"Feasibility Study of Transport-Aircraft Control Systems for Turbulence Effects Mitigation"

Christopher J. Borland
Vincent M. Walton

The Boeing Company
Commercial Airplane Group
Seattle, WA

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Study Objectives

- Use turbulence inputs from injury-accident FDR data
- Assess capability of current aircraft control systems to reduce turbulence-induced acceleration response in the cabin
- Assess new control law strategies with current (on-board) and advanced (forward-looking) turbulence sensors
- Identify key issues to practical implementation

Analysis of Turbulence Accidents and Wind Field Determination

- NASA Ames provided FDR data from NTSB for five accidents (1975-85).
- Boeing Accident/Incident Investigation Group provided FDR data for five accidents (1997-99).

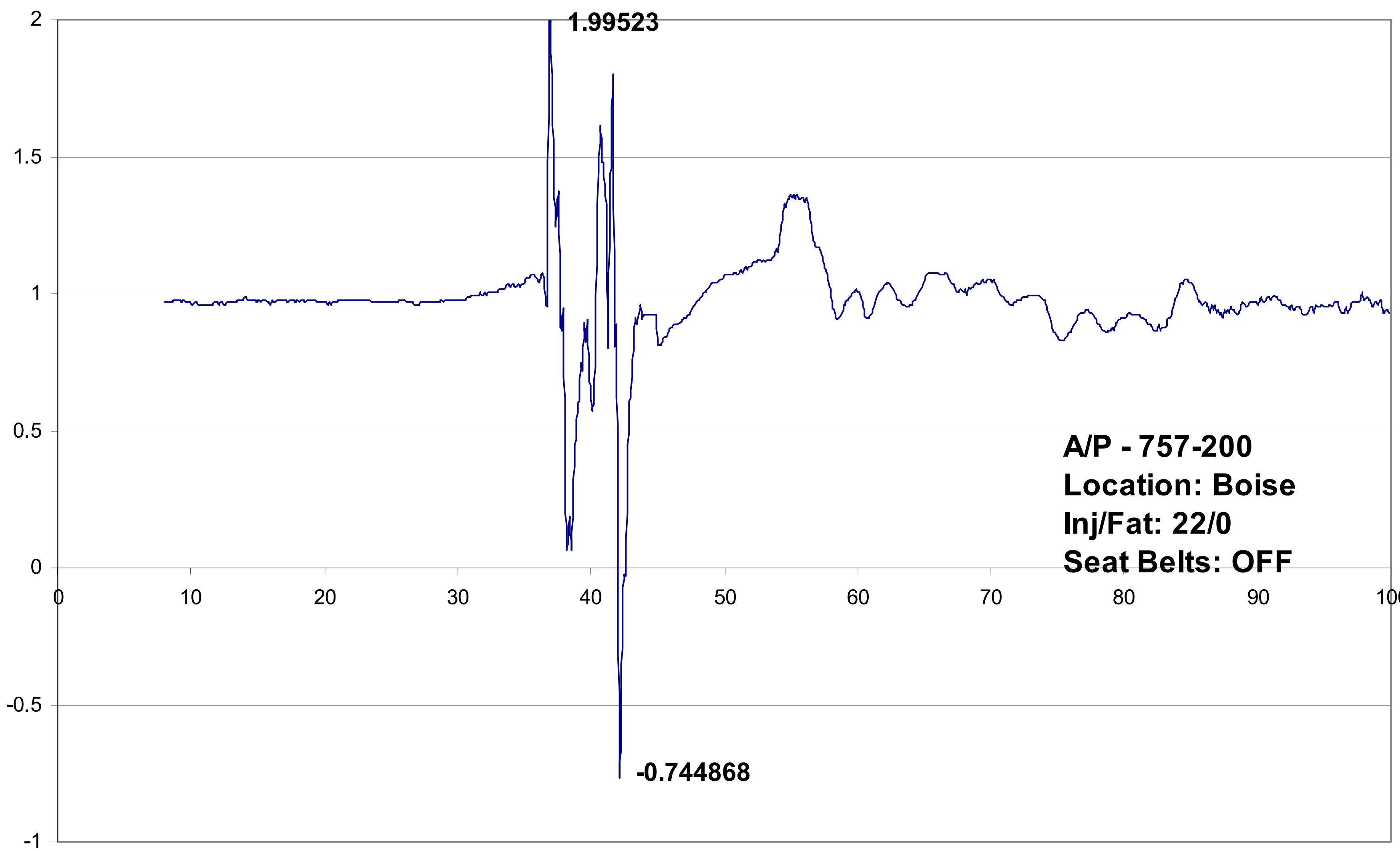
Most of these data show some interesting similarities:

- Severe turbulence onset often gives little or no warning.
- Positive and negative spikes in acceleration, with negative excursions to below 0 g, lasting about 1-2 seconds.
- Duration of severe turbulence is often brief, 5-10 seconds.

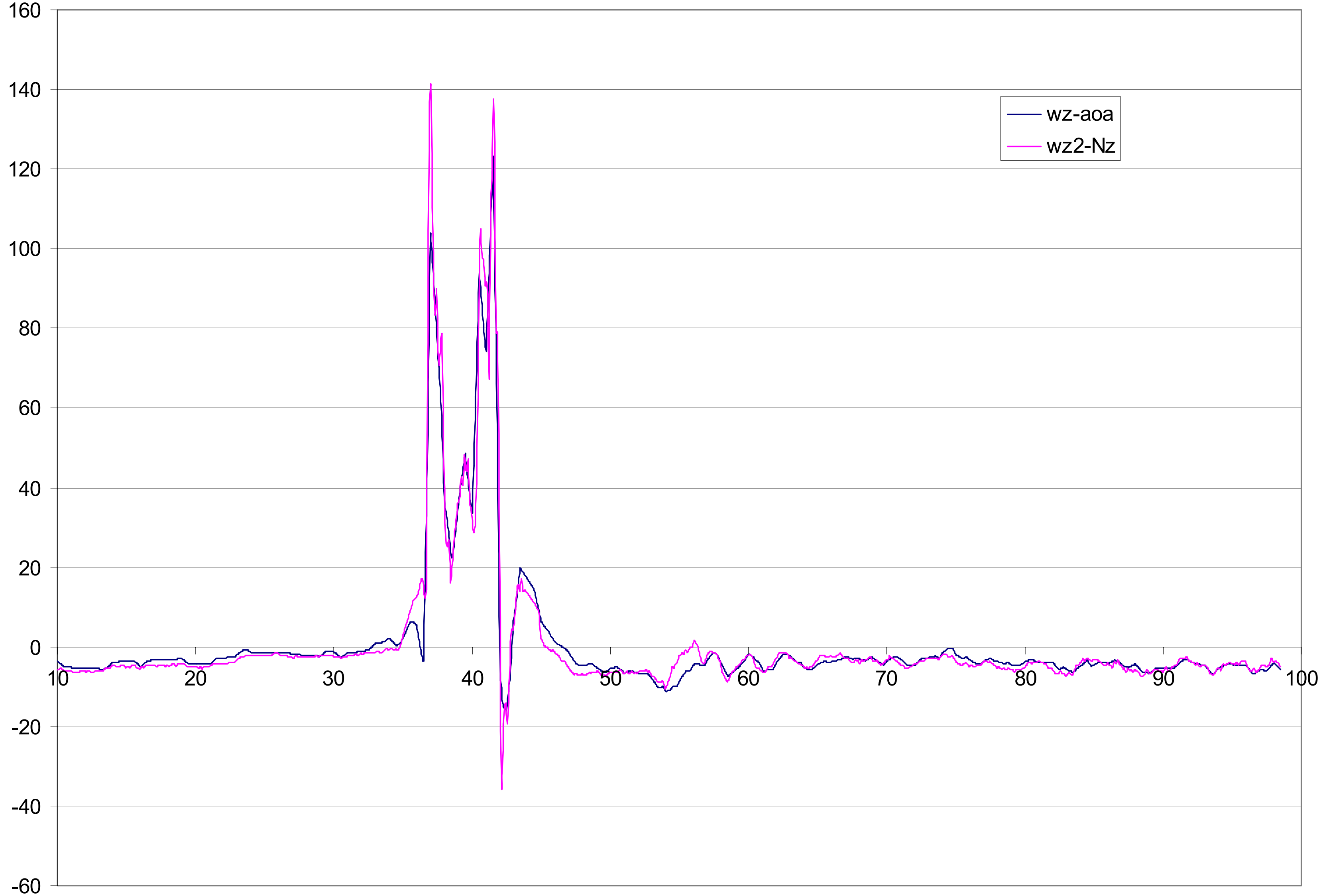
Analysis of Turbulence Accidents and Wind Field Determination (cont'd)

