Envelope Protection

Kishwar Hossain
University of Illinois

Outline

- Zeroth order envelope protection module
  - Limit detection criterion
  - Limitations of the current module and demonstration of the need for a predictive algorithm
- Proposed predictive envelope protection system
  - Prediction using solution of the full equations of motion
  - Results from simulations
- Conclusions
- Work in Progress

Introduction

Goal	Safe operation of an aircraft in icing conditions within a reduced flight envelope
Objective	Develop predictive envelope protection system
Approach	Analyze available 2-D and 3-D airfoil data to identify limit detection criteria in icing
	Develop a predictive method to avoid limit violation
	Validate prediction method against simulated FDC data and flight test data
	Implement and test the predictive envelope protection system in the flight simulator

Open Loop Envelope Protection Version 0.1

- Zeroth order envelope protection model is currently used in the SIS simulator
- Provides protection in the longitudinal mode
  - Critical Parameter - α
- Utilizes the phenomenon of lift reduction due to icing to estimate stall angle envelope limits during flight
- The stall angle limits are relayed to the pilot through limit indicators in the glass cockpit and stick shaker

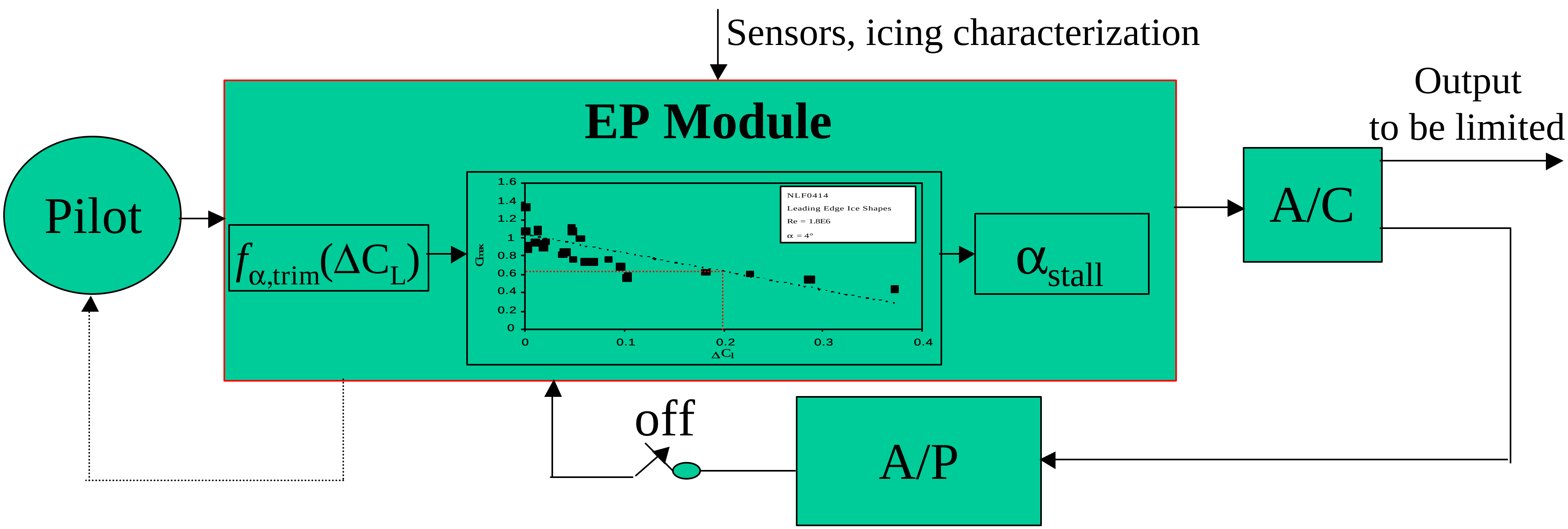
Envelope Protection Version 0.1

- C_{lmax} vs ΔC_l fitted as linear functions for several α

$$C_{l_{\max}} = f_{\alpha_{trim}}(\Delta C_l)$$

- The α_{stall} corresponding to the C_{lmax} is then set as the limit

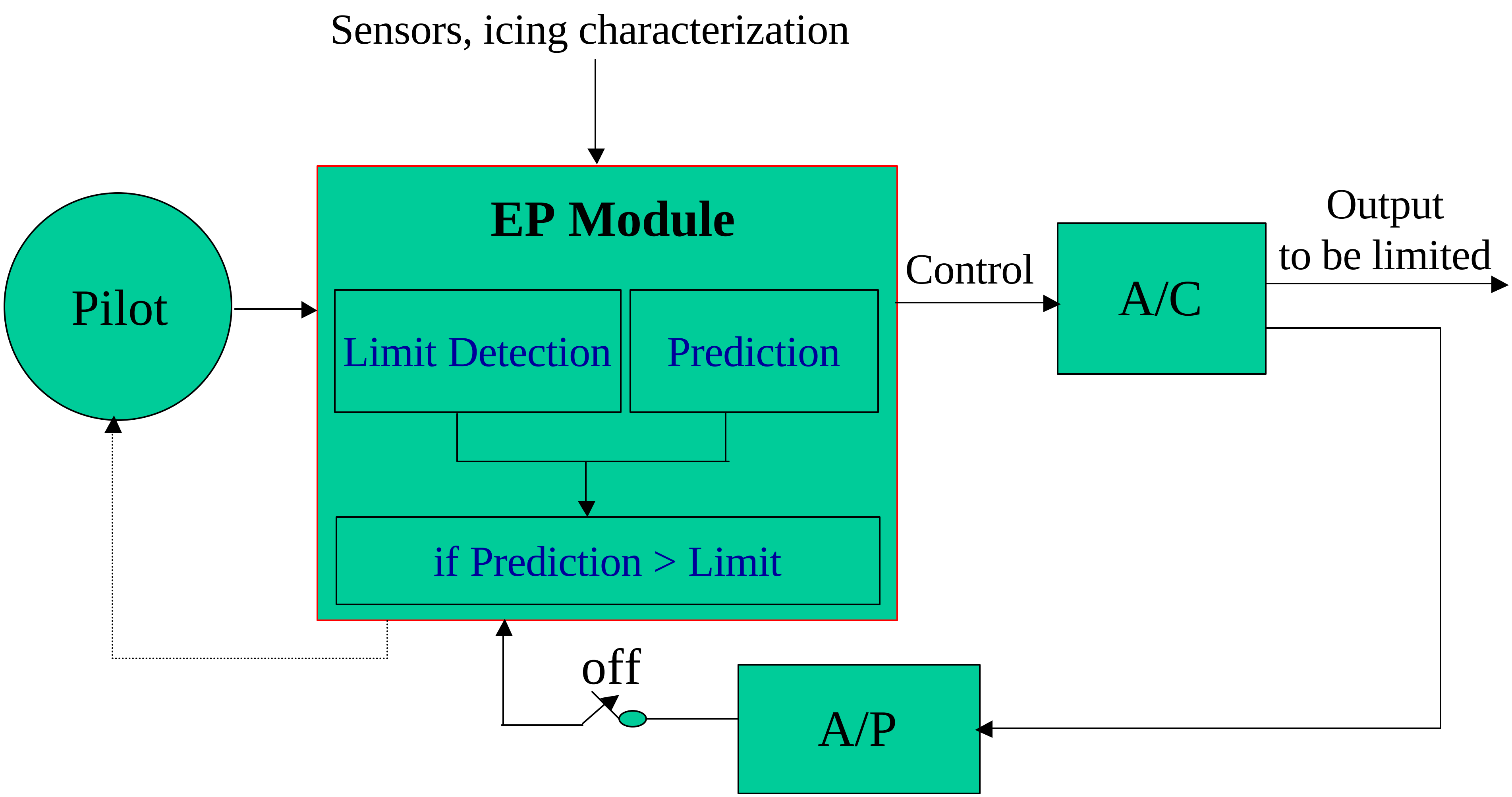
$$\alpha_{stall} = \frac{C_{L_{\max}}}{C_{L\alpha}}$$



System Limitations

- Instantaneous limits and sensor data are used to cue the pilot
- The pilot is not warned of possible limit exceedence due to rapid changes in the aircraft state during dynamic maneuvers
- Lead time needed for pilots to take counter measures and avoid crossing limit boundaries
- System needed for prediction of future values from available sensor data including control positions

