



AEROSPACE INFORMATION REPORT

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Superseding AIR4543/1

Aerospace Hydraulics and Actuation Lessons Learned

RATIONALE

This document has been determined to contain basic and stable technology which is not dynamic in nature.

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1. SCOPE

This SAE Aerospace Information Report (AIR) contains Lessons Learned from aerospace actuation, control and fluid power systems technologies. The lessons were prepared by engineers from the aerospace industry and government services as part of the work of SAE Committee A-6, Aerospace Actuation, Control and Fluid Power Systems. Each lesson was presented to the appropriate A-6 technical panel. The technical topics are organized into five sections covering systems, actuation, hydraulic components, electrical components and miscellaneous, each further divided into subsections. The information topics are presented in a concise format of Problem, Issue, Solution and Lesson Learned, often with accompanying descriptive diagrams and illustrations for clarity and understanding.

1.1 Further Comment on Document AIR4543 and This Document AIR4543/1

AIR4543B contains lessons learned presented to the A-6 Committee during meetings held from 1989 through 1999. This AIR4543/1 document contains lessons presented during the period 2000 through 2010. Subsequent AIR4543/X documents will similarly contain material segregated by the date of presentation.

The structure of the numbering of the technical topics contained within section 3 of each document will be maintained constant and each new lesson in each new AIR will be numbered consecutively from the material contained in earlier documents.

To help the reader navigate the material, a complete index of all lessons published up until the closing date of this new AIR is included as Appendix A. Each subsequent AIR will similarly contain an updated complete index of all published lessons.

NOTES:

1. Where known, the year of the activity described in each lesson is provided.
2. The allocation of the lessons to the various categories is typically obvious, because of their focused content, but occasionally arbitrary because of mixed content. Text searches are suggested to ensure that all lessons of interest are found.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. Unless otherwise specified the applicable issue of the SAE and other publications shall be the issue in effect during the year of the activity described in each lesson. In the event of conflict between the text of this document and the references cited herein, the text of this document takes preference. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

ARP1827	Measuring Aircraft Gas Turbine Engine Fine Fuel Filter Element Performance
ARP4205	Aerospace Fluid Power - Hydraulic Filter Elements - Method for Evaluating Dynamic Efficiency With Cyclic Flow
ARP4386	Terminology and Definitions for Aerospace Fluid Power, Actuation and Control Technologies
ARP5007	Development Process - Aerospace Fly-By-Wire Actuation System

ARP5454	Multi-Pass Method for Evaluating Filtration Performance of Fine Lube Filter Elements Utilized in Aerospace Power and Propulsion Lubrication Systems
AS4716	Gland Design, O-Ring and Other Elastomeric Seals
AS8879	Screw Threads - UNJ Profile, Inch Controlled Radius Root With Increased Minor Diameter

2.1.2 ISO Publications

Available from American National Standards Institute, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, www.ansi.org.

ISO 12103-1 Road vehicles - Test dust for filter evaluation - Part 1: Arizona test dust

2.1.3 Radio Technical Commission for Aeronautics Documents (RTCA)

Available from Radio Technical Commission for Aeronautics Inc., 1828 L Street, NW, Suite 805, Washington, DC 20036, Tel: 202-833-9339, www.rtca.org.

RTCA/DO-160/ISO7137 Environmental conditions and test procedures for airborne equipment

2.1.4 US Government Publications

Available from the Document Automation and Production Service (DAPS), Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, <http://assist.daps.dla.mil/quicksearch/>.

MIL-F-8815 Filter and Filter Elements, Fluid Pressure, Hydraulic Line, 15 Micron Absolute and 5 Micron Absolute, Type II Systems; General Specification For

2.2 Abbreviations, Acronyms, Symbols and Their Definitions

AC	Alternating Current
ACCTD	A.C. Coarse Test Dust
ACFTD	A.C. Fine Test Dust
AIR	Aerospace Information Report
APU	Auxiliary Power Unit
ATP	Acceptance Test Procedure
BIT	Built-In-Test
COM	Command Channel in Command-monitor Control Architecture
CRES	Corrosion Resistant Steel
CTD	ISO Coarse Test Dust
DC	Direct Current
ΔP	Differential Pressure
EBHA	Electrical Back-up Hydraulic Actuator
EDM	Electrical Discharge Machining