- FDR data can be used (sort of) to extract the wind field (Ref: Bach and Wingrove AIAA papers)
  - Alpha vane, Nz, θ, air data using kinematics only
  - Nz, θ, δe using aero characteristics from A/C model
- Peak velocities of over 140 ft/sec have been seen.
- Some time histories strongly suggest vortex encounters due to Kelvin-Helmholtz instabilities (shear layers from jet streams, thunderstorms, mountain waves).

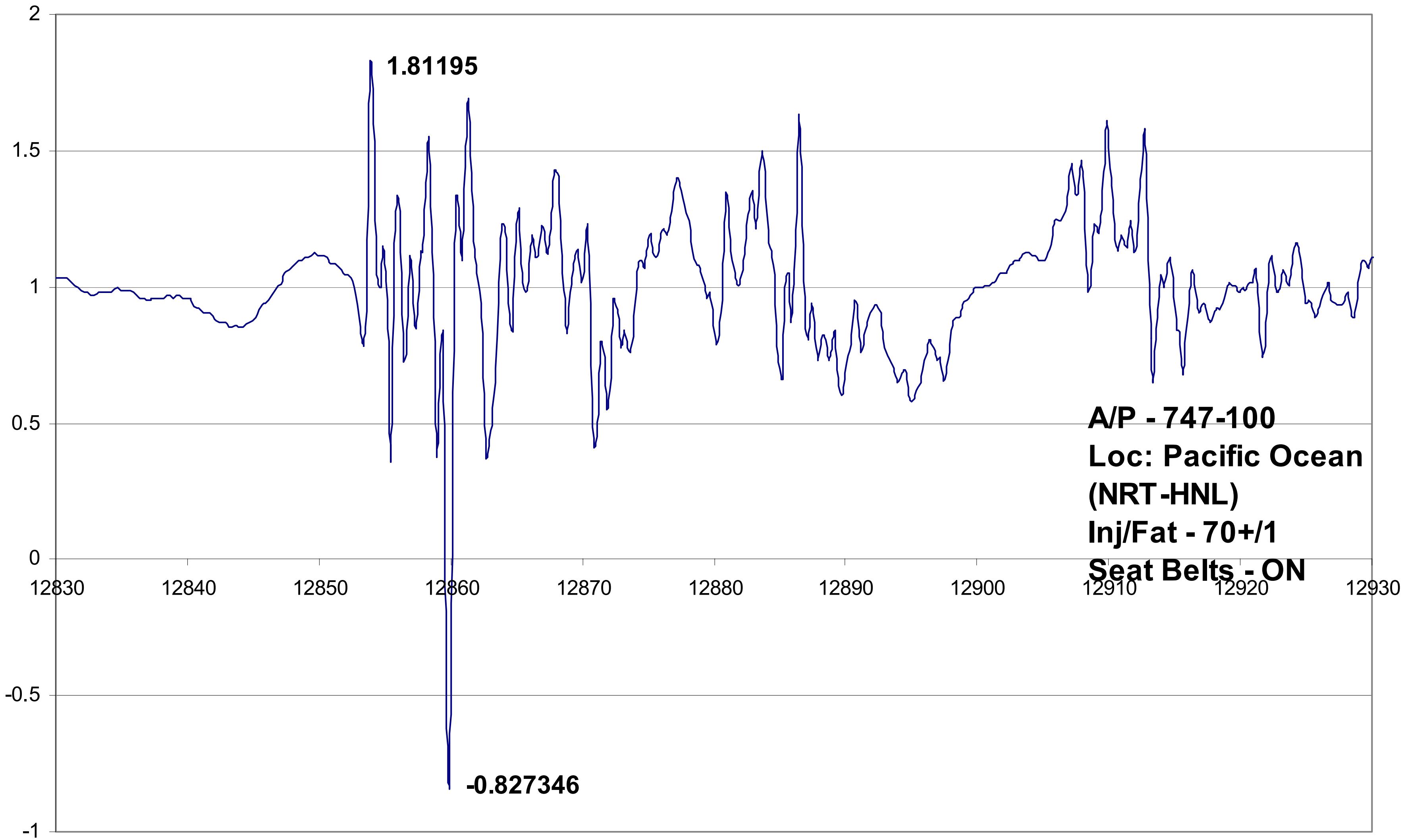
Case B-1 - Nz (c.g.)


1.99523
-0.744868
A/P - 757-200
Location: Boise
Inj/Fat: 22/0
Seat Belts: OFF
2
1.5
1
0.5
0
-0.5
-1
0
10
20
30
40
50
60
70
80
90
100

