National Aeronautics and Space Administration

# Launch Vehicle Manual Steering with Adaptive Augmenting Control:

## In-Flight Evaluations using a Piloted Aircraft

NESC GNC TDT Face-to-Face
October 21, 2014

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# Motivation to Test Manual Steering

- **Manual steering is a human-in-the-loop attitude control mode under consideration for the SLS.**
- **LVAC Objectives:**
  1. Demonstrate closed-loop tracking with negligible adaptation in an environment that is commensurate with the nominal controller design.
  2. Demonstrate improved performance in an environment where the nominal controller performance is less than desired.
  3. Demonstrate the ability to recover from unstable, mis-modeled parasitic dynamics to a bounded nondestructive limit cycle.
  4. Explore interactions between manual steering and the AAC.
- **At the time of the LVAC flights,**
  - there was an SLS requirement for manual steering capability, but
  - there was no official manual steering mode design for SLS.
- **In-flight pilot evaluation of deficiencies and/or adverse Pilot-AAC interactions could:**
  - inform design choices in the SLS manual steering mode, or
  - restrict simultaneous use of AAC and manual steering.

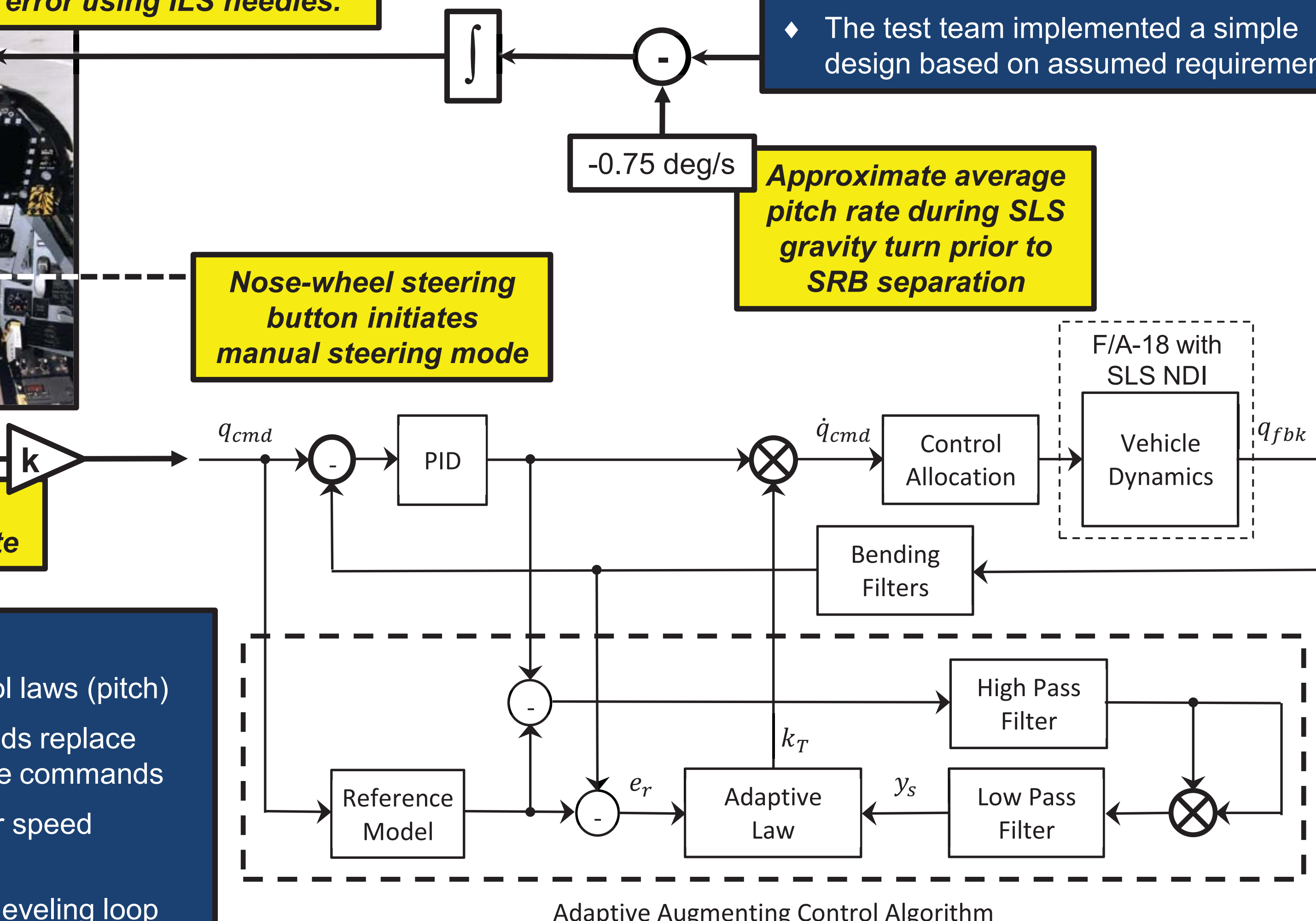
***Note: The LVAC flights addressed the SLS launch trajectory prior to SRB separation, while the SLS manual steering requirement applies to post-SRB separation.***

