Optimal Control Allocation with Load Sensor Feedback for Active Load Suppression

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AIAA SciTech 9-13 January 2017
Grapevine, Texas

Background

Problem Statement:

- Current control applications account for structural load limits by:
  - Limiting the types of control algorithms that can be applied to a given application
  - Requiring high structural margins resulting in less efficient designs
  - Placing procedurally enforced restrictions on pilot control actions 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
  - Control laws 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."

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
- Control law utilizes secondary surfaces with available margin to achieve desired dynamic response

Key Benefits:

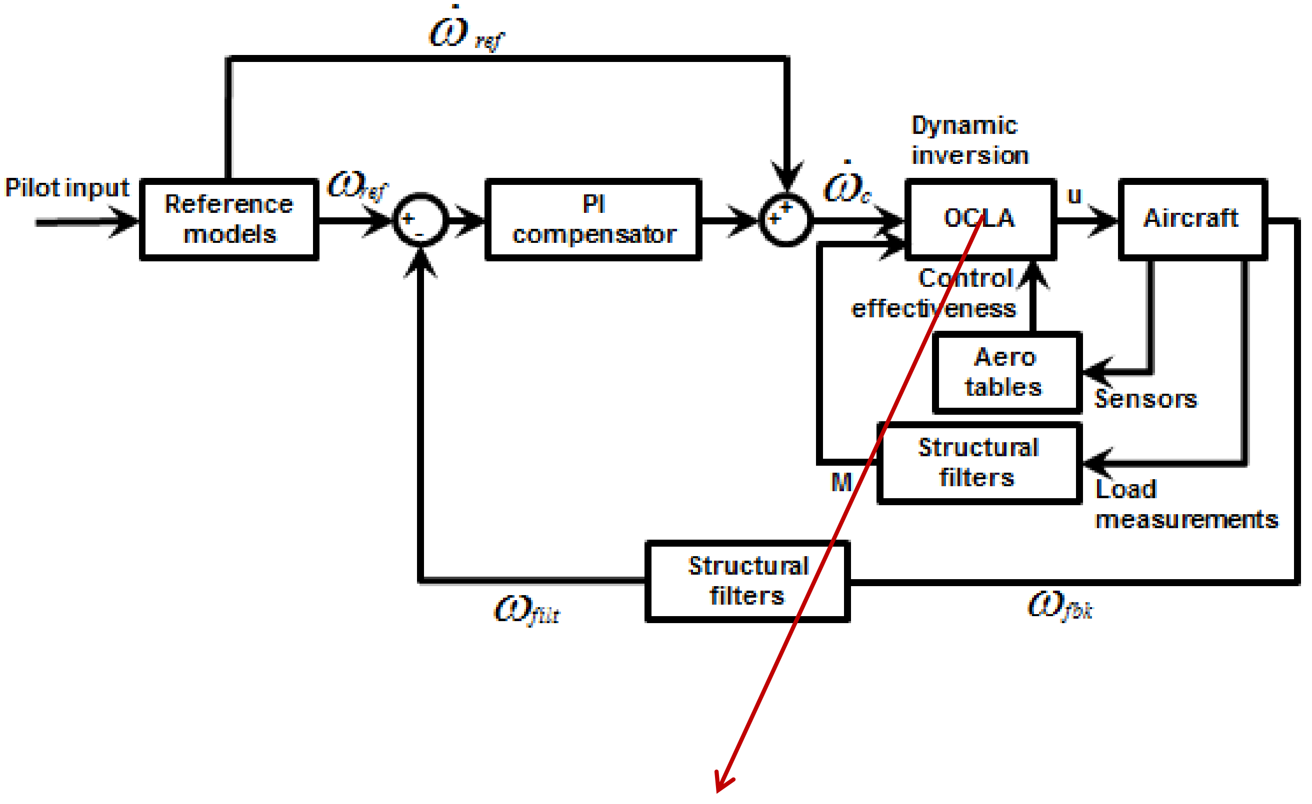
- Enables lighter weight aircraft structure
- Automatically adapts to many damage scenarios
- Increases aircraft robustness in loss of control scenarios
- Enables advanced control techniques

Experiment Objectives and Scope

- Evaluate a control law utilizing Optimal Control Allocation with structural feedback for on a full scale piloted vehicle in a real flight environment (3 flights flown)
- Utilize existing aircraft instrumentation on a robust platform in a limited envelope to help steer future developments
- Utilize measured strain within an optimal control allocator to actively limit the sensed aileron hinge-moments to specified values while maintaining aircraft handling qualities and performance
- Specific Objectives:
  - Objective 1: Limit the aileron motion subject to a defined load constraint.
  - Objective 2: Maintain the roll performance of the original controller that does not utilize structural load as a constraint.
  - Objective 3: Maintain the handling qualities ratings of the original controller that does not utilize structural load as a constraint.

