NONLINEAR AEROELASTIC ANALYSIS OF FIGHTER-LIKE AIRCRAFT WITH EXTERNAL STORES

Funded by:
- EDA/FMV
- NFFP/Vinnova/FMV/Swedish Armed Forces

Anders Karlsson, Saab Aeronautics

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INTRODUCTION

WHAT DO WE DO ?

STABILITY

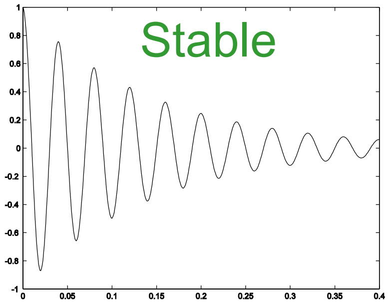
$$\boxed{M + K + A = 0}$$

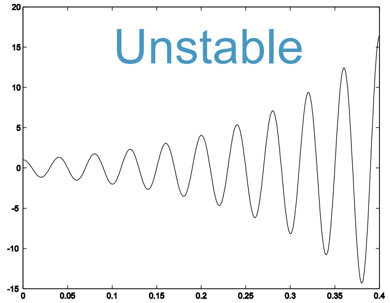
Dynamic:

- Flutter
- AeroServoElasticity (ASE)

Static:

- Divergence





X-29

RESPONSE

$$\boxed{M + K + A = F_r}$$

Dynamic:

- Gust

A-310
On the Azores

INTRODUCTION

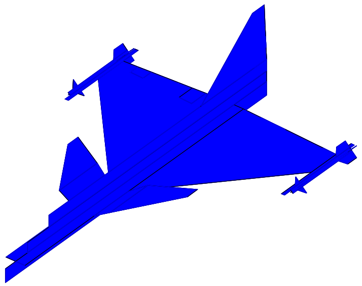
WHAT DO WE NEED ?

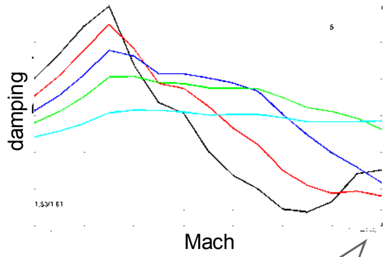
- ***Several*** **tools** depending on purpose of analysis

- **Linear analysis** *(prediction tool)*

  minutes

  - Production tool within the industry
  - Panel models
  - Analyse hundreds of configurations

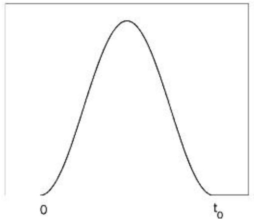


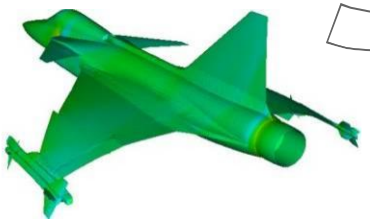


- **Medium fidelity** *(prediction tool)*

  Hours (days)

  - Dynamic linearization
  - CFD aerodynamics + standard tools

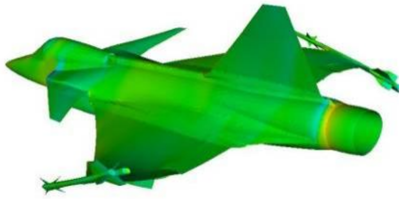


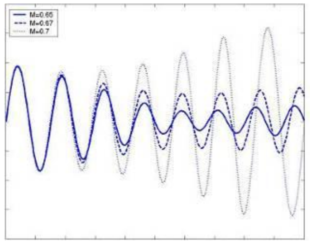


- **High fidelity** *(simulation tool)*

  Days (weeks)

