National Aeronautics and
Space Administration

Structural “Pain” Compensating Flight Control

Aerospace Control and Guidance Systems Committee Meeting #114

October 15-17, 2014

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Background

Problem Statement

- **Current aircraft designs utilize high design structural margins and fixed* control allocation schemes to prevent structural over load for a priori operating conditions and maneuvers.**
- **As a result:**
  - The control laws provide no explicit guarantee of structural overload prevention
  - Operators must rely on pilot awareness and training to avoid maneuvers which would damage the aircraft
  - Fixed* allocators lack adaptability to damage, system failures, and flight outside of the design flight envelope (stall/spin)
  - Aircraft structure must be overbuilt resulting higher vehicle weight and more fuel burn

American Airlines Flight 587, Nov. 12 2001
NTSB Number AAR-04/04

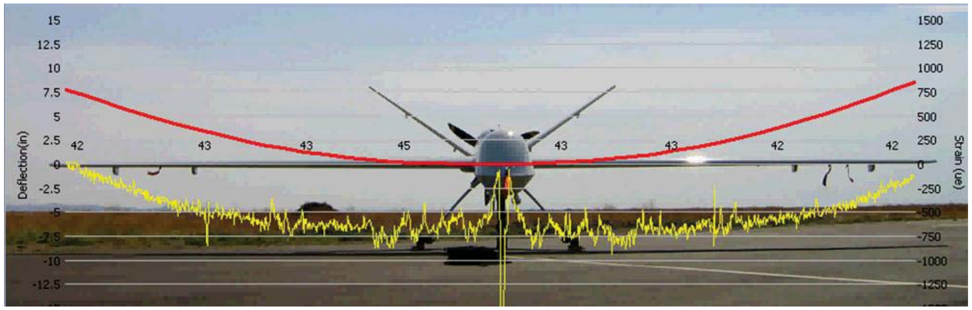
"The National Transportation Safety Board determines that the probable cause of this accident was the in-flight separation of the vertical stabilizer as a result of the loads beyond ultimate design that were created by the first officer's unnecessary and excessive rudder pedal inputs. Contributing to these rudder pedal inputs were characteristics of the Airbus A300-600 rudder system design and elements of the American Airlines Advanced Aircraft Maneuvering Program."

**The term fixed in this context does not necessarily mean that the control allocation is the same across all flight conditions simply the lack of ability to redistribute control mixing based on sensed data or failure detection.*

Conceptual Idea

Solution Concept

- Distributed measurements of structural load
  - Analogous to a nervous system
- These sensors provide an indication of "pain" in the aircraft structure to the controller
- Control system redistributes control away from overloaded structure
  - Analogous to a "limp" reflex
- Utilizes secondary surfaces with available margin to achieve desired dynamic response

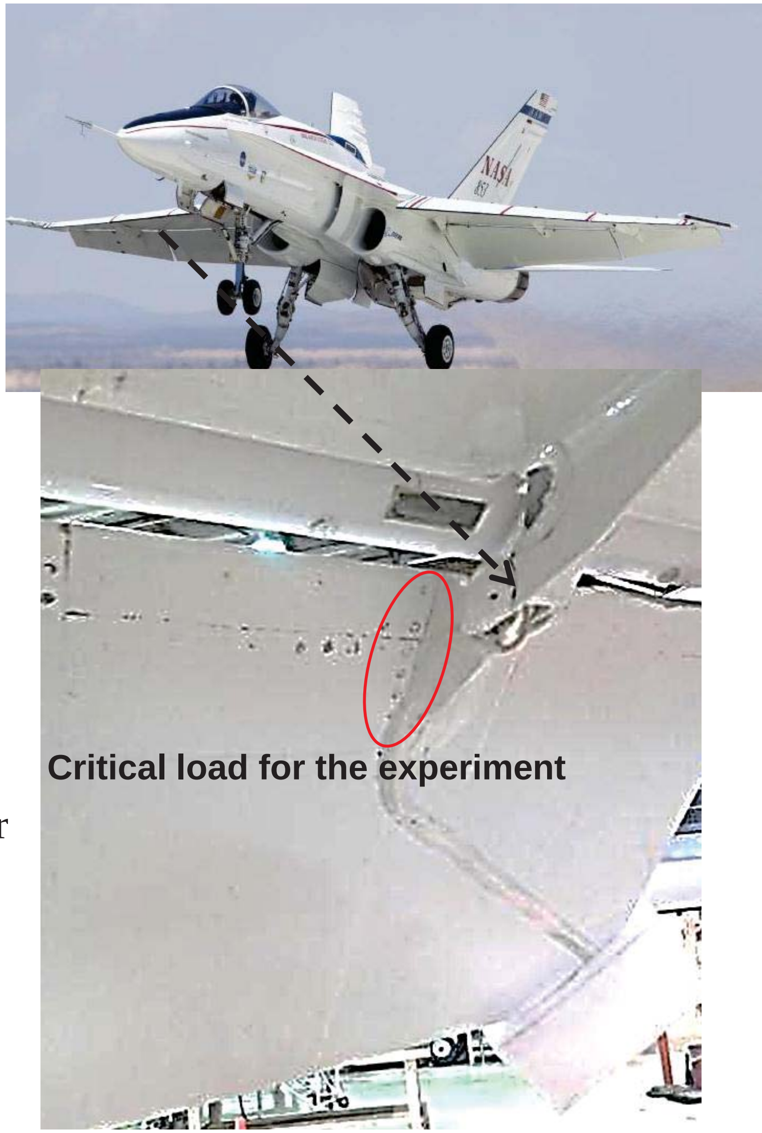


Key Benefits

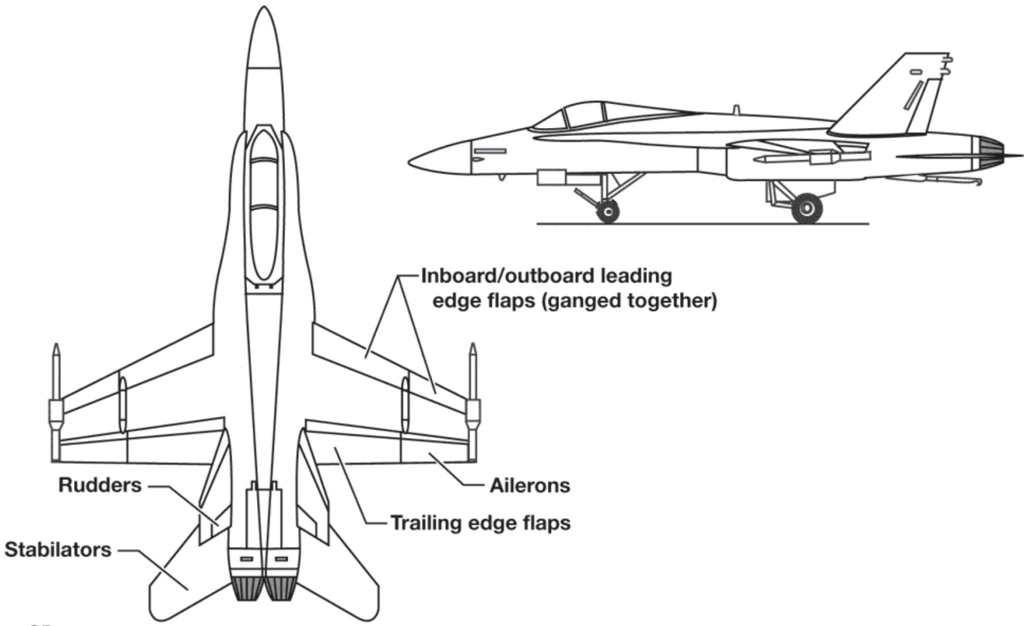
- Enables lighter weight aircraft structure
- Automatically adapts to many damage scenarios
- Increases aircraft robustness in loss of control scenarios
- Enables advanced control techniques

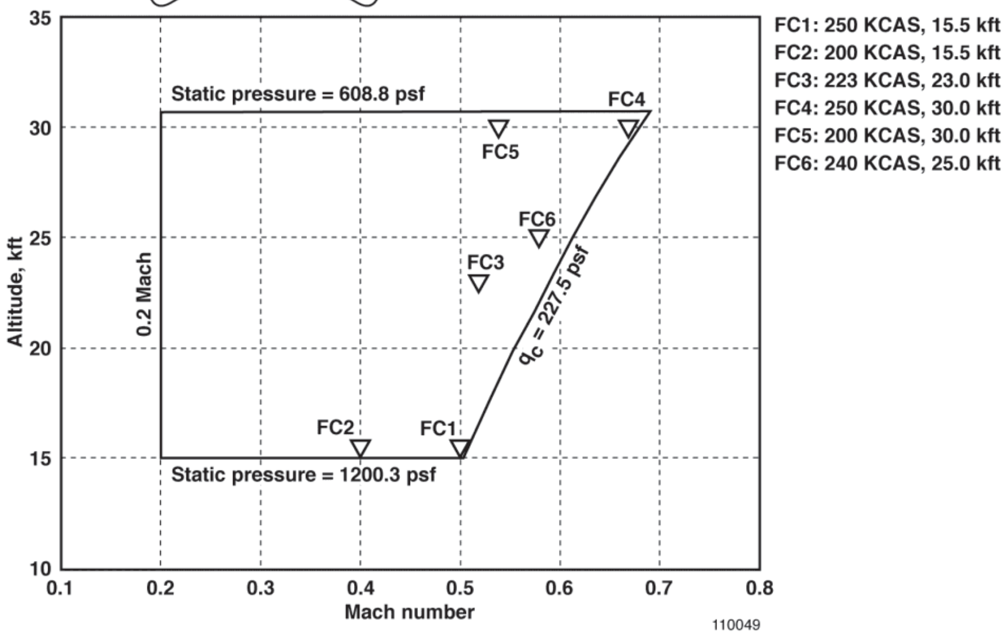
Experiment Objectives and Scope

- **Explore the merits of Optimal Control Allocation with structural feedback in flight on a full scale piloted vehicle (3 Flights)**
- **Feedback strain gauge measured aileron hinge moment**
  - Limited envelope allows rapid prototyping
  - Utilizes research instrumentation as a primary feedback parameter
- **Utilize measured strain within an optimal control allocator to actively limit the load on aileron attachment rivets to specified values maintaining aircraft handling qualities and performance**
- **Objectives:**
  - Objective 1: Limit the aileron motion subject to a defined load constraint.
  - Objective 2: Maintain the roll axis frequency response of the controller that does not utilize structural load as a constraint.
  - Objective 3: Maintain the handling qualities ratings of the controller that does not utilize structural load as a constraint



