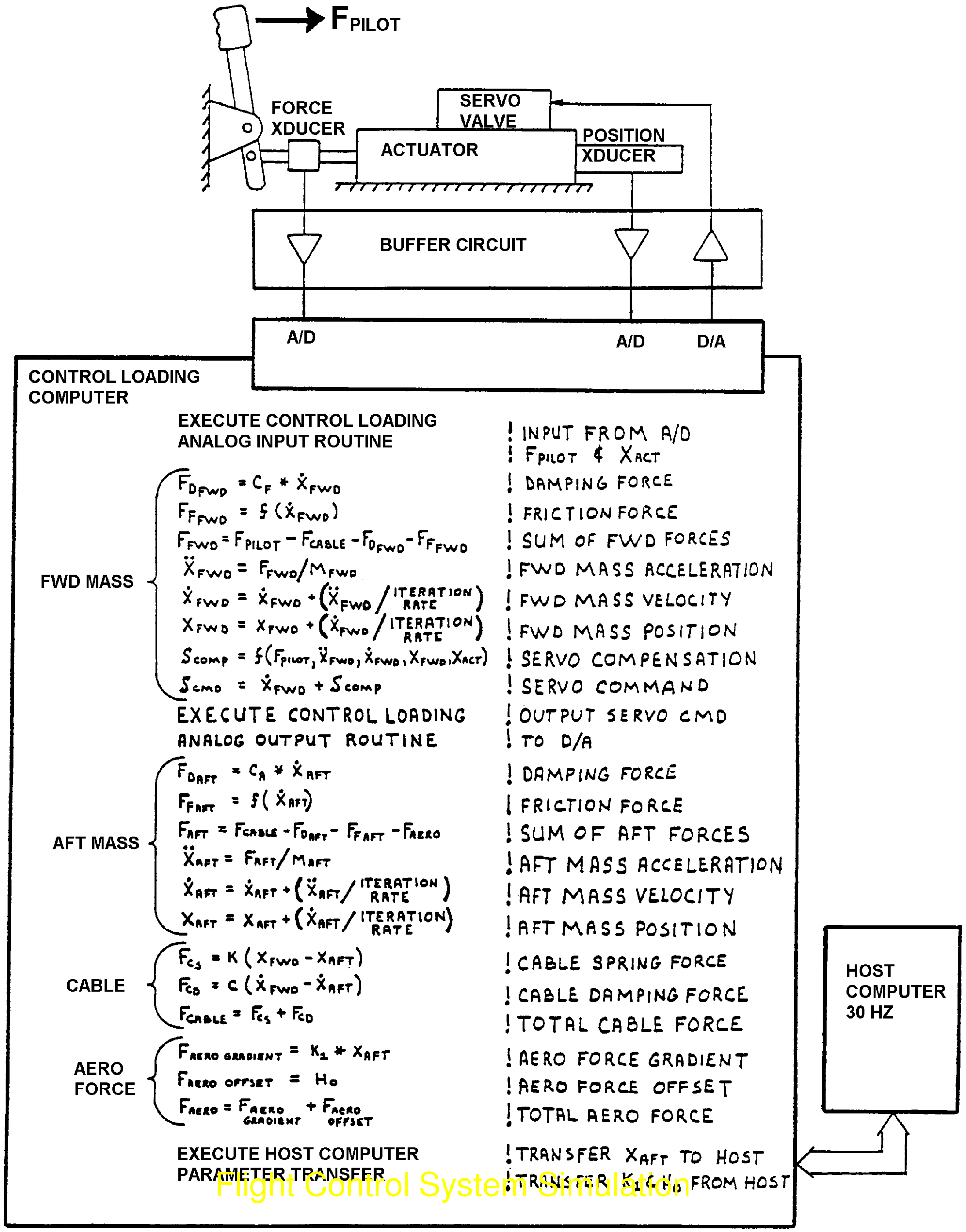
INTEGRATION OF CONTROL LOADING SYSTEMS

Model Implementation

- Analog Model (obsolete)
- Hybrid Analog/Digital (obsolete)
- Digital Model

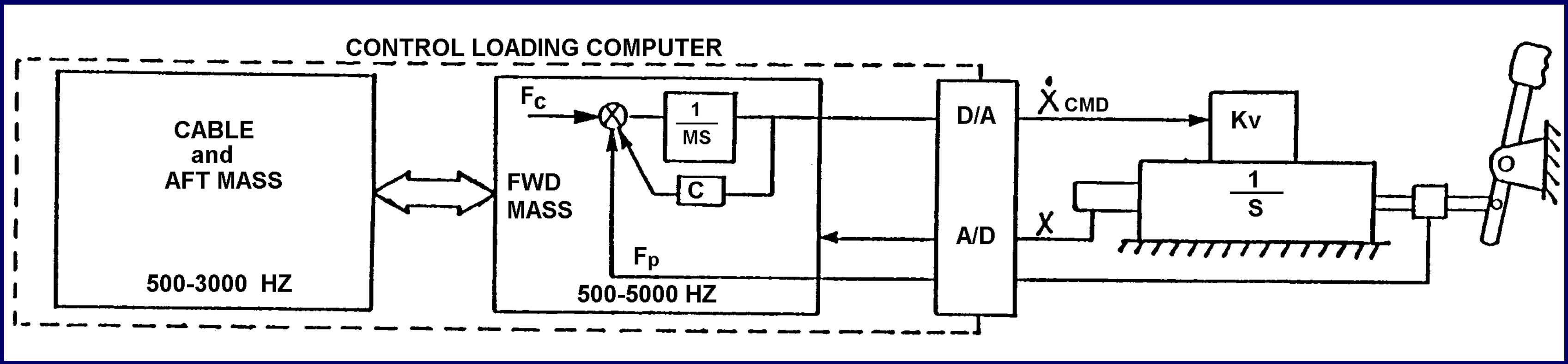
Simplified Digital Model

- See Next Slide -


F PILOT
FORCE XDUCER
SERVO VALVE
ACTUATOR
POSITION XDUCER
BUFFER CIRCUIT
A/D
A/D
D/A
CONTROL LOADING COMPUTER
EXECUTE CONTROL LOADING ANALOG INPUT ROUTINE
! INPUT FROM A/D
! FPILOT & XACT
FWD MASS
FDFWD = CF * ẊFWD
! DAMPING FORCE
FFFWD = f (ẊFWD)
! FRICTION FORCE
FFWD = FPILOT − FCABLE − FDFWD − FFFWD
! SUM OF FWD FORCES
ẌFWD = FFWD/MFWD
! FWD MASS ACCELERATION
ẊFWD = ẊFWD + (ẌFWD / ITERATION RATE)
! FWD MASS VELOCITY
XFWD = XFWD + (ẊFWD / ITERATION RATE)
! FWD MASS POSITION
Scomp = f(FPILOT, ẌFWD, ẊFWD, XFWD, XACT)
! SERVO COMPENSATION
Scmd = ẊFWD + Scomp
! SERVO COMMAND
EXECUTE CONTROL LOADING ANALOG OUTPUT ROUTINE
! OUTPUT SERVO CMD
! TO D/A
AFT MASS
FDAFT = CA * ẊAFT
! DAMPING FORCE
FFAFT = f(ẊAFT)
! FRICTION FORCE
FAFT = FCABLE − FDAFT − FFAFT − FAERO
! SUM OF AFT FORCES
ẌAFT = FAFT/MAFT
! AFT MASS ACCELERATION
ẊAFT = ẊAFT + (ẌAFT / ITERATION RATE)
! AFT MASS VELOCITY
XAFT = XAFT + (ẊAFT / ITERATION RATE)
! AFT MASS POSITION
CABLE
FCS = K (XFWD − XAFT)
! CABLE SPRING FORCE
FCD = C (ẊFWD − ẊAFT)
! CABLE DAMPING FORCE
FCABLE = FCS + FCD
! TOTAL CABLE FORCE
AERO FORCE
FAERO GRADIENT = K1 * XAFT
! AERO FORCE GRADIENT
FAERO OFFSET = H0
! AERO FORCE OFFSET
FAERO = FAERO GRADIENT + FAERO OFFSET
! TOTAL AERO FORCE
EXECUTE HOST COMPUTER PARAMETER TRANSFER
! TRANSFER XAFT TO HOST
! TRANSFER K1 & H0 FROM HOST
HOST COMPUTER 30 HZ

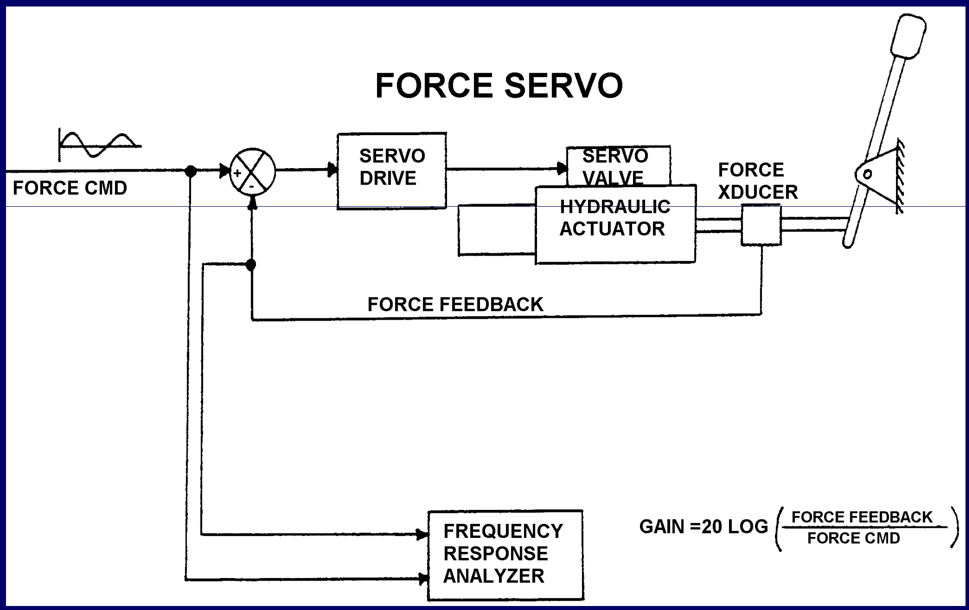
BASIC APPROACH TO DIGITAL CONTROL LOADING

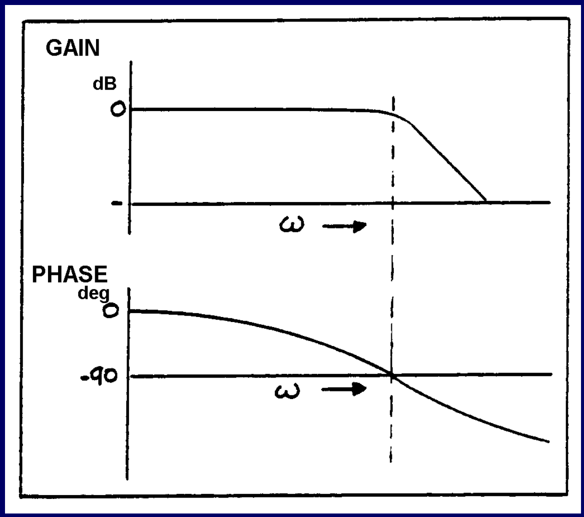
Standard Approach: Fully Digital System



DESIGN OF CONTROL LOADING SYSTEMS

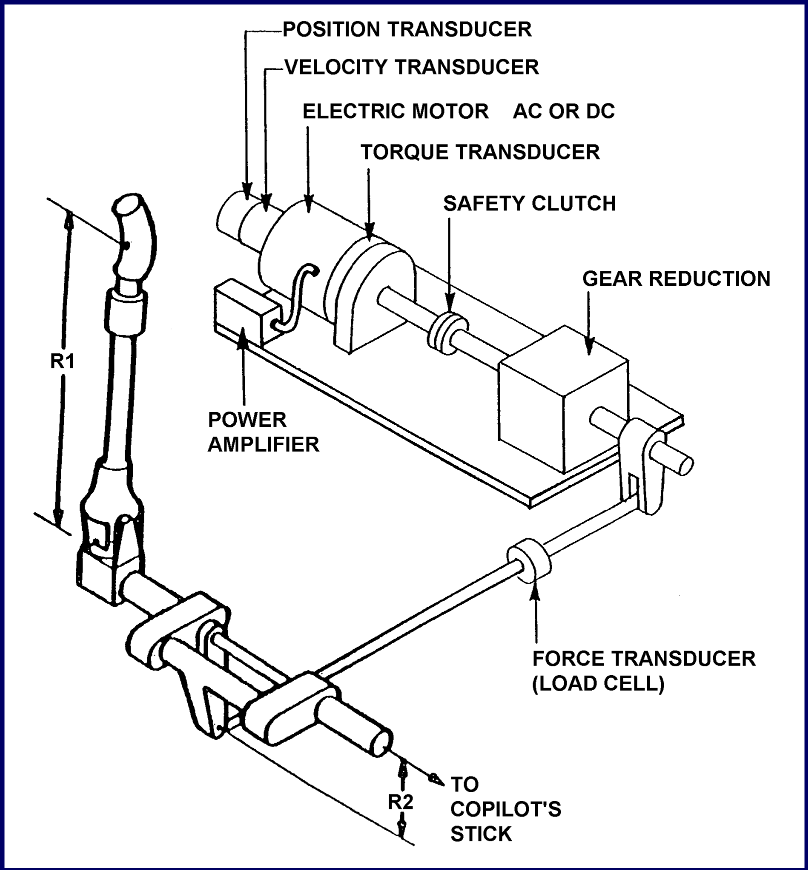
Force Loop Frequency Response Measurement