  - Coupled CFD + CSM (aero + structure)
  - Time domain simulation

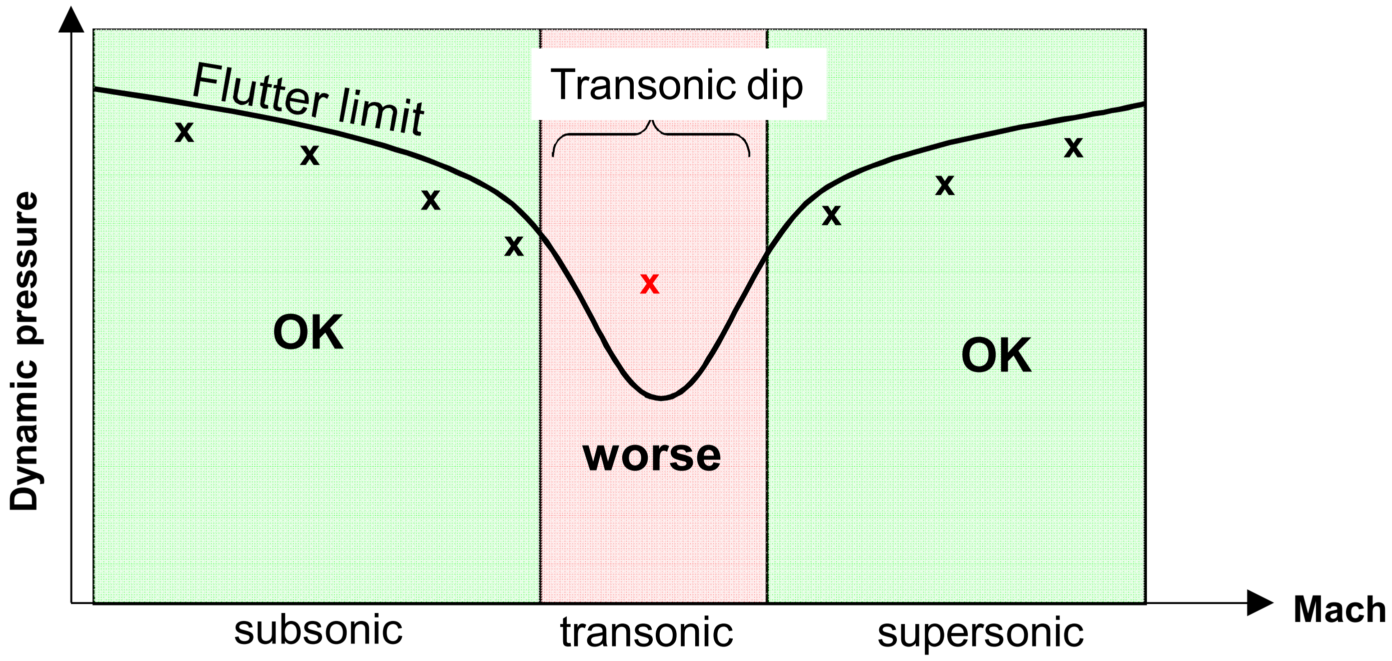




INTRODUCTION

WHY NONLINEAR TOOLS ?

