The Increased-Order Modeling Approach to Nonlinear Aeroelasticity

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Background

- Most common aeroelastic analysis and design tools in the aeronautical industry are linear.
- Introduction of nonlinear effects is usually based on ad-hoc, problem-dependent formulation and simulation processes.
- Nonlinear high-fidelity models are often inefficient and are not naturally integrated in industrial design processes.
- Reduced-order modeling (ROM) approaches that start from the high-fidelity models may provide adequate solutions but they might:
    - hard to be related to linear results
    - hard to be integrated in existing design processes
    - not exhibit the required conservatism for certification
    - not well accepted by engineers.

The Increased-Order-Modeling (IOM) Approach

- Start with common linear models.
- Identify phenomena of potentially important nonlinear effects.
- Formulate the problem based on a main linear block and nonlinear wrapped-around correction feedback loops.
- Add corrections that adequately represent the key nonlinear effects.
- Perform simulations in a way that takes advantage of this formulation.
- Verify/update the models by comparisons with selected tests and/or high-fidelity solutions of rigid and elastic vehicles.

IOM Framework for nonlinear aeroservoelastic simulations

- IOM research at Technion resulted in three software packages for various IOM applications:

  - Matlab/Simulink R&D code with
    - Time-domain (TD) linear aeroelastic model based on rational-function approximations.
    - Nonlinear feedback elements.

  - FORTRAN (industrial application) and Matlab (R&D) codes with:
    - Frequency-domain (FD) linear aeroelastic model
    - FFT/IFFT between FD and TD
    - Nonlinear TD elements and feedback by convolution integrals

Initial Motivation: Dynamic Loads with Nonlinear Control

- A400M is a military cargo aircraft currently in flight tests.
- Dynamic gust, maneuver and ground loads, calculated by Airbus Military (formerly EADS-CASA), provide critical design cases.
- Symmetrically actuated ailerons and wide-band actuators facilitate maneuver and gust loads alleviation.
- Control limits, activation zones and operation logics introduce important nonlinear effects.
- The DYNRESP code was designed to account for these nonlinearities based on the IOM approach.

Max. Payload = 32 tonnes @ 2.25g

Range @ Max. Payload = 2580nm

Cruise Speed Range (M = Mach No.) = 0.68 - 0.72 M

Overall Dimensions
Length = 42.2 Metres
Height = 14.7 Metres
Span = 42.4 Metres

DYNRESP Main Objectives

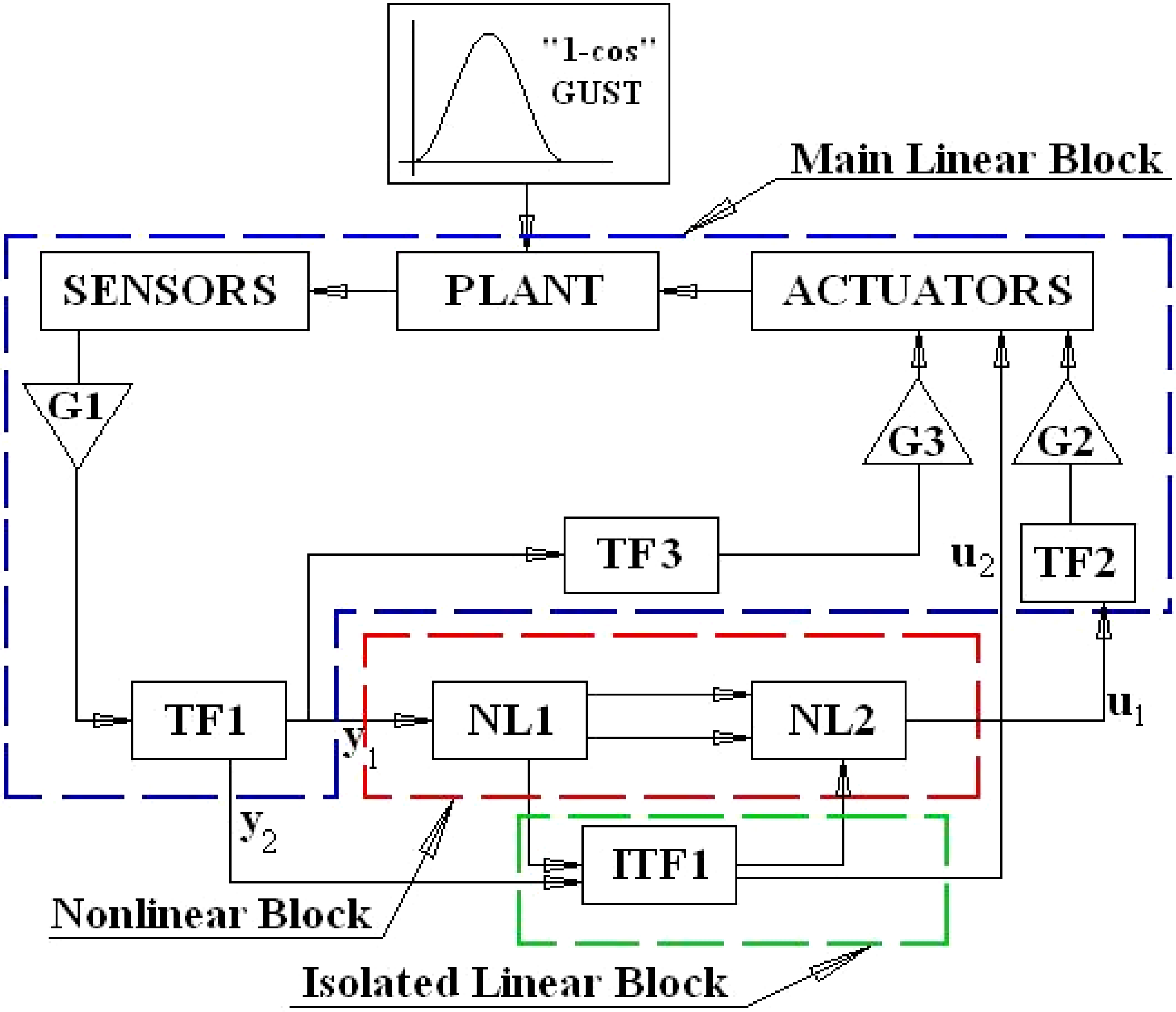
- Coverage of all aspects of aircraft dynamic loads analysis
- Efficient massive computations in industrial environment
- Robustness
- Advanced analysis capabilities and functionality
- Flexibility is adding new features and non-linear effects
- Use data from commonly used structural, multi-body, aerodynamic and control software packages.
- Compatibility with typical in-house loads codes.
- Applicability with a variety of computational platforms.

Dynamic Response and Loads Disciplines

- Modal and control-surface response to:
  - deterministic gusts
  - pilot commands
  - direct forces.
- Response simulations are used in subsequent calculations of

Short-signal loads:	Long-signal loads:
– discrete gusts	- continuous gust
– maneuvers	- actuator oscillatory failure
– store ejection	- taxi
– blade/nacelle imbalance	- ground structure-control coupling tests
– landing	

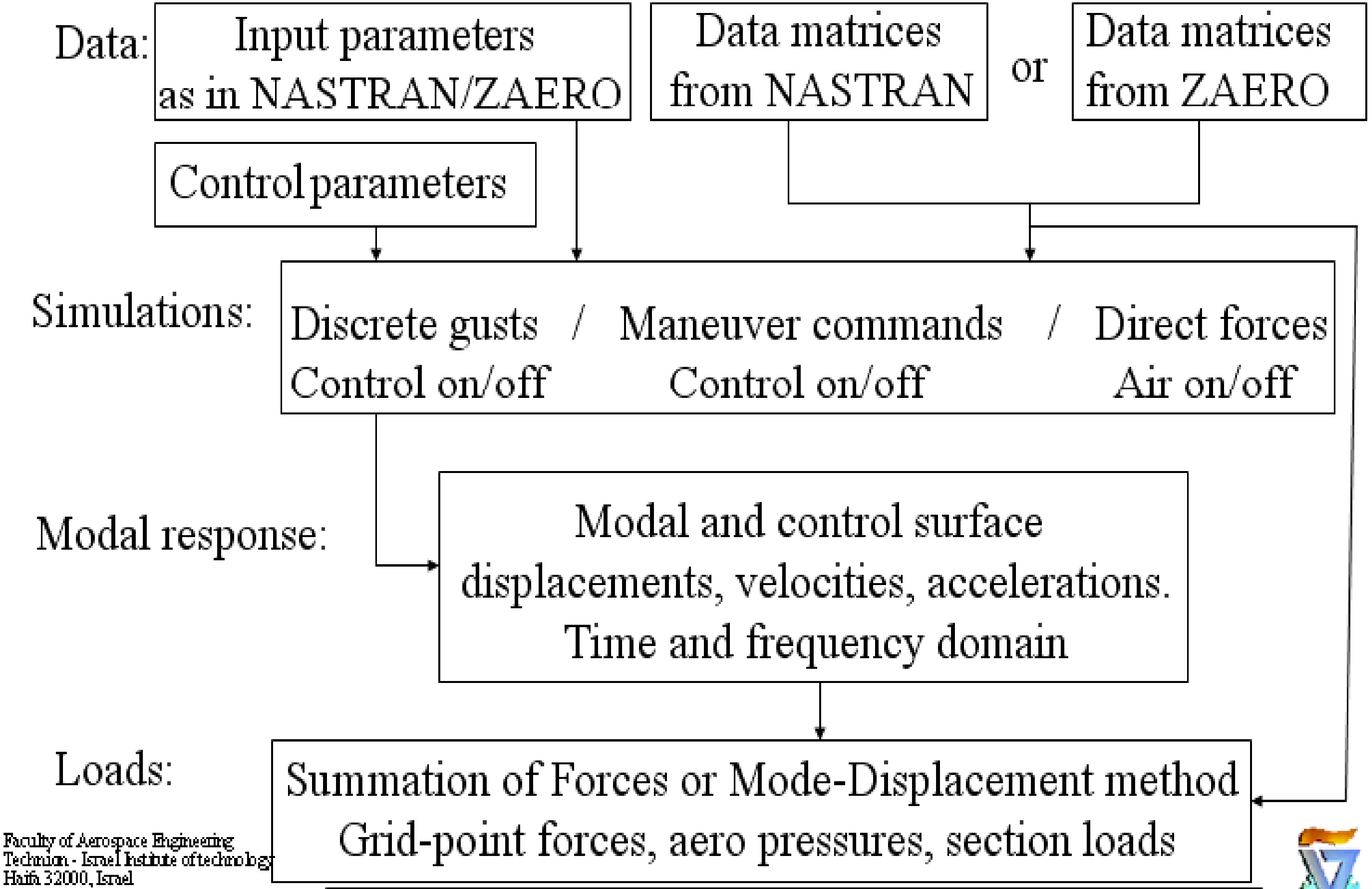
Sample Model Architecture for Discrete Gust Response



Basic Formulation of the Main Linear Block

- Second-order frequency-domain equations of motion.
- FFT/IFFT techniques for FD-TD conversions.
- Treatment of zero-frequency singularities by enforcement of initial conditions.
- Segmentation of long excitation signals.
- Unified implementation to all loads disciplines.
- Most general control system architecture.
- Control commands through actuators and by direct forces.

DYNRESP General Flow Chart



Data:

Input parameters as in NASTRAN/ZAERO

Data matrices from NASTRAN

or

Data matrices from ZAERO

Control parameters

Simulations:

Discrete gusts / Maneuver commands / Direct forces

Control on/off Control on/off Air on/off

Modal response:

Modal and control surface displacements, velocities, accelerations.

Time and frequency domain

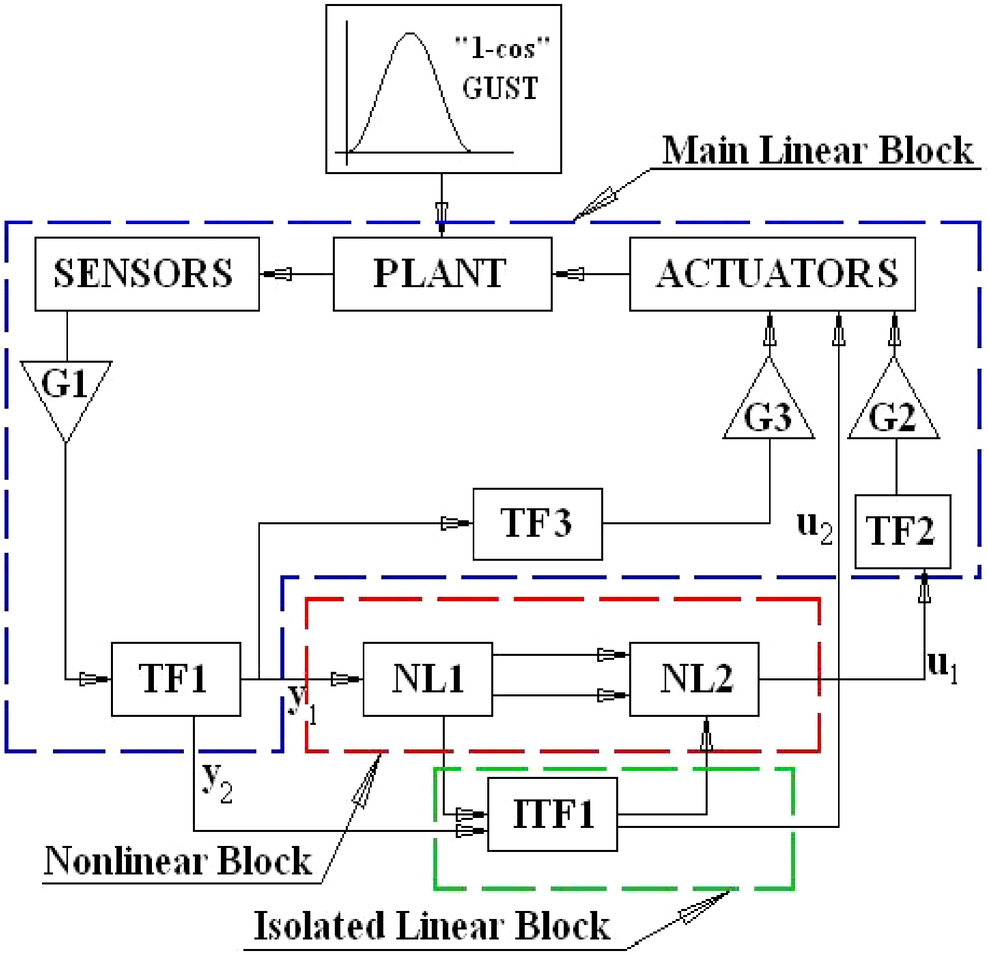
Loads:

Summation of Forces or Mode-Displacement method

Grid-point forces, aero pressures, section loads

Time Simulation with Nonlinear Control

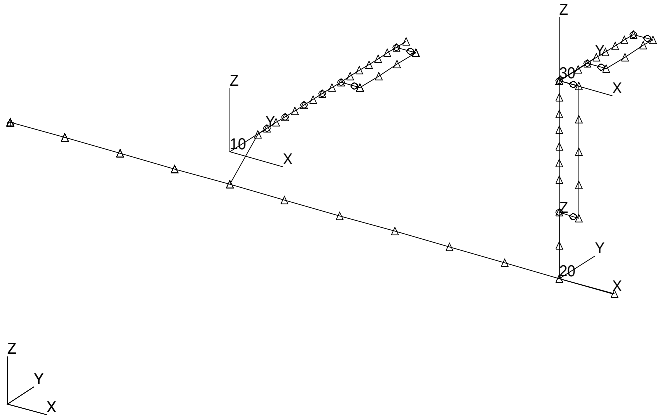
- Stage 1: FD response of the main linear block to sinusoidal excitations and control commands with the nonlinear block disconnected.
- Stage 2: TD response of the linear block to gust and to unit impulses from the nonlinear block using FFT techniques.
- Stage 3: Adding nonlinear effects based on nonlinear models and convolution with impulse responses.