Control Law Overview

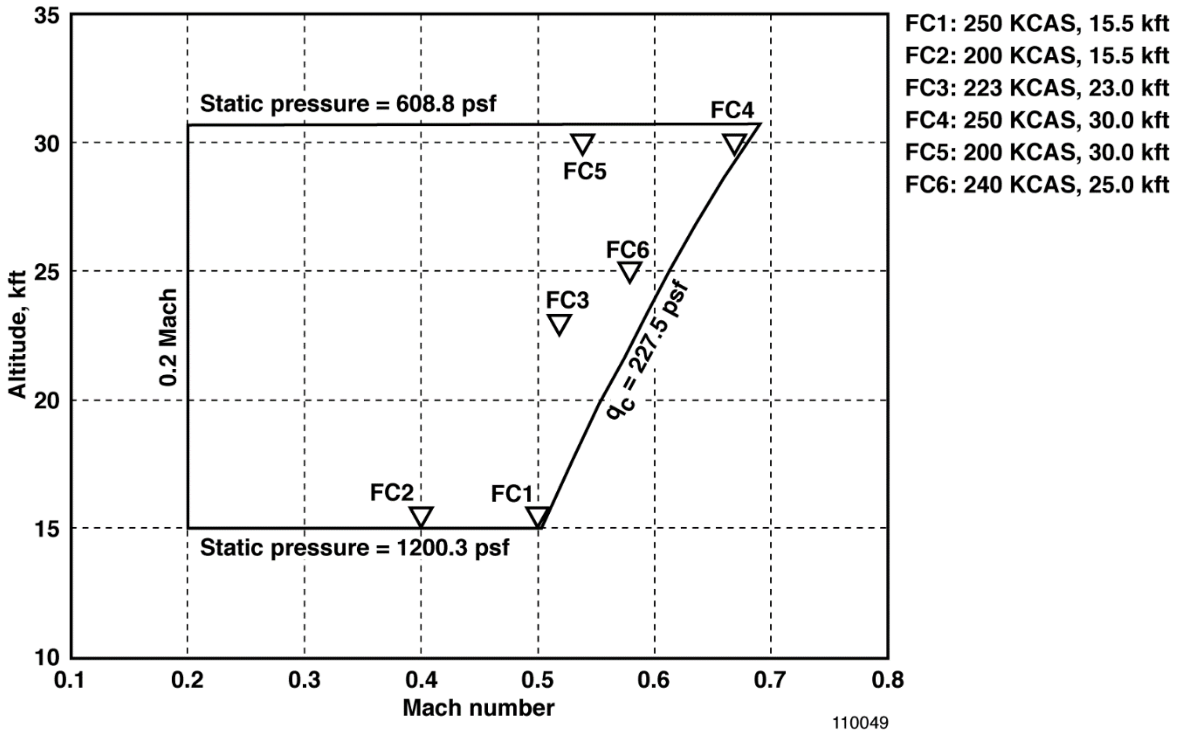
- Based on an existing Nonlinear Dynamic Inversion control law framework utilized for past experiments on the Full-scale Advanced Systems Test-bed (FAST)
- Reference Models
    - Compute desired vehicle dynamics from pilot commands
- Proportional plus Integral Compensator (PI)
    - Adds robustness and disturbance rejection
- Aerodynamic Tables (Aero Tables)
    - Tabulates control surface effectiveness
- Control Allocator (OCLA)
    - Computes surface positions to produce desired dynamics, limit loads, and trim the aircraft
    - Primary research topic for this work
    - Based on the optimization of a cost function
- Structural Filters
    - Prevent undesirable structural modal interactions from coupling with the control laws



$$J = \|Bu - a_d\|_2^2 + \varepsilon\left\|H(u - u_p)\right\|_2^2 + \gamma[\|M + L(u - u_m)\|_2^2]^n$$

Flight Test Approach

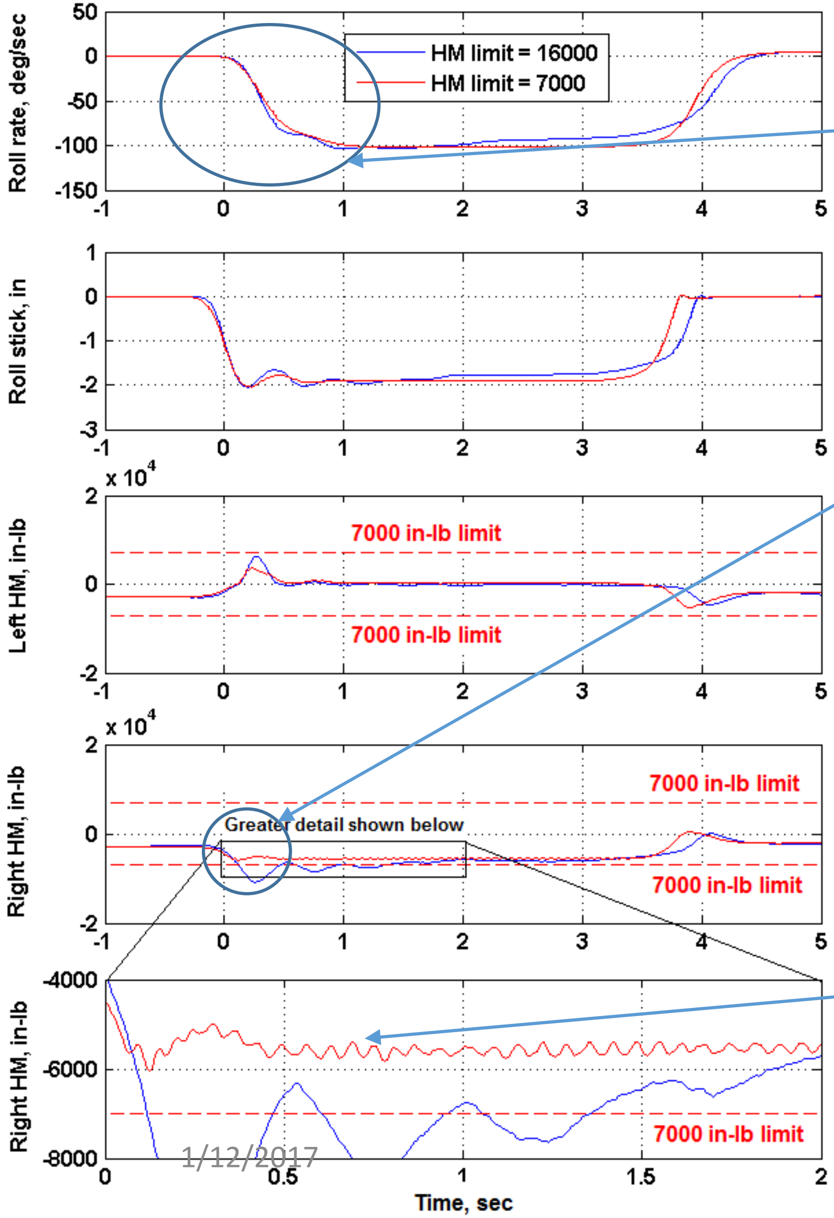
- Experimental Configurations: (All selectable inflight)
  - 3 Allocation schemes (Production, NDI, OCLA)
  - 3 Load constraint exponent (n) values (4, 10, 20)
  - 4 Trim weight (ε) values (1e-4, 1e-3, 5e-3, 1e-2)
  - 5 load level limits (none; 16,000 in-lb; 12,000 in-lb; 10,000 in-lb; 7,000 in-lb; 5,000 in-lb)
  - Hinge-moment feedback filtering on, and filtering off
- Flight Test Approach:
  - 3 flights with 3 different test pilots
  - Each configuration (including production control law) evaluated with a range of load limits
  - Integrated test block at 25kft 240kcas, and 25kft 200kcas
    - Pitch, Roll and Yaw doublets
    - Pitch and bank captures
    - Full pedal steady heading side slip
    - 360 degree 1⁄2 to 3⁄4 stick rolls
    - 2.0g load ½ stick roll
    - 2.5g level turn
    - Pitch and roll frequency sweeps
  - 2.0 g air to air tracking with Cooper-Harper Ratings at nominally 25kft 240kcas