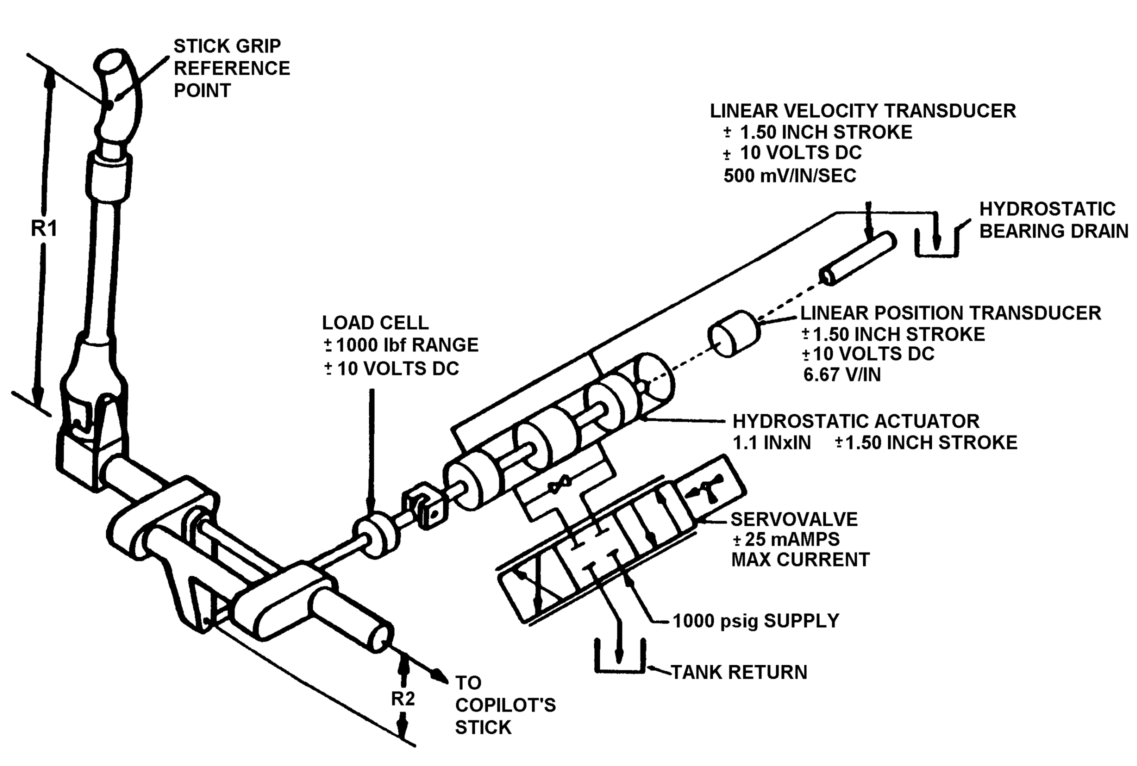
CONTROL LOADING HARDWARE INSTALLATION

Basic Electric Loader Servo Hardware



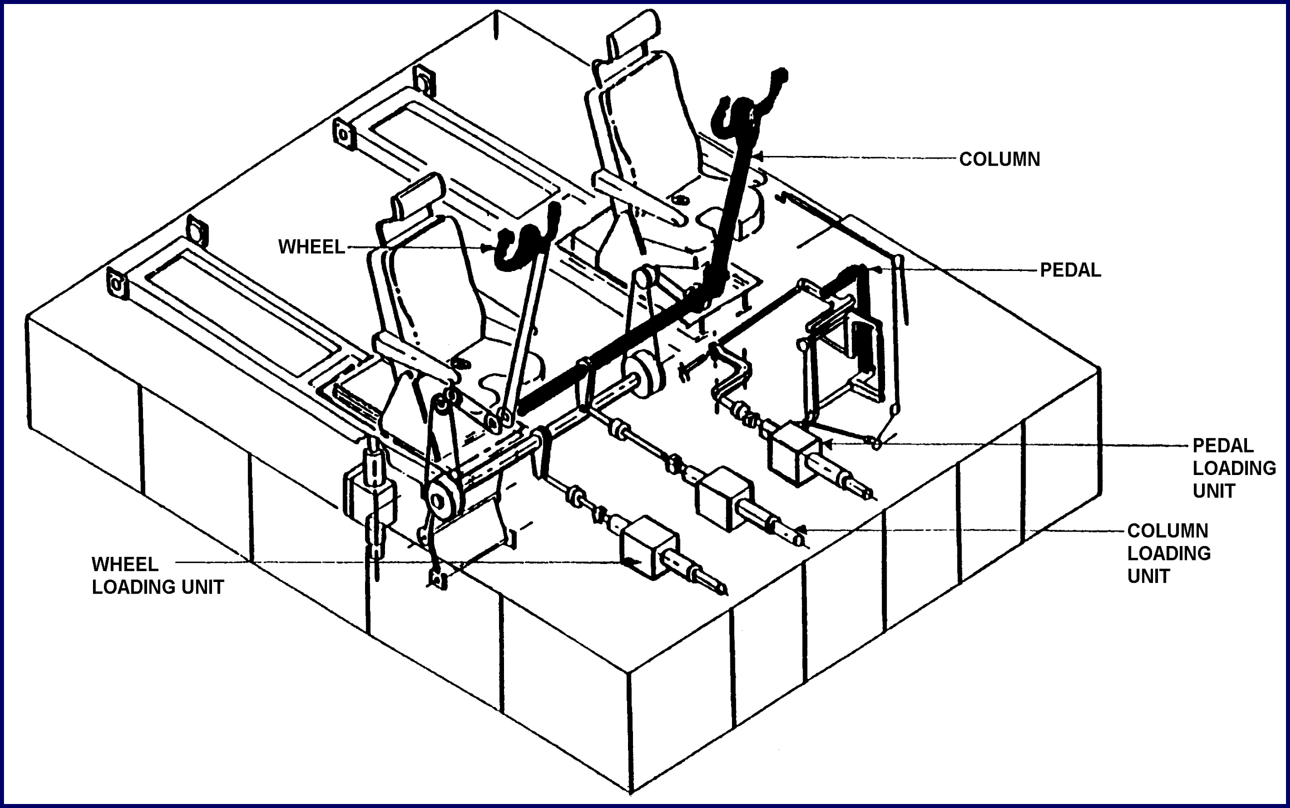
CONTROL LOADING HARDWARE INSTALLATION

Basic Hydraulic Loader Servo Hardware

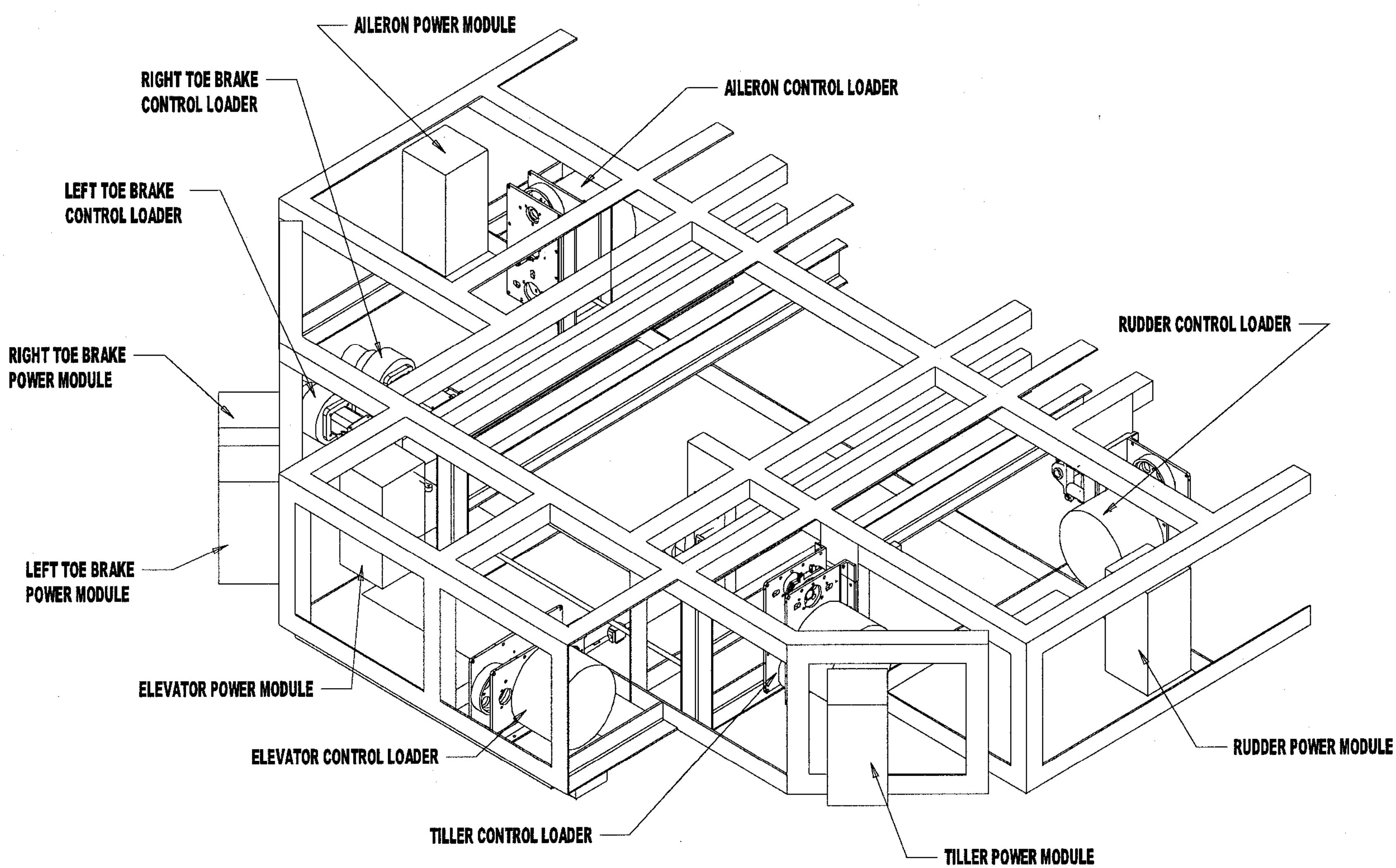


CONTROL LOADING HARDWARE INSTALLATION

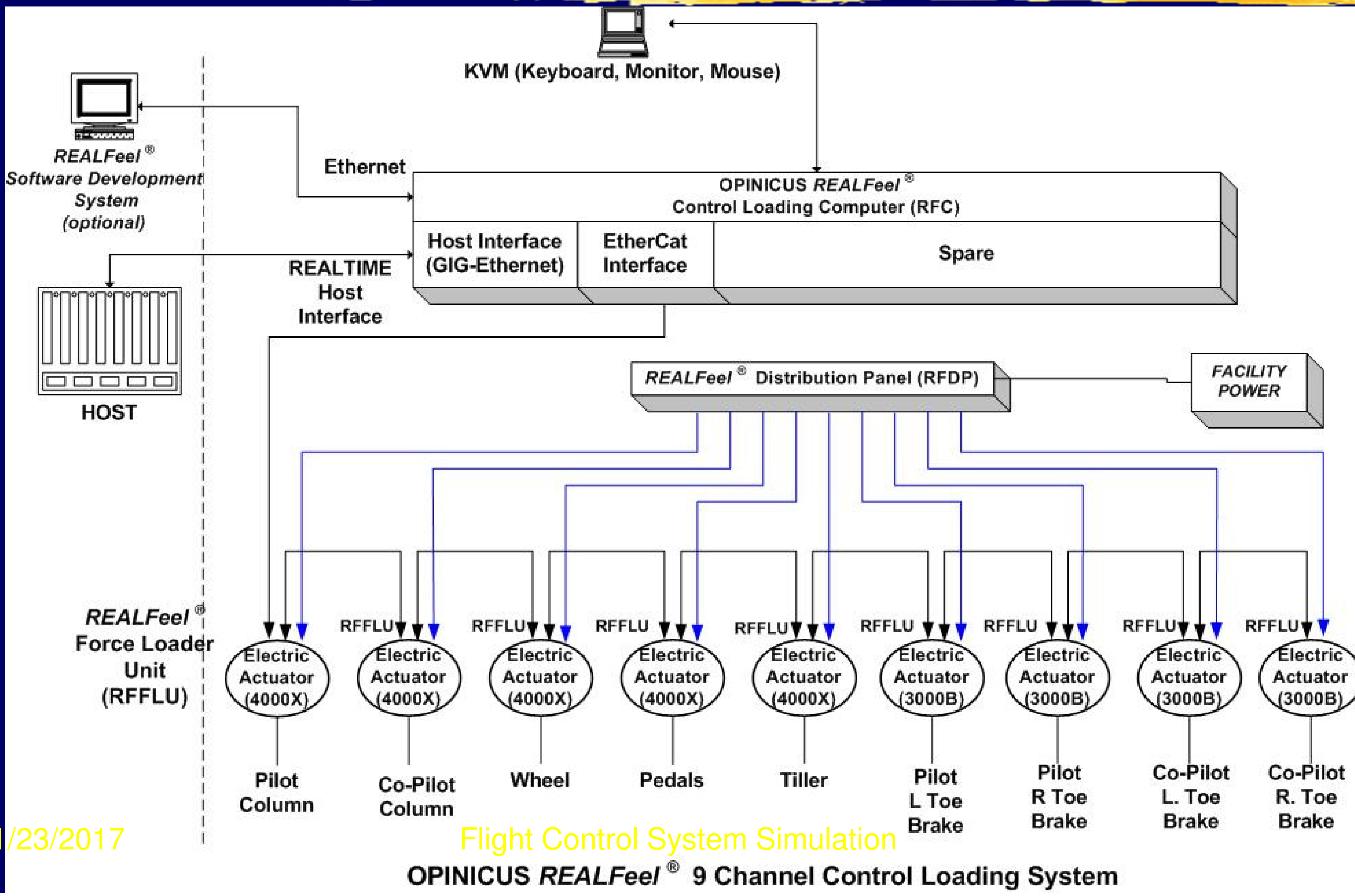
Basic Three Axis Hydraulic Installation - Column, Wheel, Pedals



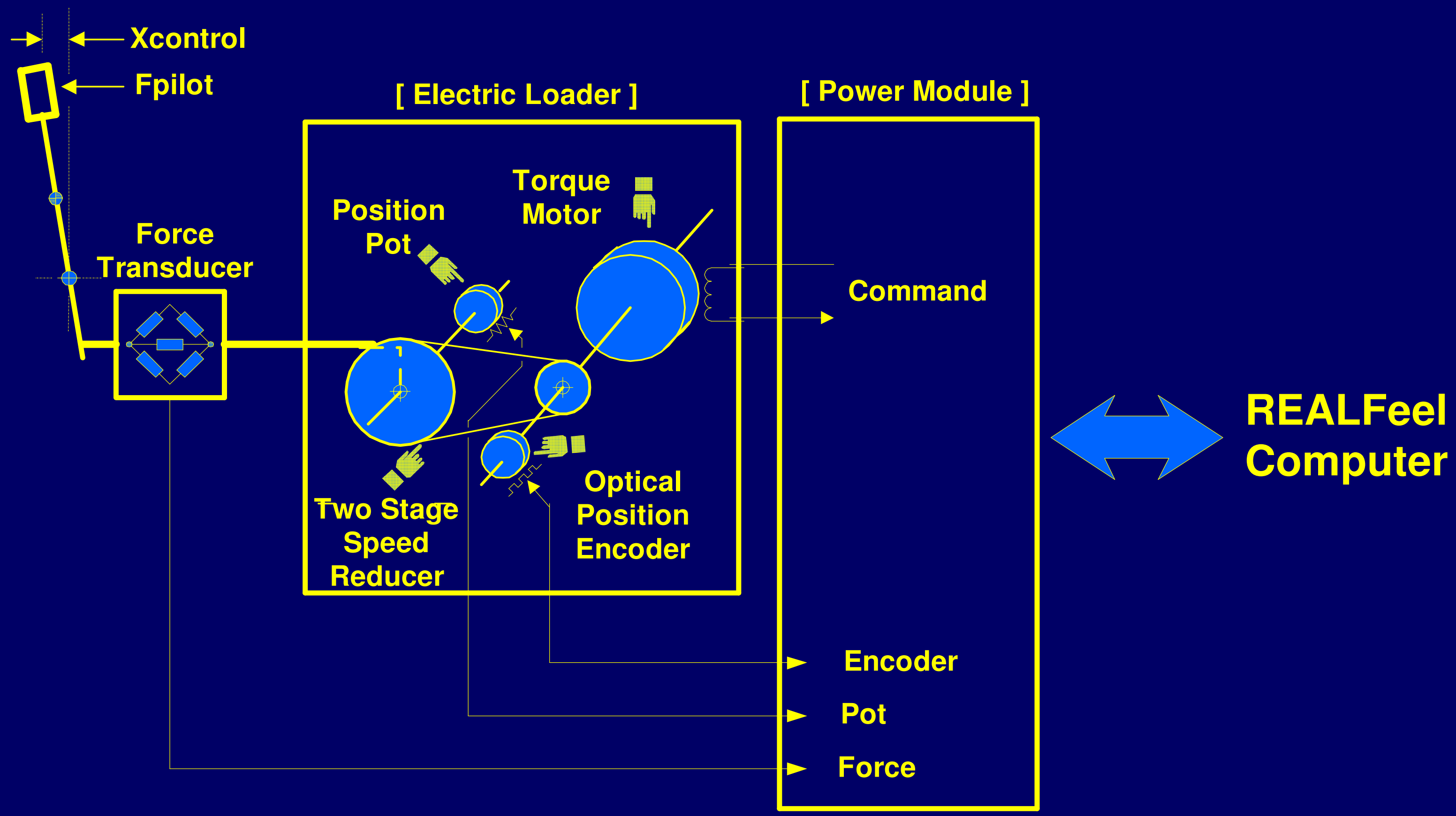
Basic 6 Axis Electrical Installation –
Column, Wheel, Pedals, Tiller, Left Toe Brake, & Right Toe Brake



CONTROL LOADING SYSTEM BLOCK DIAGRAM - *REALFeel®* NG



REALFeel® *NG* ELECTRIC LOADER ARCHITECTURE



REALFeel® NG ELECTRIC LOADER

GENERAL SERVO REQUIREMENTS

Basic Active Control Loading Systems

Static Requirements

- Force Threshold
  - 0.1 lb
- Maximum Force
  - 250 lb
- Maximum Force Gradient
  - 300 lb/in

Dynamic Requirements

- Large Amplitude Free Response (Natural Frequency)
  - > 5 Hz
- Small Signal Force Bandwidth
  - > 50 Hz

THE NEW STANDARDS (DESIRABLE SERVO CAPABILITIES)

High Fidelity Electric Active Control Loading Systems

Static Requirements

- Force Threshold
  - 0.05 lb
- Maximum Force
  - Dependent on Control Channel (see next slides)
- Maximum Velocity
  - Dependent on Control Channel (see next slides)
- Maximum Force Gradient
  - 300 lb/in

Dynamic Requirements

- Large Amplitude Bandwidth between Force in and Position out should have less than 90 degrees phase lag at 7Hz.
- Small Signal Force Bandwidth
  - > 100 Hz

DESIRABLE PERFORMANCE CAPABILITIES

Maximum Force Requirements at the Controls (Electric C/L Systems)

	Force - Short Term	Force - Sustained
Column	250 lb	150 lb
Wheel	125 lb	75 lb
Pedal	325 lb	250 lb
Tiller	100 lb	75 lb
Toe Brake	300 lb	200 lb

DESIRABLE PERFORMANCE CAPABILITIES

Maximum Velocity Requirements at the Controls (Electric C/L Systems)

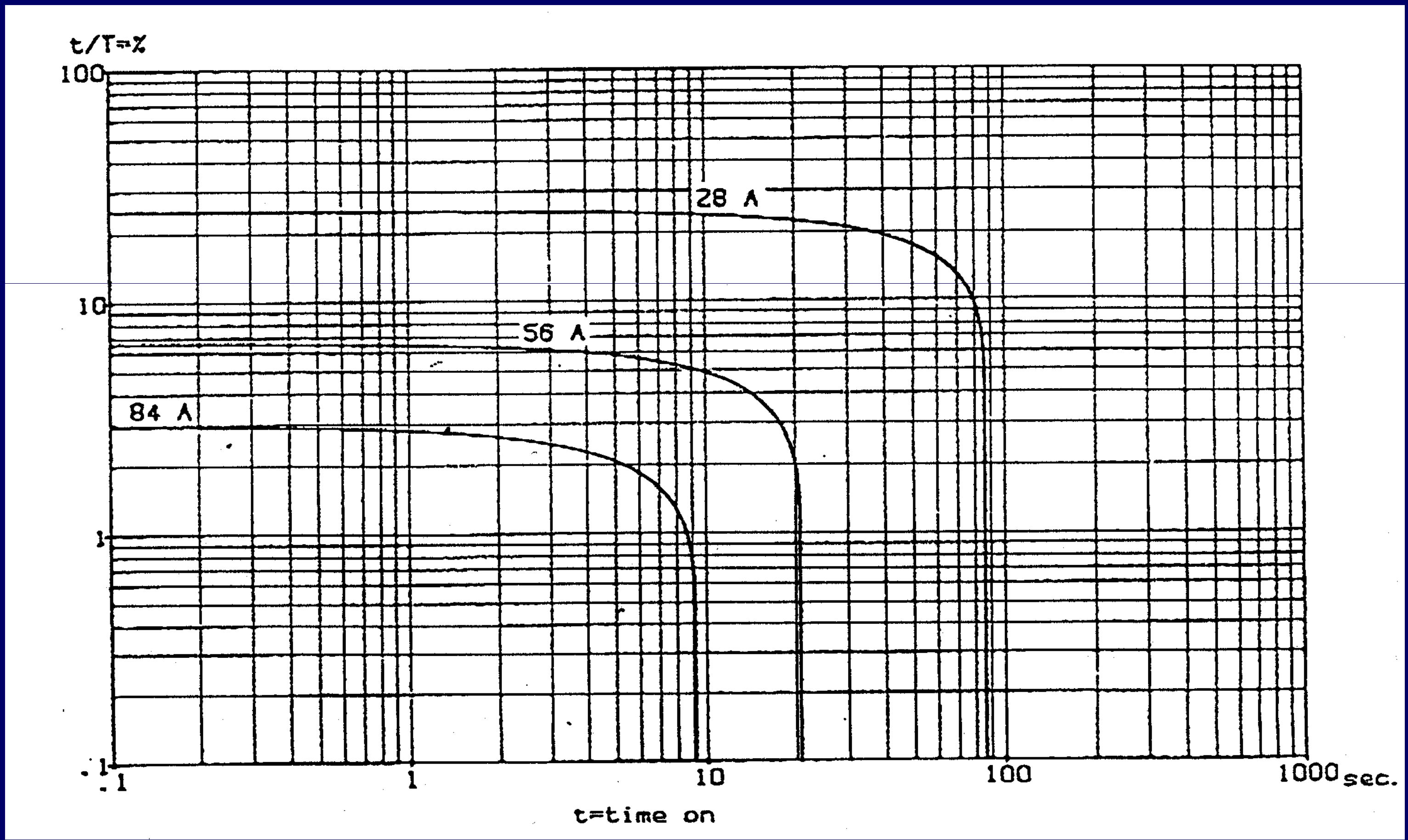
	Velocity – Required	Velocity - Desired
◆ Column	95 deg/sec	128 deg/sec
◆ Wheel	715 deg/sec	967 deg/sec
◆ Pedal	95 deg/sec	126 deg/sec
◆ Tiller	360 deg/sec	450 deg/sec
◆ Toe Brake	240 deg/sec	300 deg/sec

ELECTRIC LOADER FORCE / ACCELERATION CAPABILITIES

- **Electric DC Torque Motor**
  - High Torque Constant
  - Amplifier Current Capability
  - S3 Curve – defines sustained torque duration
  - Cooling Fan Option – increases duration by approx. 40%

- **Speed Reducer**
  - Gearing
  - Low Inertia (2 Stage)
  - Force / Velocity Relationship