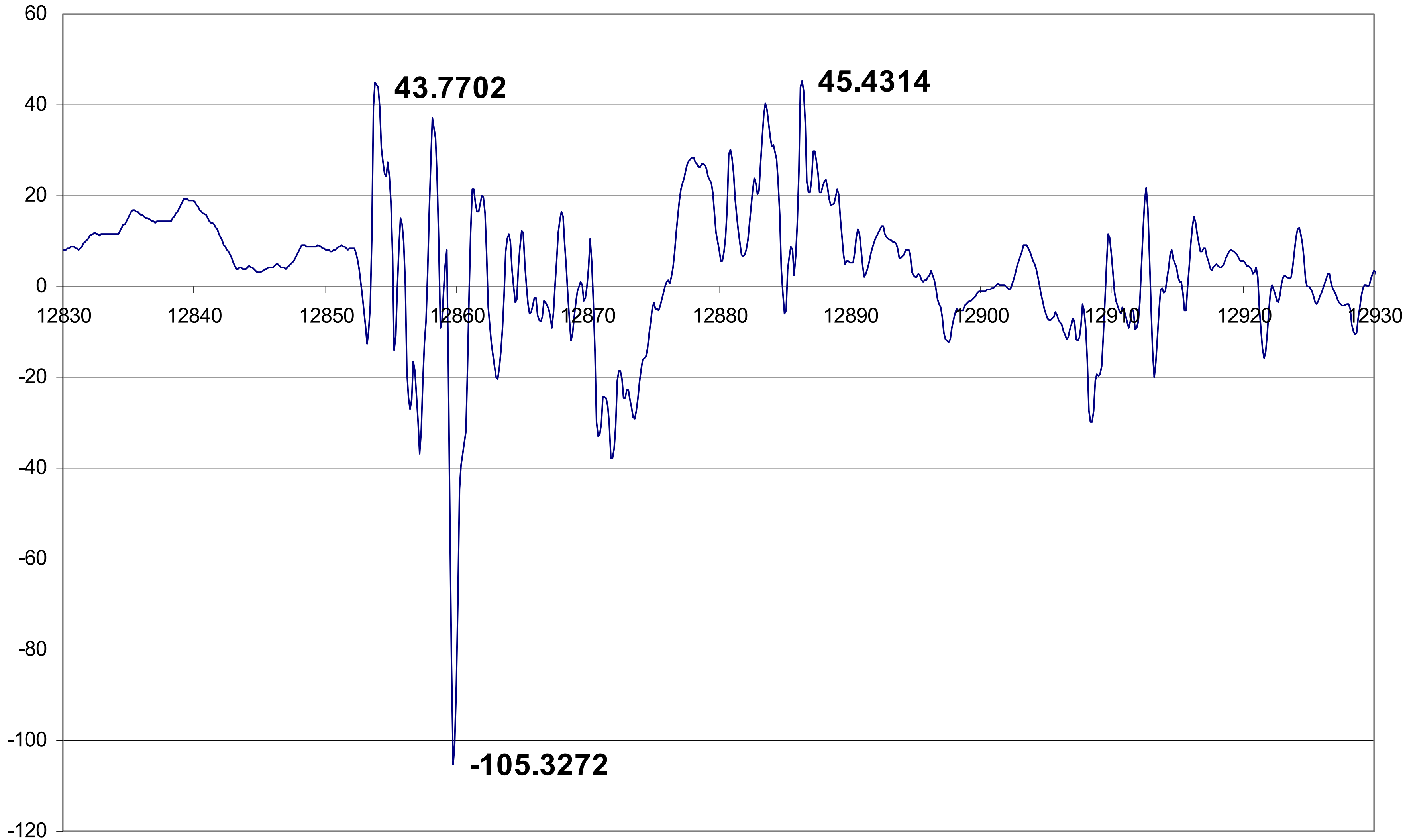
Case B-1 - Wz


160
140
120
100
80
60
40
20
0
-20
-40
-60
10
20
30
40
50
60
70
80
90
100
wz-aoa
wz2-Nz

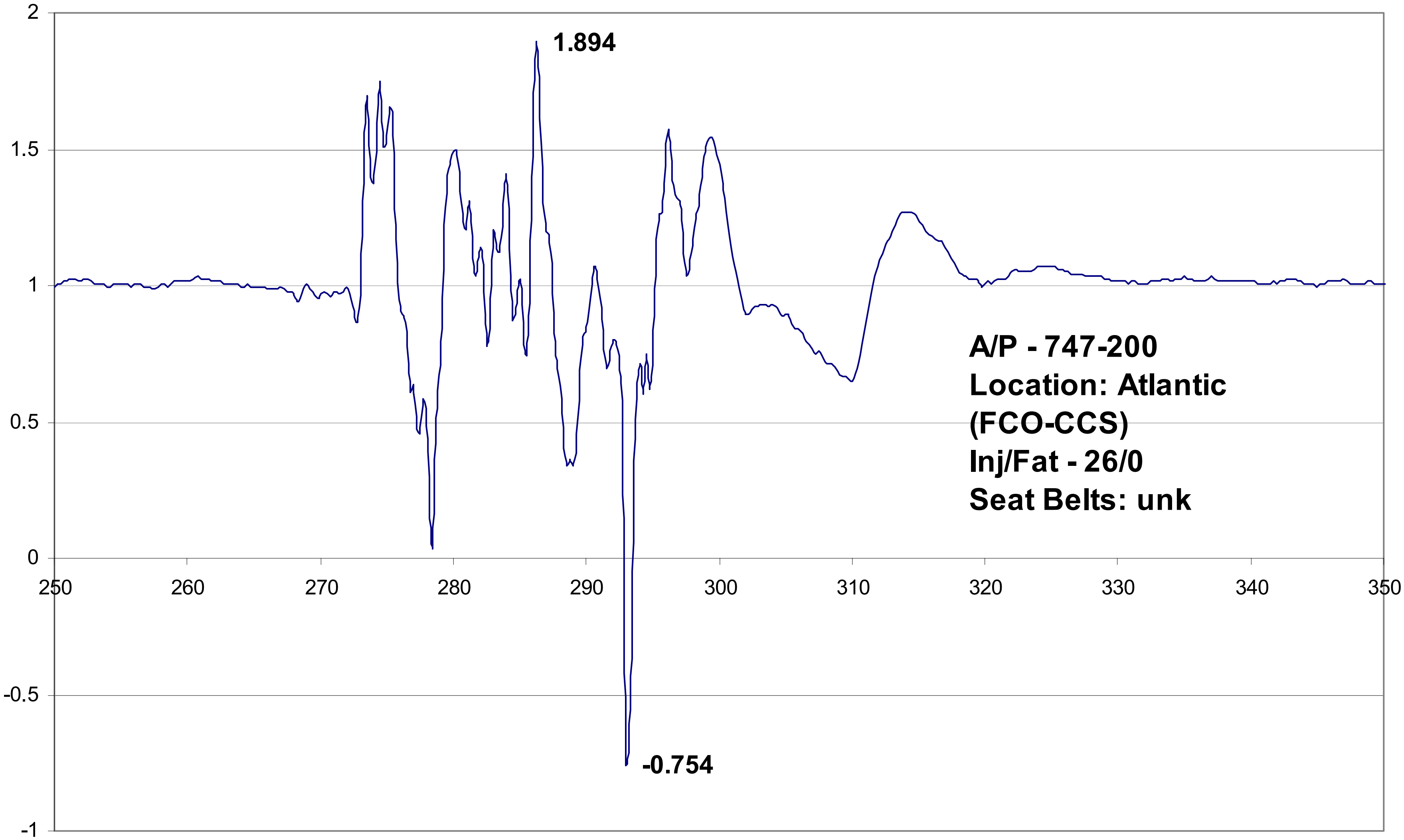
Case B-2 - Nz (c.g.)


