Challenges in Flight Control Design
Development and Testing

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Basic Facts About Unstable Plants

- Unstable systems are fundamentally, and quantifiably, more difficult to control than stable ones.
- Controllers for unstable systems are operationally critical.
- Closed-loop systems with unstable components are only locally stable.

The practical, physical (and sometimes dangerous) consequences of control must be respected, and the underlying principles must be clearly and well taught.
Overview

• The Airframe
• The Control Law Design Cycle
• Ground Testing and Validation
• Flight Tests
• Design Challenges
• The Way Ahead
Salient Features of LCA

- **Light weight, single engine, multirole supersonic** aircraft with all weather day / night capability

- **Tail-less compound delta airframe** configuration uses extensive carbon composites and co-cured co-bonded technology for realizing low weight and high strength

- **Relaxed longitudinal stability** with scheduled leading edge slats for high alpha maneuvering and combat

- **Quadruplex all digital fly-by-wire flight control system** with built-in redundancy management system and re-configurable control laws ensures safety of flight with agility and maneuverability
The Sensors

1. Nose Airdata Probe
2. Side Airdata Probes
3. AoA Vanes
4. Acceleration Sensor
5. Temperature Sensor
6. Rate Sensor

Vertical Datum: X=0
A/C C/L: Y=0
FRL: Z=0
The Air Data System

- Total Air Temperature sensor
- Side air data probe
- Nose air data probe
- AoA Vane
Why Relaxed Static Stability?

Unstable

Stable

Decrease in Drag

Gain in Lift
Limits on Level of Instability

- Hardware (actuator, sensors etc.) capabilities poses restriction on level of instability
  - if $K_1 > K_2$, aircraft can never be stabilised
  - more stringent requirement for guaranteeing margins i.e. for $\pm 6$ dB gain margin $1/2 K_1 \leq 2K_2$
Key Elements which affect the performance of FCS

- Airframe
- Control Laws and associated Hardware
- Pilot Seat location
- Stick Characteristics and Type
- Displays
- Operating Environment (Cockpit / External)
Human Pilot Modeling & Pilot – Aircraft Coupling

**Visual Cues**

**Control Force**

**Motion Cues**

**Pilot Model**

\[
\frac{y(s)}{u(s)} = \frac{K (1 + T_A s)e^{-Ds}}{(1 + T_L s)(1 + T_N s)}
\]

- **K** = 1-100; **D** = 0.2 sec
- **T_A** = 0-2.5 sec (lead)
- **T_L** = 0-20sec (Error smoothing Lag)
- **T_N** ≈ 0.1 sec (Neuro muscular lag)
Control Law Requirements

• To Recover Stability and Provide Good Handling Qualities to the Pilot
  – Stability Robustness
    • Guarantee the required stability margins
  – PIO Resistance
    • Ensure good stability margins with pilot in the loop
  – Performance Robustness
    • Invariant response with respect to aerodynamics, fuel, etc.
Margen Requirements

Requirements (Based on MIL-SPEC-9490D)

Nichols Plot

- For computational tractability, the trapezium is approximated by an ellipse. This leads to the definition of a metric, Closeness Parameter (CP) that incorporates both GM and PM.
Control Law Requirements Contd...

– Level 1 Handling Qualities
  • Crisp and Predictable Response to the Pilot

– Carefree Handling
  • In respect of AoA, Sideslip, Nz, Inertia Coupling, etc.

– Sufficient Structural Stability Margins
  • No coupling with structural modes

– Autopilot Modes
  • For ease of delivering stores, prevent disorientation, etc.
INTEGRATED FLIGHT CONTROL SYSTEM

Quadraplex digital fly-by-wire fault tolerant flight control system with control laws for carefree maneuvering

Complete flight control system status display to the pilot through glass cockpit
Mathematical Model of Aircraft

Control Law Development Environment (NAL)

Engineer-in-loop Simulator (NAL)

Pilot-in-loop Real Time Simulator (ADE)

Structural Coupling Test Facility (HAL)

Lightning Test Facility (CABS)

Non-Real Time Test Facility (ADA)

Aircraft Tests (HAL)

IFCS Facility (ADA)

Iron Bird (HAL)