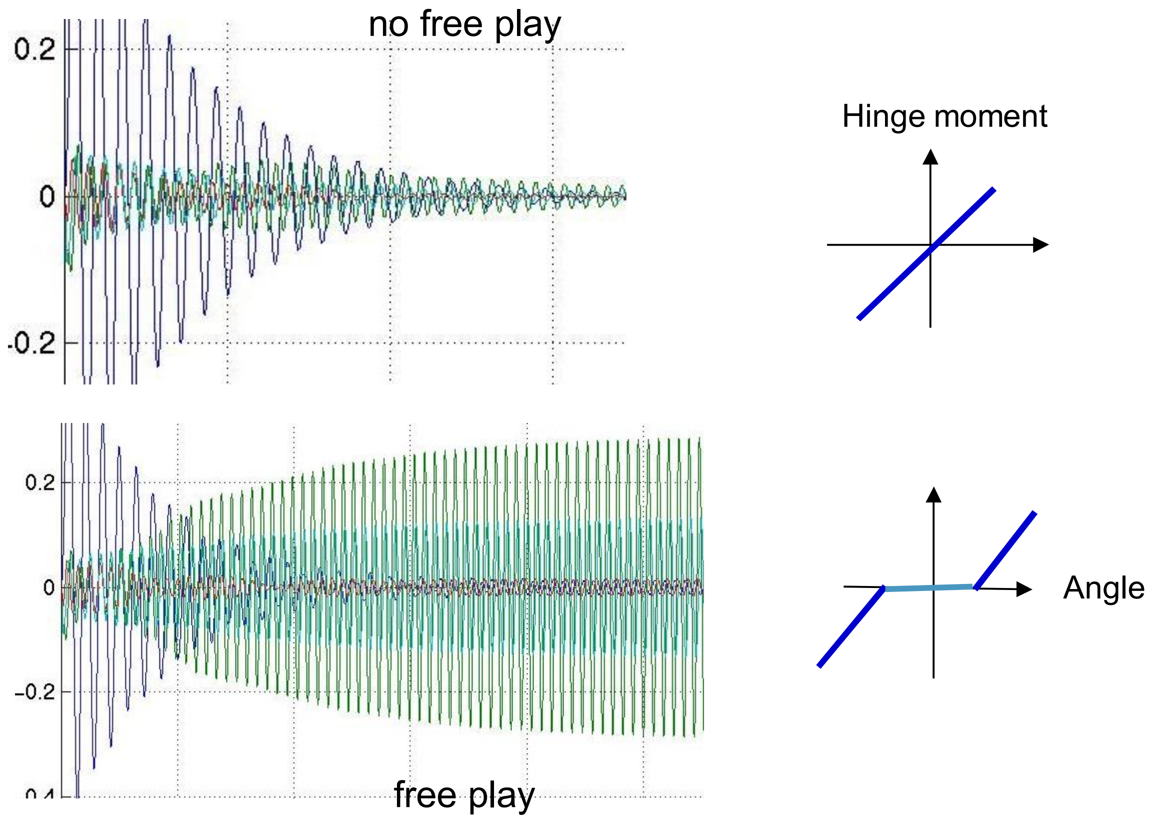
- Nonlinear **aerodynamics**
  - For sub- and supersonic speeds the unsteady aerodynamics from a linear panel model works quite well
  - In the **transonic** regime the linear methods have deficiencies (shocks etc. give **nonlinear effects**)



INTRODUCTION

WHY NONLINEAR TOOLS ?

- Possibility to analyse **structural** nonlinearities
  - Control surface free play
  - Store-to-pylon interface (friction)
  - Nonlinear stiffness
  - etc.



INTRODUCTION

WHY NONLINEAR TOOLS ?

- Increased complexity
  - New complex external stores
  - Higher risk of encountering nonlinear phenomena

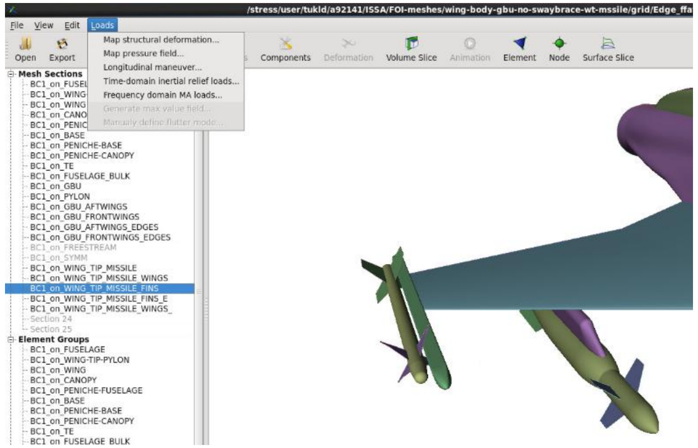
Gripen C/D

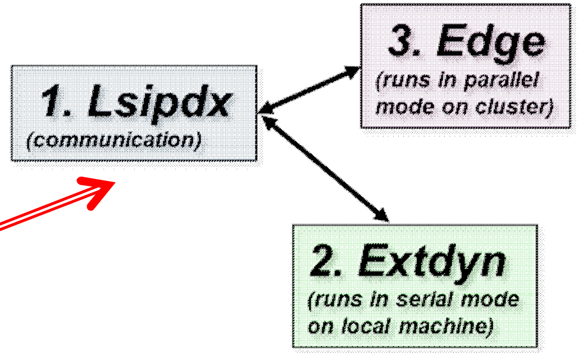
Gripen E/F

INTRODUCTION

DEVELOP TOOL / COMMERCIAL ?