EHA	Electrohydrostatic Actuator
EHM	Electrohydrostatic Module
EHSV	Electrohydraulic Servovalve
EMA	Electromechanical Actuator
FAA	Federal Aviation Authority
FBW	Fly-By-Wire
FCC	Flight Control Computer
FCS	Flight Control System
Fi, Fo and Fa	Pilot Input Force, Output Force and Actuator Force
FTD	ISO Fine Test Dust
GVT	Ground Vibration Test
HP	High Pressure
HSTA	Horizontal Stabilizer Trim Actuator
IBIT	Initiated Built-In-Test
ICD	Interface Control Document
ISA	International Standard Atmosphere
ISO	International Standardization Organization
LVDT	Linear Variable Differential Transformer
MON	Monitor Channel in Command-monitor Control Architecture
MSV	Mode Select Valve
MTD	ISO Medium Test Dust
NDI	Non-destructive Inspection
OEM	Original Equipment Manufacturer
OTS	Off-The-Shelf
P _E	Extend Pressure
PEEK	Polyether Ether Ketone Thermoplastic
P _R	Retract Pressure
PTFE	Polytetrafluoroethylene
RTCA	Radio Technical Commission for Aeronautics

SOF Safety-Of-Flight

Xi and Xo Input Command Displacement and Output Displacement

2.3 Definitions

Refer to ARP4386.

3. TECHNICAL INFORMATION

3.1 Systems Lessons Learned

3.1.1 All Systems

This subsection addresses lessons generally applicable to systems of all types. No Lessons Learned on this subject submitted for this document.

3.1.2 Flight Control Systems

This subsection contains lessons learned from the design and development of aircraft flight control systems and critical control functions for other vehicles.

3.1.2.4 Loss of All Three Hydraulic Systems from Failure of One Engine

PROBLEM: Meeting FAA certification requirements on a three-engine commercial transport aircraft with three or more primary, completely separate, hydraulic systems to cover all phases of flight

