Designing Aircraft Systems within Systems of Systems

Hydro-Mechanical and Electrical Systems Examples

October 26, 2004

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Sources of materials

- The system schematics are Boeing proprietary graciously given by Boeing personnel for the educational purposes of this course
  - Page 6 MD-11 braking system architecture
  - Page 15 B717 autobrake system control
  - Page 17 MD-11 electrical power system architecture
  - Page 18 MD-11 hydraulic power system architecture
- The rest of the material is taken from the personal experience of the author as first a system design engineer and as an engineering executive

Designing within Systems of Systems

- Braking System design examples

Within….

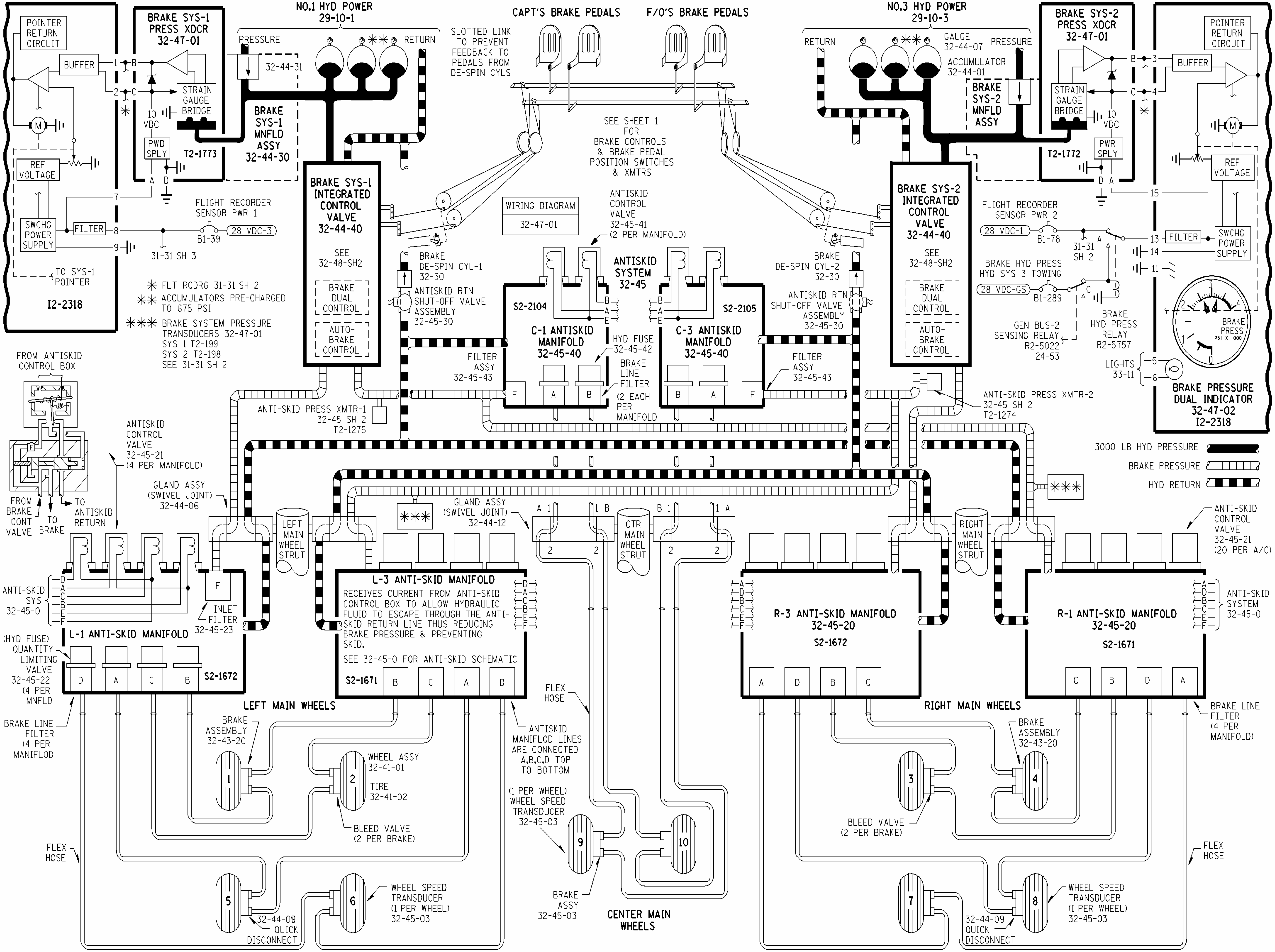
- An aircraft system of systems
- A design process & corporate system
- Airline and ATC systems
- Economic and educational systems

Systems Engineer/Manager Certification Course

- “The course I wanted when I was a starting system designer”
- 15 Subjects from aero to electrical installations, to design for safety, maintainability, certification, to…
- 58 class periods, a year’s commitment
- Applauded by the FAA certification branch

Braking System Design Objectives

- Safety
- Performance: Landing, RTO distances, energy
- Longevity, reliability, dispatchability
- Design, production, maintenance costs (DTC)
- Weight, strength
- Schedule, cycle-time
- Technology
- Certification / Regulatory compliance / Testing
- Human Factors / Pilot interface