MOTOR CHARACTERISTICS - S3 CURVE



REALFeel® NG FORCE CAPABILITY

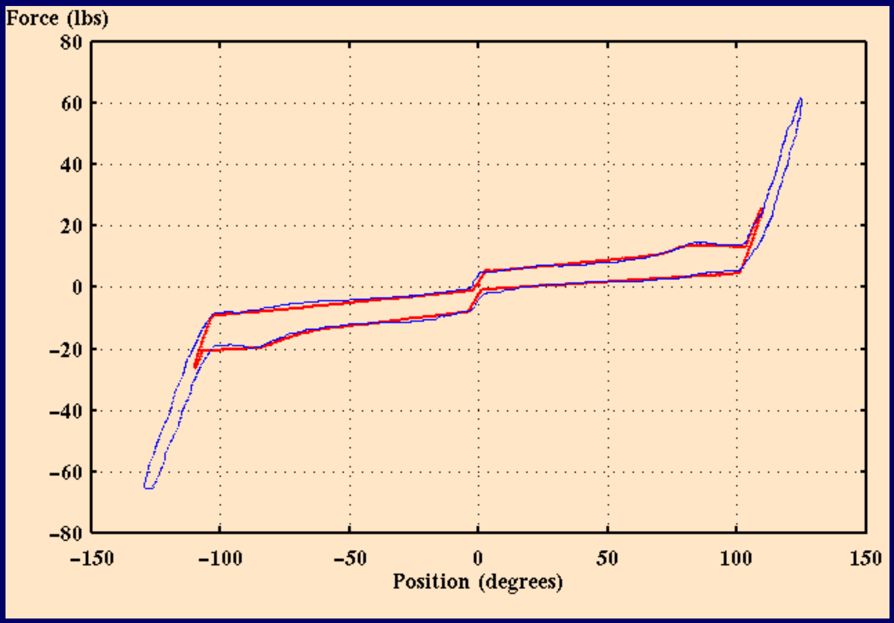
The ENHANCED FORCE CAPABILITY of the *REALFeel™* 4000 Series Force Loaders	*REALFeel™* 4000XX		*REALFeel™* 4000X		*REALFeel™* 3000B	
	w/o cooling	w/cooling	w/o cooling	w/cooling	w/o cooling	w/cooling
Option A: Output Stroke	+/- 2 in	+/- 2 in	+/- 2 in	+/- 2 in	+/- 1.5 in	+/- 1.5 in
Continuous Force	694 lbs	864 lbs	412 lbs	512 lbs	237 lbs	332 lbs
Intermediate Force (30 sec)	886 lbs	1109 lbs	600 lbs	839 lbs	390 lbs	390 lbs
High Force (10 sec)	1109 lbs	1109 lbs	1000 lbs	1000 lbs	390 lbs	390 lbs
Maximum Force (2 sec)	1774 lbs	1774 lbs	1600 lbs	1600 lbs	623 lbs	623 lbs
Option B: Output Stroke	+/- 1.75 in	+/- 1.75 in	+/- 1.75 in	+/- 1.75 in	+/- 1.25 in	+/- 1.25 in
Continuous Force	819 lbs	1019 lbs	487 lbs	606 lbs	277 lbs	388 lbs
Intermediate Force (30 sec)	1048 lbs	1310 lbs	708 lbs	992 lbs	455 lbs	455 lbs
High Force (10 sec)	1310 lbs	1310 lbs	1180 lbs	1180 lbs	455 lbs	455 lbs
Maximum Force (2 sec)	2095 lbs	2095 lbs	1889 lbs	1889 lbs	727 lbs	727 lbs

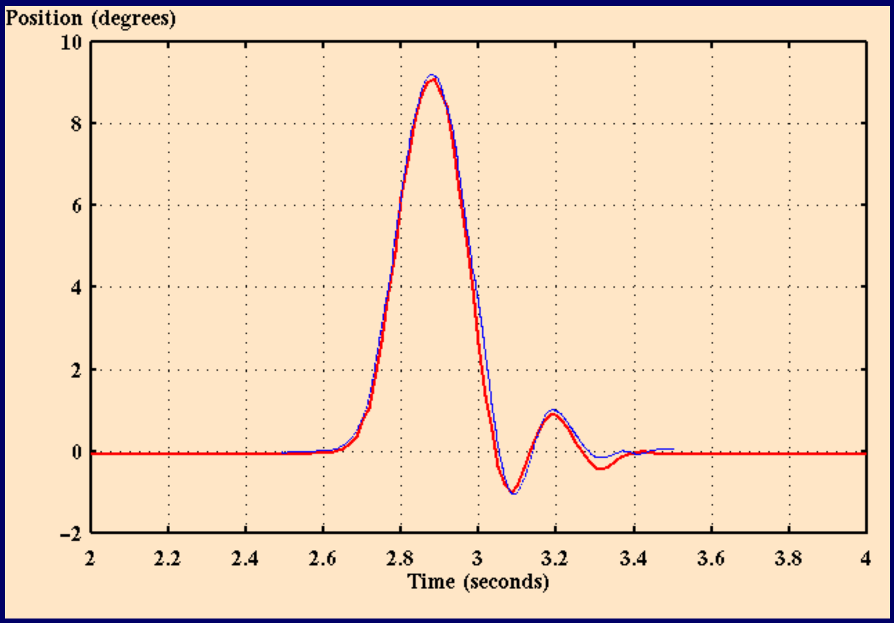
REALFeel® *NG* PERFORMANCE SUMMARY

Example: *REALFeel®* *NG* 4000X

Tolerances	- Exceeds FAA and JAA Level D fixed & rotary wing (Static and Dynamic)
Iteration Rate	- 4000 Hz
System Bandwidth	- > 100 Hz
Backlash	- 0 deg
Velocity (max.)	- 32.2 in/sec
Torque (continuous)	- 1339 in-lb
Torque (max. peak)	- 5195 in-lb
Force (max.)	- 2095 lbs

REALFeel® NG PERFORMANCE EXAMPLES





- DC9 Static Plot
- DC9 Dynamic Plot

MOOG FCS Q-LINE CONTROL LOADING SYSTEM

- **Q-LINE**
  - **Direct-drive, high fidelity performance**
  - **The Q-line actuators are based on high torque motors in a direct-drive setup, capable of generating an output torque of up to 200Nm continuously**
  - **They are designed for primary controls with high fidelity requirements in applications related to high fidelity control force simulation for aerospace simulation**

MOOG-FCS Q-LINE PERFORMANCE SPECIFICATION

Model	Q100	Q150	Q200
Cont. Output Torque	100 Nm (885 lb in)	150 Nm (1325 lb in)	200 Nm (1770 lb in)
Output Torque < 30 sec	120 Nm (1050 lb in)	175 Nm (1550 lb in)	250 Nm (2210 lb in)
Output Torque Peak < 1 sec	240 Nm (2125 lb in)	300 Nm (2650 lb in)	350 Nm (3100 lb in)
Output Stroke	+/- 45°	+/- 45°	+/- 45°
Max. Velocity (1x 208-230 VAC)	600°/s	590°/s	500°/s
Weight	28 kg	37 kg	42 kg
Dimensions of Motor	341x332x223 (LxWxH)	341x332x248 (LxWxH)	341x332x273 (LxWxH)
Max. Power Consumption	1000 Watt	1150 Watt	1500 Watt
Average Power Consumption	250 Watt	300 Watt	350 Watt
CE Approved	Yes	Yes	Yes

MOOG FCS L-LINE CONTROL LOADING SYSTEM

- L-LINE
  - Compact, high force performance
  - The L-line actuators are compact motor-ballscrew combinations capable of generating an output force of up to 2,400 N continuously
  - Their primary use is for heavily loaded primary controls control force simulation for aerospace simulation

MOOG-FCS L-LINE PERFORMANCE SPECIFICATION

Model	L-Line
Stroke Length	127 mm (5.0 in)
Lubrication	Oil Lubrication-Lifetime Lubrication
Finish	Paint Flat Black
Position Feedback	Encoder (Absolute)
Static Design Load	4.0 Kn (900 LBF)
Weight	13 kg
CE Approved	Yes
Actuator Continuous Force Capability	2.2 Kn (500 LBF)
Actuator Peak Velocity Set by Controller	609 mm/s (24 in/sec)
Actuator Screw Lead	20 mm/rev
Total Actuator Inertia	.006 in-lb-s^2 (Rotor, Screw, Interface of Bearings, Nute, Keyways)
Actuator Design Life	Dynamic Load Rating of Screw - 19.5 Kn

WITTENSTEIN SIDESTICK CONTROL LOADING SYSTEM

- Sidestick
  - Re-Configurable Active 2-Axis Sidestick that provides programmable feel characteristics using force feedback.
  - It's high performance and programmability make it suitable for both reconfigurable and high fidelity controllers.

WITTENSTEIN SIDESTICK PERFORMANCE SPECIFICATION

- Travel
  - +/- 18 Degrees in each axis
- Force
  - Continuous torque - 24 NM (212 lb.in)
  - Peak torque – 64 NM (510 lb.in)
- Equivalent Force at 6.4 inches pivot radius
  - 156 N (33 lb.) Continuous
  - 404 N (80 lb.) Peak
- Size
  - 10.67 in x 4.18 in x 4.88 in (H,W,D)

WITTENSTEIN STEERING WHEEL CONTROL LOADING SYSTEM

- Steering Wheel
  - A full range of Re-Configurable Active Steering Wheels for road vehicle driving simulators provide programmable feel characteristics.
  - Their high performance and programmability make them suitable for re-configurable controllers

WITTENSTEIN STEERING WHEEL PERFORMANCE SPECIFICATION

Motor Option	Level	Torque	Force'
MYTA010 Gear ratio 61.1	Cont.	34 Nm (300 lb.in)	89 N (20lbf)
	Peak	72 Nm (640 lb.in)	189 N (43 1bf)

INSTALLATION & SETUP OF CONTROL LOADING SYSTEMS

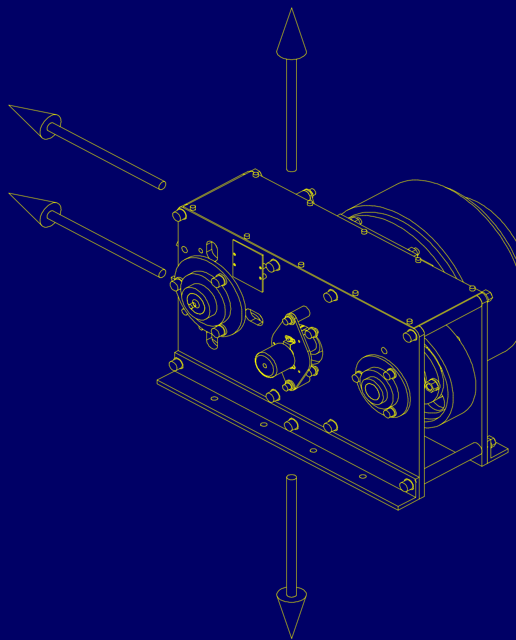
INSTALLATION OPTIONS

- Dimensions:
  - 4000X
    - 19.3L x 11.9H x 15.2W
  - 3000B
    - 15.3L x 9.7H x 13.0W

- 1 Mounting Surface

- 16 Actuating Configurations

- Power Required –
  200W @ 10% duty cycle of rated motor power



FLIGHT SIMULATOR CONTROL LOADING HARDWARE

OPINICUS *REALFeel®* Force Loader Unit (4000X)

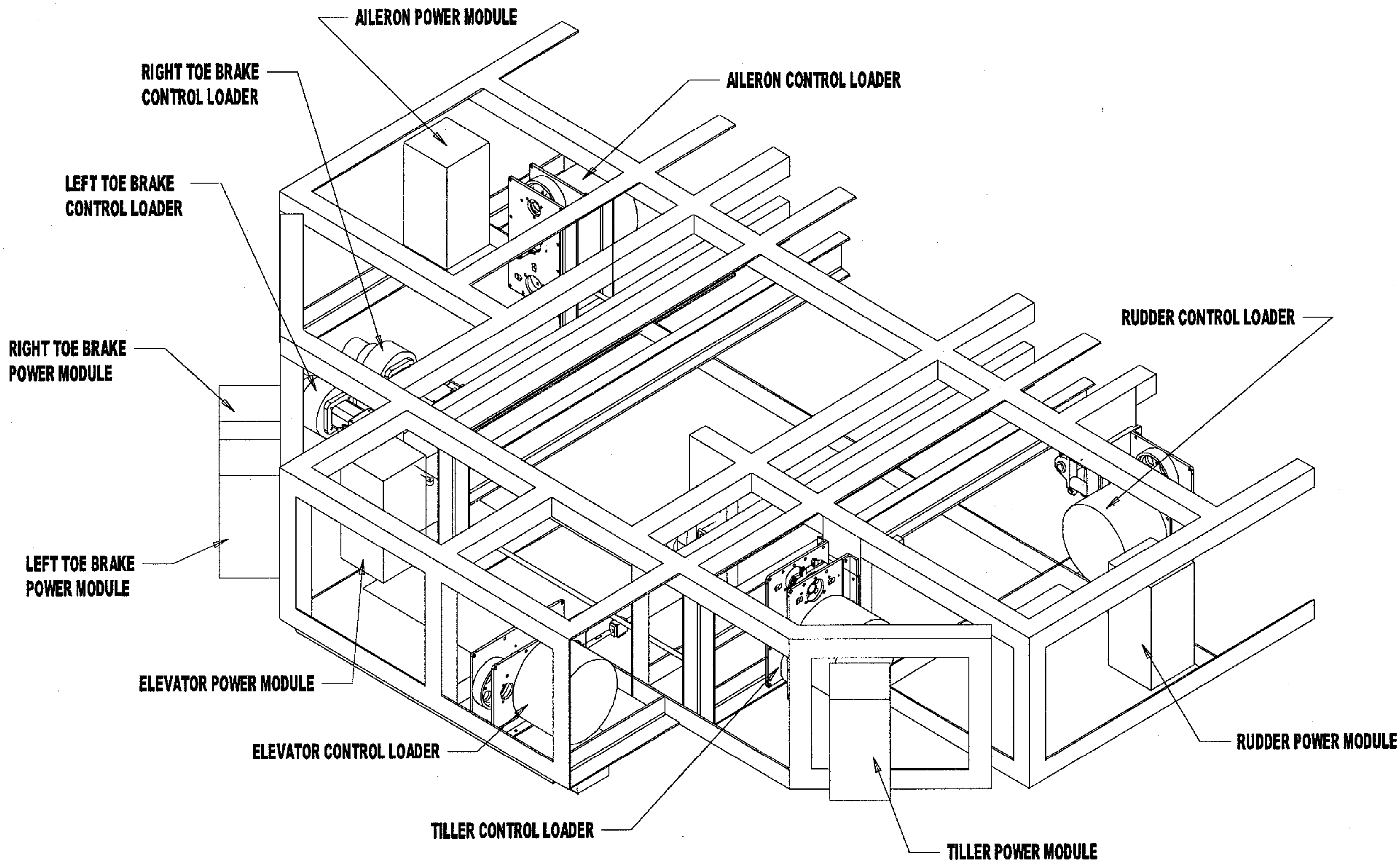
FLIGHT SIMULATOR CONTROL LOADING HARDWARE

Moog FCS *L-Line Q-Line* & *sidestick Box* Loaders

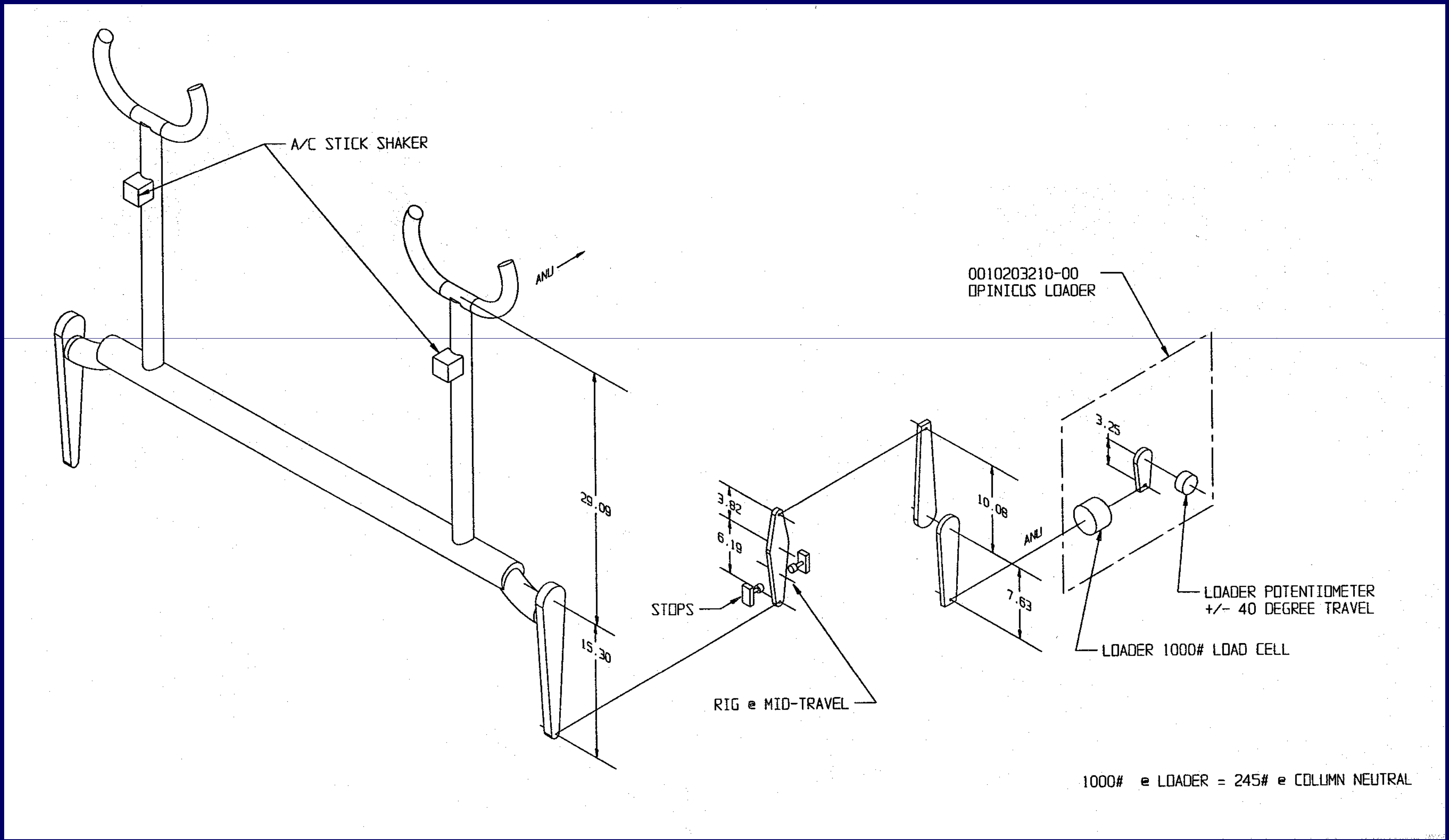
FLIGHT SIMULATOR CONTROL LOADING HARDWARE