# LVAC Manual Steering Mode Implementation

**Prototype Design**

- No official SLS manual steering design existed at the time of the experiment
- The test team implemented a simple design based on assumed requirements

*Re-located ADI gage near HUD to display pitch rate error using ILS needles.*

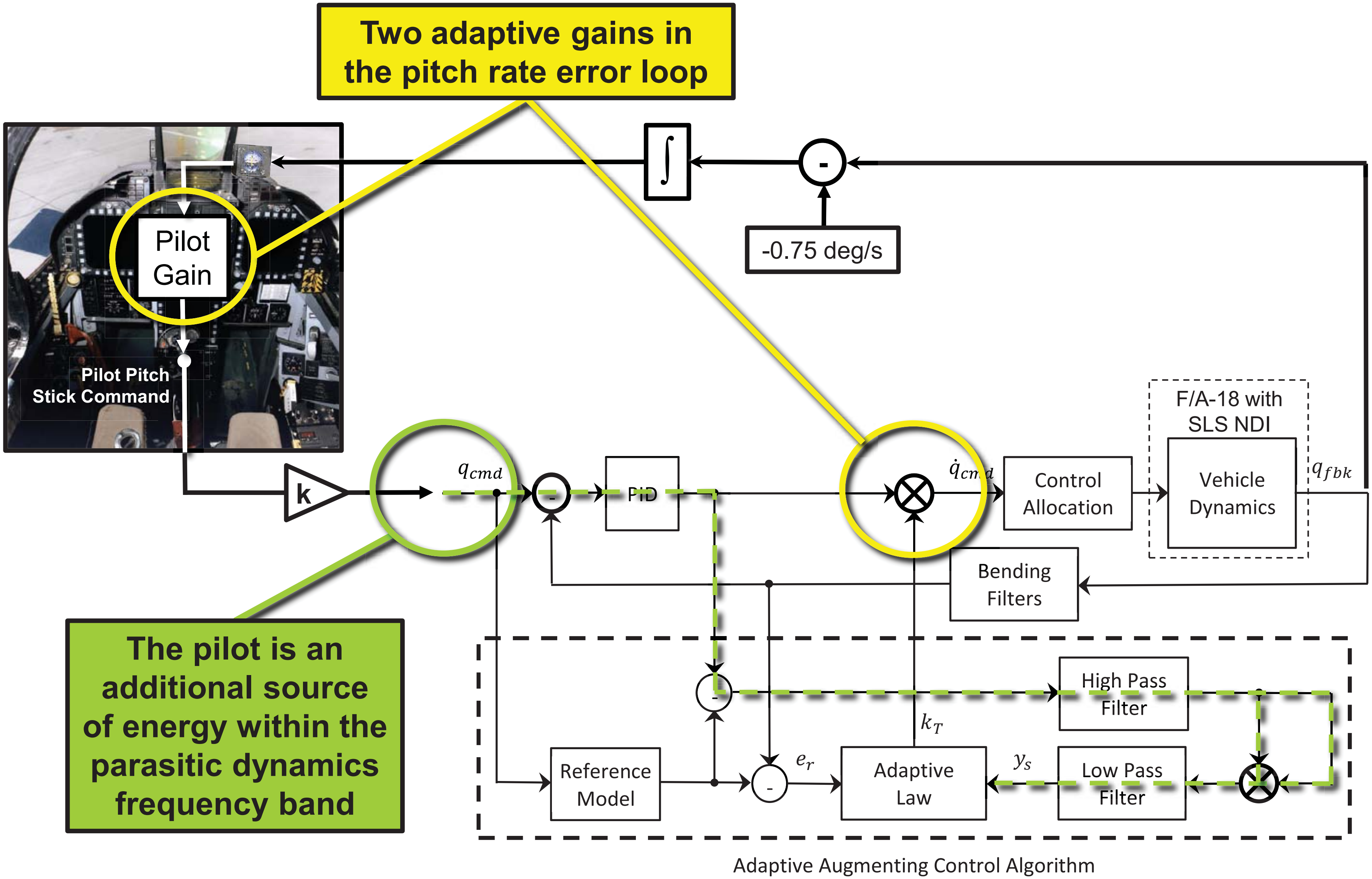




*1" stick displacement equals 1 deg/s pitch rate*

**Control Strategy**

- Single axis SLS control laws (pitch)
- Pilot steering commands replace SLS autopilot guidance commands
- Pilot throttle control for speed modulation
- NDI contains a wings-leveling loop

