Autopilot and Envelope Protection

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SMART ICING SYSTEMS
Research Organization

Smart Icing Systems Review, May 28, 2003

Core Technologies

- Aerodynamics and Propulsion
- Flight Mechanics
- Control and Sensor Integration
- Human Factors/ Cognitive Engineering
- Aircraft Icing Technology

IMS Functions

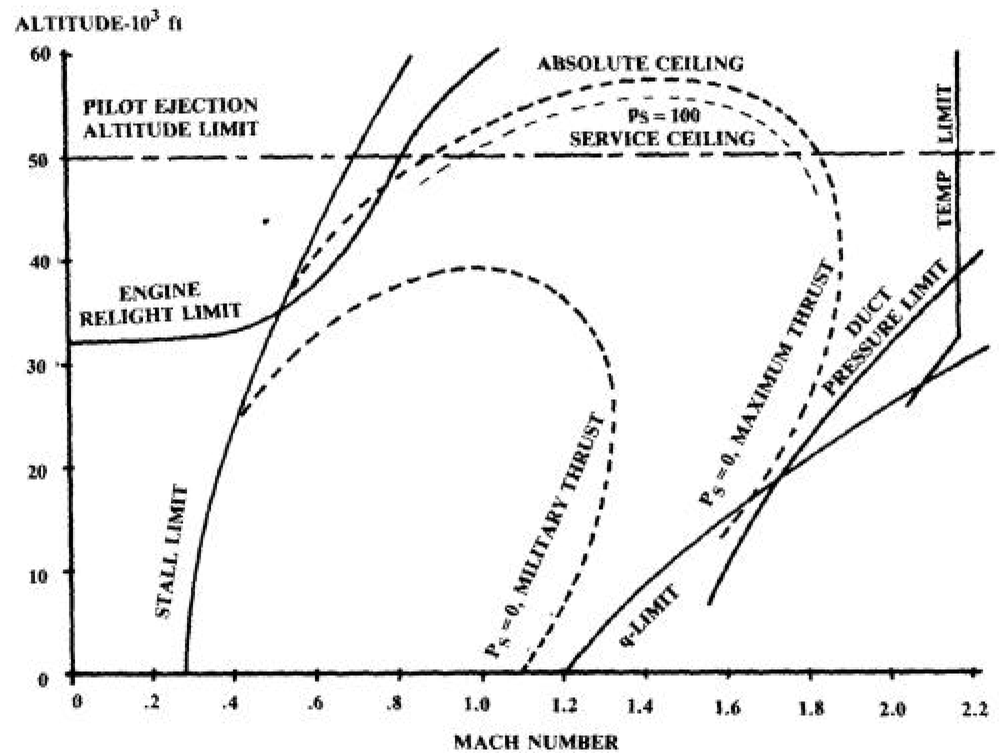
- Characterize Icing Effects
- Operate and Monitor IPS
- Envelope Protection
- Adaptive Control

System Research/Integration

- Flight Simulation
- Flight Test

Typical Flight Envelope

- Aerodynamic Limits
- Thrust/Power Limits
- Structural Limits
- The flight envelope is primarily a function of load factor, velocity and altitude
- The *clean* aircraft flight envelope remains *constant*



Example of a Clean Aircraft Flight Envelope from Ramer 1989.

Envelope Protection for Commercial Jets

- Fly-by-wire system
- Pre-set limits
- Feel actuators
- Bank angle protection
- Stall protection
- Boeing: soft limits on control surface deflections
- Airbus: hard limits on the aircraft aerodynamic angles

Current System Limitations

- **Problem**: Limits change with level of ice accretion.
- **Solution**: In icing conditions the limits have to be determined and enforced ***dynamically*** during flight.
- **Problem**: Limits may be exceeded during maneuvers if only current sensor data is used to provide protection
- **Solution**: System needed for ***prediction*** of future values from available sensor data including control positions.

Objectives

- Develop and analyze envelope protection techniques for operation in icing conditions

- Investigate standard autopilot behavior in icing conditions

Approach

- Prediction-based, dynamic, envelope protection
- Two modes: A/P off, A/P on
- A/P stability and performance characterization using robust control techniques
- Implement and test a ‘0^{th} order’ EP scheme for flight simulator: if $\alpha > \alpha_{max}$ generate warning
- Develop more sophisticated schemes based on prediction of future values

Why two EP schemes

- Current guidelines suggest A/P off under icing ⇒ 'open loop' EP necessary

- Future planes will rely heavily on automation ⇒ 'closed loop' EP is essential

Dynamic Envelope

- **The critical parameters:**
  - a_w : Wing angle of attack
  - a_t : Tail angle of attack
  - f : Roll angle
- Limits can be defined for these parameters as a function of ice accretion.

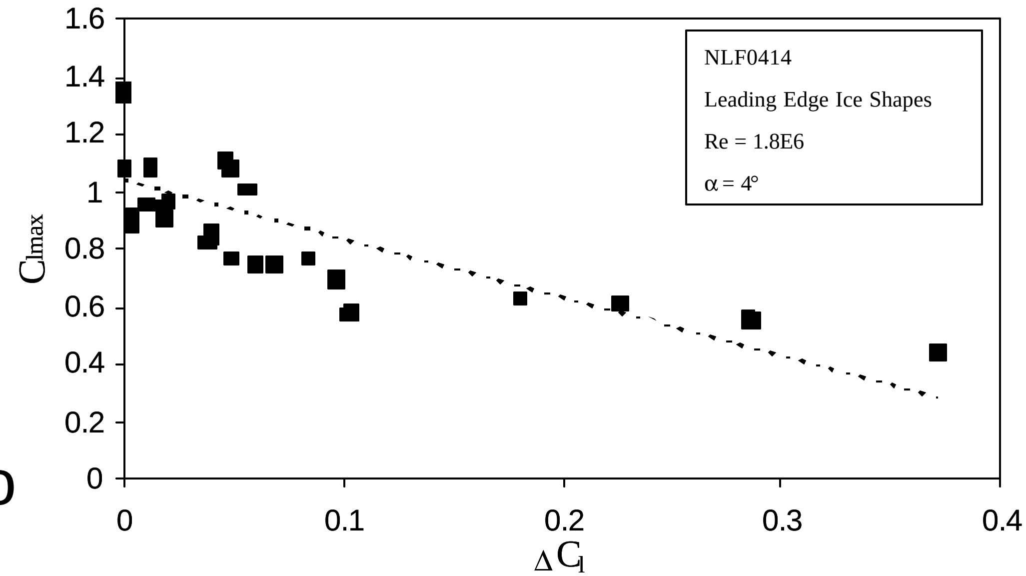
Angle of Attack Limiting

- C_{lmax} vs DC_l fitted as linear functions for several AOA.