NO.1 HYD POWER 29-10-1
NO.3 HYD POWER 29-10-3
CAPT'S BRAKE PEDALS
F/O'S BRAKE PEDALS
POINTER RETURN CIRCUIT
BUFFER
REF VOLTAGE
SWCHG POWER SUPPLY
FILTER
TO SYS-1 POINTER
I2-2318
BRAKE SYS-1 PRESS XDCR 32-47-01
STRAIN GAUGE BRIDGE
10 VDC
PWD SPLY
T2-1773
PRESSURE
RETURN
32-44-31
BRAKE SYS-1 MNFLD ASSY 32-44-30
BRAKE SYS-1 INTEGRATED CONTROL VALVE 32-44-40
SEE 32-48-SH2
BRAKE DUAL CONTROL
AUTO-BRAKE CONTROL
FLIGHT RECORDER SENSOR PWR 1
B1-39
28 VDC-3
31-31 SH 3
✳ FLT RCDRG 31-31 SH 2
✳✳ ACCUMULATORS PRE-CHARGED TO 675 PSI
✳✳✳ BRAKE SYSTEM PRESSURE TRANSDUCERS 32-47-01 SYS 1 T2-199 SYS 2 T2-198 SEE 31-31 SH 2
SLOTTED LINK TO PREVENT FEEDBACK TO PEDALS FROM DE-SPIN CYLS
SEE SHEET 1 FOR BRAKE CONTROLS & BRAKE PEDAL POSITION SWITCHES & XMTRS
WIRING DIAGRAM 32-47-01
ANTISKID CONTROL VALVE 32-45-41 (2 PER MANIFOLD)
ANTISKID SYSTEM 32-45
BRAKE DE-SPIN CYL-1 32-30
ANTISKID RTN SHUT-OFF VALVE ASSEMBLY 32-45-30
S2-2104
C-1 ANTISKID MANIFOLD 32-45-40
S2-2105
C-3 ANTISKID MANIFOLD 32-45-40
HYD FUSE 32-45-42
BRAKE LINE FILTER (2 EACH PER MANIFOLD)
FILTER ASSY 32-45-43
BRAKE DE-SPIN CYL-2 32-30
ANTI-SKID PRESS XMTR-1 32-45 SH 2 T2-1275
ANTI-SKID PRESS XMTR-2 32-45 SH 2 T2-1274
RETURN
GAUGE 32-44-07
PRESSURE
ACCUMULATOR 32-44-01
BRAKE SYS-2 MNFLD ASSY
BRAKE SYS-2 PRESS XDCR 32-47-01
T2-1772
PWR SPLY
BRAKE SYS-2 INTEGRATED CONTROL VALVE 32-44-40
FLIGHT RECORDER SENSOR PWR 2
28 VDC-1
B1-78
31-31 SH 2
BRAKE HYD PRESS HYD SYS 3 TOWING
28 VDC-GS
B1-289
GEN BUS-2 SENSING RELAY R2-5022 24-53
BRAKE HYD PRESS RELAY R2-5757
LIGHTS 33-11
BRAKE PRESS PSI X 1000
BRAKE PRESSURE DUAL INDICATOR 32-47-02 I2-2318
3000 LB HYD PRESSURE
BRAKE PRESSURE
HYD RETURN
FROM ANTISKID CONTROL BOX
FROM BRAKE CONT VALVE
TO BRAKE
TO ANTISKID RETURN
ANTISKID CONTROL VALVE 32-45-21 (4 PER MANIFOLD)
GLAND ASSY (SWIVEL JOINT) 32-44-06
LEFT MAIN WHEEL STRUT
GLAND ASSY (SWIVEL JOINT) 32-44-12
CTR MAIN WHEEL STRUT
RIGHT MAIN WHEEL STRUT
ANTI-SKID CONTROL VALVE 32-45-21 (20 PER A/C)
ANTI-SKID SYS 32-45-0
INLET FILTER 32-45-23
L-1 ANTI-SKID MANIFOLD
S2-1672
(HYD FUSE) QUANTITY LIMITING VALVE 32-45-22 (4 PER MNFLD)
L-3 ANTI-SKID MANIFOLD
RECEIVES CURRENT FROM ANTI-SKID CONTROL BOX TO ALLOW HYDRAULIC FLUID TO ESCAPE THROUGH THE ANTI-SKID RETURN LINE THUS REDUCING BRAKE PRESSURE & PREVENTING SKID.
SEE 32-45-0 FOR ANTI-SKID SCHEMATIC
S2-1671
R-3 ANTI-SKID MANIFOLD 32-45-20
S2-1672
R-1 ANTI-SKID MANIFOLD 32-45-20
S2-1671
ANTI-SKID SYSTEM 32-45-0
LEFT MAIN WHEELS
RIGHT MAIN WHEELS
CENTER MAIN WHEELS
BRAKE LINE FILTER (4 PER MANIFLOD)
BRAKE ASSEMBLY 32-43-20
WHEEL ASSY 32-41-01
TIRE 32-41-02
BLEED VALVE (2 PER BRAKE)
FLEX HOSE
ANTISKID MANIFLOD LINES ARE CONNECTED A,B,C,D TOP TO BOTTOM
(1 PER WHEEL) WHEEL SPEED TRANSDUCER 32-45-03
BRAKE ASSY 32-45-03
WHEEL SPEED TRANSDUCER (1 PER WHEEL) 32-45-03
32-44-09 QUICK DISCONNECT
BRAKE LINE FILTER (4 PER MANIFOLD)

Braking system architecture

- Architecture determined by ***Safety***
- Basic safety design requirements
- Architecture largely determines economics
  - Modularity, LRU's, reuse…
  - Partition to control variability (redundancy)
  - Interfaces
- Basic system engineering trades
  - Design/production cost, performance, cycle time

Architecture – safety analysis

- FAR 25.1309 Probabilistic safety analysis
- The analytical tools
  - Functional Hazard Analysis (FHA), redundancy, hazard level, separation
  - Fault Tree Analysis (FTA)
  - *Failure Mode and Effects Analysis (FMEA)*
  - *Zonal Analysis & Events Reviews*

Design challenges
Landing gear dynamics

- Brake energy

  $K(e) = ½ W/g \times (Vx,z)^2$

  $= ½ (450{,}000 \text{ lb})/32.5 \text{ ft/sec}^2 \times (220 \text{ ft/sec})^2$

  ~ 340,000,000 ft lbs.