Testbed Overview

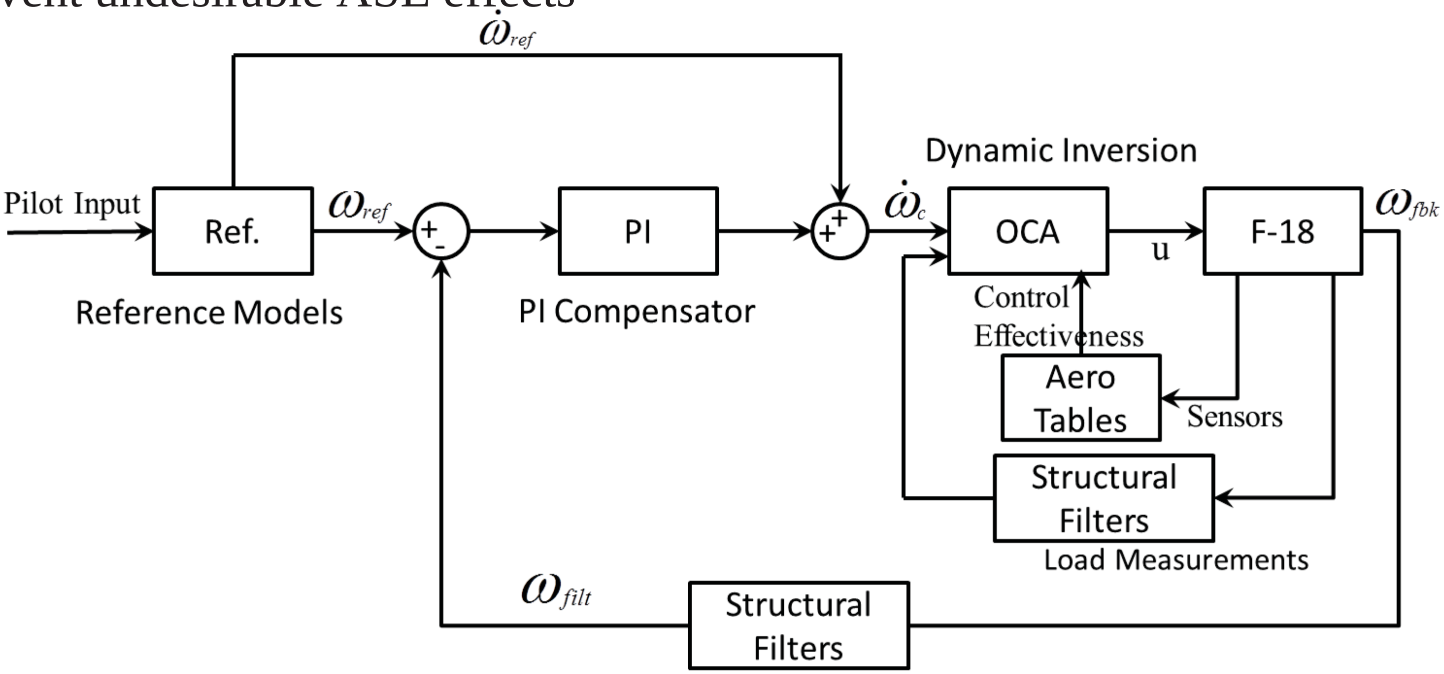




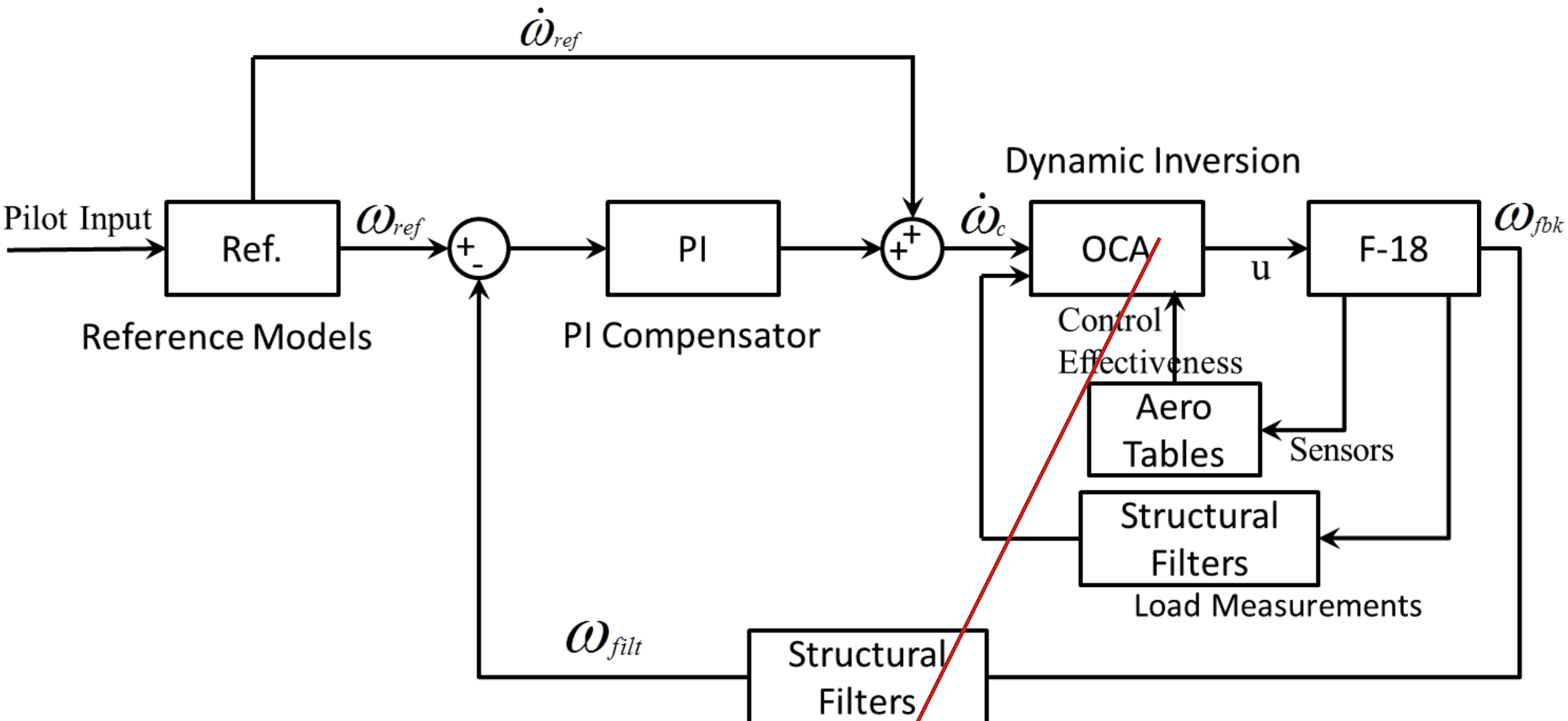
- **Modified Single Seat F/A-18**
  - Research flight control computers
    - Dual redundant
    - Host autocoded Simulink
  - Research instrumentation system
    - Linked to research flight control computers
    - Research quality inertial data (EGI)
    - Structural instrumentation
      - Foil strain gauges with calibrated load equations for wings
      - Accelerometers on wings, fuselage, and control surfaces
    - Surface position data
    - Nose boom

Control Law Overview

- **Reference Models (Ref.)**
  - Compute desired vehicle dynamics from pilot commands
- **Proportional plus Integral Compensator (PI)**
  - Adds robustness and disturbance rejection
- **Aerodynamic Tables (Aero Tables)**
  - Tabulates control surface effectiveness
- **Control Allocator (OCA)**
  - Computes surface positions to produce desired dynamics
- **Structural Filters**
  - Prevent undesirable ASE effects



Optimal Control Allocation Formulation



Command tracking from conservation of angular momentum (normal NDI)

Desired trim

Load Constraint

$$J = \boxed{\left\| \boldsymbol{B}\boldsymbol{u} - \frac{1}{q_c S}\left[I\dot{\vec{\omega}}_c^{\,b} + \vec{\omega}^b \times I\vec{\omega}^b - Ax \right] \right\|_2^2} + \boxed{\boldsymbol{\varepsilon}\left\| \boldsymbol{H}(\boldsymbol{u} - \boldsymbol{u}_p) \right\|_2^2} + \boxed{\boldsymbol{\gamma}\left[\left\| \boldsymbol{M} + \boldsymbol{L}(\boldsymbol{u} - \boldsymbol{u}_m) \right\|_2^2 \right]^n}$$

Load feedback

Cost Function Explanation

Measured surface
positions
(M is based on current
Position)

Relative importance
of achieving desired
trim positions

Aircraft state data
(α,p,q,r)

Relative importance
of load constraint

Load constraint
power (used to
tailor steepness)

Command tracking from conservation
of angular momentum (normal NDI)

Desired trim

Load Constraint
(normalized by load limit)

$$\boldsymbol{J} = \left\| \boldsymbol{Bu} - \frac{1}{q_c S}\left[I\dot{\vec{\omega}}_c^{\,b} + \vec{\omega}^b \times I\vec{\omega}^b - Ax\right] \right\|_2^2 + \boldsymbol{\varepsilon}\left\| \boldsymbol{H}(\boldsymbol{u} - \boldsymbol{u_p}) \right\|_2^2 + \boldsymbol{\gamma}\left[\left\| \boldsymbol{M} + \boldsymbol{L}(\boldsymbol{u} - \boldsymbol{u_m}) \right\|_2^2\right]^n$$