$$C_{L_{\max}} = f(\Delta C_L(\boldsymbol{h}_{ice}, \boldsymbol{a}))$$

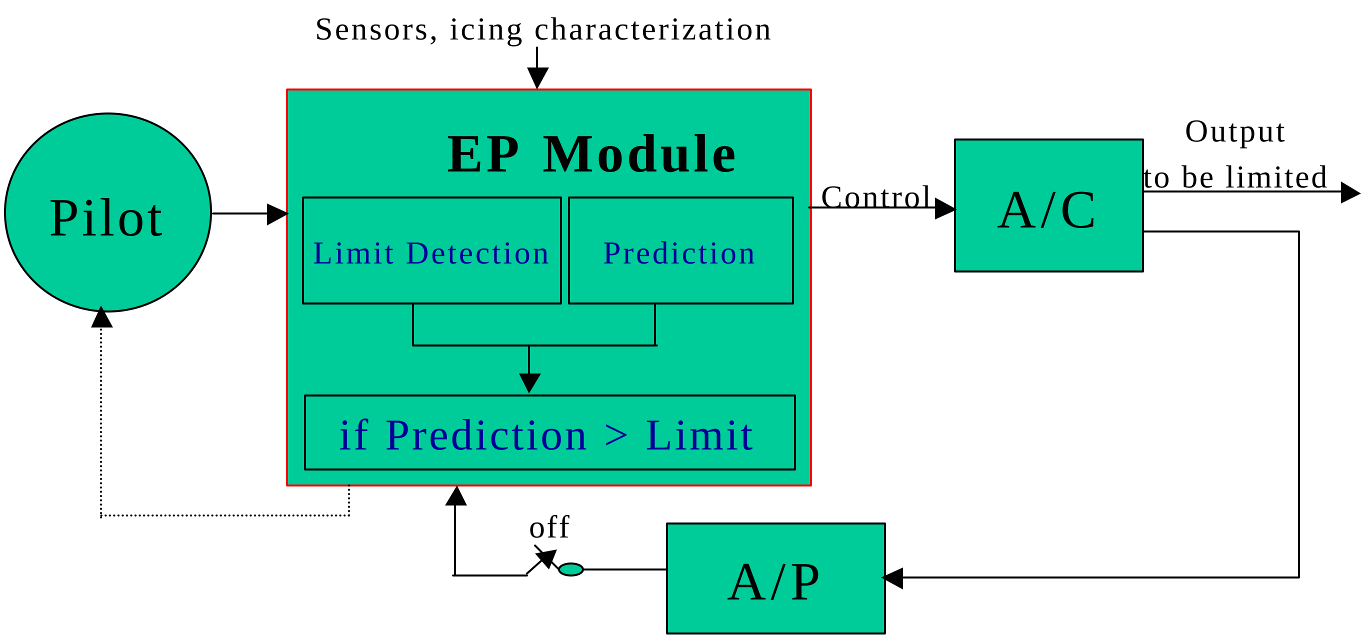
- The trim AOA used to find corresponding fit.

- The *AOA* corresponding to the C_{lmax} is then set as the limit



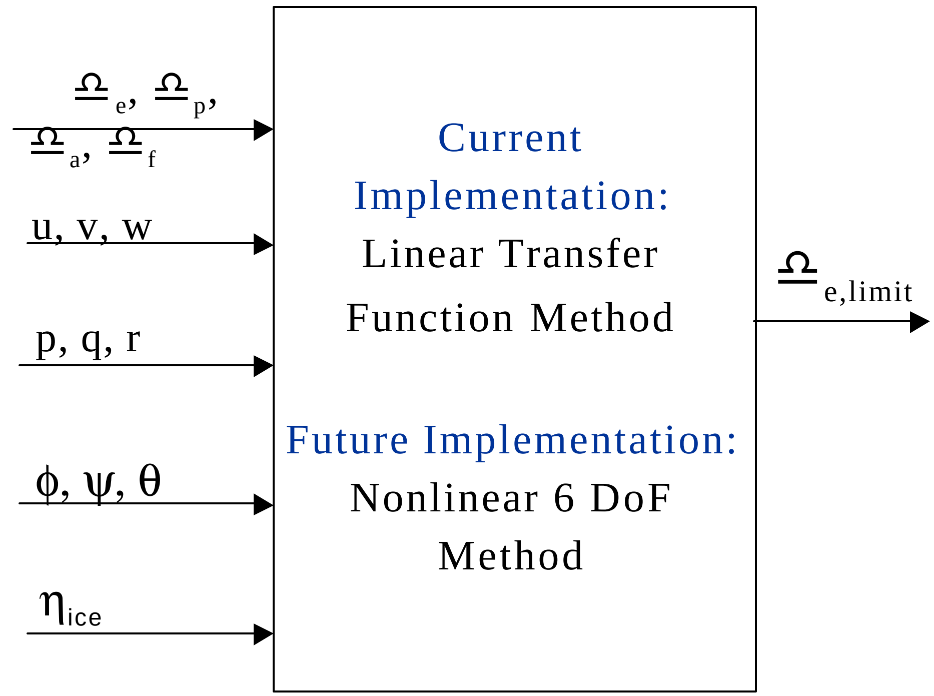
EP with A/P off

- **Limit detection:** Estimate limit boundaries using information from icing characterization
- **Prevention of limit violation:** Predict control limits and restrict the control deflection to safe values
- **Envelope Protection Interface:** Display limit information in the glass cockpit and use force feedback to avoid limit violation