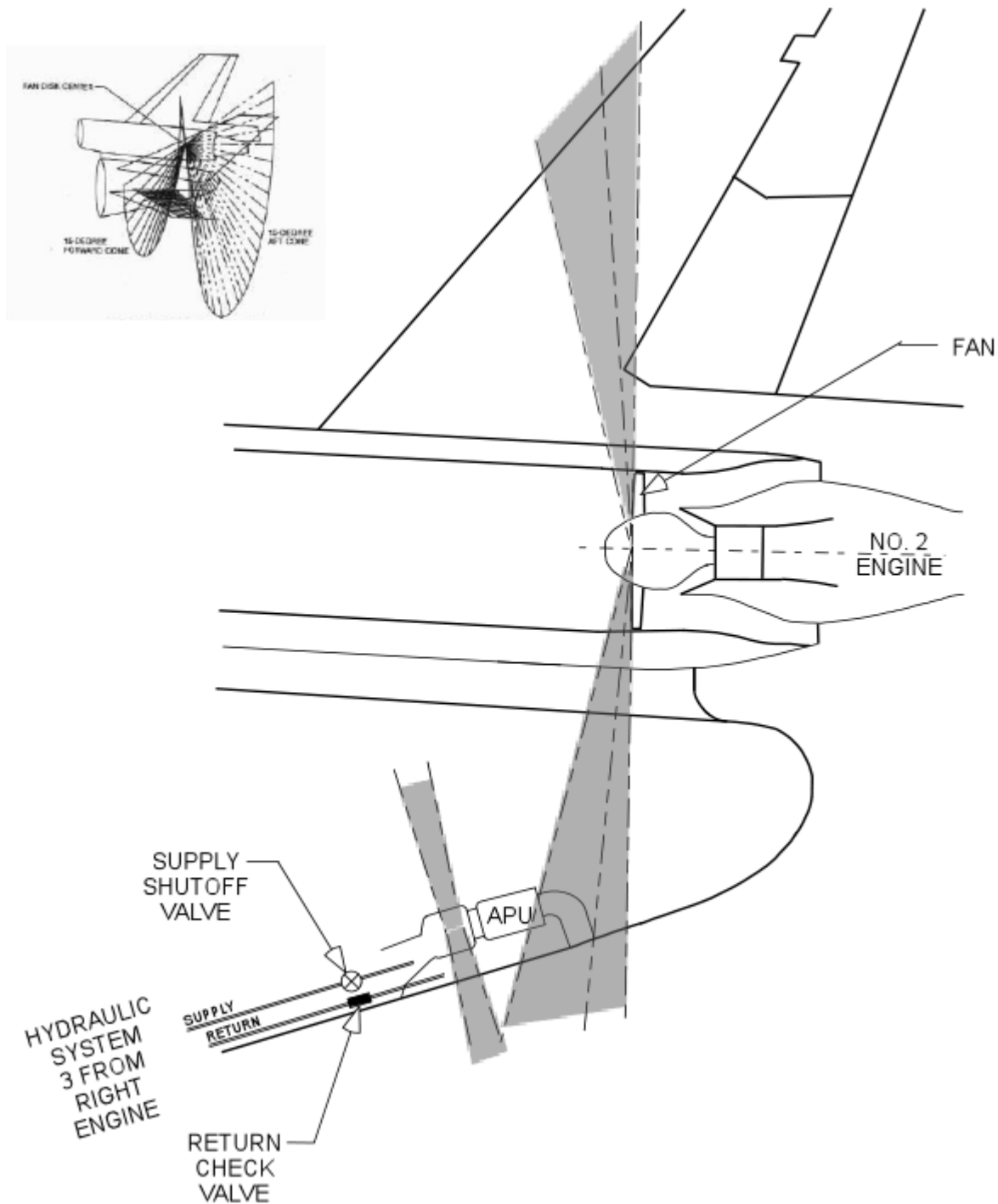
YEAR OF ACTIVITY: 1989

ISSUE: A massive uncontained tail engine rotor burst failure caused loss of all three hydraulic systems used for flight control actuation on a commercial transport aircraft. The landing with no control other than engine throttle manipulation resulted in a hull loss with many fatalities.

SOLUTION: Enhance the right engine hydraulic system to sustain minimum acceptable control despite massive tail engine failure. This system has two AC electric auxiliary motor driven pumps to provide “secondary” control and utility power in the event of the loss of all engines. Preclude a complete loss of all fluid in this system by:

- a. Adding a sensor switch in the right system reservoir set to an acceptable minimum fluid level for the operation of the secondary system.
- b. Adding an electrically operated shutoff valve in the right main hydraulic system supply line and a check valve in the return, with both valves installed forward of the tail engine and APU fan disk paths. The fast acting shutoff valve is automatically commanded closed and a cockpit alert light illuminated if the reservoir fluid level drops to a minimum design level detected by the switch.

ILLUSTRATION



LESSON LEARNED

Reviewing the extreme failure case required additional protection to be added to the design.

If you think you designed for all possible failures, think of the proverb: "If it can happen it will happen."

3.1.2.5 Effect on Aeroelastic Stability of Changes in Control System Kinematics

PROBLEM: The kinematic layout of a manually controlled aileron system was rearranged while the original system gearing ratio was kept unchanged. The effect of the layout modification on the system characteristics was, however, overlooked, and the frequency of the symmetric aileron rotation increased to a level such that the wing-aileron flutter mode became unstable.

YEAR OF ACTIVITY: 2006

ISSUE: During the development of a new derivative airplane, the kinematic layout of the manually controlled aileron system was rearranged to improve the system maintainability. In the process, the original system gearing ratio was kept unchanged to retain the similar system characteristics of the existing model, but the effect of the change in the kinematic layout on the overall system stiffness was overlooked. As a result, even with the same system gearing ratio maintained, the aileron control system became much stiffer, and the frequency of the symmetric aileron rotation, which affects the airplane's wing-aileron flutter stability, exceeded the acceptable level.

The frequency of the symmetric aileron rotation is defined as the natural frequency of the aileron control system at which both left and right ailerons are rotating in phase. Since the wing-aileron flutter is induced by an aeroelastic coupling of the wing torsion and the symmetric aileron rotation, the frequencies of these two modes must be safely separated under all flight conditions. For manually controlled aileron systems, the frequency of the aileron symmetric rotation is usually kept lower than the wing torsional frequency. The maximum allowable frequency is determined depending on the aeroelastic design of wings and ailerons.