Angular Accel.
command
(ref + PI)

Vector of load
measurements

Surface trim positions
Anything in the null(B)

Matrix of surface
Influence coefficients
for each load

Square matrix used to
set relative importance of
trim positions for each surface

Control effectiveness
Matrix and homogenous
contribution (Aero tables)

Tuning the Cost Function (Trim)

- **ε – Scalar weight for attraction to trim**
  - Small enough to allow for the surfaces to move to track the desired dynamics but large enough to attract the surfaces back to their desired trim positions in the absence of large commands
    - Analogous to an integrator zeroing out steady state error
  - Without this type of term the surfaces trim in odd and not intuitively obvious ways
  - Tuned empirically by trial and error. HQ’s do not appear to be very sensitive to it’s value. Basically just need to get the order of magnitude right.
- **H – Square matrix used to set relative importance of achieving trim position for each surface**
  - Not in any of the publications, but found to be very helpful.
  - Allows the designer fine control of the surface usage priorities without dedicating a surface to one role
    - For example: F-18 the TEFs are slow and used mostly for trim while the ailerons are fast and primarily used for tracking roll commands
  - Tuning is straight forward and can be done empirically
  - A diagonal matrix was found to yield the desired flexibility desired..
- **u_p – Trim surface commands**
  - Anything in the null space of B is permissible
  - Used to trim for angle of attack and to keep surfaces in desirable positions for control authority

Command tracking from conservation of angular momentum (normal NDI)

Desired trim

Load Constraint (normalized by load limit)

$$J = \boxed{\left\| \boldsymbol{Bu} - \frac{1}{q_c S}\left[I\dot{\vec{\omega}}_c^{\,b} + \vec{\omega}^b \times I\vec{\omega}^b - Ax\right] \right\|_2^2} + \boxed{\boldsymbol{\varepsilon}\left\| \boldsymbol{H}(\boldsymbol{u} - \boldsymbol{u}_p) \right\|_2^2} + \boxed{\boldsymbol{\gamma}\left[\left\| \boldsymbol{M} + \boldsymbol{L}(\boldsymbol{u} - \boldsymbol{u}_m) \right\|_2^2 \right]^n}$$

Tuning the Cost Function (Load)

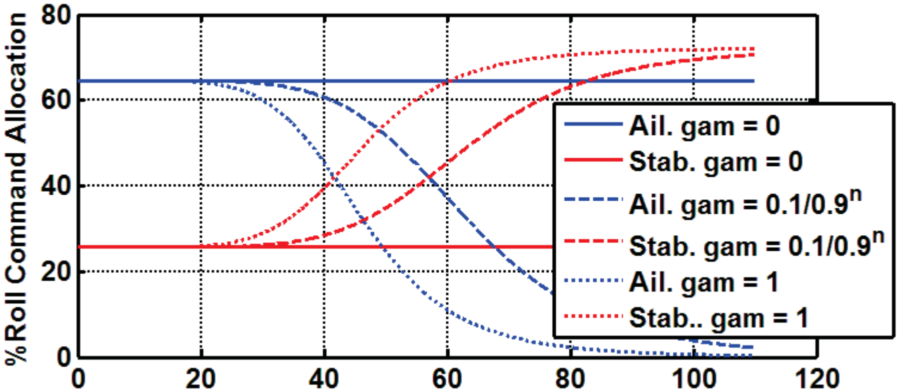
- **γ – Scalar weight for load constraint**
  - Must be tuned in conjunction with n to tailor at what load level this constraint dominates the cost function
  - This experiment tuned so that 80% is the cross over point such that below 80% the load constraint plays little to no role, but over 80% it dominates the cost function
- **n – Exponent on the load constraint**
  - Tuned to provide a steeper load constraint at higher load and a nice flat near zero value at lower load
  - Higher powers can exhibit convergence issues, and if the power is too low the constraint behaves less like a hard constraint and more as a load minimization constraint
  - Higher values of n makes the control response more sensitive to time delay in the load measurement
- **This formulation provides a practical hard constraint on the load without requiring a unique mapping from surface positions to loads**
  - Publications with hard load constrains implement them as surface position limits which requires a uniqueness in the load equations
  - The other published approaches minimize load which is also not desirable for this application

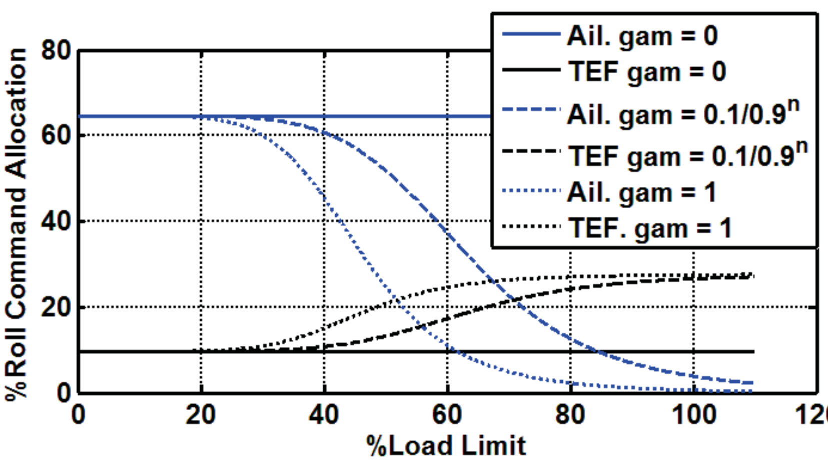
$$J = \underbrace{\boxed{\left\| \boldsymbol{Bu} - \frac{1}{q_c S}\left[I\dot{\vec{\omega}}_c^{\,b} + \vec{\omega}^b \times I\vec{\omega}^b - Ax\right] \right\|_2^2}}_{\text{Command tracking from conservation of angular momentum (normal NDI)}} + \underbrace{\boxed{\boldsymbol{\varepsilon}\left\|\boldsymbol{H}(\boldsymbol{u}-\boldsymbol{u}_p)\right\|_2^2}}_{\text{Desired trim}} + \underbrace{\boxed{\boldsymbol{\gamma}\left[\left\|\boldsymbol{M}+\boldsymbol{L}(\boldsymbol{u}-\boldsymbol{u}_m)\right\|_2^2\right]^n}}_{\text{Load Constraint (normalized by load limit)}}$$

Tuning n and γ Illustration

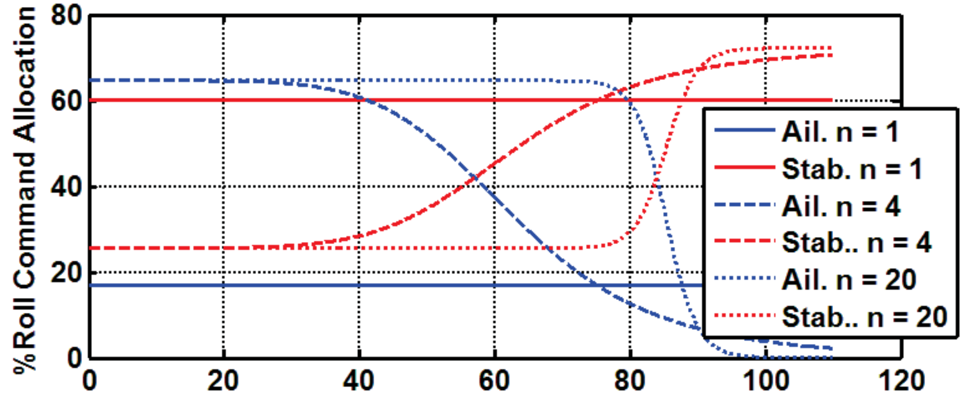
- **Decreasing γ**
  - Increases load at which transition between aileron and Stab/TEF dominates roll (better aileron usage)
  - Leaves some residual aileron command at high load (undesirable)
- **Increasing n**
  - Increases load at which transition between aileron and Stab/TEF dominates roll (better aileron usage)
  - Allows full transition away from aileron usage prior to 100% load (desirable)

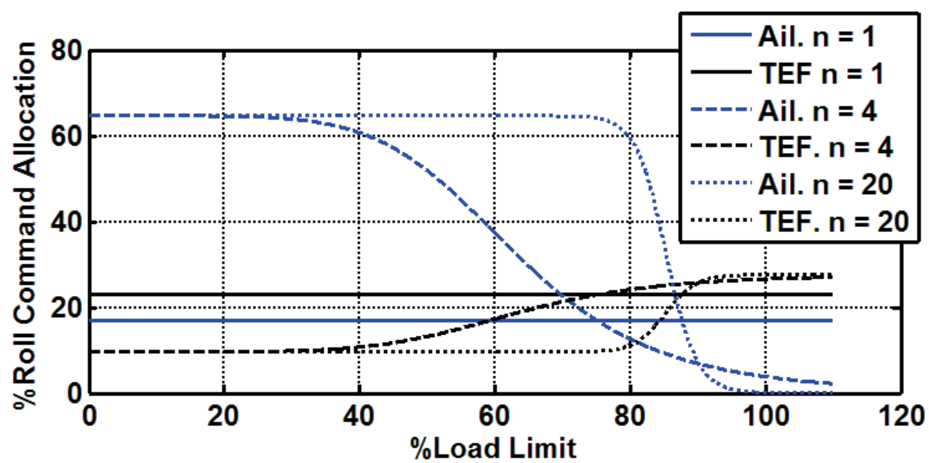
Effect of Varying γ with n=4





Effect of Varying n with γ = $0.1/0.9^n$





Minimizing the Cost Function (subject to rate and position limits)

$$J = \left\| Bu - \frac{1}{q_c S}\left[I\dot{\vec{\omega}}_c^{\,b} + \vec{\omega}^b \times I\vec{\omega}^b - Ax\right] \right\|_2^2 + \varepsilon \left\| H(u - u_p) \right\|_2^2 + \gamma\left[\left\| M + L(u - u_m) \right\|_2^2\right]^n$$