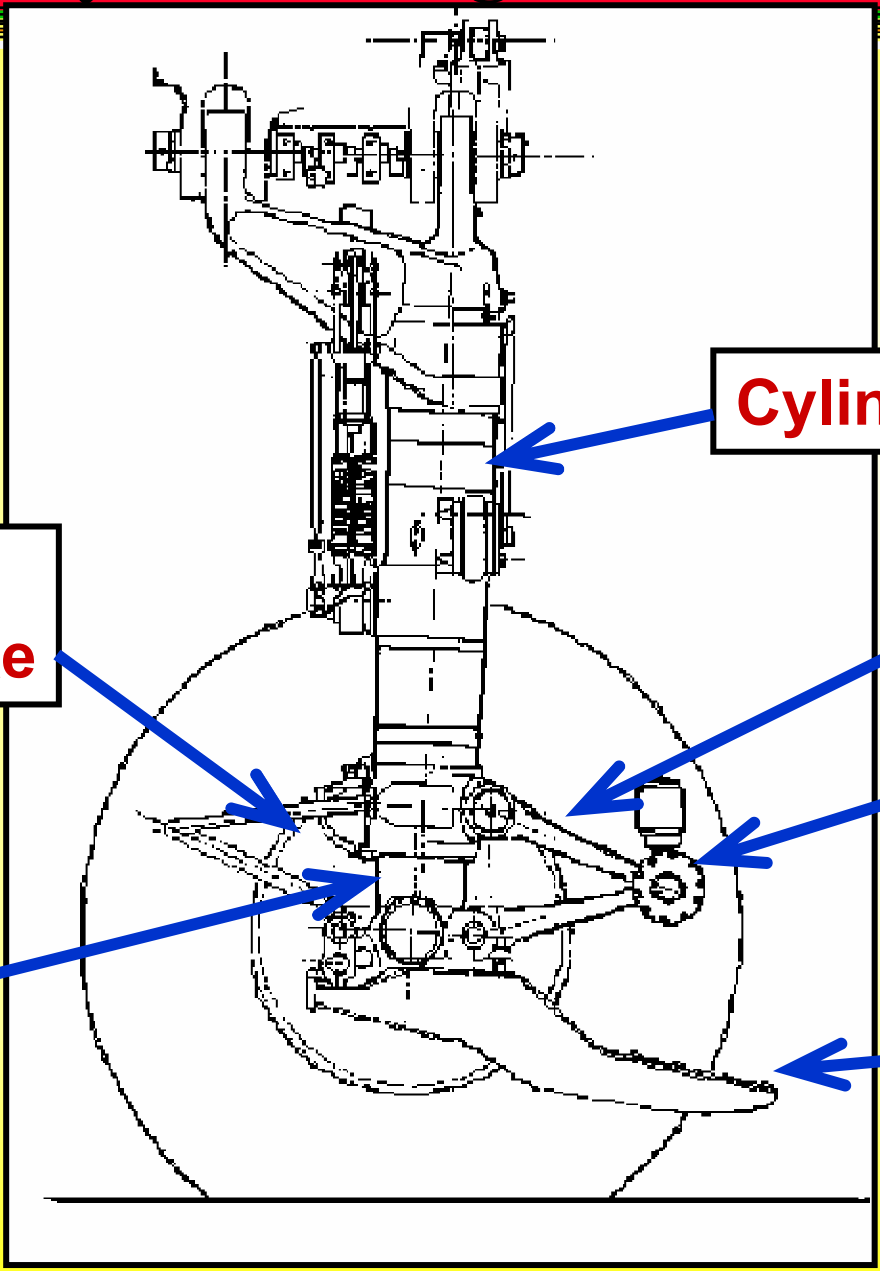
- Vertical energy

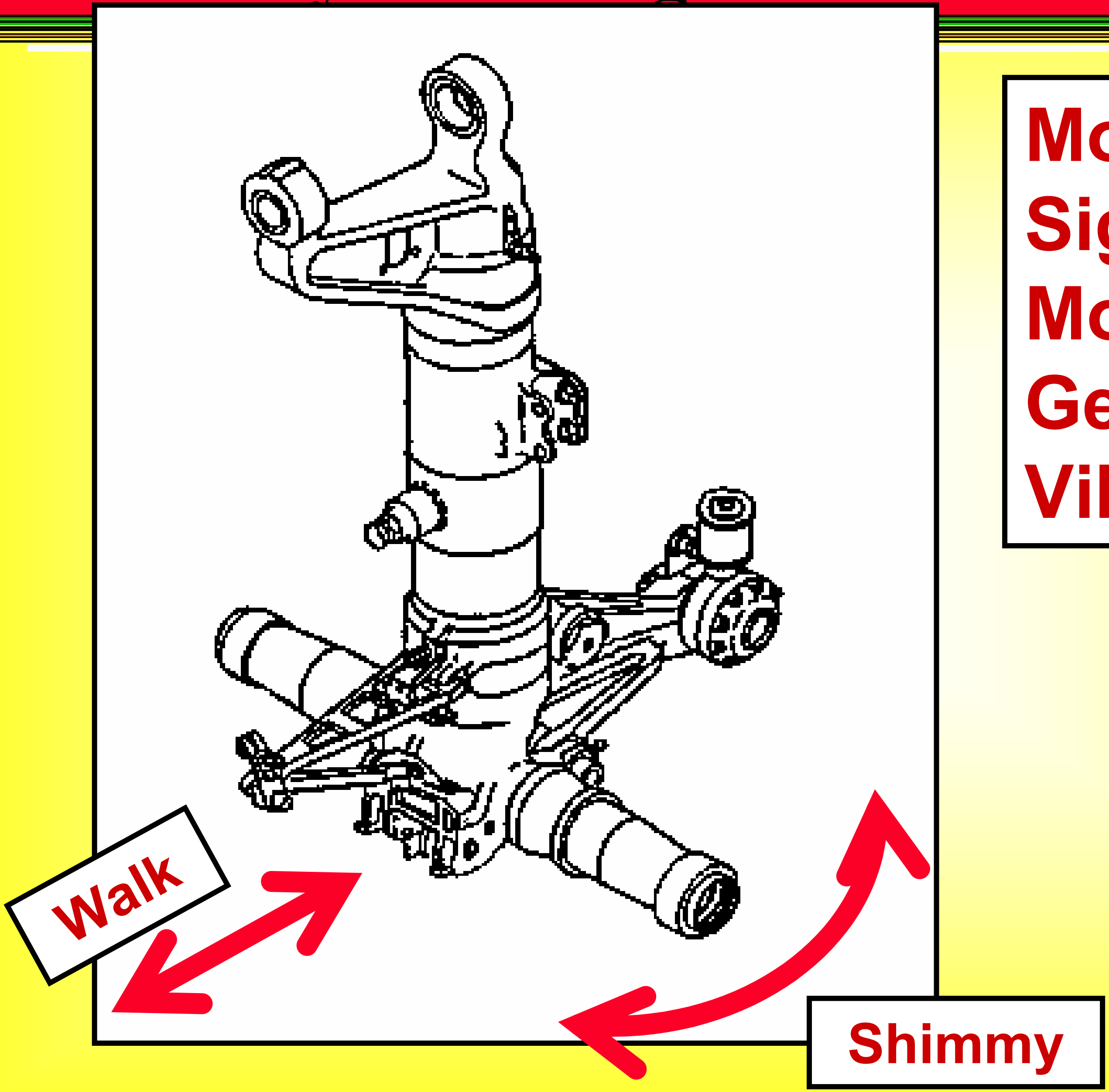
  $= ½ (450{,}000 \text{ lb})/32.5 \text{ft/sec}^2 \times (10 \text{ft/sec})^2$

  ~ 700,000 ft lbs.

