JAN 22 2007

B17350828

TL
678-8
L34
2046

Control Design and State of the Art for Fly-By-Wire Systems

By:

Sean A J Lahey

B. Eng Aerospace, Carleton University, Ottawa, 1999

A Project Report

Presented to Ryerson University

In partial fulfilment of the requirements for the degree of

Masters of Engineering

In the Program of

Mechanical Engineering

Toronto, Ontario, Canada, 2006

©(Sean A J Lahey) 2006

UMI Number: EC53597

INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

UMI Microform EC53597
Copyright 2009 by ProQuest LLC
All rights reserved. This microform edition is protected against
unauthorized copying under Title 17, United States Code.

ProQuest LLC
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106-1346

Author's Declaration

I hereby declare that I am the sole author of this project report, except as noted. I authorize Ryerson University to lend this report to other institutions or individuals for the purpose of scholarly research.

Sean A J Lahey

I further authorize Ryerson University to reproduce this report by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

Sean A J Lahey

Abstract

The report discusses the design and operation of electro-hydraulic servo-valves, illustrates a basic control implementation design for an electro-hydraulic servo-valve controlled hydraulic actuator [for aircraft flight control actuation] and provides a survey of the state of the art of flight control of aircraft using fly-by-wire (FBW) architecture. The electro-hydraulic servo-valve figures prominently in typical FBW implementations and is an essential part of a modern aircraft flight control system. The scope of this report represents a large area of research, presented at a general level, and serves as a general summary of technologies and considerations for modern aircraft flight control.

Fly-by-wire provides many advantages over traditional forms of aircraft flight control, and it represents both the state of the art in this area and also the future of almost all civilian and military aircraft flight control. The architecture, characteristics and control design relating to electro-hydraulic servo-valve controlled actuators is discussed in the report. The application of such actuators to fly-by-wire implementation is discussed in some depth, and the process by which fly-by-wire systems are developed is discussed.

Acknowledgements

The project builds upon knowledge collected in several Ryerson University graduate courses, including advanced systems control, and the support and assistance of Professor G. Liu, Ryerson University, is gratefully acknowledged.

The Society of Automotive Engineers, SAE, collects a great deal of information on many subjects relating to aerospace and mechanical engineering and design as a means of promoting improved design standards across many industries. Several SAE papers were heavily referenced in the research for this report (see notes and bibliography).

Alex Parsi, Flight Control System Specialist at Bombardier Aerospace, Toronto, provided guidance and explanation of several aspects of valve design and aircraft system architecture. This assistance is greatly appreciated and has helped ensure the integrity of this report.

Dedication

This report is dedicated in two parts.

First, to my family, who has always believed in my efforts, and has supported me in the Masters Degree endeavour, as in all other aspects of life. My greatest thanks to Dad, Mom, and Jen.

Secondly, to my technical mentors at Bombardier, who provided the structure and perspective to guide not only the development of this report, but also my career. Thanks Alec, Alex, Harry, Dave, Zoran, Dan, Jacek, Bill and Heather.

Table of Contents

Author's Declaration.....	ii
Abstract.....	iii
Acknowledgements.....	iv
Dedication.....	v
Table of Contents.....	vi
Table of Figures.....	vii
Table of Equations.....	1
Parameter Glossary.....	2
1: Introduction.....	3
2: Electro-hydraulic Servo Valves.....	5
3: Servo-valve Design and Modelling Considerations.....	7
4: Modelling of Electro-hydraulic Servo-valve for Control Design.....	9
5: Control Design and Simulation.....	16
6: Results of Simulation and Discussion.....	18
7: Simulation and Control Design Conclusions.....	27
8: Aircraft Flight Control Systems Overview.....	28
9: Hydraulic System Architecture.....	30
10: Fly-by-wire Flight Controls Overview.....	33
11: Fly-by-wire Design Considerations.....	39
12: Fly-by-wire: the State of the Art.....	41
Airbus 320/330/340.....	41
Servo-actuator Operating Modes and System Reconfigurations.....	44
Boeing 777.....	47
Actuator Modes of Operation 777.....	47
13: Design and Development Process for Fly-by-wire.....	50
Major Design Phases.....	50
Actuation Requirements.....	55
Controller Requirements.....	55
Actuator Requirements.....	56
Servo-electronics Requirements.....	57
Interface Requirements.....	59
Details Design.....	59
14: Fly-by-wire Future Developments.....	62
15: Conclusions – Fly-by-wire Survey.....	64
16: References.....	65
Appendix A: Matlab Code.....	A
Appendix B: Modified Code.....	D

Table of Figures

Figure 1Figure 1 – Single Stage EHSV Showing Control Coils, Flapper Design Flow Control (Moog, Ref.1).....	5
Figure 2 - Primary Stage Hydraulic Nozzle (typical)	6
Figure 3 - Typical EHSV (Moog, Ref. 1) - Flapper Arrangement	8
Figure 4 - Model of Electro-hydraulic Servo Valve	9
Figure 5 - Top Level Electro-hydraulic Actuator Diagram	10
Figure 6 - Block Diagram for a Typical EHSV Implementation (Ref. 3)	11
Figure 7 - Generic Servo Valve With Mechanical Feedback Wire	12
Figure 8 - State Matrix for Electrohydraulic Actuator – Representative State Matrix.....	15
Figure 9 - Actuator Output Response to Sin Input (+/- 40mA) in Inches (Time scale (x-axis) in seconds).....	18
Figure 10 - Transient [Step] Response of Natural System vs. System with State Gain Implemented	19
Figure 11 - Bode Frequency and Phase Response of Natural System vs. System with State Gain Implemented	20
Figure 12 - Schematic Showing Scaling of Gain Feedback	21
Figure 13 - Bode plot - Transformation Method	22
Figure 14 - Response to SIN Input (response in inches, time scale in seconds).....	22
Figure 15 - Closed Loop Response with Gain Feedback.....	23
Figure 16 – Pole Iteration 1	24
Figure 17 – Pole Iteration 2	24
Figure 18 - Pole Iteration 3	25
Figure 19 - Step Response of with Gain Scaling	26
Figure 20 - Typical Aircraft Hydraulic Systems Architecture - 3 System Design (Canadian National Transportation Safety Board).....	32
Figure 21 - Fly-by-wire Actuation Schematic (SAE, Ref. 6)	34
Figure 22 - Concorde Supersonic Transport W/Analogue FBW Primary Control.....	35
Figure 23 - F-111 ('Ardvark') Variable Geometry Strike Aircraft.....	36
Figure 24 - - Illustration of EHSV Sensitivity and Resulting Spoiler Panel Extension (Ref. 4). 36	
Figure 25 - Typical FBW Actuator Implementation.....	38
Figure 26 - - Airbus Generic (A330) Flight Control Layout (Y, G, B = Yellow, Green, and Blue Hydraulic Systems, Respectively)	43
Figure 27 - Airbus A320 Fly-by-wire Controlled Aircraft	45
Figure 28 - Airbus A330 Typical Actuator Schematic	46
Figure 29 - Boeing 777 Rudder Actuator Schematic.....	49
Figure 30 – System Development Milestones	51
Figure 31 – System Development Timeline	52

Table of Equations

Equation 1 – Chamber #1 Flow Calculation.....	12
Equation 2 – Bulk Stiffness Calculation.....	12
Equation 3 – Chamber #2 Flow Calculation.....	13
Equation 4 – Chamber #1 Flow Calculation – Pressure Relations.....	13
Equation 5 Chamber #2 Flow Calculation – Pressure Relations	13
Equation 6 – Coil Dynamics: Current/Voltage Relation	13
Equation 7 – Spool Control Sensitivity Relation.....	13
Equation 8 – Actuator Dynamics.....	14
Equation 9 – Linearized Equations	14
Equation 10 – State Representation Format.....	14
Equation 11 – Sate Variables Vector	14
Equation 12 – Actuator Plant Model –State Form.....	14
Equation 13 - Actuator Model State, Input, and Output Matrices	15
Equation 14 – Controllability Matrix.....	16
Equation 15 – State Matrix Calculation with State Feedback	17
Equation 16 – Transformed Sate Matrix Calculation	17
Equation 17 – Transformed Input Matrix Calculation.....	17
Equation 18 – Controllable Canonical State Matrix Calculation.....	20
Equation 19 – Transformation Matrix	20

Parameter Glossary

K_{fs}	Failsafe spring constant	100 lbf/in
K_{ft}	Fluid Bulk stiffness	2.2×10^5 lbf/in
A_p	Piston Area	3.5 in ²
F_c	Coulomb friction	200 lbf
F_a	External shroud force	Arbitrary
$\dot{P}_1 = P_s/2$	Chamber 1 Pressure Rate	1500 psi
$\dot{P}_2 = 2P_a$	Chamber 2 Pressure Rate	100 psi
P_s	Supply Pressure	3000 psi
P_a	Return Pressure	50 psi
m	Servo-valve mass	2.4 lb, 3.08×10^5 lbs ² /in
V_a	Volume	2.13 in ³
V_r	Volume	1.66 in ³
C_d	Valve Discharge coefficient	0.618
F_a	Actuator force	8000 lbf
D_s	Spring diameter	0.5 in
X_a	Actuator position	State variable
P_1	Actuator pressure chamber 1	State variable
P_2	Actuator pressure chamber 2	State variable
x_s	Servo spool position	State variable
I	Servo current	Controller output
I_r	Rated current	40 mA
R_c	Coil resistance	80 ohm
L_c	Coil Inductance	0.02H
τ	Time constant	1.8 ms
c	Actuator damping	0.5
G	Sensitivity to driving current	3.0 cis/mA
K_{pq}	Leakage coefficient	0.1
ρ	Fluid density	9×10^{-5} lbs ² /in

1: Introduction

The overall goal of the research activity that culminated in this report is the full understanding of aircraft flight control systems; specifically the focus was on fly-by-wire systems, and associated technologies. In support of this end, and also as a means of supplementing the survey portion of the undertaking, a control design for an electro-hydraulic actuator and simulation is conducted.

In order to examine a simple control design for a typical fly-by-wire aircraft actuator using state space methods, it was first required to fully understand the mechanisms and physics involved. Although incomplete models are available for such actuators, a thorough understanding of the required modelling was sought. First, the design and function of electro-hydraulic servo-valves are summarized; these devices take an electrical signal (from a pilot and/or computer) and turn it into a mechanical movement by means of controlling hydraulic fluid flow to an actuator.

This type of actuator is increasingly typical in modern aircraft flight control architecture and is incorporated into digital flight control (fly-by-wire) systems. Basic state feedback using proportional control was selected as the control method. Simulation of the control design is performed using the Matlab/Simulink package in support of ensuring that the controller is stable as designed and that the actuator obeys the aircraft level laws that are imposed on the system. Included, where applicable, are Matlab code, block diagrams, and simulation results (ref. Appendices)

Special attention is paid to development considerations and process for fly-by-wire flight control systems of aircraft.

This report provides a close look at the means of hydraulically powering and controlling an aircraft's primary and/or secondary control surfaces by means of electro-hydraulic servo-valves and appropriate actuators. The architectures of several modern aircraft are used as examples of typical fly-by-wire implementations. It is noted that the author has experience in the integration and certification of a fly-by-wire based systems on the modern business aircraft whose secondary controls are all digitally monitored, electronically controlled, and hydraulically or electrically powered.

Typically, the actuator is hydraulically powered and its characteristics are determined by the operational requirements such as rate, force, and phase response. Hydraulic fluid powers the ram or piston of the actuator in either the extending or retracting direction, in accordance with the required surface position (as

determined by the pilot or flight guidance computer and autopilot). Linear motion of the piston results in rotation of the surface about a hinge-line due to the attachment of the actuator to the surface relative to its hinge location.

Electrical feedback of position (typically a linear variable differential transformer) is provided to the controller. The controller modulates hydraulic pressure to the extension or the retraction side of the actuator (input) in order to achieve the desired position output. The pressure is modulated by the controller via an electro-hydraulic servo valve (EHSV), which uses current in coils to control the position of the fluid-metering device. The metering device is typically a flapper valve. Therefore the input and output quantities are EHSV current and position, respectively.

Modelling of such an actuator as the plant to be controlled involved some assumptions where real-world parameters were not known. Such actuators typically include non-linearities, and linearization may be used in the control design. For the purposes of this project, the plant will be modelled as linear. Research showed that this is a reasonable approximation, and typical aircraft actuator design is modelled in this fashion, as will be described in more detail herein. Since the non-linearities are often part of the lower level operation of the actuator, but the overall position of the actuator's output is the controlled variable, these approximations are generally accepted, especially for trial and comparison of different system configurations during initial design trade studies.

In a real application, once modelled, the control system's response characteristics will be refined and adjusted based on overarching aircraft level response and performance requirements. Where possible, these will be based on actual aircraft requirements, or on the limitations imposed by utilizing non-cutting edge processing power (i.e. the flight control computers on many modern aircraft have computing power analogous to 086 processors from the late 1980s).