Solve for: $\frac{\partial J}{\partial u} = 0$

Which is global minimum because $\frac{\partial^2 J}{\partial u^2}$ is positive definite as long as B, L, and H are properly formulated

$$u_{k+1} = u_k - R * pinv\left(\frac{\partial^2 J}{\partial u^2}\right)\frac{\partial J}{\partial u}$$

$$u_{k+1} = saturation(u_{k+1})$$

R is a relaxation factor added to improve convergence properties

$$\frac{\partial J}{\partial u} = 2\{B^T[Bu - ad] + \varepsilon H^T H(u - u_p) + \gamma n N^{n-1} L^T [M + L(u - u_m)]\}$$

$$\frac{\partial^2 J}{\partial u^2} = 2\{B^T B + \varepsilon H^T H + 2\gamma n(n-1)N^{n-2}[L^T M + L^T L(u - u_m)][L^T M + L^T L(u - u_m)]^T + \gamma n N^{n-1} L^T L\}$$

$$N = M^T M + M^T L(u - u_m) + (u - u_m)^T L^T M + (u - u_m)^T L^T L(u - u_m) = \|M + L(u - u_m)\|_2^2$$

Other Numerical "Fixes" and Checks

- **Self adjusting relaxation factor to address poor convergence due to steepness of cost function at high load**
  - Each iteration should reduce J, if J increases reduce the relaxation factor (R) by a factor of 10 and redo the iteration
  - Repeat this until J is reduced by the iteration
- **Rank check of the control effectiveness matrix (B) using minimum singular value check**
- **Condition number check on second derivative of the cost matrix**
- **Number of iterations limited to avoid over running the allowed computation time**
- **Convergence verified by the value of the cost function and the norm of the first derivative of the cost function**

Experiment Configurations

- **Unique combinations for each unique cost function weighting scheme selectable prior to engagement (Not all combinations flown)**
  - Allocation schemes
    - Production Controller
    - Weighted pseudo inverse (NDI)
    - Cost function optimization via Newton-Rapson (OCA)
  - Load constraint exponent (n) values (only available for OCA)
    - 4, 10, 20
  - Trim weight (ε) values (only available for OCA)
    - 1e-4, 1e-3, 5e-3, 1e-2
- **Five load level limits selectable by nose wheel steering presses once engaged (only available for OCA)**
  - 0 – no load limit
  - 1 – 16,000 in-lbs
  - 2 – 12,000 in-lbs
  - 3 – 10,000 in-lbs
  - 4 – 7,000 in-lbs
  - 5 – 5,000 in-lbs

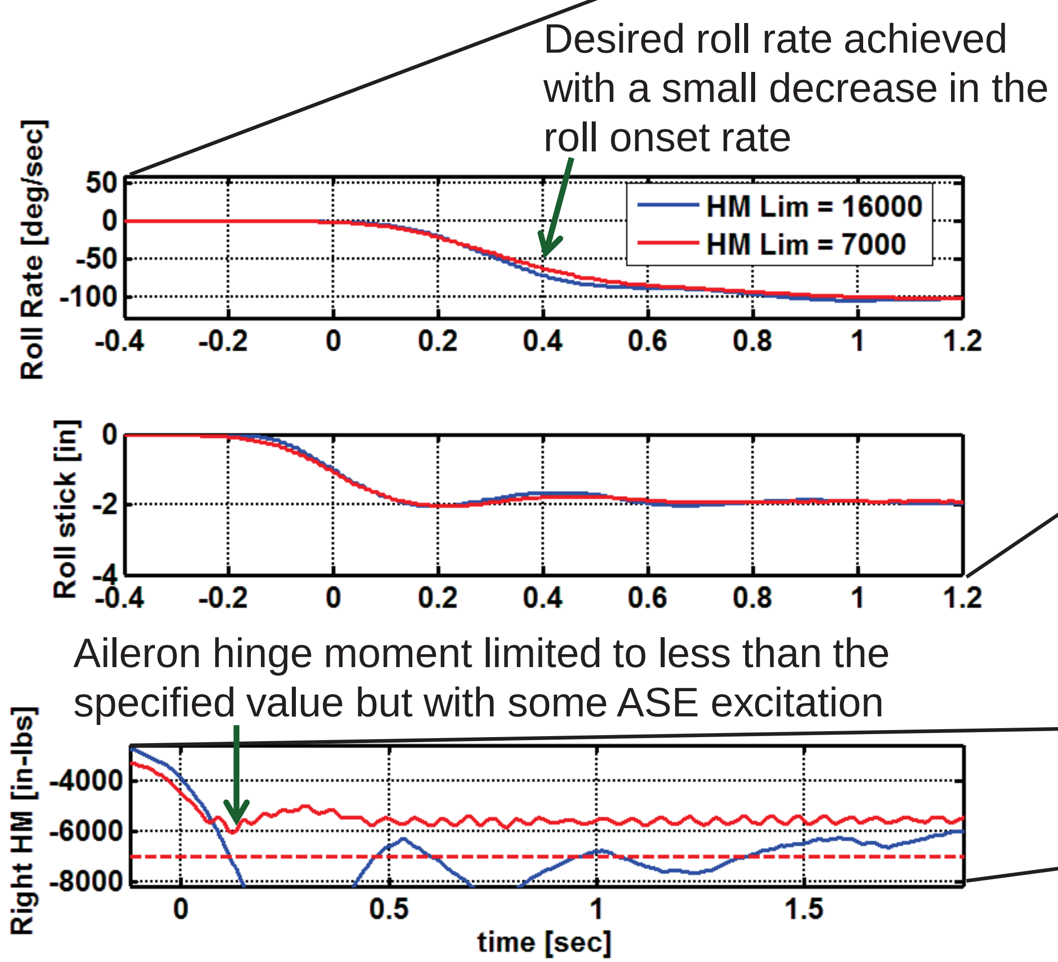
$$\boldsymbol{J} = \left\| \boldsymbol{Bu} - \frac{1}{q_c S}\left[I\dot{\vec{\omega}}_c^{\,b} + \vec{\omega}^b \times I\vec{\omega}^b - Ax\right] \right\|_2^2 + \boldsymbol{\varepsilon}\left\|\boldsymbol{H}(\boldsymbol{u}-\boldsymbol{u}_p)\right\|_2^2 + \boldsymbol{\gamma}\left[\|\boldsymbol{M}+\boldsymbol{L}(\boldsymbol{u}-\boldsymbol{u}_m)\|_2^2\right]^n$$

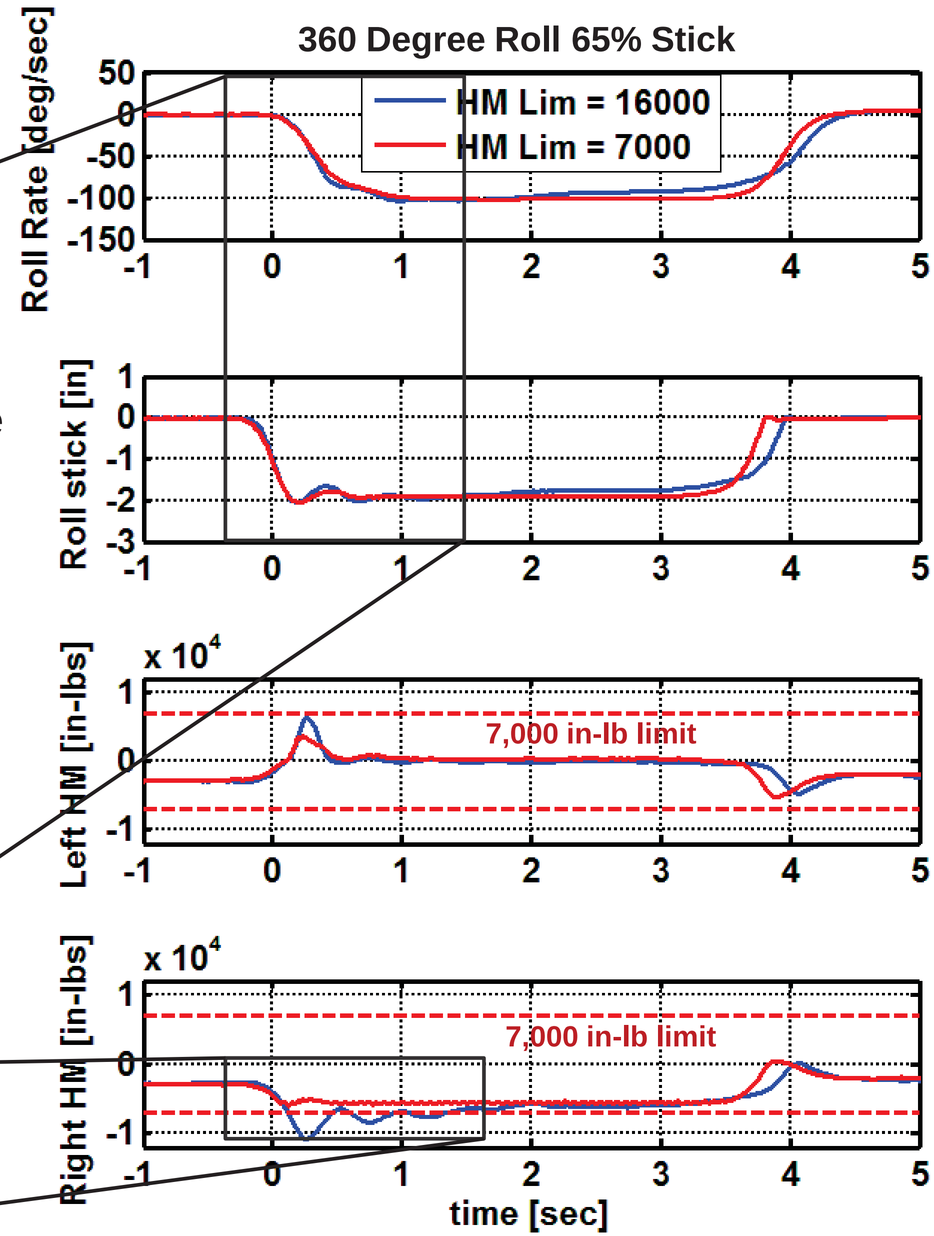
Flight Test Approach

- **3 flights with 3 different test pilots**
- **Each configuration (including production F-18) evaluated with a range of load limits**
  - Integrated test block at 25kft 240kcas, and 25kft 200kcas
  - 2.0 g air to air tracking with Cooper-Harper Ratings at nominally 25kft 240kcas (Illustration to follow)
- **Integrated test block consists of:**
  - Pitch, Roll and Yaw doublets
  - Pitch and bank captures
  - Full pedal steady heading side slip
  - 360 degree $^1/_2$ to $^3/_4$ stick rolls (limited by yaw rate required to coordinate rolls)
  - 2.0g load ½ stick roll
  - 2.5g wind up turn
  - Pitch and roll frequency sweeps