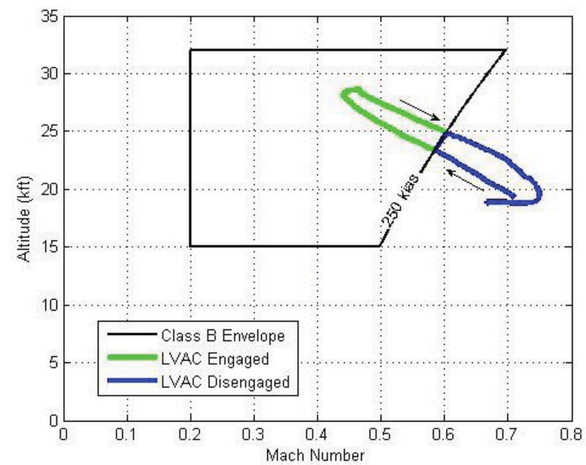
# Sources of Adverse Pilot-AAC Interaction



# Test Approach

- **Two pilots, 25 test trajectories, 6 test scenarios**
  - Pilot A: 13 trajectories, 5 scenarios / Pilot B: 12 trajectories, 5 scenarios
  - Back-to-back evaluations, AAC Off vs. On, for each scenario
  - Nominal case flown at the beginning and end of each flight
  - Pilot hot-mic comments and HUD video recorded during and immediately following each test point, along with PIO ratings

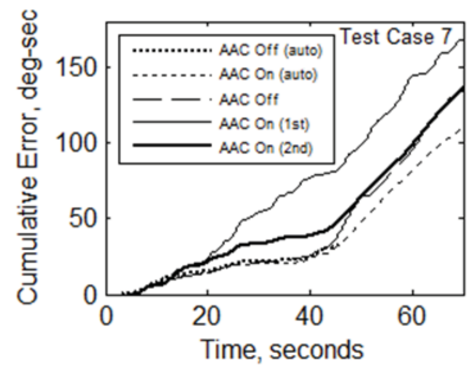
| Objective | Case | SLS Scenario Description | AAC | Pilot A (number of attempts) | Pilot B (number of attempts) |
|---|---|---|---|---|---|
| 1 | 0 | Nominal Plant and Environment | on<br>off | 2<br>2 | 2<br>2 |
| 2 | 5 | Two-Spaced Hard-Over Failures | off<br>on | 1<br>1 | 1<br>1 |
| | 7 | Wind Shear, Two Hard-Over Failures | off<br>on | 1<br>2 | 1<br>1 |
| 3 | 15 | High Gain plus Slosh Excitation | off<br>on | 0<br>0 | 1<br>1 |
| | 16 | High Gain with Unstable Flex | off<br>on | 1<br>1 | 0<br>0 |
| | 17 | High Gain plus Rigid Body Instability | off<br>on | 1<br>1 | 1<br>1 |



# Pilot-AAC interaction Evaluation Metrics

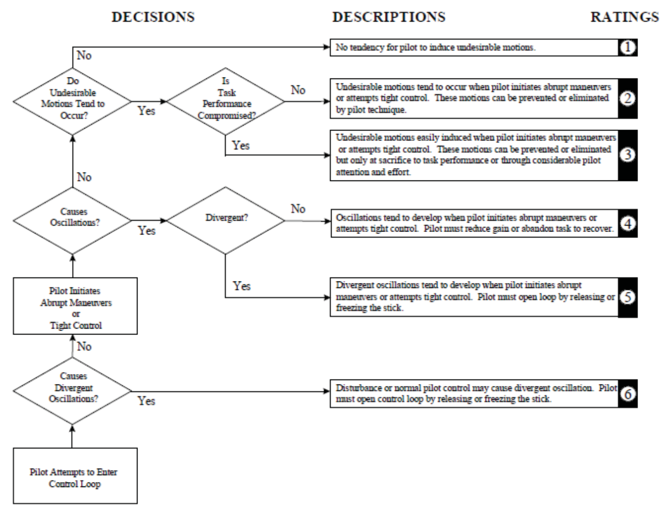
## ♦ Cumulative Tracking Error

- Integral of the square of the pitch attitude tracking error vs. time.
- Metric for evaluating Objectives 1 and 2




## ♦ PIO Rating Scale

- From MIL-STD-1797B, Flying Qualities of Piloted Aircraft, Feb. 15, 2006
- Qualitative and quantitative measure of tendency to instability resulting from pilot attempts to control the vehicle