- **No commercial alternative available … =>**
- Continuos development via R&D projects
- EU-projects
  - UNSI 1997-2001 (nonlinear aerodynamics part 1) 100%
  - TAURUS 2001-2004 (nonlinear aerodynamics part 2) 100%
  - MOB 1999-2002 (Multidisciplinary, ASE etc) small part
  - ALEF 2009-2012 (Loads project certain part aeroel.) small part
- FoT-25
  - Active flutter supression 2004-2006
- NFFP
  - NFFP4 2006-2008 (Robust aeroservoelastic analysis and optimization)
  - NFFP5 2009-2014 (Effective process for airworthiness approval based on robust aeroelastic analysis)
- EDA
  - ISSA 2013-2016 (LCO, nonlinear aerodynamics & structure non-modal approach) 100%





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NEW DEVELOPMENT

NFFP5: MAPPING CFD ←→ FEM

- Previous method:
  - ***Could not handle underwing stores*** (resulted in distorted geometry)
  - ***Could only one way mapping***

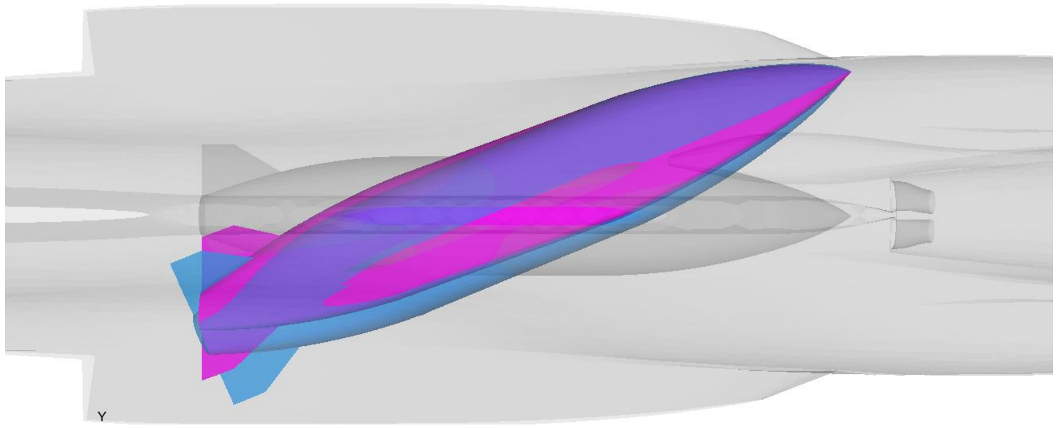
$$u_a = H\, u_s$$

displacements from structure (s) to aerodynamics (a)

For non-modal approach it is also required to have

$$F_s = H^T F_a$$

Forces from aerodynamics (a) to structure (s)