- Dynamics – natural frequencies

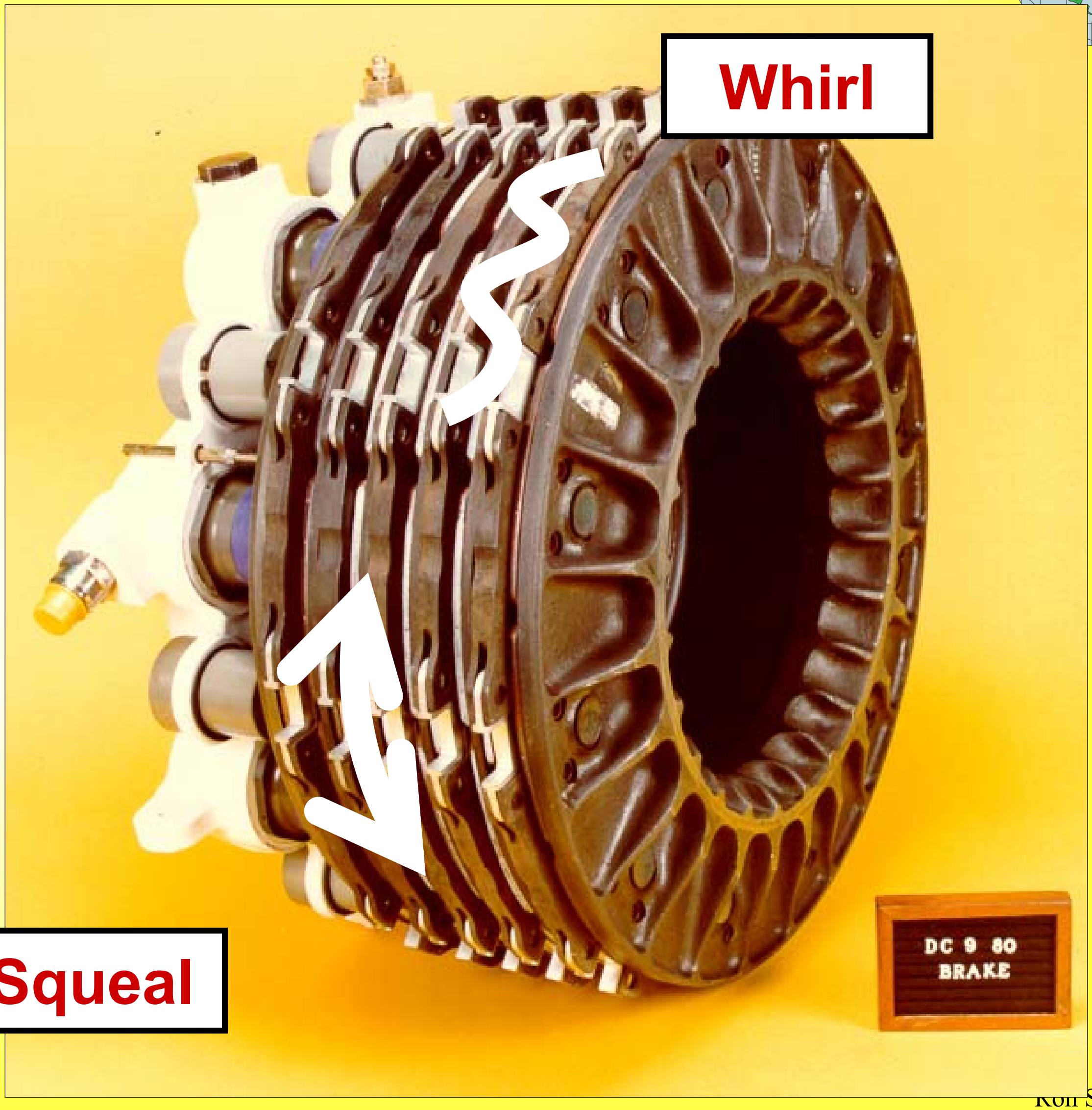
Aircraft System Design - MIT



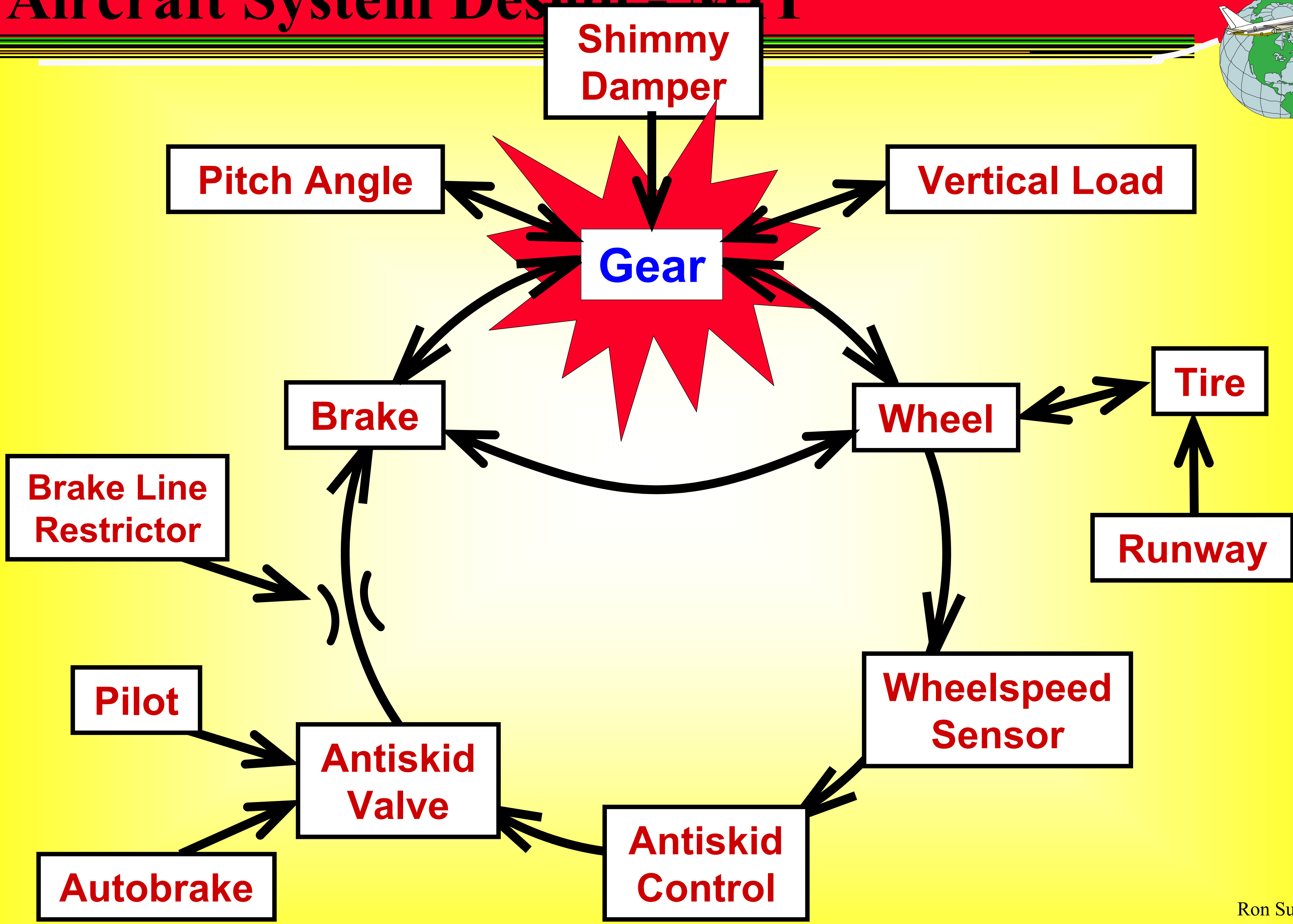


Most Significant Modes of Gear Vibration

Most Significant Modes of Brake Vibration

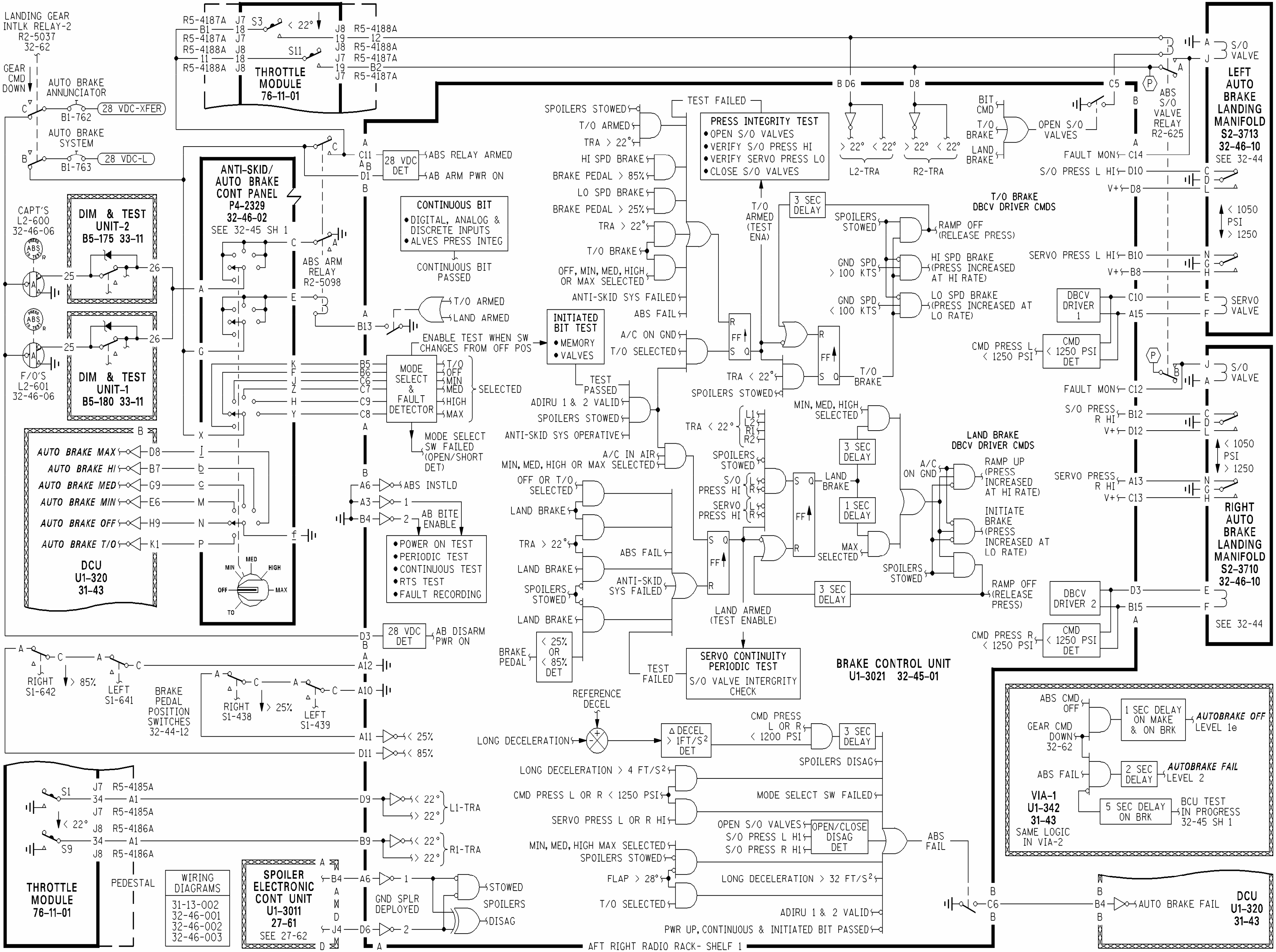