## ♦ Pilot Workload Metrics

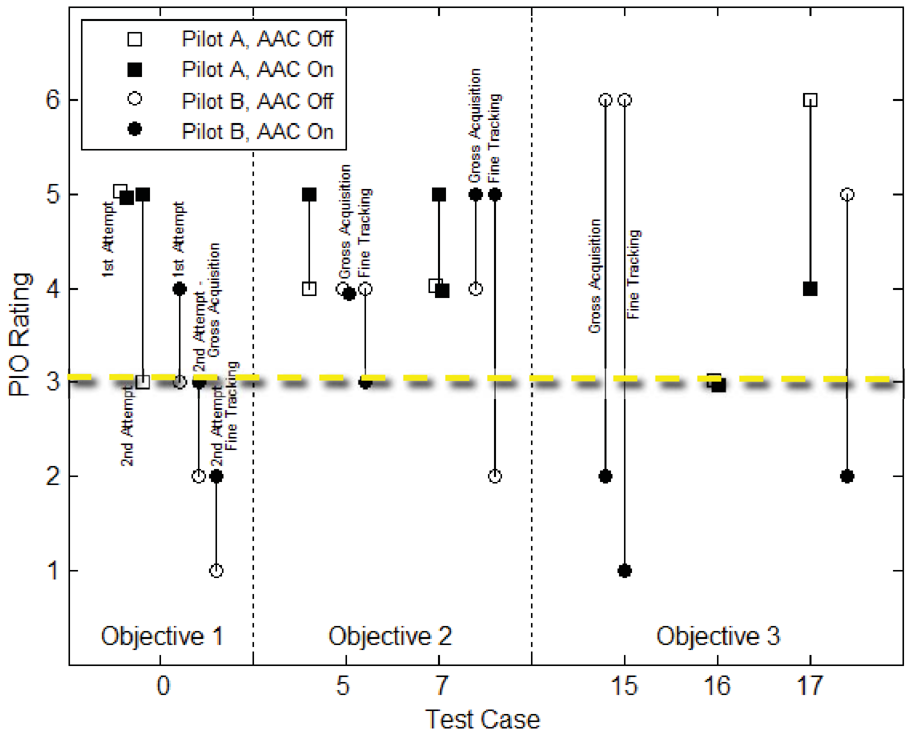
- Cross-plot of Duty Cycle vs. Aggressiveness
  - Duty Cycle: frequency with which the pilot reverses control direction
  - Aggressiveness: measure of dynamic control inceptor deflection

$$J_A = \frac{100\%}{t_f - t_0} \sum_{\tau=t_0}^{t_f} \left( \frac{|q_{cmd}(\tau) - \bar{q}_{cmd}(\tau)|}{q_{cmd}^{max} - q_{cmd}^{min}} \right) \Delta\tau$$

# Top-Level PIO Ratings Summary

**AAC increased PIO tendency for Objectives 1 and 2** (small effect)

**AAC reduced PIO tendency for Objective 3** (large effect)




**Pilot A / Test Case 0 / AAC Off**

1st Attempt – "Any attempt to tighten control leads to PIO. Task performance is affected, but with a lot of compensation I can make this work." (PIO rating 5)

2nd Attempt – "Tight control definitely causes oscillations - they're not necessarily divergent - somewhat open-loop task." (PIO rating 3)

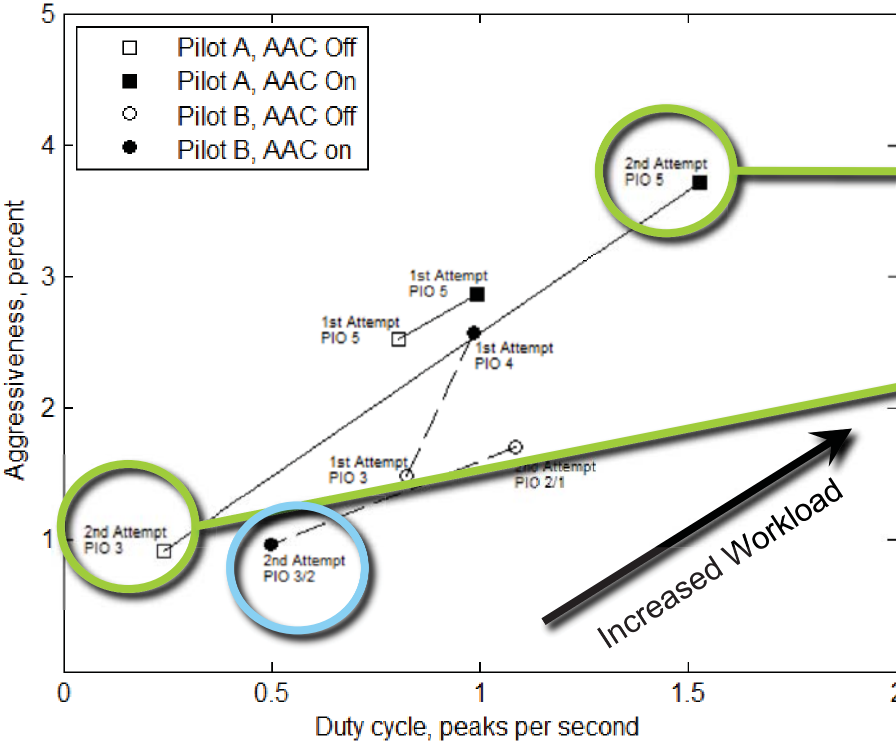
**~80% of test points rated as "Task Performance Compromised" or worse**

**The SLS in manual steering mode* is very PIO-prone, with or without AAC.**

* This experiment did not evaluate any official SLS manual steering mode designs.