Wittenstein *Centerstick, Steering Wheel* & *Sidestick* Loaders

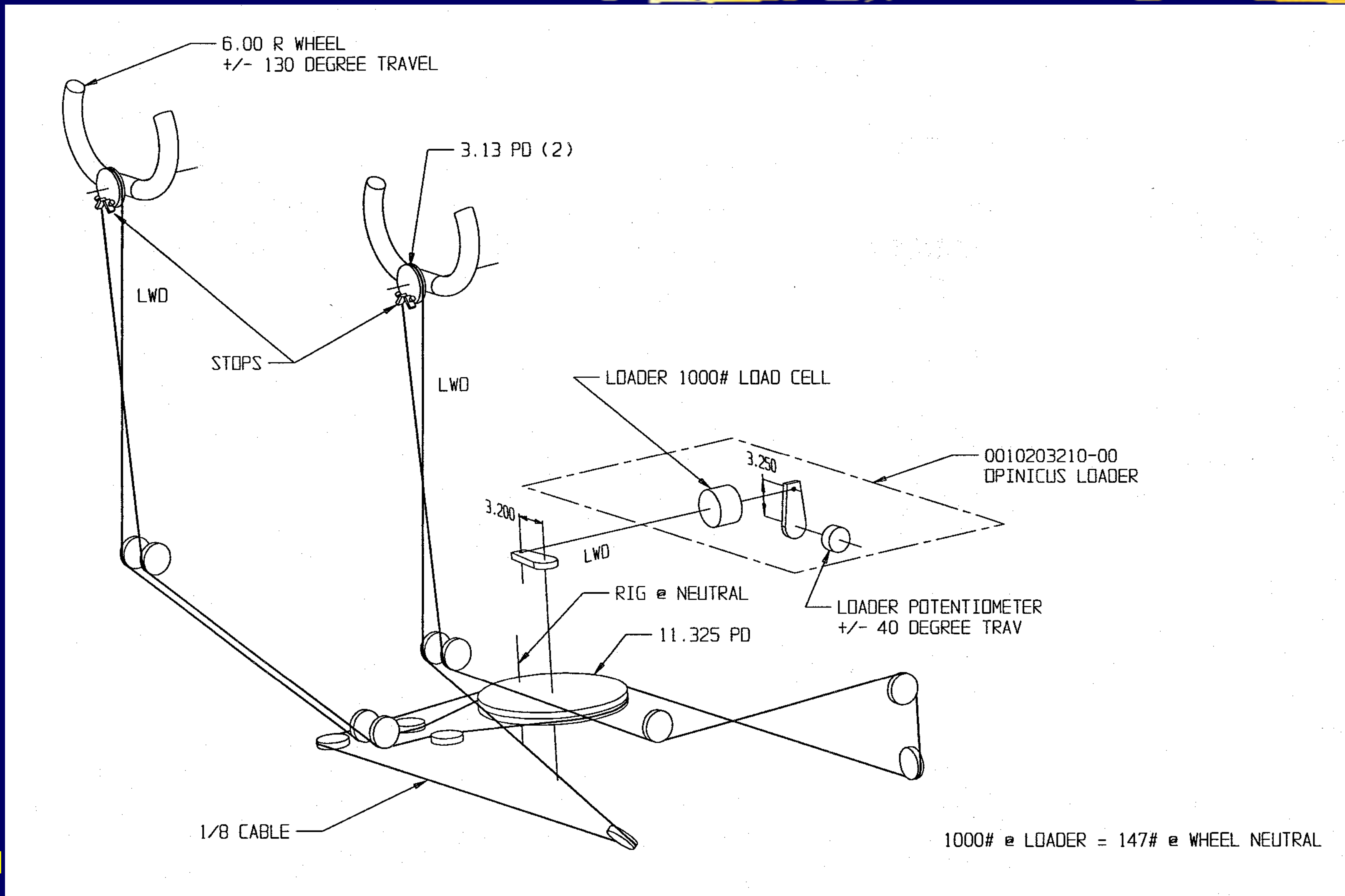
Basic 6 Axis Electrical Installation –
Column, Wheel, Pedals, Tiller, Left Toe Brake, & Right Toe Brake



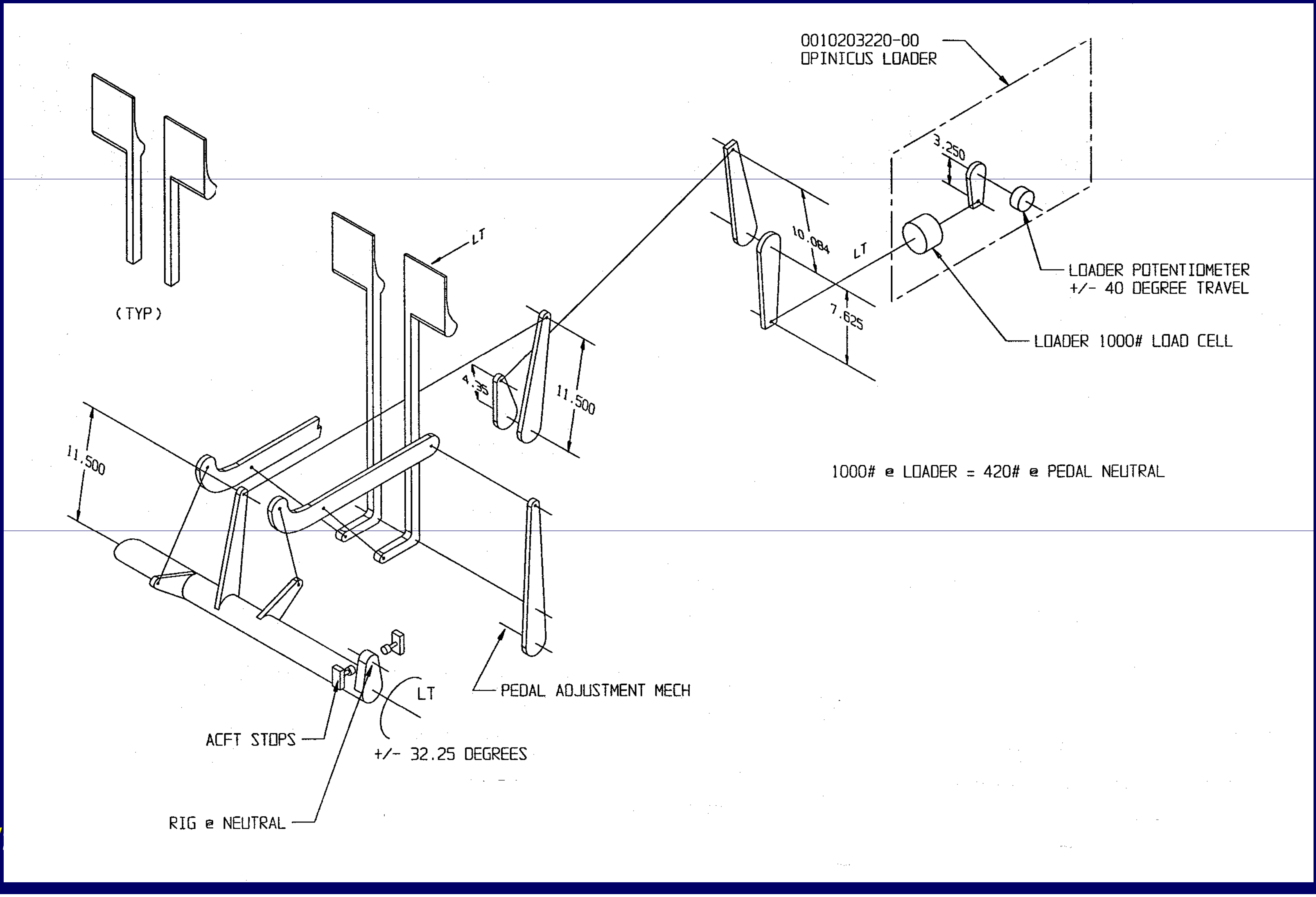
CONTROL vs. LOADER UNITS (Column)



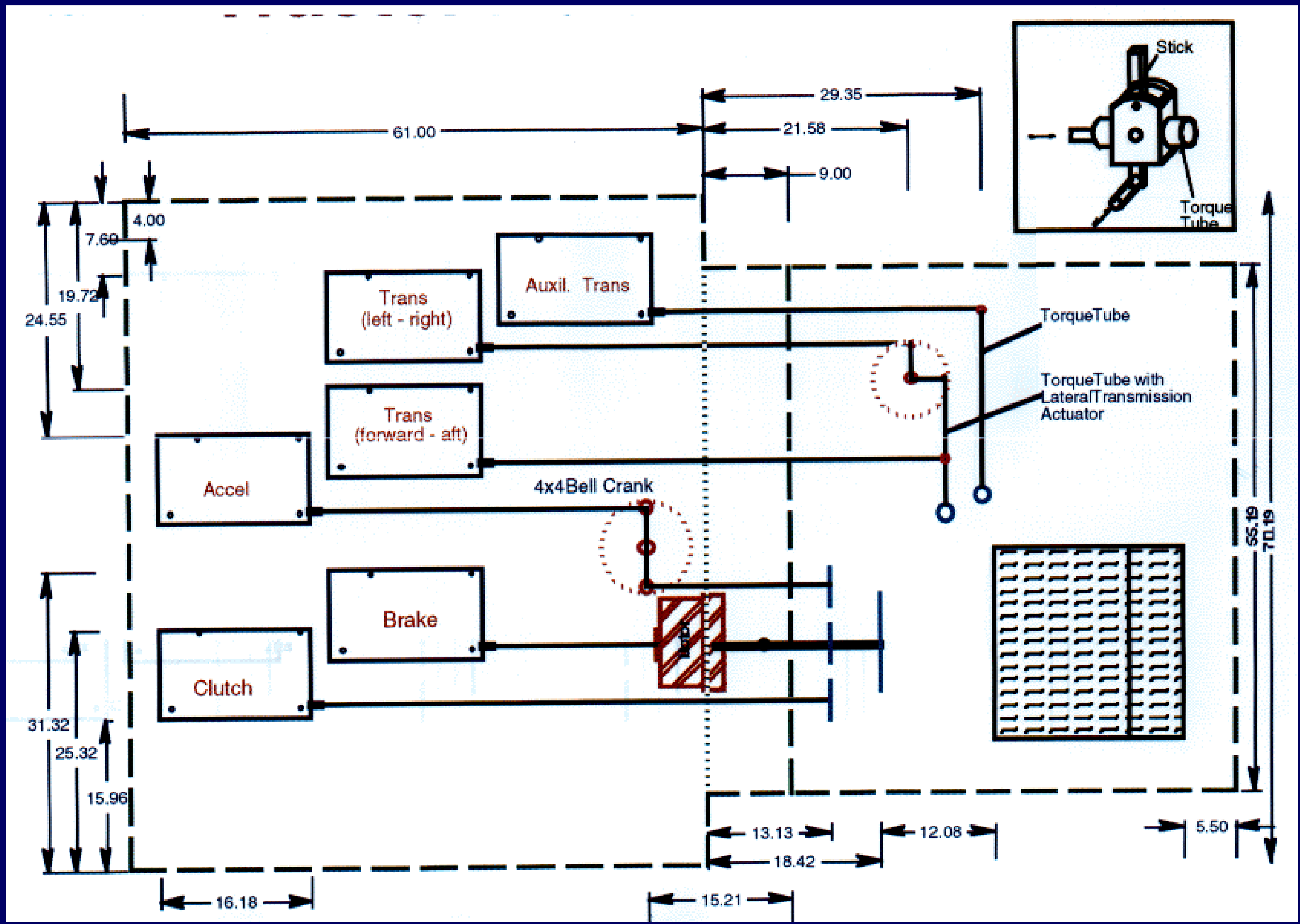
CONTROL vs. LOADER UNITS (Wheel)



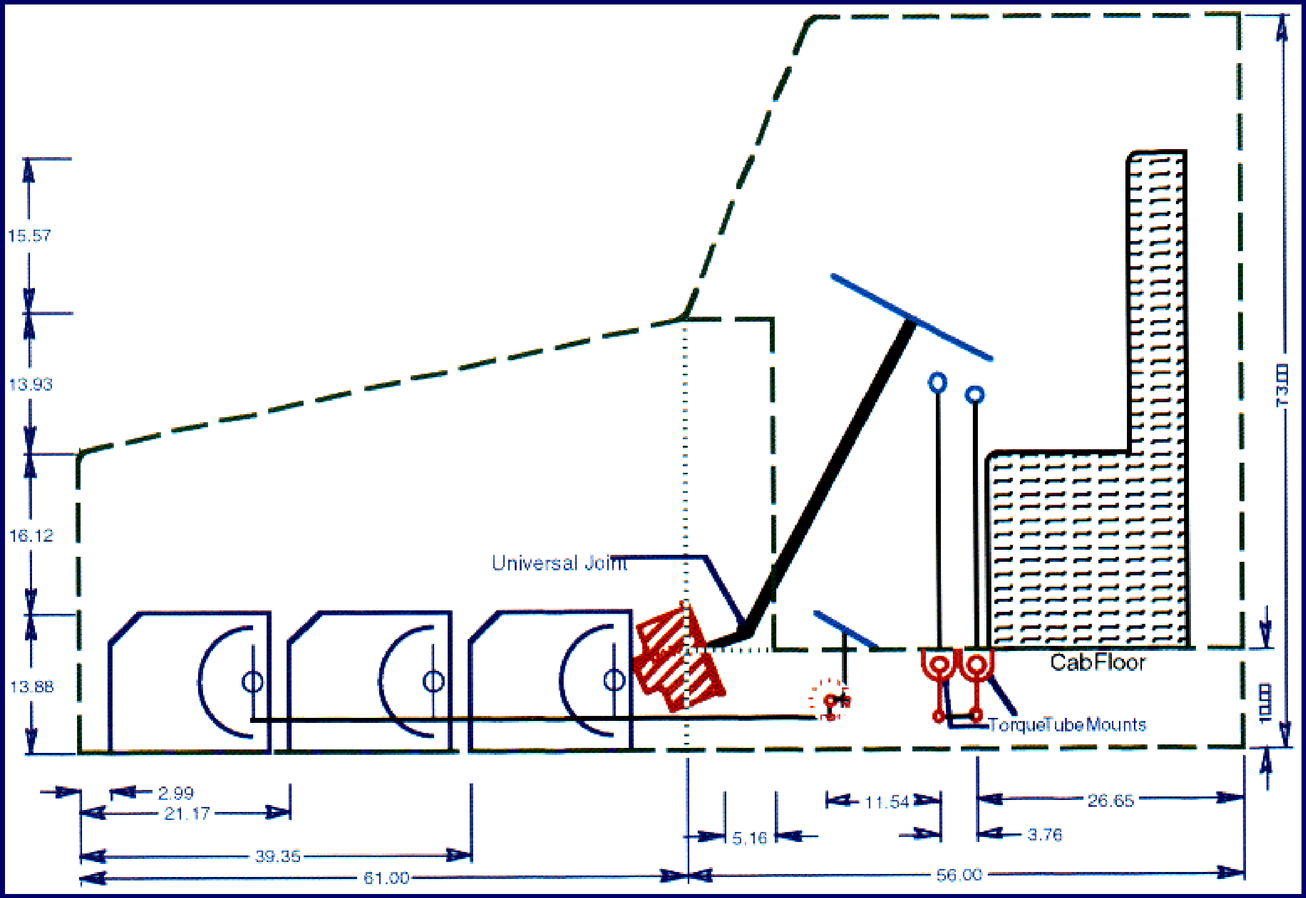
CONTROL vs. LOADER UNITS (Pedal)