2
1.5
1
0.5
0
-0.5
-1
12830
12840
12850
12860
12870
12880
12890
12900
12910
12920
12930
1.81195
-0.827346
A/P - 747-100
Loc: Pacific Ocean
(NRT-HNL)
Inj/Fat - 70+/1
Seat Belts - ON

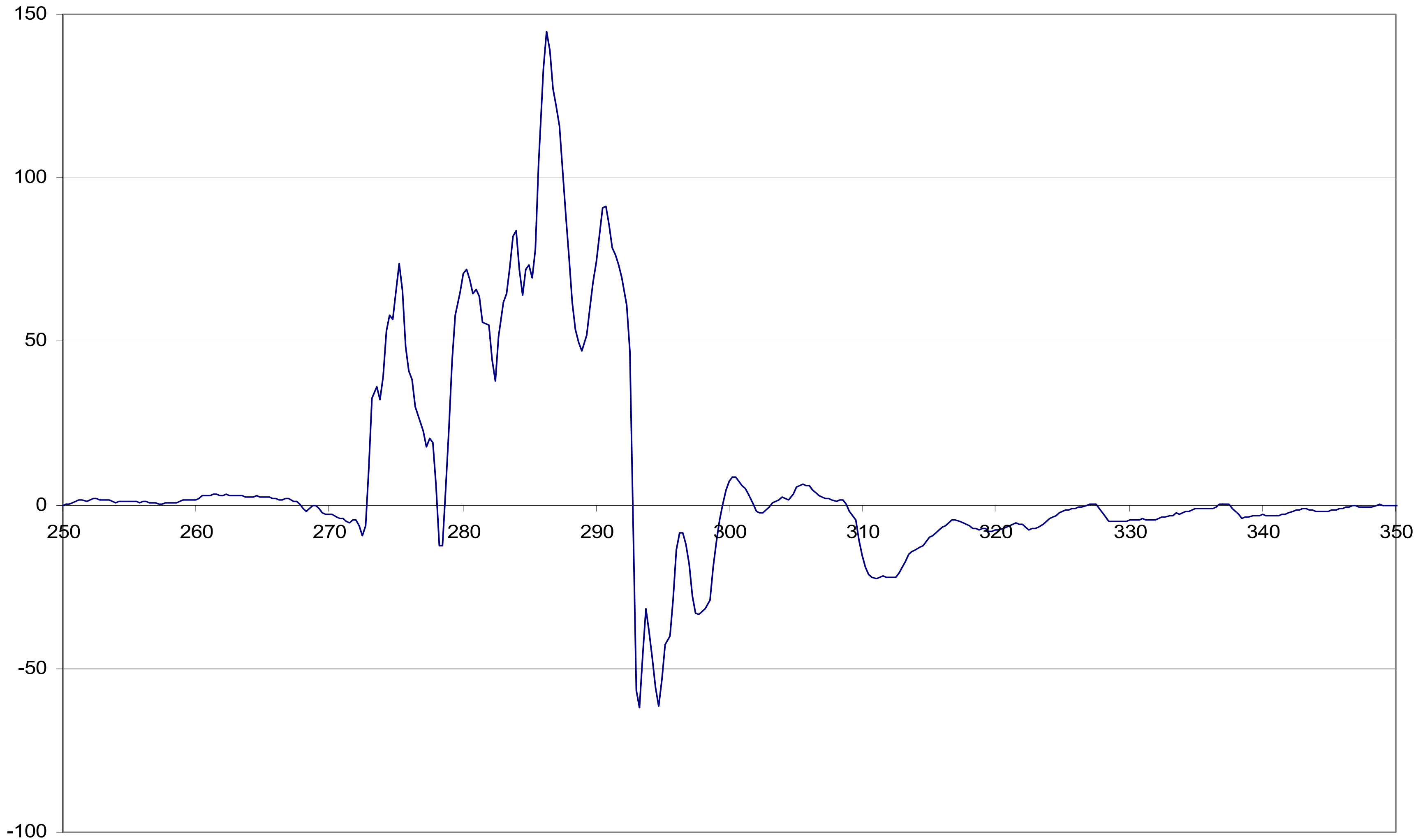
Case B-2 - Wz


43.7702
45.4314
-105.3272
60
40
20
0
-20
-40
-60
-80
-100
-120
12830
12840
12850
12860
12870
12880
12890
12900
12910
12920
12930

Case B-3 - Nz (c.g.)


2
1.5
1
0.5
0
-0.5
-1
250
260
270
280
290
300
310
320
330
340
350
1.894
-0.754
A/P - 747-200
Location: Atlantic
(FCO-CCS)
Inj/Fat - 26/0
Seat Belts: unk

Case B-3 - Wz



Current aircraft systems and requirements

- Turbulence Mitigation requires modification of the aircraft lift and pitching moment through:

- Direct lift control ; and / or
- Pitch Control

- Current non fly-by wire aircraft in the commercial fleet (737,747,757,767) have no direct lift control surfaces.

- For this study, pitch control alone has been used. Current elevator rate and deflection limits (with nonlinear limiting) have been used to set requirements.

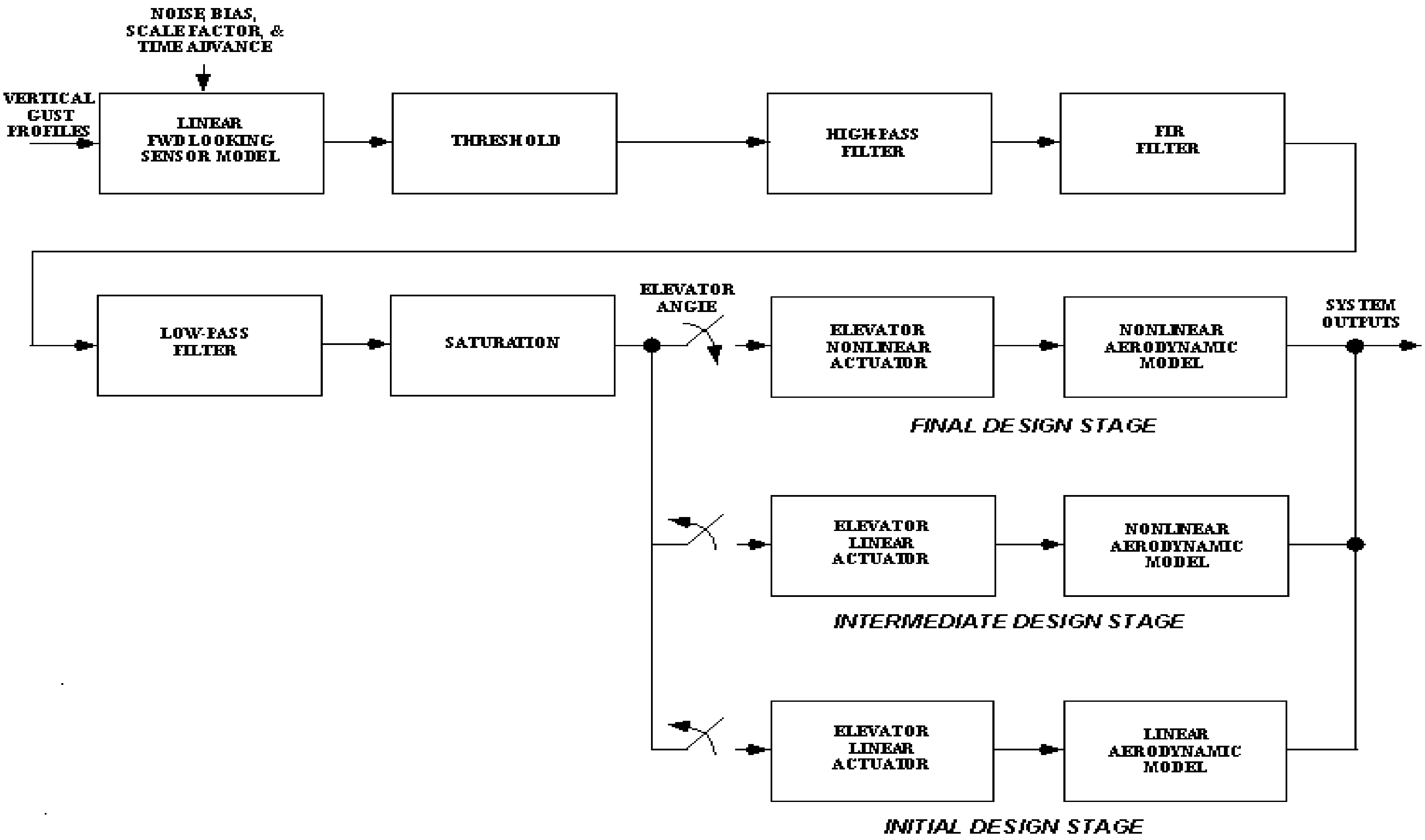
- Current autopilot modes do not effectively counteract severe turbulence.