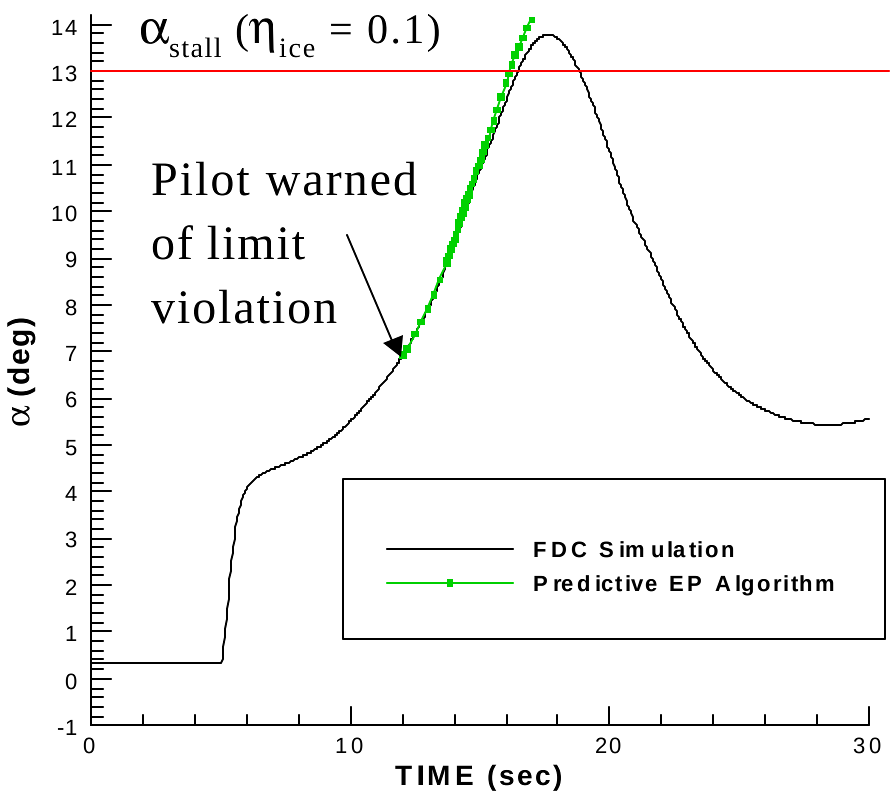
Estimation of Safe Elevator Limits

- **Initialize the EP System:**
  The aircraft configuration and state at each time step is used to initialize the code
- **Aircraft Model:**
  The iced non-linear aircraft model is used to calculate the force and moment coefficients within the code
- **Calculate Elevator Limit:**
  The equations of motion are used to calculate the safe elevator limit
- **Enforcing the Limit:**
  Pilot δ_e input "limited" by $\delta_{e,limit}$



Simulation Results

Nonlinear Prediction of Angle of Attack Response



Simulation Results

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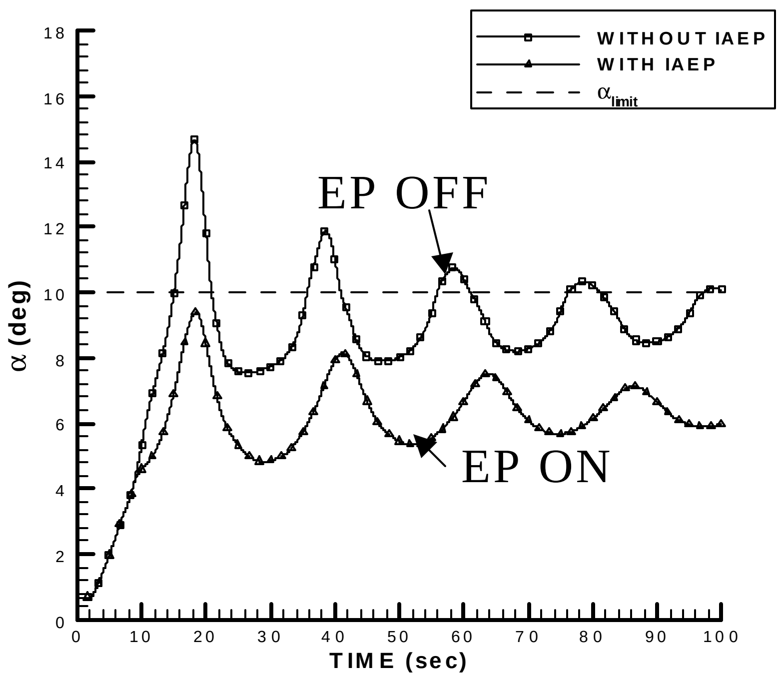
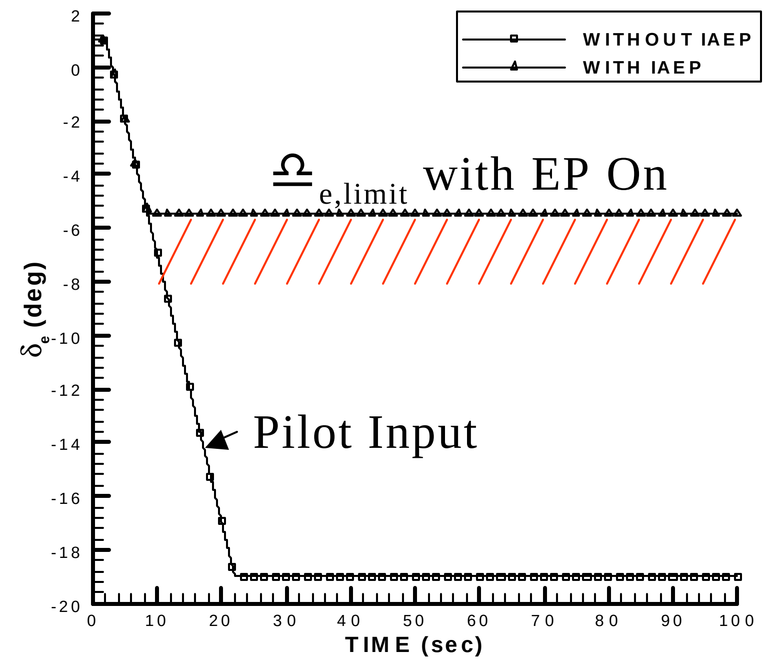
Linear Prediction of Elevator Limit