Predictive Envelope Protection



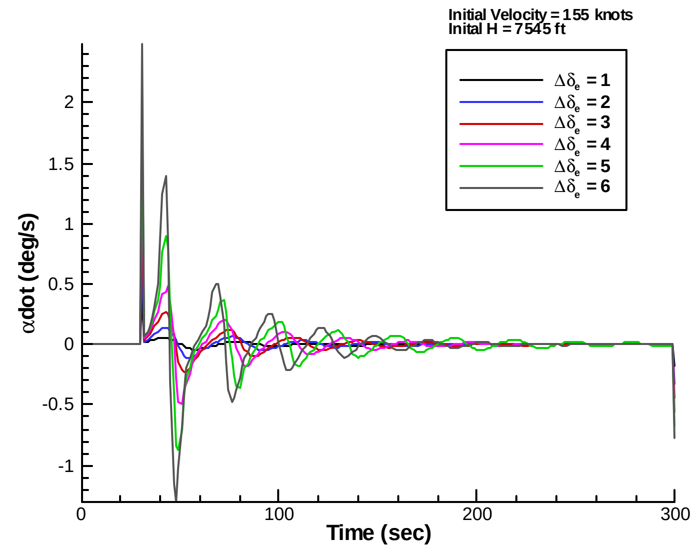
Open-loop Predictive Envelope Protection

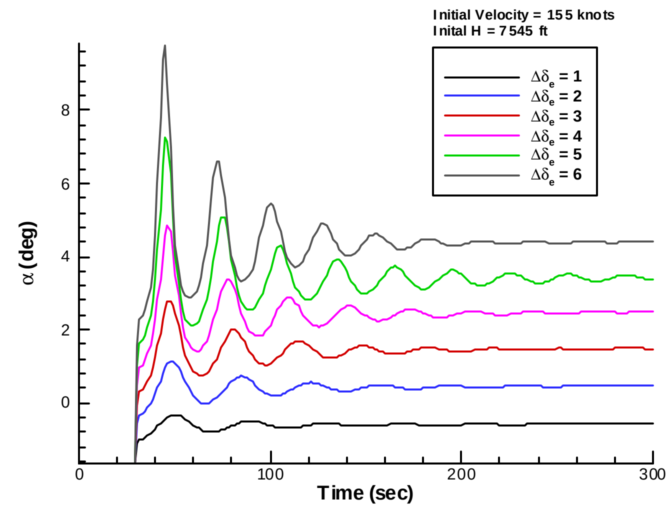
- Limit detection
  - Use information from icing characterization for estimating limit boundaries
- Prediction of limit violation
  - Use instantaneous sensor data and stick position to predict aircraft response
  - Ascertain whether a limit is breeched
- Envelope Protection Displays
  - Display limit information in the glass cockpit
  - Use force feedback to avoid limit violation