Successful Demonstration of Load Limiting

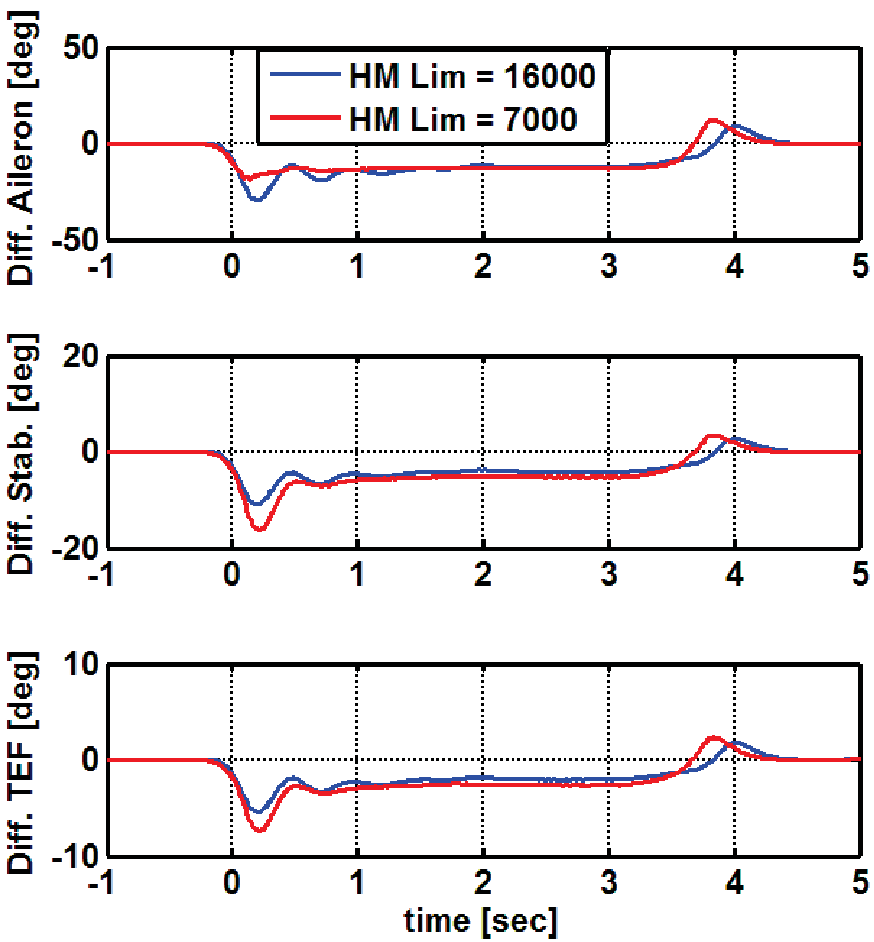
- The experiment successfully demonstrated the use of strain feedback as a means to actively limit the aileron loads
- The allocator redistributed roll control to other surfaces and achieved the desired roll rate

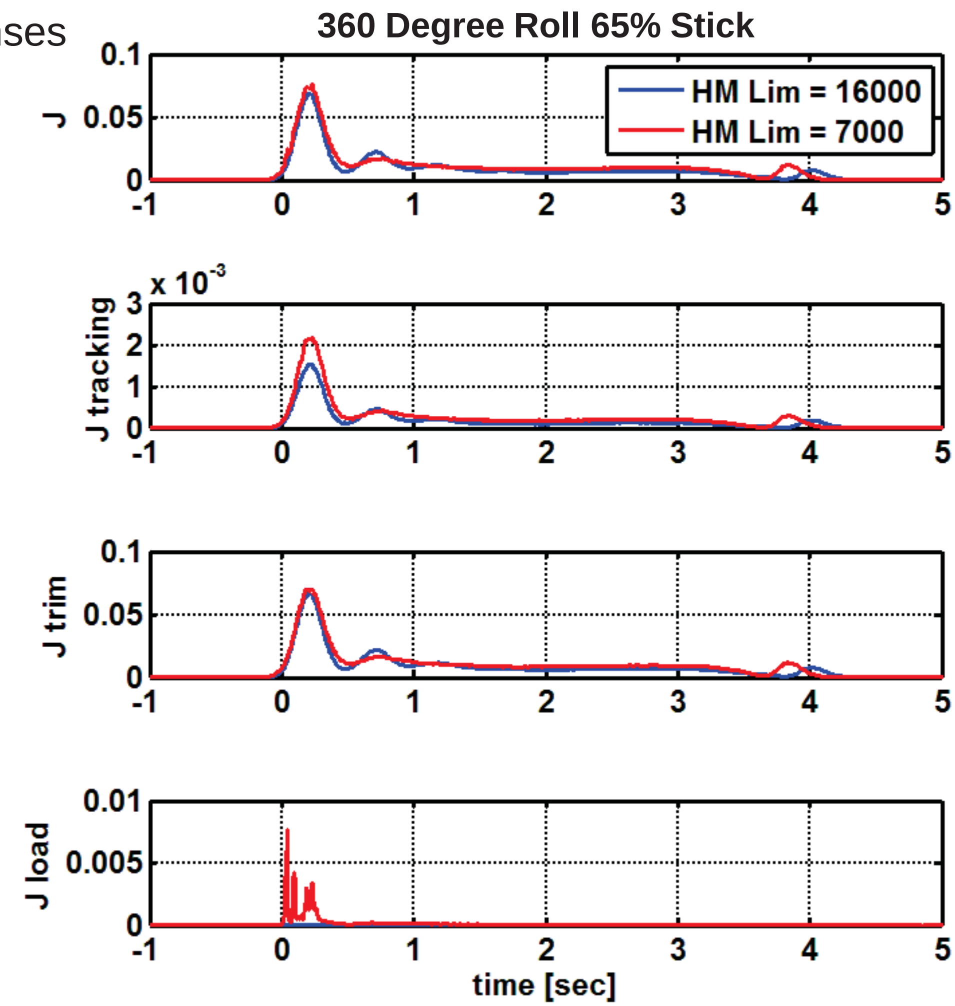




Control Surface Reallocation and Cost Function Behavior

- **With hinge moment limiting engaged the controller allocates more of the roll command to the stabs and TEF's as expected**
- **Which results in:**
  - A slight increase in the trim contribution to the cost function
  - More tracking error due to slower actuator responses