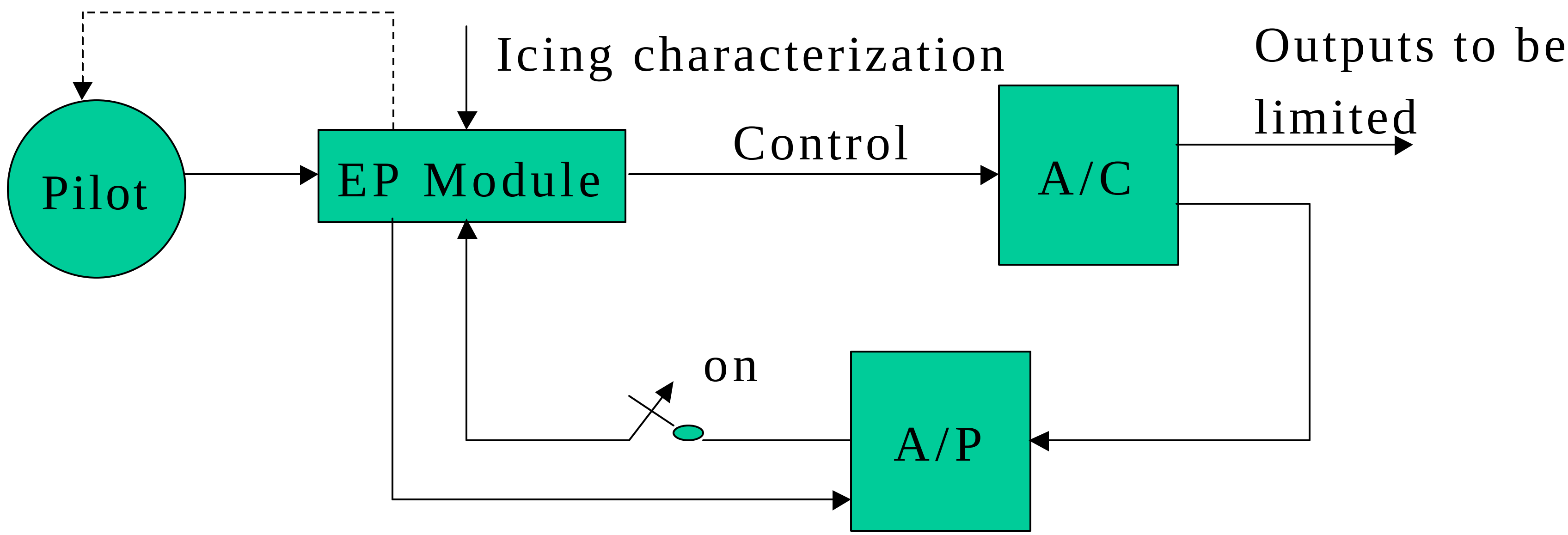


Open Loop EP Conclusions

- The method developed to estimate the stall angle of attack showed promising results
- Estimates based on limited airfoil data
- Need to include 3-D wind tunnel or flight test data in order to improve stall estimates
- Linearized $\delta_{e,limit}$ predictions show encouraging results for cases tested
- Explore nonlinear $\delta_{e,limit}$ predictions

EP with A/P on

- Pilot stick position dynamically affects control position
- EP continuously calculates limits on stick position and informs A/P



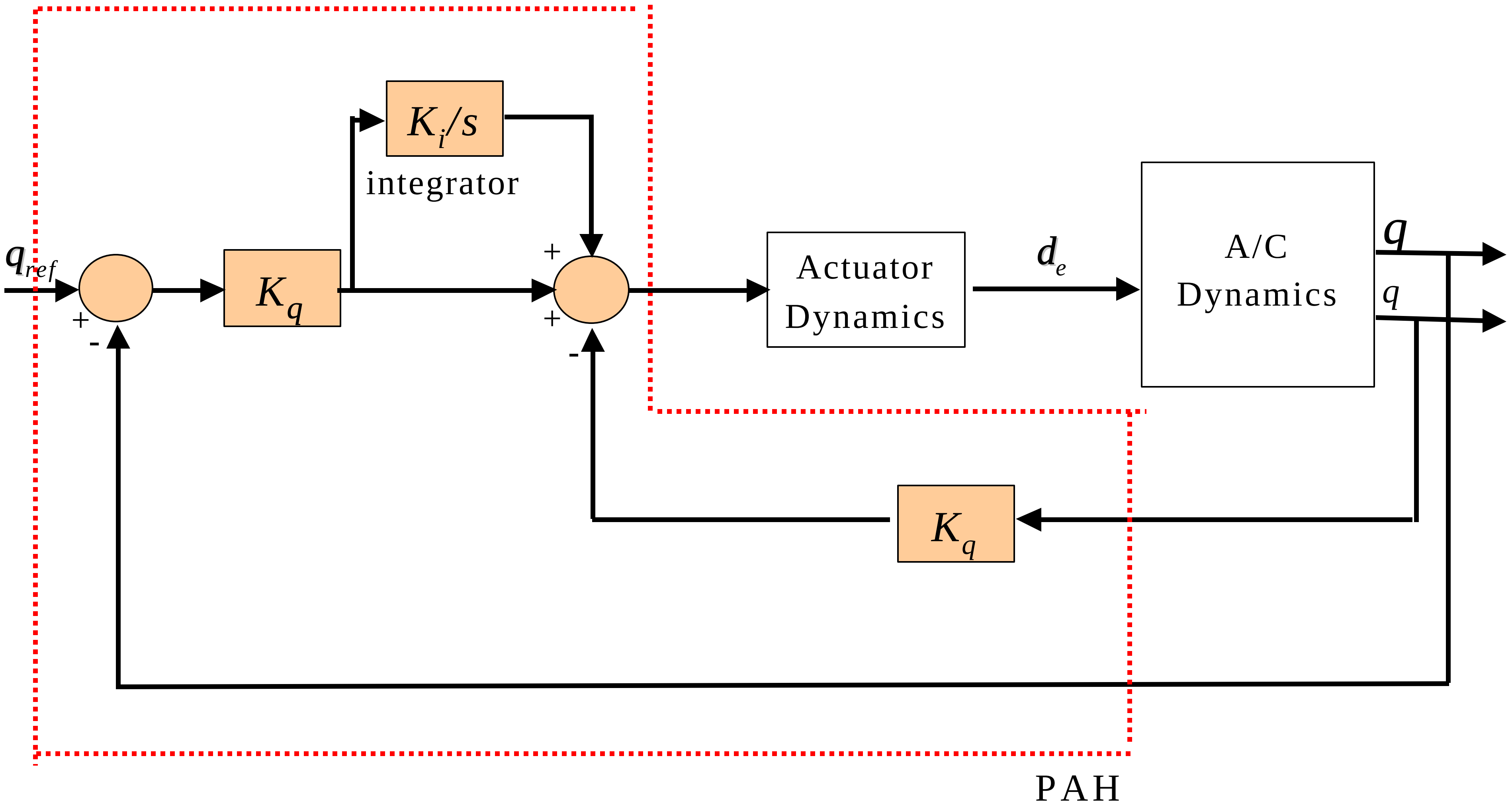
Closed Loop EP

- Monitor A/C state, A/P state and icing level
- Predict on-line future A/C state with current pilot input
- Adjust input based on prediction, inform pilot
- Same principle as open loop; different dynamical equations