Problems with Previously Proposed Predictive Method

Smart Icing System Review, September 30, 2002

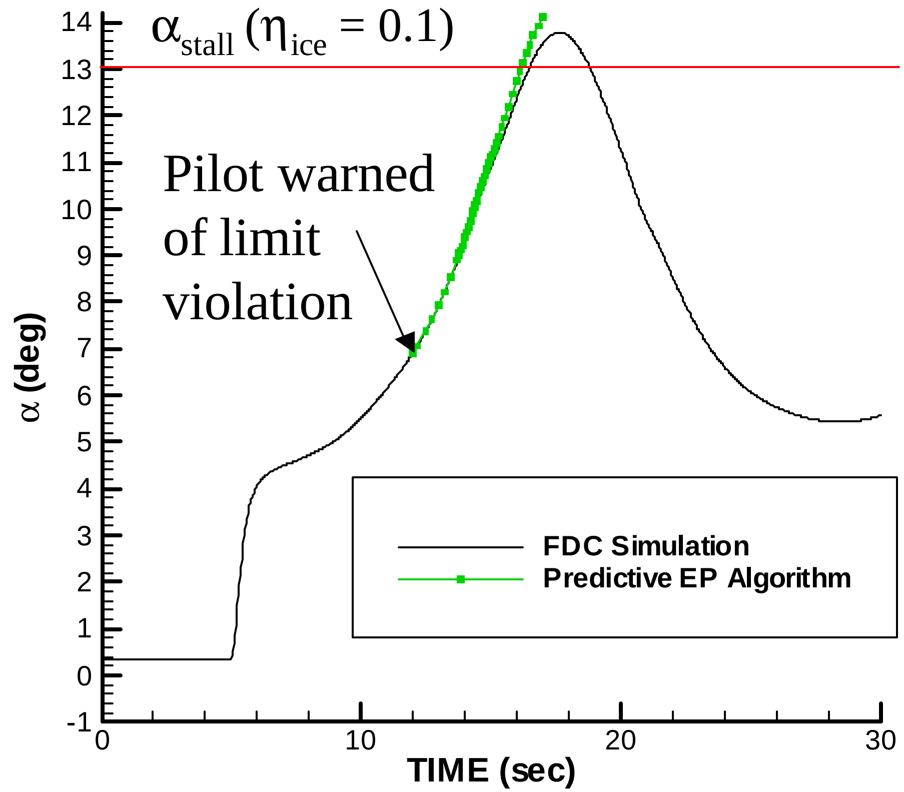
- The method of Calise et al. proposed in the last review cannot be applied to the Twin Otter in the open loop case
  - The time taken to reach the dynamic trim state ($\alpha = 0$, $\beta = 0$) too long
  - The transient peaks following stick inputs higher than steady state values
  - The response of the Twin Otter not damped enough
- An alternative method, using on-line solutions of the 6 DoF nonlinear equations of motion, was thus developed for predicting future limit violations





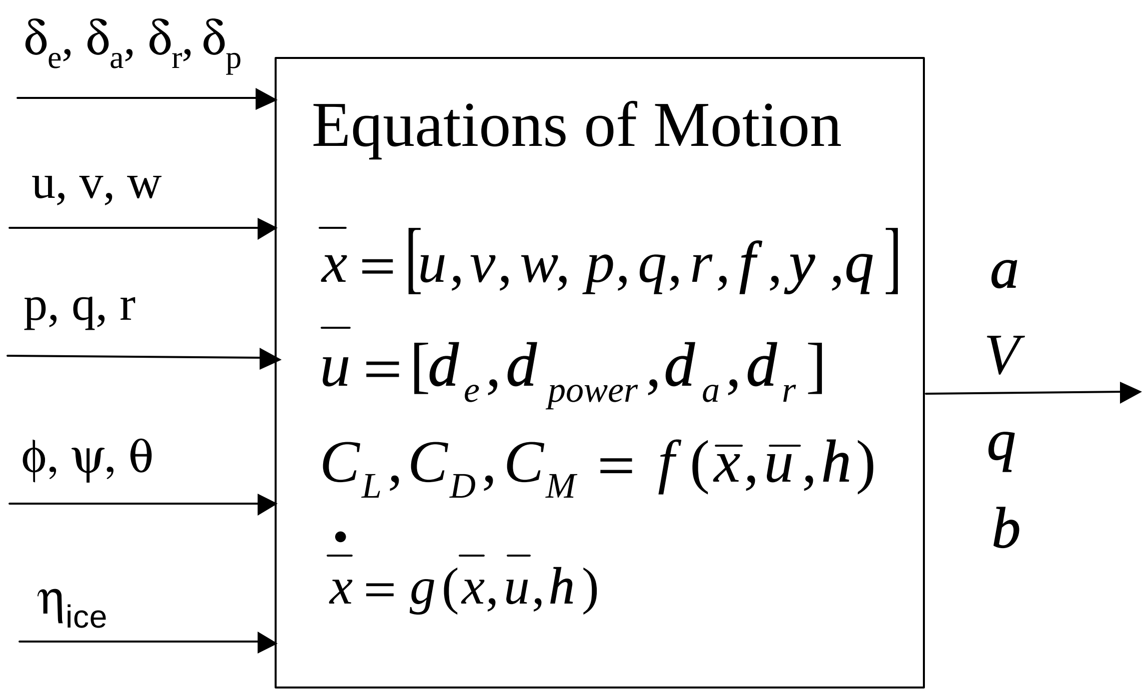
Open Loop Envelope Protection 1.0

- Solve the equations of motion to predict the aircraft state 5 sec into the future
- Assume all control inputs fixed at current values
- Compare the critical parameter response to calculated real-time limit boundaries
- Determine whether a limit is exceeded within 5 sec of current time
- Inform the pilot of any predicted limit violations and take other appropriate action