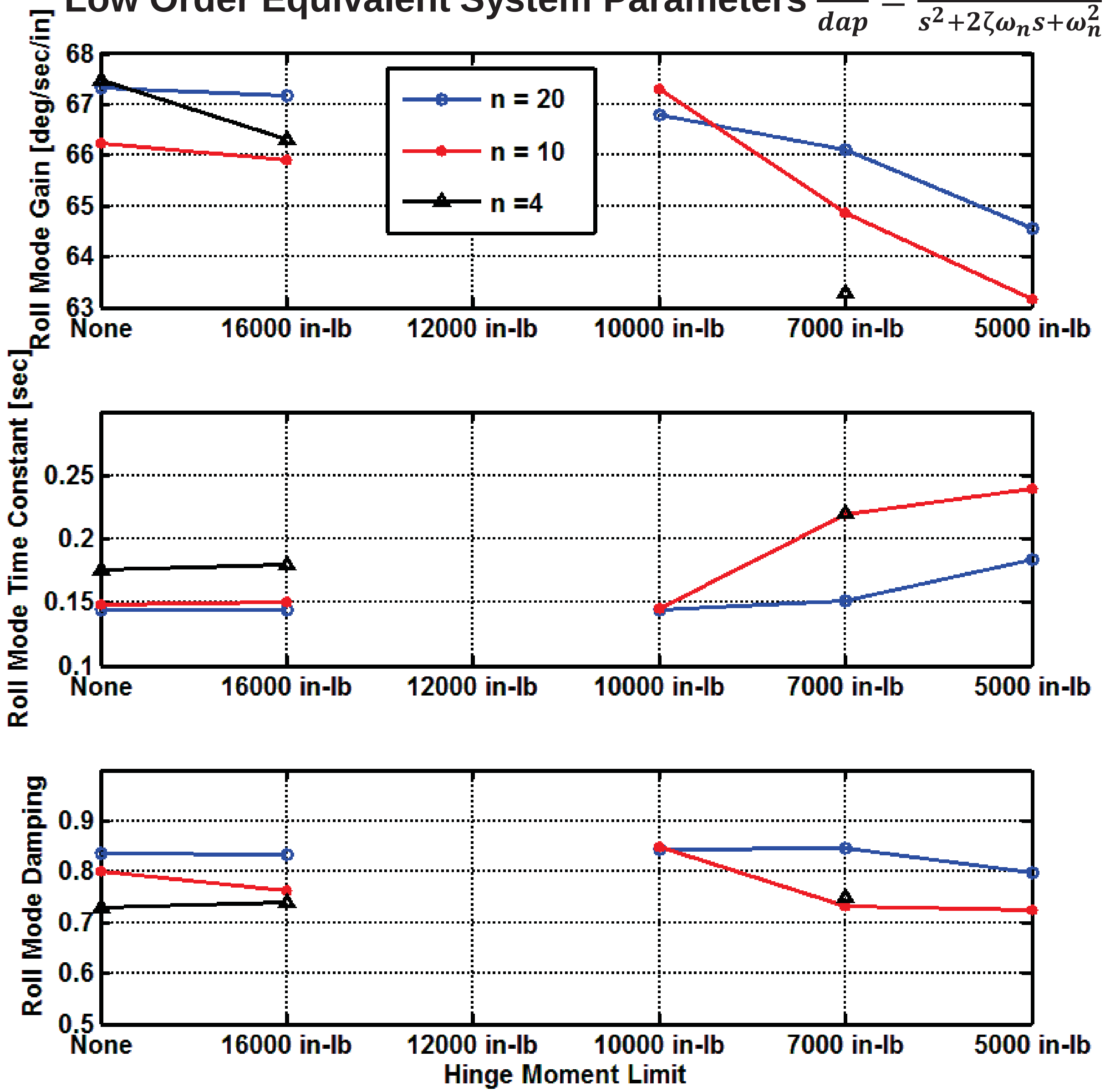




Roll Mode Behavior with Load Limiting

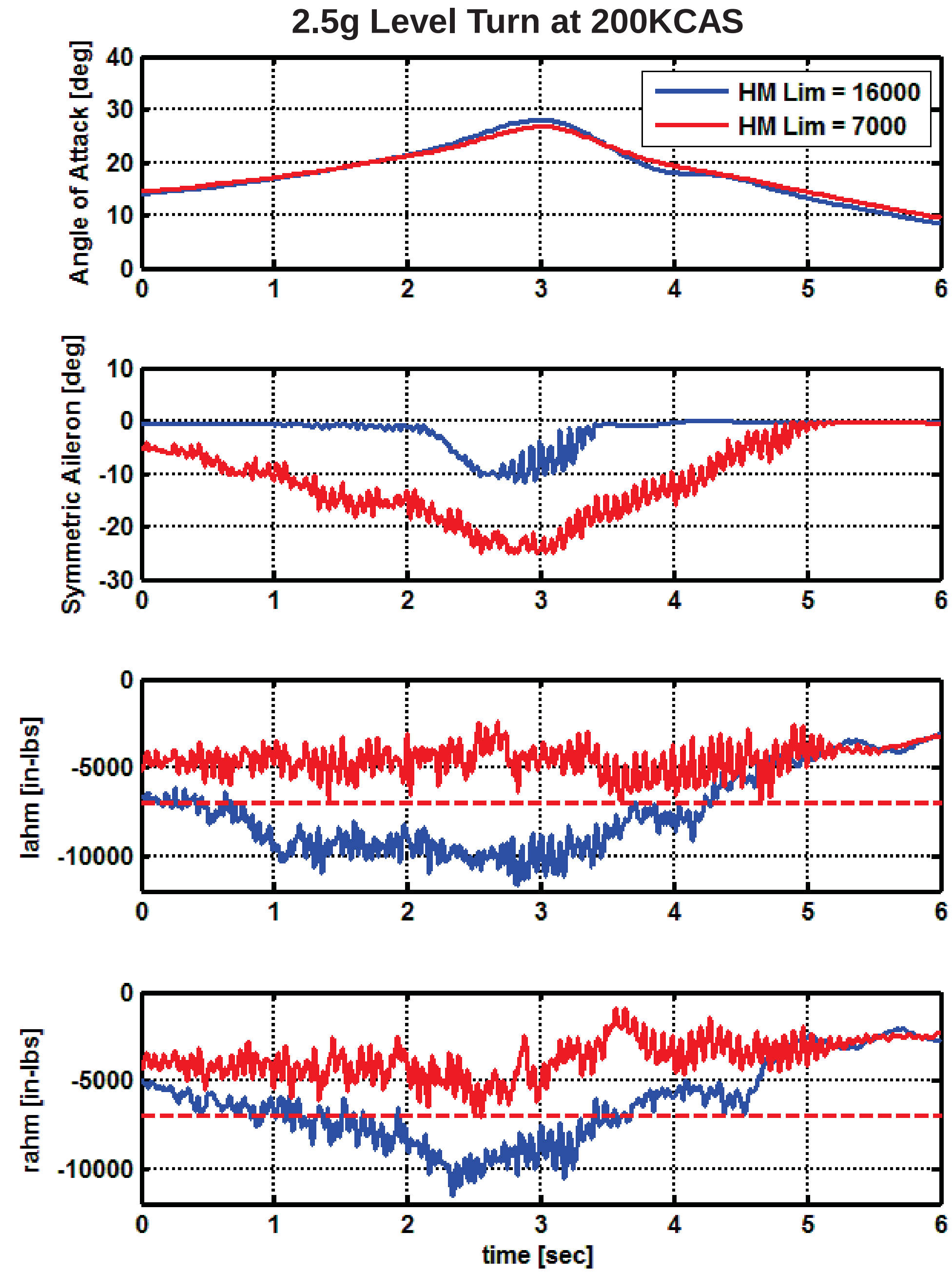
- **Roll Mode Gain (K)**
  - Decreases slightly with decreasing hinge moment limit
    - Less aileron command allowable translates to reduced roll rate
  - Steeper load constraints (higher n) preserve more roll authority
- **Roll Mode Time Constant $\left(\frac{1}{\omega_n}\right)$**
  - Increases with decreasing roll rate
    - Less aileron command allowable translates to reduced roll bandwidth
  - Steeper load constraints (higher n) preserve more roll authority even with restrictive load limits
- **Damping (ζ)**
  - No significant trends that affect the response

Low Order Equivalent System Parameters $\frac{p}{dap} = \frac{K\omega_n^2 e^{-0.08s}}{s^2+2\zeta\omega_n s+\omega_n^2}$



Symmetric Maneuver Behavior

- **The Good**
  - Hinge moment is limited to below the 7000 in-lb limit by fairing both ailerons symmetrically up to reduce load
- **The Not So Good**
  - Significant oscillatory behavior on both hinge moment measurement and the symmetric ailerons command
    - Exacerbated by tighter hinge moment limit
  - Related to exciting of a wing structural mode by the high angle of attack flow buffet on the aileron and wing
  - Average aileron hinge moment not as close to limit as desired (65% instead of 80%)
    - Due to two measurements nearing their limit instead of just the one
    - Suggests that further shaping of load measurements beyond just the load constraint exponent may be desirable

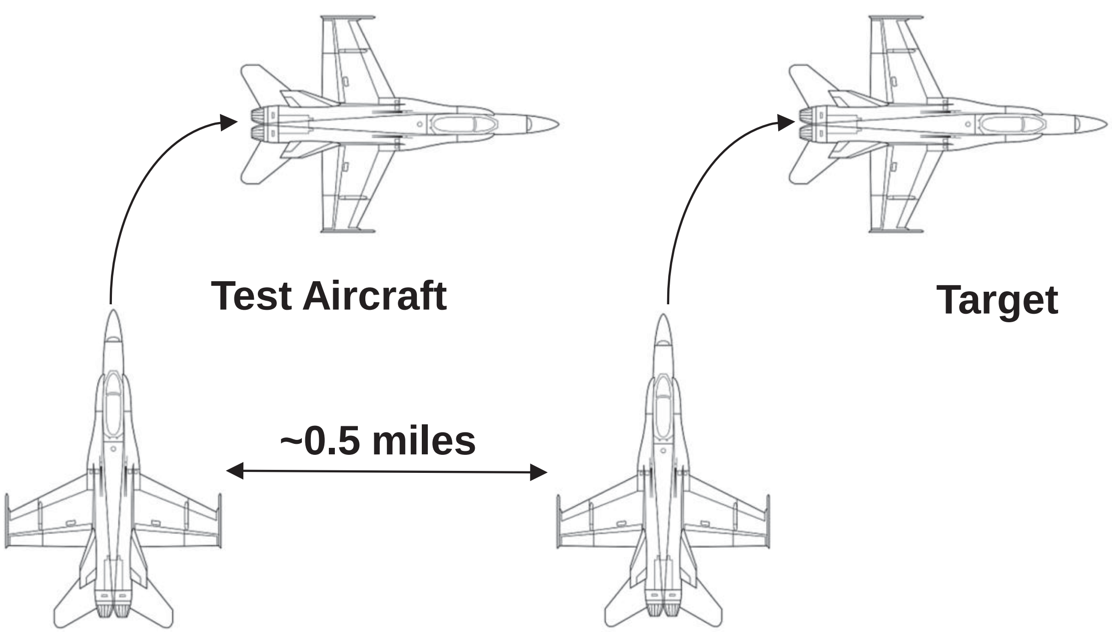


Tracking Task Description

♦ Gross Acquisition

- Target aircraft starts line abreast with the test aircraft at ~0.5 miles separation
- Target initiates a 2g level turn
- Test aircraft aggressively places the target within the reticle
  - Desired Criteria – No overshoots
  - Adequate Criteria – One overshoot