The first illustration shows a schematic of the aileron control system in question, which consists of mechanical elements such as sectors, cables, and linkages. The system gearing ratio (G_A), which is defined as a ratio of the pilot force (P) to the aileron hinge moment (HM_A), can be also expressed by the system design parameters as follows:

$$G_A = \frac{P}{HM_A} = \pm \frac{R_H R_{MO}}{R_W R_{MI}} \cdot \frac{12}{R_S G_S} \quad [1/ft] \quad (\text{Eq. 1})$$

Sign Convention: + for Right Aileron, - for Left Aileron

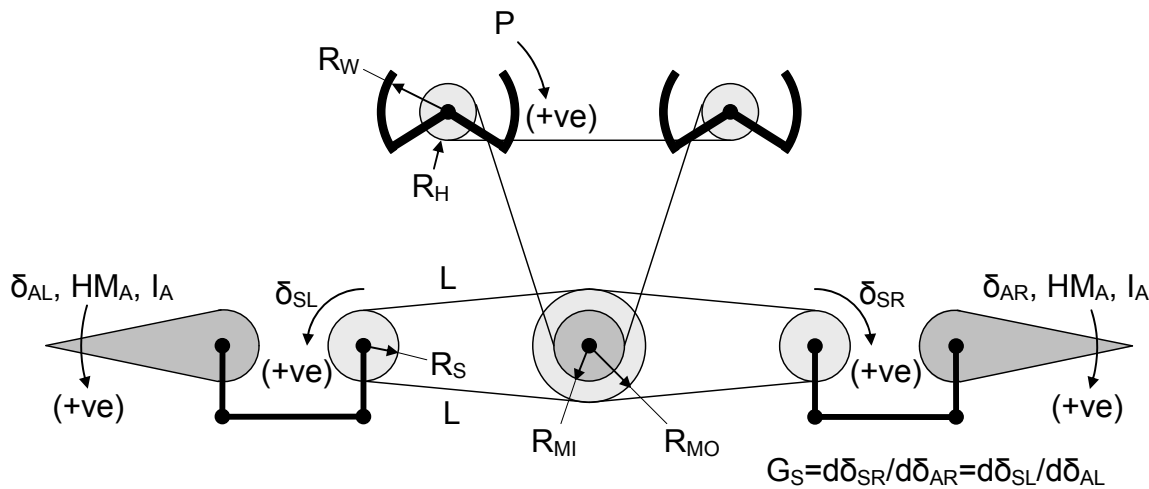
The frequency of the symmetric aileron rotation (f_A) of this system can be calculated by the following equation:

$$f_A = \frac{R_S G_S}{2\pi} \sqrt{\frac{386}{I_A} \cdot \frac{2EA(1-\zeta^2)}{L}} \quad [\text{Hz}] \quad (\text{Eq. 2})$$