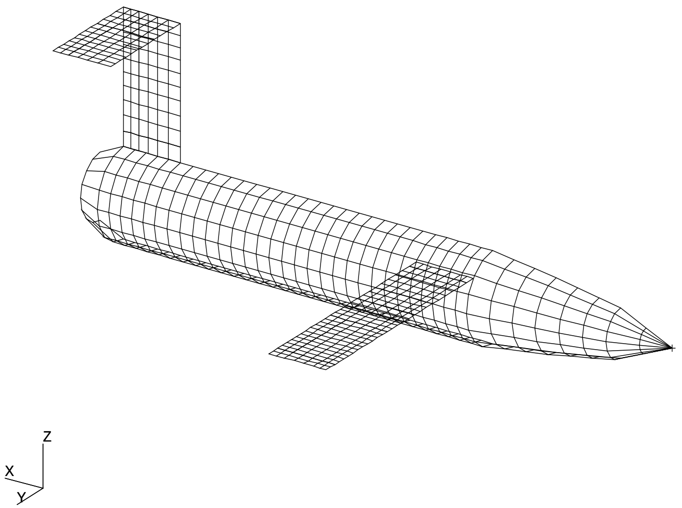


Case 1: Gust loads on Generic Transport Aircraft (GTA) model with nonlinear control

with H. Climent and C. Maderuelo and L. Anguita of Airbus Military

- Structural and aerodynamic models

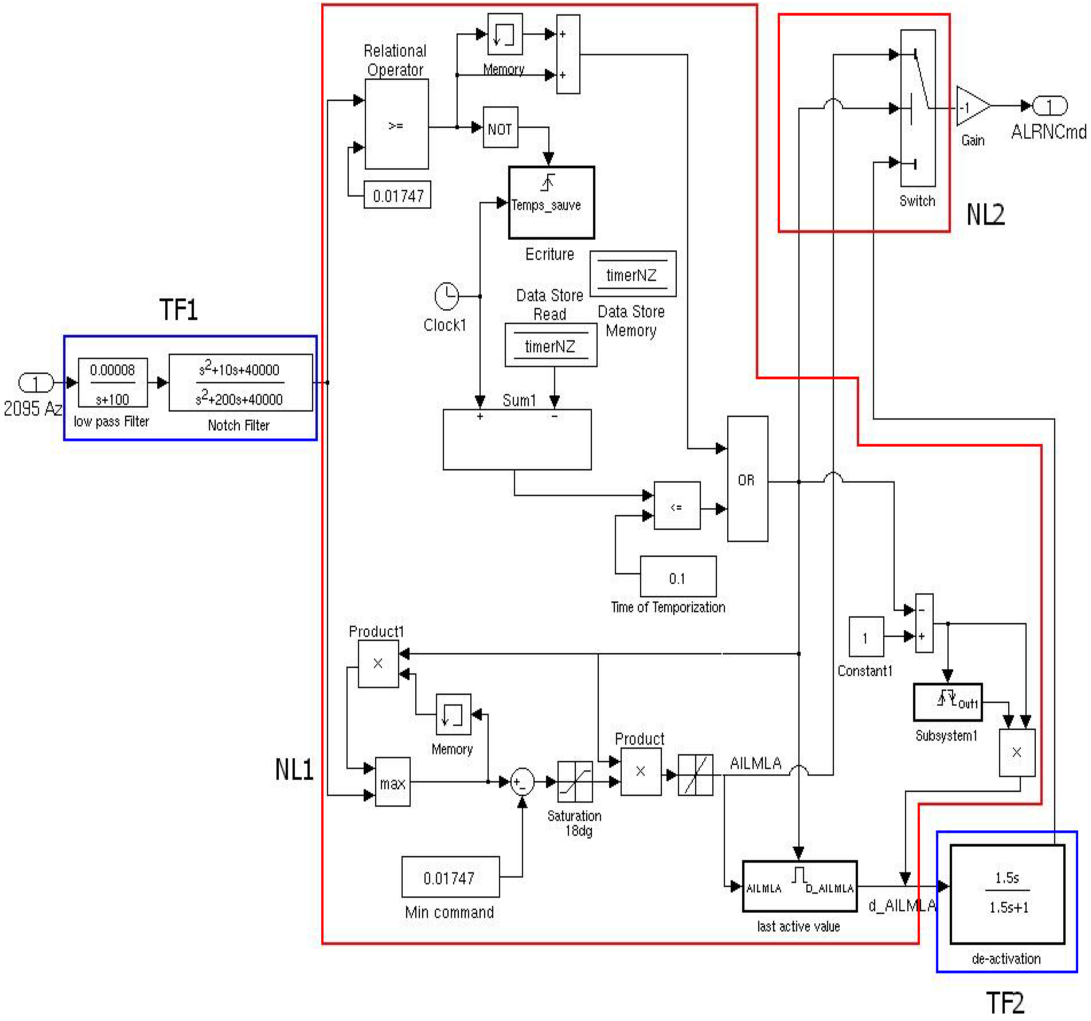




- 11 symmetric model up to 45 Hz.
- Control system: symmetrically activated ailerons based on accelerometer near CG

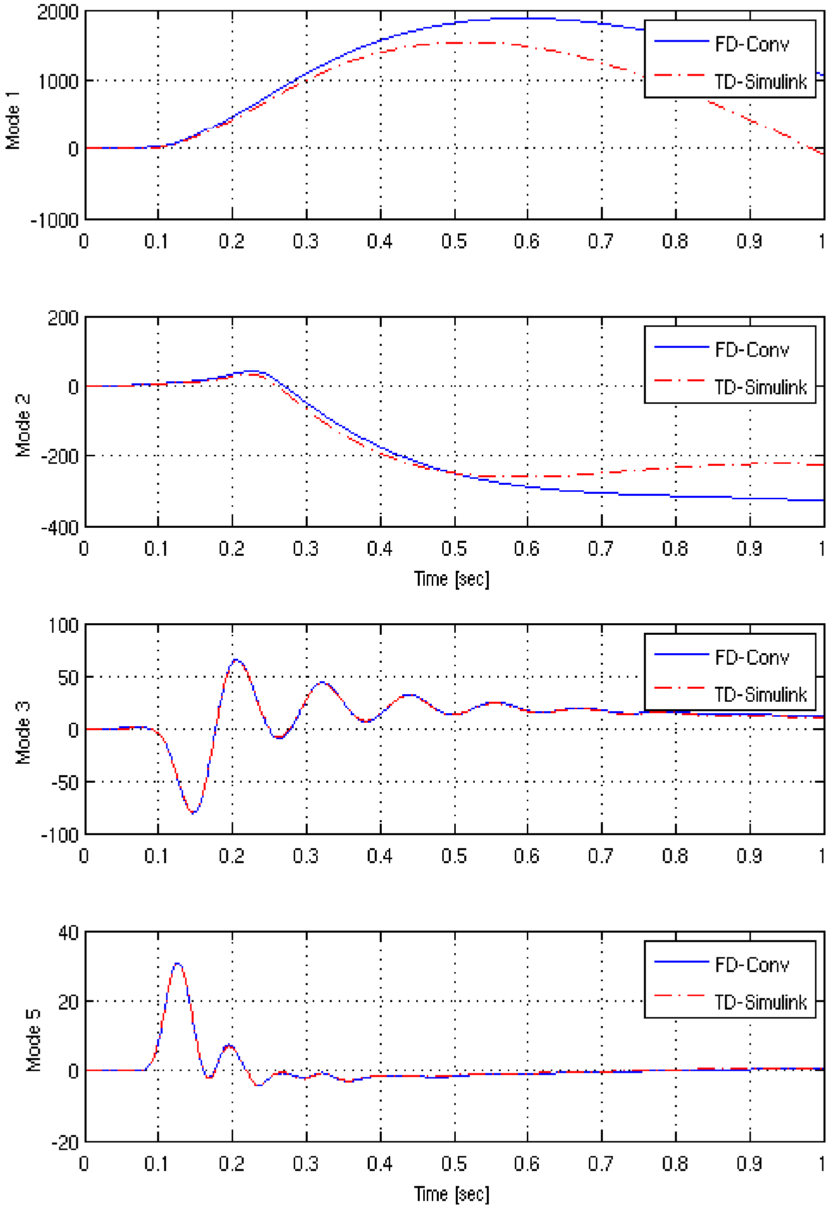
Nonlinear control system

- TF1: basic linear control law
- NL1: Cluster of nonlinear elements. Main features:
  - limit the deflections and rates
  - hold peak deflections
  - minimal deflection 1^o
- TF2: enforces slow decay
- NL2: selection switch

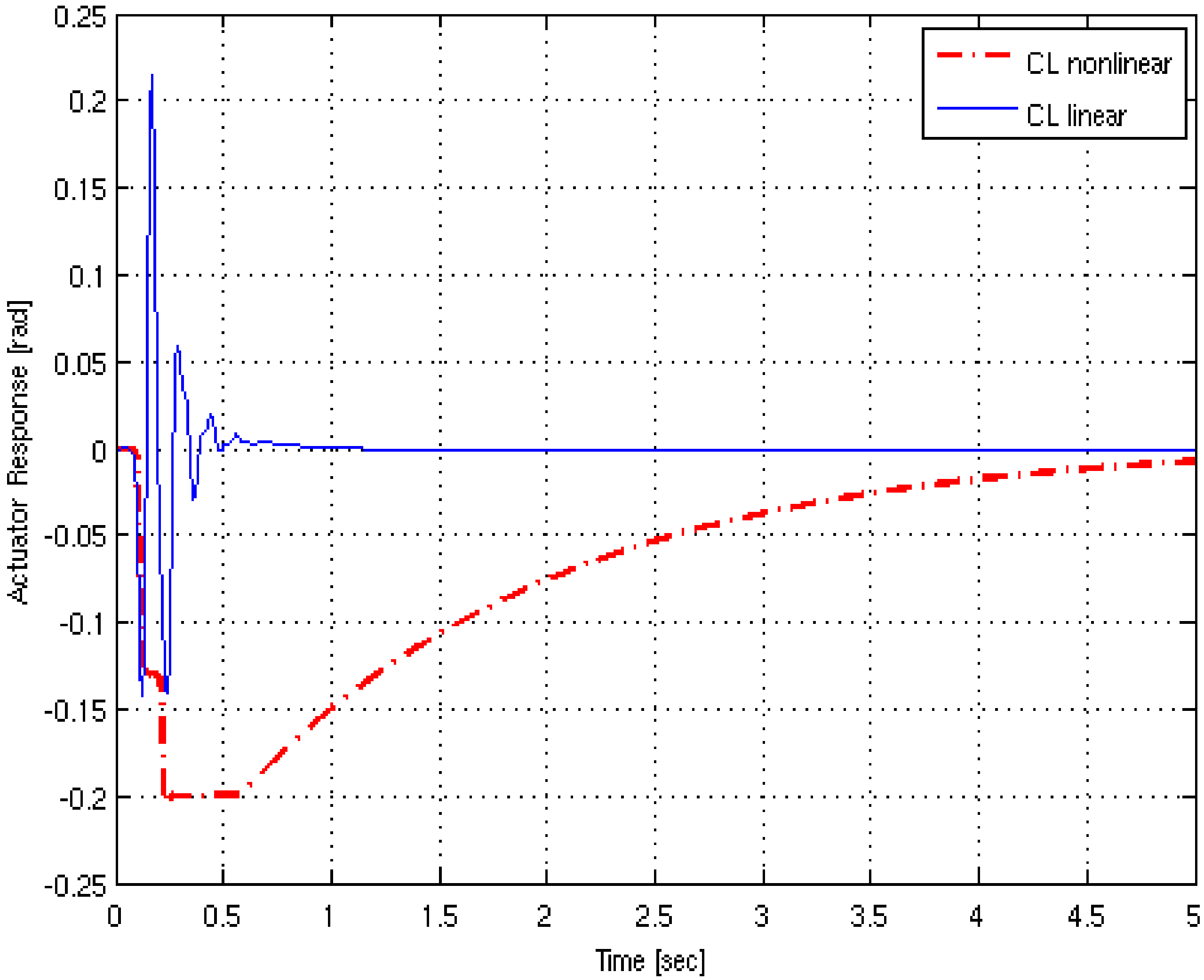


Modal response

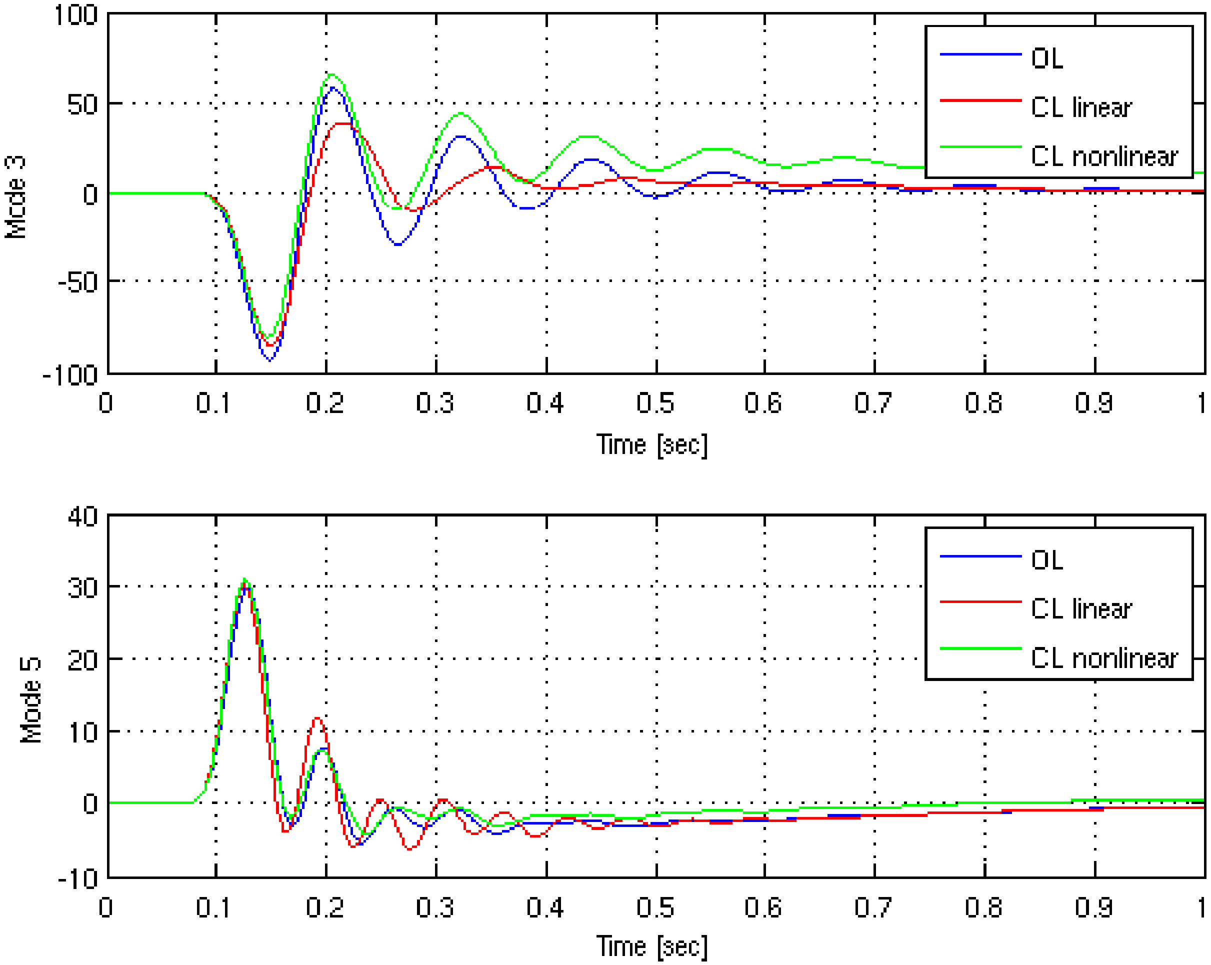
- FD-convolution vs. TD-Simulink
- FD signals return to zero at *T*=8.192 *sec*
- Differences in rigid-body response (Modes 1 , 2) do not affect loads.
- Elastic responses practically identical.