Autopilots

- **Longitudinal Modes**
  - Pitch Attitude Hold (PAH)
  - Altitude Hold (ALH)
- **Lateral Modes**
  - Roll Attitude Hold (RAH)
  - Heading Hold (HH)

Block Diagram for PAH



A/P Performance in Clean Conds

- Gains are scheduled on A/C speed
- Local designs exhibit good performance and stability margin properties
- Overall A/P performs well over the operational envelope of Twin Otter for clean conditions

Closed Loop PAH in Icing Conds

- The closed loop model is affinely dependent on the icing parameter h, i.e.

$$dx/dt = A(h)x$$

$$A(h) = A_0 + h(t)A_1$$

where $h \in \Delta$, with $\Delta = [0, h_{max}]$

- Is iced closed loop stable?

Quadratic Stability

- Stability condition in terms of two LMIs

$$A(h=0)^T K + KA(h=0) < gI$$

and

$$A(h=h_{max})^T K + KA(h=h_{max}) < gI$$

where $g < 0$ and $h(t) \in [0, h_{max}]$

- Above can be checked with LMILAB

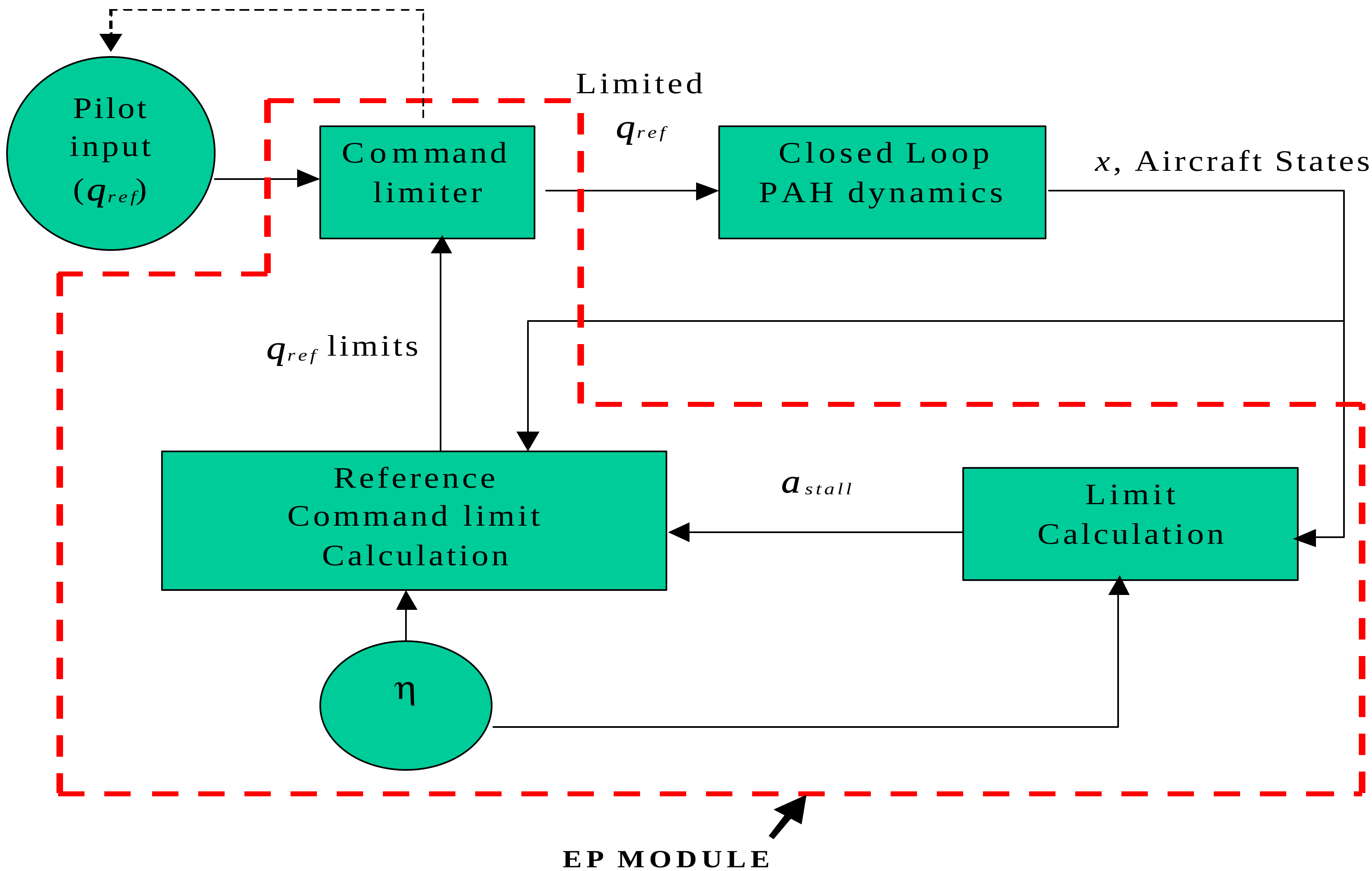
Stability Analysis

- Pitch Attitude hold A/P maintains stability under icing for all icing conditions