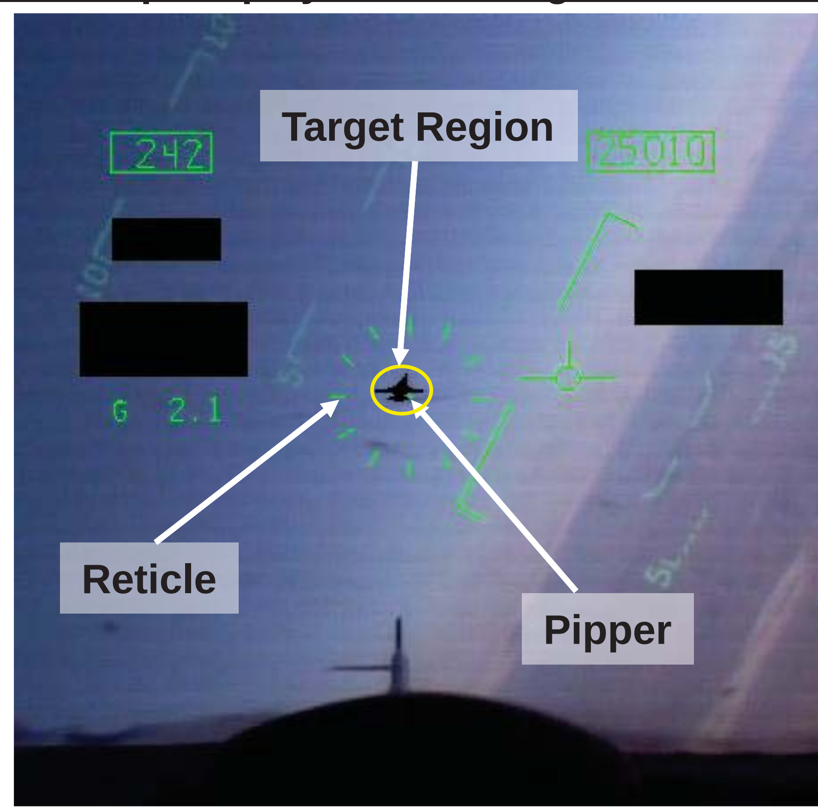
Gross Acquisition Setup



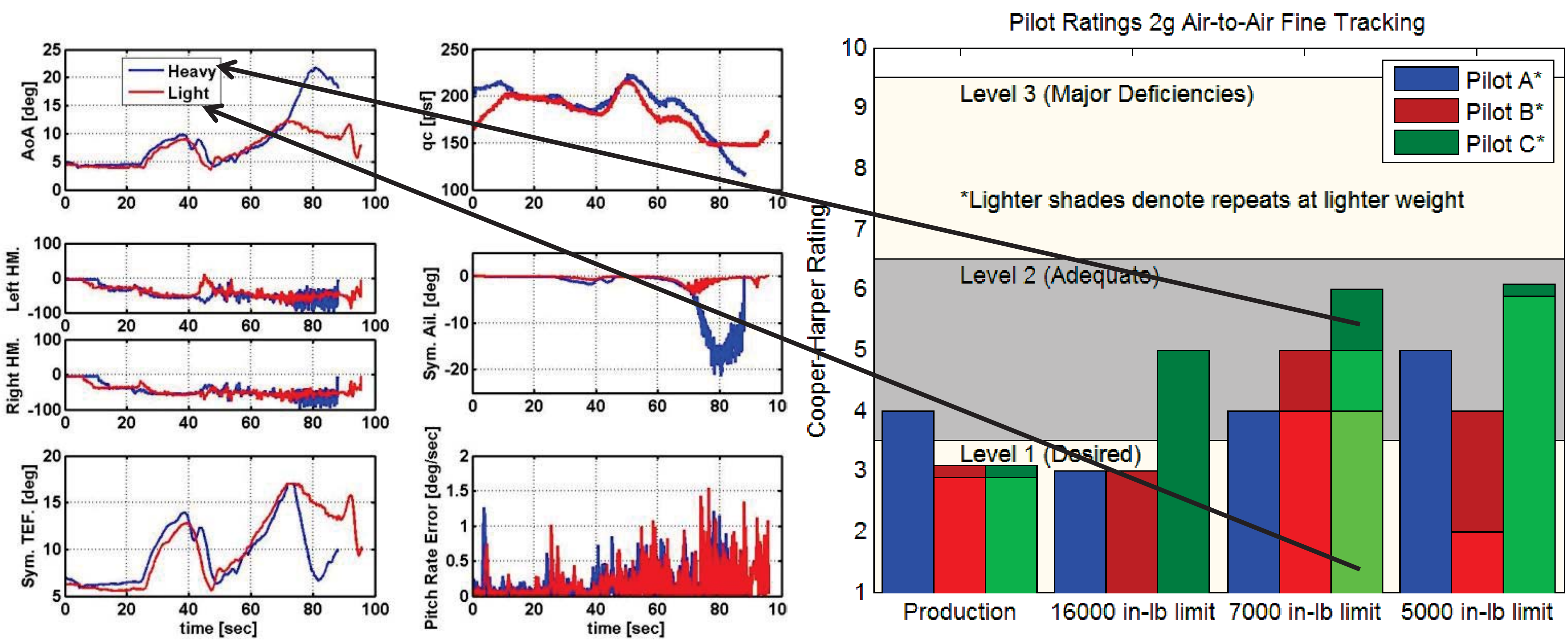
♦ Fine Tracking

- Target aircraft begins gentle roll maneuvers
- Test aircraft tracks the target with the pipper
  - Desired Criteria – Pipper on target 80% of the time
  - Adequate Criteria – Pipper on the target 50% of the time

Heads Up Display View During Fine Tracking



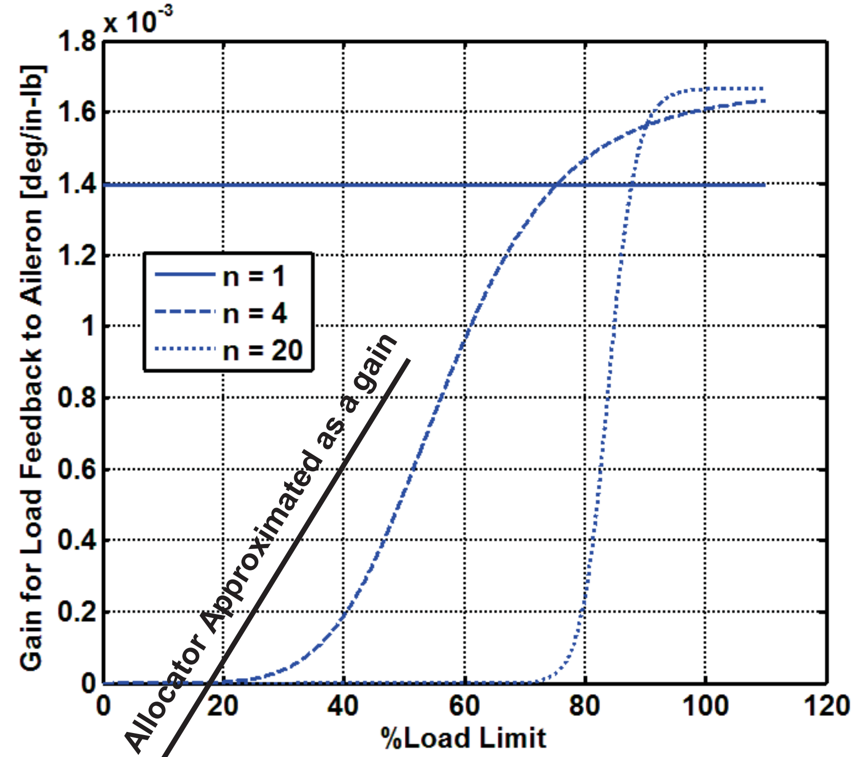
Handling Qualities Degradation

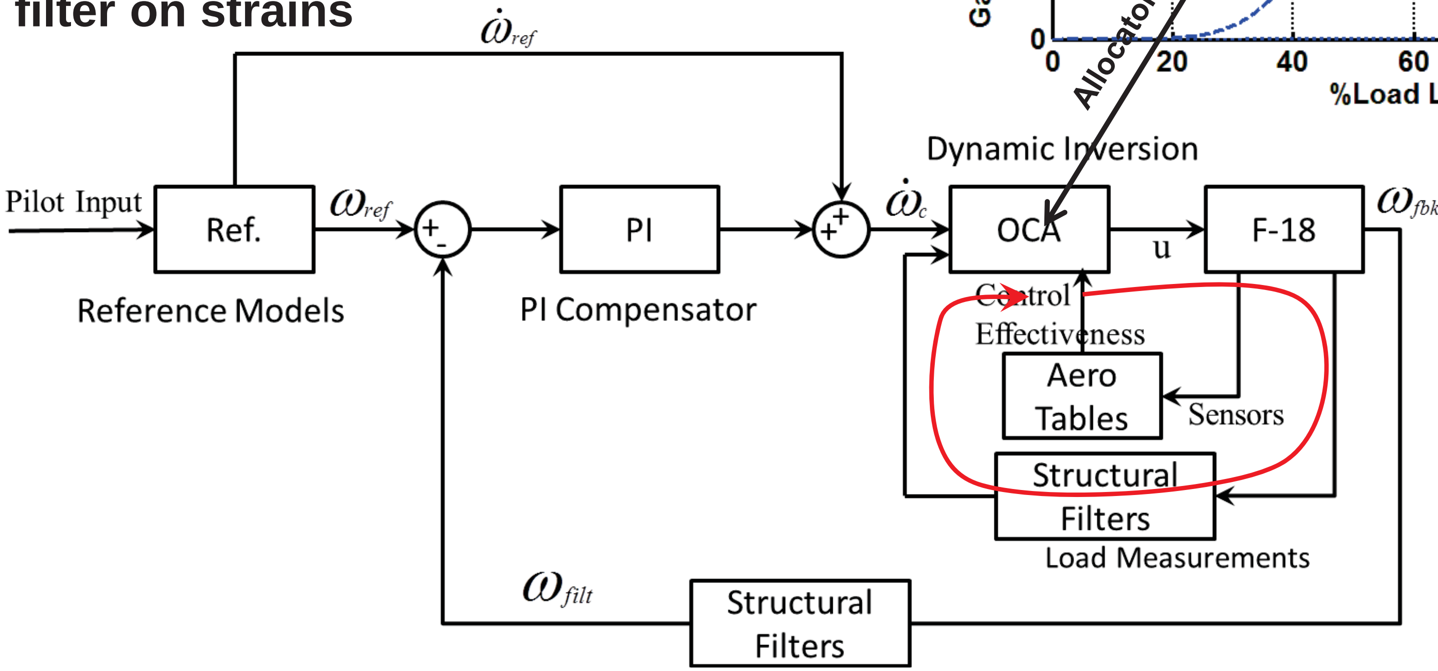


- **The ratings generally degraded with more restrictive limits as expected**
- **As AOA increased (heavier weighs and lower airspeeds) the more restrictive limits exhibited poor HQ's due to alleviation of HM resulting in poor pitch axis ratings which was a surprise**
- **Pilot C specifically commented that the task was easier at the beginning but as airspeed decreased and AOA increased the task was more difficult**