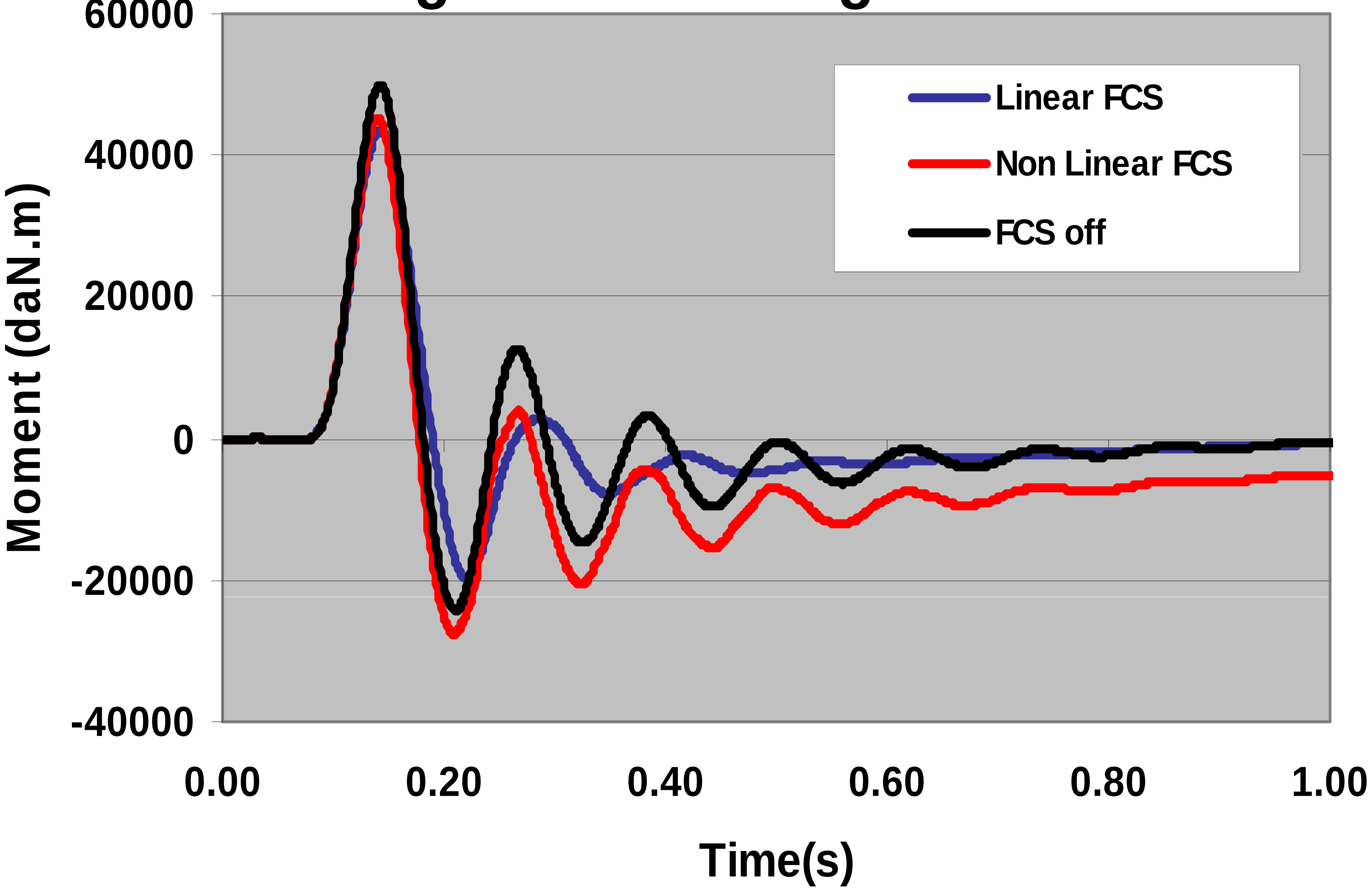
Actuator response, linear and nonlinear FCS



Modal response in the open- and closed-loop cases



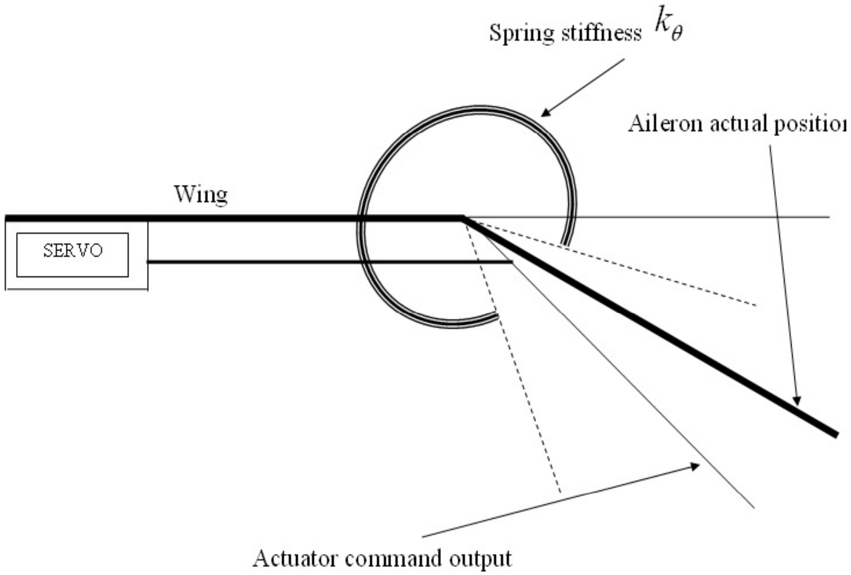
Wing Root- Bending Moment

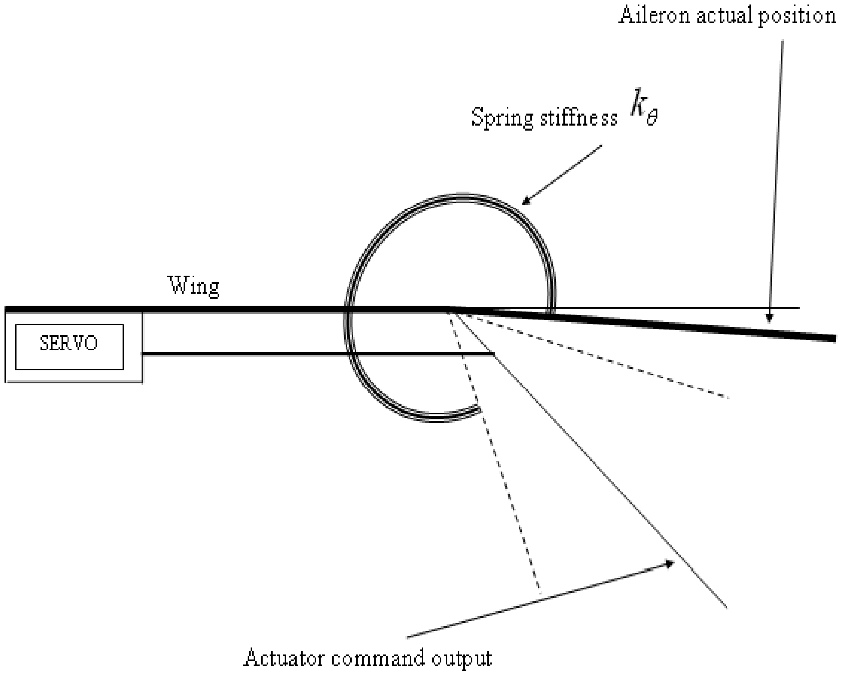


Case 2: LCO Simulations with actuator free play

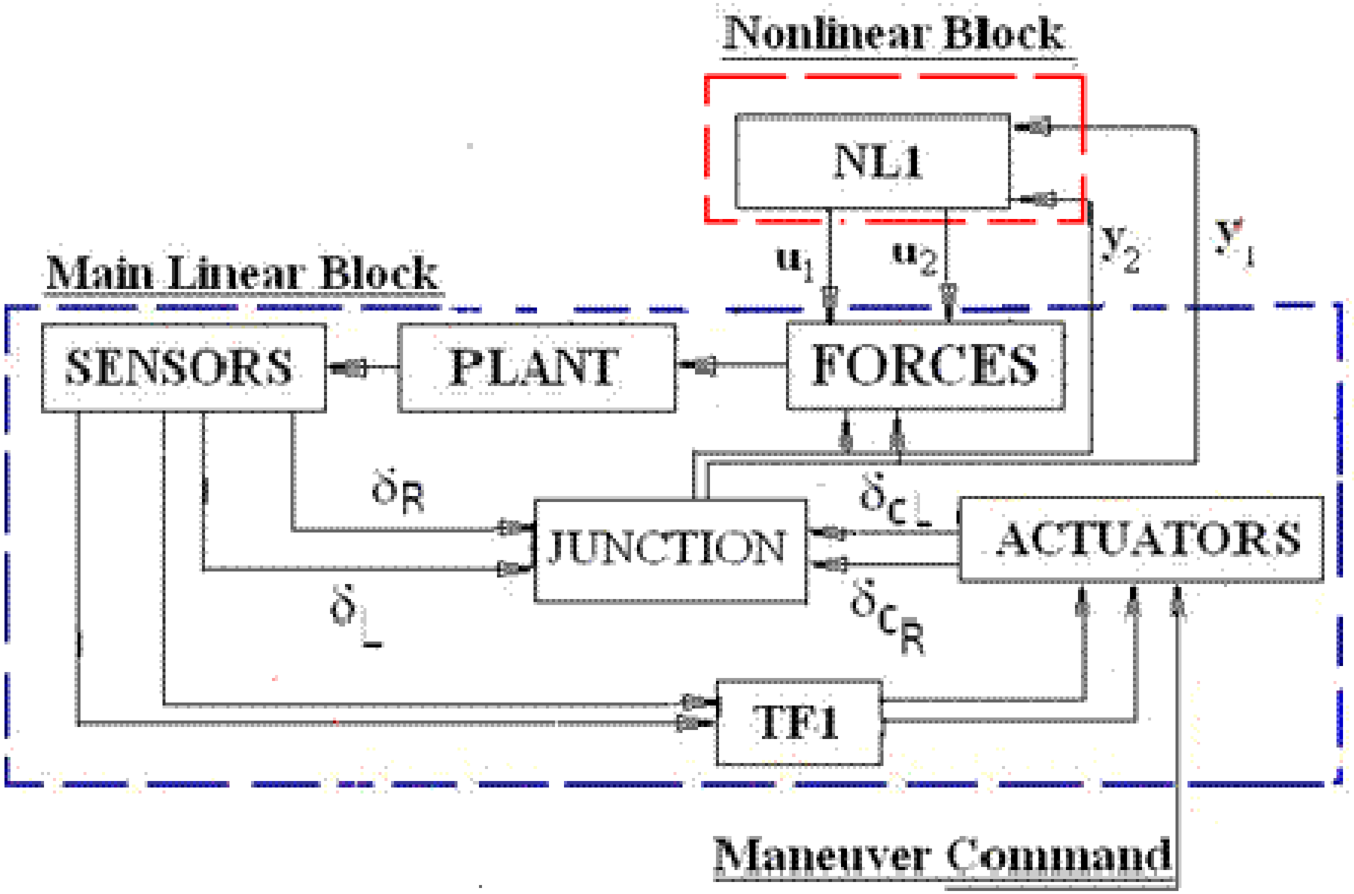
with Paul Gold

- A common strong nonlinearity is free play in the actuator connections to the control surfaces.
- Aileron in the free-play zone: out of the free-play zone:





Free-play IOM Block Diagram

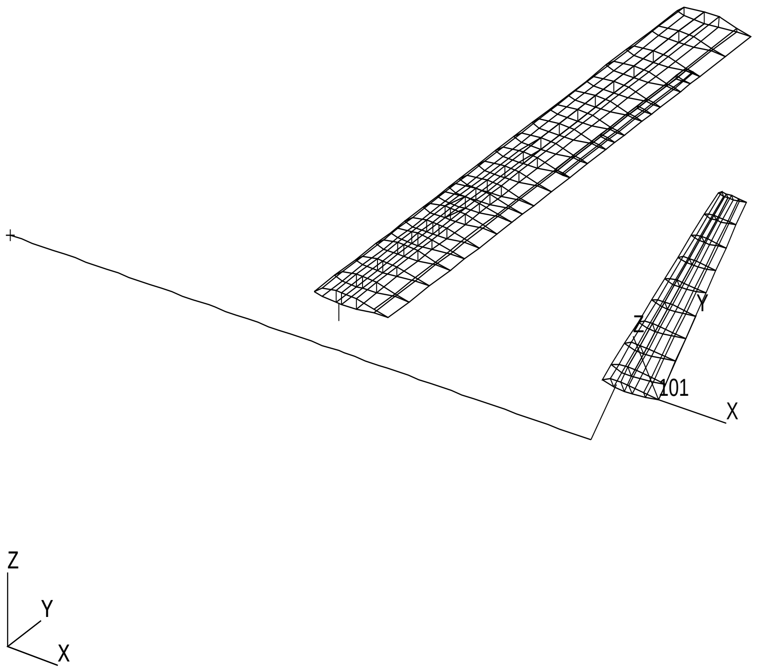


Main Modeling Difficulties and Solutions

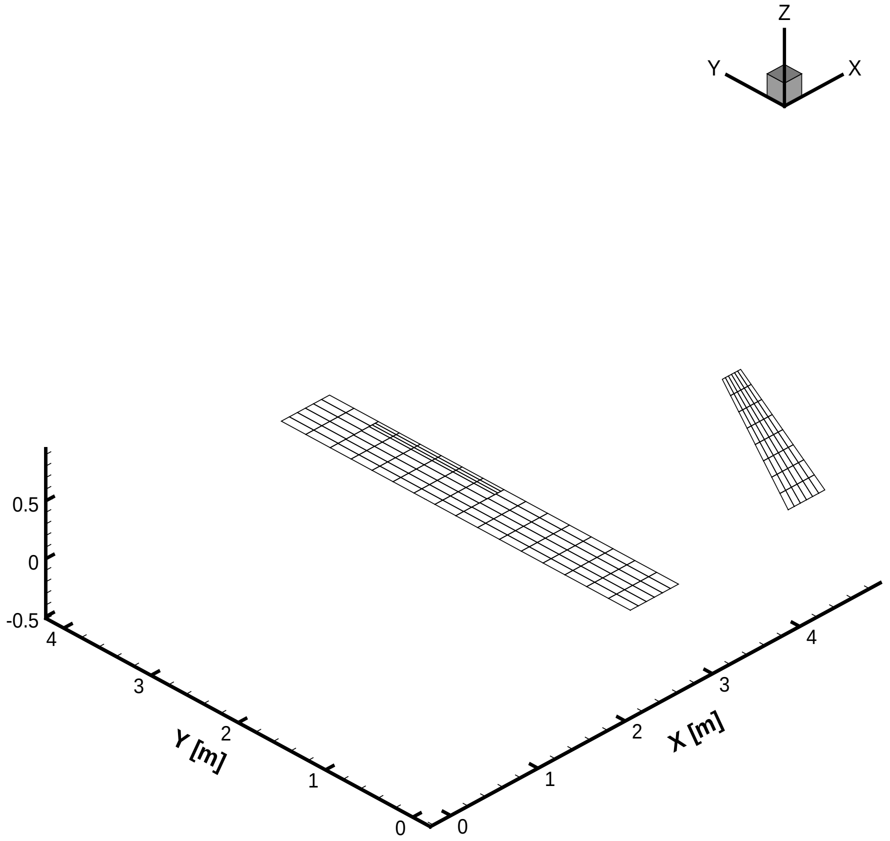
- Efficient models are based on a single set of normal modes
  - Problem: How to represent large local concentrated force changes during time simulations?
  - Solution: Use local fictitious masses.
- Free-play causes asymmetric response.
  - Problem: Do we have to use full-aircraft models?
  - Solution: No, we can use symmetric and antisymmetric modes with modal coupling effects.

Demonstration UAV Model

Structural finite-element model



Aerodynamic panel model

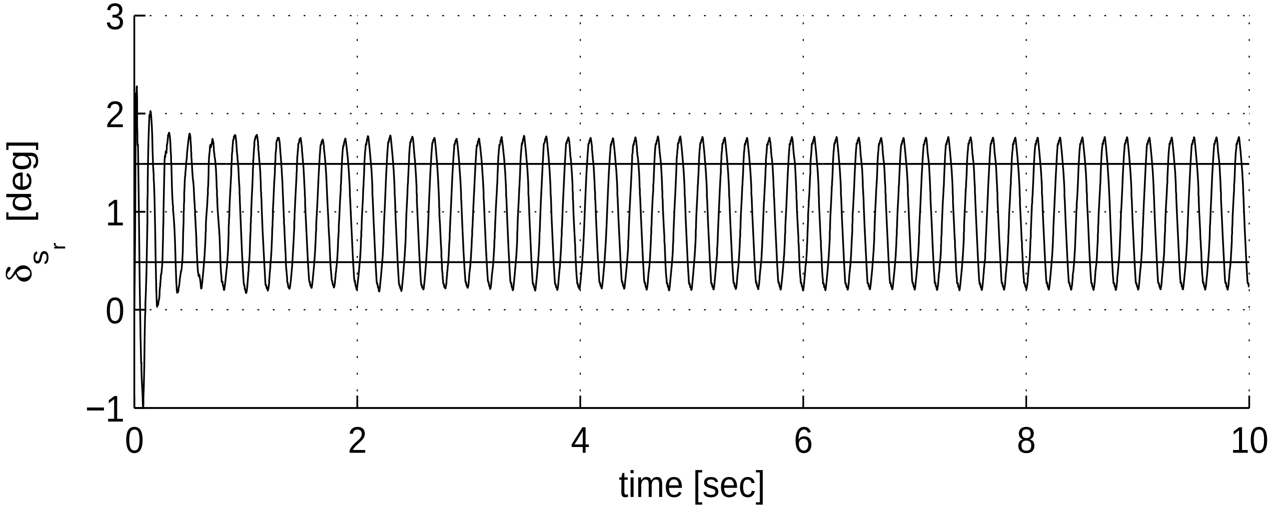


Asymmetric LCO in response to unit aileron command

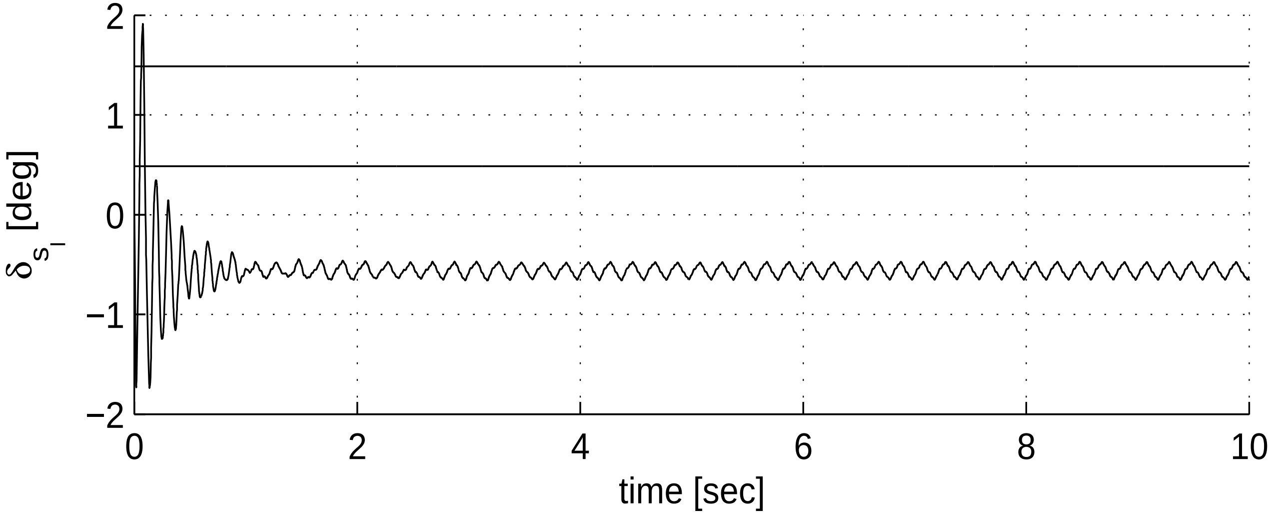
- The linear ASE plant, with the nonlinear feedback loop was implemented in DYNRESP.
- Simulations performed for deviations from the steady level flight.
- The right and left aileron elastic rotations δ_{s_r} and δ_{s_l} were calculated relative to the initial δ_t=- 1^o.
- A roll simulation was performed for response to an antisymmetric step actuator command δ_c =3.67^o that brings the right aileron to the middle of the free play zone.
- The right aileron experiences almost harmonic LCO at 5 Hz.

Elastic rotations of right and left ailerons, unit command

Right:

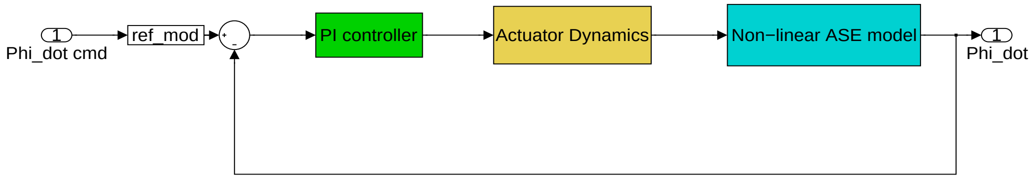


Left:



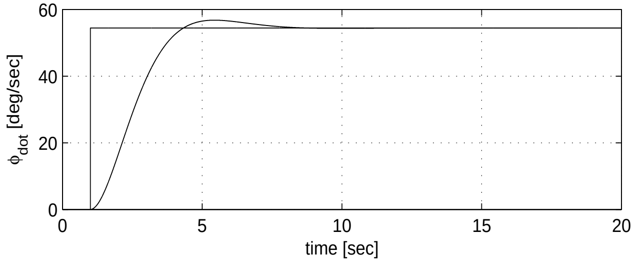
LCO during Roll Maneuvers of a Controlled Vehicle

- The nonlinear ASE model is augmented with a 3rd-order actuator and a classical proportional-integral (PI) roll controller.
- The PI controller was designed to yield acceptable closed loop stability margins for the no-free-play case.

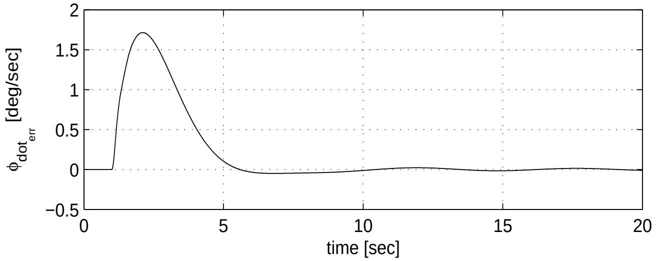


- Time histories of system response with no free play case:

roll rate:

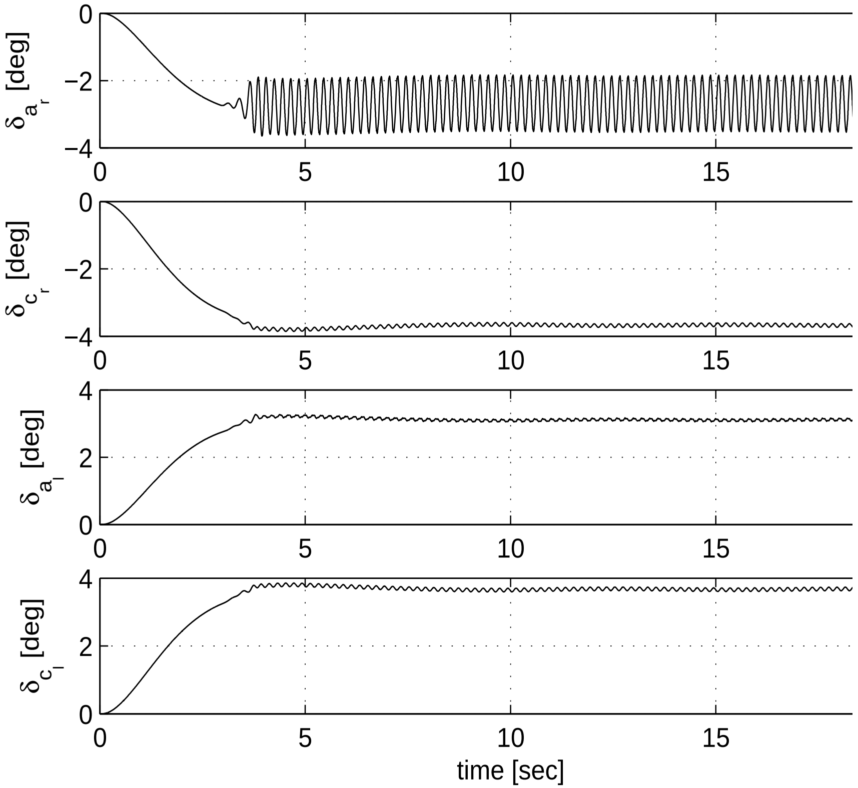


roll-rate error:

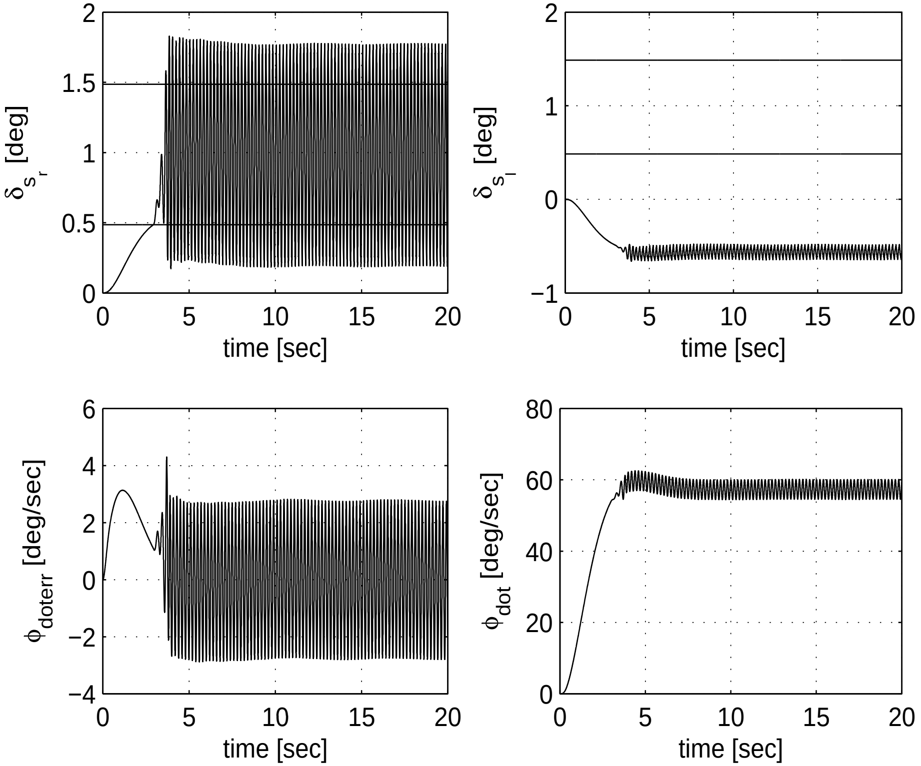


Closed loop response, with actuator free play

Actual and commanded aileron rotations:

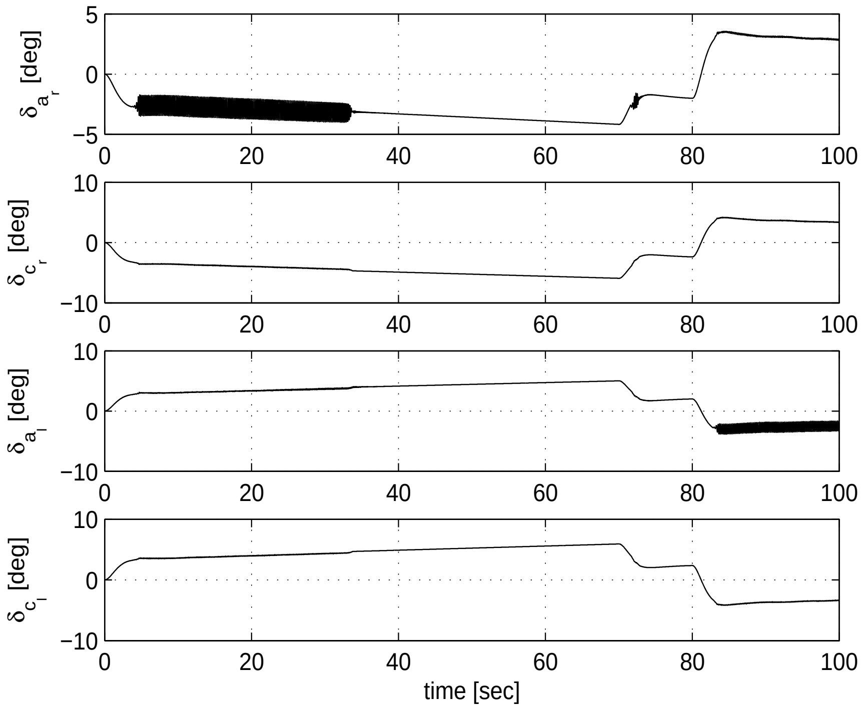


Elastic aileron rotations, roll rate and roll-rate error:

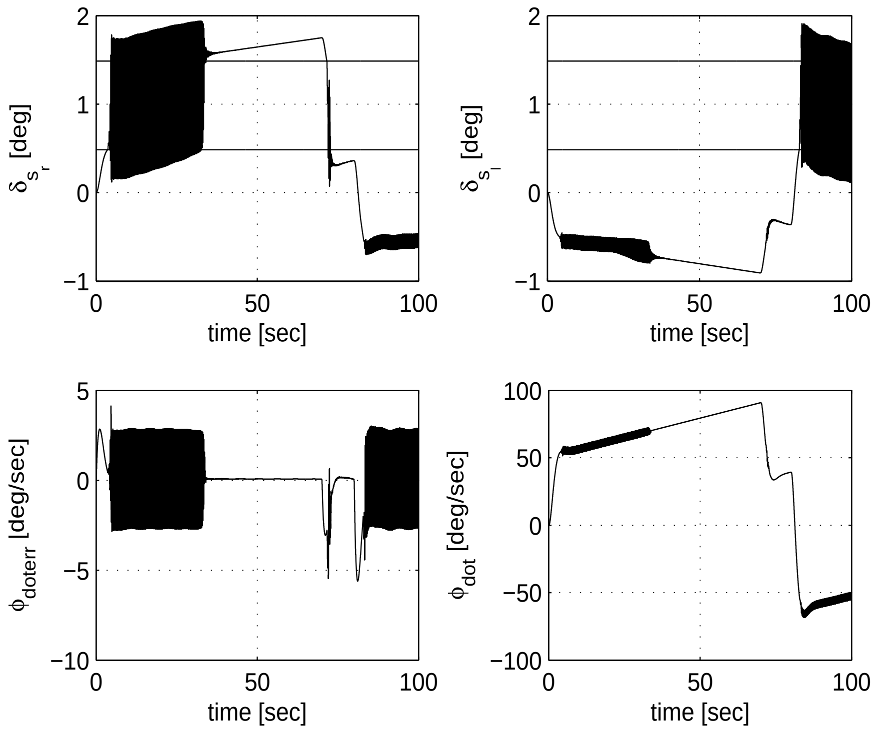


Closed-loop response with actuator free play in typical roll maneuver sequence

Actual and commanded aileron rotations:

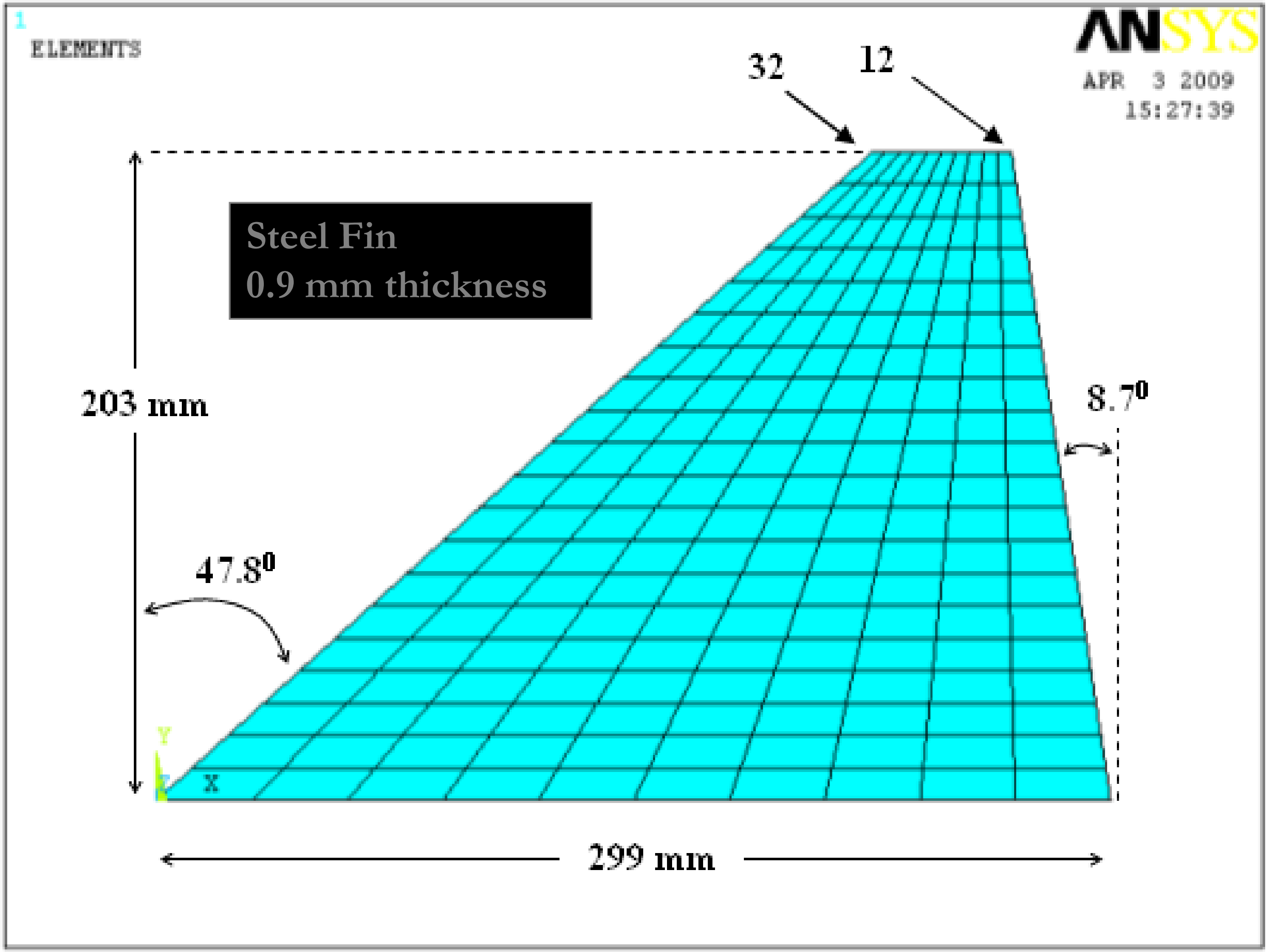


Elastic aileron rotations, roll rate and roll-rate error:



Case 3: Solid fin with nonlinear plate elements

with Dani Levin



Basic equation of motion

$$\overbrace{[m]\{\ddot{u}\}+[c]\{\dot{u}\}+[k]\{u\}}^{\text{Structural Part}}=\{\underbrace{F_A(t)}_{\text{Unsteady aerodynamic forces}}\}$$

Stiffness matrix changes due to stress stiffening

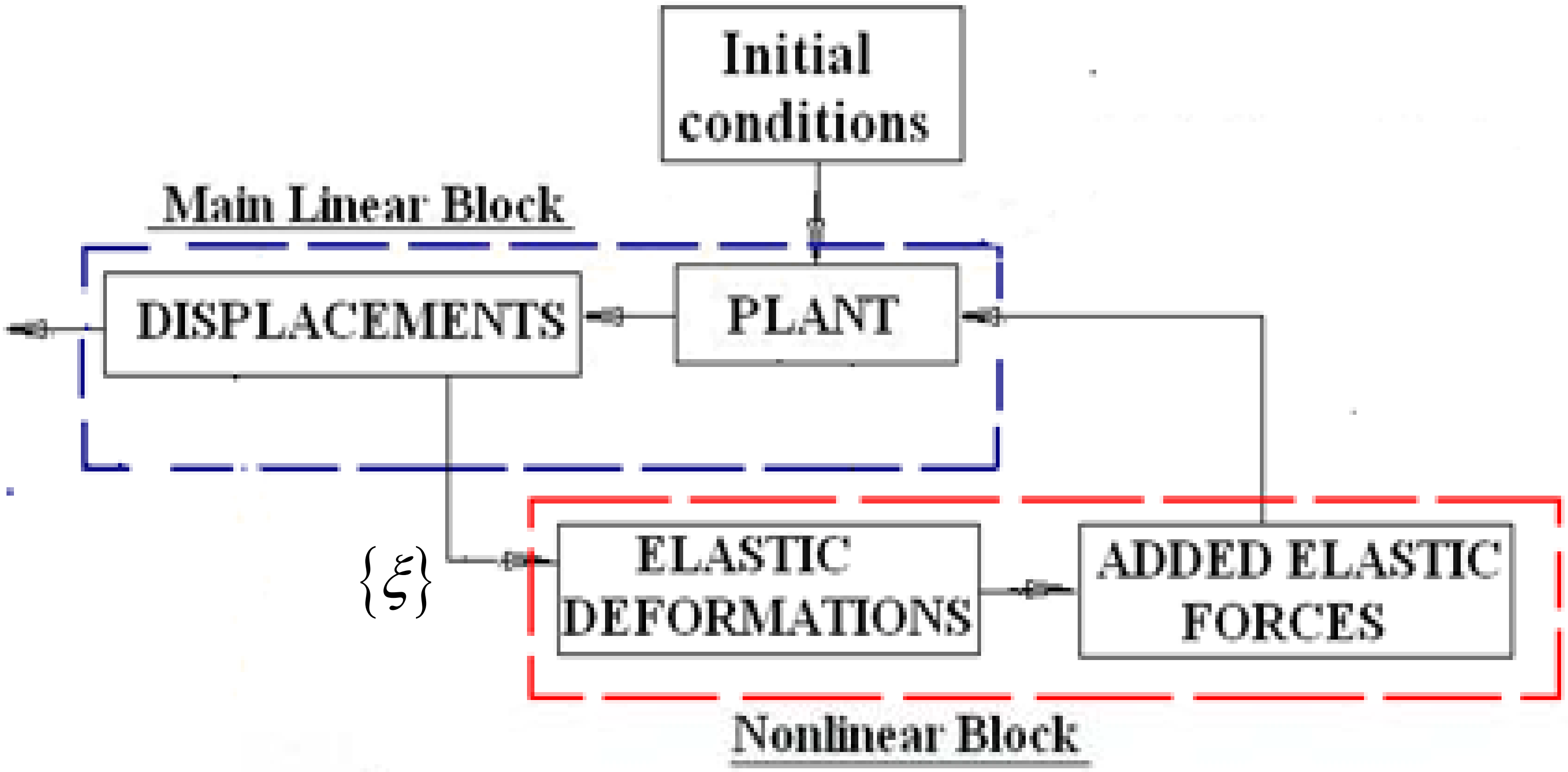
Nonlinear in-plane strain

$$\varepsilon = \begin{Bmatrix} \dfrac{\partial u}{\partial x} \\ \dfrac{\partial v}{\partial y} \\ \dfrac{\partial u}{\partial y} + \dfrac{\partial v}{\partial x} \\ -\dfrac{\partial^2 w}{\partial x^2} \\ -\dfrac{\partial^2 w}{\partial y^2} \\ 2\dfrac{\partial^2 w}{\partial x \partial y} \end{Bmatrix} + \begin{Bmatrix} \dfrac{1}{2}\left(\dfrac{\partial w}{\partial x}\right)^2 \\ \dfrac{1}{2}\left(\dfrac{\partial w}{\partial y}\right)^2 \\ \left(\dfrac{\partial w}{\partial x}\right)\left(\dfrac{\partial w}{\partial y}\right) \\ 0 \\ 0 \\ 0 \end{Bmatrix} = \begin{Bmatrix} \varepsilon_0^{pl} \\ \varepsilon_0^{b} \end{Bmatrix} + \begin{Bmatrix} \varepsilon_{NL}^{pl} \\ 0 \end{Bmatrix}$$

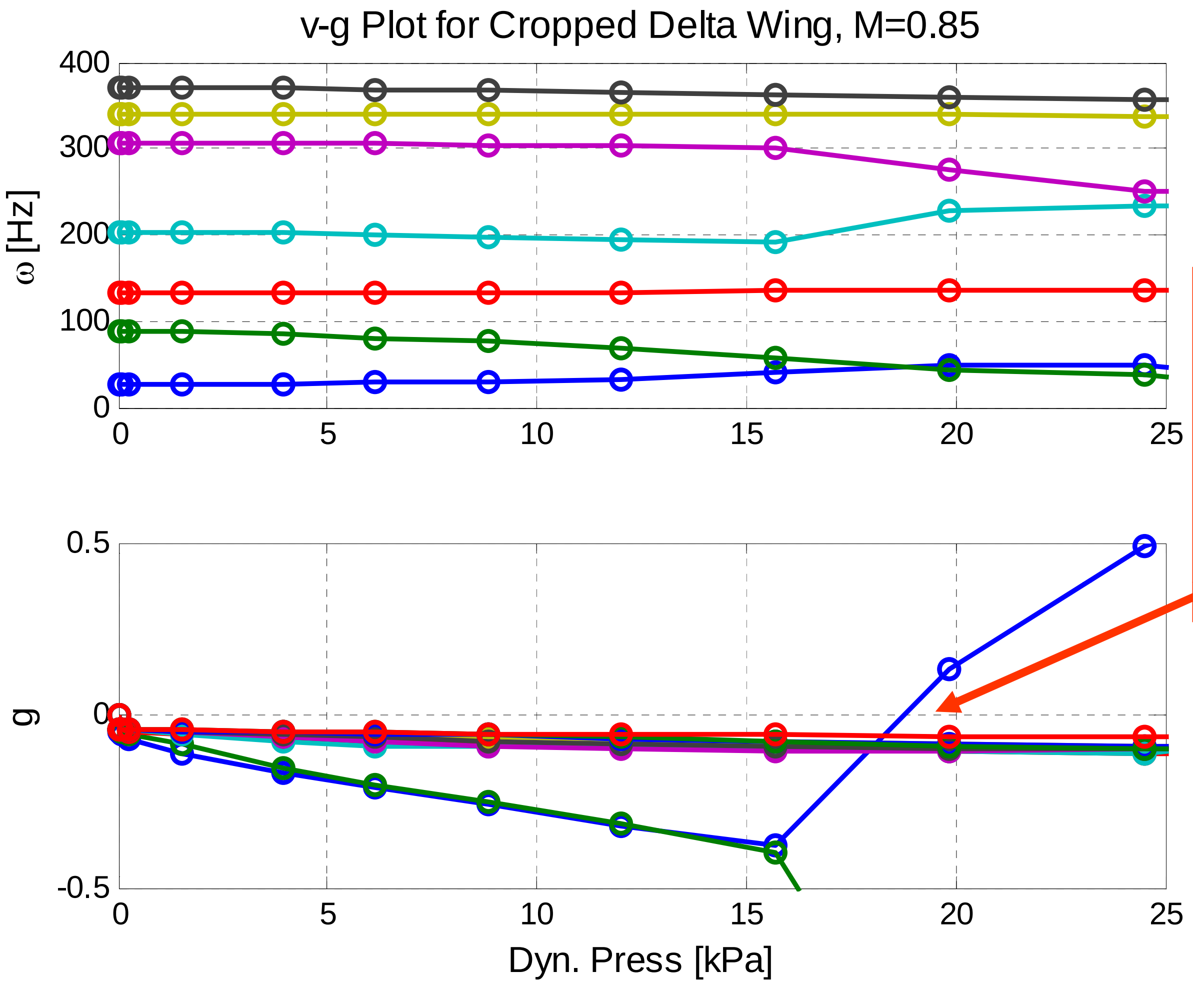
Non linear strain addition

- Von Karman equations are used.
- Nonlinear strain part is added due to stretching of the plate in bending.