- There is a small degradation in the guaranteed stability level

- Nonlinear phenomena not captured

PAH A/P with EP Module



Envelope Protection for PAH Autopilot

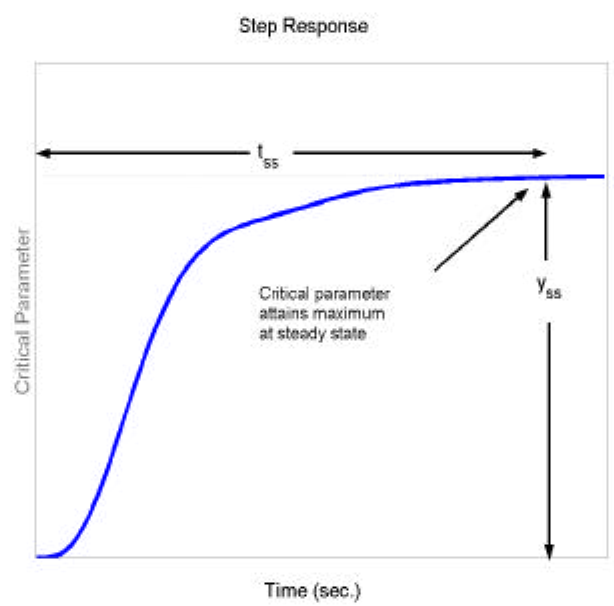
PROBLEM: Insure for all time

$$a(t) < a_{\max}(h(t))$$

APROACH: Modify accordingly $q_{ref}(t)$

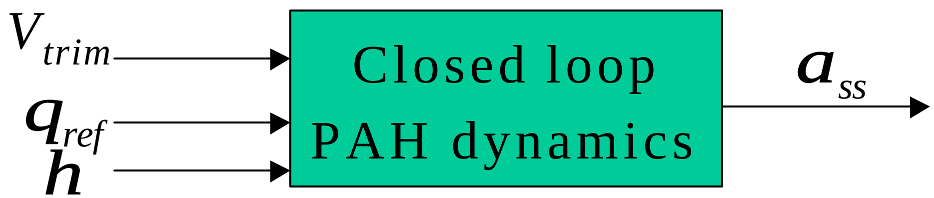
Envelope Protection Scheme

- Look at step pilot inputs
- Look at steady state response of the angle of attack

Step Response	Envelope Protection System
	***Steady State Estimation*** LIMIT DETECTION – Estimate value of limited parameter in steady state LIMIT AVOIDANCE – Find control value that causes the limited parameter to reach envelope limit in steady state

Data Generation

- Data is generated by issuing a range of reference pitch commands at different flying conditions



- Steady state angle of attack values corresponding to trim state values of V, h and q_{ref} are recorded

EP Module Coding Scheme

EVERY 5 SECONDS

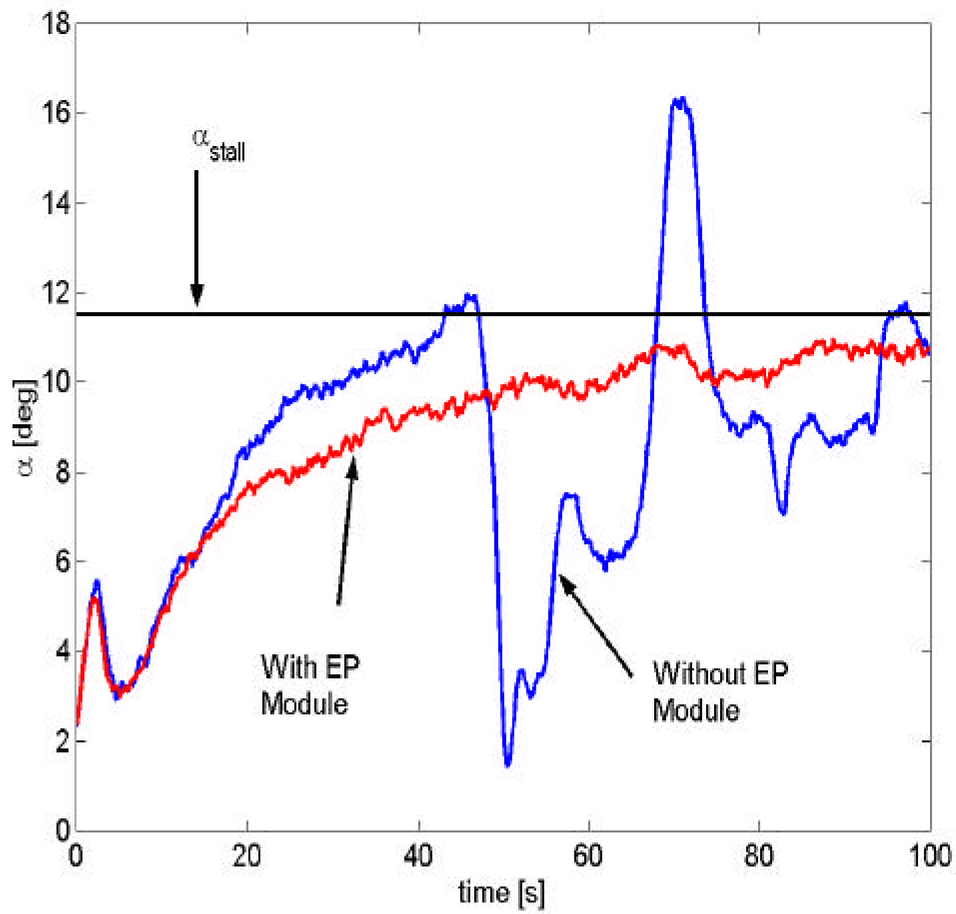
- Treat the state reached as a trim state
- Use the data generated to obtain maximum allowable q_{ref} ($q_{ref}^{\max}$) at that state

$$\alpha_{ss} = f(V, h, q_{ref}^{\max}) \approx \alpha_{stall}(h)$$

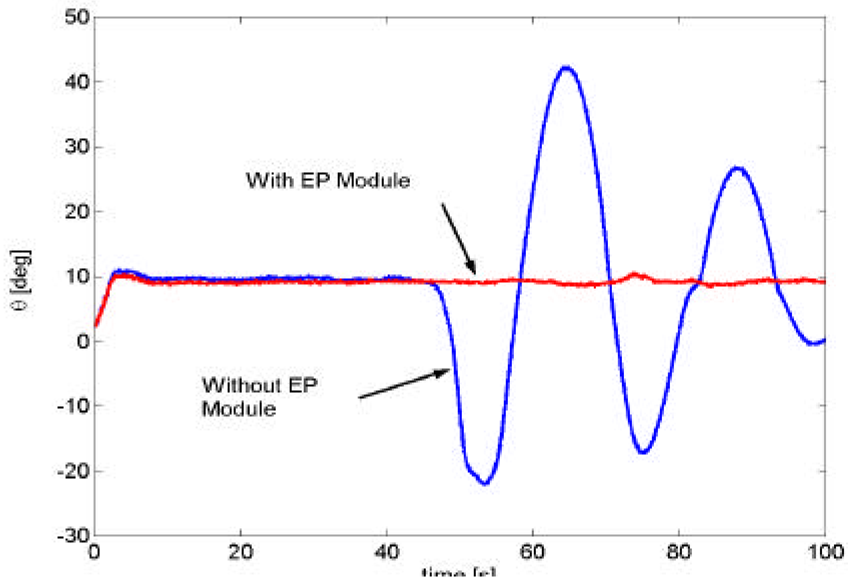
- Compare q_{ref} at the current point with the $q_{ref}^{\max}$ value and pitch down if necessary