2: Electro-hydraulic Servo Valves

Servo-valves are used extensively in hydraulic actuator implementation, where pressure and/or position feedback is required. The pressured hydraulic oil provides the motive power for the control valve actuation, and also provides the fluid power to extend or retract a hydraulic actuator (or to spin a hydraulic motor at a given rate). Servo-valves may be used to precisely control the flow of hydraulic fluid in order to provide position control, velocity (speed) control, or force control (or a hybrid requirement of these and other types of actuation). Typically, a servo-valve is a valve that uses its own spool position to feedback to control; regardless of whether it is active (processor intensive) or passive (i.e. governor).

Figure 1 – Single Stage EHSV Showing Control Coils, Flapper Design Flow Control (Moog, Ref.1)

The type of servo valve depicted in Figure 1 is often used for steady state control, rather than to control position using an error signal. Flow control of fluid through a hydraulic actuator, for example, would be controlled in this fashion. This type of valve is a single stage design (only one spool ports hydraulic fluid), and variations are sometimes referred to as a direct drive valve since the control signal (driving the coils in the torque motor) controls the power stage almost directly.

Typically a servo-valve has two stages; the primary stage is the control stage, and determines how oil is ported to the second stage, which opens larger ports to control flow of hydraulic fluid to an actuator – the

power stage. The second stage is passive, and its position is determined by the primary stage. The second stage is typically a sliding spool type of valve, that selectively covers or uncovers hydraulic ports by sliding, and allows fluid to flow to an extend or retract actuator side.

The primary stage of the valve in this case is controlled by voltage applied to the coils of a torque motor (see Figure 1). The torque motor, in turn, positions a nozzle that creates a jet of hydraulic fluid (see Figure 2). When the jet is biased to one direction or the other by the torque motor, the second stage valve spool receives a differential pressure signal, causing it to shuttle in the desired direction, and allow the high-pressure hydraulic oil to reach the actuator. This method of controlling the power stage is called a jet-pipe design, after the jet of hydraulic fluid that is used to alter the hydraulic balance acting on the second stage. And alternate type of valve (depicted in Figure 1) has a similar layout, but the armature controls a flapper device that meters fluid pressure to either side of the actuator.

Figure 2 - Primary Stage Hydraulic Nozzle (typical)

The design of the ports, jet nozzle, and valve spool is an exercise in precision hydraulic and mechanical engineering, and is much guarded proprietary information in the actuator industry.

A modern variation on valves for control of actuators replaces the two stage design with a single large stage, which is powered by a powerful electrical torque motor. These valves have advantages of less moving parts, and can have improved dynamic response.

A consideration in all servo-valve design is its chip-shearing capability. That is its ability to shear a chip of metal that may be washed into the valve as contamination. This is important to preventing jams, although most small clearance valves and devices in aircraft hydraulic systems will incorporate a screen filter to prevent large debris from entering the controlling portions of the valve.

3: Servo-valve Design and Modelling Considerations

A discussion of servo valve design considerations is included here for completeness. From the cited references for this report (including information from Moog), the following discussion is provided. Moog designs servo-valves and EHVS devices for many of the world's aerospace applications.

It is often convenient in analysis of servo valves to represent an electro-hydraulic servo-valve by a simplified transfer function. Such a representation is, at best, only an approximation of actual servo-valve performance. However, the usefulness of linear transfer functions for approximating servo-valve response in analytical work is well established. The difficulty in assuming an explicit transfer function for electro-hydraulic servo-valves is that many design factors and many operational and environmental variables produce significant differences in the actual dynamic response. Consider the variables of the valve design. It is known that internal valve parameters (e.g., nozzle and orifice sizes, spring rates, spool diameter, spool displacement, etc.) may be adjusted to produce wide variations in dynamic response. This was evidenced in the simulation portion of this project, as discussed later (Ref. 2).

Once a servo-valve is built, the actual dynamic response will vary somewhat with operating conditions such as supply pressure, input signal level, hydraulic fluid temperature, ambient temperature, valve loading, and so forth. Hydraulic fluid stiffness also varies a large amount with air contamination. These effects are insignificant for small variations about design values, but would need to be considered in a real application where wide excursions are anticipated. Another difficulty in assigning simplified, linear transfer functions to represent servo-valve response is that these valves are highly complex devices that exhibit high-order, nonlinear responses. If a first, second, or even third-order transfer function is selected to represent servo-valve dynamics, still only an approximation to actual response is possible. Fortunately, for most physical systems, the servo-valve is not the primary dynamic element, so it is only necessary to represent valve response throughout a relatively low frequency spectrum. For instance, if a servo-valve-actuator is coupled to a load which exhibits a 10 Hz resonant frequency, it is really meaningful, only, to represent valve dynamic response in the frequency range to 50 Hz. This obeys the generally applied factor of 5 margin between the load resonant frequency and the servo-valve response. Similarly, for lower response physical systems, the contribution of valve dynamics throughout correspondingly smaller frequency range need be considered. Further discussion of system simplification is provided in the modeling section of this report (4).

Figure 3 - Typical EHSV (Moog, Ref. 1) - Flapper Arrangement

A simple first or second order model yields only an approximation to actual behavior, however the servo-valve is not the primary dynamic element in a typical hydraulic servo system and is generally selected such that the frequency of the 90 degree phase point is a factor of at least three times higher than that of the actuator. For this reason it is usually only necessary to accurately model valve response through a relatively low range of frequencies, and the servo-valve dynamics may be approximated by a second order transfer function without serious loss of accuracy.

This is supported by the fact that aircraft controls need a no phase lag response only to a frequency of approximately 2-3 Hz in application. A valve that is designed to have gain larger than is absolutely required, and a phase response as described, is said to have adequate gain and phase margins; these are commonly referenced terms in the servo-valve design field.

4: Modelling of Electro-hydraulic Servo-valve for Control Design

The accurate modelling of the plant and control implementation is a non-trivial task that requires an understanding of the mechanics and physics of the plant; in this case, a hydraulic actuator. A block diagram of an actuator controlled by means of electro-hydraulic servo valves is provided below, and is based on analysis of such an actuator as used in an actual fly-by-wire implementation (Bombardier).

It was determined that a simplified, mostly pre-existing model would be used for this research project, to demonstrate the control design method. Research, however, was conducted, and a basic model constructed in the initial stages of this project; the below model represents an electro-hydraulic servo-valve as coupled with a spoiler flight control surface. The fully comprehensive model would take into account the following dynamics as subsystems or transfer functions:

- Fluid dynamics
- First stage (spool) dynamics
- Actuator body dynamics
- Load dynamics (hinge moment as a function of surface deflection magnitude and rate)
- Non-linearities (backlash, pressure effects, etc.)
- Backup structural stiffness

Electrohydraulic Servo Actuator Block Diagram

Figure 4 - Model of Electro-hydraulic Servo Valve

Removing the surface and external non-linearities from consideration, and adding consideration for some more external system components the system can be represented as in the next figure. The actual system is typically non-linear, as will be explained later in this section.

Figure 5 - Top Level Electro-hydraulic Actuator Diagram

The design of systems incorporating such actuators and valves would typically employ several methodologies in order to simplify the task. First, the model is often treated as linear, when, in fact (as discussed above), the actuator displays higher order non-linear behaviour. Most analysis, therefore, would be approximating, with a reasonable error to the physical plant. Again, because the overall performance requirements are at the control surface itself, and the control feedback is provided in the form of position. This tends to wash out the non-linearities, supporting the use of a linear model for the actuator. The non-linearities associated with stiction, backlash, and other effects must be accounted for in the overall accuracy of the surface position sensing, and in its control. The overall system must be stable and in some cases, damping may be controlled to produce the required response rate and no more.

The complexity in modelling the actuator completely includes uncertainty over some parameters, as well as non-linearities such as hysteresis and mechanical backlash of the actuator and connections to the flight control surface (where the output feedback is acquired). Modelling the behaviour of such actuators,

therefore, can require in-depth knowledge of hydraulics, actuator and valve dynamics, as well as electromagnetic effects, owing to the design of the control valve.

It should be pointed out that a simplified (linearized) control design required for such an electro-hydraulic servo valve is within the scope of this report, used as demonstration of the application of control theory to the fly by wire design problem. However, the full modelling of such a system is outside the scope of this project report. The model for the electro-hydraulic actuator for the purposes of this control design project, therefore, is simplified using certain assumptions of linearity, as discussed above.

Figure 6 - Block Diagram for a Typical EHSV Implementation (Ref. 3)

Figure 6 represents the simpler system that will be modeled for the purposes of this project. The model that is used as basis for this project is extracted from a referenced paper (DeCastro and Melcher, NASA, Ref. 3). The model includes the electrical portion of the electro-hydraulic valve, but linearizes the model using several assumptions.

Matlab is used for the basic modeling and simulation since the mathematical model for the system is established. Simulink would be useful if modeling the actuator from first principals and using empirical data to refine the model. Simulink allows for adjustment of parameters that may change during the design process, such as servo-valve constants, backlash requirements, and surface load conditions.

The following description defines the development of the nonlinear servo-hydraulic actuator models and linearization assumptions used for the controller/estimator design, as discussed in the NASA paper; this analysis is in turn based on a popular modern hydraulics text (Hewitt et al).

The following figure is provided for illustration of the analysis; it is a generic electro-hydraulic servo valve, where varying current in the command coils positions the primary stage by porting fluid from a jet pipe orifice. The actuator is provided with fluid from this spool valve, and extends or retracts accordingly.

Figure 7 - Generic Servo Valve (With Mechanical Feedback Wire)

The extend and retract chambers of the actuator are arbitrarily referred to as #1 and #2 for this analysis. The net flow entering chamber #1 depends on the actuator velocity, the leakage induced by the chamber pressure, and the chamber fluid compliance, expressed as:

$$q_1 = A_p \cdot \dot{x}_a + K_{pq} \cdot P_1 + (A^2/K_\beta) \cdot \dot{P}_1$$

Equation 1 – Chamber #1 Flow Calculation.

where A_p is the piston area, K_{pq} is the leakage coefficient (here expressed as a linearized parameter), and K_β is the fluid's bulk stiffness. This bulk stiffness is a function of the fluid's modulus β and the chamber volume V , as described by the following equation:

$$K_\beta = (4 \cdot \beta \cdot A^{2p})/V$$

Equation 2 – Bulk Stiffness Calculation

It is assumed that the chamber volumes and piston areas on either side of the actuator are identical. For this study, a K_β of 2.2×10^6 lbf/in was used, representative of DTE-24 hydraulic fluid ($\beta = 150 \times 10^5$ psi). This figure was refined by the author based on research in separate references, as shown in the Matlab model (see Appendix A). The fluid exiting chamber #2 is described by a similar equation in terms of the pressure p_2 , and is expressed as follows:

$$q_2 = A_p \cdot \dot{x}_a - K_{pq} p_2 - (A_p^2 / K_{fl}) \cdot \dot{P}_2$$

Equation 3 – Chamber #2 Flow Calculation

The flow both into and out of the actuator are described by an orifice characteristic equation that accounts for resistive losses. The flow into chamber #1 is a function of the pressure drop across the orifice and the orifice size, which is piecewise about $x_s = 0$ assuming that the spool and orifice do not overlap or underlap at the null region:

$$q_{1+}(x_s, P_1) = C_d P_i d_s x_s \text{sgn}(p_s - p_1) \cdot \sqrt{(2/\rho |p_s - p_1|)}$$

$$q_{1-}(x_s, P_1) = C_d P_i d_s x_s \text{sgn}(p_1 - p_a) \cdot \sqrt{(2/\rho |p_1 - p_a|)}$$

Equation 4 – Chamber #1 Flow Calculation – Pressure Relations

Although this is not strictly accurate for actual servo-valves. The superscripts (+) and (–) denote the sign of x_s . Here, we assume that the valve is perfectly symmetric, so the flow coefficient C_d and the orifice areas are equal on both sizes of the valve. A similar relationship can be written for chamber #2 as:

$$q_{2+}(x_s, P_2) = C_d P_i d_s x_s \text{sgn}(p_2 - p_a) \cdot \sqrt{(2/\rho |p_2 - p_a|)}$$

$$q_{2-}(x_s, P_2) = C_d P_i d_s x_s \text{sgn}(p_s - p_2) \cdot \sqrt{(2/\rho |p_s - p_2|)}$$

Equation 5 Chamber #2 Flow Calculation – Pressure Relations

Direct substitution of Eqs. 5 into Eqs.4, respectively, gives a piecewise representation of the coupling between spool position and supply pressure. In order to couple the driving voltage to the actuator input flow, the dynamics of the coil and servo-compensator must also be incorporated into the model. Those of the coil are introduced by relating the loop current to the load voltage by writing:

$$u = L_c \cdot (d_i/d_t) + R_c \cdot i$$

Equation 6 – Coil Dynamics: Current/Voltage Relation

where L_c and R_c are the inductance and resistance of the coil, respectively. The time constant τ of the servo-compensator is reported by most manufacturers, which relates current to spool position.