Mini Bird (ADE)
Multi-disciplinary modeling & Simulation Requirements for Fly-by-Wire Control Law Development

- Aerodynamics
- Control Engineering
- Human Pilot Dynamics
- Structural Dynamics
- Landing Gear
- Hydraulics
- Propulsion
- Flight Control System
- Flight Dynamics

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The Design Cycle

Design Requirements
- Stability
- HQ

FCS Constraints etc

Linear Models

Linear Control Designs

Non-linear Control Shaping

6 DOF Simulation

Non Real Time
Real Time (‘ELS’)
Real Time (‘RTS’)

Validated Control Law

In-flight Simulation

Design O.K.?

YES

NO

YES

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Flight Control System Structure

Control Decision

Handling Quality
Mil Spec 1797

±6dB-35°
Mil Spec F9490D

Forward CLAW

Actuators

Flexible

Rigid

Aircraft

Rate & accln sensors

Gain Scheduling

Offline Design
(Table lookup f^n of Mach and altitude)

Feedback CLAW

Notch Filters

+ 8dB (small gain stabilization)
Mil Spec F9490D

Carefree Maneuvering
+ Low Speed Flying
CLAW

Air-data computation

Airdata Sensors

Pilot Input

Visual and Motion Cues

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CLAW Reversionary Modes

- **AoA failure**
  - An equivalent AoA signal is generated for feedback by processing total normal acceleration in addition to suitably reducing the command authority.

- **Airdata system failure**
  - A fixed gain reversionary mode as an ultimate backup.
  - Gains are frozen at the last good value,
  - Pilot can then manually switch over to the standby gains using a switch in the cockpit.
  - Two sets of fixed gains in the standby mode, which get automatically selected depending on the status of the undercarriage lever.

- **Elevon Failure**
Optimum Fixed Gain Selection

- Air Data Scheduled Gain
- U/C Down Gain
- U/C Up Gain

Dynamic Pressure

Gain
Longitudinal Feedback Controller Schematic

\[ 1g \cos \theta \]

\[ N_z \text{-alpha conversion gain} \]

\[ \text{Gain and Washout Filter PFC10} \]

\[ \text{Scheduled Gain} \]

\[ \text{Scheduled Gain and Phase Advance Filter} \]

\[ \text{Gain and Low-Pass Filter PFC10} \]

\[ \text{Scheduled Bias} \]

\[ \text{Gain} \]

\[ \text{Low Pass Filter} \]

\[ \text{Scheduled Bias} \]

\[ \text{Scheduled Gain} \]

\[ \text{Scheduled Gain and Phase Advance Filter} \]

\[ \text{Gain} \]

\[ \text{Low Pass Filter} \]

\[ \text{Scheduled Bias} \]

\[ \text{Gain} \]

\[ \text{Low Pass Filter} \]

\[ \text{Scheduled Bias} \]

\[ \text{Gain} \]

\[ \text{Low Pass Filter} \]

\[ \text{Scheduled Bias} \]
Longitudinal Axis Command Path

From Feedback

Trim Correction

Saturation and Rate-Limiter

δe

Pitch Stick

Shaping & Limiting

Small Amplitude

Pre-Filter

Desensitizer

Rate-Limiter

Pitch Stick Command

No-Windup Integrator

Limits as a function of Pitch Stick Command

Auto-Pilot

Pitch Trim
Lateral/Directional Controller Schematic

- **Roll Stick Position**
- **Pitch Stick Position**
- **Lateral**
- **Limiter**
- **No-Windup Integrator**
- **Shaping & Limiting**
- **Desensitizer**
- **Rate-Limiter**
- **Pre-Filters**
- **Gain As a function of Pitch Stick Position**
- **Saturation and Rate-Limiter**

- **Gain and Phase Advance**
- **Gain**
- **Estimated \( \beta \)**
- **Estimate \( \beta \) and \( \beta \)**

- **Anti-aliasing and Notch Filter**
- **Low-Pass Filter**
- **Phase Advance**

- **Roll Stick to Rudder Interconnect Gain**
- **Pitch Stick Position**
- **Gain As a function of Pitch Stick Position**
- **Saturation and Rate-Limiter**