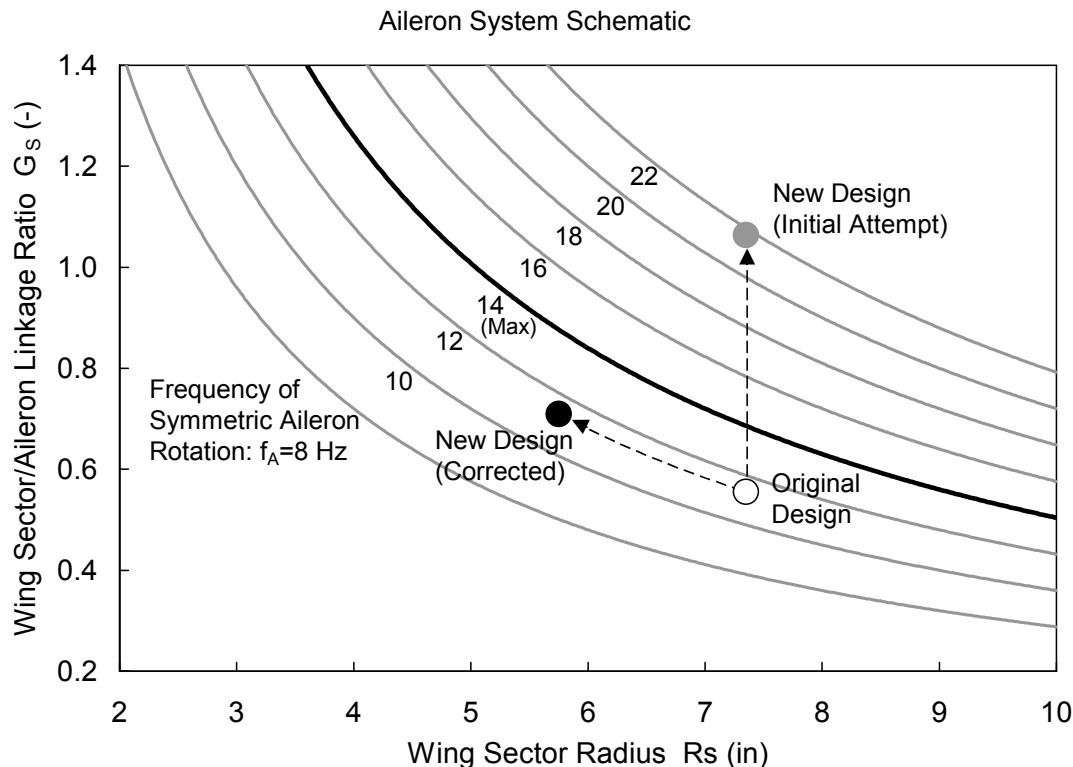
Definition of the symbols used in these equations are provided in the aileron system schematic. The Equation 2 reveals that the frequency of the symmetric aileron rotation will increase proportionally with the product of the two parameters, the wing sector radius (R_S) and the wing sector/aileron linkage ratio (G_S), assuming that the other parameters remain unchanged.

In the initial modification, the wing sector/aileron linkage ratio (G_S) was increased by 92 % to improve the aileron position adjustability, then the sector radii (R_H , R_{MI} , R_{MO}) were rearranged to retain the original system gearing ratio, while the wing sector radius (R_S) was kept unchanged. As a result, the estimated frequency of the symmetric aileron rotation went up twice as high (from 11 Hz to 22 Hz), exceeding its acceptable limit of 14 Hz. If this problem had not been detected until the ground vibration testing (GVT), right before the envelope expansion flight testing, a design change in the control system in such a late stage could have caused a serious program delay.

ILLUSTRATIONS:



Symbol	Definition	Symbol	Definition
EA	cable primary modulus (lbs)	P	pilot force (lbs)
f _A	frequency of symmetric aileron rotation (Hz)	R _H	control wheel hub radius (in)
G _A	system gearing ratio (1/ft)	R _{MI}	mid-sector radius - input (in)
G _S	wing sector/aileron linkage ratio (-)	R _{MO}	mid-sector radius - output (in)
HMA	aileron hinge moment (ft-lbs)	R _S	wing sector radius (in)
I _A	aileron surface inertia (lbs-in ²)	R _W	control wheel radius (in)
L	wing cable length (in)	ζ	damping factor (-)



Frequency of Symmetric Aileron Rotation Related to System Kinematics

SOLUTION: Fortunately, this issue was identified during the preliminary design phase and a corrective action was taken in a timely manner. Knowing from the Equation 2 that the constant $R_S G_S$ value would retain the frequency of the symmetric aileron rotation unchanged, the radius of the wing sector (R_S) was reduced, and the wing sector/aileron linkage ratio (G_S) increased, so that the original $R_S G_S$ value remained constant. In this way, the original system gearing ratio could be also retained without rearranging the radii. of the other sectors. The second illustration compares the design steps taken in the initial attempt and the corrective action.

The final configuration of the aileron control system successfully regained desired system characteristics, with the same system gearing ratio and frequency of the symmetric aileron rotation as those of the existing model, and at the same time, achieved the originally intended improvement of the aileron position adjustability to an acceptable level.