Prediction Algorithm

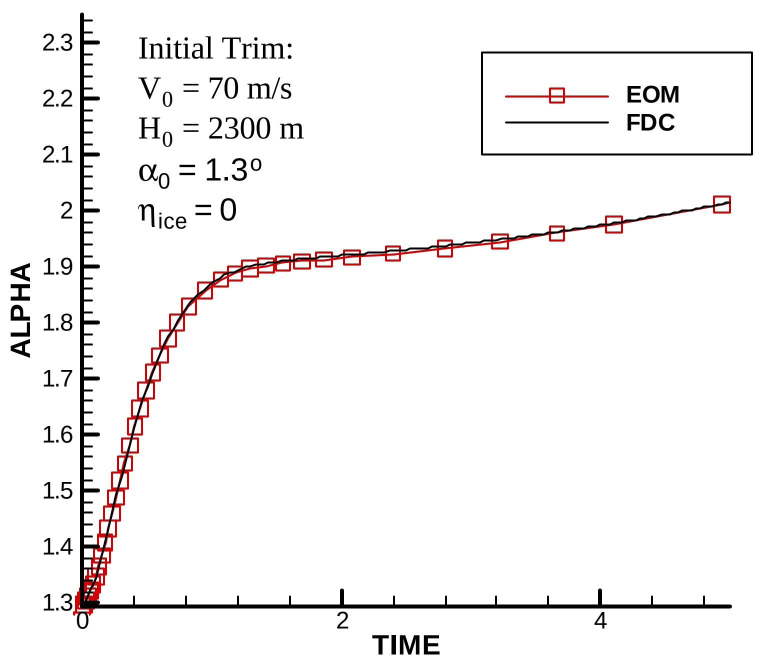
- The aircraft configuration and state at each time step is used to initialize the code
- Control deflections are assumed to be constant during the 5 sec
- The iced non-linear aircraft model is used to calculate the force and moment coefficients within the code
- A 6 Dof system is then solved using a non-linear ODE solver



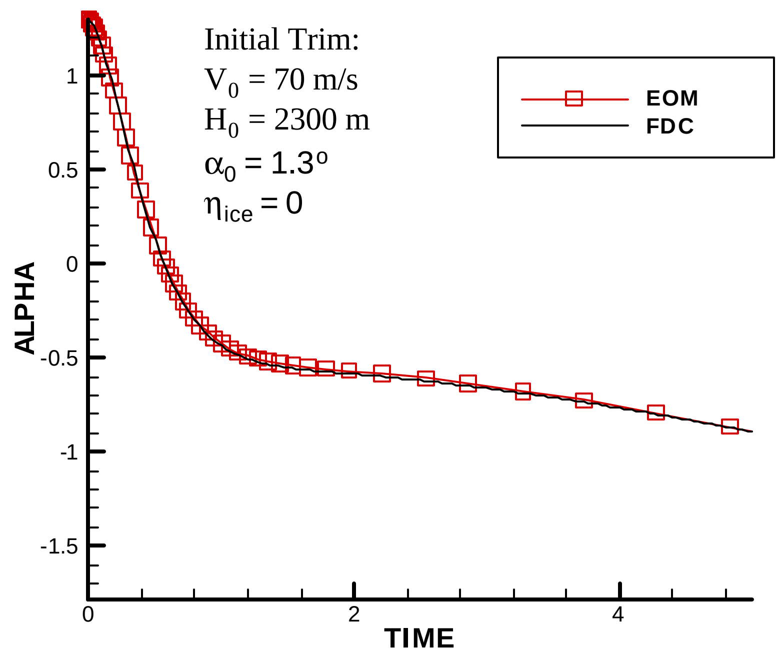
Validation with FDC

The predictive algorithm was validated against FDC results for different scenarios