This is modeled as:

$$G_i = \tau \cdot \dot{x}_s + x_s$$

Equation 7 – Spool Control Sensitivity Relation

where G is the sensitivity between current and spool position. Taking the expected actuator output of 0.750", and the EHSV coil capacity of +/-40mA derives this. The equation of motion for the actuator and shroud hangar completes the system model. These dynamics are incorporated by writing:

$$M \ddot{x}_a + c \dot{x}_a + F_c \text{sgn}(\dot{x}_a) + k_{fs} x_a = (p_1 - p_2) A_p - F_a$$

Equation 8 – Actuator Dynamics

Here, m is the combined mass of the shroud hangar and actuator rod, c is the viscous damping coefficient, k_{fs} is the stiffness of the failsafe return spring, F_c is the Coulomb friction force and F_a is the external (aerodynamic + other) force.

Eqs. 1 through 8 constitute the complete nonlinear model for the servo-hydraulic system. The linear model was developed by assuming that $x_s > 0$ for all time in order for the system to be described by $q_1(x_s, p_1)$ and $q_2(x_s, p_2)$ and only $p_s > p_1$ and $p_2 > p_a$, and $F_c = 0$. Eqs. 4 were evaluated at assumed mean chamber pressures to eliminate the nonlinear dependence on flow. To this end, p_1 and p_2 were heuristically linearized as being half of the supply pressure (3000psig for this application) and twice the return pressure (50psig), respectively. Eqs. 4 may then be substituted into Eqs. 1 and 3 as follows:

$$C_d P_i d_s x_s \sqrt{(2/\rho) (p_s - \bar{p}_1)} = A_p \dot{x}_a + K_{pq} p_1 + (A_p^2/k_{ft}) \dot{P}_1$$

$$C_d P_i d_s x_s \sqrt{((2/\rho) (\bar{p}_2 - p_a))} = A_p \dot{x}_a - K_{pq} p_2 + (A_p^2/k_{ft}) \dot{P}_2$$

Equation 9 – Linearized Equations

Now, the state space representation is taken (typically) to be as follows:

$$\dot{x} = Ax + Bu + Fw$$

$$y = Cx + Du + v_i$$

Equation 10 – State Representation Format

Formed by populating the state variables vector as:

$$X = \{x_a, \dot{x}_a, p_1, p_2, x_s, i\}^T$$

Equation 11 – Sate Variables Vector

Using the above equations, and transforming to state space form, as in equation 10, the plant behaviour:

$$A = [0, 1, 0, 0, 0, 0; (-K_{fs}/m), (-c/m), (A_p/m), (-A_p/m), 0, 0; 0, (-K_{ft}/A_p), -(K_{ft} * K_{pq})/A_p^2, 0, ((K_{ft} * C_d * 3.1415 * d_s)/A_p^2) * ((2 * (P_s - \bar{p}_1)/\rho)^{1/2}), 0; 0, K_{ft}/A_p, 0, -(K_{ft} * K_{pq})/A_p^2, ((K_{ft} * C_d * 3.1415 * d_s)/A_p^2) * ((2 * (\bar{p}_2 - P_a)/\rho)^{1/2}), 0; 0, 0, 0, 0, -(1/\tau_a), (G/\tau_a); 0, 0, 0, 0, 0, -(R_c/L_c)];$$

$$B = [0; 0; 0; 0; 0; 1/L_c];$$

$$C = [1, 0, 0, 0, 0, 0];$$

Equation 12 – Actuator Plant Model –State Form

The following figure shows the same equation in true state representation, after NASA: “A Study on the Requirements for Fast Active Turbine Tip Clearance Control Systems”:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -\frac{k_{fs}}{m} & -\frac{c}{m} & \frac{A_p}{m} & -\frac{A_p}{m} & 0 & 0 \\ 0 & -\frac{k_{fl}}{A_p} & -\frac{k_{fl}K_{pq}}{A_p^2} & 0 & \frac{k_{fl}C_d\pi d_s}{A_p^2} \sqrt{\frac{2}{\rho}(p_s - \bar{p}_1)} & 0 \\ 0 & \frac{k_{fl}}{A_p} & 0 & -\frac{k_{fl}K_{pq}}{A_p^2} & -\frac{k_{fl}C_d\pi d_s}{A_p^2} \sqrt{\frac{2}{\rho}(\bar{p}_2 - p_a)} & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{\tau} & \frac{G}{\tau} \\ 0 & 0 & 0 & 0 & 0 & -\frac{R_c}{L_c} \end{bmatrix}$$

Figure 8 - State Matrix for Electrohydraulic Actuator – Representative State Matrix

Inputting the values for these parameters as described and from literature and aerospace industry standards, the above state matrix becomes:

$$A = 1.0e+006 \cdot [0, 0, 0, 0, 0, 0; -0.001, 0, 0, 0, 0, 0; 0, -0.0629, -0.0013, 0, 4.9778, 0; 0, 0.0629, 0, -0.0013, 0.9088, 0; 0, 0, 0, 0, -0.0001, 0.0010; 0, 0, 0, 0, 0, -0.0004]$$

$$B = [0, 0, 0, 0, 0, 4.5455]^{-1}$$

$$C = [1, 0, 0, 0, 0, 0]$$

Equation 13 - Actuator Model State, Input, and Output Matrices

Note that the ‘process’ noise vector, denoted by ‘F’ in Equation 10, was not modeled, as the parameters are not known, and the effect on system behaviour is not required for this project.

See Appendix C for values incorporated to model (various references). Note that the input vector is specific only to the EHSV driver current, and the output includes only the actuator position. This is in agreement with the general description of the application for fly-by-wire implementation as discussed in this report. The Matlab code to generate the above state space system is attached, in Appendix A and B.

5: Control Design and Simulation

The control design proceeded using the transformation pole placement method. It is noted that Matlab has several systems design functions that aided in the exercise; one feature allows the placement of poles directly. This is useful since the manipulation of the desired characteristic equation is cumbersome with an $N=6$ system.

The intent was to create state feedback gain, as a means of producing favourable system response (as determined by the closed loop poles). No more complex control implementation is described, although this could be an extension of the project for future endeavour. In practice, the feedback gain would be applied in a control unit, such as a basic computer processor, with analogue to digital signal processing capabilities. Since the plant, in this case, is fairly complex, especially when the requirement for a 3000psi hydraulic system is considered.

With the state space representation of the actuator model established in Matlab, it was possible to place the poles arbitrarily, and to iterate any model parameters. This represents the objective of modeling – to describe the behaviour of the system (as modeled) and to perform trade studies to determine the relative effect of changes. Poles were placed in the negative real plane, as follows:

$[-2; -5+5i; -5-5i; -10; -15; -20]$

This seems to provide a reasonable overshoot and decay time. It is noted that in practice, the damping coefficient and load factors would result in almost no overshoot – this is desired since the actuator is not required to react more quickly than at a rate of approximately 2Hz. In other words, the system has low requirements for bandwidth, but does have high requirements for resolution and accuracy. The bandwidth characteristic is evident in the Bode plot for the actuator – even the model without state gain implementation shows phase lag and magnitude drop off past 10Hz.

See Appendix 1 for the Matlab script used to construct the state feedback model. Once assembled, the controllability of the state matrix, A and input matrix B was evaluated as follows:

$$M = [B, A \cdot B, A^2 \cdot B, A^3 \cdot B, A^4 \cdot B, A^5 \cdot B]$$

Equation 14 – Controllability Matrix

The controllability matrix was found to have less than full rank, indicating that some states could not be directly controlled. However, since we only need to control one input, the driving current I, the

controllability was deemed initially not to be a problem; this was re-evaluated and the system was transformed at a later stage in the analysis. Matrix A was also evaluated to determine the stability of the system; the eigenvalues were all found to be in the negative half plane, and therefore, we conclude that the system is inherently stable.

Subjecting the closed loop system to a step input and plotting the response demonstrates the effect of different poles on the system response. The magnitudes have extreme values, but significantly, we can see the effect of pole placement (gain feedback) on the behaviour of the system. The plant state equation was revised using the state gain feedback as follows:

$$A_c = A - B \cdot K$$

Equation 15 – State Matrix Calculation with State Feedback

Where K is the gain matrix as calculated using the desired pole positions. Matlab allows pole placement directly, although the code was written to perform the pole placement by transformation method. The transformation matrix, T, was used, in any case, to transform the system to controllable canonical form, as follows:

$$A^* = T_{inv} \cdot A \cdot T$$

Equation 16 – Transformed State Matrix Calculation

The input matrix B was also transformed as follows:

$$B^* = T_{inv} \cdot B$$

Equation 17 – Transformed Input Matrix Calculation

6: Results of Simulation and Discussion

It is noted that the model is sensitive to actuator parameters such as leakage coefficient and servo-valve gain (actuator response per mA input). Some of these parameters were improvised based on a variety of industry sources. Disparity was also noted in different sources referencing the stiffness of hydraulic fluid. Based on the majority of references, a value of 2.2×10^5 lb/in was used.

The basic effect of pole placement is simple to visualize, by subjecting the closed loop system (with state feedback gain applied) to a step input and plotting the response. The first plot, also, shows the response of the system, given a sinusoidal input. A small phase lag is evident, but the response is appropriate.

Initial trials produced the following results:

Figure 9 - Actuator Output Response to Sin Input (+/- 40mA) in Inches (Time scale (x-axis) in seconds)

This is indicative that the model is scaled correctly; the driving current of up to 40mA produces our maximum required actuator excursion of approximately one inch.

Figure 10 - Transient [Step] Response of Natural System vs. System with State Gain Implemented

The response of the system with the state gain feedback implemented is seen to have a smaller excursion above the commanded position (as determined by the step function). This is a desired effect, given that the actuator should, in actual implementation, have no overshoot at all. The actuator, for aircraft applications, typically has quite damped characteristics by design.

Figure 11 - Bode Frequency and Phase Response of Natural System vs. System with State Gain Implemented

The plot in figure 11 suggests that the frequency response of the system is not significantly affected by the placement of our feedback gain pole placement. The system is quite robust with respect to changes in its fundamental properties.

Review of the generated data reveals that the state defined by the physical description of the plant was not completely state controllable, (ie $M = [B, A \cdot B, A^2 \cdot B, A^3 \cdot B, A^4 \cdot B, A^5 \cdot B]$; Controllability Matrix has rank of 4, not 6). This suggests that arbitrary pole placement is not possible in this form. The state must be transformed to controllable canonical form (modal form) as follows:

$$A^* = T^T A T \text{ and } T^* = T^T B \text{ [Double check.]}$$

Equation 18 – Controllable Canonical State Matrix Calculation

Where P is a non-singular transformation matrix, defined using the eigenvalues of A. Matlab is used to advantage again, and the transformation is found using the canon function (see Appendix B for the modified code).

$$T = M^* W$$

Equation 19 – Transformation Matrix

Where M and W are the controllability matrix and the characteristic equation coefficients matrices, respectively. Transformation of the gain matrix using the inverse of matrix T is not required since the pole placement takes into account the transformed states A and B . As can be seen in the coming graphs, the transformation was not required, since the system response to pole placement was not affected, except to be substantially scaled.

In addition, in the above plots, we don't compare the output to the reference; instead we measure all the states, multiply by the gain vector K , and then subtract this result from the reference. We should now, therefore, expect that $K \cdot x$ will be equal to the desired output. To eliminate this problem, we can scale the reference input to make it equal to $K \cdot x$ steady state. This scale factor is often called $Nbar$ and is added to the input to the gain matrix before meeting the state matrix, as shown in the following figure.

Figure 12 - Schematic Showing Scaling of Gain Feedback

Now, if we want to find the response of the system under state feedback with this introduction of the reference, we simply note the fact that the input is multiplied by this new factor, **Nbar**:

$$\text{System} = (A, B \cdot Nbar, C, D) \text{ instead of } (A, B, C, D)$$

See the attached code for explanation of $Nbar$ `rscale` function; it is in accordance with code written by Sanji Sun of the University of Michigan. The function `rscale(A,B,C,D,K)` finds the scale factor N that will eliminate the steady-state error to a step reference. The result of the gain scaling is discussed below; the simulations were run with and without this adjustment. The adjustment is seen to change the magnitude of the responses, but not the fundamental characteristics, as seen in the plots.

Figure 13 - Bode plot - Transformation Method

Clearly the frequency response of the system has changed – this means that the transformation affected the system response characteristics – the transformation was required.

Figure 14 - Response to SIN Input (response in inches, time scale in seconds)

The phase response of the system is slightly affected, as seen in the above plot. The magnitude of the output is changed and is not corrected for the current, which is in mA, so it was multiplied by a factor to create this plot.