Aircraft System Design - MIT



Auto Brake design for safety

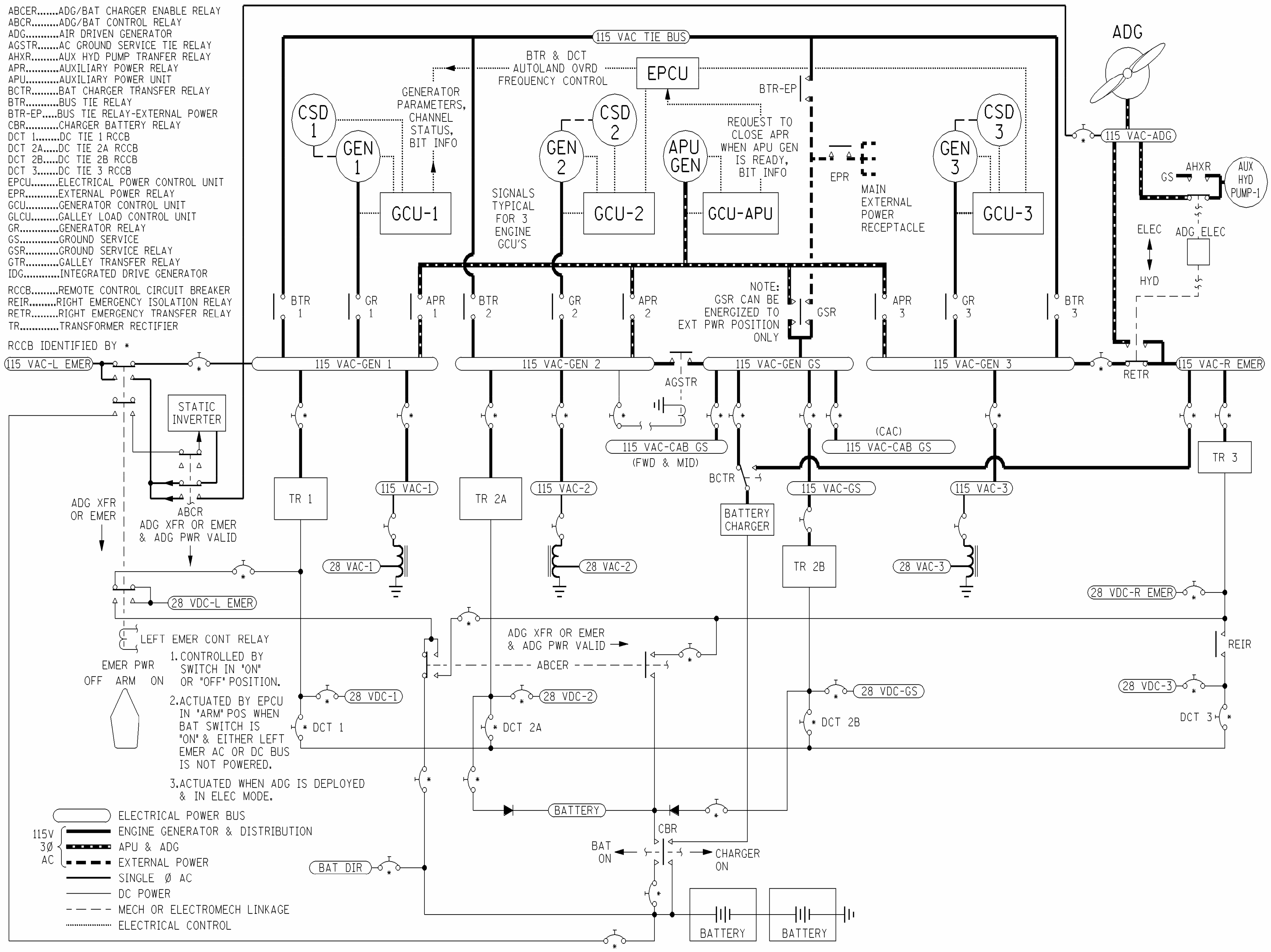
- Fault tree analysis to ensure the probability of the brakes coming on when not commanded is less than 10^{-9}
- 100 Seat aircraft Autobrake design objective met using Fault Tree Analysis