$$J = \overset{\text{J tracking}}{\boxed{\|Bu - a_d\|_2^2}} + \overset{\text{J trim}}{\boxed{\varepsilon\left\|H(u-u_p)\right\|_2^2}} + \overset{\text{J load}}{\boxed{\gamma[\|M + L(u-u_m)\|_2^2]^n}}$$

Roll Performance with Load Limiting

Active Load Limiting – 360° Roll Maneuver



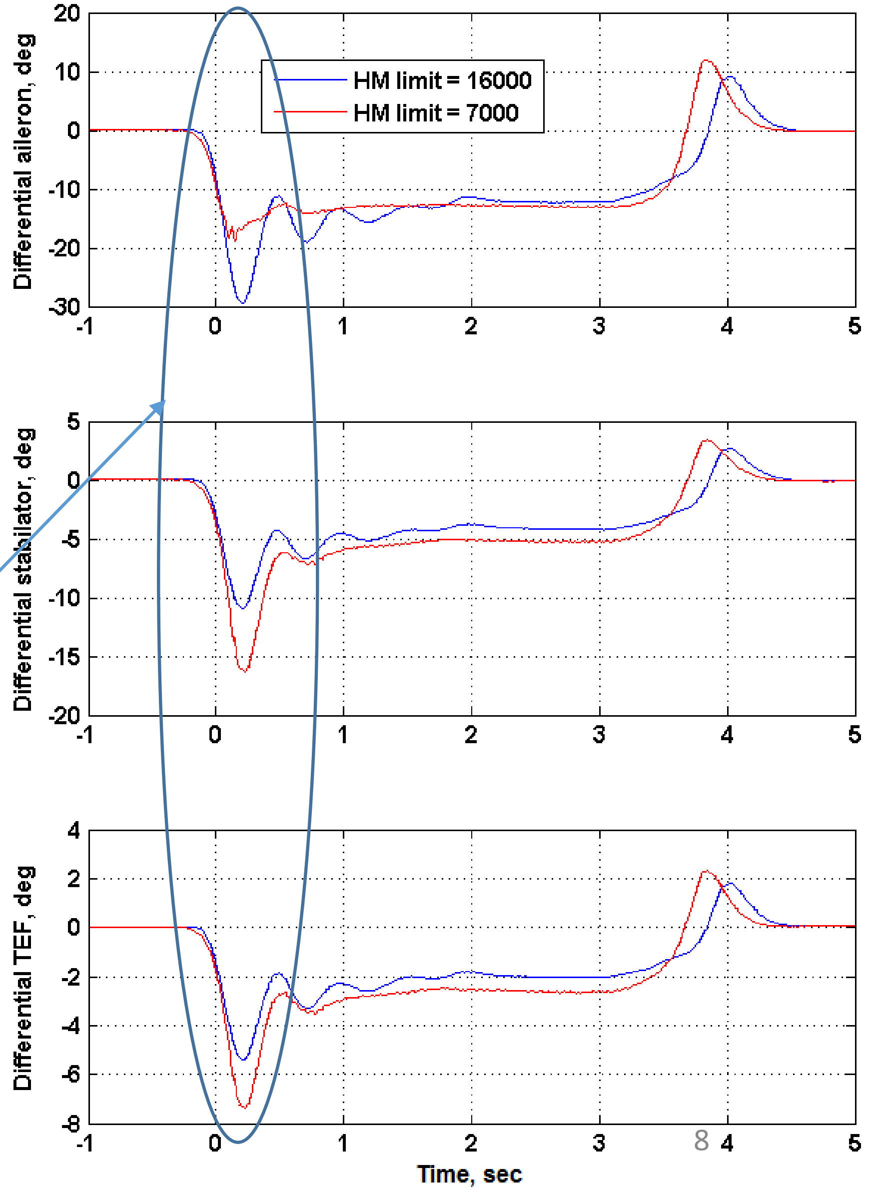
Preserves peak roll rate, and roll rate onset