LESSON LEARNED: Characteristics of a manually controlled aileron system could be appreciably affected depending on how the entire system is kinematically laid out, even if the system gearing ratio is retained unchanged. When the system layout needs a modification, the effect of the design change on the system characteristics, such as the system gearing ratio, the system stiffness, and the frequency of the symmetric aileron rotation, should be carefully evaluated in the early design phase, as characteristics out of the acceptable limits may lead to an unsafe flutter mode or unfavorable handling qualities.

3.1.2.6 Similar Components Subject to Contamination Common Mode Failure

PROBLEM: FBW servoactuators - fluid contamination as a common failure mode

YEAR OF ACTIVITY: Mid 1970s

ISSUE

- FBW servoactuator controlled by two electronic channels
 - COMMAND (COM) controls the EHSV
 - MONITOR (MON) controls the shut –off valve which is a modified EHSV of identical technology
- A runaway occurred that could not be passivated by the monitoring lane
- Fluid contamination disturbed both valve first stages simultaneously
- By design these two first stages were equally sensitive to fluid contamination

SOLUTION: Hardware dissimilarity introduced in subsequent designs (ex: COM uses EHSV, MON a solenoid valve)

LESSON LEARNED: In command/monitor architectures employ dissimilar components in the two channels to minimize the risk of common mode failures.

3.1.2.7 Digital Noise with Actuator in Damped Mode

PROBLEM: Servovalves on a FBW transport aircraft were responding to high frequency digital noise inputs when the actuator was in the Damped mode, which caused excessive pressure fatigue within the actuator.

Actuators were being returned from the field with cracked manifolds.

YEAR OF ACTIVITY: Late 1990s.

ISSUE: The control surfaces each have two actuators in an Active/Standby arrangement. The Standby actuator normally is in Damped mode, but its servovalve remains pressurized with its input commanded to null and output control ports are blocked.

The Flight Control Computer (FCC) digital noise on the servovalve command would pass through the valve and create pressure oscillations. These oscillations, exacerbated by the small trapped fluid volumes and the long exposure times, caused excessive fatigue on the manifold housing.

SOLUTION: The FCC was modified to add a bias command to the servovalve when the actuator is in Damped mode. The bias was sufficient to ensure the valve is commanded outside its null region for any feasible valve null tolerance.

Thus the servovalve output control ports are fixed at either supply or return pressure, eliminating the pressure oscillations.

LESSON LEARNED: Even in Damped mode, a pressurized servovalve can cause unwanted effects if its input and output are not carefully considered.

- Conduct early integration testing with the FCC and look carefully for unusual interactions between the digital FCC and servocontrol devices, causing effects such as damaging cyclic pressures.
- Ensure that the integration test units include any instrumentation required, such as cylinder port pressures.
- Characterize and control the digital electronic noise with the FCC to servocontrol Interface Control Document (ICD).

3.1.2.8 Digital Noise on Actuator Command Signal

PROBLEM: Surface oscillations were observed on some FBW commercial aircraft at approximately 30 Hz.

YEAR OF ACTIVITY: Late 1990s.

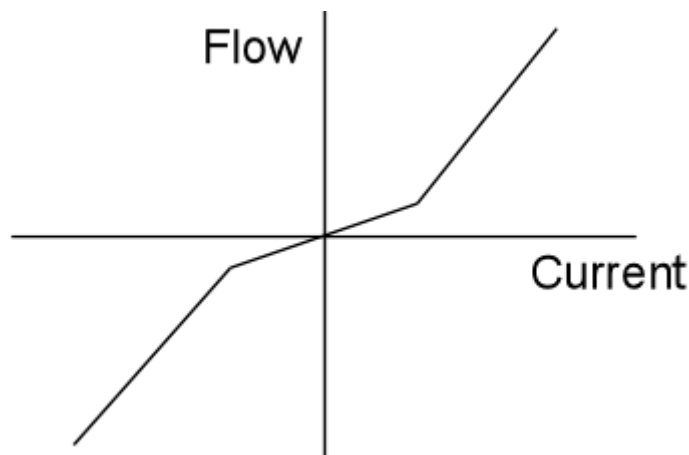
ISSUE: The servovalves on the flight control actuators were responding to 30 Hz FCC digital noise on their command signals

- This servovalve response was causing the surface to move at a small, but noticeable, amplitude.