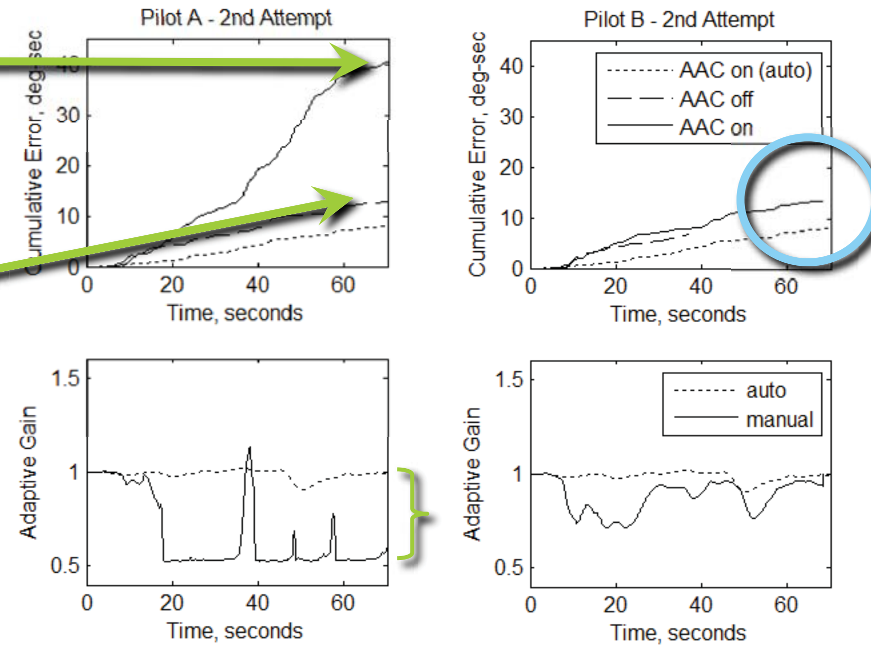
# Objective 1: Minimal Adaptation in the Nominal Case

## Test Case 0: Nominal Plant and Environment




**Pilot A – 2nd Attempt**
Much higher workload and reduced tracking performance with AAC.

**Pilot B – 2nd Attempt**
Reduced workload and little change in tracking performance with AAC.




**In 3 of 4 attempts, adaptation increased pilot workload.**

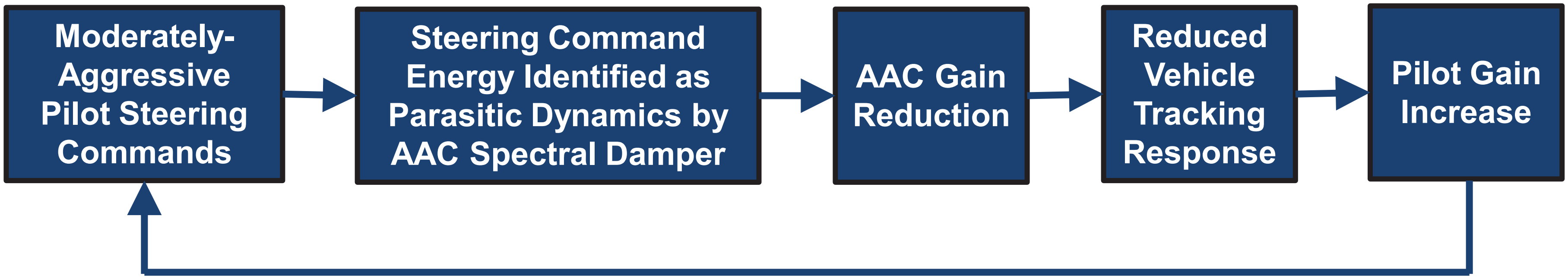
**In all cases, adaptation resulted in the same or worse PIO rating.**

With manual steering, the adaptive gain is at or near its lower limit for much of the maneuver.

The adaptive gain with manual steering remains near the nominal value of 1, similar to the autopilot.

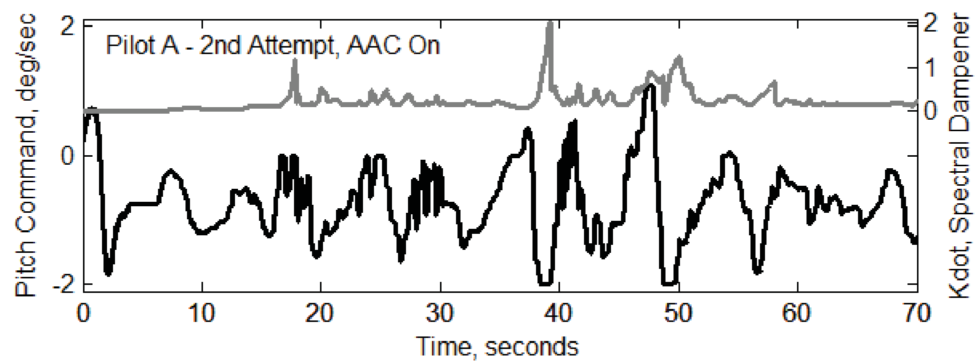
# Objective 1: Minimal Adaptation in the Nominal Case