Figure 15 - Closed Loop Response with Gain Feedback

It is evident, when comparing to the natural system step response (see fig. 14) that the step response of the system is affected positively by the implementation of gain feedback. The overshoot has been eliminated, with a short settling time of less than 3s. It is now demonstrated the effect of the pole selection on the response of the system.

Figure 16 – Pole Iteration 1

Clearly, moving the poles further to the left in the negative half plane (especially the dominant smallest pole) affects the system by increasing its speed. There is still no overshoot, but the peak time is about half of the original closed loop system.

Figure 17 – Pole Iteration 2

Figure 18 – Pole Iteration 3

Further evidenced in this plot, the further speeding of the system occurs when the poles are moved further to the left.

It should be noted that the magnitude of the responses is not significant, given that scaling can be accomplished. The scaling that is accomplished as an exercise (using the `rscale` function) is not in correct proportion, but does illustrate the effect of gain scaling – the magnitude of the response is much larger in the following system step response plot.

Figure 19 - Step Response of with Gain Scaling

7: Simulation and Control Design Conclusions

Valuable experience was gained while investigating and performing the control design of a typically modelled electro-hydraulic servo-valve. While considerable effort was expended in refining the code and theory of the preceding analysis, more work is possible for such a plant featuring typical non-linearities. Exploration of different control methodologies such as integral, or proportional plus integral plus derivative (PID) etc. would also be areas for further work on this subject. However, given the described desired characteristics of aircraft actuation and its reliance on damped position based controlling, it is doubtful that PIC would be chosen.

The basic goal to implement the methods of pole placement, and to perform the design and simulation has been accomplished. The background information provided on electro-hydraulic servo-valves will be useful in consideration of their application in the control of actuators that are part of digital fly-by-wire flight control systems.

This report will now examine flight control systems, then describe the origin and constitution of a typical fly-by-wire control system, and then detail the development process for such a system.

8: Aircraft Flight Control Systems Overview

The following sections of this report are a deviation from the specific areas of electro-hydraulic servo-valve design, and also from the control design dedicated to such a valve. Flight control architecture will now be examined at a high level, as a means of an introduction to fly-by-wire technology for aircraft control. This technology relies heavily on electro-hydraulic servo-valves in actuators, and also on simple, robust proportional control methods (as well as other control implementations).

Aircraft are controlled in pitch, yaw, and roll by the primary surfaces located on the horizontal stabilizer (small wing located on the tail or empennage), the vertical stabilizer (tail fin) and the wingtips, respectively. Typically, and for almost all commercial transport aircraft these are the elevators, rudder, and ailerons, respectively. Some non-conventional aircraft configurations may make use of different primary control surfaces that may act in combinations to produce the required aircraft response. Such surfaces may be named, typically, for the dual operational nature, such as ‘elevons’, tailerons, spoilerons, stablator, etc.

Primary control surfaces are sometimes assisted by secondary control surfaces, whose operation is generally viewed as somewhat less critical to the aircraft safe operation, but relied up nonetheless for nominal aircraft control and performance properties. These may be a combination of high lift surfaces such as leading edge slats, wing flaps, tail trim, and lift and drag control devices such as spoilers.

Traditionally, aircraft are controlled from the cockpit with the pilots’ inputs to the controls transmitted to the surfaces via complex systems of cables, pulleys, pushrods, and bell cranks. Such systems are reliable and accurate when well designed and maintained in-service, but the components which comprise them are numerous and expensive.

When aircraft began to grow as a result of payload requirements during the Second World War, the forces needed to deflect the control surfaces began to grow beyond the comfortable capability of pilots. This is particularly true of the pitch and yaw forces required to maintain control of the aircraft of ever increasing length and weight, and given the required rudder authority to account for engine failure on one wing.

Hydraulically ‘boosted’ or powered flight control surfaces were developed, where the pilot input mechanically controlled hydraulic servo-valves. These valves in turn controlled actuators that moved the

surfaces in question. This was the birth of modern precision hydraulics and aircraft control surfaces are, for the most part, powered with similar actuators to this day.

9: Hydraulic System Architecture

As discussed in previous sections, modern aircraft require powered actuation to overcome the large hinge-moments imposed on control surfaces by aerodynamic forces at high speeds. Most commercial aircraft travel at approximately 0.8 Mach, which translated, to over 600 mph at altitude and these forces are large. Hydraulic power has proven to be the most effective way of providing motive force to increase the pilots' ability to move control surfaces.

Energy losses in hydraulic systems are low relative to alternative means of providing power such as pneumatics and mechanical. It is a means of extracting some of the vast shaft power of aircraft engines and transferring it efficiently to all parts of the aircraft. Since liquid fluids are essentially incompressible, there is low occurrence of problems associated with compressibility and phase lag. Inputs at hydraulic control valves, such as electro-hydraulic valves, are transformed to surface movement effectively to a frequency that is beyond the requirements of aircraft control. The limitations of hydraulic actuation are defined by valve speed and hysteresis, fluid pressure production capability and pump compensation design, as well as by the load inertia that is being driven by a given actuator.

Aircraft hydraulic systems are all generally similar and can be summarized as follows. A hydraulic pump, usually driven by direct connection to the aircraft engines, provides pressure to the system. The pump consists of a driven barrel containing pistons that reciprocate due to their reference to an angled plate. The angle of the plate can be changed, changing the stroking length of the pistons, and therefore changing the volume output of the pump. Most aircraft operate at a pressure of 3000 pounds per square inch (psi). In order to preserve system efficiency, the pump produces only as much flow as is demanded by the system (actuators and motors etc), rather than venting excess fluid over a pressure control valve, producing unnecessary losses in the form of heat and shaft work. When pressure falls in the system as a result of an actuator demand, the pump compensator mechanism allows the angle of the plate (called the hangar assembly) to increase the volume of the pump output to restore the system pressure to the nominal operating pressure. This is therefore a simple mechanical (fluid) feedback and is called pressure compensated feedback.

The pump draws fluid from a system reservoir, which is sized to provide fluid to the pump under all foreseeable user conditions (worst case would be several high-rate hydraulic fluid consumers operating at once, for example). The reservoir sizing (capacity) must also account for expansion and contraction of the

system's fluid under all temperature extremes. Fluid under pressure is filtered before it flows to hydraulic actuators – typically 5-micron (μ) filtration is provided. This is important since hydraulic control valves have very close tolerances and debris can cause valves to fail prematurely, or jam and malfunction. In addition, fluid containing particle contamination will cause wear to all actuators, pumps, and control valves, shortening service life.

Fluid is controlled by valves; in conventional actuator design, a pilot input directly moves the control valve and a mechanical feedback linkage zeroes the command when the surface achieves the commanded position. In fly-by-wire applications, as discussed in previous sections, the fluid is controlled by electro-hydraulic servo-valves. Once fluid has accomplished the work intended, either movement of an actuator or the rotation of a motor, it is allowed to flow through the control valve to the return lines of the hydraulic system. The return lines are maintained at approximately the same low pressure as the reservoir; 50psi is a typical system return pressure. This low pressure ensures that the pump inlet pressure is always slightly above atmospheric so as to prevent pump cavitation.

The main engine driven pump is usually backed up by an electrically driven pump, which, in the event of an engine failure or pump failure, is powered ON by an electrical system driven by another engine. These are generally AC, due to the prevalence of AC power on aircraft, as opposed to DC pumps. These are referred to as AC motor pumps or ACMPs. Also, DC pumps may require modulation of voltage by pulse width modulation or other means – this can be costly or expensive. AC powered pumps operate at the frequency of the supply, which can vary with engine speed. The detriment of this arrangement is that the pump must be sized to provide the required flow using off-peak input power, resulting in a larger and heavier unit. Some modern aircraft, however, include constant frequency AC systems (400Hz).

The mechanical side of the pump is similar to the engine driven pumps as described above, and are pressure compensated. An alternative to ACMPs is called a power transfer unit (PTU). This is a hydraulic motor driven by one hydraulic system, powering a pump on another hydraulic system, therefore transferring hydraulic power between the systems without sharing hydraulic fluid. Separation of the fluid supplies is important in order to avoid a common-mode failure that could lead to the loss of two hydraulic systems given one failure that resulted in the loss of hydraulic fluid (such as a tube failure for example). A PTU may operate as a uni-directional device, transferring power only from one system to another, or bi-directional, transferring power between systems according to need. The former case is more common. PTUs are generally constant displacement pumps (unlike the engine driven pumps and ACMPs described

above); their speed, therefore, varies according to the required output. A modern aircraft may have three or more main hydraulic systems in order to support system and actuator redundancy requirements.

Figure 20 - Typical Aircraft Hydraulic Systems Architecture - 3 System Design (Canadian National Transportation Safety Board)

Note that military aircraft operate at a higher pressure than most commercial aircraft – 5000 or 6000psi operating pressures are not uncommon. This allows great power to be transferred using less fluid, and also allows smaller actuators to have higher movement rates, and greater force output. The complication with higher system pressure is that all tubing and pressure vessels must be designed with higher strength, and the pumps designed to sustain the higher pressure.

10: Fly-by-wire Flight Controls Overview

As discussed, in classical aircraft control design, the control surface in question is linked to controls in the cockpit by mechanical means, usually a combination of mechanical devices such as bell cranks and torque tubes, as well as with tensioned cable systems. Chains and geared interfaces are also typical for some controls. Mechanical precision is important to the proper operation of these systems, and the dynamic response of the control linkage from end to end is important to preserve the capabilities of the authority for that surface, and to prevent unwanted effects such as flutter (includes structural stiffness).

Fly-by-wire is a term that describes a modern design for aircraft primary (roll, pitch, yaw) and secondary (lift enhancement and drag devices, trim actuation, artificial feel actuation) controls. A development that was first pioneered for military aircraft involved removing much of the linkage and mechanism between the pilot and the control surfaces and replacing these with electronic signals that would control electro-hydraulic servo-valves. Indeed, the first such 'fly-by-wire' systems were not digital at all – analogue signals controlled electro-hydraulic servo-valves directly. Fly-by-wire systems are more generally, and more correctly referred to as electrically signalled systems. These systems have numerous benefits over conventional mechanical flight control systems (Ref. 5):

- Cost
- System complexity
- Design and installation man-hour savings
- Access to components
- Control system maintenance savings
- Damage tolerance/redundancy
- Weight and volume savings
- System availability increase
- Aircraft handling qualities improved
- Immunity to aircraft structural deformation
- Cockpit design and layout flexibility
- Ease of integration of auto-flight [and auto-land] systems
- Ease of implementing changes
- Overall safety improvement (relating to availability)

There are of course, detriments to all technologies, relative to their contemporary and preceding versions.

Fly-by-wire may include the following unique complexities:

- Cost of development and certification [But cost also tops the above list. Explain.]
- High level of technical training required by maintenance personnel
- Difficulty in implementing mechanical redundancy
- Weakness associated with software and difficulties testing software

Fly-by-wire replaces the direct mechanical linkage between the pilot(s) and the control surfaces with electrical signals, which may be either or both of analogue and digital. Command signals from the flight crew are interpreted by flight control computers and used to control the EHSV at a control surface, via another analogue signal. Gains, protections, and control laws may be applied or used to modify the input in order to increase safety and/or performance.

Figure 21 - Fly-by-wire Actuation Schematic (SAE, Ref. 6)

Some of the first design implementations of electrically signalled control systems were partial implementations, with analogue components, and some degree of manual reversion (mechanical backup). Such systems were seen on the Avro Arrow (a bold, 1960s era, defunct Canadian private/military supersonic interceptor design), and the British/French joint supersonic transport, The Concorde. In the case of the Concorde, flight control modules provided electrical signals in order to control electro-hydraulic servo-valves. There was a mechanical backup system, consisting of reduced control authority that prevented supersonic flight. This system was never used in service.

The United States' experience with these systems goes back a considerable way to the development of guidance and control systems for intercontinental ballistic missiles (such as the Bomarc Interceptor missile and the Minuteman solid fuelled intercontinental ballistic missile) and similar weapons during the cold war that followed the conclusion of WWII. Short-range attack missiles and cruise missiles were also

early implementations of digital control of fly-by-wire control systems; in the latter, however, electromechanical actuation replaced hydraulic actuation. Notably, the Saturn V rocket was controlled by digital fly-by-wire systems. The guidance computer in this case provided inputs to the hydraulically gimballed main engines for flight control of the craft; mechanical feedback was used in this application (Ref. 5).