NEW DEVELOPMENT

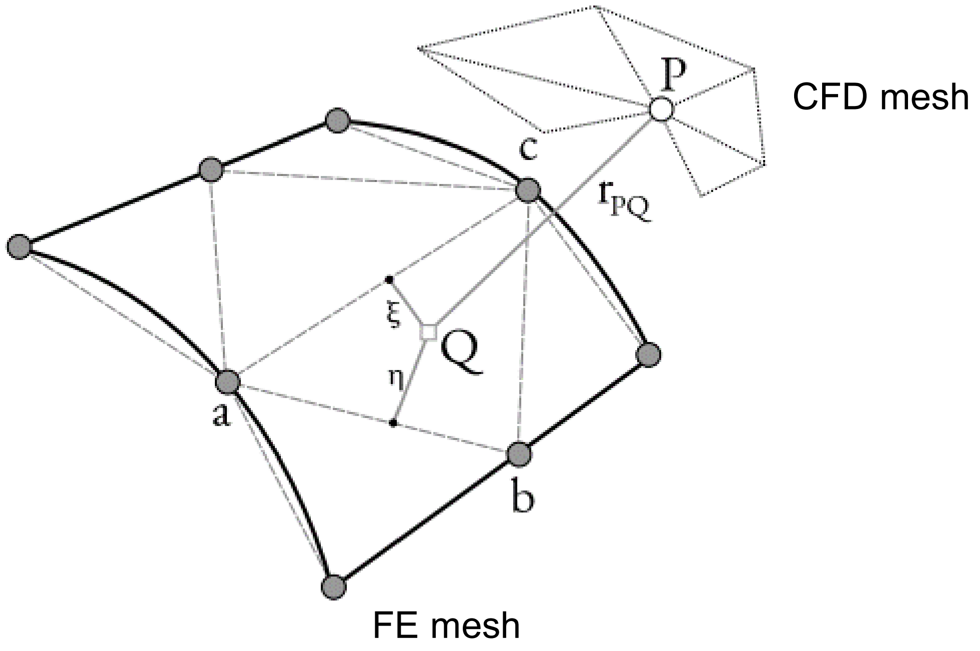
NFFP5: MAPPING CFD ←→ FEM

- New method(s):

  - developed by KTH (D. Eller) in NFFP5, tailored for aeroelastic purposes, implemented in ***Dwfscope***
  http://www.larosterna.com/scope.html

  Various methods available for mapping e.g.
  - Radial Basis Functions
  - **Surface Projection Method**

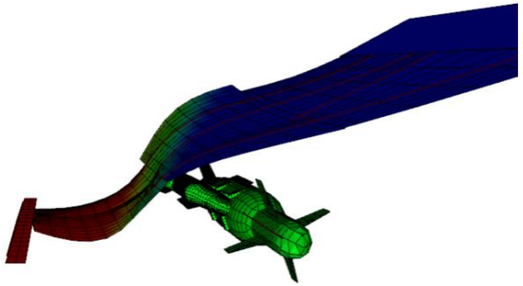
  Other Features
  - Smoothing capabilities
  - Writes mapping matrix H
  - Writes aeroelastic output files for *Edge* (.bdis)

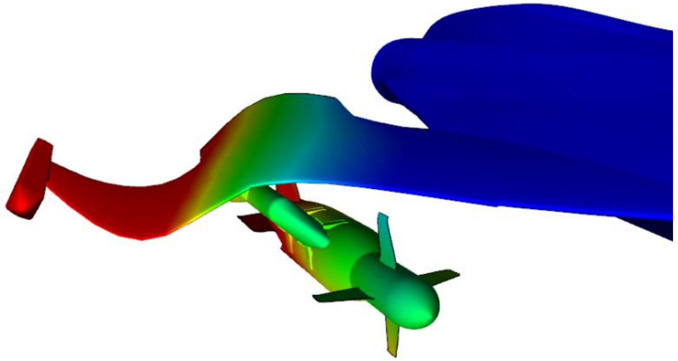


NEW DEVELOPMENT

NFFP5: MAPPING CFD ←→ FEM

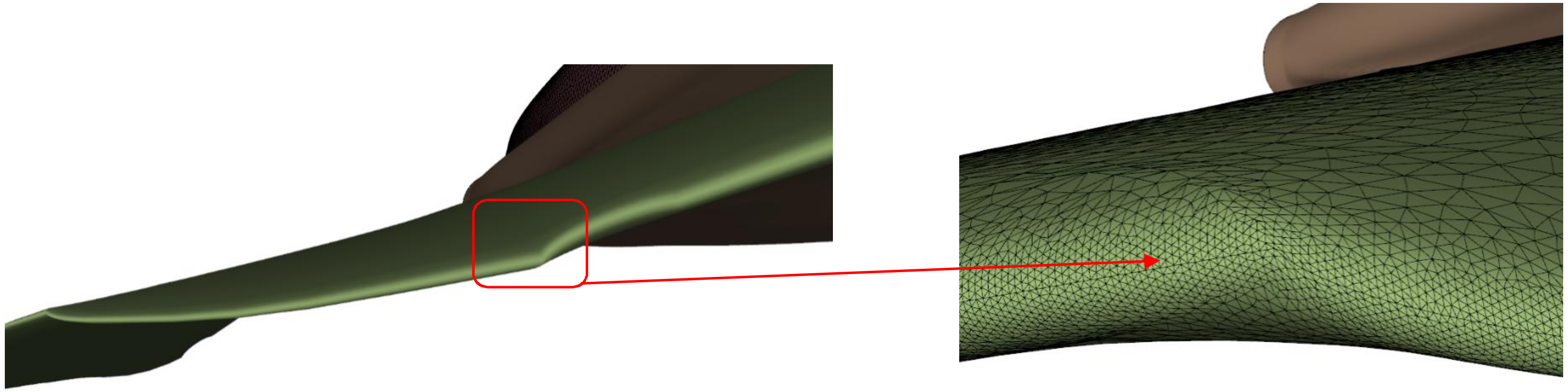
- New method(s):