SOLUTION: A dual slope flow gain was introduced into the servovalve design - low flowgain in the null region and a normal flowgain outside the null region.

- This helped filter out the response flow to the actuator.

ILLUSTRATION:



Servovalve Dual Slope Flow Gain

LESSON LEARNED:

- Conduct early integration testing with the FCC and look carefully for unusual interactions between the digital FCC and servocontrol devices causing effects such as unacceptable surface motions or damaging cyclic pressures.
- Ensure that the integration test units include any instrumentation required, such as cylinder port pressures.
- Characterize and control the digital electronic noise with the FCC to servocontrol ICD.

3.1.3 Power Distribution Systems

3.1.3.15 Tailoring Flight Control Hydraulic System Power Demands

PROBLEM: Advanced aircraft place large demands on the hydraulic system. The challenge is to design a system that can meet the demands, minimize weight, volume, cost, heat rejection, while improving reliability and maintainability.

YEAR OF ACTIVITY: Mid 1990s

ISSUE: There are numerous control surfaces on today's and future tactical aircraft. Many of the surfaces serve double duty. For instance, the leading and trailing edge flaps are scheduled to maximize performance (minimize drag and maximize lift), but they are also used to roll the aircraft. Since ailerons, flaps and differential stabilator are used for roll, an aircraft can lose functionality of a surface, or even two surfaces and still retain enough roll power to safely land the aircraft. It is possible for several of the surfaces to move at near their maximum rate simultaneously. This places large demands on the hydraulic system. Weight is critical for aircraft. Therefore a way to keep the hydraulic system horsepower to a minimum while meeting the aircraft requirements was needed.

SOLUTION: Hydraulic flow and pressure multiply to produce horsepower. Hydraulic power requirements drive aircraft weight, volume and cost. Control surface size and deflection and aircraft maximum speed are hinge moment drivers. They influence system pressure and actuator size. Control surface rates and actuator size determine the flow rate. The surface rates are determined by airframe dynamics and by flying qualities requirements. At high speed, where high hinge moments (and therefore high pressures) are required, surface rate requirements are generally lower than at low speed. The actuator rates can be controlled by the Flight Control Computer (FCC) to limit horsepower requirements. The pump itself limits flow at the high pressure setting, thereby limiting horsepower. At low speed, where the high surface rates are required, the FCC limits pump pressure, and allows full-pump flow, thereby limiting horsepower requirements and heat dissipation. Requirements based on the combination of high pressure and low rates or low pressure and high rates results in an efficient pump that has a lower horsepower requirement than a conventional system. This leads to reduced requirements on the drive train and lower heat dissipation requirements. Weight savings to the pump, drive train and heat dissipation system can be significant. Aircraft range will be increased when cruising at the low pressure setting, since horsepower extraction from the engine is reduced.

LESSON LEARNED: Integration of requirements is the key to energy efficient lower weight hydraulic system design:

- Dual hydraulic pressure
- Limiting of pump horsepower
- Limiting component installation envelopes

Aircraft benefits from tailoring hydraulic power demands:

- Reduced weight
- Lower heat rejection for low speed and ground operation
- Increased range
- Reduced production cost

3.1.3.16 Tube Failures in Long, Dead-Ended Pipelines

PROBLEM: Tube failure in long dead-ended pipelines

YEAR OF ACTIVITY: 2005

ISSUE: Failures were reported of some tubes that supply small hydraulic actuators in landing gear and landing gear door uplocks. Investigation into the cause of these tube failures revealed that there was a significant movement of these tubes when the landing gear or their associated doors was selected to extend or retract.

It was subsequently found that the presence of a significant quantity of free air in these lines caused the large pressure spikes which in turn caused these large tube movements which in turn ultimately caused the failures. The presence of this free air was considered to be due to the tube geometry and because they were long and dead-ended with only a small amount of fluid required to operate the uplock actuators.