Extensive work was also done in the United States for the defunct Supersonic Transport (SST) on an electrically signalled flight control system (with mechanical backup). True fly-by-wire control of aircraft is determined by some to be the critical step when there is no design consideration given to mechanical backup – all system redundancy is electrical and the authority of the fly-by-wire system is absolute. Some initial implementations of fly-by-wire were not such systems, as they had limited parallel authority relative to the mechanical primary flight control system; such systems were used for stability augmentation of military aircraft. This is useful for reduced or zero static margin aircraft (designed for increased manoeuvrability) and for implementation of terrain following capability, such as seen on the spoiler systems of the variable geometry F-111 low-level bomber. Analogue, electrically signalled, control of secondary surfaces for augmentation of manual flight control is correctly referred to as a Stability Augmentation System (SAS) – in this type of system, small inputs are added to the pilot inputs (therefore, in series) to increase performance of the aircraft, reduce loads, etc in response to aircraft parameters. A Control Augmentation System (CAS), in contrast, operates in parallel to a conventional control system, although by virtue of increased gain and servo authority, the electrically signalled portion of the system was for all intents and purposes, controlling the aircraft. The SST, Concorde, American XB-70 [Valkyrie] are examples of the first implementations of such systems.

Figure 22 - Concorde Supersonic Transport W/Analogue FBW Primary Control

The F-111 was the first US aircraft to be equipped with analogue FBW control of spoiler panels. The following figure illustrates the typical control signal gain for control of a spoiler panel in a FBW application, without any superimposed additional protective or control augmentation logic.

Figure 23 - F-111 ('Ardvark') Variable Geometry Strike Aircraft

Figure 24 - Illustration of EHSV Sensitivity and Resulting Spoiler Panel Extension (Ref. 4)

The F-16, a statically unstable fighter design of the early 1970s, used a full analogue FBW system for full authority control of all flight control surfaces. Some flight dynamic stability and flight envelope protection was built into the logic controlling the surfaces on this aircraft, therefore taking advantage of the inherent capability of FBW to exceed traditional mechanical control. True fly-by-wire systems, as they have come to be defined, are fully digital, meaning that a microprocessor controls the outputs to servo-actuators (although analogue output signalling is likely, still, to be used). This is in contrast to the early systems, which used simpler control implementation of proportional analogue error correction, based on analogue inputs. These inputs may be comprised of control stick inputs, rudder pedal inputs, inertial sensors, air data, angle of attack sensors, motion rate gyros and normal accelerometers (these are all typical of the implementation on the F-16).

When more complex requirements are placed on the control law, the implementation becomes more complex, and items such as response time, accuracy, phase lag and system non-linearities become important. One such application is stability augmentation, whereby the aircraft dynamic stability (usually due to Mach effects and control reversal at high speed) is compensated in real time by the flight control surfaces. This takes place independently of the pilot, and depends on rapid feedback of the aircraft response (accelerations from the inertial reference system) and rapid and accurate surface positioning. Similar applications are flutter control and load alleviation, whereby fast actuation allows the controller to respond to instantaneous changes in the airfoil condition that arise due to aero elastic effects (for the former) and vertical gust components (for the latter). These are areas of current research, although some basic implementations of gust load alleviation system have been certified for flight so far (Airbus aircraft, US B2 bomber).

The F/A-18 fighter/bomber was the first aircraft to include some digital control, including microprocessors, and therefore, has inherently higher capability than purely analogue systems than came before it. It is noted that FBW is especially well exploited in military aircraft in terms of expansion of aircraft operating envelope and related performance gains, as opposed to commercial aircraft, where benefits are more related to commercial benefits (cheaper to design and to operate) system simplicity, cockpit commonality (pilot training benefits), and redundancy (safety).

Typical implementations of FBW primary flight control in the latest generation of commercial and military aircraft are summarized in the following section of this report. Figure 19 depicts a typical layout of a modern digital FBW system. In this case, the control of a spoiler surface is performed digitally by a computer ('Flight Control Module') and an electrically signalled electro-hydraulic servo-valve (EHSV).

There is a control law implemented in the flight control computer, which incorporates such logic as rate limits, gains for different aircraft configurations, and also failure monitoring for the actuator and controller itself. The control laws and gains typical for a spoiler panel are not complex, and have some Boolean logic statements to address different aircraft configurations (i.e. Different rate and gains for the case when the aircraft's flaps are extended). Basic proportional control, however, suffices for these applications.

Figure 25 - Typical FBW Actuator Implementation

11: Fly-by-wire Design Considerations

Designers for any aircraft system that is critical to the continued safe flight of an aircraft must consider certain requirements for these systems:

1. Fault monitoring
2. Fault tolerance
3. Nuisance robustness
4. Redundancy
5. Actuation requirements (speed, load etc)

The flight crew must always have awareness of the condition of the system; indication in the cockpit of any non-normal condition is important to the pilots' actions in addressing the proper handling of the aircraft. Similarly, the system controller itself must know if there are faults on the system that require reconfiguration (de-activate a faulty component and activate a standby component, perhaps), or that require changes in control logic or gains. These require the system to include monitoring of its own function, including processing and signal conditioning, as these are critical items in a FBW system. Built in Test (BIT) is a common feature of fly-by-wire systems and modern electronic system (Ref. 5).

Typically, failure modes that would otherwise be dormant until a higher-level failure exposed them (perhaps catastrophically) will be tested once at the power-on of the control unit. In this power-on mode, a fault condition may be simulated and monitor must correctly detect and report the condition or the problem is flagged and a flight may be prevented, depending on severity of the fault.

Fault tolerance and redundancy are closely related, and may be summarized collectively as availability. A system is said to have high availability if it maintains a high degree of its nominal function when faults are present. This is where fly-by-wire systems can exceed traditional mechanical control systems for aircraft in impact to crew workload and overall safety. It must be said that traditional systems are no less (or more) safe than FBW actuated systems, however, the design of FBW systems often means that the system may endure more failures of a given magnitude before performance is substantially impacted. This is appealing, of course, to military aircraft designers, who must account for the possibility of battle damage in their designs. Availability is designed into fly-by-wire systems by reconfiguration and by shear redundancy – a digitally controlled FBW aircraft may have 4, 5, or 6 effectively redundant computers, providing a high level of system availability for a given system problem.

To allow for this redundancy to be effective, common mode failures must be anticipated, and/or designed against. Redundant system components, computers, for example, will often have slightly different design

implementations, processors, digital to analogue circuitry, and code that is written by different people in different programming languages. Care must be taken, of course, when implementing the control laws in different codes, that differences in the control behaviours are not significant to the operation of the actuators. As an oversight, such differences can, at best, become nuisance problems.

Nuisances are false indications of a problem, or sporadic ones, or ones that are confusing and not useful to the flight crew and/or interfacing systems and components. Monitors must be designed to detect major failures with a high degree of confidence but while being resistant to transient conditions and small perturbations that only represent 'noise' in the data.

12: Fly-by-wire: the State of the Art

For purposes of exemplifying the modern implementation of fly-by-wire technology particular to commercial (civilian) aircraft, we will briefly examine the Airbus 320/330/340 family and the more recent Boeing 777. These represent the first and second implementations of modern digital fly-by-wire implementations for primary flight control in commercial aircraft, respectively. Much material in this section is summarized after Reference 6, “Description of Actuation Systems for Aircraft with Fly-By-Wire Flight Control Systems” Rev A, SAE.

Airbus 320/330/340

The Airbus 319 and 320 are derivative aircraft, carrying between 140 and 180 passengers, therefore competing with the venerable Boeing 737 aircraft. The fledgling company designed the Airbus 320 in the 1980s; an intelligent design decision that has helped to allow the company to usurp Boeing as the world’s leading aircraft manufacturer (although this title is hotly contested, based on total aircraft deliveries per annum).

The basic premise that was assumed by Airbus at the outset of the 320 development was that the fly-by-wire system could be made to be simpler and less expensive to maintain during the lifetime of the aircraft, and that the system’s basic architecture would not only allow airlines to train pilots to fly several type of aircraft with a common rating, but also allow Airbus to develop a family of larger aircraft using largely identical flight control systems.

The Airbus A330 and 340 aircraft are much larger, more recent aircraft, being classified as ‘wide body’ aircraft (two or more isles instead of one). These aircraft, however share the architecture and many of the components of the A320 aircraft. Only rates and force capabilities separate the actuation design of most of the aircraft, and with the addition of aileron pairs for the larger aircraft. It is clear to see how this benefits both the designer and the operator. One need only examine the basic architecture to understand the design of all these families of aircraft, as we will do here. It is notable that the most recent and largest development in aerospace design, the Airbus A380 (capable of carrying 600-800 passengers depending on configuration and weighing in excess of 1.2 kilotons) shares much of its flight control architecture with these previous Airbus designs.

The aircraft is equipped with standard flight control surfaces consisting of rudder, elevator(s) and ailerons for primary control, with spoilers, flaps, slats, horizontal tail trim, and various trimming actuators for

secondary control. Primary (non-reversionary) control of all of these surfaces is via digital fly-by-wire, with one exception as will be discussed.

All surfaces are hydraulically powered, including the horizontal stabilizer, slats and flaps. Three independent hydraulic systems power the actuators in varying combinations. A basic design premise is to ensure that basic (safe) aircraft control is still possible even in the case of a dual engine failure. The ailerons and elevators are fitted with two servo-actuators, the rudder with three, the spoiler surfaces each with one, and two redundant hydraulic motors driving the horizontal stabilizer trim system. The author notes that the simplicity of hydraulic motors is preferable to the complications of electrical power for these applications. Position feedback and high power requirements make electrically powered systems problematic, even on some of the most modern aircraft.

Figure 26 - Airbus Generic (A330) Flight Control Layout (Y, G, B = Yellow, Green, and Blue Hydraulic Systems, Respectively)

The fly-by-wire ailerons, elevator and spoilers are controlled directly by the flight control computers. The rudder takes commands from the yaw damper servo-actuators, which drive input levers on the hydro-mechanical rudder servo-actuators. This allows the auto flight system to coordinate turns that are instigated by aileron and spoiler control, as well as to input yaw damping commands. The horizontal stabilizer actuator has electronics onboard and its position commands come from the flight control computers through digital data buses. Servo-loops and control laws are shared between five digital computers of two dissimilar types, the three Flight Control Primary Computers (FCPC) and the two Flight

Control Secondary Computers (FCSC). Additionally, the rudder and horizontal stabilizer actuators can be mechanically controlled via cables from the pedals and the pitch trim handwheel, respectively. This assures a minimal level of manual reversion for minimum aircraft control under extremely unlikely circumstances of failure of all primary FBW control and/or electrical power.

Servo-actuator Operating Modes and System Reconfigurations

Operating modes allow the system to respond to failure conditions by disabling certain actuators without disabling a surface. This is a key advantage of fly-by-wire over traditional, mechanical systems. The ability of the flight control system to endure one or more failures without a decrease in functionality is called system availability and correlates with safety. In military aircraft, this correlates with survivability when battle damage has been endured.

The Aileron elevator, rudder and spoiler actuators achieve different operating modes by selectively energizing solenoid powered 'mode select' valves on each actuator. Solenoid valves are common in the aerospace industry where the requirement exists for a binary hydraulic gate. The operating modes are described in the following paragraphs.

Ailerons are powered by two actuators, one of which is maintained in a damped bypass mode (offers low resistance to the powered actuator and does not actively move the surface). In the event of a failure of the primary actuator or its hydraulic system, it switches to damped bypass mode while the adjacent actuator switches to active mode. In the unlikely event of failure of both actuators and/or hydraulic systems, they are both commanded to damped bypass; in this mode, sufficient resistance to the control surface flutter must be provided.

Two actuators power each elevator; one actuator in active mode positions the surface while the adjacent actuator on the same surface is in damped bypass mode. In the event of a failure of the primary actuator or its hydraulic system, it switches to damped bypass mode while the adjacent actuator switches to active mode. In the unlikely event of failure of both actuators and/or hydraulic systems, they are both commanded to damped bypass; in this mode, sufficient resistance to the control surface flutter must be provided. If actuator failure is detected, the actuators are commanded to centered.

Three actuators drive the rudder all in active control; each actuator will revert to damped bypass mode automatically if a failure occurs. Note that the authority of the rudder system is reduced at higher

airspeeds to prevent inadvertent overloading of the vertical stabilizer. This is much more easily done in a FBW-equipped aircraft.

A single actuator positions each spoiler surface when the actuator is in normal mode. If a failure occurs the actuator is driven to retract (surface down) by supply pressure. This is accomplished, as on most aircraft, by porting supply pressure to the retract side of the actuator at all times, and an unequal (larger) extend side of the ram allows the extend command to override this 'hold down' pressure. The surface is maintained down by hydraulic lock, to address the loss of hydraulic power to the actuator.