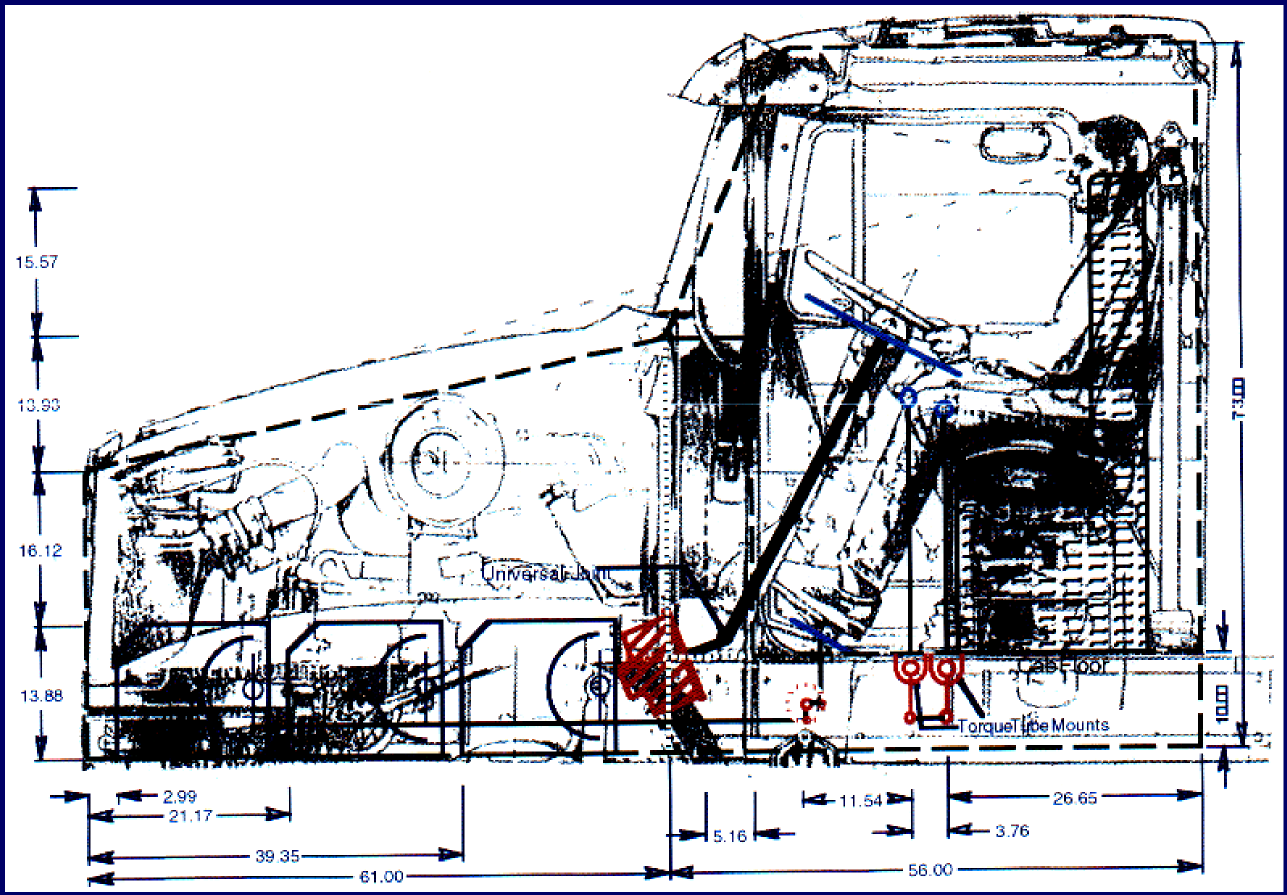
TRACTOR ACTUATOR LAYOUT - TOP VIEW

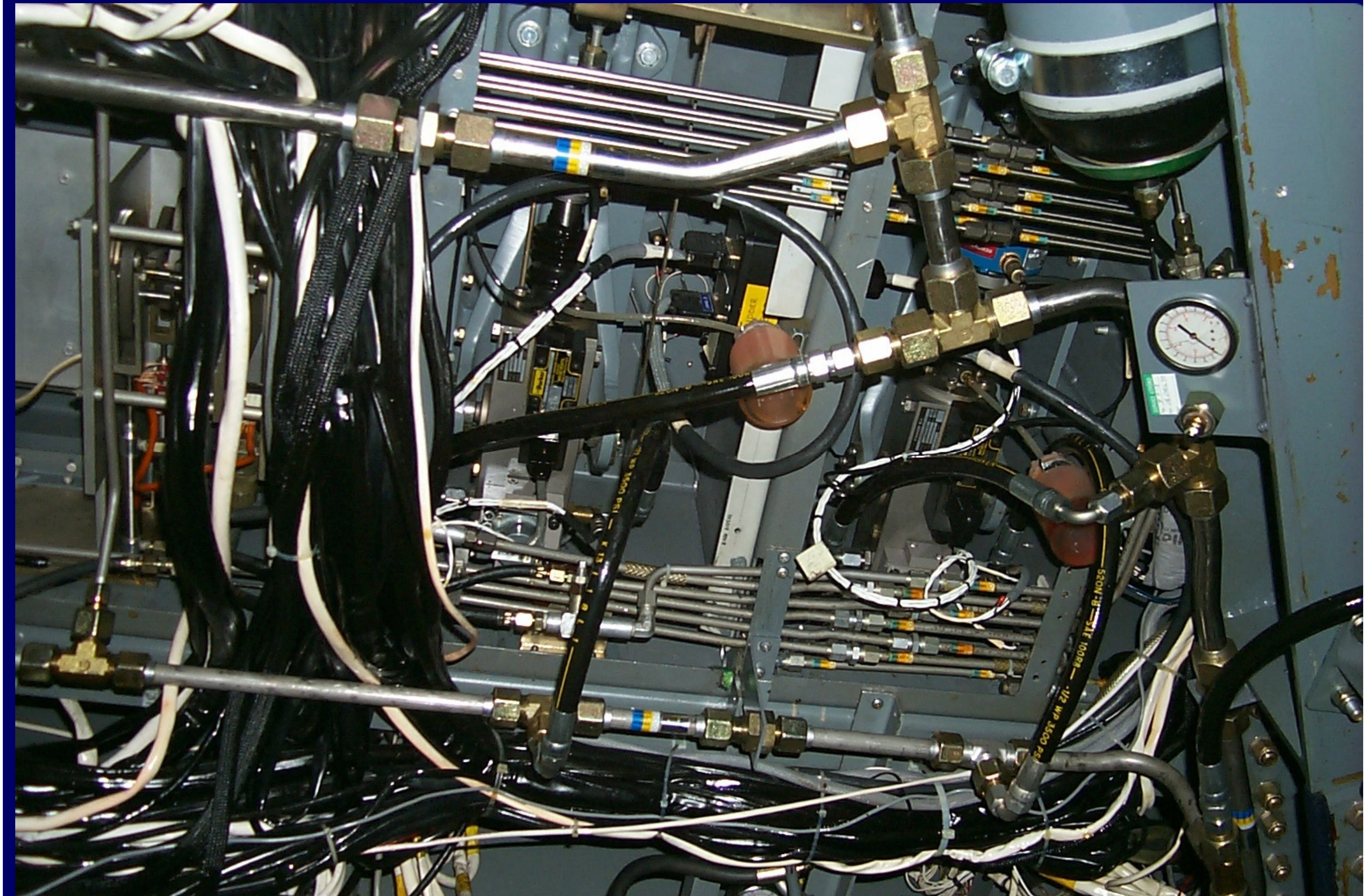


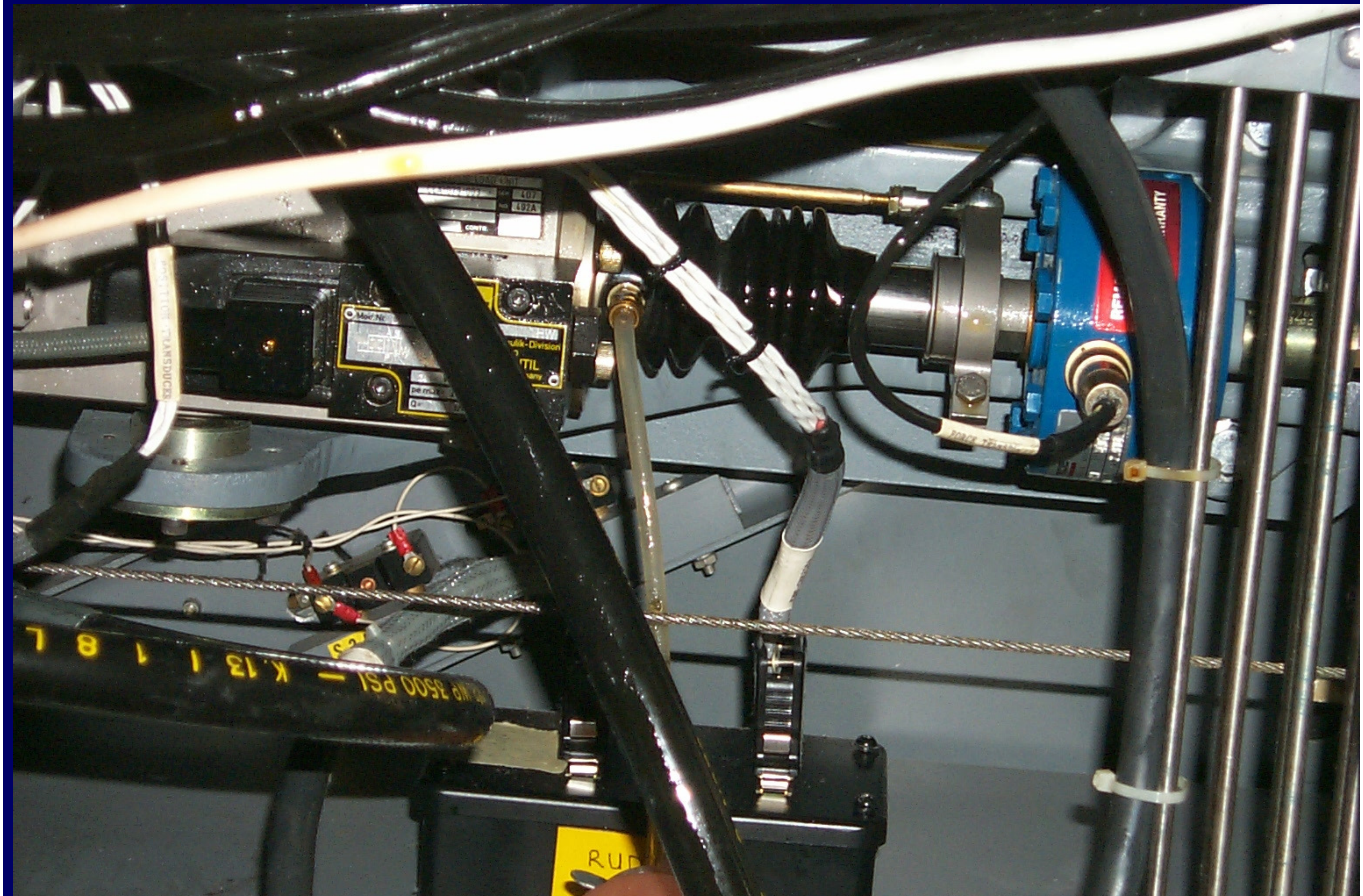
TRACTOR ACTUATOR LAYOUT - SIDE VIEW #1

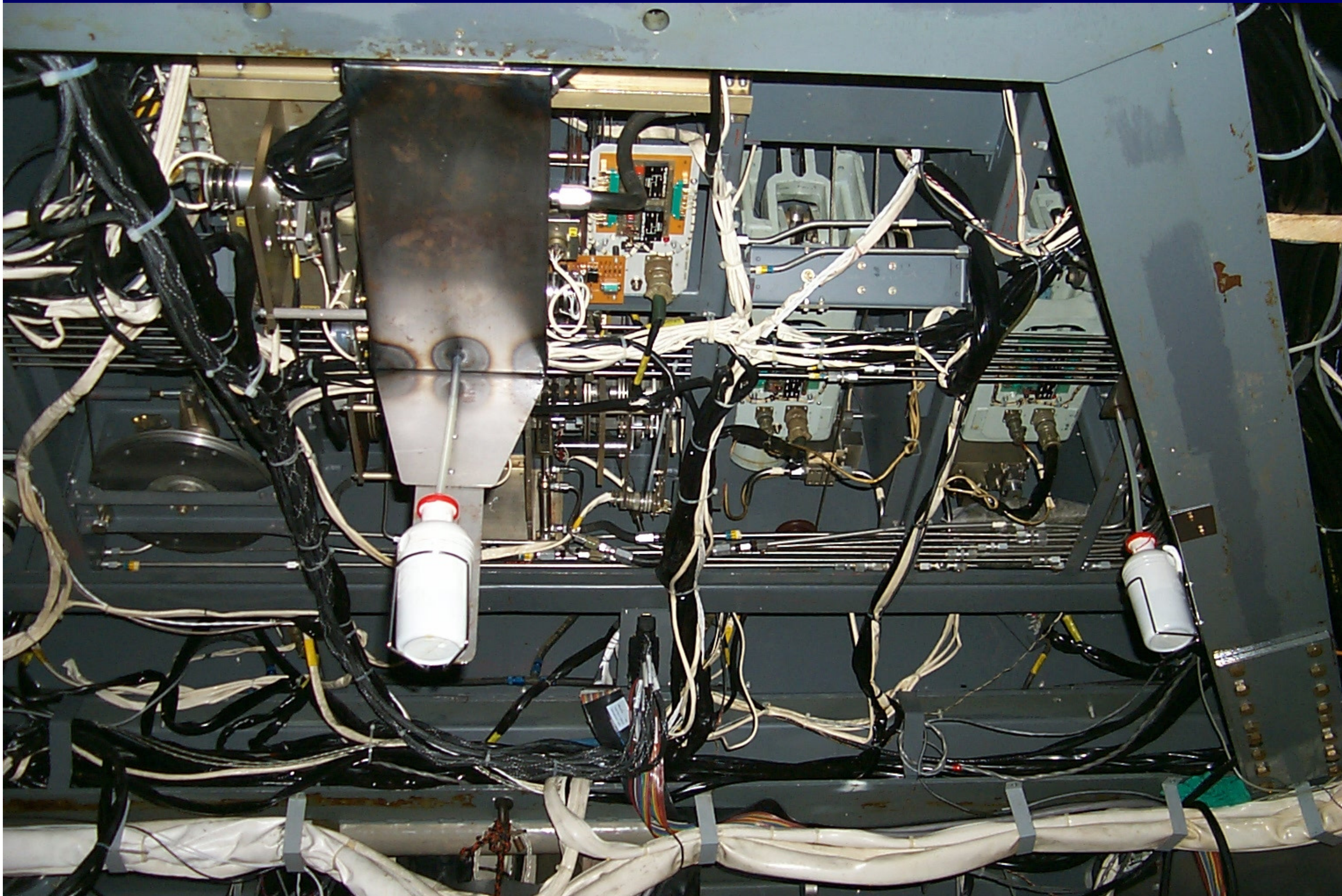


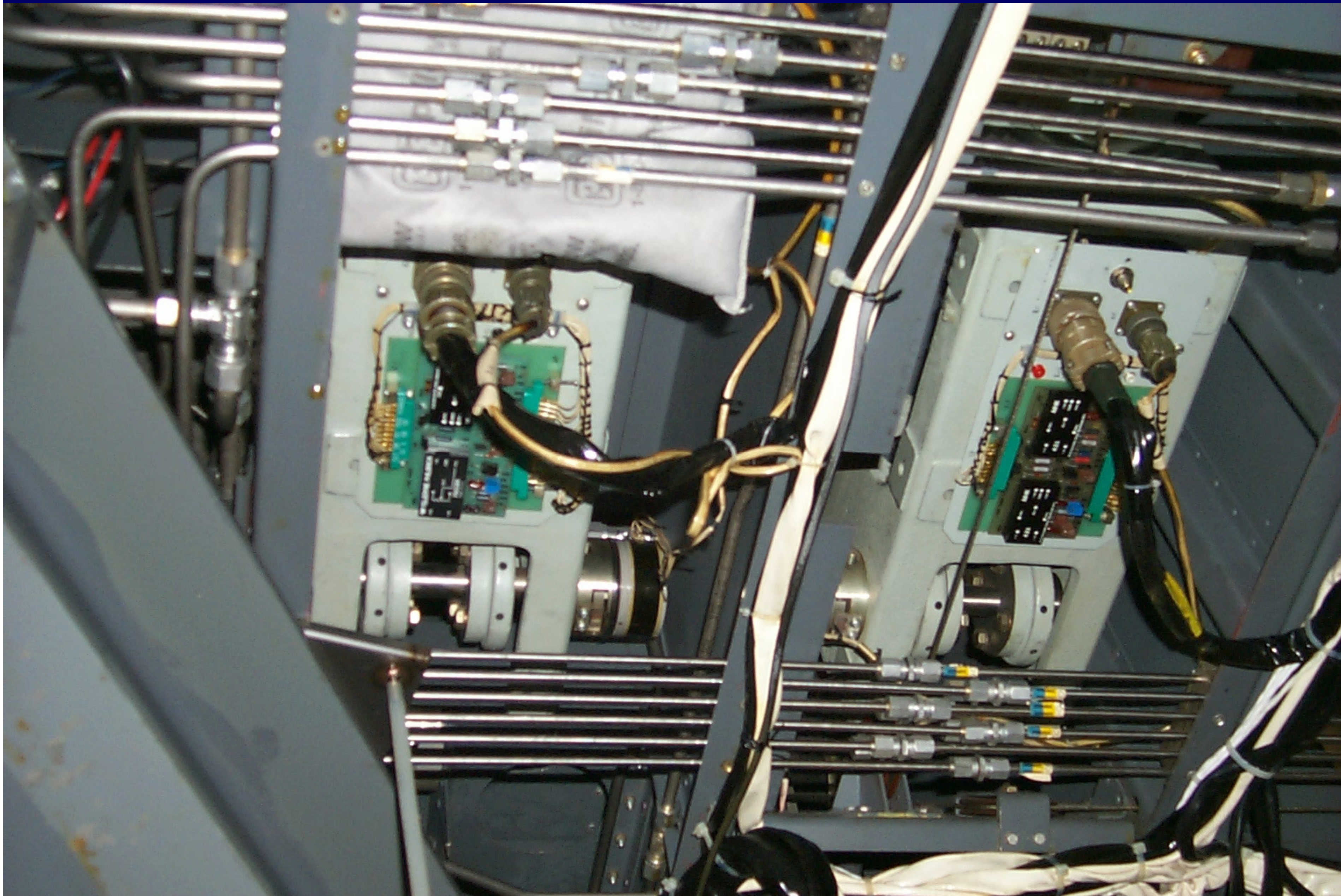
TRACTOR ACTUATOR LAYOUT - SIDE VIEW #2

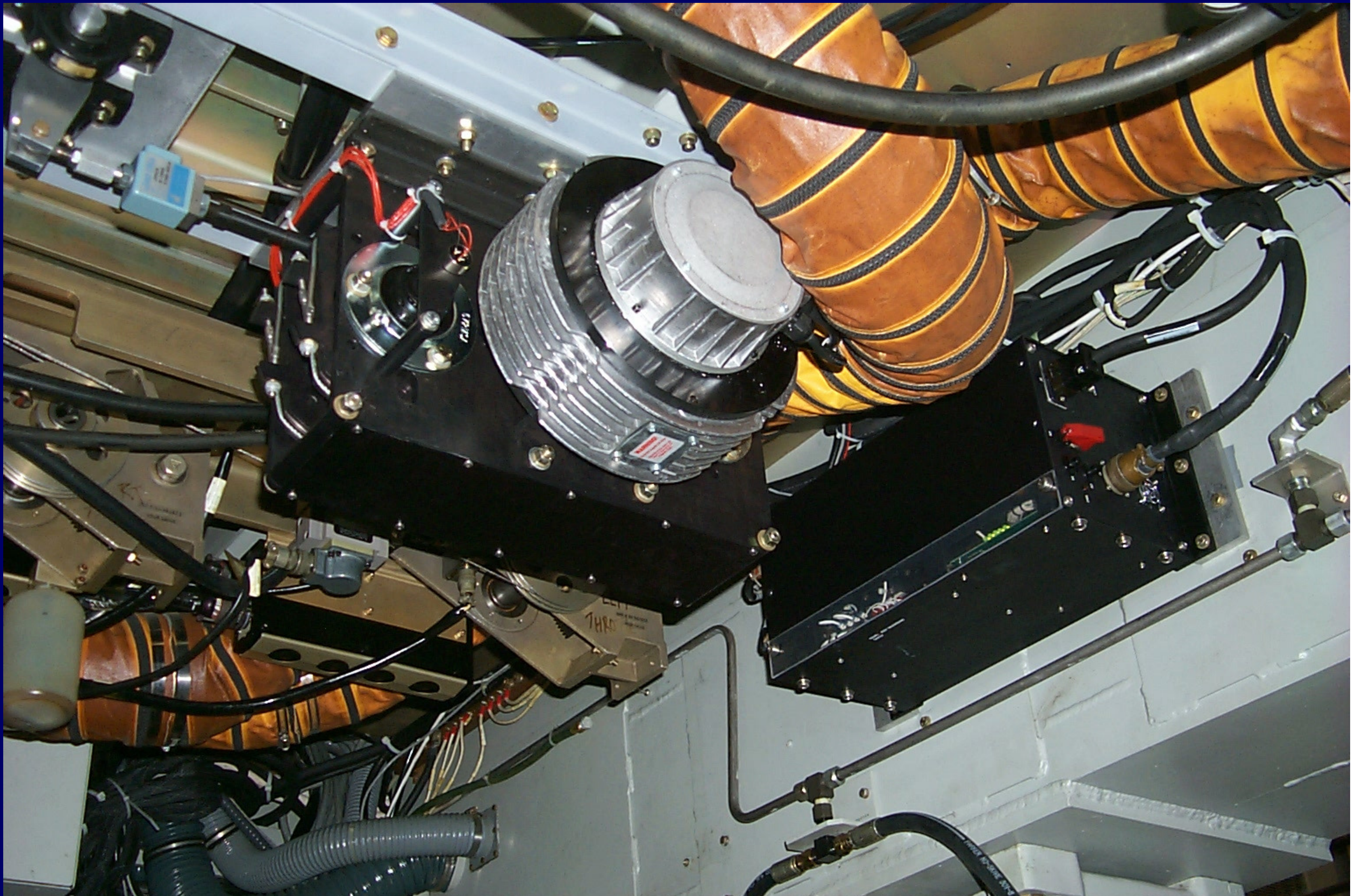


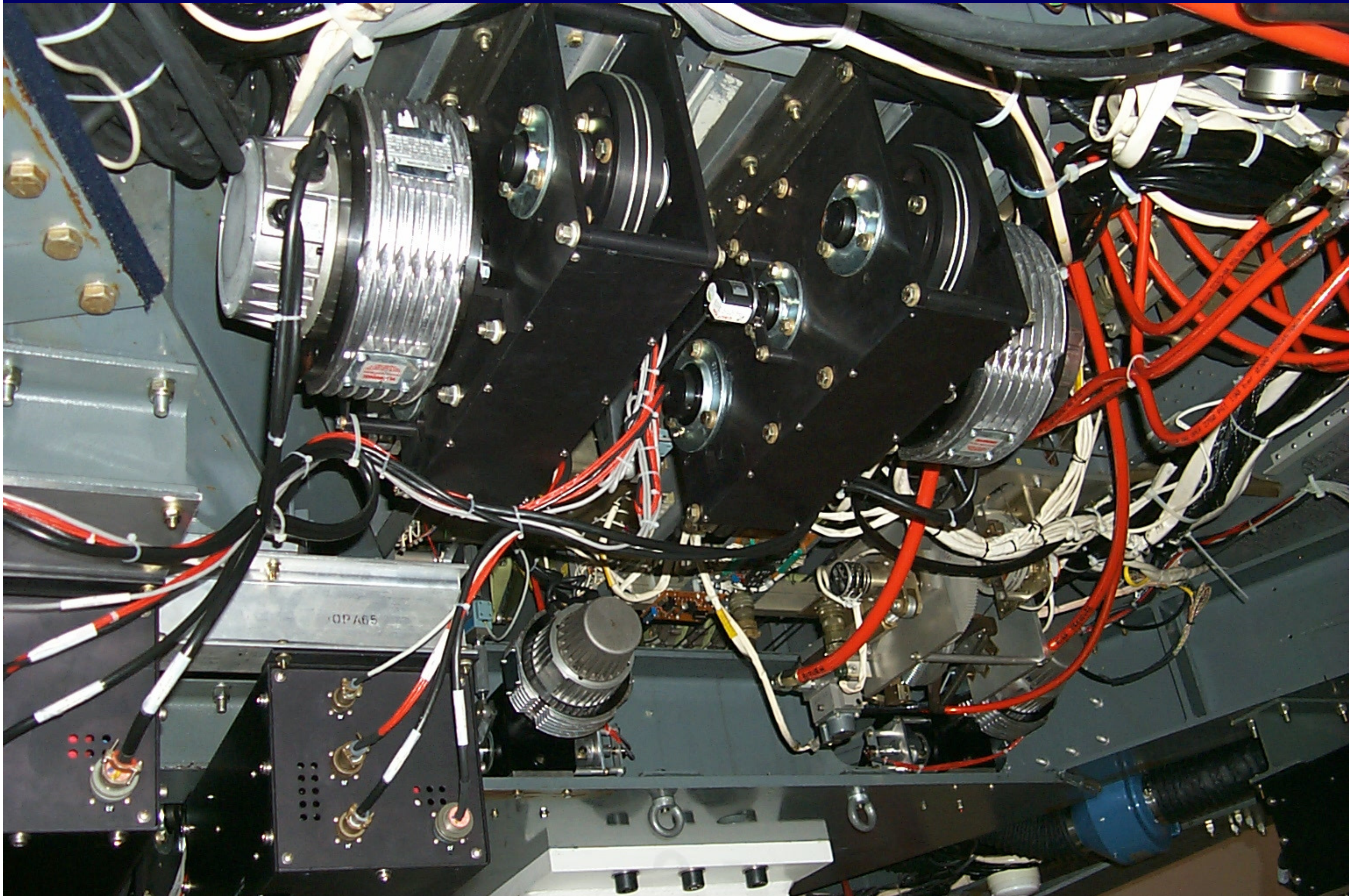


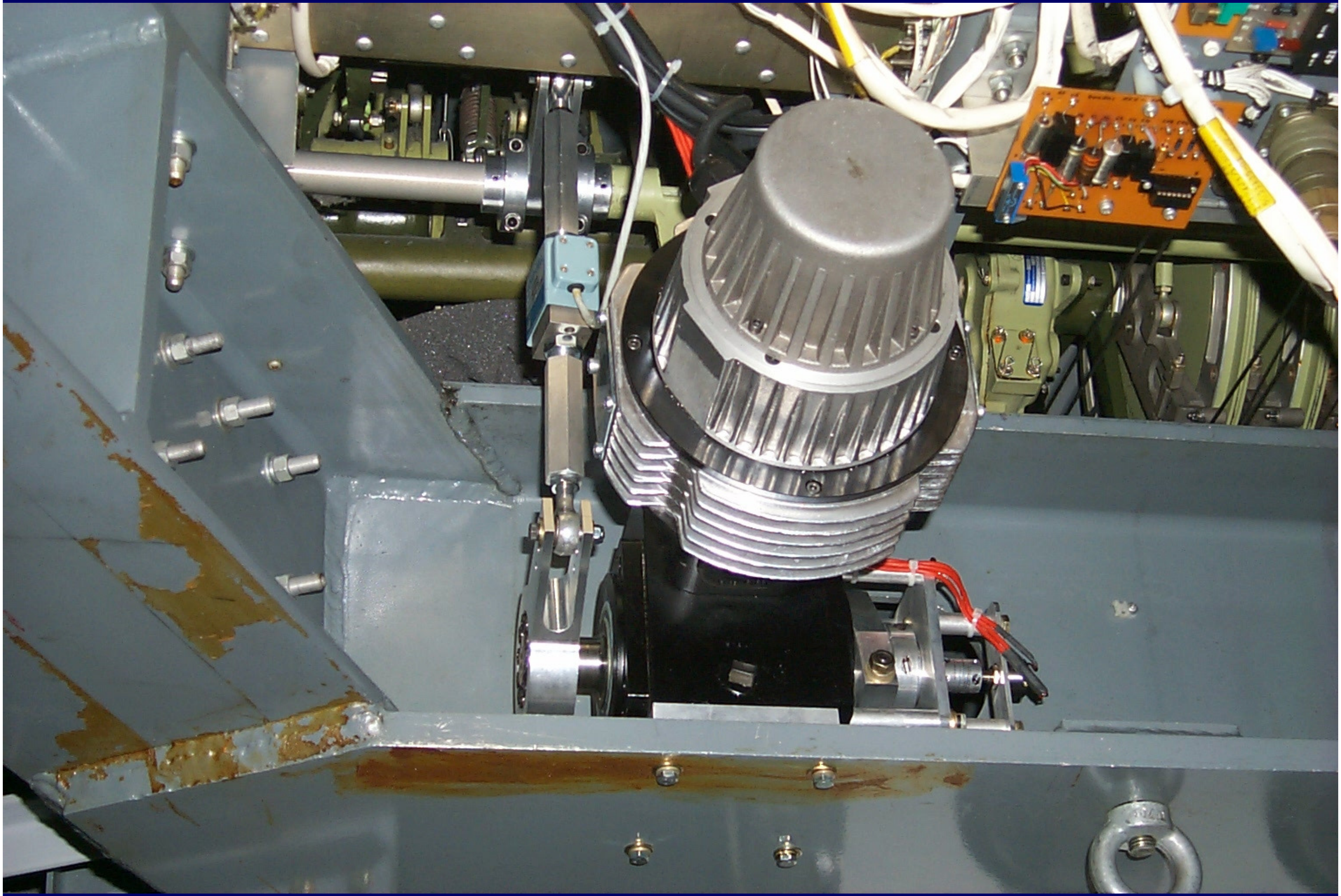

WP 3500 PSI












EH101
OPINICUS

SYSTEM SETUP & PERFORMANCE VERIFICATION

Mechanical Control Loading Setup

- **Rigging:**
  - Rig Pins should be installed and rod-ends adjusted to set up linkage per design requirements
  - All points of rotation should have rig pins
  - System should be mechanically checked and verified for proper hardware alignment, friction levels, linkage stretch and smoothness

SYSTEM SETUP & PERFORMANCE VERIFICATION

Electrical Control Loading Setup

- **Offsets and Scaling:**
  - With Controls in the Neutral position, adjusts any offsets to zero
  - Using an calibrated measurement equipment such as, digital force gauges and laser position sensors, Calibrate scaling for all sensors, such as position and force (or torque). This scales the force, velocity and position seen at the loader, with that seen at the pilots control