IOM block diagram



Linear Flutter Analysis

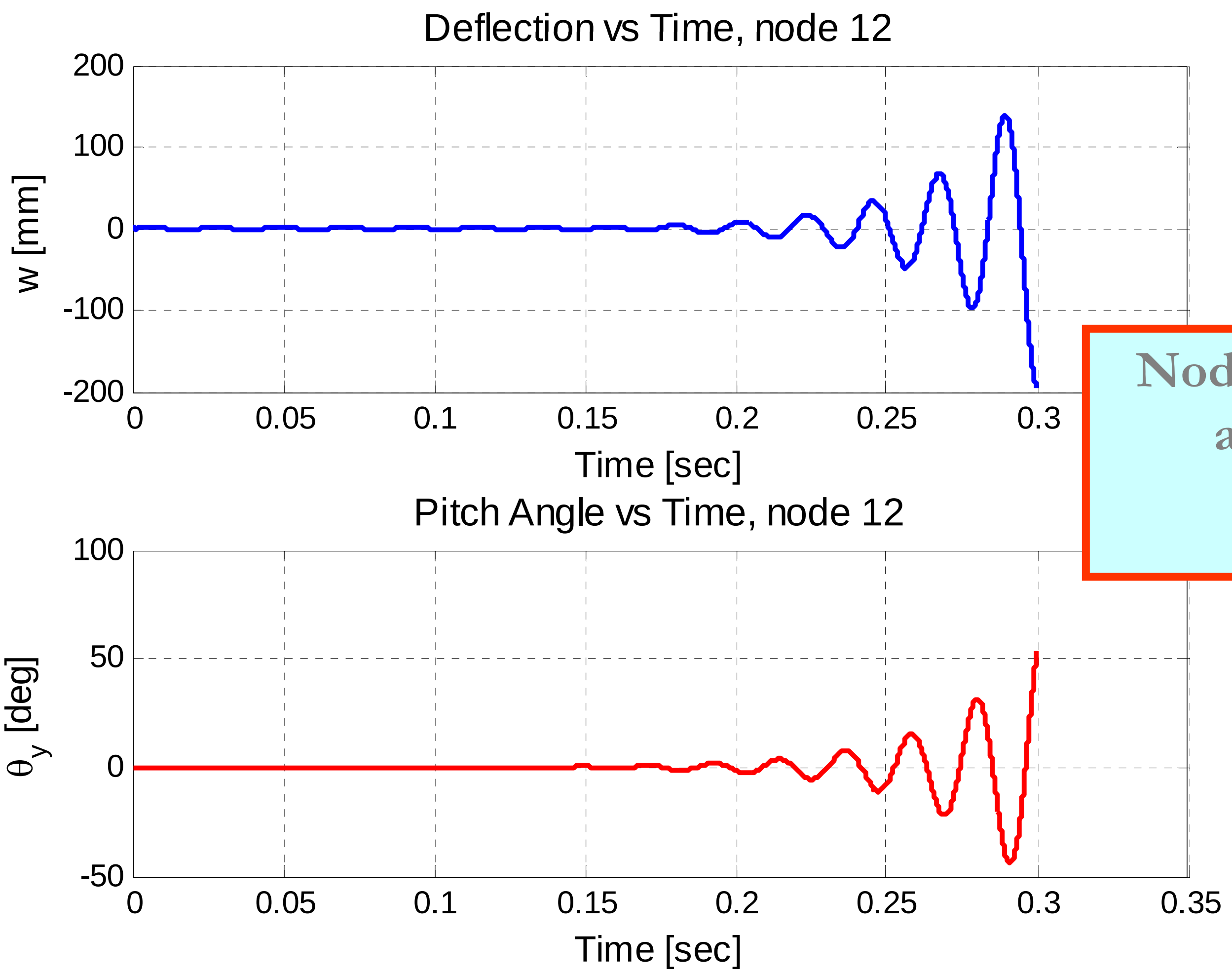


Torsion-Bending flutter mechanism at:

M=0.85, q=18.96kPa

ω_f=45.6 Hz

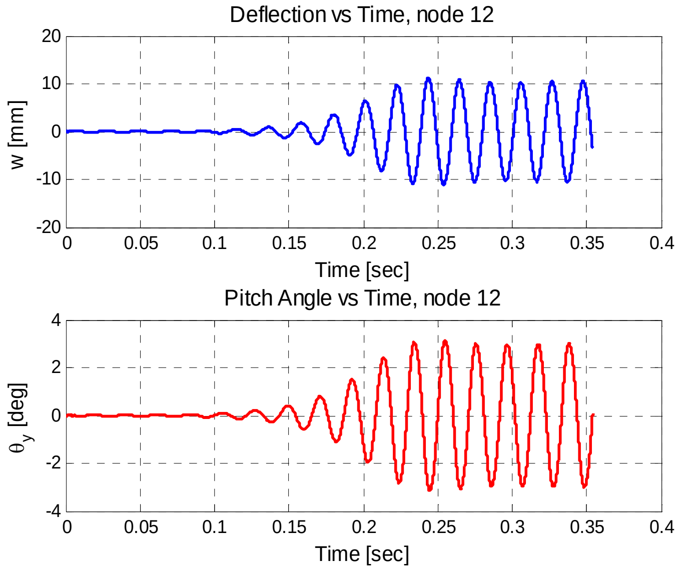
Linear System Time Simulation



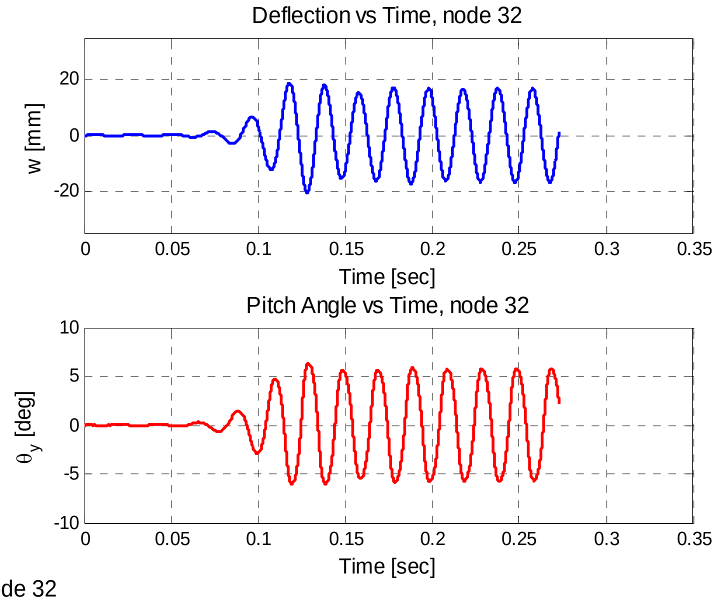
Node 12 displacement and rotation at:

q=19.8kPa

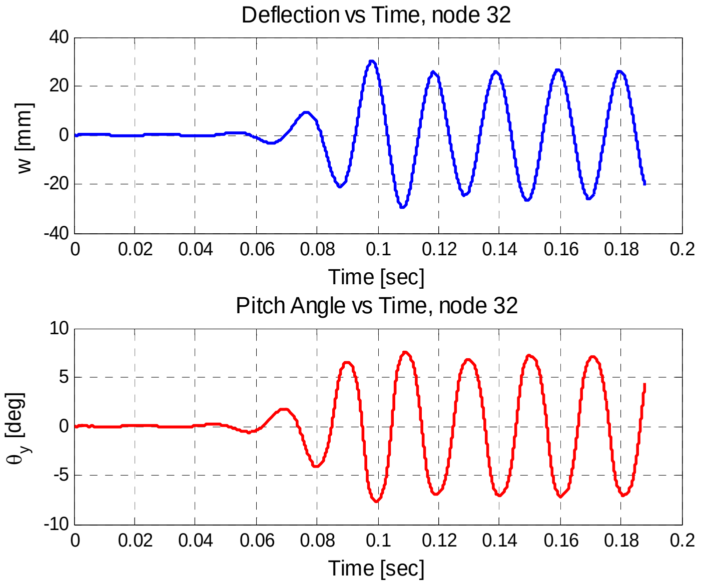
Nonlinear Time Simulation



q=19.16kPa

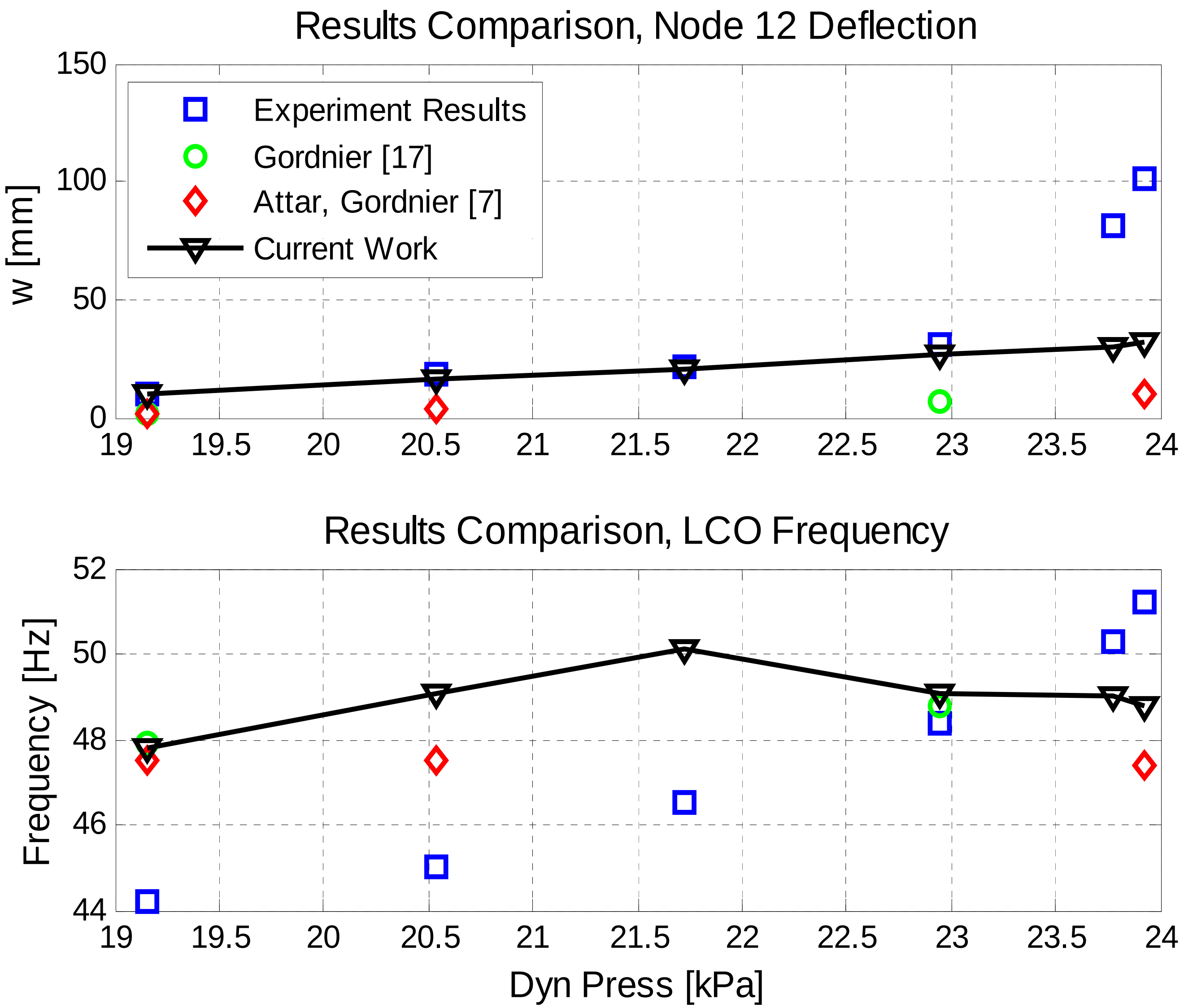


q=21.72kPa



q=23.92kPa

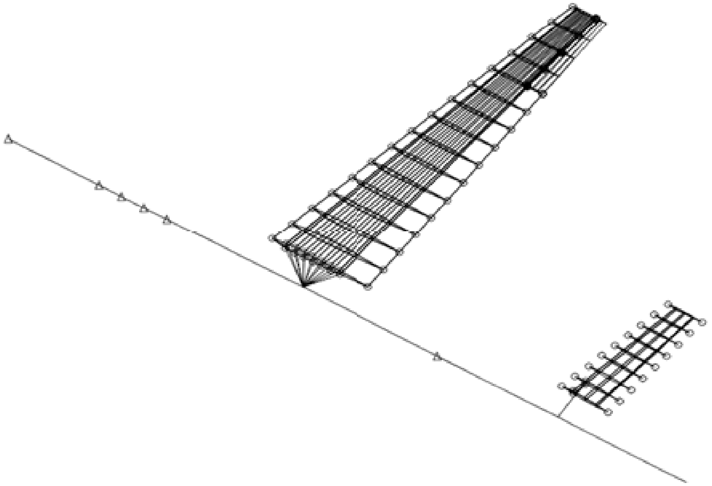
Comparison with wind-tunnel test and other works