The fly-by-wire servo-actuator functions used on the Airbus family of aircraft are common as follow. The actuator body and equal area piston rod are connected to the fixed structure of the aircraft through spherical bearings. A piston position transducer, a linear variable differential transformer (LVDT) is mounted internally to the piston rod. A manifold housing the components includes the following components:

- Hydraulic inlet filter
- Two stage electro-hydraulic servo-valve
- Solenoid valve for piloting the mode selector valve
- Mode selector valve position transducer for monitoring the valve spool position
- Differential pressure transducer for pre-flight checking of the damped bypass mode

The pre-flight checks are performed by the flight control computers on power-up, and address certain dormant failure modes and test major system monitors. This is typical of modern digitally monitored systems; dispatch cannot be permitted without checking for some types of dormant failures.

Figure 27 - Airbus A320 Fly-by-wire Controlled Aircraft

Figure 28 - Airbus A330 Typical Actuator Schematic

Boeing 777

The Boeing 777 was designed in the early 1990s as the first third-generation aircraft from Boeing; it was the first use of 3 dimensional solid modelling to design and integrate an entire aircraft for the Boeing Company. Notable is that Airbus was using the same software (indeed, the design software, Catia, is a product of French Dassault), and Bombardier designed and certified a smaller business aircraft (Global Express) using 3D modelling around the same time.

Hydraulically powered actuators position the control surfaces of the 777. The elevators, ailerons, and flaperons (surfaces which are controlled as ailerons, located on the inboard wing, and which can also augment the high lift flap system for landing) are controlled by two actuators on each surface. Three actuators power the single rudder; each spoiler by one actuator, and the horizontal stabilizer is positioned by two hydraulic motors driving a jackscrew type device.

Primary flight control actuators are controlled by the Actuator Control Electronics (ACEs); four identical ACEs are used in the system. The flight control functions are distributed among the four ACEs, such that a total failure a single unit will leave the major functionality of the flight control system intact. An ACE failure, therefore, has similar effects as the loss of a hydraulic system, and is managed without impact to the aircraft's controllability.

The primary ACEs decode signals from the transducers that comprise the cockpit controls and the primary actuation. Signals are converted to digital values and then transmitted over a digital data bus for use by the Primary Flight Computers (PFCs). The PFCs use these pilot control positions and surface positions to calculate the surface commands. The PFCs then transmit the surface commands over the same data bus (ARINC 629 third generation data bus) to the ACEs, which convert them to analogue signals commands for each actuator. Electro-hydraulic servo-valves control the actuators in response to the analogue (current) control signals. Note the physical and functional separation of the control electronics (PFCs) and signal processing (ACEs).

Actuator Modes of Operation 777

The actuators on the elevators, ailerons, flaperons, and rudder have several operational modes that are described here. In normal mode, the actuators receive commands from their respective ACEs and position the surfaces accordingly. The actuators will remain in the normal state unless commanded otherwise by the ACEs.

In Bypass mode (compare to Airbus architecture discussion), the actuator does not respond to commands from the ACE at all; the actuator is allowed to move freely, so that one or more 'sister' actuators on a surface can move the unencumbered. This mode is not available on the elevator actuators, because of the need to retain stiffness to prevent surface flutter in the event that all systems fail.

In the damped mode, the actuator does not respond to commands from the ACE. The actuator is allowed to move, but at a restricted rate in order to provide surface flutter damping. The other actuators on the surface can control the surface at a rate sufficient for aircraft control. This mode exists on the elevator and rudder actuators.

In blocked mode, the actuator does not respond to commands from the ACE and is not allowed to move. This mode is commanded when both actuators on a surface have failed, and is designed to provide gust lock on the aileron and elevator actuators.

Clearly, it can be seen the lengths to which designers go, not only to ensure adequate redundancy, but also to prevent surface flutter in failure conditions. This is a failure mode that often, can be catastrophic to many aircraft and must be avoided.

Figure 29 - Boeing 777 Rudder Actuator Schematic

The typical power control unit (PCU) is an electro-hydraulic servo-actuator of three-mode design, featuring a two-stage servo-valve and a balanced area piston. The PCU control module and cylinder are integrated to form a single component. The electro-hydraulic servo-valve responds to a current command from the ACE by metering fluid to the actuator ram. The actuator rod end is connected directly to the control surface. The PCU contains a servo-valve, a mode selector valve (to engage one of the four described modes), two solenoid valves, two position transducers, a compensator (to assist flutter damping in the blocked mode), load and thermal relief valves, and check valves. Bypass and blocking solenoid valves are operated by ACEs to achieve, via the mode select valve, one of the three modes: normal, bypass, and blocked. Two transducers provide servo-valve position and ram position to the corresponding ACE.

13: Design and Development Process for Fly-by-wire

This discussion is provided based on research and experience gathered by the author in the design and certification of various systems and components in the aerospace industry (Bombardier Aerospace), and on the summary of recommended practices as compiled by the Society of Automotive Engineers (Ref. 7). The society has amassed a sizable base of aerospace industry design information.

Aircraft system design processes are similar for many aircraft programs, despite the differing aims of different aerospace design firms and military contractors and the different operating environments and performance for aircraft, whether they are military fighters, bombers, or civilian transports (or other, such as the space shuttle flight control system).

A template is easily established for discussion purposes, and may be used as a model for future aircraft system developments. It must be noted that since the advent of micro processing and the integration of electronics and software into once entirely mechanical flight control systems, that new and specialized design requirements exist. By the same token, some traditional design principals associated with mechanical control systems are becoming less important in modern aircraft, or, in some aircraft, are not required at all. Cable systems, complex idler and crank levers, and balancing for disconnect are examples of design requirements that are becoming lost art in the modern aerospace industry.

This report examines in high-level detail the development stages of a FBW system up to production of the new aircraft/system. The process, it should be noted, is written from the point of view of the aircraft level integrator or system integrator, rather than at the component design level. Typically, the mechanical actuation is developed by a specialist manufacturer, independently of the controlling electronics, once the required operational and performance parameters have been established and interfaces agreed and frozen.

Major Design Phases

Generally, a desired system performance envelope is expressed, based on the known or perceived available technologies of the day, which defines the requirements for the new aircraft system. The requirements are summarized in one or several large Systems Requirements Documents (SRD), which form the major part of the definition of the system.

The following stages are typical in most modern aerospace design processes (see figure 24):

1. Concept Exploration and Definition (CE&D) aka Joint Conceptual Definition Process

2. Demonstration and Validation (DEM VAL)
3. Engineering and Manufacturing Development (E&MD)

Figure 30 – System Development Milestones

The requirements documents may be fluid in the initial exploration and definition portion of development; this is the point entirely of this portion of the process, as will be discussed further. The milestones illustrated above are typical of most aerospace initiatives; the process is designed to prevent changes from becoming required at a juncture that is beyond recovery, and also to provide ample opportunity for all parties to collectively review interfaces, difficulties, and trade studies.

With development of the actuation and control (mechanical and electronic) possibly following independent detailed design phases, the success of the overall design process is dependent on establishing actuation system schedules and a procurement cycle that requires these concurrent design reviews (see Figure 25). To assure successful integration, there must be regular communication and interaction between design teams that are responsible for each sub-system.

A Systems Requirements Review (SRR) is normally conducted during the CE&D phase of an aerospace system development – this is a joint review, as are most of the major milestones.

Figure 31 – System Development Timeline

The objectives of the CE&D phase are to define the most promising system concepts, to develop supporting analysis and data, to identify areas of high risk (to development or certification, and to finalize system design requirements that may still be fluid.

A system review is normally conducted as the final phase of the DEM VAL phase of development. The objectives of this phase are to define the critical characteristics and expected capabilities of the system, to demonstrate that the required technologies can be incorporated, and to establish a baseline configuration for the most promising approach. For example, years before Bombardier will attempt its first fully fly-by-wire controlled aircraft configuration, demonstration of concept has been accomplished through flying the most likely configuration on a test aircraft (with separate systems available as safety back-ups).

A system safety assessment will evaluate many considerations as follows:

- Vehicle electronics architecture
 - Redundancy
 - Distributed or central
 - Digital, analogue, other

- Preliminary Interfaces
 - Servo-electronics loop architecture
 - Failure detection and isolation (ie: reconfiguration logic)
 - Transients
 - BIT
- Power Source
 - Hydraulic power
 - Electrical power
- Actuation type
 - Linear
 - Rotary
 - Electro-hydro-mechanical
 - Electro-hydrostatic

Note: Electromechanical actuators (EMA) are actuators that do not use hydraulic fluid for motive force, but rather, use electrical energy (motors, gears, servos, linear actuators etc.). Electro-hydrostatic actuators (EHA) include a small hydraulic supply and pressurization system, and are capable of delivering the high power of hydraulic actuation without the requirement for a central hydraulic system. Both are compact actuators that require only electrical input, and are well suited to Fly-by-wire. EHA has been used in fighter aircraft, but is generally avoided for civilian aircraft, so far, because of associated weight penalties. Recent exceptions are back-up actuators, which will provide a reduced surface control capability in the event of loss of all aircraft hydraulic systems. Continuing with the system safety assessment requirements:

- Servo-loop stability
 - Geometry
 - Rigging
 - Stiffness (backup structure stiffness is important, as is the stiffness of the actuator itself)
- Actuation System Redundancy
 - Electronic components
 - Hydraulic systems
 - Electrical system (no power to excite the sensor coils results in no actuation)
 - Mechanical (structural)
- Installation Considerations

- Geometry
- Rigging (Ease of setting up and maintaining nominal operating tolerances)
- Stiffness (as above)
- Preliminary sizing
 - Actuator stroke
 - Load capability (aero input is required here)
 - Surface deflection rates (for response rate and phase margin of EHSV)
 - Envelope (limitations)
 - Weight (limitations)

Actuation Requirements

The primary objective of the final, Engineering and Manufacturing Development phase is to define and translate the most promising design configuration into a product that is producible, cost effective, and (especially for civil/commercial aviation) certifiable. The requirements development process produces Specification Control Document (SCD); this may alternately be called Design Document, Technical Requirements Document (TRD) or similar. It functions as the procurement specification for components and electronics – from it, a component manufacturer must be able to develop and certify the required component (controller or actuator) with minimal guidance from the system integrator. Both the controller and actuator will have separate Specification Control Documents, and there will be at least one Interface Control Document (ICD) that is of high importance, especially in the multi-partner development. Digital, electrical, hydraulic, and mechanical interfaces may all have separate interface control documents and or drawings. The overall actuation system requirements are captured entirely by these several documents; qualification requirements and any other design assurances will be included in these documents, also. The list provided above must be addressed in the SCDs, as well as the following additional areas:

Controller Requirements

- Frequency response (bandwidth, gains)
- Stability of control loops
- Thresholds
- Hysteresis
- Accuracy
 - Null bias and null shift
 - Linearity of sensors and EHSVs
 - Temperature deviation
- Maximum allowable uncommanded motion (drift or other causes)
- Surface slew rate and resulting actuator extend rate
- Control surface hinge moment characteristics (driving load capabilities)
- Force fight (where multiple actuators are installed – minimize the out-of-synch motion)
- Failure detection
- Degraded and Fail Safe Modes (Fail safe generally is required after levels of redundancy have been exhausted, i.e., the actuator may no longer be useful, but cannot be harmful)
- Survivability (military aircraft)

- Service life requirements (operating hours before overhaul, flight cycles, years)
- Corrosion requirements and dissimilar metals
- Reliability requirements and allocations (certain sub-components must sometimes have minimum reliabilities)
- BIT and Test point definition

Actuator Requirements

- Fluid type and operating pressures, including supply and return pressure delta)
- Proof and burst pressure requirements (including impulse transient requirements)
- Load acceleration (rate requirements or limitations)
- Peak power required (referred to as the actuator's 'stall load')
- Actuator ram velocity
- Heat rejection and heat sinking requirements (systems may include a dedicated hydraulic fluid heat exchanger if excess heat is thought to be a problem)
- Vibration environment
- Fatigue design requirements and test criterion
- Servo Characteristics:
 - Travel
 - Slew rate
 - Output force and chip shearing requirement (a spool may be required to be able to shear a metal chip to prevent hydraulic contamination from jamming the valve)
 - Dynamic performance
 - Electrical characteristics
 - Quiescent leakage (hydraulic leakage that occurs at all times across the small tolerance gaps in the valve)
 - Null bias and null shift
 - Linearity and $\square$ ysteresis
 - Active travel and over-travel
 - Flow characteristics and pressure gain (important)
- Main Control valve position sensor (this is critical to the interface with the controller)
- Main ram position sensor (also important – this is the primary loop closing element of the surface control)

- Pressure sensors
- Shutoff valve characteristics (SOV is usually required for fault isolation requirements)
- Transient requirements for fail-safe transition (reversion)
- Hydraulic and electrical schematics
- Installation requirements and physical characteristics
- Structural Design
 - Service life
 - Bottoming cycling for qualification (ram bottoming in actuator housing)
 - Pressure cycling
 - Dynamic stiffness (this is important for the interface with the controller – characteristic frequencies must be given adequate clearance)
 - Limit and ultimate loads
 - External leakage (all dynamic seals leak a very small amount, therefore, actuators will always leak or ‘weep’ fluid to some extent)
 - Reliability and maintainability requirements (costs may be linked to these attributes, depending on if commercial or military)
 - Duty cycle
 - Power consumption

Servo-electronics Requirements

The control design exercise that was provided in sections 4 through 7 of this project report provided an illustration of the order of magnitude of the control design required to be implemented in the servo-electronic portion of an integrated fly-by-wire system. The control logic would reside in computers, where sensor parameters are used to provide input to the electro-hydraulic servo-valves that control the actuator. It is not unusual for a model of the actuator to exist in the controller memory; this is used to predict the response of the actuator and surface being controlled, and aids in fault monitoring.