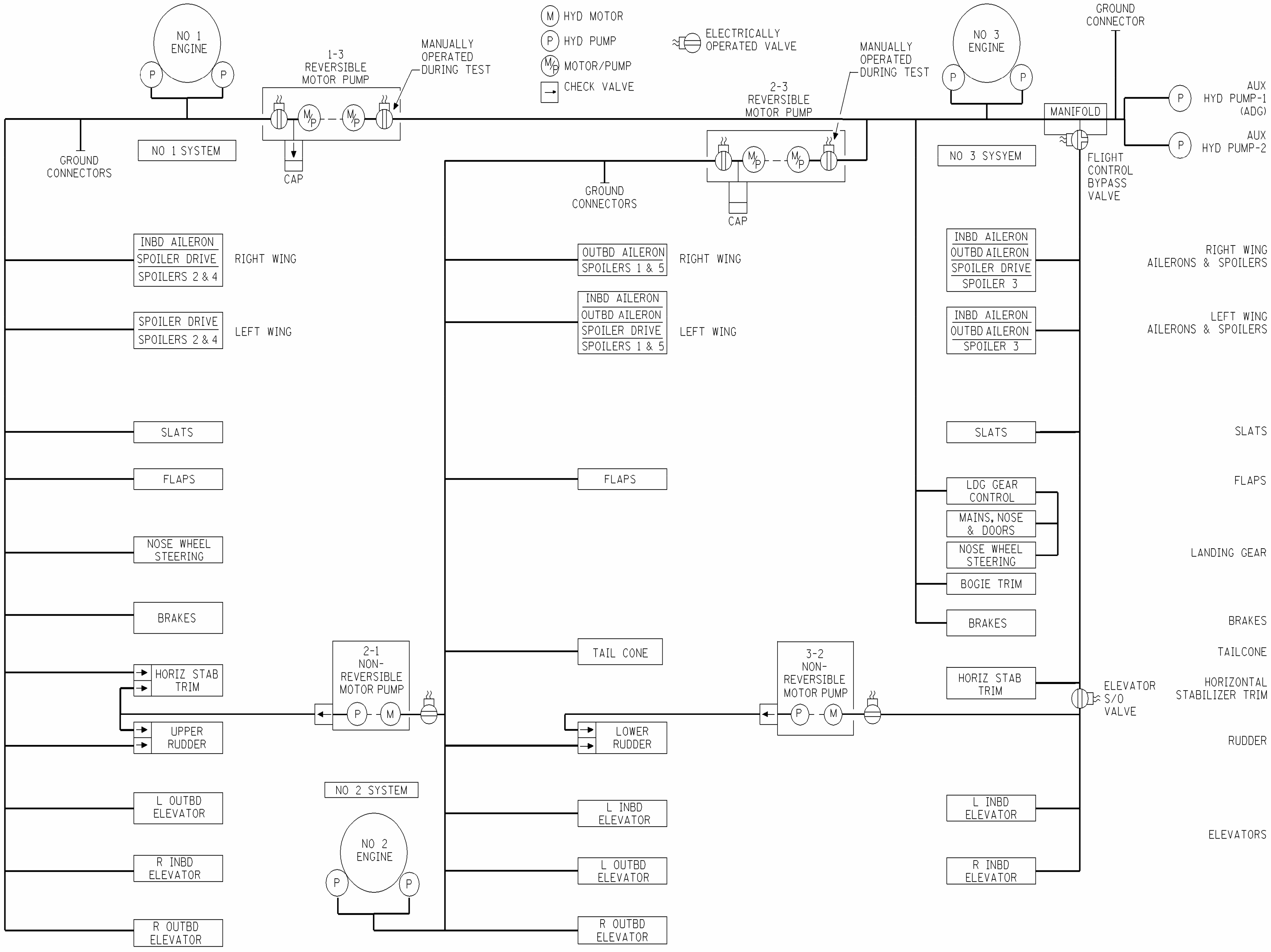
LANDING GEAR INTLK RELAY-2 R2-5037 32-62
GEAR CMD DOWN
AUTO BRAKE ANNUNCIATOR
B1-762
28 VDC-XFER
AUTO BRAKE SYSTEM
B1-763
28 VDC-L
THROTTLE MODULE 76-11-01
R5-4187A
R5-4188A
S3
S11
< 22°
ANTI-SKID/ AUTO BRAKE CONT PANEL P4-2329 32-46-02
SEE 32-45 SH 1
ABS ARM RELAY R2-5098
CAPT'S L2-600 32-46-06
F/O'S L2-601 32-46-06
DIM & TEST UNIT-2 B5-175 33-11
DIM & TEST UNIT-1 B5-180 33-11
28 VDC DET
ABS RELAY ARMED
AB ARM PWR ON
CONTINUOUS BIT
• DIGITAL, ANALOG & DISCRETE INPUTS
• ALVES PRESS INTEG
CONTINUOUS BIT PASSED
T/O ARMED
LAND ARMED
ENABLE TEST WHEN SW CHANGES FROM OFF POS
INITIATED BIT TEST
• MEMORY
• VALVES
TEST PASSED
MODE SELECT & FAULT DETECTOR
T/O
OFF
MIN
MED
HIGH
MAX
SELECTED
MODE SELECT SW FAILED (OPEN/SHORT DET)
AUTO BRAKE MAX
AUTO BRAKE HI
AUTO BRAKE MED
AUTO BRAKE MIN
AUTO BRAKE OFF
AUTO BRAKE T/O
DCU U1-320 31-43
ABS INSTLD
AB BITE ENABLE
• POWER ON TEST
• PERIODIC TEST
• CONTINUOUS TEST
• RTS TEST
• FAULT RECORDING
AB DISARM PWR ON
RIGHT S1-642
LEFT S1-641
> 85%
BRAKE PEDAL POSITION SWITCHES 32-44-12
RIGHT S1-438
LEFT S1-439
> 25%
SPOILERS STOWED
T/O ARMED
TRA > 22°
HI SPD BRAKE
BRAKE PEDAL > 85%
LO SPD BRAKE
BRAKE PEDAL > 25%
T/O BRAKE
OFF, MIN, MED, HIGH OR MAX SELECTED
ANTI-SKID SYS FAILED
ABS FAIL
A/C ON GND
T/O SELECTED
ADIRU 1 & 2 VALID
ANTI-SKID SYS OPERATIVE
A/C IN AIR
MIN, MED, HIGH OR MAX SELECTED
OFF OR T/O SELECTED
LAND BRAKE
TEST FAILED
PRESS INTEGRITY TEST
• OPEN S/O VALVES
• VERIFY S/O PRESS HI
• VERIFY SERVO PRESS LO
• CLOSE S/O VALVES
T/O ARMED (TEST ENA)
3 SEC DELAY
L2-TRA
R2-TRA
BIT CMD
OPEN S/O VALVES
ABS S/O VALVE RELAY R2-625
FAULT MON
S/O PRESS L HI
T/O BRAKE DBCV DRIVER CMDS
RAMP OFF (RELEASE PRESS)
GND SPD > 100 KTS
HI SPD BRAKE (PRESS INCREASED AT HI RATE)
GND SPD < 100 KTS
LO SPD BRAKE (PRESS INCREASED AT LO RATE)
SERVO PRESS L HI
DBCV DRIVER 1
CMD PRESS L < 1250 PSI
CMD 1250 PSI DET
LEFT AUTO BRAKE LANDING MANIFOLD S2-3713 32-46-10
SEE 32-44
S/O VALVE
SERVO VALVE
< 1050 PSI > 1250
TRA < 22°
L1 L2 R1 R2
S/O PRESS HI
SERVO PRESS HI
MIN, MED, HIGH SELECTED
LAND BRAKE DBCV DRIVER CMDS
RAMP UP (PRESS INCREASED AT HI RATE)
INITIATE BRAKE (PRESS INCREASED AT LO RATE)
RAMP OFF (RELEASE PRESS)
1 SEC DELAY
MAX SELECTED
A/C ON GND
S/O PRESS R HI
SERVO PRESS R HI
DBCV DRIVER 2
CMD PRESS R < 1250 PSI
RIGHT AUTO BRAKE LANDING MANIFOLD S2-3710 32-46-10
LAND ARMED (TEST ENABLE)
SERVO CONTINUITY PERIODIC TEST
S/O VALVE INTERGRITY CHECK
< 25% OR < 85% DET
BRAKE PEDAL
BRAKE CONTROL UNIT U1-3021 32-45-01
REFERENCE DECEL
LONG DECELERATION
Δ DECEL > 1FT/S² DET
CMD PRESS L OR R < 1200 PSI
SPOILERS DISAG
LONG DECELERATION > 4 FT/S²
CMD PRESS L OR R < 1250 PSI
MODE SELECT SW FAILED
SERVO PRESS L OR R HI
OPEN S/O VALVES
S/O PRESS L HI
S/O PRESS R HI
OPEN/CLOSE DISAG DET
ABS FAIL
MIN, MED, HIGH MAX SELECTED
FLAP > 28°
LONG DECELERATION > 32 FT/S²
ADIRU 1 & 2 VALID
PWR UP, CONTINUOUS & INITIATED BIT PASSED
AFT RIGHT RADIO RACK- SHELF 1
ABS CMD OFF
GEAR CMD DOWN 32-62
1 SEC DELAY ON MAKE & ON BRK
AUTOBRAKE OFF LEVEL 1e
2 SEC DELAY
AUTOBRAKE FAIL LEVEL 2
5 SEC DELAY ON BRK
BCU TEST IN PROGRESS 32-45 SH 1
VIA-1 U1-342 31-43
SAME LOGIC IN VIA-2
AUTO BRAKE FAIL
L1-TRA
R1-TRA
R5-4185A
R5-4186A
PEDESTAL
WIRING DIAGRAMS
31-13-002
32-46-001
32-46-002
32-46-003
SPOILER ELECTRONIC CONT UNIT U1-3011 27-61
SEE 27-62
GND SPLR DEPLOYED
STOWED
SPOILERS
DISAG

Interfaces w/ the aircraft system

- Electrical power
  - Failure modes
  - Power quality, transients + & -, power xfer
  - Voltage levels & frequency, 115vac 400 Hz, 28vdc
  - Wire separation, EMI & redundancy
- Hydraulic power
  - Availability, redundancy, system separation, failures
  - Flow rates
  - Fluid properties
- Environment
  - Temperature, cooling
  - Vibration & shock, EMI