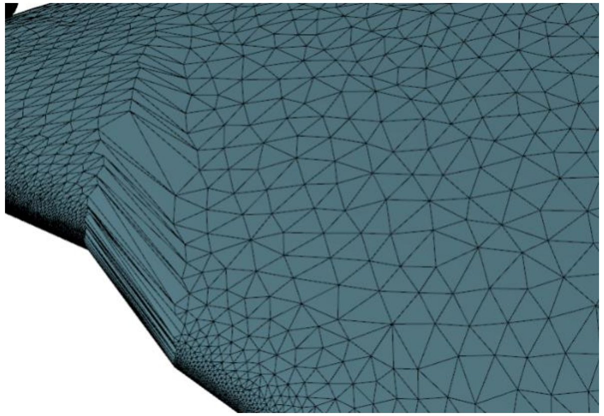


Can handle:

- Complex geometries (underwing stores)
- discontinuous deformations, e.g. gap between control surface and wing



With smoothing

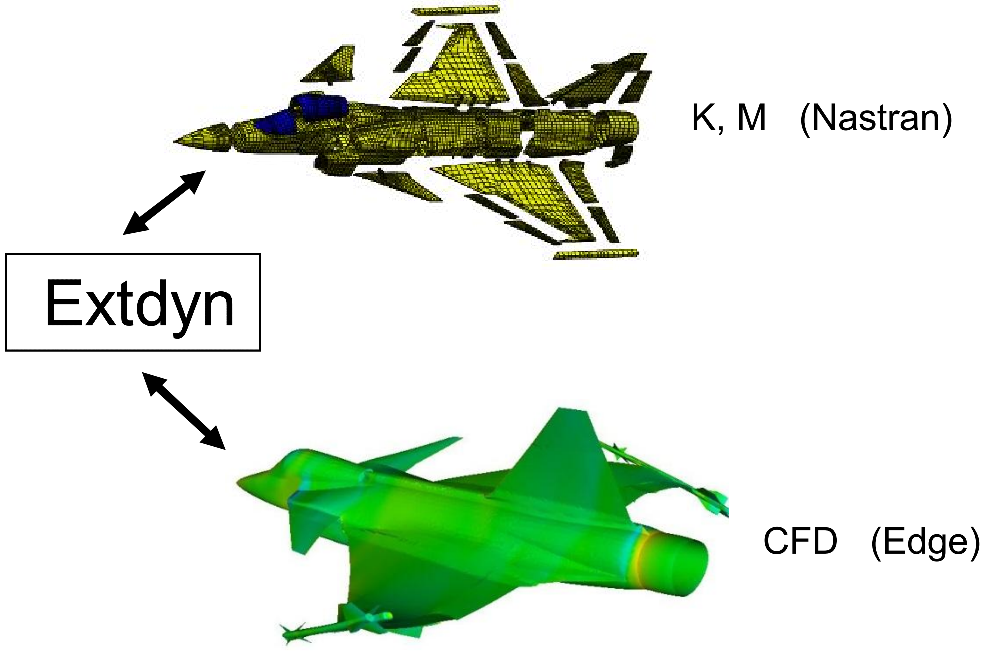


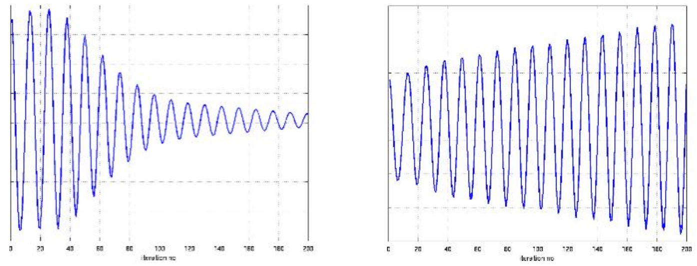
No smoothing

NEW DEVELOPMENT

ISSA: NON-MODAL CFD-FEM

- New method:
  - Developed by FOI, A. Jirasek & O. Amoignon
  - Enables **coupling** the CFD solver ***Edge*** with an **external structural solver** in time domain, implemented in ***Extdyn***
  - *Extdyn* is a solver which integrates structural equations in time domain. The mass and stiffness matrices, **M and K**, of the structural problem are defined and exported **from NASTRAN**
  - can be run in **steady state** mode for a **static analysis** or in **time dependent mode** for a **dynamic aeroelastic analysis**