The following comprise the primary design considerations that must be part of the design parameters for the servo-electronic portion of an integrated fly-by-wire implementation (after SAE).

- System management and architecture
- Redundancy management
- Failure mode effects and monitoring
- Fault detection (and interface with cockpit or other systems)

- Fault monitor status
- BIT
- Maintenance Diagnostics (there may be a requirement for on-command tests, to help maintenance personnel troubleshoot system anomalies on the ground)
- Servo-loop characteristics
 - Algorithms and control laws
 - Iteration rates and processing rate
 - Resolution
- Digital to analogue and analogue to digital converter requirements (important as determined by system response requirements)
- Initialization and power-up
- Hardware requirements (moisture, heat, vibration...)
- Servo-amplifier
 - Bandwidth
 - Range
 - Resolution
- Position sensor excitation and signal conditioning requirements
- Solenoid valve drivers (required additional onboard power)
- Processor
 - Software development plan (critical certification item, especially to commercial aircraft equipment)
 - Software requirements (how control laws are ported to software)
 - Onboard memory (RAM)
 - Speed
- Input/output (signal and power polarity)
- Electrical power requirements (does the controller have to operate down to a minimum voltage?)
- Data bus interfaces
- Electrical bus interfaces
- Wiring configuration (is shielded wire required for some interfaces and/or in some areas of the aircraft installation?)
- Signal conditioning and compensation
- Thermal conditioning (designed to remove infant mortalities from production units and may be accompanied by vibration cycling)

- Growth capability
- Interchangeability and repairability
- Materials, parts, and processes
- Lighting, bonding and static requirements (this is critical to certification in commercial aircraft; such aircraft are frequently struck by lightning and are subject to large EMI fields and possible static discharge conditions)

Interface Requirements

As discussed, the interface requirements must be detailed and well integrated by the aircraft level designers to ensure that the actuator and servo-electronics can perform as a complete Fly-by-wire system. The Interface Control Document(s) contains information required to properly define the external interfaces and the interface between the electronics (controller) and actuators. The areas covered have been addressed indirectly above; the detail design phase will now be examined.

Details Design

The preliminary design review (PDR) is normally conducted at the conclusion of the preliminary design phase (see fig. 25). Its purpose is to evaluate the technical adequacy of the selected design, to determine its compatibility with performance and engineering specialty requirements (adherence to the SCDs), to assess technical risk, to establish compatibility of the physical and functional interfaces among the components in subsystems and to provide approval to continue the final design process. PDR is generally an opportunity to review deliverables. The following list is provided by the SAE, but is typical of Bombardier deliverables expected at PDR for a given system:

- Preliminary design synthesis
- Trade studies
- Requirements allocation
- Layouts
- Environmental and thermal design
- Preliminary parts list
- Preliminary weight analysis
- Risk mitigation (mockups, electrical breadboards, prototypes)
- Preliminary specifications for procured components or subsystems
- Preliminary EMI compatibility
- Preliminary stress analysis

- Development test schedules and plans
- Interface Control Documents and drawings
- Failure modes and effects

Refining of the design takes place through and following the PDR timeframe, with requirements driving design decisions and detail-level optimization.

A critical design review (CDR) is normally conducted at the conclusion of the detailed design phase (this will be the extent of the discussion here, although manufacturing and qualification are additional discussions). The CDR focuses on assessing the adequacy of the detailed design, performance, and test characteristics of the system, and the adequacy of the associated documentation. The specific purposes of the CDR are to determine that the detailed design satisfies the performance and engineering requirements of the specification, to establish the detailed compatibility among the components in the subsystems, to assess risk areas, to assess the results of the design and producibility analysis, to review the assembly and detail-level drawings, and to provide approval to proceed with the product fabrication and assembly process. The checklist of items for CDR is similar to that expected at PDR, except that final formats are to be provided and reviewed. In addition, the following may be reviewed and finalized:

- Design study results
- Detail drawings
- Mechanical design adequacy
- Electrical design adequacy
- Environmental design adequacy
- Producibility analysis
- Performance analysis
- Prototype hardware demonstration and review
- Development test results
- Manufacturing readiness
- Materials and processes
- Design to cost analysis
- Quality assurance program
- Wiring diagrams and electrical interfaces
- All SCD requirements (see Controller, Actuator and Servo-electronics requirements

A Test Readiness Review (TRR) is general conducted prior to commencement or formal qualification testing. This is designed to ensure that the test articles, test procedures and acceptance limits for testing are adequate for the certification of the system and components.

Qualification testing is a large undertaking and can account for a significant amount of time and expense dedicated to the development of a flight critical system such as a FBW flight control system.

Qualification testing is designed not only to demonstrate the components' adherence to their design requirements, but also to applicable airworthiness requirements. This is critical to commercial system development.

Component level testing will be augmented by integration testing, where all hardware and controlling electronics is tested to ensure compliance to specifications and all performance requirements. The system integrator may choose to host or replicate the integrated testing, and to include interfacing systems, representative hydraulic system components and installations, and representative load simulation. All expected failure modes will be explored, and fault monitoring and isolation verified.

This is a concise description of qualification testing, preceding aircraft ground and flight-testing and the reader is encouraged to explore this subject further.

It is clear from the description provided that the development phase of an integrated FBW system alone is a substantial task, requiring high levels of expertise and coordination of several specialty-engineering disciplines.

14: Fly-by-wire Future Developments

This short discussion is dedicated to discussion of some current and future developments of fly-by-wire and similar technology in aircraft. Areas of current research in the FBW field include the application of feedback linearization, artificial intelligence (heuristic logic), and control of non-linear systems using linear control. Some other areas of mention are the following

- Adaptive control
- Laser light signalled actuation systems (Fly by light)
- Fluid signalling
- Electrically Powered Actuation Systems (Power by Wire)

Adaptive control will likely have several applications in aircraft flight control, and is already finding a place in modern military aircraft control (as in the American F-22 and F-35 fighter designs, as well as the European Typhoon, French Rafale, and Swedish Grippen fighter designs).

These applications make use of adjustable control parameters that aid the pilot in controlling the aircraft in different situations including high angle of attack and low speed configurations, and high-speed situations where aircraft dynamic stability is affected.

Adaptive control is also applied to gust load alleviation systems in Airbus aircraft to shed excess lift from the wings during vertical wind gusts by controlling spoiler or lift shedding control surfaces. This is similar to the function as described in section 9 for the spoiler system on the F-111 low-level bomber design.

Fly By Light aims to improve on data bus and analogue signal carrier weaknesses and shortcomings, with promises of increased bandwidth, phase response, and a marked weight savings. The electrical interconnections that comprise the signalling network of a typical digital fly-by-wire system are, in the case of a fly by light system, replaced by fiber optics connections and laser transmitters. This has the benefit of much larger communications bandwidth and faster transmission rates. In addition, and significantly for military aircraft especially, these systems are essentially immune to electromagnetic effects. Electromagnetic compatibility of components in aircraft and robustness with respect to interference from sources such as powerful earth-bourn television and radio signals is an important part of system design for fly-by-wire, and this can add considerable weight to the wired interfaces by requiring that wire shielding be used to protect the signals from interference.

Power by wire systems are otherwise known, in modern developments, as ‘more electric’ actuation implementations. These systems aim to reduce the reliance on a central hydraulic power system and to provide the power for actuation locally at actuators using electrical power. The lines required to carry electrical power to actuators are lighter and simpler than the hydraulic tubes. They also offer considerably less maintenance over the life of the aircraft; this may be of great value to the next generation of airlines seeking to improve aircraft operating economics when all reasonable gains have been achieved from aerodynamic and fuel burn points of view. In addition, electrical power is less susceptible to damage, which makes power by wire appealing to designers of actuation for military applications. Hydraulic power can be lost entirely if a tube is damaged anywhere in the system, while it is reasonably easy to provide redundant electrical power provisions while still saving weight and complexity. The inherently susceptible nature of hydraulic systems has required that they be redundant on aircraft, but the latest generation of aircraft, the Airbus A380, and possibly the proposed Bombardier CSeries 110 – 130 seat aircraft, make use of small electrical actuators as backup actuation to cater to the case of double hydraulic system failure. These actuators are less powerful than the main system actuators, and so offer the aircraft a means to fly and land safely in an emergency situation, if at a reduced performance level.

15: Conclusions – Fly-by-wire Survey

This project report illustrates the interaction between the technology represented by electro-hydraulic servo-valves, the control challenge involved in controlling a hydraulic actuator that uses such valves for control, and describes their inclusion in modern flight control systems on commercial and military aircraft. Electro-hydraulic servo-valves are increasingly important in today's world of robotics and aircraft controls where high specific forces and rapid responses are required. The control method defined herein is only the most basic form of control, and in the future a great deal of attention will be paid to linearizing and dealing with non-linear systems. In addition, adaptive control and artificial intelligence (neural network, fuzzy logic) will play increasing roles. The aerospace industry will depend heavily on advanced systems control as the next generation of aircraft is being designed to include fly-by-wire, and various digital aircraft stability augmentation systems.

Fly-by-wire has already enabled two generations of aircraft to exceed the performance and cost impacts of the previous, entirely mechanical systems. Analogue fly-by-wire systems saved weight and provided benefits appealing to unique aircraft designs such as fighters and cutting edge supersonic transports. Digitization allowed increased control over system response in certain circumstances, increased availability, and allowed aircraft to reach unprecedented levels of structural efficiency. Pilots benefit from ergonomic improvements, flight envelope protection, cockpit commonality, and passengers may experience a better ride in FBW equipped aircraft. More than ever before, maintenance crews are learning the language of computers, exploiting well designed interfaces to aid in troubleshooting, while the designing engineers can see, with a simple download of flight and fault data, the problems that a FBW system may experience in service and make corrections either to that aircraft's hardware or to a subsequent revision to the system design (which is common).

The intricate, precise, performance and safety driven design art that was mechanical flight control design will increasingly be relegated to small aircraft control system design, while the major airframe manufacturers of the world embrace Fly-by-wire technology and its coming evolutions.

16: References

1.
D'Amore, Marco, Pellegrinetti, Gordon;
“Dissecting High Performance Electro-hydraulic Valves”
Moog Inc., East Aurora, N.Y.
Machine Design, April 2001
2.
Thayer, W. J.
“Transfer Functions for Moog Servo Valves”
Moog Inc., East Aurora, N.Y.
Service Letter 103, Rev January 1965
3.
DeCastro, Jonathan A., and Melcher, Kevin J.
“A Study on the Requirements for Fast Active Turbine Tip Clearance Control Systems”
NASA / TM-2004-213121
AIAA-2004-4176, July 2004
4.
Spisak, John
“Proportional and Servo-valve Technology”
Fluid Power Journal, March/April 2003
5.
Raymond, ET, with Chenoweth, CC
“Aircraft Flight Control Actuation Systems Design”
Society of Automotive Engineers, 1993
6.
Society of Automotive Engineers (SAE)
“Description of Actuation Systems for Aircraft with Fly-By-Wire Flight Control Systems” Rev A
Aerospace Information Report AIR 4253, Published 04/1989, revised 04/2001
7.
Society of Automotive Engineers (SAE)
“Development Process – Aerospace Fly-By-Wire Actuation System”
Aerospace Recommended Practice ARP 5007, Issued 06/1997
8.
Honeywell Inc.
“The More Electric Architecture Revolution”
MEA Article for Honeywell Website, 2005