a response to a 2º step elevator input at t = 0



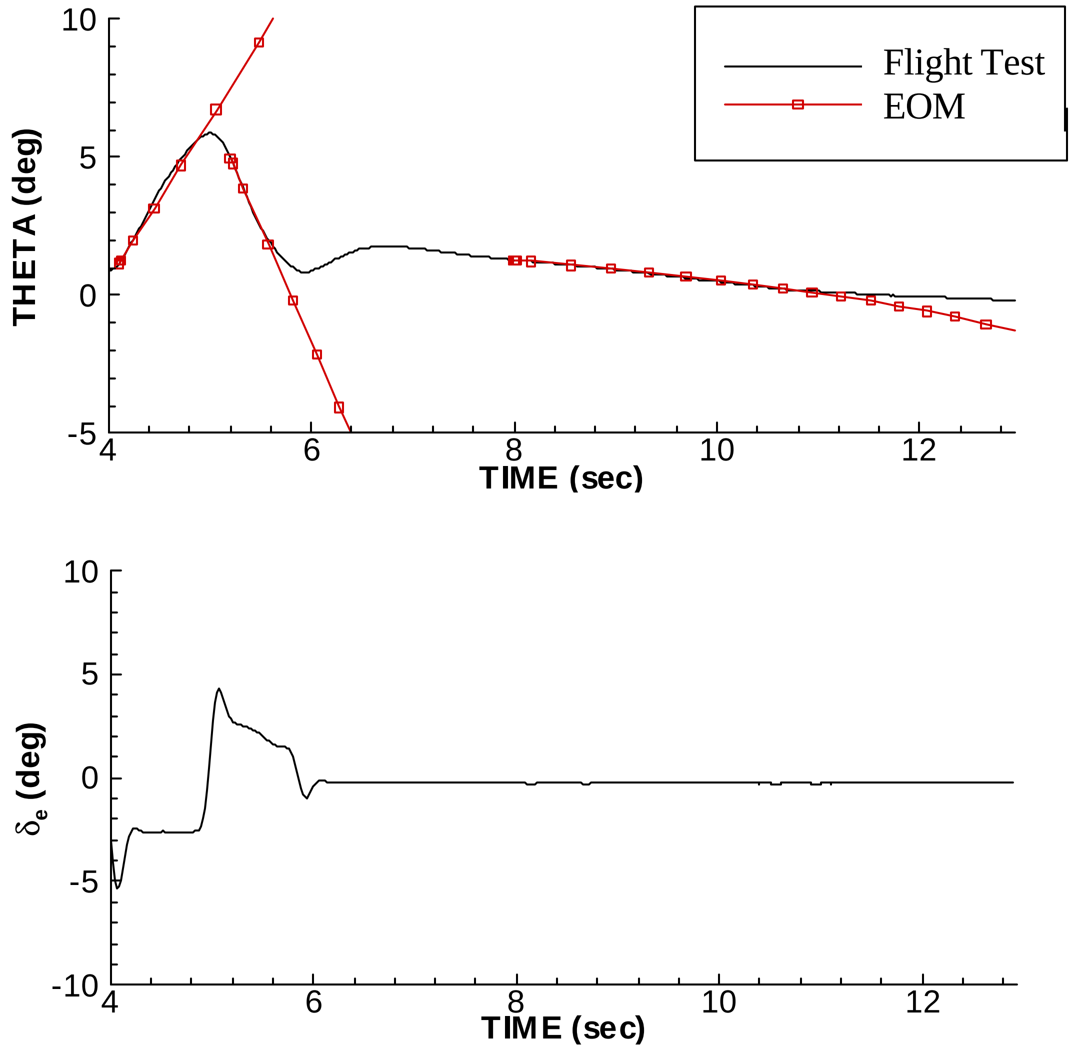
a response to a -2º step elevator input at t = 0