- **Roll Trim**
- **Pitch Stick Position**
- **Gain As a function of Pitch Stick Position**
- **Saturation and Rate-Limiter**

- **Anti-aliasing and Notch Filter**
- **Low-Pass Filter**
- **Phase Advance**

- **Signal Conditioning Filter**
- **Gain and Phase Advance**

- **Estimated \( \alpha \)**
- **\( \beta \)**
- **Ny**

- **Aileron to Rudder Interconnect Gain**
- **Directional**

- **Rudder Pedal**
- **Shaping & Limiting**
- **Rate-Limiter**
- **Pre-Filter**

- **Yaw Trim**
- **No-Windup Integrator**
- **Limiter**
Air Data Signal Consolidation and Leading Edge Slat Controller

Air Data Signal Consolidation

For Air Data Gain Scheduling

Low Pass Filter and Rate Limiter

Low Pass Filter and Rate Limiter

÷

\( \sqrt{ } \)

MP

SP

Leading Edge Slat Control Law

Slat Authority Limiters as function of Dynamic Pressure and Mach

Saturation and Rate-Limiter

Normalised Slat Command

Pitch Stick

Shaping & Limiting

Washout Filter

Hysteresis

Low – Pass Filter

Processed \( \alpha \)
Kinematic coupling of AoA and AoSS
Control Law Validation

- Cost
- Realism

Prototype Aircraft (LCA)

In-flight Simulator (CALSPAN)

Iron Bird (HAL)

Engg. Simulator (ADE, BAe)

“Design” Simulator (NAL)

ADE, BAe
Fixed Base Real Time Flight Simulator
ELS - NAL
Important Requirements of RTS

• Accurate Dynamics

• Realistic Delays

• Adequate Cueing for Task

• Feel System Dynamics
Importance of Pilot in the Loop Simulation

Visual and Motion Cues

Sensor Feedback

Pilot → CLAW → Aircraft

Importance of Pilot in the Loop Simulation

Visual and Motion Cues

Sensor Feedback

Pilot → CLAW → Aircraft
Ironbird Schematic

Test Rig Consists of Real Actuators, Undercarriage, Hydraulic System

- Real sensors
- DFCC
- I/O RACK
- Aircraft Simulation
- ADA-FDS Computer
- Cockpit
- DH-EU

Test Rig
Typical Test for RM Logic

Ch. 1

Ch. 2

Ch. 3

Ch. 4

RM

Selected Value

\[ t_{1/2} \]

\[ T \]

\[ -t_{1/2} \]
Aircraft Rigid Body & Structural Mode Dynamics

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Gain Margins – Simplified Schematic

\[ L1 = \frac{A}{de}, \quad L2 = \frac{B}{de} \]
Notch Filter Design based on SCT Experiments

A systematic approach was evolved to design notch filters for the various sensor paths in the presence of coupling between structural responses of all three axes of the aircraft.

A difficult optimisation problem was converted into five independent simple optimisation problems without introducing conservativeness.

Bode’s Gain-Phase Relation

\[ \phi(w_c) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{dM}{du} \ln \left( \coth \left( \frac{u}{2} \right) \right) du \]

Where, \( u = \ln \left( \frac{w}{w_c} \right) \)

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Control Law Design & Validation

Cost

Realism

Prototype Aircraft
In-flight Simulator
Iron Bird
Engg. Simulator
“Design” Simulator
Objectives of Flight Tests

- Validate the performance of the FCS in flight
- Establish the handling qualities of the aircraft
- Calibrate the airdata system
- Identify the aerodynamic stability and control characteristics and establish the correlation of flight responses with the Real time simulator responses
- Verify Stability Margins in Flight
Online Gain and Phase Margins

\[ G := \text{TF from } P_1 \text{ to } P_2 \]
\[ L := \text{TF from } A \text{ to } B \]

\[ G = \frac{1}{1 - L} \quad L = \frac{G - 1}{G} \]
Modern Robust Control Applied to LCA Control Laws