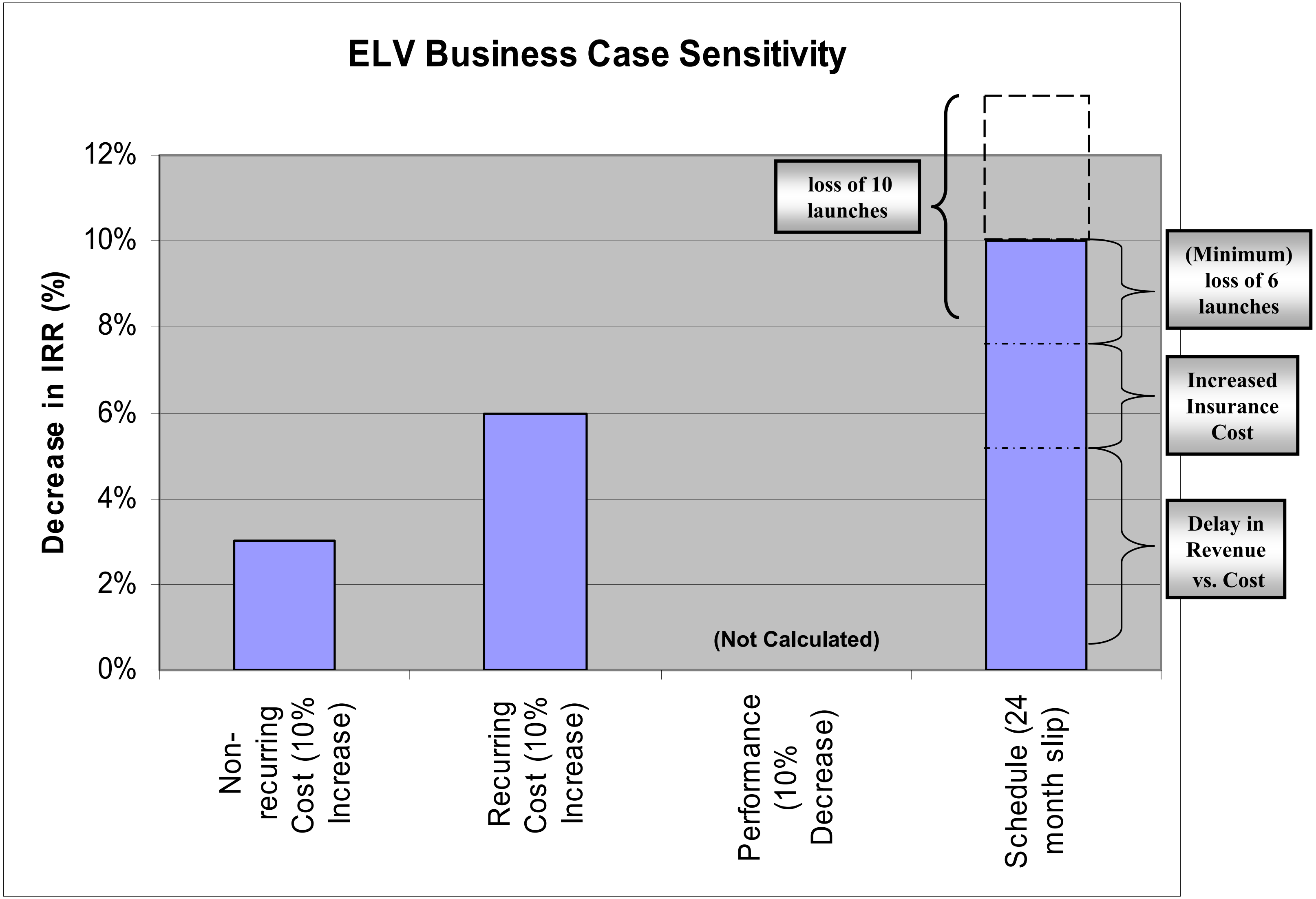
ABCER.......ADG/BAT CHARGER ENABLE RELAY
ABCR.......ADG/BAT CONTROL RELAY
ADG.........AIR DRIVEN GENERATOR
AGSTR.......AC GROUND SERVICE TIE RELAY
AHXR.......AUX HYD PUMP TRANFER RELAY
APR.........AUXILIARY POWER RELAY
APU.........AUXILIARY POWER UNIT
BCTR.........BAT CHARGER TRANSFER RELAY
BTR.........BUS TIE RELAY
BTR-EP.....BUS TIE RELAY-EXTERNAL POWER
CBR.........CHARGER BATTERY RELAY
DCT 1.......DC TIE 1 RCCB
DCT 2A.....DC TIE 2A RCCB
DCT 2B.....DC TIE 2B RCCB
DCT 3.......DC TIE 3 RCCB
EPCU.........ELECTRICAL POWER CONTROL UNIT
EPR.........EXTERNAL POWER RELAY
GCU.........GENERATOR CONTROL UNIT
GLCU.........GALLEY LOAD CONTROL UNIT
GR.........GENERATOR RELAY
GS.........GROUND SERVICE
GSR.........GROUND SERVICE RELAY
GTR.........GALLEY TRANSFER RELAY
IDG.........INTEGRATED DRIVE GENERATOR
RCCB.........REMOTE CONTROL CIRCUIT BREAKER
REIR.........RIGHT EMERGENCY ISOLATION RELAY
RETR.........RIGHT EMERGENCY TRANSFER RELAY
TR.........TRANSFORMER RECTIFIER
RCCB IDENTIFIED BY *
115 VAC TIE BUS
ADG
EPCU
BTR & DCT AUTOLAND OVRD FREQUENCY CONTROL
GENERATOR PARAMETERS, CHANNEL STATUS, BIT INFO
CSD 1
GEN 1
GCU-1
CSD 2
GEN 2
GCU-2
APU GEN
GCU-APU
CSD 3
GEN 3
GCU-3
SIGNALS TYPICAL FOR 3 ENGINE GCU'S
REQUEST TO CLOSE APR WHEN APU GEN IS READY, BIT INFO
BTR-EP
EPR
MAIN EXTERNAL POWER RECEPTACLE
115 VAC-ADG
GS
AHXR
AUX HYD PUMP-1
ELEC
HYD
ADG ELEC
BTR 1
GR 1
APR 1
BTR 2
GR 2
APR 2
NOTE: GSR CAN BE ENERGIZED TO EXT PWR POSITION ONLY
GSR
APR 3
GR 3
BTR 3
115 VAC-L EMER
115 VAC-GEN 1
115 VAC-GEN 2
AGSTR
115 VAC-GEN GS
115 VAC-GEN 3
RETR
115 VAC-R EMER
STATIC INVERTER
115 VAC-CAB GS
(FWD & MID)
(CAC)
115 VAC-CAB GS
BCTR
TR 3
TR 1
115 VAC-1
TR 2A
115 VAC-2
115 VAC-GS
115 VAC-3
ABCR
ADG XFR OR EMER & ADG PWR VALID
ADG XFR OR EMER
BATTERY CHARGER
28 VAC-1
28 VAC-2
TR 2B
28 VAC-3
28 VDC-L EMER
28 VDC-R EMER
LEFT EMER CONT RELAY
ADG XFR OR EMER & ADG PWR VALID
ABCER
REIR
EMER PWR
OFF ARM ON
1. CONTROLLED BY SWITCH IN "ON" OR "OFF" POSITION.
2. ACTUATED BY EPCU IN "ARM" POS WHEN BAT SWITCH IS "ON" & EITHER LEFT EMER AC OR DC BUS IS NOT POWERED.
3. ACTUATED WHEN ADG IS DEPLOYED & IN ELEC MODE.
28 VDC-1
28 VDC-2
28 VDC-GS
28 VDC-3
DCT 1
DCT 2A
DCT 2B
DCT 3
BATTERY
CBR
BAT ON
CHARGER ON
BAT DIR
BATTERY
BATTERY
ELECTRICAL POWER BUS
115V 3Ø AC
ENGINE GENERATOR & DISTRIBUTION
APU & ADG
EXTERNAL POWER
SINGLE Ø AC
DC POWER
MECH OR ELECTROMECH LINKAGE
ELECTRICAL CONTROL