SYSTEM SETUP & PERFORMANCE VERIFICATION

Electrical Control Loading Calibration

- Calibration table should include checking and calibrating at various points, taking into account any significant non-linearities created by linkage Kinematics and Stretch
  - Position vs. Position
  - Force vs. Force
  - Position vs. Position vs. Force
  - Force vs. Force. vs. Position

CONTROL LOADING PERFORMANCE VERIFICATION

CONTROL LOADING SYSTEM VERIFICATION

System Test and Verification

Compare Simulator Results with Aircraft Data

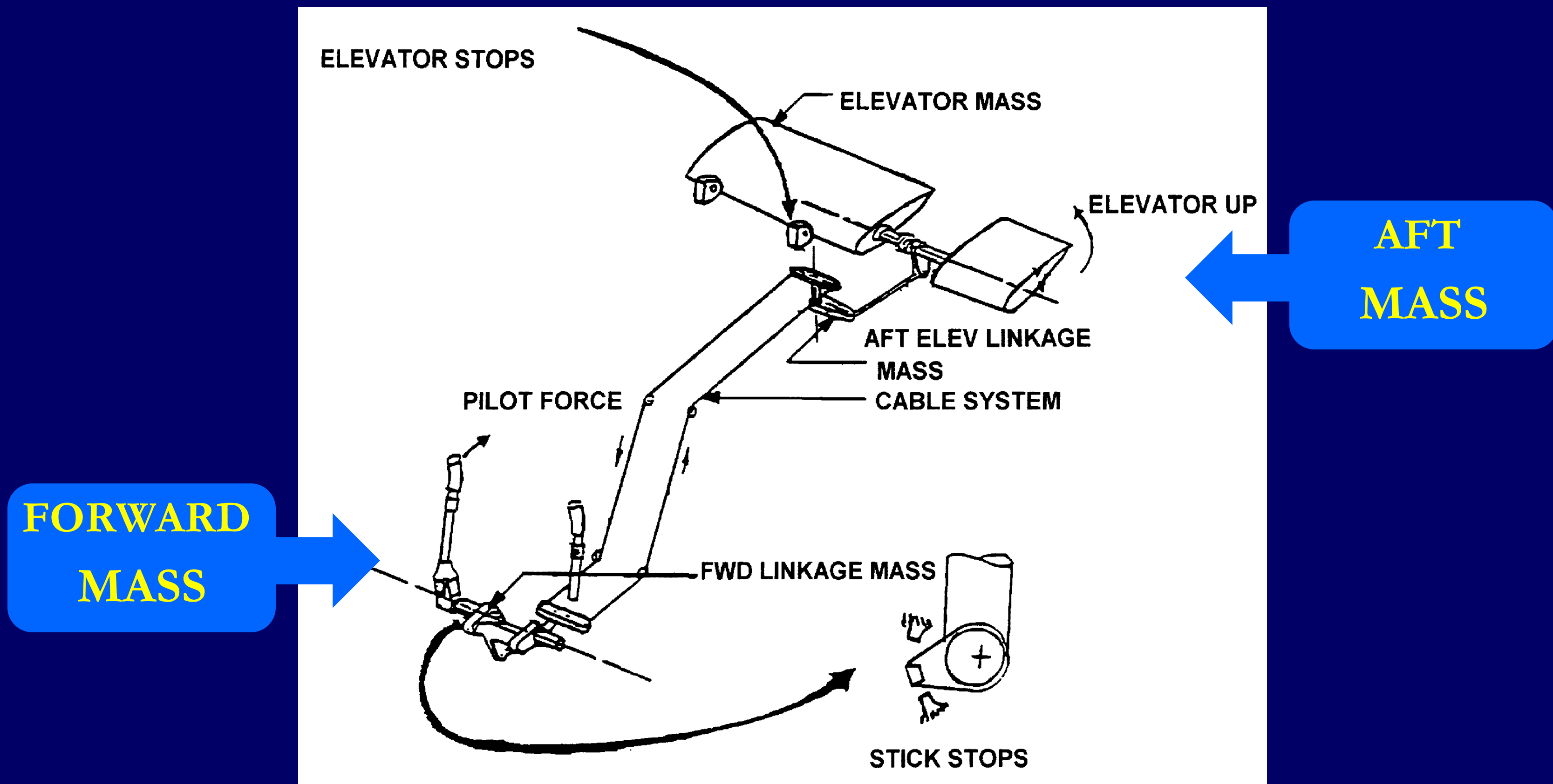
- **On Ground Checks**
  - Static Force Checks
  - Control-to-Surface Calibration
- **In Flight Checks**
  - Change in Control Force with Change in Aircraft Velocity
  - Change in Control Force with Change in Load Factor
  - Control Surface Position with Zero Control Trim
  - Dynamic Response

Fly-By-Wire Control Systems

- **On Ground Checks**
  - Control-to-Surface Calibration
- **In Flight Checks**
  - Closed Loop Response (Computer Controlled Aircraft)
  - Open Loop Response (Natural Aircraft)

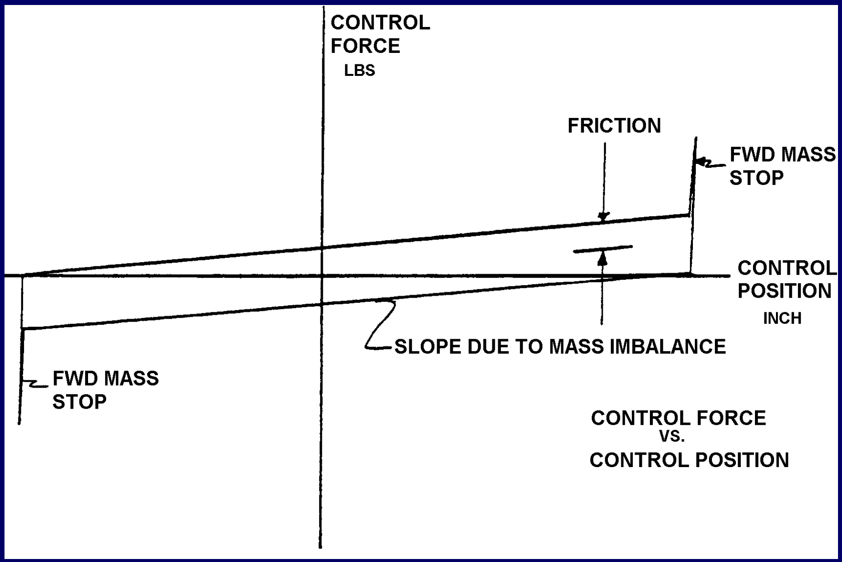
SYSTEM TUNING & PERFORMANCE VERIFICATION

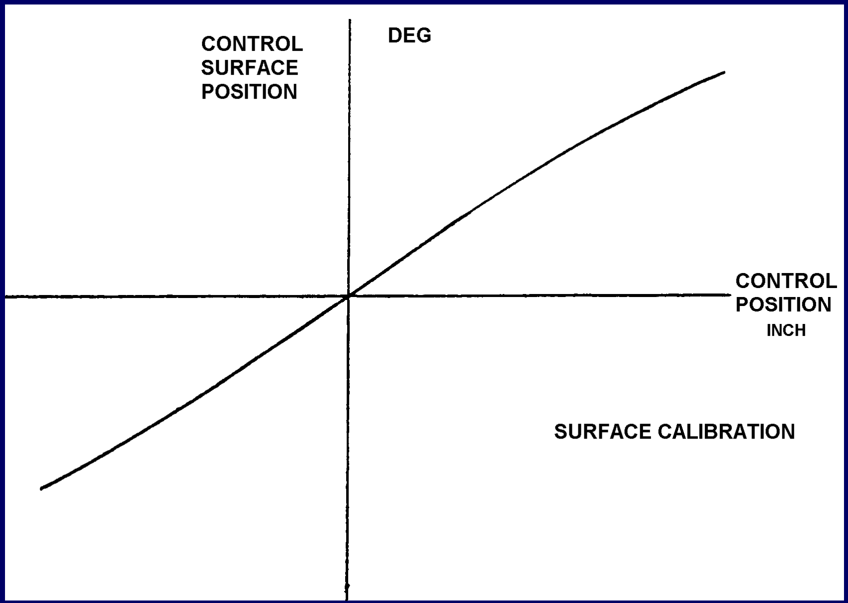
Reversible Pitch Flight Control System - Example