  - Includes advanced data communication for parallel computations





NEW DEVELOPMENT

ISSA: NON-MODAL CFD-FEM

Coupling in Extdyn:

– integrates the equation of motion in the time domain on a subset (Aset) of the original global set (Gset) according to

$$M_A\ddot{u}(t) + C_A\dot{u}(t) + K_A u(t) = f_A(t)$$

while n<MAX do

Receiving data CFD solver f^n_{CFD}

CFD to FEM: $f_I \leftarrow H^T_{fs} f^n_{CFD}$

FEM to ASET: $\tilde{f}_A \leftarrow H^T_A f_I$

ASET b.c.: $f^n_A \leftarrow \tilde{f}_A$

ASET solver: $u^n_A \leftarrow S(K_A, M_A, C_A, u^{n-1}_A, f^n_A)$

ASET to FEM: $u_I \leftarrow H_A \tilde{u}_I$

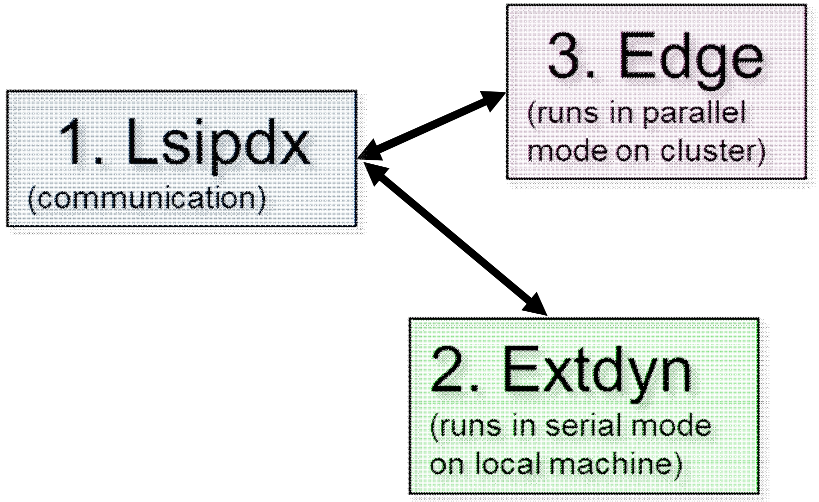
FEM to CFD: $u^n_{CFD} \leftarrow H_{fs} u_I$

Sending to CFD solver

Running the non-modal coupling:

– The non-modal coupling is run by starting three different processes (programs) in different terminal windows