## Pilot-AAC Adverse Interaction



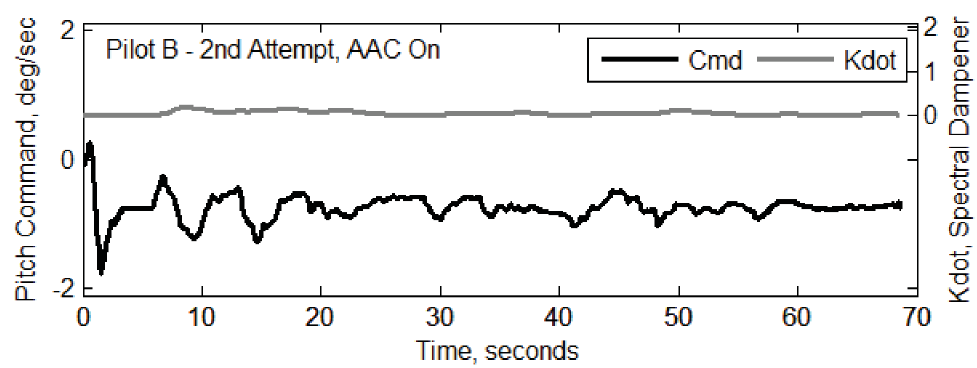

**Pilot A – 2nd Attempt**

With AAC On, the pilot's manual steering inputs were interpreted as parasitic dynamics by the spectral damper component of the adaptive law, driving the gain lower. The pilot had to increase his gain to compensate, causing the pilot and AAC to enter into an adverse interaction.




**Pilot B – 2nd Attempt**

In this case, the pilot's commands were of a low enough frequency to avoid detection by the spectral damper, and did not affect the adaptive gain.



# Summary

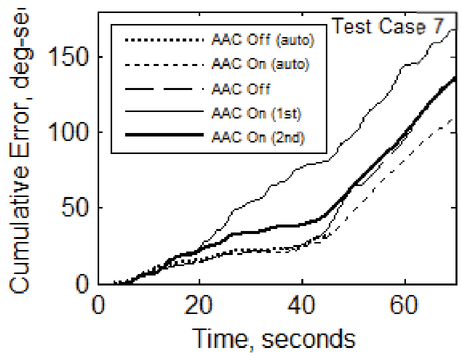
- **Manual steering* did not improve performance or robustness beyond what could be achieved using just the AAC algorithm.**
- **Scenarios from all 3 Objectives showed a tendency for adverse interaction between the pilot and the adaptive controller.**
  - The use of manual steering tends to suppress the adaptive gain below its ideal value.
  - In many cases, the AAC increased pilot workload and tendency for PIO.
  - Beneficial interactions included cases where the fixed gain is too high, or where mis-modeled dynamics such as slosh create an increased likelihood of PIO without AAC.
- **Pilot technique can reduce the likelihood of adverse pilot-AAC interaction.**
  - Early in each flight, the pilots adjusted their approach from tight control to more of an open-loop task.
  - In an emergency situation, it may be difficult for the pilot to lower his/her gain and avoid attempts at tight control.
- **Use of manual steering with AAC is not recommended without MSM design changes.**

* This experiment did not evaluate any official SLS manual steering mode designs.