SOLUTION: A manifold was introduced into the affected lines that incorporated:

- An external bleed valve
- A one-way restrictor device

The use of the one-way restrictor enabled any free air in the pipelines to be purged out of the affected line, when the gear or door was in transit, to a separate return line back to the hydraulic reservoir. The size of the restrictor was established by test to be the minimum required to purge the lines and the manifold is only pressurized when the gear or door is being operated (thereby reducing any heating effect to the minimum).

LESSON LEARNED: When designing a hydraulic system that uses long dead-end tubes and supplies small amounts of hydraulic fluid, take care that there are means to ensure that an accumulation of air cannot occur. If it is deemed that there is a possibility of the accumulation of air, then either design the installation of the lines such that this cannot occur, or introduce a means of removing the air.

3.1.4 Utility Control Systems

This subsection applies to systems that provide control of non-critical functions for aircraft and other vehicles.

3.1.4.3 Incorporation of Off-The-Shelf Hardware

PROBLEM: Incorporating Off-the-shelf (OTS) hardware into new launch vehicle application

YEAR OF ACTIVITY: 2009/2010

ISSUE: A government agency has experienced many different issues while trying to incorporate existing OTS aircraft hardware into the hydraulic system for a new launch vehicle:

- Tried to incorporate hydraulically pressurized aircraft boot-strap reservoir
- Tried to incorporate an OTS aircraft motor pump

OTS hardware qualification requirements may not completely envelop qualification requirements for new applications.

Any design changes that may be required to be made to OTS hardware may nullify its qualification history.

Vendor may decide they do not want to incorporate any changes to an existing production OTS hardware design.

Incorporating OTS hardware into new application often leads to compromised design solution not optimized for new application.

OTS hardware design may not be able to adapt to significant requirements changes for new application.

Vendor may be phasing out production of OTS hardware or vendor may no longer be in business.

SOLUTION: The agency plans to incorporate custom design solutions into the hydraulic system of the new vehicle.

- Incorporating a custom gas pressurized bellows reservoir as opposed to a modified OTS hydraulically pressurized aircraft boot-strap reservoir
- Incorporating a custom designed motor pump as opposed to an existing OTS aircraft motor pump

LESSON LEARNED: Although incorporating OTS hardware into a new application may appear to offer significant benefits early on, a custom hardware design solution may be the best overall approach in the long run especially for a new space launch vehicle program.

- As is often experienced during launch vehicle development, requirements may not be well established early in the program.
- Vendors are more likely to fully participate throughout duration of flight program if they are involved in developing hardware early in program.

3.2 Actuation Lessons Learned

3.2.1 Electrohydrostatic Servoactuators and Actuators

This subsection will contain Lessons Learned in the design and development of electrically powered servoactuators and actuators, including Electrohydrostatic Actuators (EHA) and Electrohydrostatic Modules (EHM), though not electromechanical servoactuators, which are addressed in 3.2.3.

3.2.1.1 Entrapped Air and EHA Pump Failures

PROBLEM: Hydraulic pump failure during integration test on EHM/EHA

YEAR OF ACTIVITY: 2005

ISSUE: Significant number of pump failures (piston jamming) occurred during integration tests on the Electrohydrostatic Module (EHM) and the Electrohydrostatic Servoactuator (EHA), at the early stage of the program (development phase). After pump assembly on motor, the motor-pump is tested to verify its performance before its integration on the EHA. Pump failure occurred during partial tests or during EHA acceptance tests due to presence of air in the EHM/EHA hydraulic fluid circuits.

SOLUTION: Motor pump bleeding procedure has been improved on motor-pump integration test stand and during motor-pump integration on EHA to remove air from EHA hydraulic circuits.

Motor-pump and actuator designs have been modified (bleeding points added) to achieve a better bleeding of the actuator and of the motor-pump during integration phases.

Very few failures were reported then in serial production.

LESSON LEARNED: EHM and EHA shall be designed to avoid entrapment of air volumes within EHA hydraulic circuits, the actuator power ram and in the motor-pump during EHM/EHA assembly and tests.

3.2.1.2 Unbalanced Area EHA Instability

PROBLEM: Unbalanced area EHA (utilizing a three-port pump) instability.

YEAR OF ACTIVITY: 2005

ISSUE: Instability of unbalanced area EHA utilizing a three-port pump, involving interaction of the EHA architecture, its implementation, and EHA closed loop control.