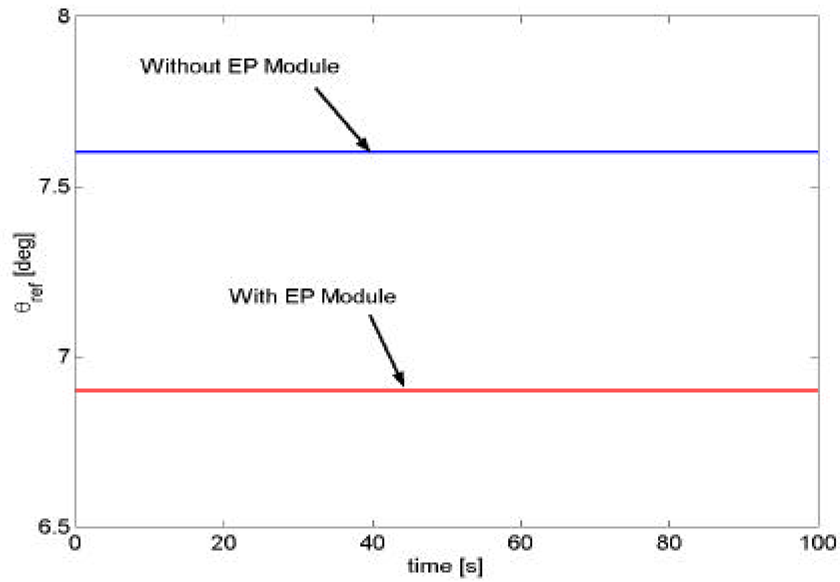
Simulation Results: *h* Fixed

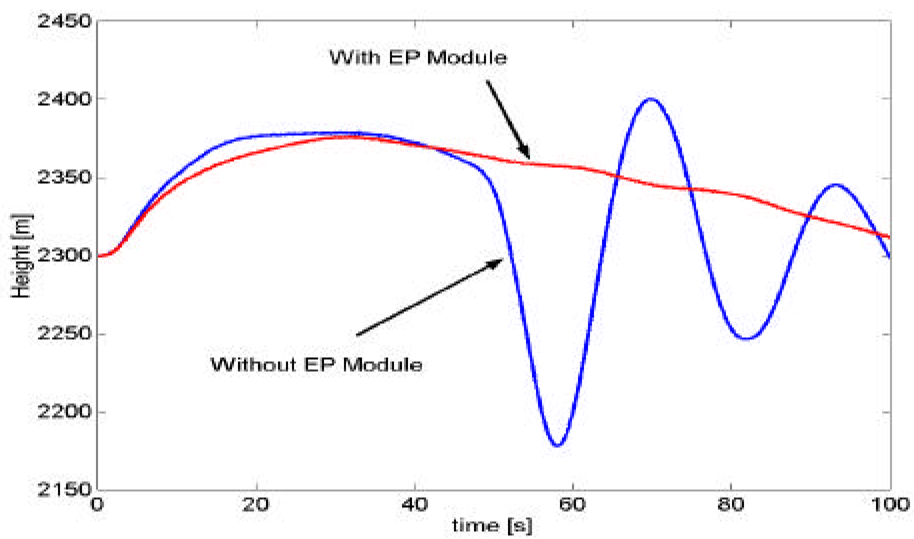
- A/C trimmed at V = 60 m/s with η=0.06 at H=2300m
- A pitch up command of 7.6 degrees issued
- α_{stall}=11.4 degrees