- Autopilot actuator capabilities may be inadequate to provide mitigation.

Control System Development and Performance

Study Assumptions:

- Nonlinear aircraft model (757-200) with existing nonlinear actuators
- Knowledge of the vertical gust profile ahead of the aircraft
- Quasi-static elastic aircraft (no flexible mode dynamics)
- Feed-forward controller design to avoid stability issues
- Control law parameters varied for optimal performance
- Direct input to control actuator (not currently available)



CONTROL SYSTEM DESIGN MODEL

Sensitivity Studies

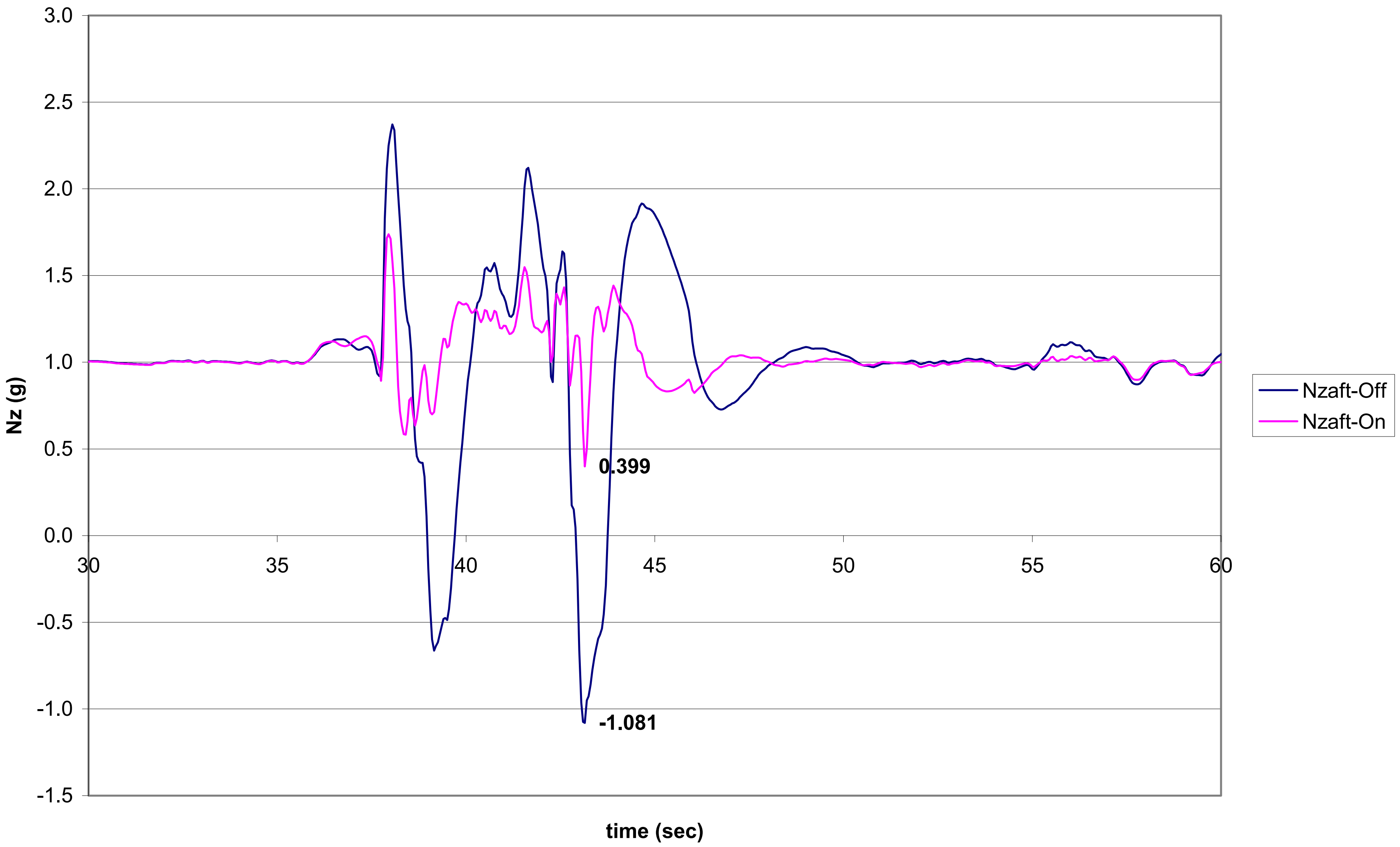
Turbulence input sensitivity

- 13 Time histories used as input to 757-200 nonlinear simulation model, control performance assessed
  - 5 NTSB Cases
  - 3 Boeing Cases
  - 5 Vortex Cases