SYSTEM TUNING & PERFORMANCE VERIFICATION

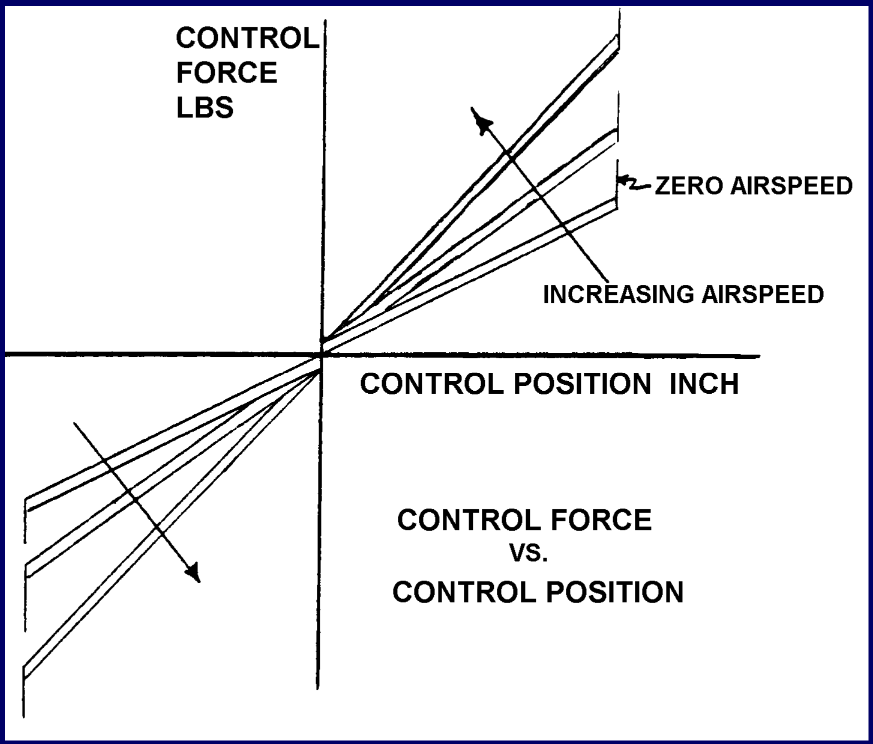
On Ground Flight Control Measurements, Reversible Control System

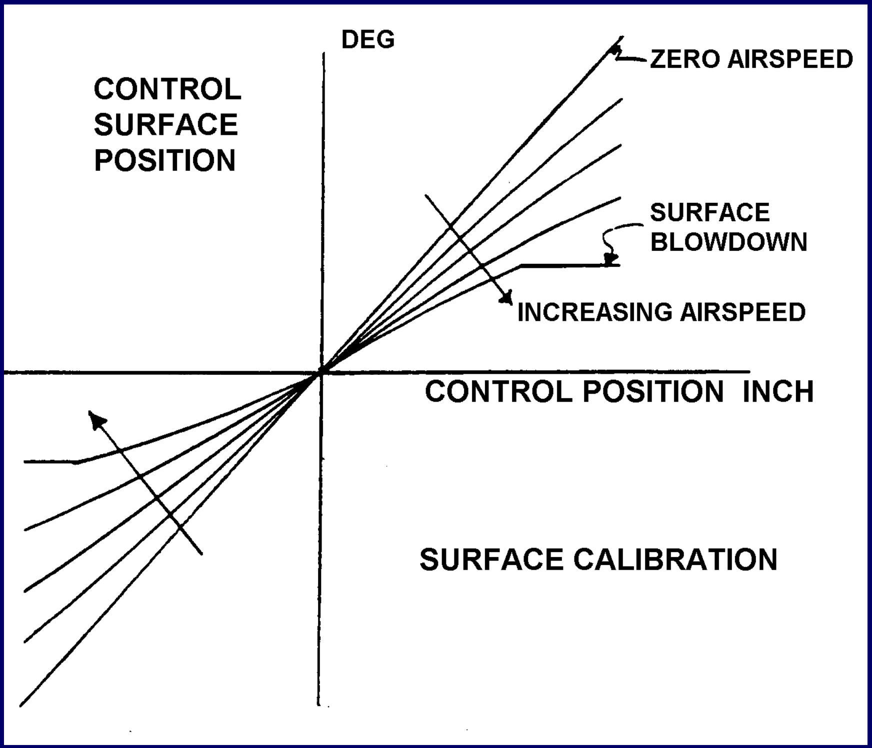




SYSTEM TUNING & PERFORMANCE VERIFICATION

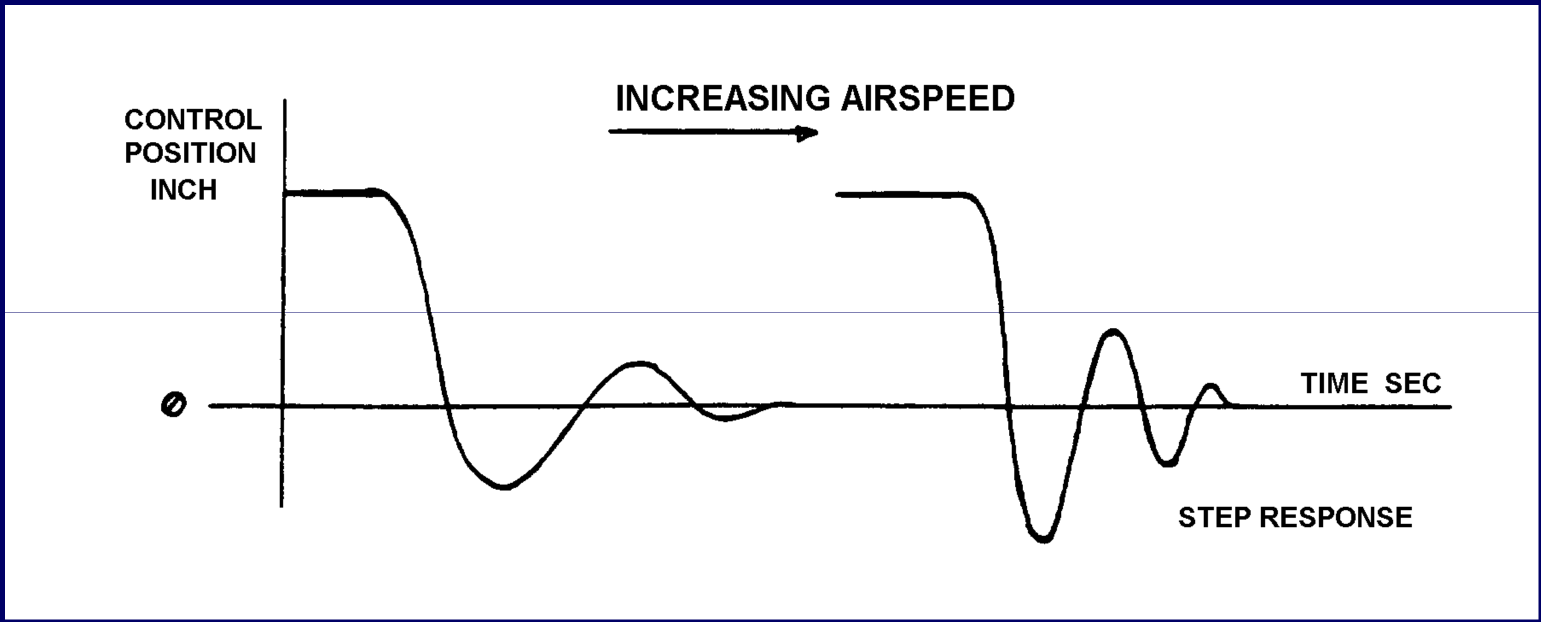
Static Checks





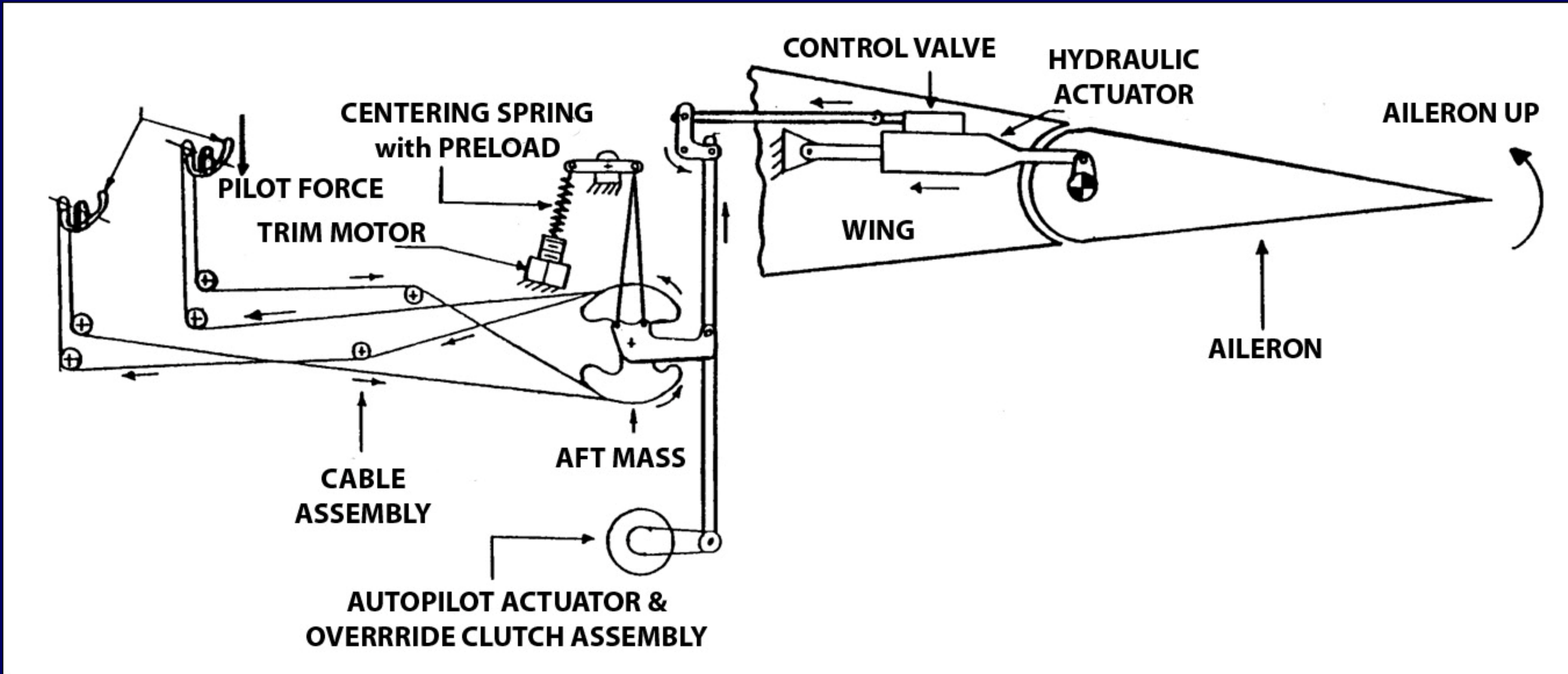
SYSTEM TUNING & PERFORMANCE VERIFICATION

Dynamic Checks



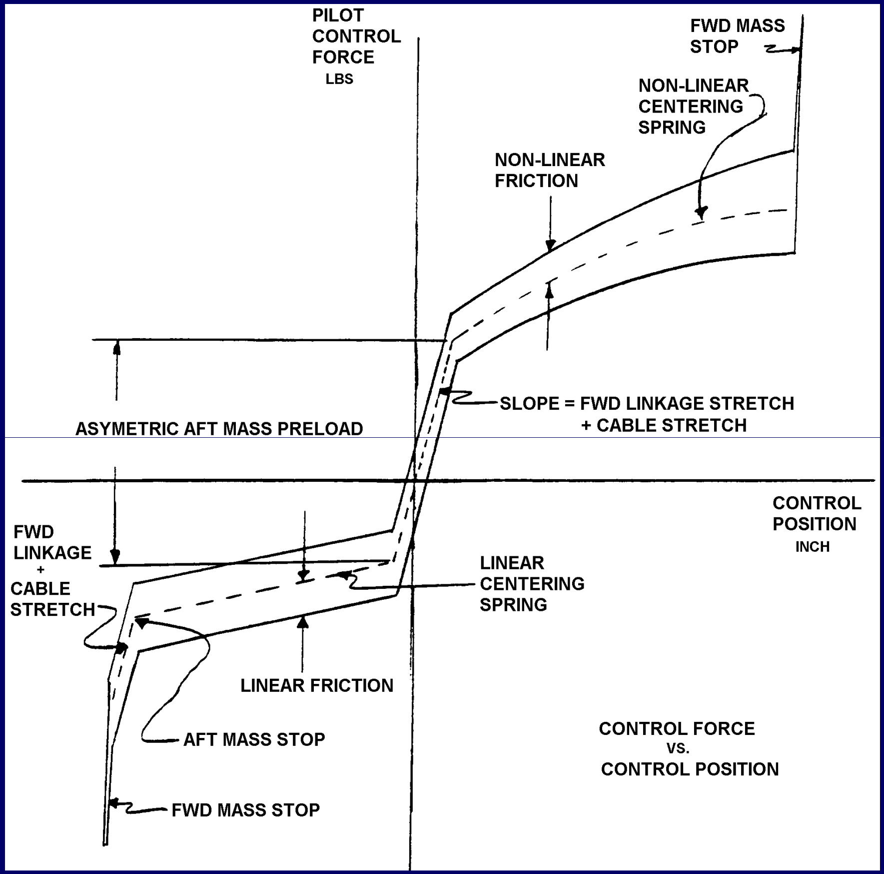
SYSTEM TUNING & PERFORMANCE VERIFICATION

Typical Irreversible Aileron Flight Control Systems



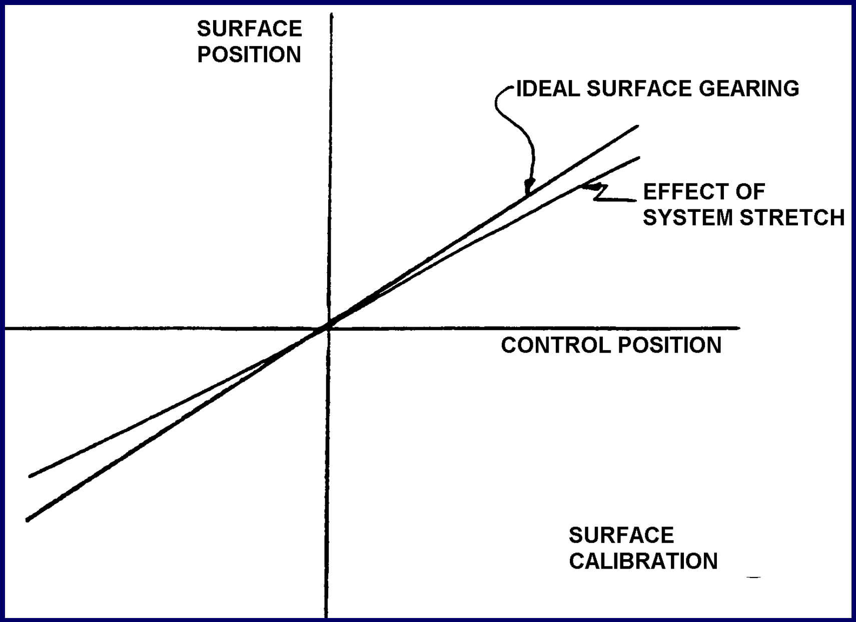
SYSTEM TUNING & PERFORMANCE VERIFICATION

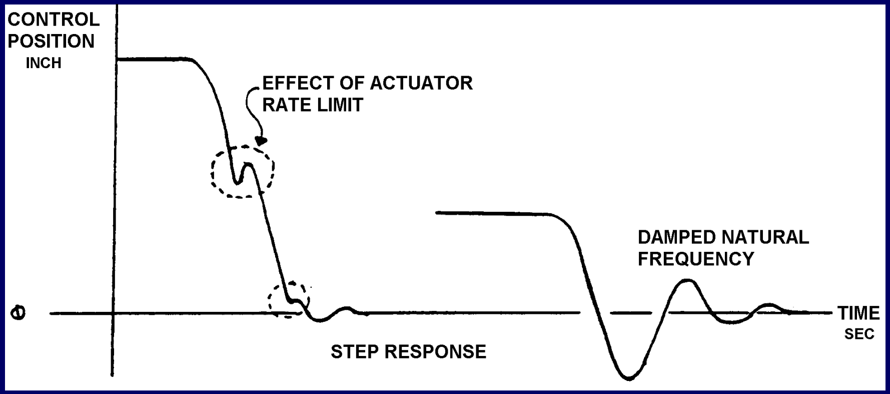
On Ground Flight Control Measurements, Typical Irreversible System