h Fixed continued…

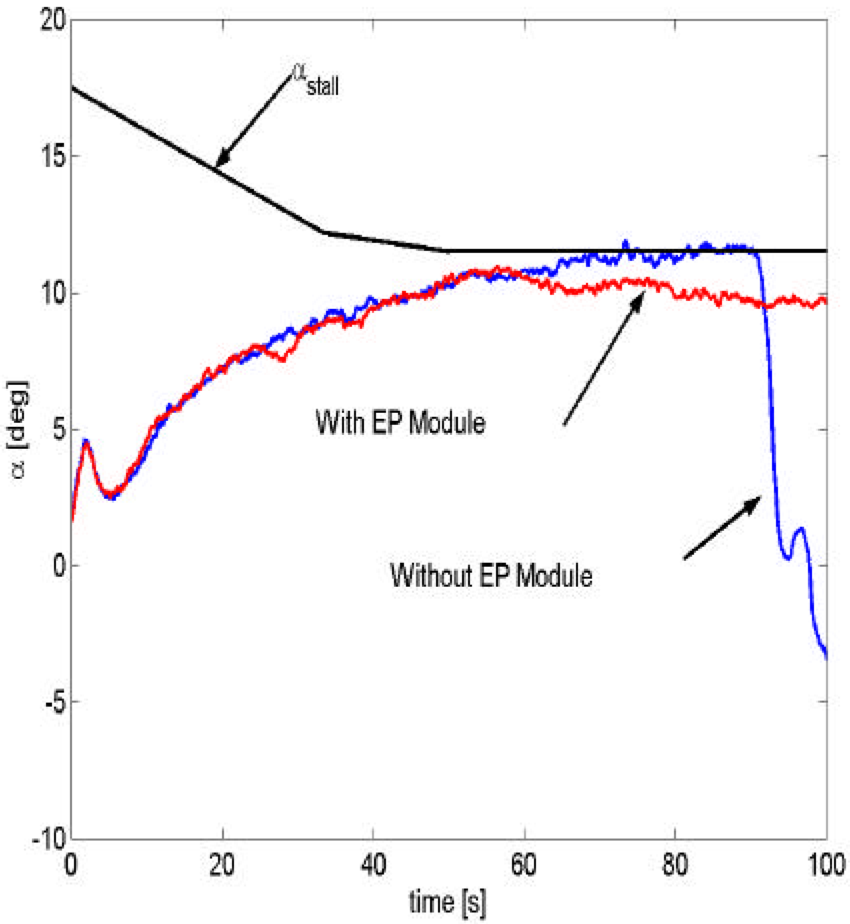




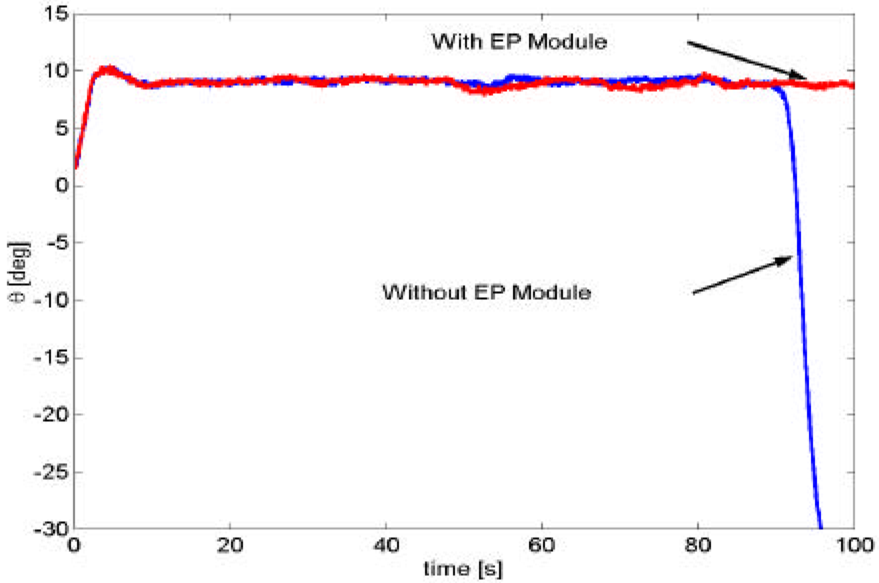


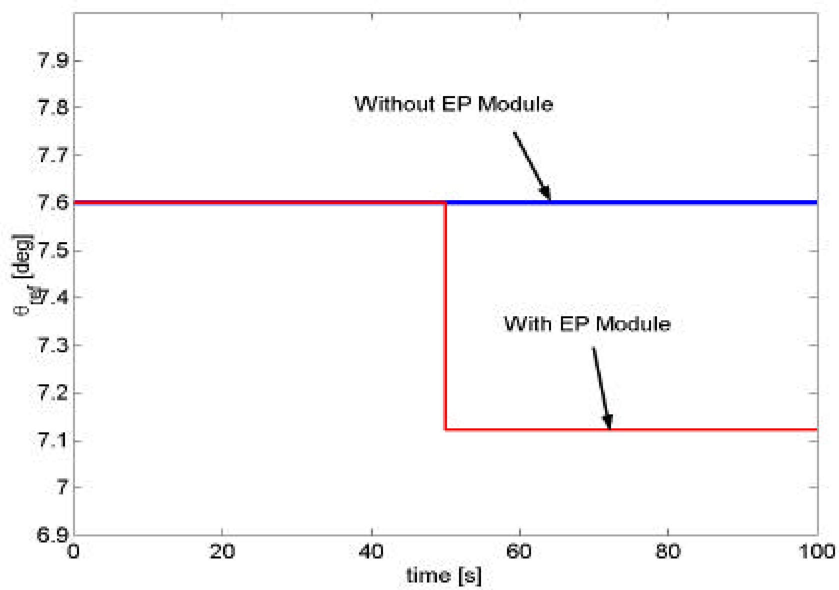
A Time Varying *h* Case

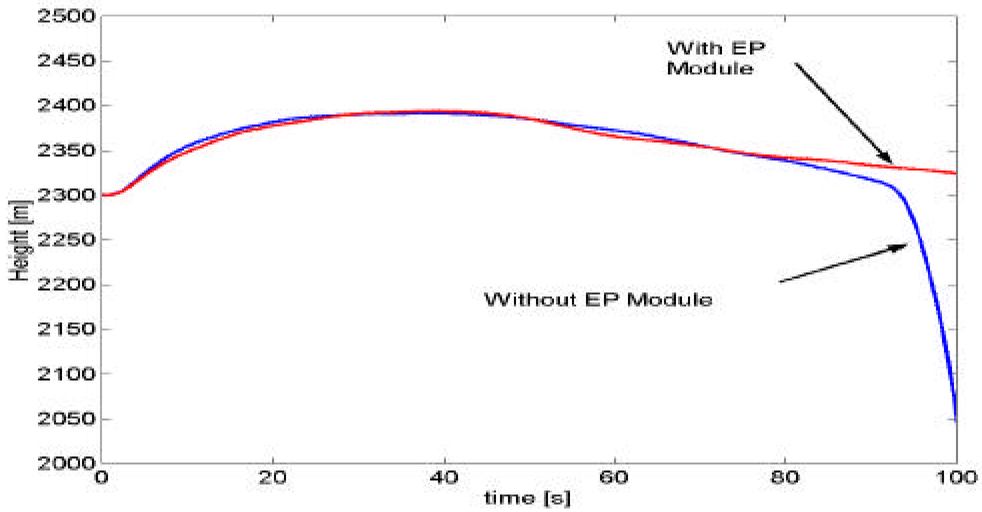
- A pitch up command of 7.6 degrees with V=60m/s is issued and ice starts to build and grows from η=0 at t=0 to η=0.06 at t=50 s.



Varying h Continued…







Closed Loop EP Conclusions

- The pitch command inputs need to be reduced in case of icing to stay within the prescribed limit
- The EP module works well with varying stall angle limits due to ice accretion

Summary

- Developed prediction based EP methods for AoA limiting in icing conditions that show great promise in preventing envelope excursions
- Established stability of standard PAH schemes in icing conditions
- Demonstrated that standard PAH schemes can be safe if combined with appropriate closed loop EP modules
- Full scale development of prediction-based EP modules and validation of AP schemes is needed to establish full confidence