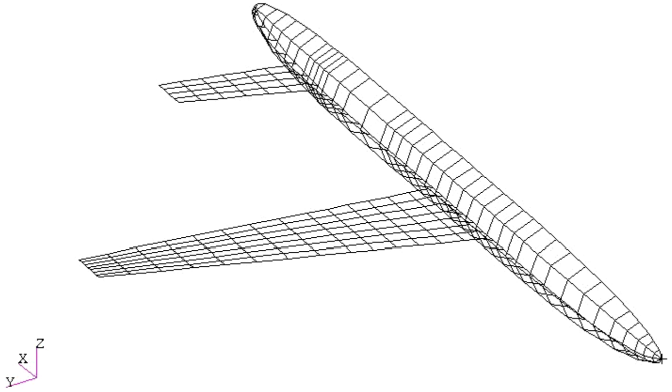


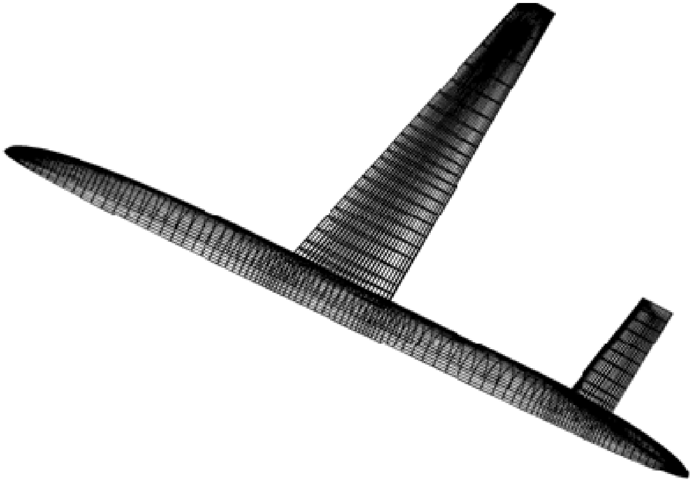
Cases 4: Gust Response with Nonlinear aerodynamics

with Daniella Raveh and Alex Shousterman

- MSC/NASTRAN structural model, ZAERO aero model and EZNSS Euler surface grid of generic transport aircraft:

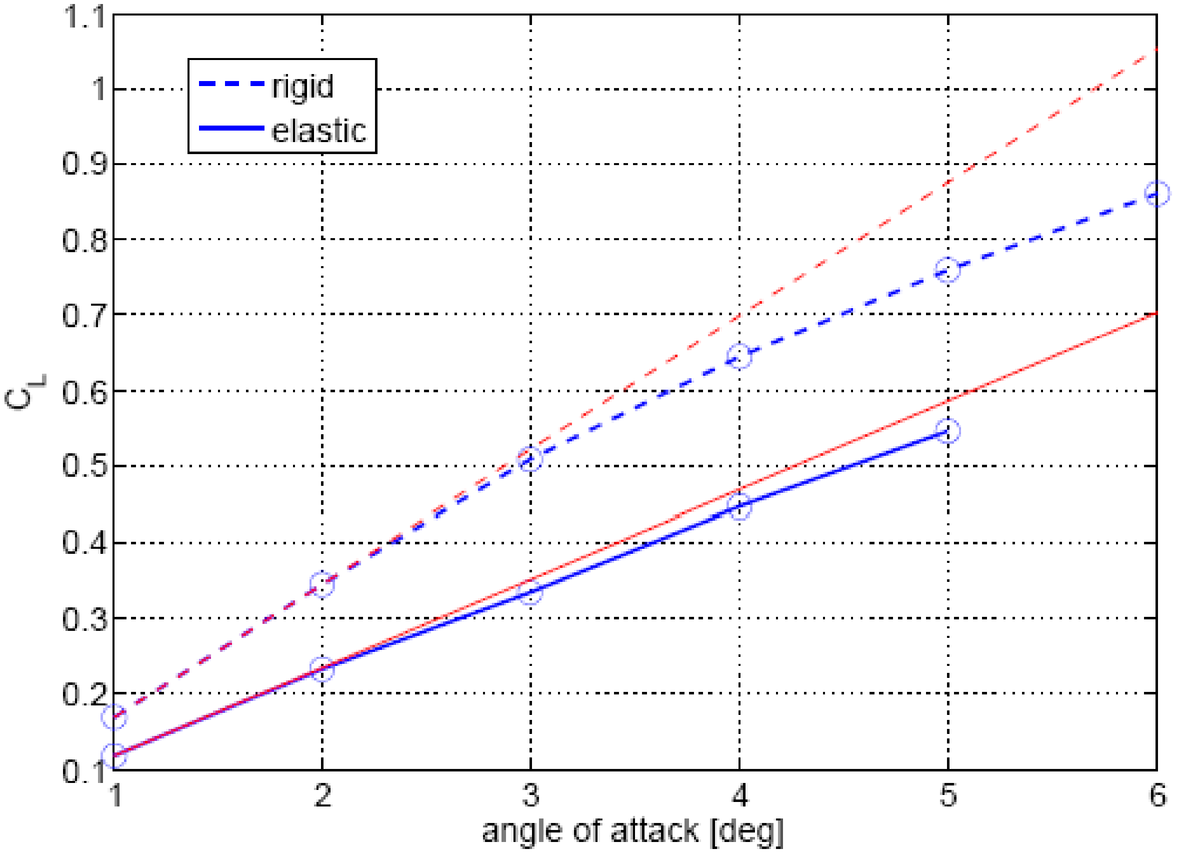




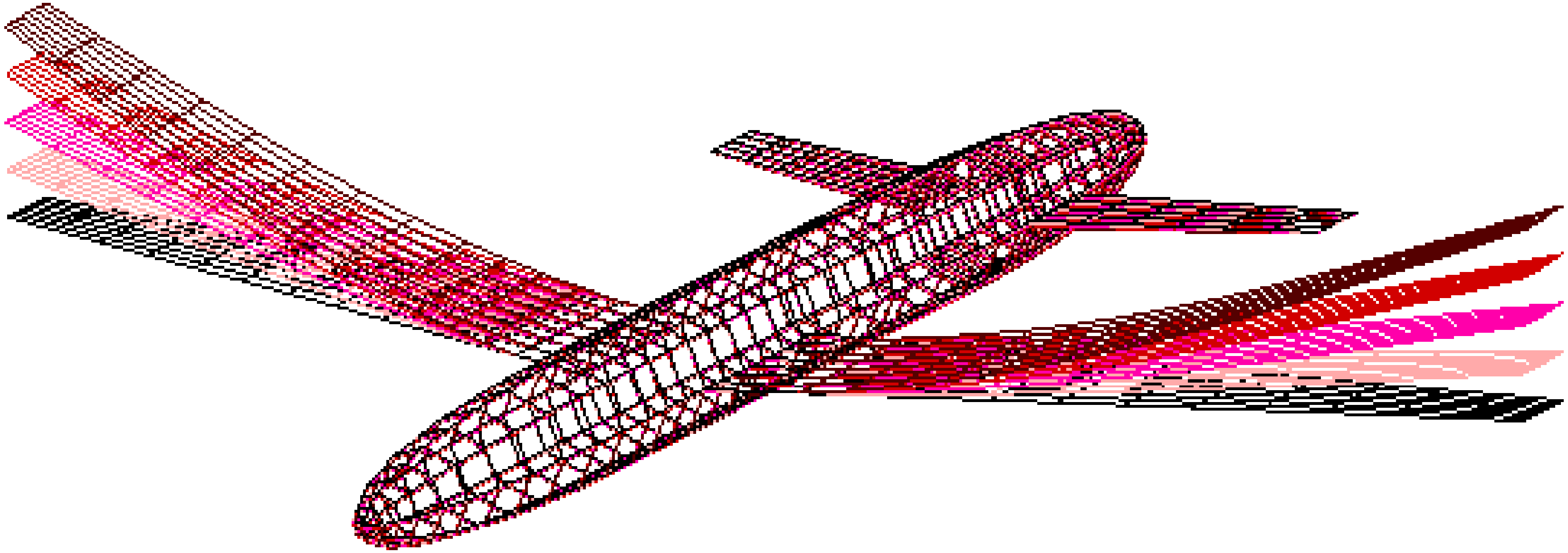


CFD Static Lift Coefficent at Mach 0.85

- Lift coefficient vs. AOA, CFD and linear models.
- Nonlinear aerodynamic effects may yield reduced gust loads in practical design cases.



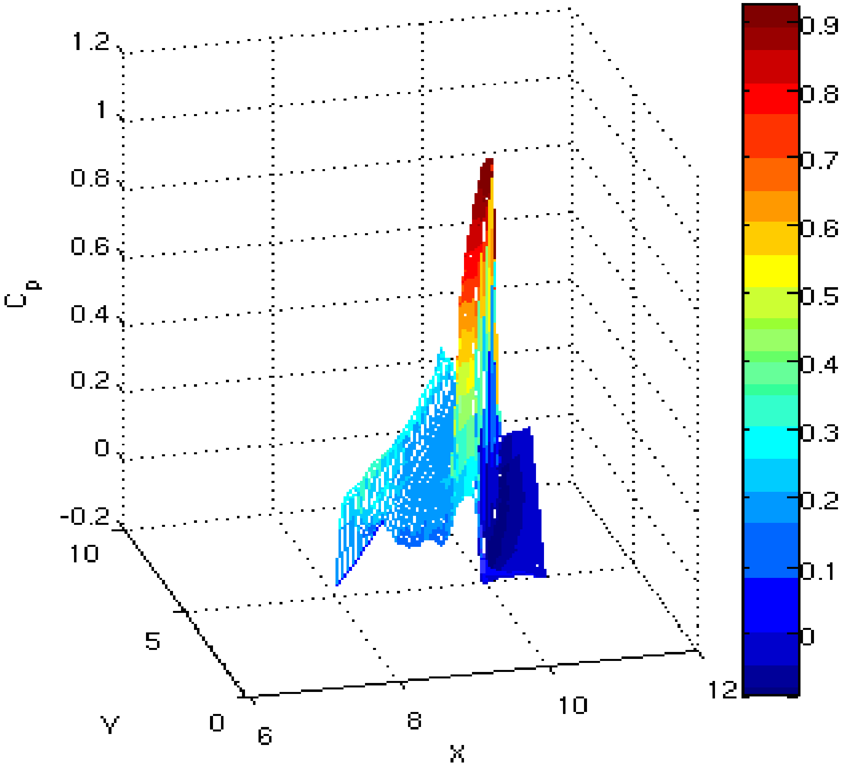
Elastic deformations at steady α=0 to 4^o