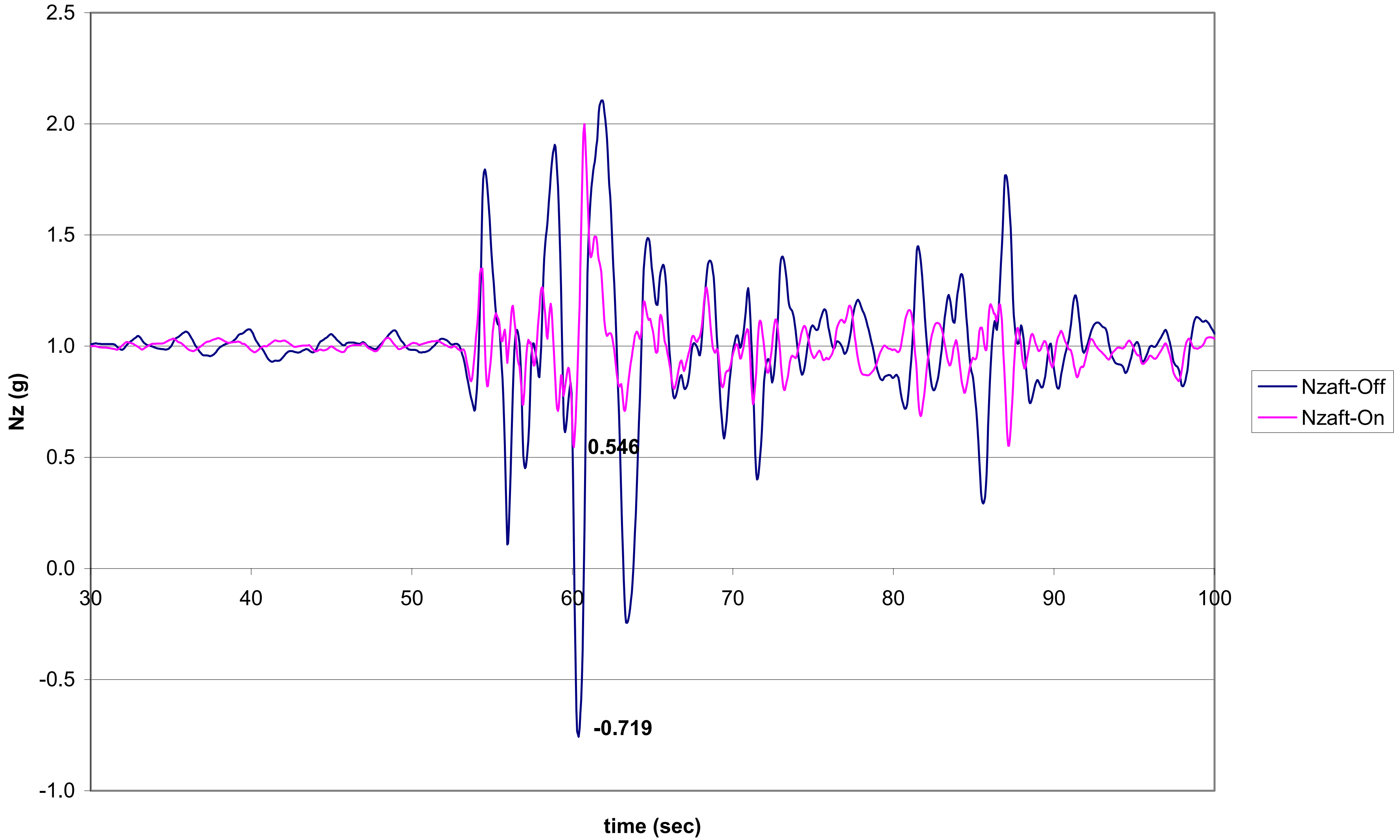
Sensor sensitivity

- Forward looking sensor compared with nose air data sensor for one case

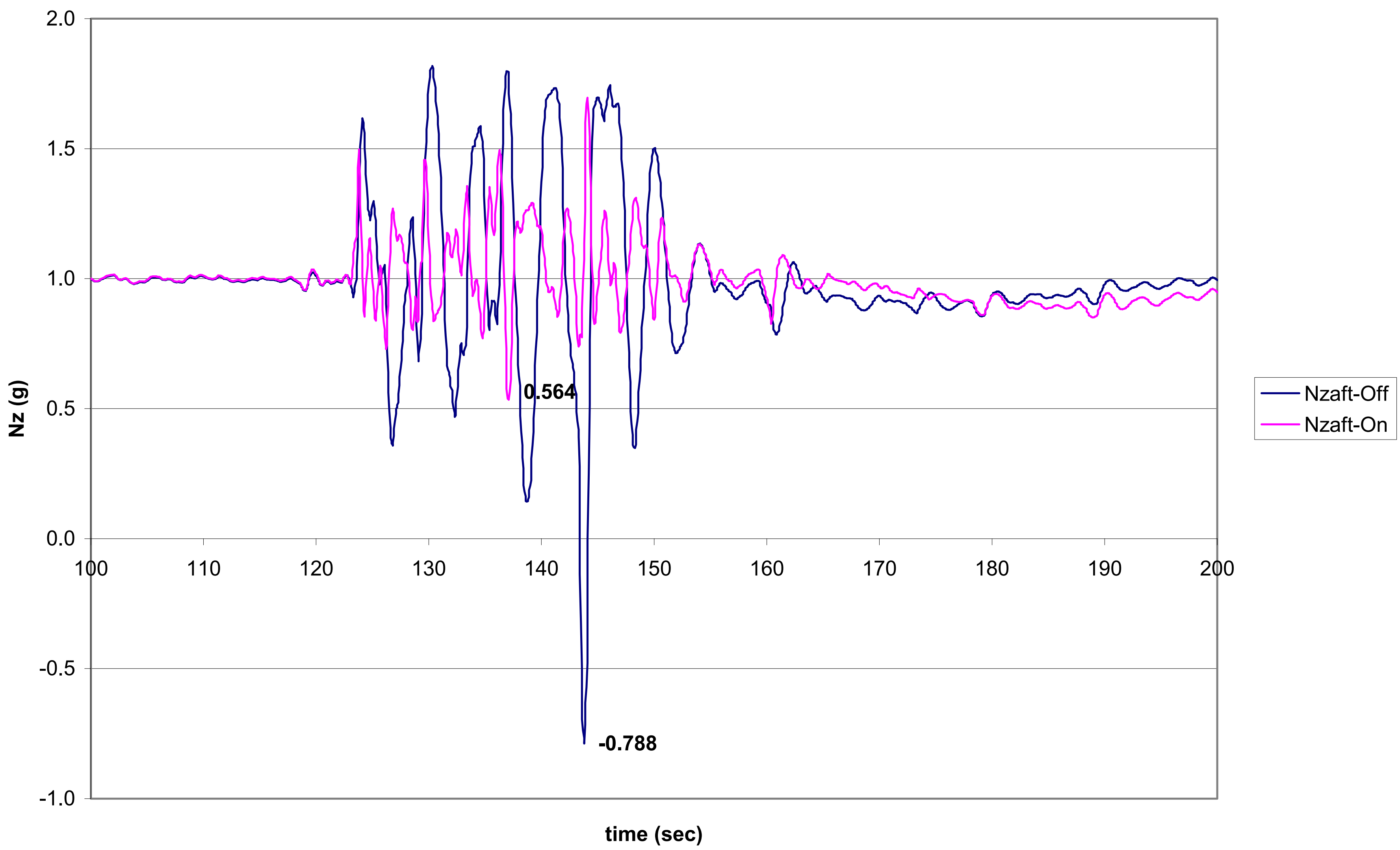
Case B-1 Nz-aft System Off vs On



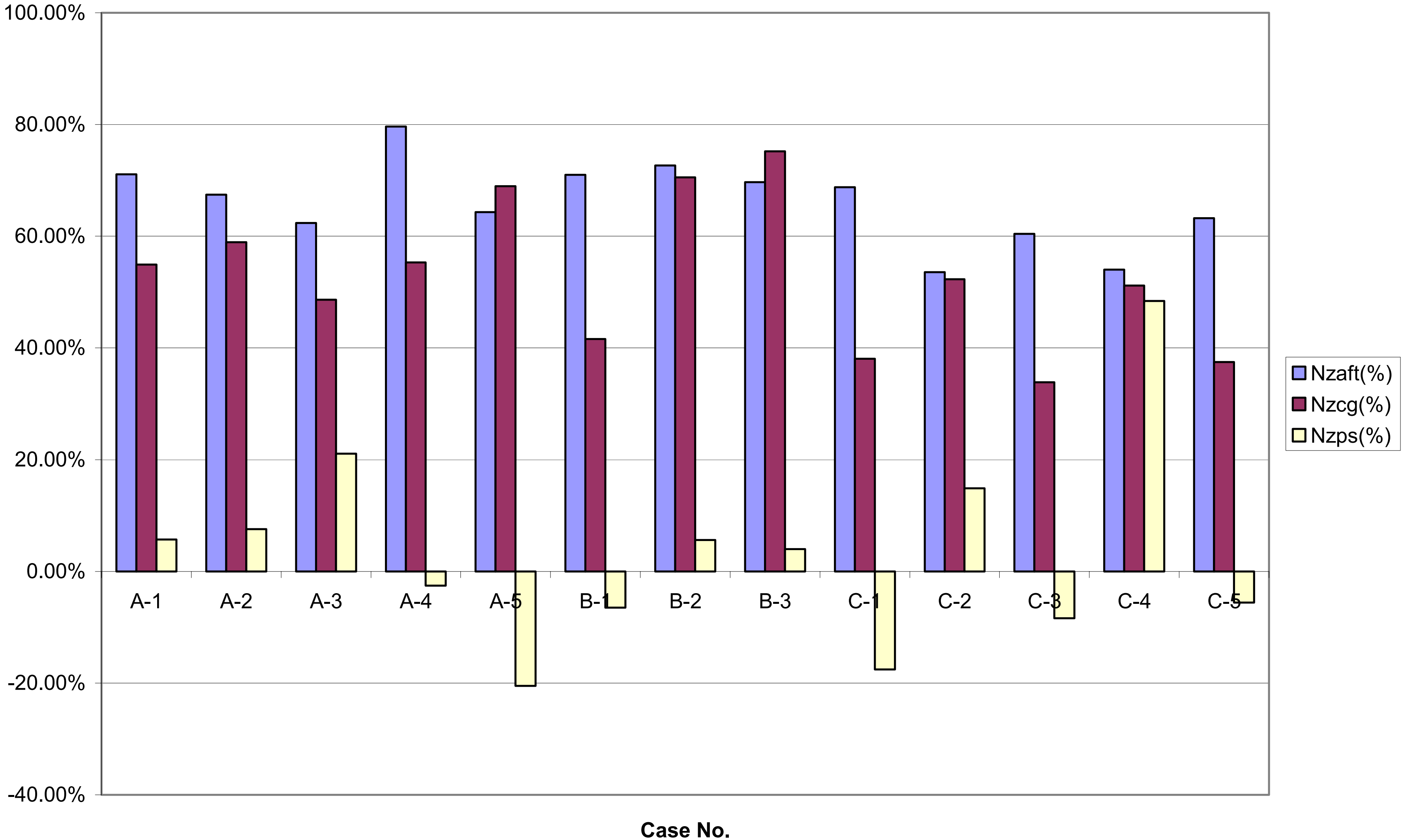
Case B-2 Nz-aft System Off vs On



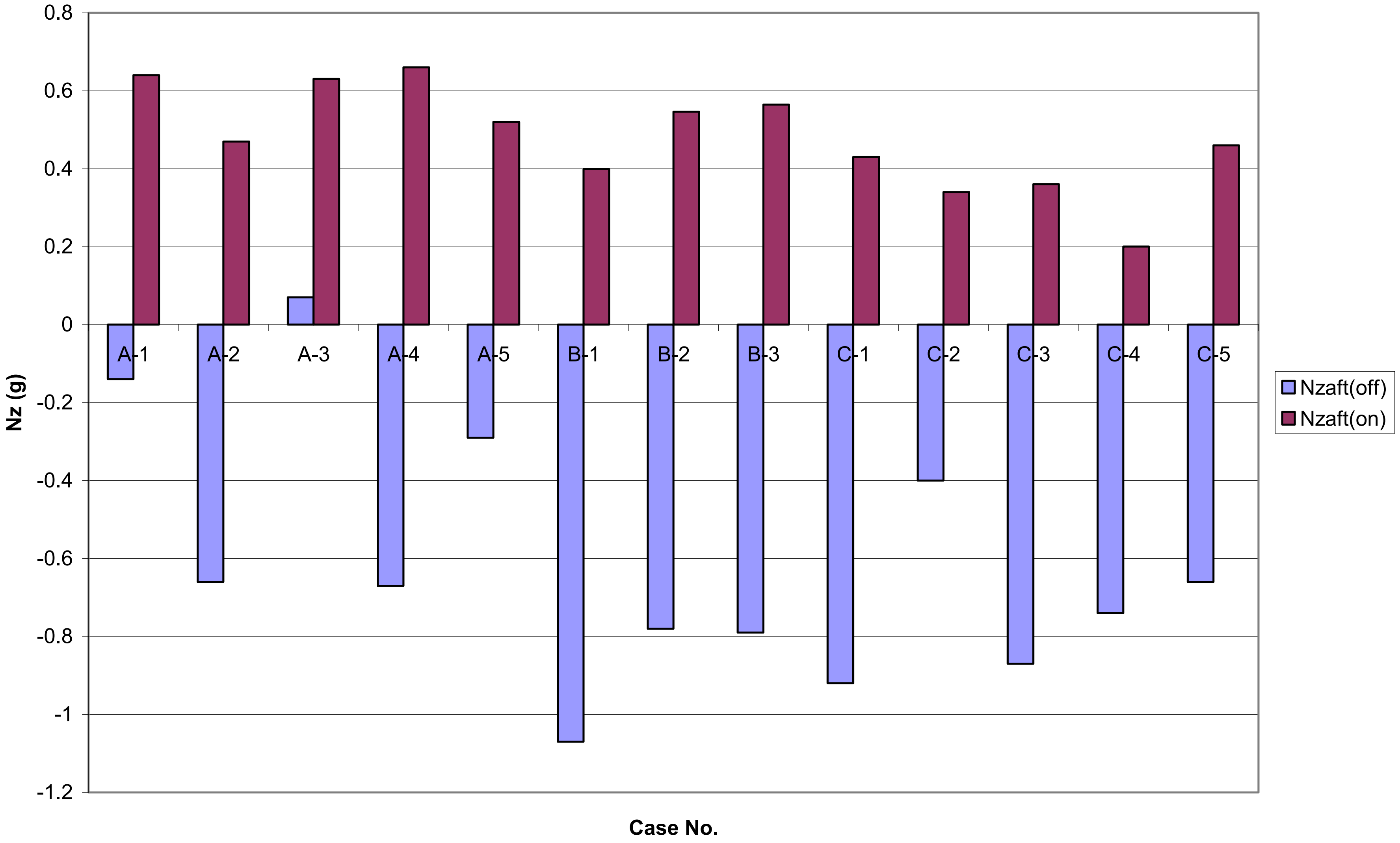
Case B-3 Nz-aft System Off vs On



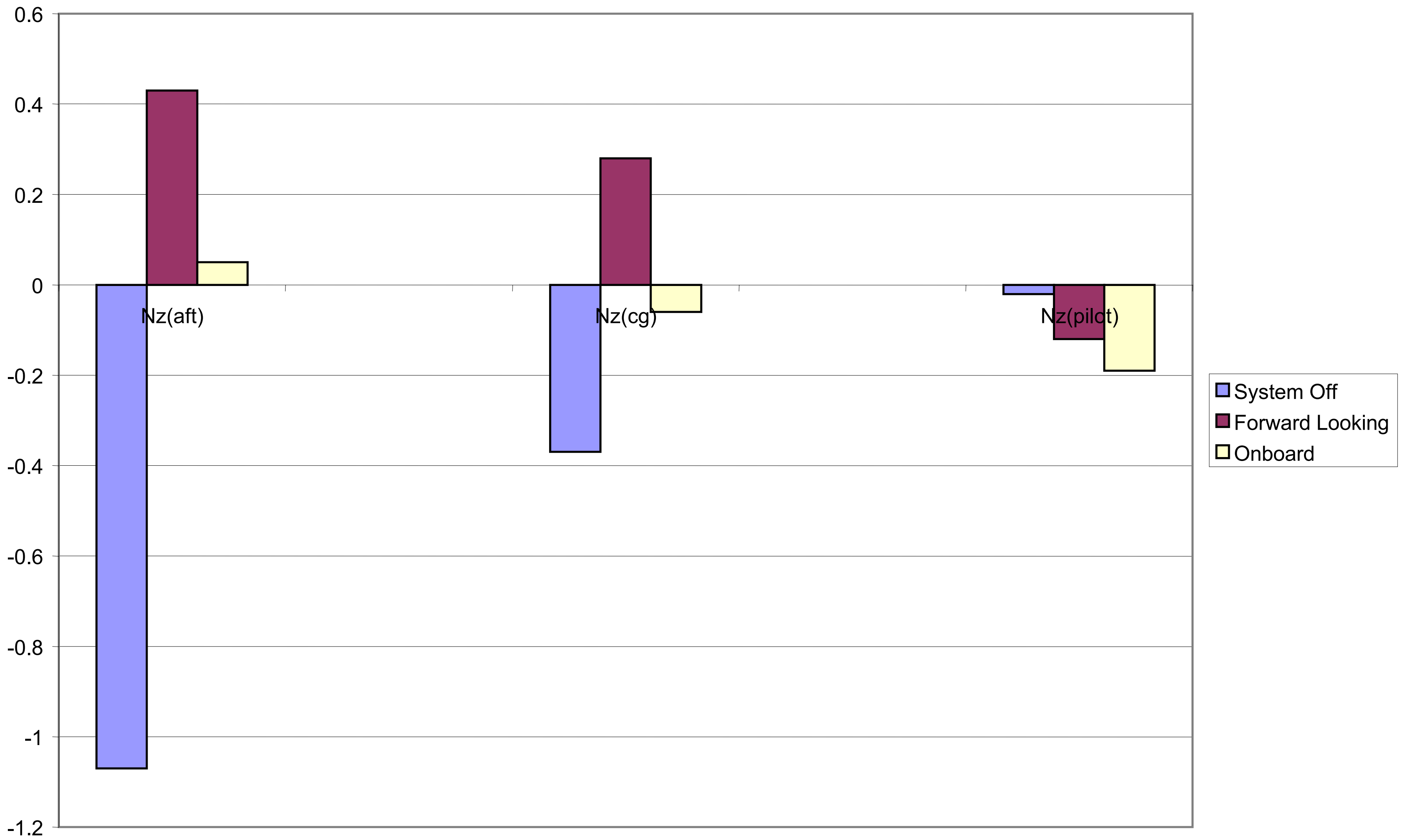
Percent Peak Negative Nz Reduction (1.1sec look ahead)



Aft Cabin Peak Negative Acceleration - System Off vs On



Forward Looking vs. Nose Air Data - System Off vs. On



Issues for Further Study

Aerodynamic Modeling Issues

- Nonlinear simulation data has limited negative angle of attack range
- Unsteady aerodynamics – angle of attack, control, gust lag functions
- Gradual gust penetration – wing sweep, wing to tail lag
- Stall Hysteresis – simulation is quasi-steady

Structural Modeling

- Dynamic Aeroservoelastic Model required for loads and flutter evaluation

Actuator Modeling

- "Physical model" required in place of "functional model"