# Backup Slides

# Objective 2: Improved Tracking Performance

**Test Case 7: Wind shear and two simultaneous hard-over failures**

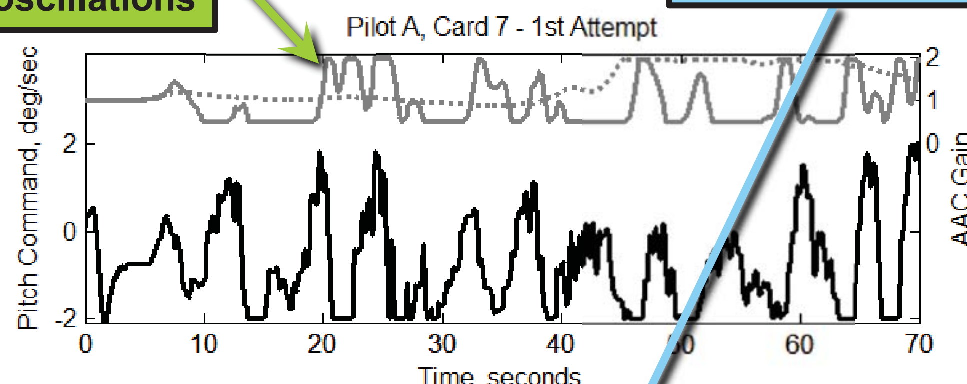


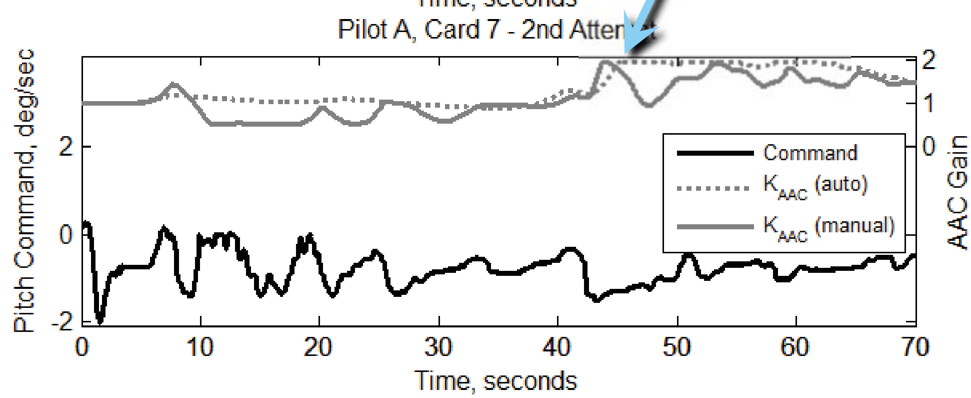

Difference in tracking error, attempt **#1** vs. **#2**

**Two back-to-back attempts by Pilot A show the effects of pilot technique on adverse interaction with the adaptive controller.**

**On attempt #1, large adaptive gain oscillations**

**On attempt #2, similar gain behavior to the autopilot case**



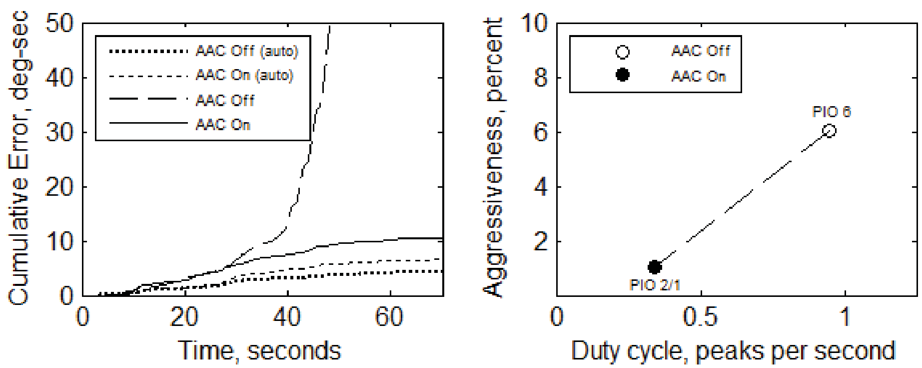




**<u>Pilot A / Test Case 7 / AAC On: 1st Attempt</u>**
"Getting into an oscillation. Seems divergent. I seem to have recovered somewhat. Any real attempt to do the task leads to pretty good oscillations that seem divergent." (PIO rating 5)

**<u>Pilot A / Test Case 7 / AAC On" 2nd Attempt</u>**
"If I'm really careful, I can sort of track this. It's very sensitive. I changed my piloting technique a lot and didn't really attempt tight control." (PIO rating 3)

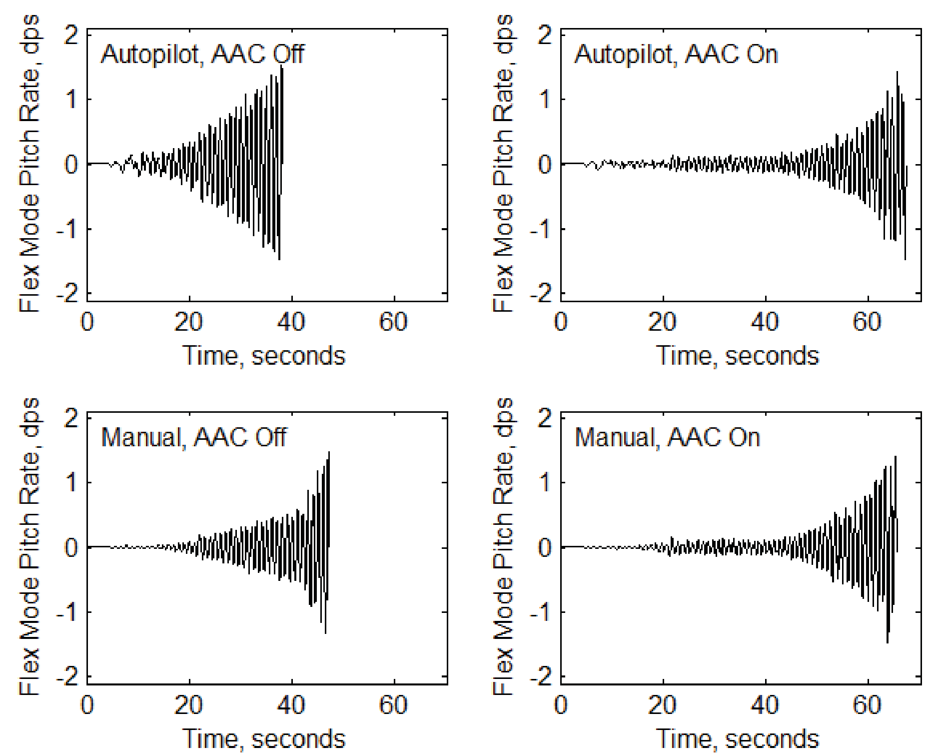
# Objective 3: Mis-Modeled Parasitic Dynamics