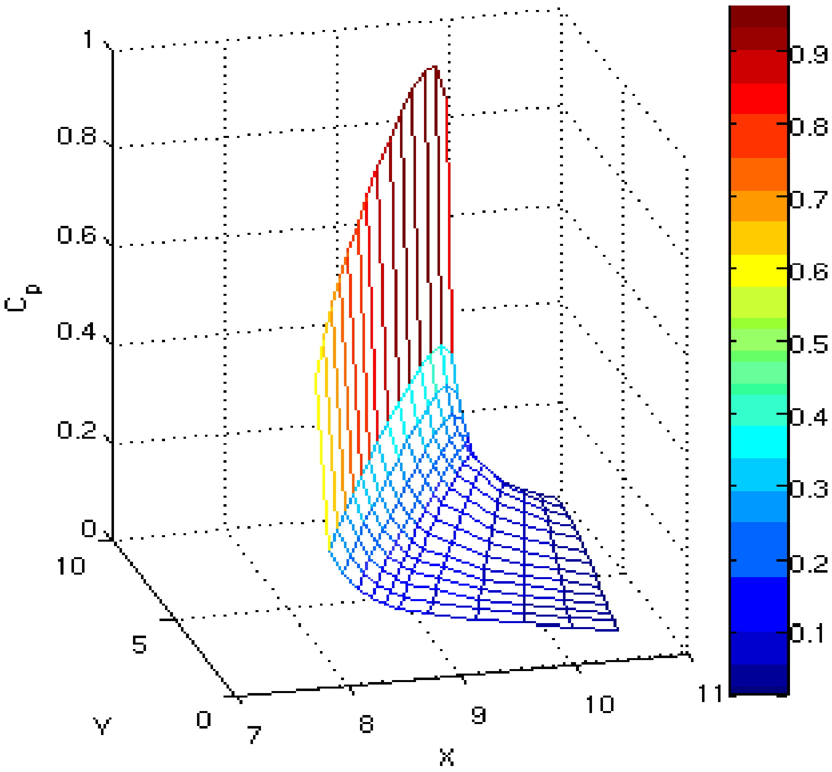


Distribution of pressure coefficients over the wing

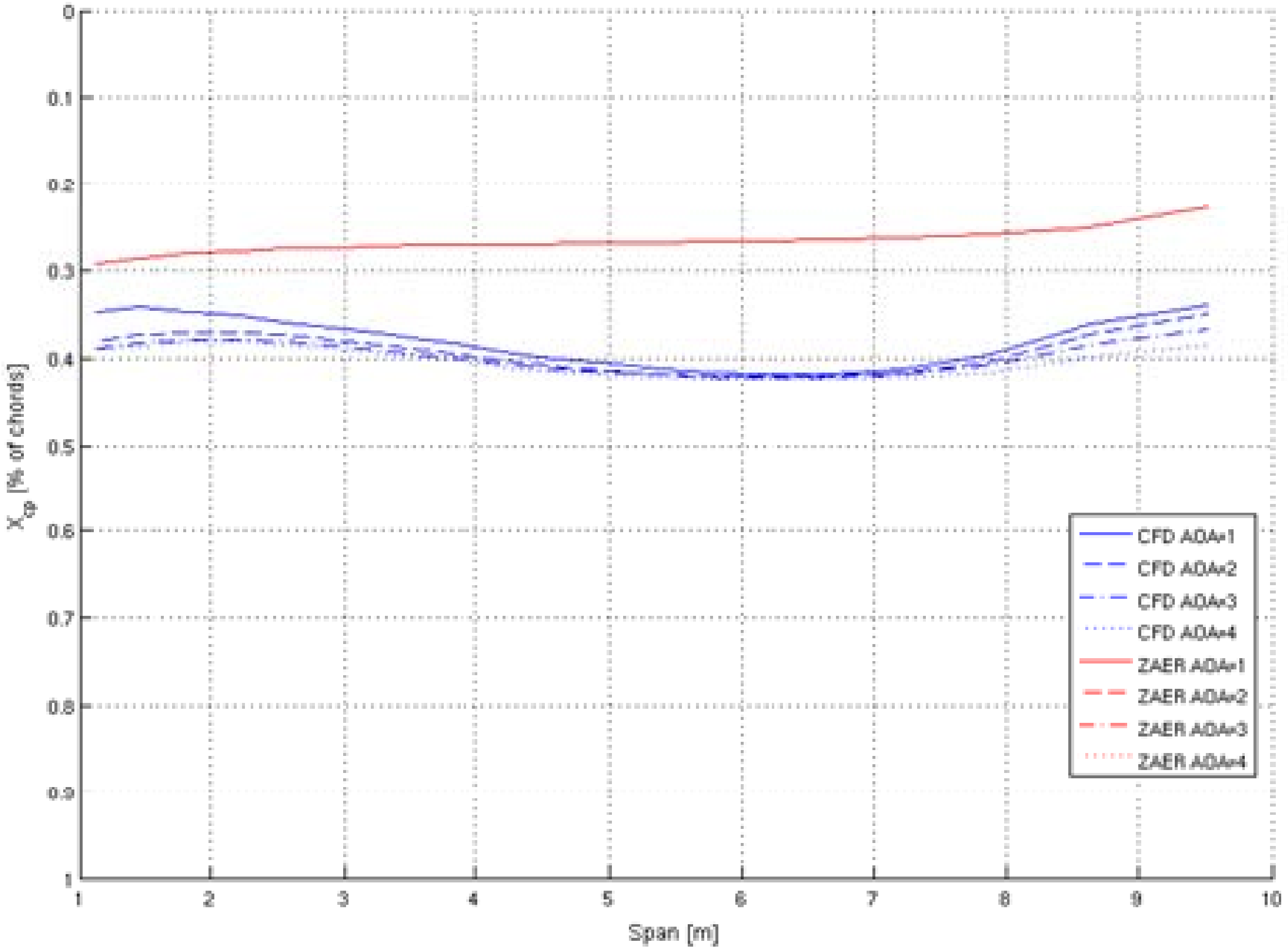
EZNSS

ZAERO





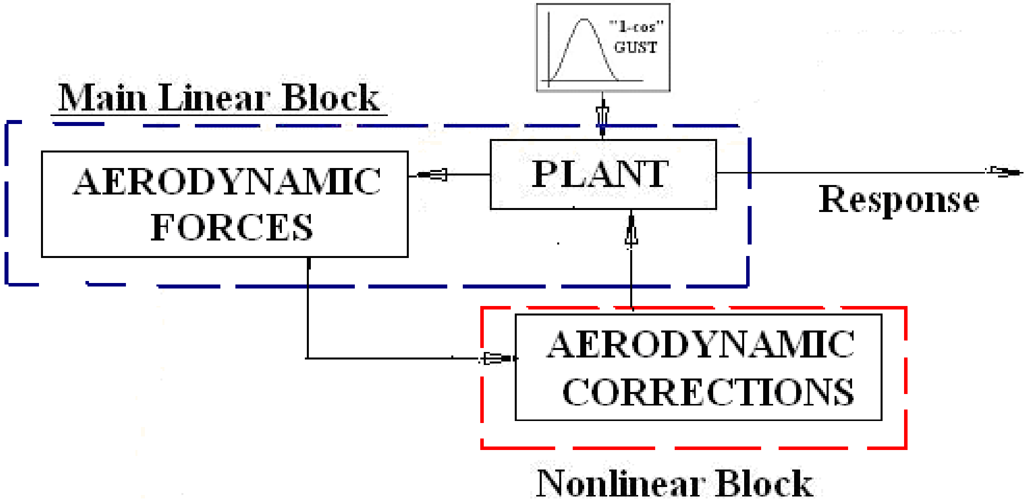
Distribution of X_{cp} over the wing



DYNRESP gust response with non-linear feedback

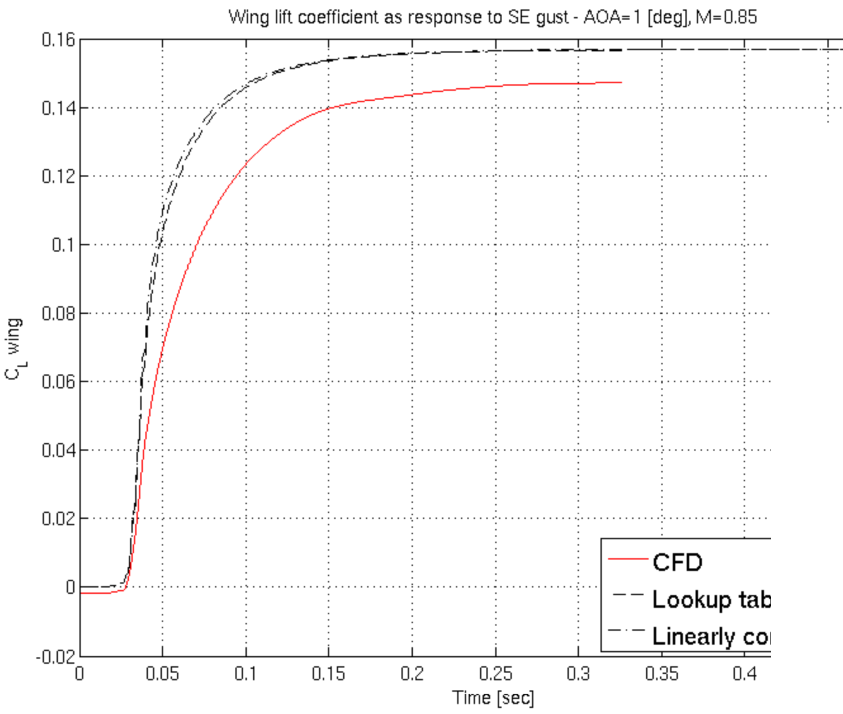
- Linear C_l and C_m of the nominal model are “sensors”
- Non-linear feedback elements are based on look-up tables from CFD

- C_l and C_m corrections are introduced by direct forces and moments at the wing and tail main spars, and forces along the fuselage
- DYNRESP calculated 2 cases:
  - Linear correction with linear look-up tables
  - Non-linear correction with nonlinear look-up tables

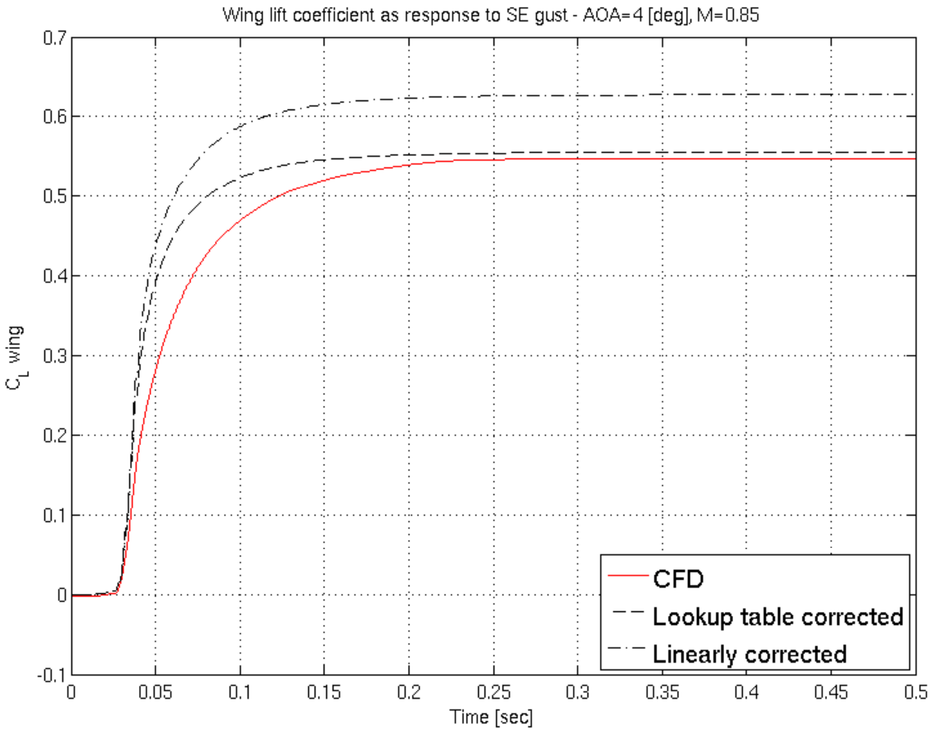


Rigid wing C_L response to sharp-edge gust

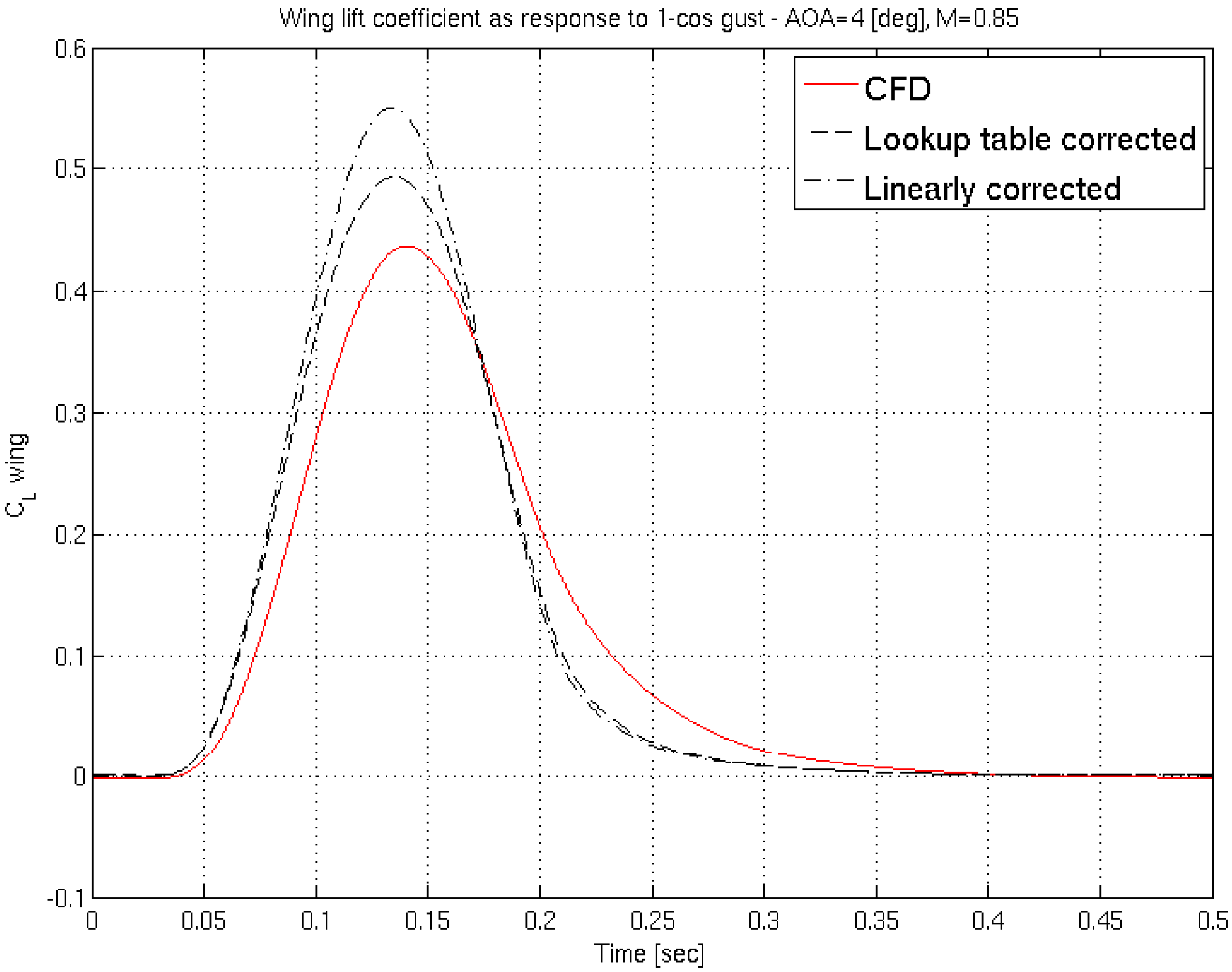
a=1 *deg*:



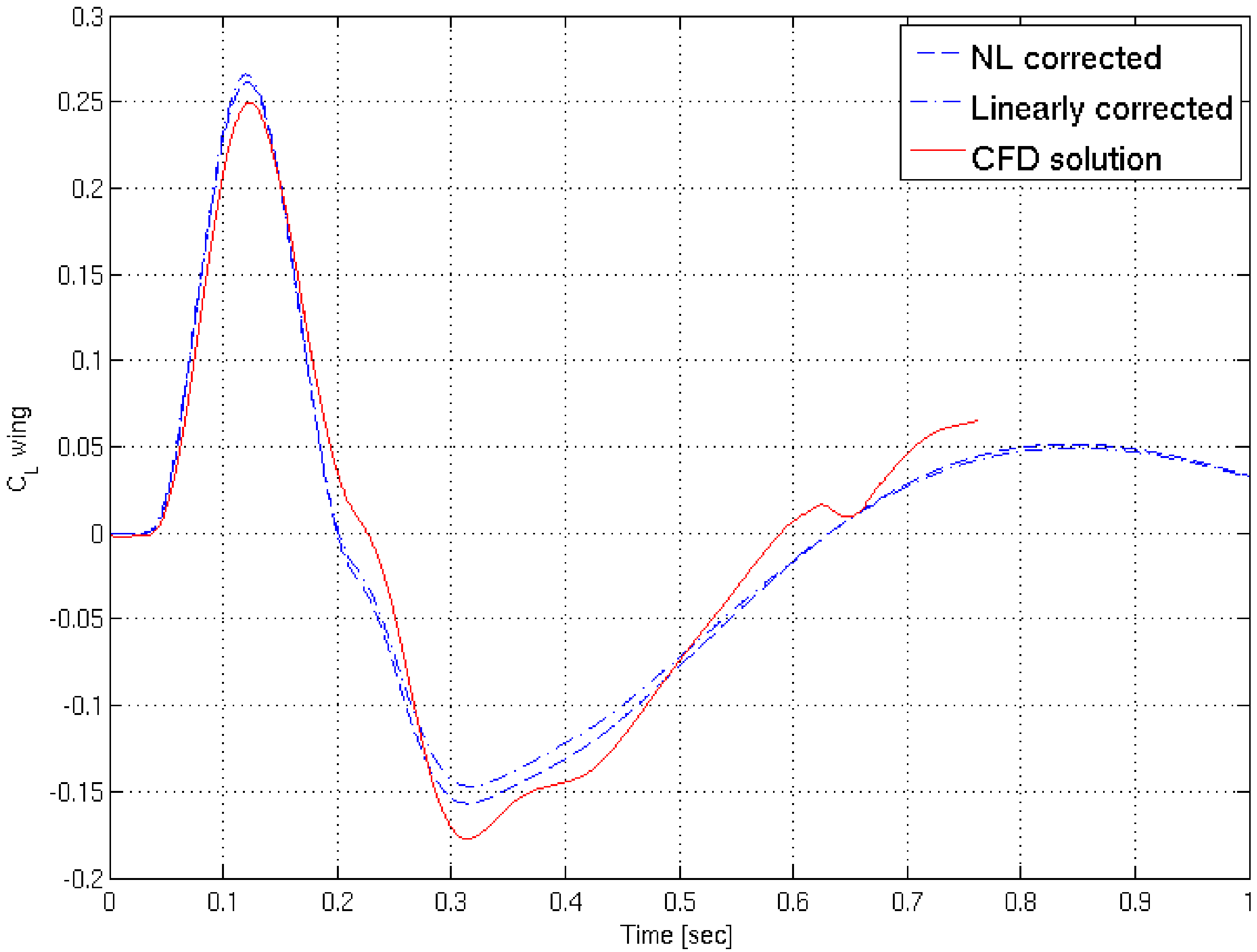
a=4 *deg*:



Rigid wing C_L response to “1-cos” discrete gust, 0 to 4º



Flexible wing C_L response to “1-cos” discrete gust, 0 to 4°



Concluding Remarks

- The Increased-Order Modeling approach provides an efficient and robust framework for the introduction of nonlinear aeroelastic effects in research studies and in industrial applications.

- Could form a bridge between high-fidelity models, industrial design practices and certification requirements.

- We will be glad to cooperate with interested parties.