Validation Flight Test Data

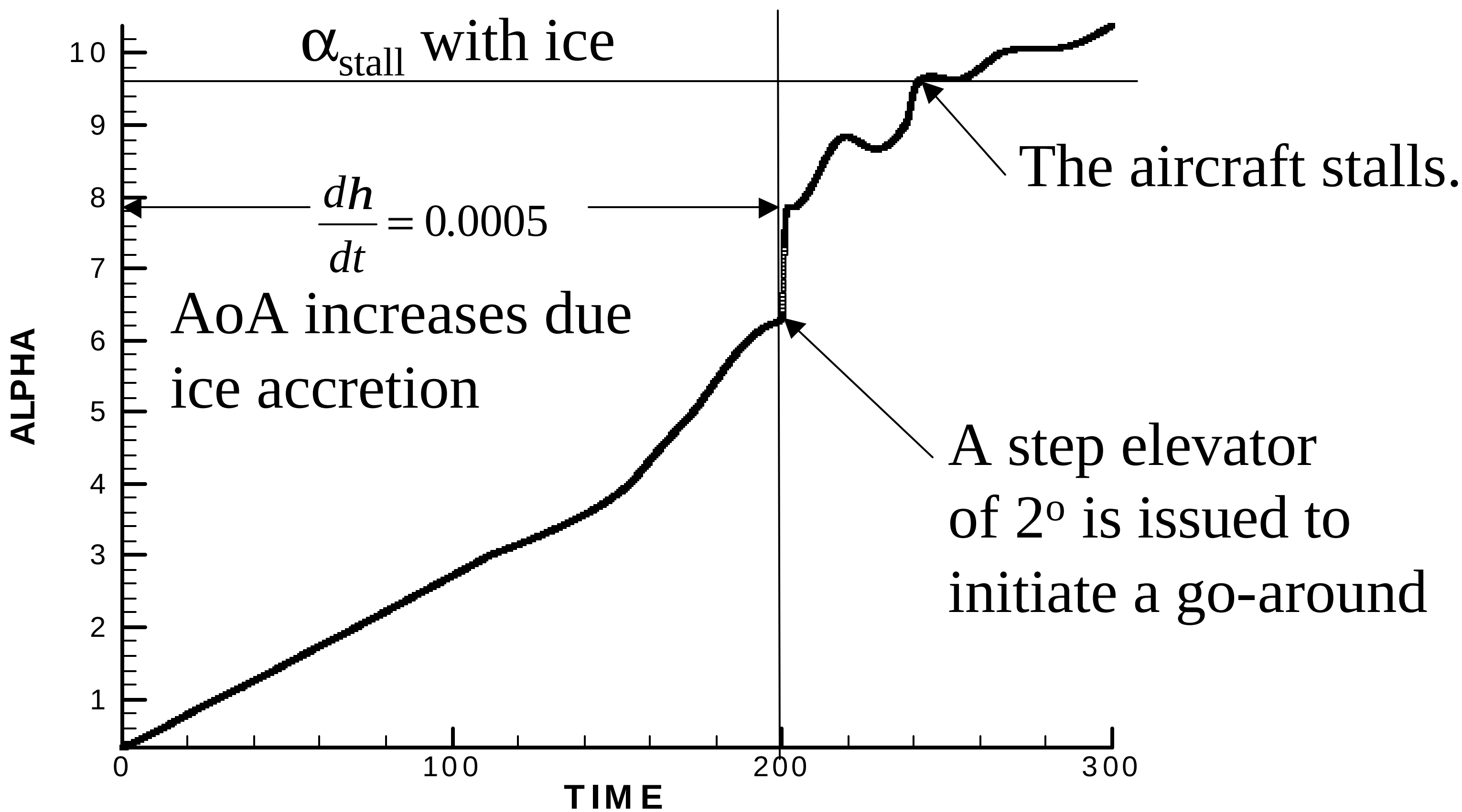
Smart Icing System Review, September 30, 2002

- The EOM algorithm was tested on clean flight test data
- Flight no. 020213f1
- As seen on the plot the predictions compare well with the flight data
- As expected, changes in control position affect the EOM comparisons