Actively limits sensed aileron hinge-moment

Redistributes control away from ailerons and to other surfaces

Low level hinge-moment oscillation, higher frequency than seen in simulation

*Related to SMI

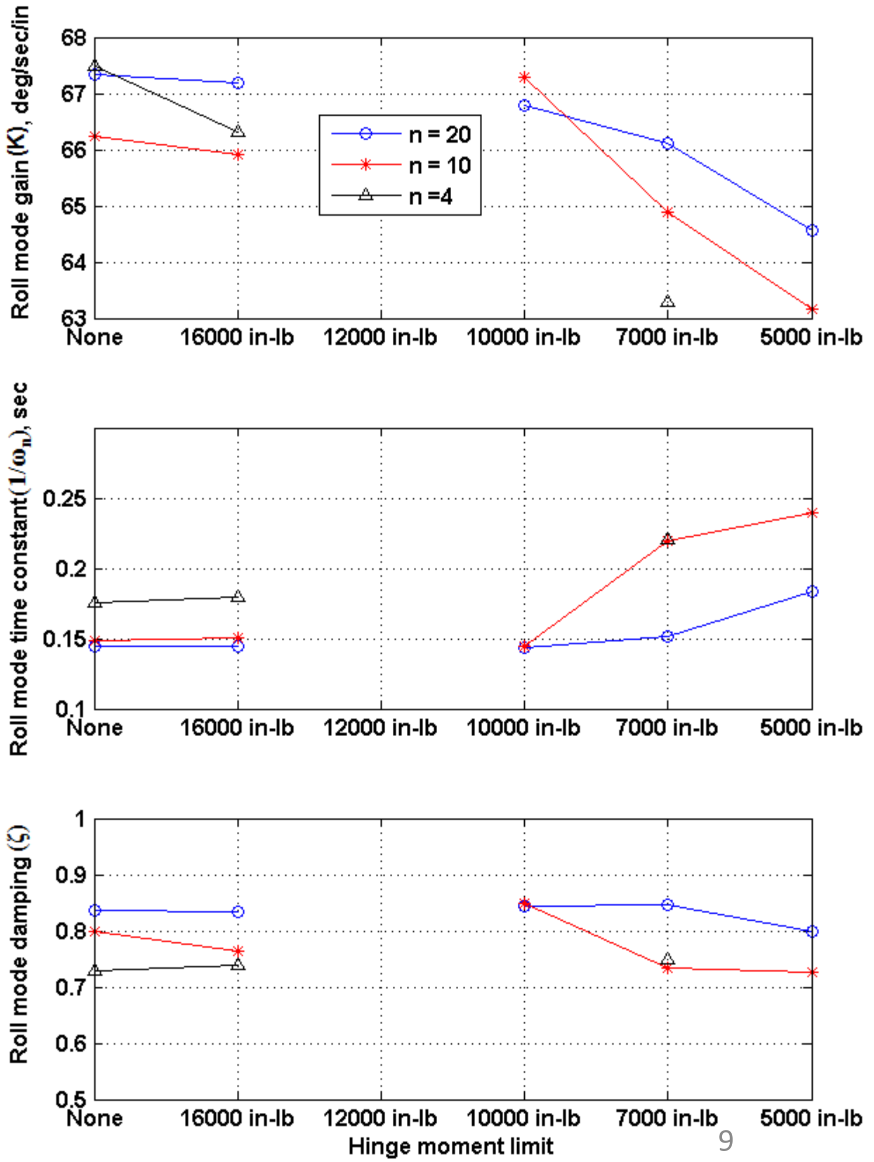


Load Limiting Effects on Roll Performance

- Low Order Equivalent Systems analysis tools were used to evaluate the effect of the load limiting on roll performance:

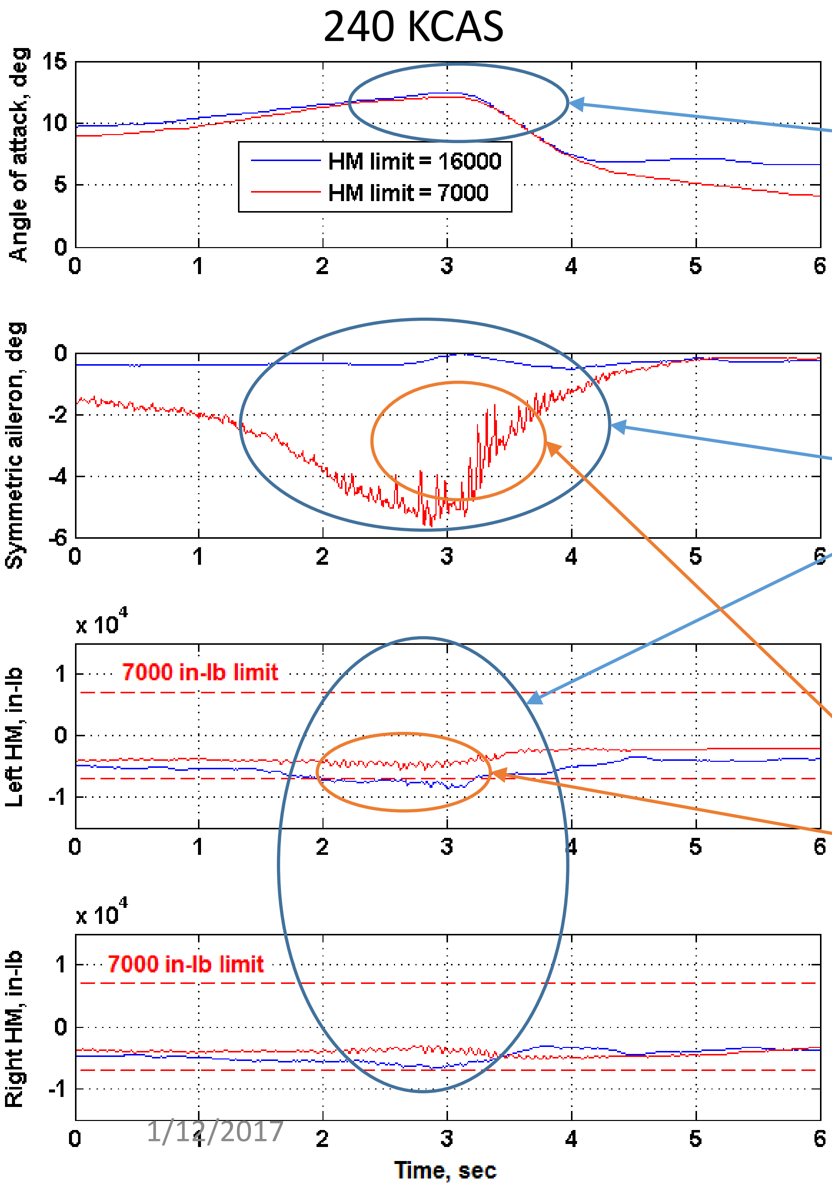
$$\frac{p}{dap} = \frac{K\omega_n^2 e^{-0.08s}}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