SYSTEM TUNING & PERFORMANCE VERIFICATION

Flight Control Measurements, Typical Irreversible System

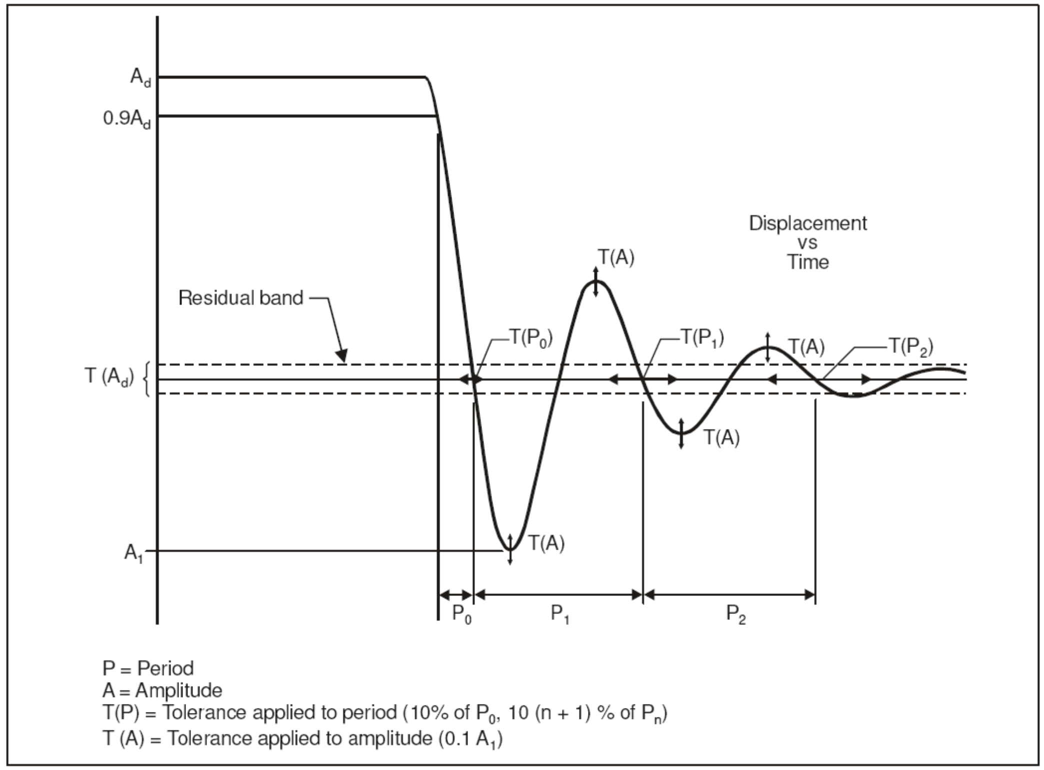




SYSTEM PERFORMANCE VERIFICATION & FSTD QUALIFICATION

Flight Control Dynamics Validation – ICAO 9625

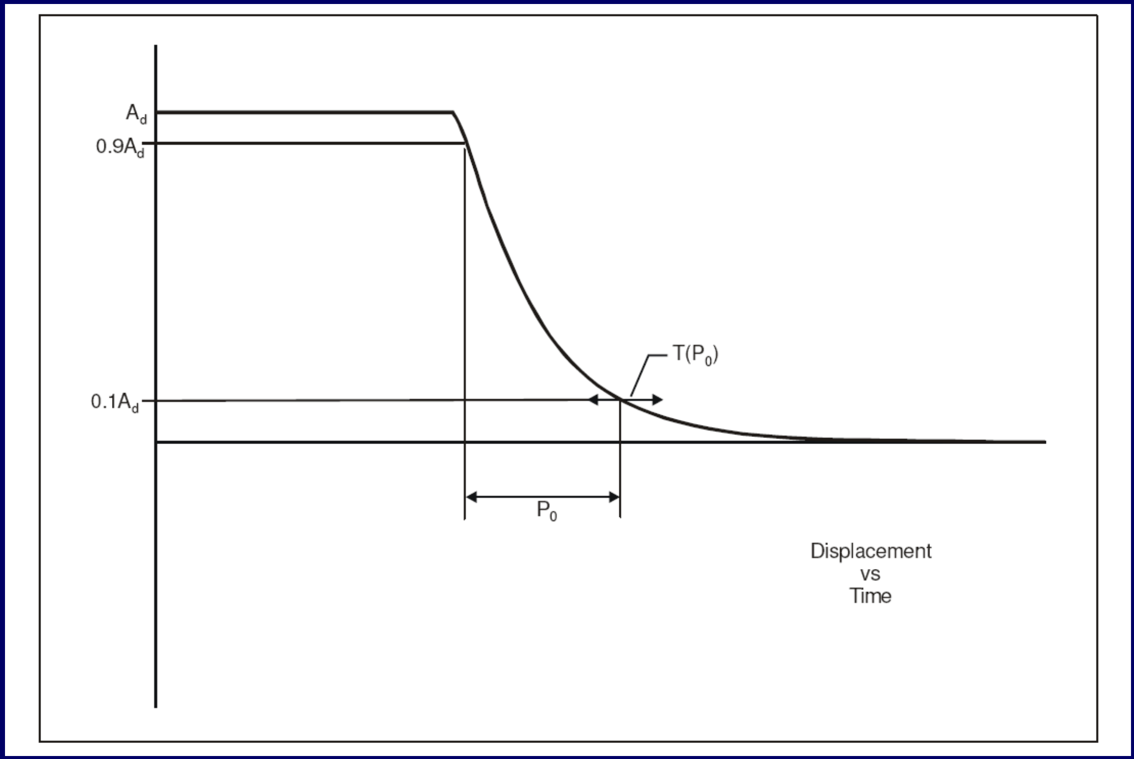
- **Tolerances**
  - $T(P_0)$ ±10 percent of P_0 or ±0.05 sec
  - T(P1) ±20 percent of P_1 or ±0.05 sec
  - T(P2) ±30 percent of P_2 or ±0.05 sec
  - $T(P_n)$ ±10*(n+1) percent of P_n
  - $T(A_n)$ ±10 percent of A_1 or ±0.5 deg
  - $T(A_d)$ ±5 percent of A_d = residual band
  - Significant overshoots = first overshoot and ±1 subsequent overshoots



SYSTEM PERFORMANCE VERIFICATION & FSTD QUALIFICATION

Flight Control Dynamics (Critically Damped) Validation – ICAO 9625

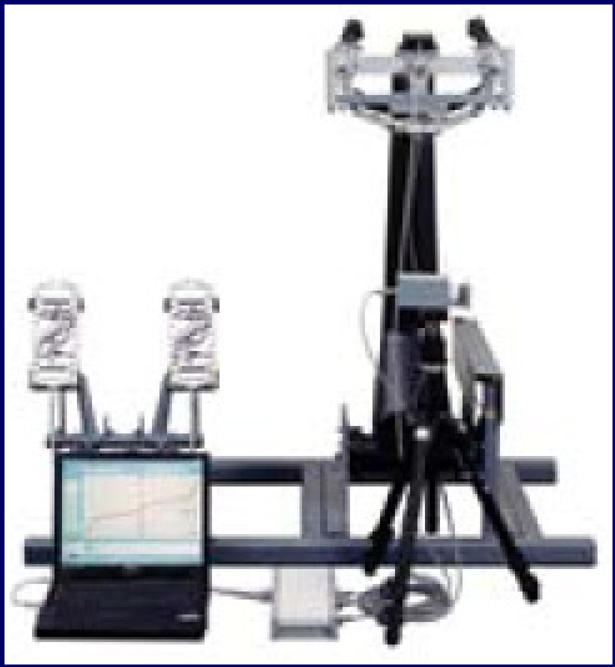
- **Tolerances**
  - $T(P_0)$ ±10 percent of P_0 or ±0.05 sec
  - Significant overshoots = first overshoot and ±1 subsequent overshoots



SYSTEM TUNING & PERFORMANCE VERIFICATION

Control Force Measurements Equipment

- **CFM – Data Collection & Training Device Performance Verification**
  - Facilitates accurate force-position measurements of aircraft flight controls
  - Used for Calibration and verification/validation of the flight control responses in simulators
- **Key Features**
  - High precision force/position measurement
  - Extensive Data Analysis
  - Position/Angle measurement by rate gyro and/or string pot
  - Cross coupling measurement possible
  - Pedal Plates with sensors for measuring heel and toe forces

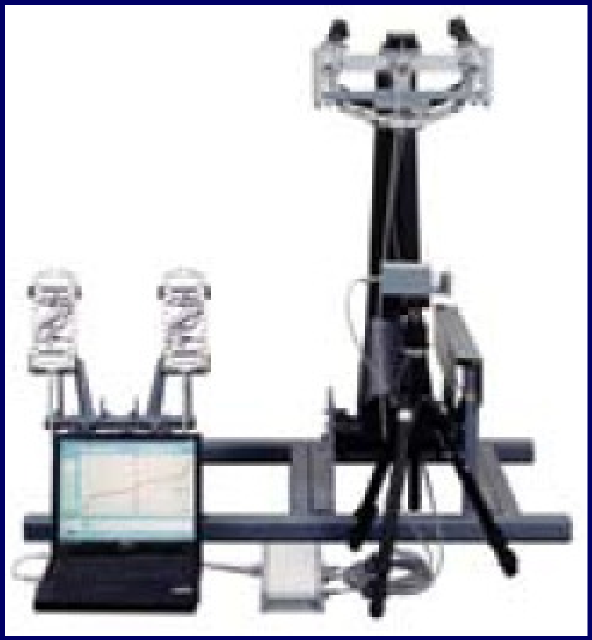


Example: Typical CFM

SYSTEM TUNING & PERFORMANCE VERIFICATION

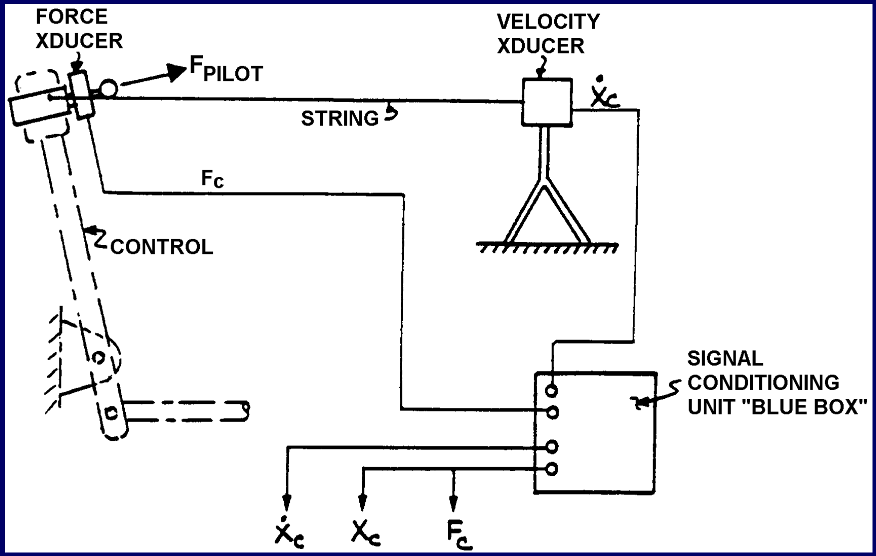
UTILIZING Control Force Measurements Equipment (initial) and/or Automated Test System (recurrent)

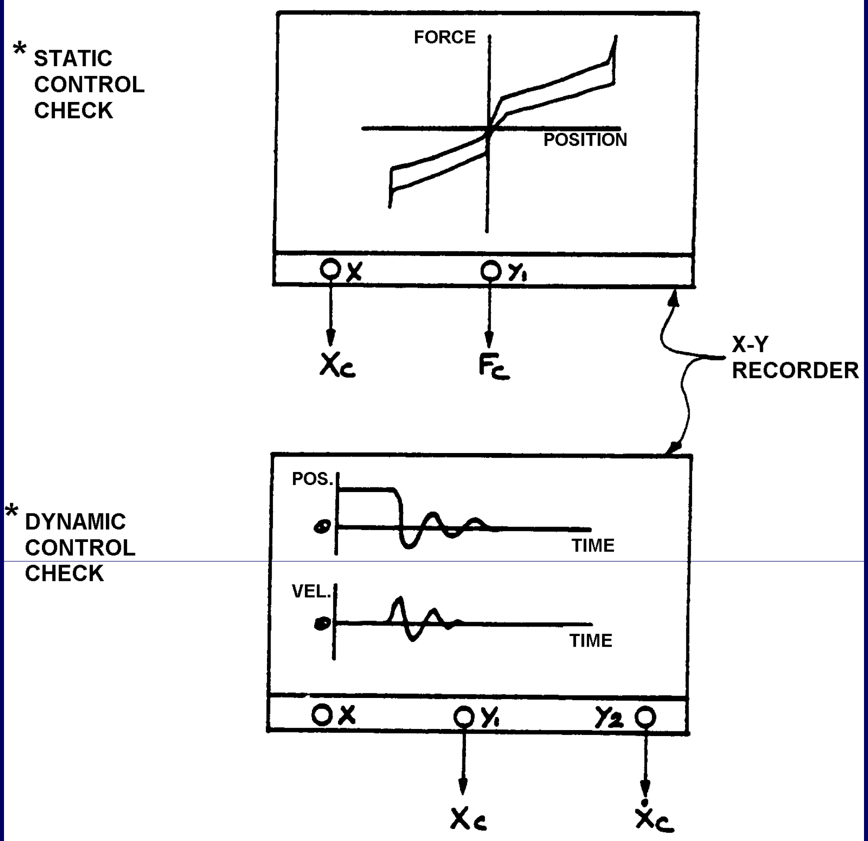
- On Ground Checks
  - Static Force Checks
  - Control-to-Surface Calibration
- In Flight Checks
  - Change in Control Force with Change in Aircraft Velocity
  - Change in Control Force with Change in Load Factor
  - Control Surface Position with Zero Control Trim
  - Dynamic Response



SYSTEM TUNING & PERFORMANCE VERIFICATION

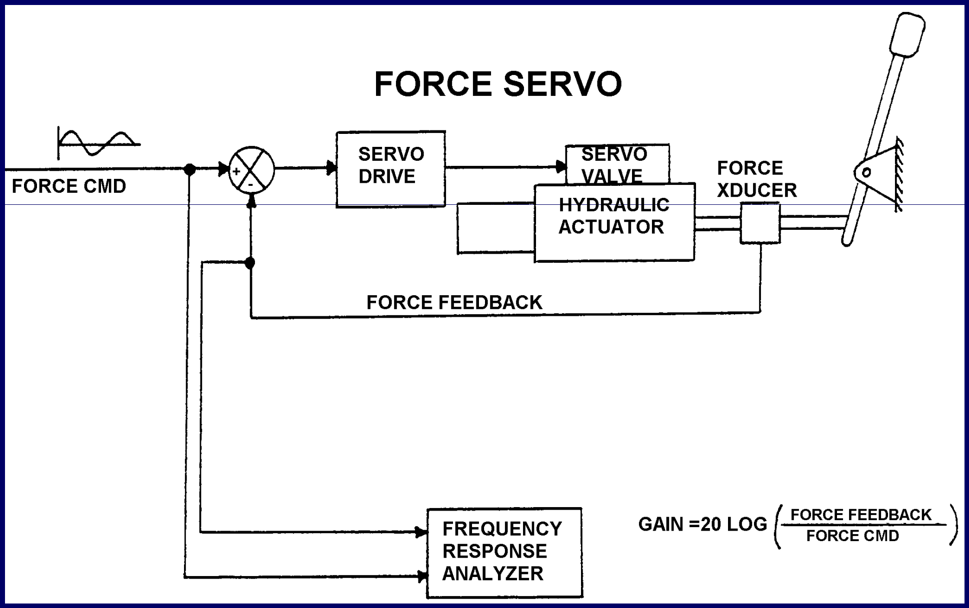
Control Force Measurements Equipment Results

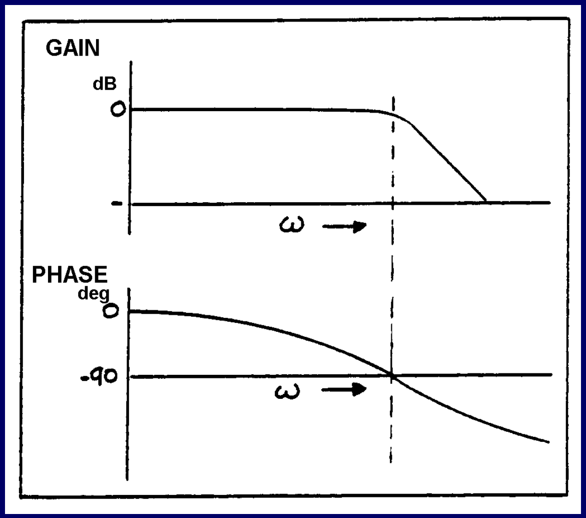




SYSTEM SETUP & PERFORMANCE VERIFICATION

Force Loop Frequency Response Measurement for system Capability (not required for Qualification)





FUTURE TRENDS

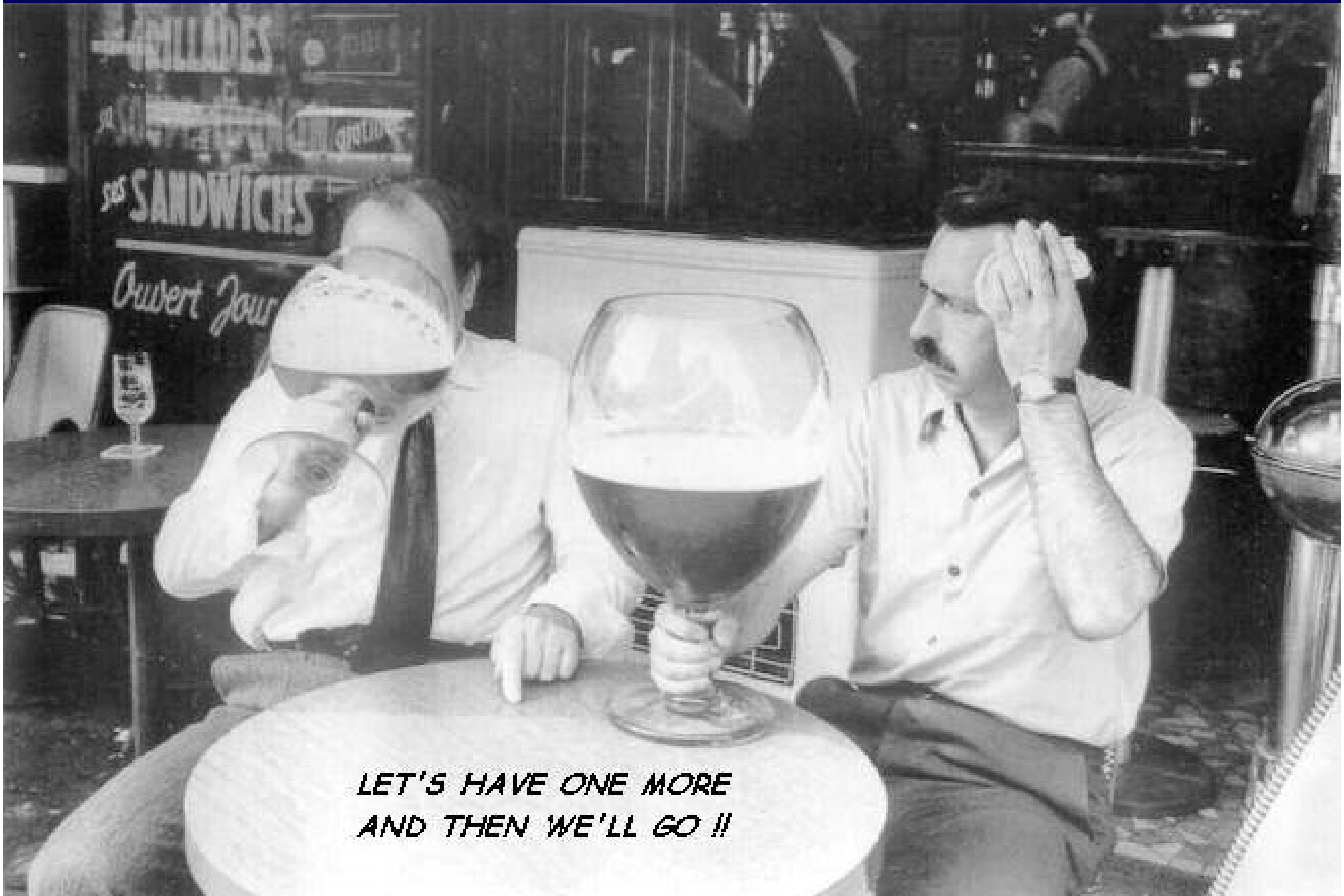
- What's next for Control Loading System Evolution?
  - Smaller packaging
  - Less Power Consumption ("GREENER" footprint)
  - Reduced Costs
  - Increased Performance
  - More 'bang for the buck'
  - Increased Reliability, Reduced Maintenance
  - More sophisticated Auto-calibration and Auto-alignment software

CONCLUSION

- Electric Control Loading Systems now outperform hydraulic systems and exceed Level D performance requirements as well as the demands of pilot training, including the sustained high forces required for control surface jams or runaway malfunctions
- Hydraulics are no longer required, and rarely used, for Control Loading and may well be a thing of the past for motion systems as well…………..
- The "Quest for the Holy Grail" may be over!

ACKNOWLEDGEMENTS

- TRU Simulation + Training
  - www.TRUsimulation.com
- MOOG
  - www.moog.com
- WITTENSTEIN AERO
  - www.wittenstein.aero


SANDWICHS
Ouvert Jour
LET'S HAVE ONE MORE
AND THEN WE'LL GO !!

Flight Control System Simulation - 2017

Thank You!

For more information about Control Loading
email
jtakats@trusimulation.com
or contact
www.TRUsimulation.com

James R. Takats
Sr. VP Global Strategy
Textron Inc.

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