Air Data System Modeling

- Need accurate measure of the "lead" for onboard air data

Issues (Cont'd)

Lidar Modeling and Accuracy

- Current simulation assumes "perfect" measurement of vertical gust velocity
- Lidar requires multiple off-axis measurements with spatial and temporal interpolation which will affect accuracy
- Additional errors such as bias and noise will affect accuracy
- Signal processing lags should be included
- Base motion "jitter" can be determined from structural dynamic model, isolation and/or motion compensation should be included

Multiple Flight Condition Modeling

- All simulation to date on single aircraft model at single flight condition. Effects of variations in altitude, Mach, gross weight, c.g. should be determined

Issues (Cont'd)

Autopilot / Manual Control Input Effects

- Current simulation models have no autopilot
- Need autopilot model to separate autopilot and manual inputs
- Need to assess whether autopilot and manual inputs make situation better or worse
- What is the effect of warning time on the pilot's reaction?
- What is the effect of various gust profiles on the pilot's reaction?
- How does the pilot react in the presence of a turbulence mitigation system?
- What do we show the pilot?
- These should be answered by a real-time simulation study.

Issues (Cont'd)

Control System Development Issues

- Redundancy Management
- Control Augmentation (SAS)
- Multiple Sensor Control
- Line of Sight Command for Maneuvering Aircraft
- Ride Quality vs Safety Requirements
- Gust Spectral Content Filtering
- Alternate Control Law Development Schemes
- New PCU Input vs Existing Autopilot Actuators (Autoland Mode)
- Direct Lift Control

Recommendations for Further Work

Continue Modeling Improvements (aerodynamic, structural, sensor, control)

Evaluate Structural Load and Autopilot Effects

Continue Control Development Studies

Select Candidate Aircraft for Demonstration

Determine Forward Looking Sensor Accuracy by Flight Test

Perform Real-Time Simulation

Design and Installation of Required Aircraft System Modifications

- Sensors
- Computer
- Actuators

Flight Demonstration