- Roll Mode Gain (K)
  - Analogous to the peak steady state roll rate achievable
  - Decreases with more restrictive hinge-moment limits due to the loss of roll moment available as aileron commands are limited
  - Steep load constraints delay the onset of this performance reduction by allowing the ailerons to be used close to their specified limits
- Roll Mode Time Constant $(1/\omega_n)$
  - Higher time constants suggest more sluggish roll rate onset
  - More restrictive limits translate to more sluggish roll modes
  - Steep load constraints delay the onset of the reduction in roll rate onset performance
- Overall, load limiting had a minimal effect on the roll performance for a well tuned cost function



Load Limiting Behavior with Elevated G

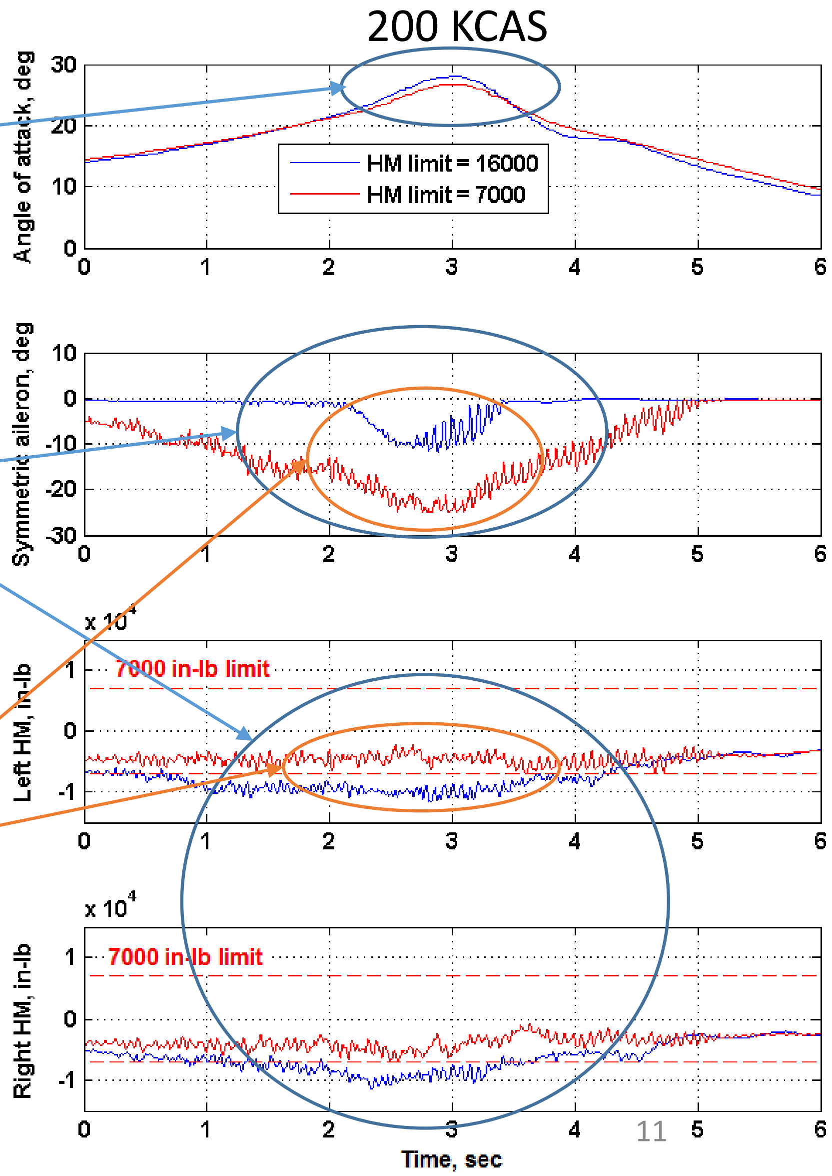
Active Load Limiting – 2.5g Level Turn



More restrictive load limit has no noticeable effect on peak AOA

Load limiting trades slight miss-trim of symmetric ailerons for load alleviation

Undesirable dither and oscillations on aileron commands from aerodynamic buffet and structural coupling



Handling Qualities with Load Limiting

Task Description

- 2-g Air-to-Air Tracking Task
- Divided into gross acquisition and fine tracking sub tasks.
- Gross acquisition
  - Target aircraft starts line abreast with the test aircraft at ~0.5 miles separation.
  - Target aircraft initiates a 2-g level turn
  - Test aircraft aggressively attempts to place the target aircraft within a targeting reticle.
  - Desired criteria: place the target inside the reticle with no overshoots
  - Adequate criteria: place the target inside the reticle with no more than one overshoot.
- Fine tracking task begins once the gross acquisition task is completed
  - Target aircraft preforms roll maneuvers.
  - Test aircraft pilot attempts to keep the pipper (center of the reticle) on the target aircraft.
  - Desired criteria: Pipper on target 80% of the time,
  - Adequate criteria: Pipper on target 50% of the time.