## Test Case 15: High Gain Controller with Slosh, Pilot B




**TC 15: Without AAC active, the pilot encountered a divergent PIO that resulted in simulated loss of vehicle.**

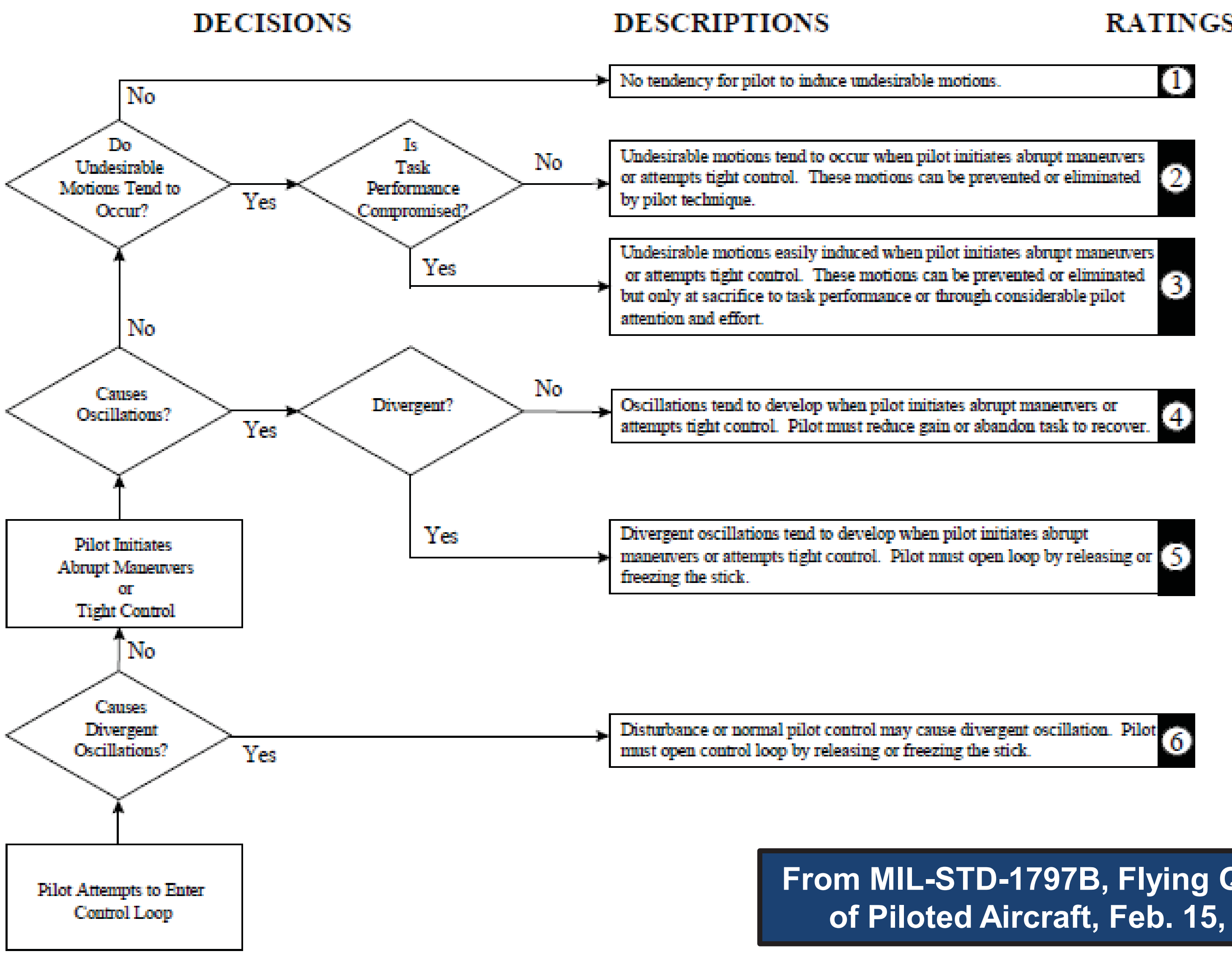
## Test Case 16: High Gain Controller with Unstable Flex, Pilot A




**TC 16: Without AAC active, the pilot extended the trajectory by about 9 seconds over the autopilot.**

**With AAC on, manual steering had little effect on the loss of vehicle.**

# PIO Rating Scale




**From MIL-STD-1797B, Flying Qualities of Piloted Aircraft, Feb. 15, 2006**