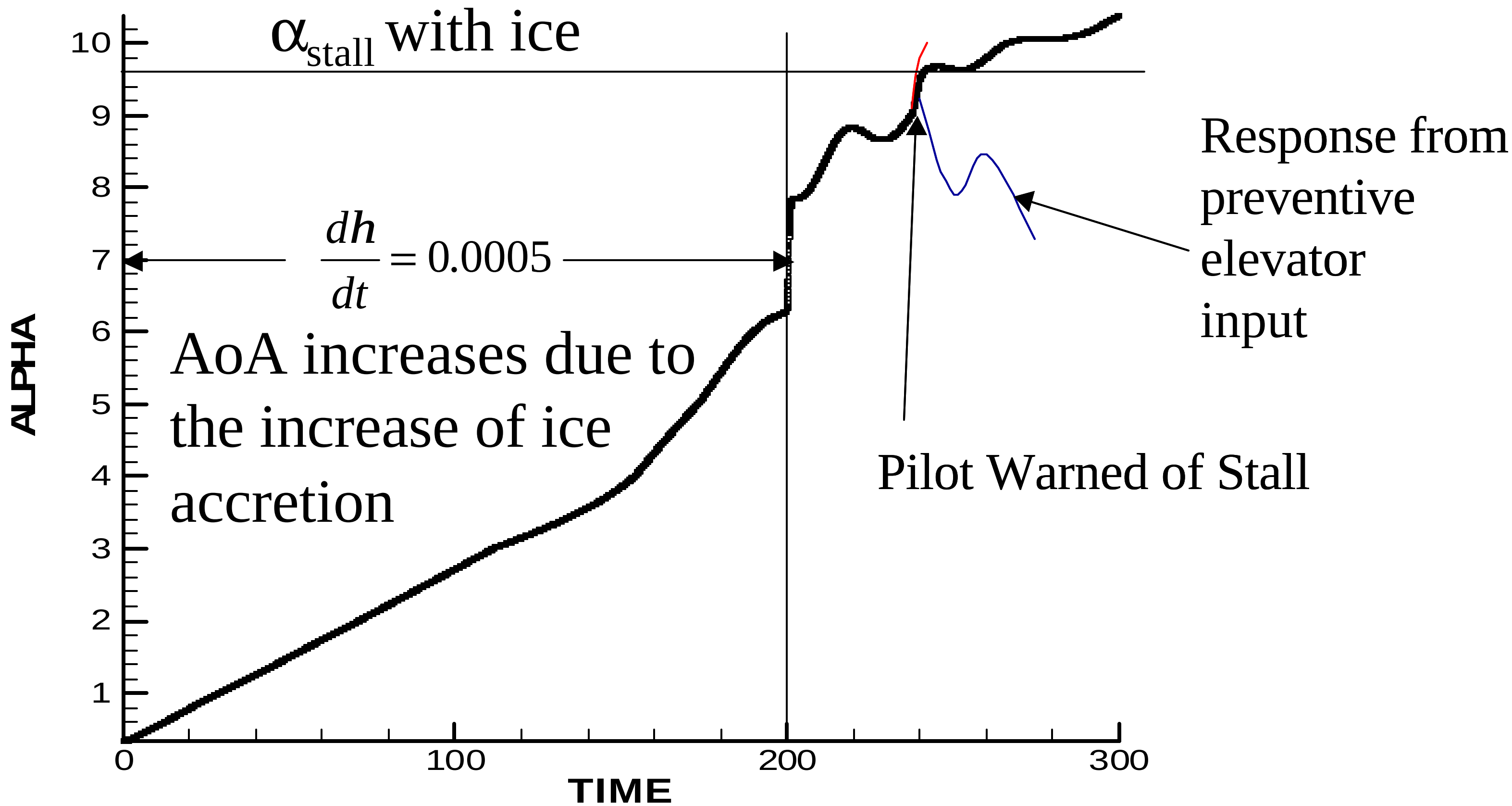
Open-loop Envelope Protection Method Simulation

Scenario without Predictive Envelope Protection
FDC Simulation



Open-loop Predictive Envelope Protection Simulation

When warning is available, an elevator command can be issued to reduce the angle of attack in time to avoid limit violation



Conclusion

- Limit boundary estimation using differences in lift generated implemented in the simulator
- Not enough time to warn pilot using instantaneous limits
- Prediction using solution of the equations of motion in the future should allow enough lead time to warn pilots of any danger of limit exceedence

Work in Progress

- Implement predictive method in the simulator
- Lateral envelope protection
  - Specify critical parameters
  - Develop method for estimation of limit boundaries
  - Test prediction method in the lateral mode
  - Implement lateral protection in the simulator