Handling Qualities Results

- Gross Acquisition
  - Ratings roughly equivalent to the baseline control law
  - Ratings do not appear to vary significantly with load limiting level, pilot, or aircraft weight
  - Controller with load limiting meets desired performance metrics

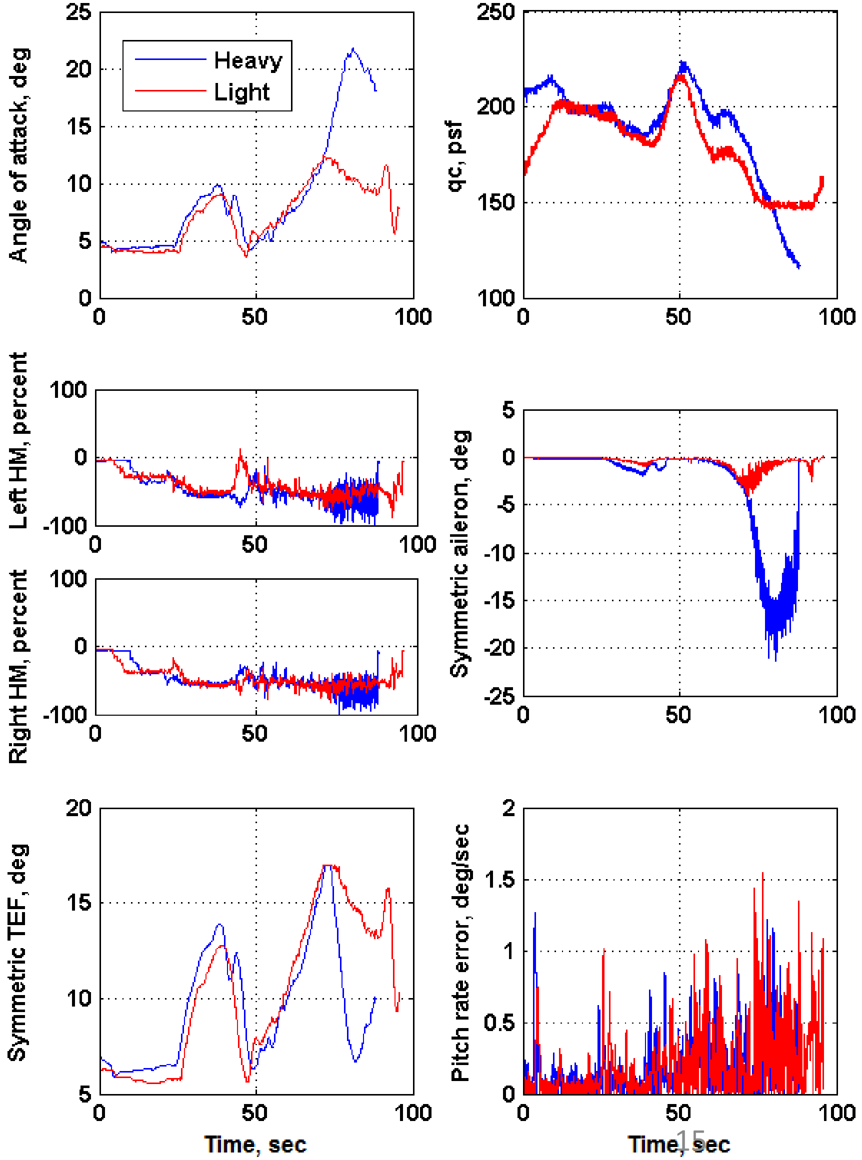
- Fine Tracking
  - Ratings slightly worse than baseline control law
  - Ratings degrade slight with more restrictive load limits as expected
  - Surprised by degradation in ratings with higher aircraft weights
    - Discussed on next chart
  - Controller with load limiting meets adequate performance metrics

Gross acquisition	Baseline	16000 in-lb	7000 in-lb	5000 in-lb
Pilot A heavy weight				
Pilot A middle weight				
Pilot A light weight	3	3	3	3
Pilot B heavy weight	5	3	4	5
Pilot B middle weight				
Pilot B light weight	3		2	3
Pilot C heavy weight	2	3	2	2
Pilot C middle weight	2		2	2
Pilot C light weight			2	

Fine tracking	Baseline	16000 in-lb	7000 in-lb	5000 in-lb
Pilot A heavy weight				
Pilot A middle weight				
Pilot A light weight	4	3	4	5
Pilot B heavy weight	3	3	5	4
Pilot B middle weight				
Pilot B light weight	3		4	2
Pilot C heavy weight	3	5	6	6
Pilot C middle weight	3		5	6
Pilot C light weight			4	