- Major Bottleneck:
  - Classical Gain and Phase Margins still the *only* Robustness Criterion used for Flight Controllers (MIL Spec)
  - Led to conservative $H_\infty/\mu$ controllers
Summary: We show by examples that optimum and robust controllers, designed by using the $H_2$, $H_\infty$, $l_1$, and $\mu$ formulations, can produce extremely fragile controllers, in the sense that vanishingly small perturbations of the coefficients of the designed controller destabilize the closed-loop control system. The examples show that this fragility usually manifests itself as extremely poor gain and phase margins of the closed-loop system. The calculations given here should raise a cautionary note and draw attention to the larger issue of controller sensitivity which may be important in other nonoptimal design techniques as well.
Margin Requirements

Nichols Plot

Nyquist Plot

Gain

Phase

Rigid

Structural

-1
Margins Template Converted to Uncertainty on the Plant  

(Non Conservative)

6dB-35° template in the Nichols Plot

The template converted to an uncertainty on the plant
Margins and Complementary Sensitivity

The Basic Design Problem becomes that of minimizing sensitivity for the nominal plant subject to a bound on the biased complementary sensitivity.

\[
\left\| \frac{CP_0}{1 + 1.25CP_0} \right\|_\infty < \frac{1}{0.75}
\]

Modified Mixed Sensitivity Minimisation Problem

– The Basic Design Problem becomes that of minimising sensitivity for the *nominal* plant subject to a bound on the complementary sensitivity of a *scaled* plant.

\[
\min_{C \text{ stabilising}} \left\| W_1 \frac{1}{1 + CP} \right\|_\infty \quad \text{subject to} \quad \left\| W_2 \frac{C(1.25P)}{1 + C(1.25P)} \right\|_\infty < 1
\]
Solution

- The Problem was “solved” using an iterative procedure

\[
\min \left| W_1^i \frac{1}{1 + C(1.25P)} \right|_\infty \quad \text{s.t.} \quad \left| W_2 \frac{C(1.25P)}{1 + C(1.25P)} \right|_\infty < 1
\]

where \[ W_1^i = W_1^{i-1} \frac{1 + C_{i-1}(1.25P)}{1 + C_{i-1}P} \quad W_1^0 = W_1 \]

till \[ \left| W_1 \frac{1}{1 + C_i P} \right|_\infty - \left| W_1 \frac{1}{1 + C_{i-1}P} \right|_\infty < \epsilon \]
Utility in Design

• Helps to benchmark a classical controller and find “limits of performance”.
• Identify new structures for a classical controller design.
• For the multivariable case the uncertainty can be added to each input of the plant - \( \mu \) synthesis for non-conservative designs.
Clearance of Flight Control Laws

• Clearance of control laws for flight – a very laborious process.
• Certification Authorities have to be shown that aircraft is safe to fly in all parts of the envelope with the nominal controller and with failures.
• Safety to be ensured with all aerodynamic tolerances and tolerances on airdata parameters.
• For all configurations of the aircraft – with different combinations of weapons, drop tanks, etc.
THE WEIGHT OF THE PAPERWORK = THE WEIGHT OF THE AIRCRAFT
FLY!!
Utility of Modern Control Techniques for Clearance

• Current approach is gridding of the envelope
• Disadvantages-
  – Number of cases goes up exponentially as a function of the parameters
  – No guarantee of satisfaction of requirements at non-grid points
  – Only extreme values of tolerances considered
Utility in Flight Clearance ...

• Recent research by the GARTEUR Group has demonstrated how the complementary sensitivity criterion for stability margins can be used for accelerated flight clearance

• Achieved by modeling all the uncertainties in database as LFTs and using $\mu$-norms to clear the flight envelope.
Air Data Sensors

- Total Air Temperature sensor
- Side air data probe
- Nose air data probe
- AoA Vane
- SSA Vane

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Presentation at IIT Kanpur
Concluding Remarks

- Design of Control Systems with a human in the control loop is a very challenging problem.

- Flight Simulation plays a very important role in the design optimization.

- A Good R&D Base has been established in the country to undertake:
  - aircraft flight control design,
  - airdata system algorithm development,
  - Aerodata update and airdata system calibration,
  - Flight testing and flight envelope expansion.
Control Law Flying on LCA

Thank You

Theory - without Practice - is Sterile;
Practice - without Theory - is Blind

-- Karl Marx
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