HYD MOTOR
HYD PUMP
MOTOR/PUMP
CHECK VALVE
ELECTRICALLY OPERATED VALVE
NO 1 ENGINE
1-3 REVERSIBLE MOTOR PUMP
MANUALLY OPERATED DURING TEST
GROUND CONNECTORS
NO 1 SYSTEM
CAP
2-3 REVERSIBLE MOTOR PUMP
MANUALLY OPERATED DURING TEST
GROUND CONNECTORS
CAP
NO 3 ENGINE
GROUND CONNECTOR
MANIFOLD
AUX HYD PUMP-1 (ADG)
AUX HYD PUMP-2
NO 3 SYSYEM
FLIGHT CONTROL BYPASS VALVE
INBD AILERON
SPOILER DRIVE
SPOILERS 2 & 4
RIGHT WING
SPOILER DRIVE
SPOILERS 2 & 4
LEFT WING
OUTBD AILERON
SPOILERS 1 & 5
RIGHT WING
INBD AILERON
OUTBD AILERON
SPOILER DRIVE
SPOILERS 1 & 5
LEFT WING
INBD AILERON
OUTBD AILERON
SPOILER DRIVE
SPOILER 3
RIGHT WING AILERONS & SPOILERS
INBD AILERON
OUTBD AILERON
SPOILER 3
LEFT WING AILERONS & SPOILERS
SLATS
FLAPS
NOSE WHEEL STEERING
BRAKES
HORIZ STAB TRIM
UPPER RUDDER
L OUTBD ELEVATOR
R INBD ELEVATOR
R OUTBD ELEVATOR
2-1 NON-REVERSIBLE MOTOR PUMP
NO 2 SYSTEM
NO 2 ENGINE
FLAPS
TAIL CONE
LOWER RUDDER
L INBD ELEVATOR
L OUTBD ELEVATOR
R OUTBD ELEVATOR
3-2 NON-REVERSIBLE MOTOR PUMP
SLATS
LDG GEAR CONTROL
MAINS, NOSE & DOORS
NOSE WHEEL STEERING
BOGIE TRIM
BRAKES
HORIZ STAB TRIM
L INBD ELEVATOR
R INBD ELEVATOR
ELEVATOR S/O VALVE
SLATS
FLAPS
LANDING GEAR
BRAKES
TAILCONE
HORIZONTAL STABILIZER TRIM
RUDDER
ELEVATORS

Design Process and Program Management systems

- **SE trades, cost, performance, schedule**
- **Risk management. What is the BIG risk?**



ELV Business Case Sensitivity
Decrease in IRR (%)
12%
10%
8%
6%
4%
2%
0%
loss of 10 launches
(Minimum) loss of 6 launches
Increased Insurance Cost
Delay in Revenue vs. Cost
(Not Calculated)
Non-recurring Cost (10% Increase)
Recurring Cost (10% Increase)
Performance (10% Decrease)
Schedule (24 month slip)

Design Process and Program Management systems

- **Long cycle times – 48 months?**
- **Development cost vs. program ROI**
- **What is the purpose of engineering?**

Impact of the design process on company viability

- Aircraft production example

Results of airplane production analysis:

- Strategic cost driver (1985 - 1990):
  personnel experience dilution
- Policy contradiction (1987-1989):
  increased build target + cap on hiring
- Parts count / design complexity
- Removal of hiring cap (1990):
  - Throughput targets achieved
  - Per-airplane cost declined 45% in one year

Design drives company viability

- 80 + % of product cost determined early
- Company viability / ability to close the business case on new designs determines ability to launch new products
- Flow of new products develops engineering experience base critical to good design

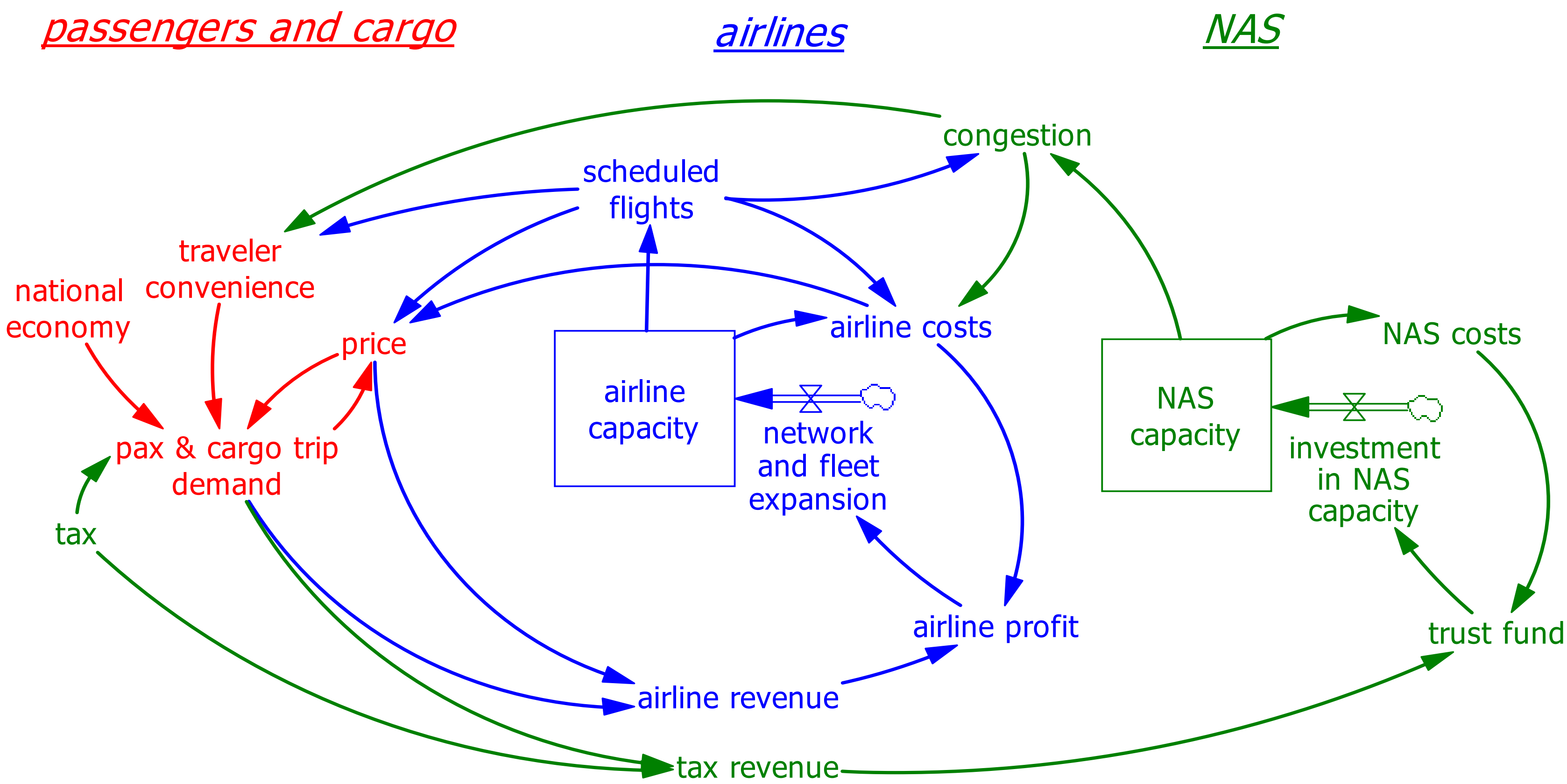
Airline systems

- Airline viability ~ ability to buy / launch airplanes
  - Driven by 7 to 10 year business cycle
  - Sensitive to special events, Gulf, 9/11
  - High capital, labor costs, very thin margins
  - Long aircraft acquisition lead times
  - Business model, network structure

ATM System (of systems)

- Challenge to expand capacity of National Airspace System (NAS) by 2X by 2025?
- Impact of aircraft economics on NAS
- Divide workload between cockpit and ground
- Value to airlines to equip?

NAS Strategy Simulator Overview



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The critical issues

- SE / program management interface
  - Ability to manage / trade the **BIG** risks
- Design cycle time
- Ability to close business case on new planes
- Personnel experience management
- Enterprise portfolio of technologies and programs to minimize risk
- Program management and corporate culture

Direction of Solution

- Top-down design tools - architecture
- Model-based design - technical **and** organization performance
- Enterprise simulation based technology and program portfolio management decision support
- *Change the paradigm in concurrent engineering & engineering personnel management*
  - *JPL Project Design Center*
  - *Drop pay-to-market HR policies*

The Future

- ***Ability to deal with complexity of systems of systems "top-down"***
  - ***The solution to your system problem can be found in the larger or adjacent systems***
- ***Designing airplanes within the context of…organization, airline/ATC, economic systems***
- ***The challenge – pick YOUR system and improve its viability***