Degradation in HQ with Higher Aircraft Weight

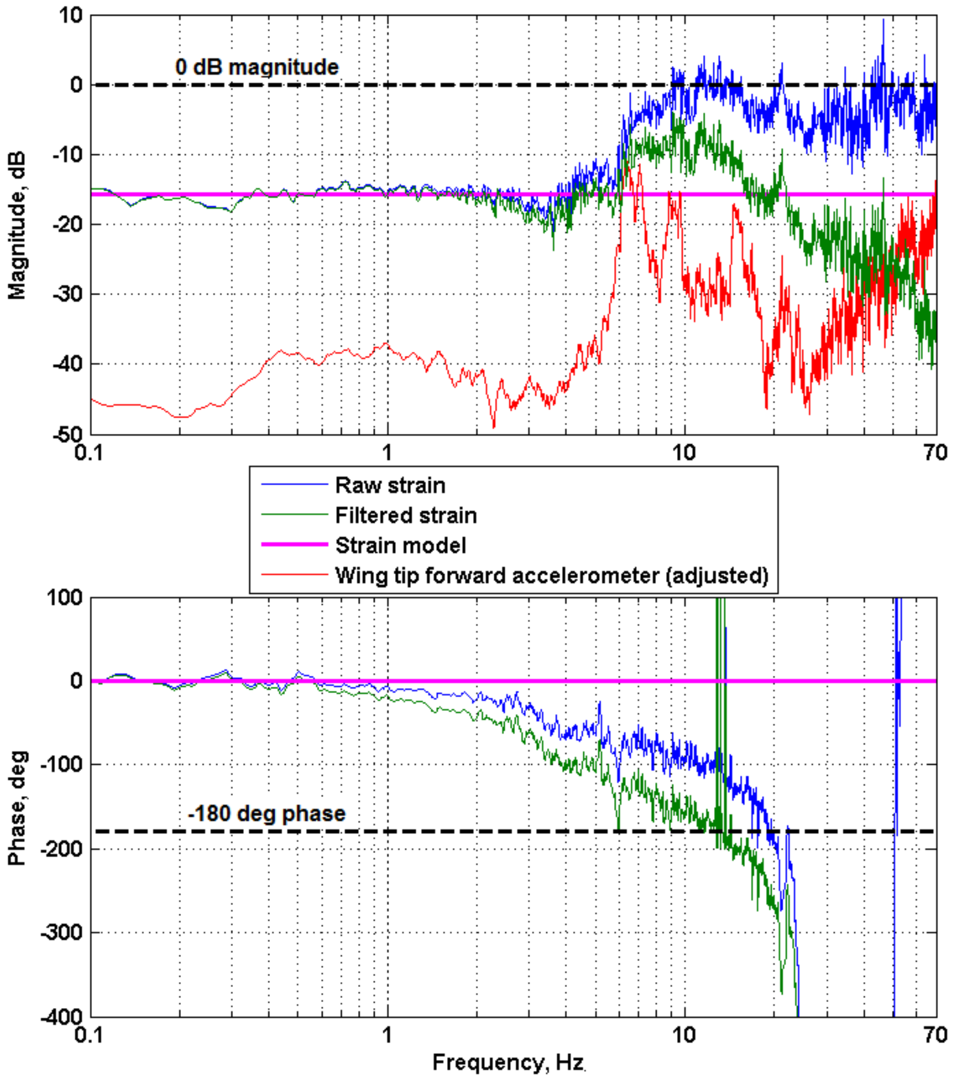
- Pilots all commented that the Fine Tracking task got harder as the task progressed
- Due to the nature of the platform, maintaining a level 2.0 g turn resulted in bleeding off airspeed
- As airspeed bleeds off, angle of attack increases, with results in increased load on the ailerons
- As the load builds on the ailerons the load limiting control law retracts the ailerons, which results in further increases in AOA
- For light weight cases the platform performance deficit is less pronounced which results is lower peak angles of attack
- In short:
  - Heavy and slow with the ailerons trimmed to reduce load, resulted in an aircraft poorly trimmed for preforming the task
  - Need to refine the control laws to account for this effect or modify the task