Appendix A: Matlab Code

```
%Define the constants required to create the state space representation of
%the electro-hydraulic servo-valve

%(Deleted unused code at Rev 2)

clear all;

Kfs = 15000; %failsafe spring constant
Ap = 3.5; %Piston area
Kft = 2.2*10^5; %fluid bulk stiffness
Kft2 = (4*150e6*Ap^2)/(Ap*0.75); %Alternate calculation
Fc = 200; %Coulomb friction
Ps = 3000; %Supply Pressure
Pa = 50; %Return pressure
P1bar = 1500; %Half supply pressure
P2bar = 100; %Twice return pressure
m = 15; %Actuator mass (non-D) **Check value
Cd = 0.618; %Discharge coefficient
Rc = 80; %Servo Valve Coil Resistance
Lc = 0.22; %Servo Valve Coil Inductance
G = 0.750/(40/1000); %Sensitivity to servo-valve driving current
c = 0.45; %Actuator viscous damping coefficient
Kpq = 0.075; %Leakage Coefficient
tau = 0.018; %Servo Valve Time Constant (s)
rho = 8.5/231; %fluid density (lb/in3)
ds = 0.5; %Servo Valve Spool Diameter

A = [0,1,0,0,0,0 ; (-Kfs/m), (-c/m), (Ap/m), (-Ap/m),0,0 ; 0,(-Kft/Ap), -(Kft*Kpq)/Ap^2,
0,((Kft*Cd*3.1415*ds)/Ap^2)* ((2*(Ps-P1bar)/rho)^(1/2)), 0; 0, Kft/Ap, 0, -(Kft*Kpq)/Ap^2,
((Kft*Cd*3.1415*ds)/Ap^2) * ((2*(P2bar-Pa)/rho)^(1/2)), 0; 0,0,0,0,-(1/tau), (G/tau); 0,0,0,0,0,-(Rc/Lc)];

B = [0;0;0;0;0;1/Lc];

C = [1,0,0,0,0,0];

digits(10);

Eig=eig(A); %System is stable if all eigenvalues are in the negative half-plane

M = [B, A*B, A^2*B, A^3*B, A^4*B, A^5*B];%Controllability Matrix

Q = [C', A'*C', A'^2*C', A'^3*C', A'^4*C', A'^5*C']; %Observability Matrix

Cont=rank(M); %Rank of controllability matrix reveals if plant is fully controllable
%Since we only need controllability of one state, less than full rank is acceptable for this simulation

Obs=rank(Q); %Rank of observability matrix reveals if plant is fully state observable

I=[1,0,0,0,0,0;0,1,0,0,0,0;0,0,1,0,0,0;0,0,0,1,0,0;0,0,0,0,1,0;0,0,0,0,0,1]; %Identity matrix

s=sym('s'); %Used to determine characteristic equation

%chareq =det(s*I-A); %Calculate the characteristic equation of the plant
```

```

chareq2=poly(A);
%Note that the above two functions should both return the characteristic equation; chareq2 produces the coefficients
directly

a1=chareq2(:,2);
a2=chareq2(:,3);
a3=chareq2(:,4);
a4=chareq2(:,5);
a5=chareq2(:,6);
a6=chareq2(:,7);
%Extracting the coefficients of the characteristic equation for use in our transformation matrix

%Plant Characteristic Equation Coefficient Matrix
W = [a5, a4, a3, a2, a1, 1; a4, a3, a2, a1, 1, 0; a3, a2, a1, 1, 0, 0; a2, a1, 1, 0, 0, 0; a1, 1, 0, 0, 0, 0; 1, 0, 0, 0, 0, 0];

%Transformation matrix
T = M*W;

%Determine desired closed loop poles - this is arbitrary and will be iterated through simulation

%desired poles
pp = [-2; -5+5i; -5-5i; -10; -15; -20];
KK = place(A,B,pp);
Kp = -KK;
%NOte: Matlab cannot place the poles exactly - it indicates 10% error...

%Alternate method - use transformation matrix to find gain matrix, using desired system pole locations
%Extract coefficients of characteristic equation
%poles=(s-pp);
%alpha=[s-pp(1,:),0,0,0,0,0; 0,s-pp(2,:),0,0,0,0; 0,0,s-pp(3,:),0,0,0; 0,0,0,s-pp(4,:),0,0; 0,0,0,0,s-pp(5,:),0;
0,0,0,0,0,s-pp(6,:0)];
%desiredchar=det(alpha);
%alpha1=alpha(1,:);
%alpha2=alpha(2,:);
%alpha3=alpha(3,:);
%alpha4=alpha(4,:);
%alpha5=alpha(5,:);
%alpha6=alpha(6,:);
%Ti = inv(T);
%K=[alpha6-a6, alpha5-a5, alpha4-a4, alpha3-a3, alpha2-a2, alpha1-a1]*Ti;

%Calculate close loop state matrices to simulate the system
Ac= [A-B*Kp];
%digits(7);
%sym(Ac,'d');
%Bc= B*N;
%Cc=C;
D=zeros;
%Dc=zeros;

%figure
sys1=ss(Ac,B,C,D);
%step(sys1, 2)
%title('Actuator Closed Loop Step Response State Feedback Gain Control')
figure

```

```

sys2=ss(A,B,C,D);
step(sys2,sys1,2)
title('Actuator Closed Loop Step Response With and Without State Feedback Gain Control')

%Calculate and plot the phase and magnitude response (Bode plots) for the
%plant and for the closed loop (state feedback implemented system
figure
bode(sys2, sys1, {0.1, 10^5});
title('Bode Diagram - Actuator with State Feedback Gain Control vs. Natural Plant Response')

t = 0:pi/100:10*pi;
%Matlab control systems toolbox provides a linear simulation tool to test
%our state space system
figure
x= 0:pi/100:pi*10;
u = 40*sin(x); %Because valve input is +/- 40mA
y5= lsim(sys1, u, t);
plot(x, y5,'r',x, u, 'k');
title('Actuator Closed Loop Response (Output) to SIN Input Wave (State Feedback)')

```

Appendix B: Modified Code

%Define the constants required to create the state space representation of
%the electro-hydraulic servo-valve

%(Deleted unused code at Rev 2)

% States transformed to provide full controllability at Rev 3

clear all;

Kfs = 15000; %failsafe spring constant

Ap = 3.5; %Piston area

Kft = 2.2*10^6; %fluid bulk stiffness

Kft2 = (4*150e6*Ap^2)/(Ap*0.75); %Alternate calculation

Fc = 200; %Coulomb friction

Ps = 3000; %Supply Pressure

Pa = 50; %Return pressure

P1bar = 1500; %Half supply pressure

P2bar = 100; %Twice return pressure

m = 15; %Actuator mass (non-D) **Check value

Cd = 0.618; %Discharge coefficient

Rc = 80; %Servo Valve Coil Resistance

Lc = 0.22; %Servo Valve Coil Inductance

G = 0.750/(40/1000); %Sensitivity to servo-valve driving current

c = 0.45; %Actuator viscous damping coefficient

Kpq = 0.1; %Leakage Coefficient

tau = 0.018; %Servo Valve Time Constant (s)

rho = 8.5/231; %fluid density (lb/in3)

ds = 0.5; %Servo Valve Spool Diameter

A = [0,1,0,0,0,0 ; (-Kfs/m), (-c/m), (Ap/m), (-Ap/m),0,0 ; 0,(-Kft/Ap), -(Kft*Kpq)/Ap^2,
0,((Kft*Cd*3.1415*ds)/Ap^2) * ((2*(Ps-P1bar)/rho)^(1/2)), 0; 0, Kft/Ap, 0, -(Kft*Kpq)/Ap^2,
((Kft*Cd*3.1415*ds)/Ap^2) * ((2*(P2bar-Pa)/rho)^(1/2)), 0; 0,0,0,0,-(1/tau), (G/tau); 0,0,0,0,-(Rc/Lc)];

B = [0;0;0;0;0;1/Lc];

C = [1,0,0,0,0,0];

D=zeros;

I=[1,0,0,0,0,0;0,1,0,0,0,0;0,0,1,0,0,0;0,0,0,1,0,0;0,0,0,0,1,0;0,0,0,0,0,1]; %Identity matrix

s=sym('s'); %Used to determine characteristic equation

Eig=eig(A); %System is stable if all eigenvalues are in the negative half-plane

M = [B, A*B, A^2*B, A^3*B, A^4*B, A^5*B]; %Controllability Matrix

OC = [C*B, C*A*B, C*A^2*B, C*A^3*B, C*A^4*B, C*A^5*B]; %Output Controllability

Q = [C', A'*C', A'^2*C', A'^3*C', A'^4*C', A'^5*C']; %Observability Matrix

Cont=rank(M); %Rank of controllability matrix reveals if plant is fully controllable

OPCont=rank(OC); %Rank of output controllability matrix reveals if all output states are controllable

%Since we only need controllability of one state, less than full rank is acceptable for this simulation

Obs=rank(Q); %Rank of observability matrix reveals if plant is fully state observable

chareq=poly(A);

%Note that the above two functions should both return the characteristic equation; chareq2 produces the coefficients directly

a1=chareq(:,2);

```

a2=chareq(:,3);
a3=chareq(:,4);
a4=chareq(:,5);
a5=chareq(:,6);
a6=chareq(:,7);
%Extracting the coefficients of the characteristic equation for use in our transformation matrix

sys=ss(A,B,C,D);
[csys,T]=canon(sys,'modal') %Automatically performs transformation of the state space
%system to controllable canonical form and produces the transformation
%matrix, T
Tinv=inv(T); %Not used

%Plant Characteristic Equation Coefficient Matrix
W = [a5, a4, a3, a2, a1, 1; a4, a3, a2, a1, 1, 0; a3, a2, a1, 1, 0, 0; a2, a1, 1, 0, 0, 0; a1, 1, 0, 0, 0, 0; 1, 0, 0, 0, 0, 0];
T2= M*W; %Alternate method of finding the transformation matrix
T2inv=inv(T2);

Ahat = T2inv*A*T2; %Transforming the A and B matrices because controllability was less than full rank
Bhat = T2inv*B;

sys=ss(Ahat, Bhat, C, D); %Matlab simulates the linear state space system

%Place the poles in the desired location by defining a vector of desired poles
pp = [-2; -5+5i; -5-5i; -10; -15; -20];
KK = place(Ahat,Bhat,pp);
Kp = -KK;

%Calculate close loop state matrices to simulate the system
Ac= Ahat + Bhat*Kp;
sys1=ss(Ac,Bhat,C,D);
Nbar=rscale(Ac, Bhat, C, D, Kp); %Not used
sys2=ss(Ac, Bhat*Nbar, C, D); %Not used

%Plot the step response of the closed loop system to illustrate the effect
%of the state gain feedback with scaled input
figure
step(sys,5)
title('Actuator Natural Closed Loop Step Response')

figure
step(sys1,5)
title('Actuator Closed Loop Step Response With State Feedback Gain Control')

%Calculate and plot the phase and magnitude response (Bode plots) for the
%plant and for the closed loop (state feedback implemented system)
figure
bode(sys, sys1, {0.1, 10^6});
title('Bode Diagram - Actuator with State Feedback Gain Control vs. Natural Plant Response')

%Matlab control systems toolbox provides a linear simulation tool to test
%our state space system - use Sinusoidal input
t = 0:pi/100:10*pi;
figure
x= 0:pi/100:pi*10;
u = sin(x);

```

```

y5= 10000*lsim(sys1, u, t); %Accounts for mA conversion
y6= lsim(sys2, u, t); %Produce sine response to gain scaled system - not used
plot(x, y5,'r', x, u, 'b');
title('Actuator Closed Loop Response (Output) to SIN Input Wave (State Feedback)')

%*****
%*****
%Scaled input

figure
step(sys2, 5)
title('Closed Loop Step Response With State Feedback Gain Scaling')

%*****
%Poles iterated to demonstrate the effect

pp = [-10; -15+5i; -15-5i; -25; -20; -30];
KK = place(Ahat,Bhat,pp);
Kp = -KK;
Ac= Ahat + Bhat*Kp;
sys1=ss(Ac,Bhat,C,D);
figure
step(sys1,5)
title('Poles at [-10; -15+5i; -15-5i; -25; -20; -30]')

pp = [-20; -30+5i; -30-5i; -50; -75; -90];
KK = place(Ahat,Bhat,pp);
Kp = -KK;
Ac= Ahat + Bhat*Kp;
sys1=ss(Ac,Bhat,C,D);
figure
step(sys1,5)
title('Poles at [-20; -30+5i; -30-5i; -50; -75; -90]')

pp = [-50; -75+5i; -75-5i; -95; -110; -120];
KK = place(Ahat,Bhat,pp);
Kp = -KK;
Ac= Ahat + Bhat*Kp;
sys1=ss(Ac,Bhat,C,D);
figure
step(sys1,5)
title('Poles at [-50; -75+5i; -75-5i; -95; -110; -120]')

```

Nbar Function

```

function[Nbar]=rscale(A,B,C,D,K)
% Given the single-input linear system:
%
%           x = Ax + Bu
%           y = Cx + Du
% and the feedback matrix K,
%
% the function rscale(A,B,C,D,K) finds the scale factor N which will
% eliminate the steady-state error to a step reference
% using the schematic below:
%

```



```

%          /-----\
%   R      +   u | .   |
%   ---> N --->() ---->| X=Ax+Bu |--> y=Cx ---> y
%          -|   \-----/
%          |       |
%          |<---- K <----|
%
s = size(A,1);
Z = [zeros([1,s]) 1];
N = inv([A,B;C,D])*Z';
Nx = N(1:s);
Nu = N(1+s);
Nbar=Nu + K*Nx

```