Strain Feedback ASE Concerns

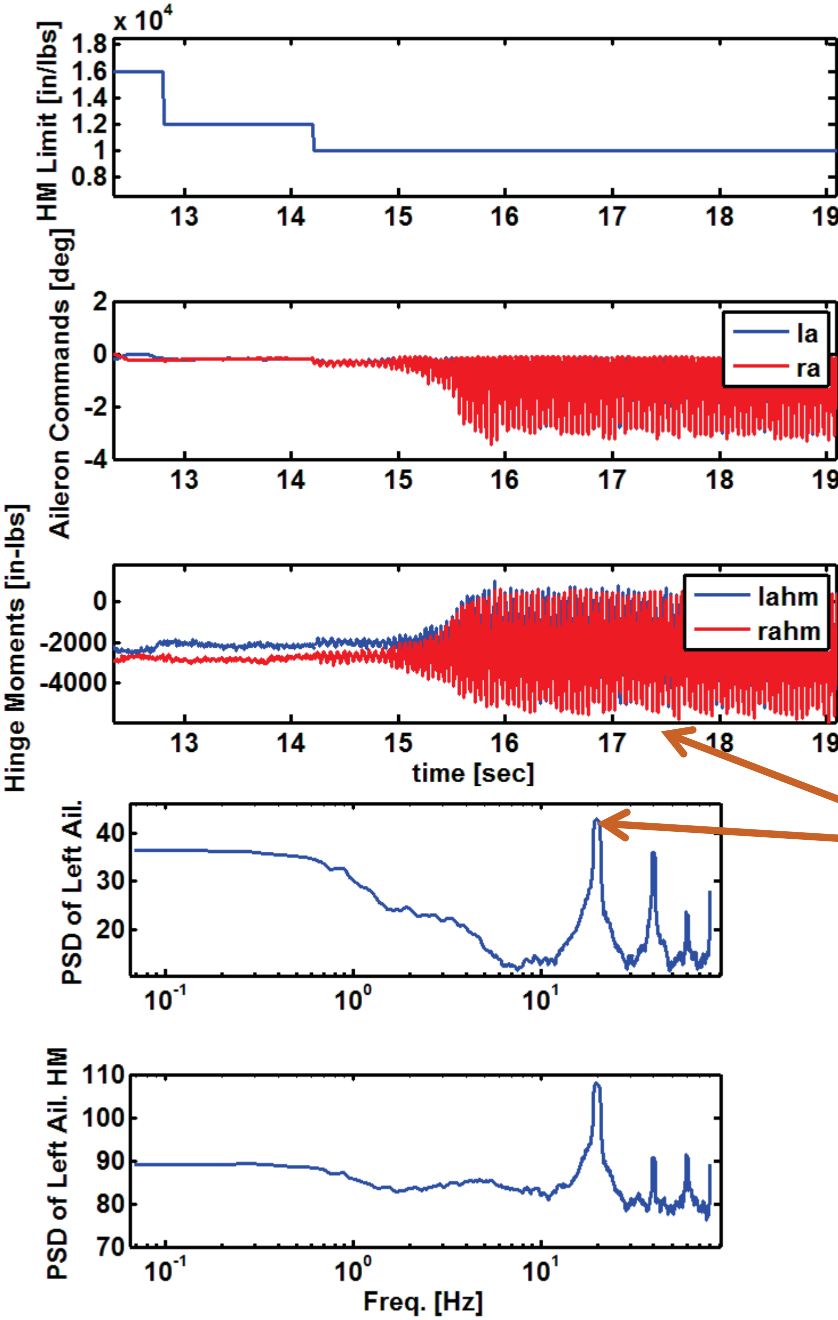
- No models or data sets available prior to flight to determine structural modal interactions on hinge moment measurements
- Unsure if the assumption that the optimization of a cost function can be reduced to a gain is valid for ASE analysis
- Concerned that excessive filtering will cause time delay problems for strain feedback
- Two options designed for flight test, one with no filter and one with a 5hz first order low pass filter on strains



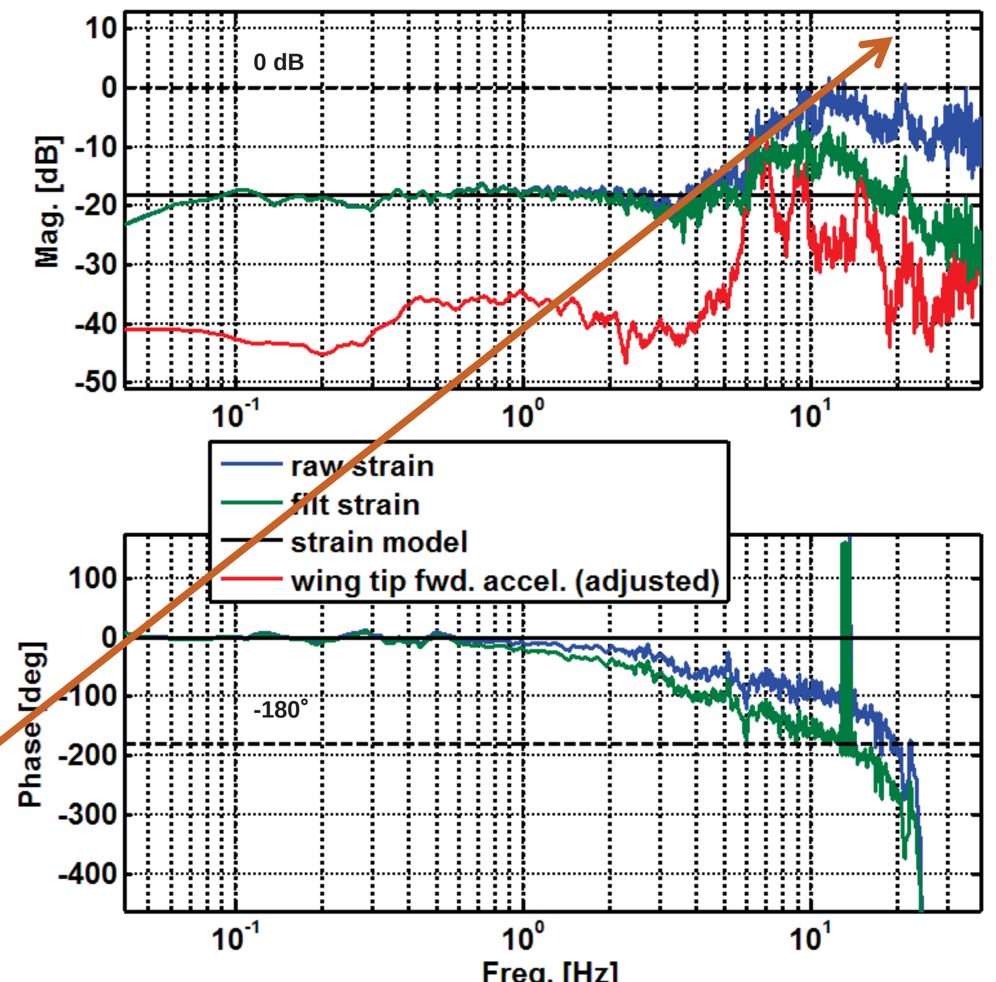


ASE Instability

Response with no filter on strain feedback



Open loop freq. response of strain feedback loop



- Without the filter as HM becomes an important feedback with sufficiently high gain an ASE instability occurs at 20hz (-180 phase crossover above)
- 5hz 1st order low pass filter put on the hinge moment feedback is sufficient

OCLA Results Summary

- **The Good**
  - Limited hinge moments as designed
  - Redistributed control commands away from the ailerons and maintained performance
  - Adequate HQ's demonstrated for all test scenarios even with very restrictive HM limits
- **The Needs Improvement (Lessons from Flight)**
  - The ASE concerns and best practices for this technique were largely unknown and difficult to predict prior to this flight series
    - With the experience gained a much better design is achievable with a good notch filter design for the hinge moment measurements
  - The increase in AOA as a result of fairing the ailerons into the flow was predicted but the HQ implications were not, some AOA compensation with flaps could have addressed this issue
  - The actual hinge moments achieved for symmetric maneuvers was lower than expected, but could be easily accounted for with some input shaping on the strain measurements

Backup Charts

Redundancy Management

- **Strain sensors on both ailerons are mission critical and are used as feedbacks to the control system**
  - Sensors were not originally intended for use as control feedbacks and as such were not installed with that level of robustness in mind
    - Foil strain gauges are not well suited as flight critical feedback sensors for production vehicles due to their lack of robustness
    - FOSS or some similar load sensors are much better suited to that application
  - Checks are implemented in the ARTS to verify the validity of the sensed strain for this experiment (Flow Chart on next slide)
    - Utilizes red and yellow voting limits to determine if a sensor has failed
    - Compares the sensors against the model to determine which sensor has failed and then latches that failure until the ARTS is disengaged and reset (FCS reset)
      - Selecting a good sensor based on which one is closer to the model allows for fail-op even with the sensors only being dual redundant (increases mission success probability)
    - Compares the voted output to a allowed range and commands a disengage if the value is outside of the allowed range (reduces probability of hardovers)

Redundancy Management Flow Chart