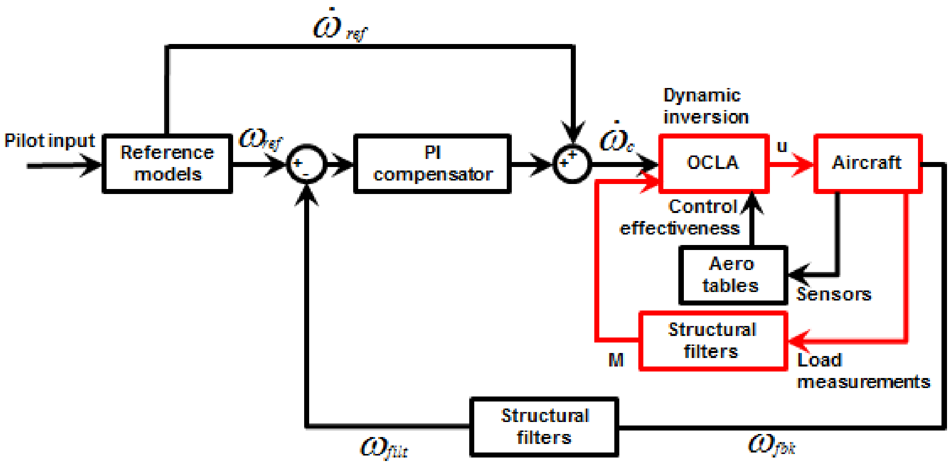


Load Limiting Control Interaction with Structural Dynamics

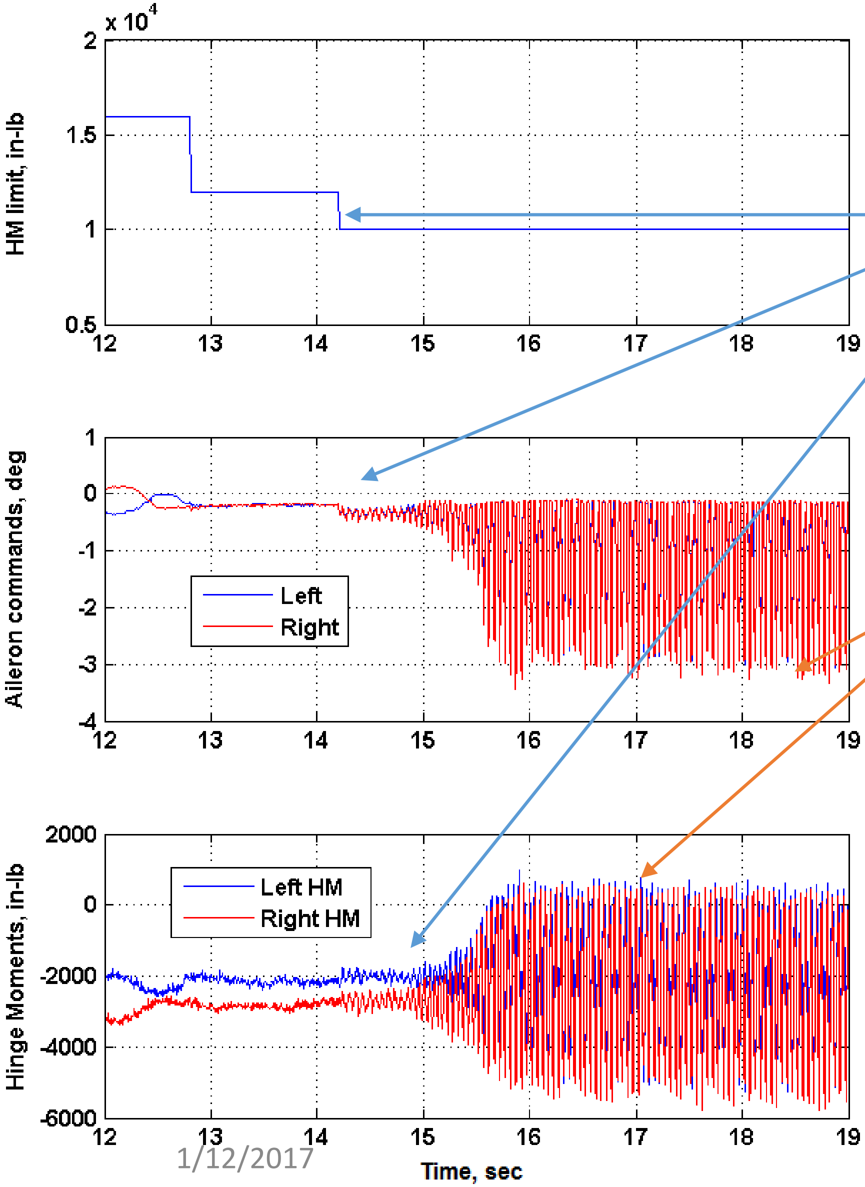
Hinge-Moment Feedback Loop Analysis

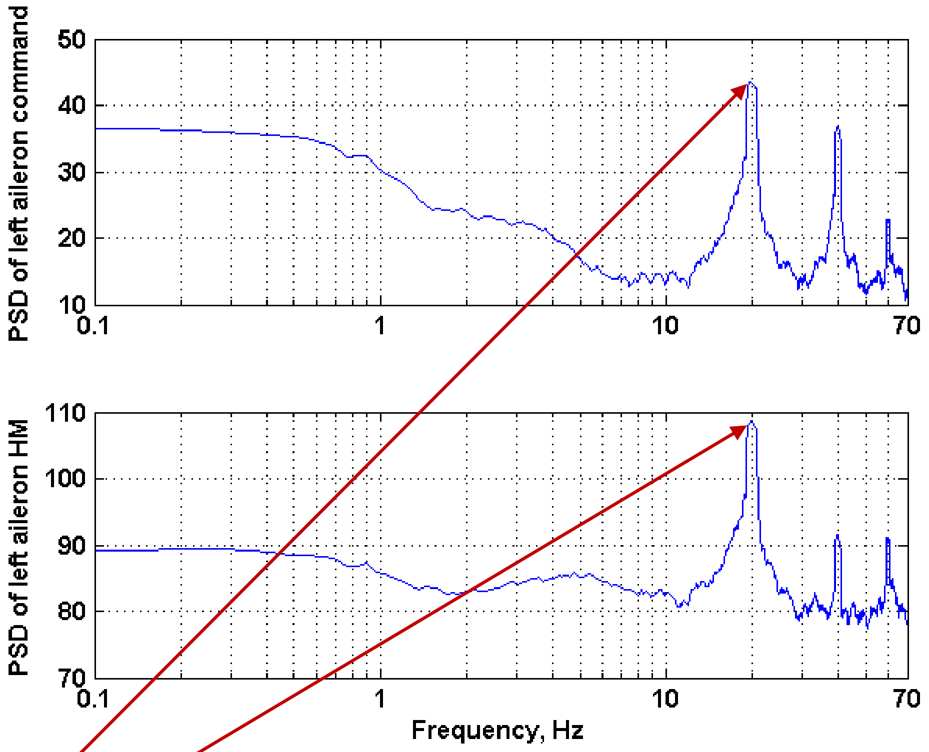
- Flight data used to reconstruct the loop properties (right) for the Hinge-Moment feedback loop (below)
  - Accelerometer data included to show that structural response
- Not a conventional feedback loop with easy to evaluate from a gain and phase perspective
  - Cost function optimization can be approximated by a gain for a given load level (details in paper)
  - Before flight the validity of this type of analysis was an open question
- From flight data and the loop analysis
- An unstable SMI is predicted at ~21 Hz, for n = 4, hinge moment limit = 10,000 in-lbs, without the structural filtering on the strain feedback signals
  - Next page shows the results of the bounded SMI testing from flight





Observed Unstable SMI Inflight





Oscillations in both aileron command and hinge-moment start to grow when the 10,000 in-lb limit is engaged

Oscillations grow to a bounded limit cycle oscillation with rate limiting on the ailerons

Frequency of the unstable oscillations occurs at ~20Hz just as the analysis would have predicted

Conclusions

- The optimal control with load limiting approach accomplished the following:
  - Overall the experiment met all of the research objectives.
  - Limited aileron hinge-moment
    - Aileron hinge moments were limited to below the specified limit 100% of the time
    - Equivalent overload protection for both roll and elevated g pitch maneuvers.
  - Preserved roll performance
    - Preserved the attainable roll rate
    - Redistributed roll control commands away from ailerons and to other surfaces as load limits were approached.
    - Steep load constraints allowed roll performance to be maintained for a range of airspeeds and load limits.
  - Maintained desirable handling qualities
    - Adequate handling qualities (Level 2) were obtained for all of the configurations tested
    - Desirable handling qualities (Level 1) obtained for gross acquisition and fine tracking for most conditions
  - Traditional structural modal interaction (SMI) analysis and mitigation techniques evaluated and applicable
  - Exhibited excellent convergence properties even for the most nonlinear load constraints.
- Issue meriting further research uncovered:
  - A number of handling qualities deficiencies were observed at elevated g due to early activation of the load constraint during elevated g pitch maneuvers.
  - Most pronounced at low airspeed with heavy weight aircraft.
  - Suggests the need for further shaping of the individual load feedback signals.
  - Need to explore the approach as applied to a platform without a robust backup control law

Questions