– In practice: Only one script has to be started



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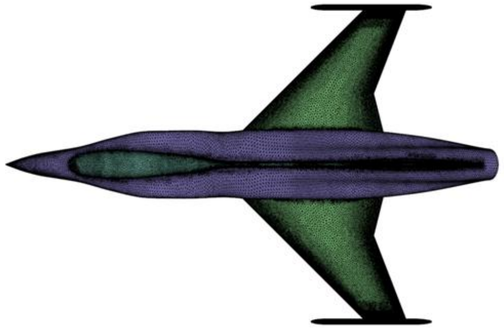
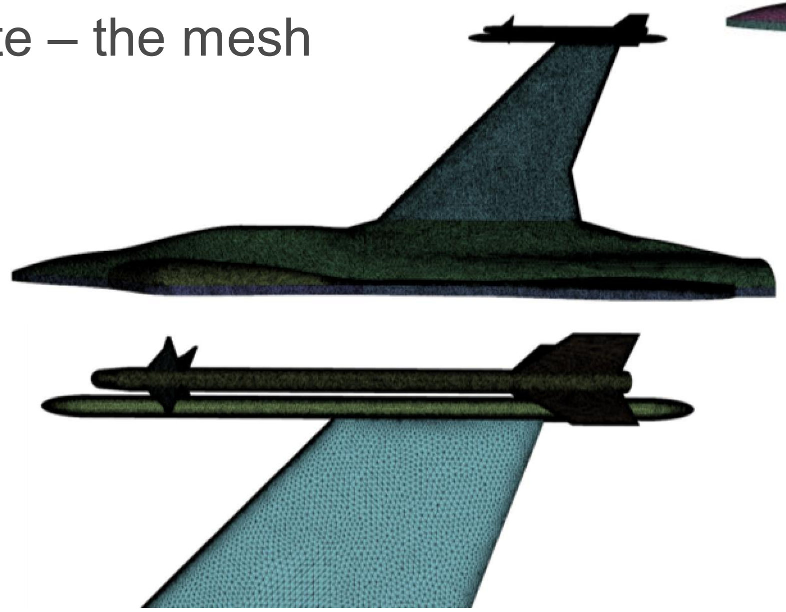
MODELLING ASPECTS

GEOMETRICAL COMPLEXITY

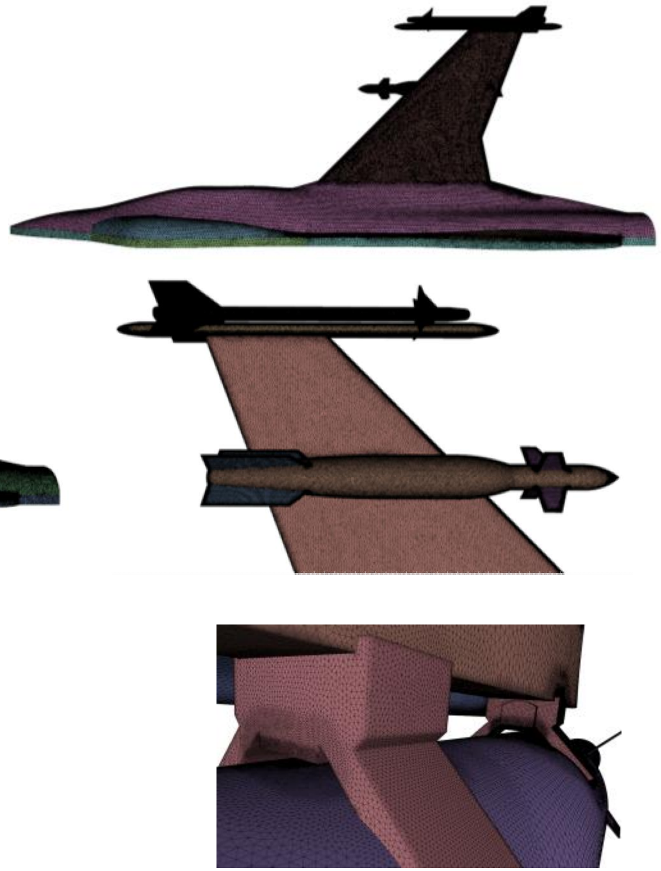
- In the ISSA project several models were studied with different geometrical complexity
- The wind tunnel tests were also performed with several configurations (different external stores)
- For aeroelastic simulations – time accurate – the mesh size has to be reasonable



750 000 points



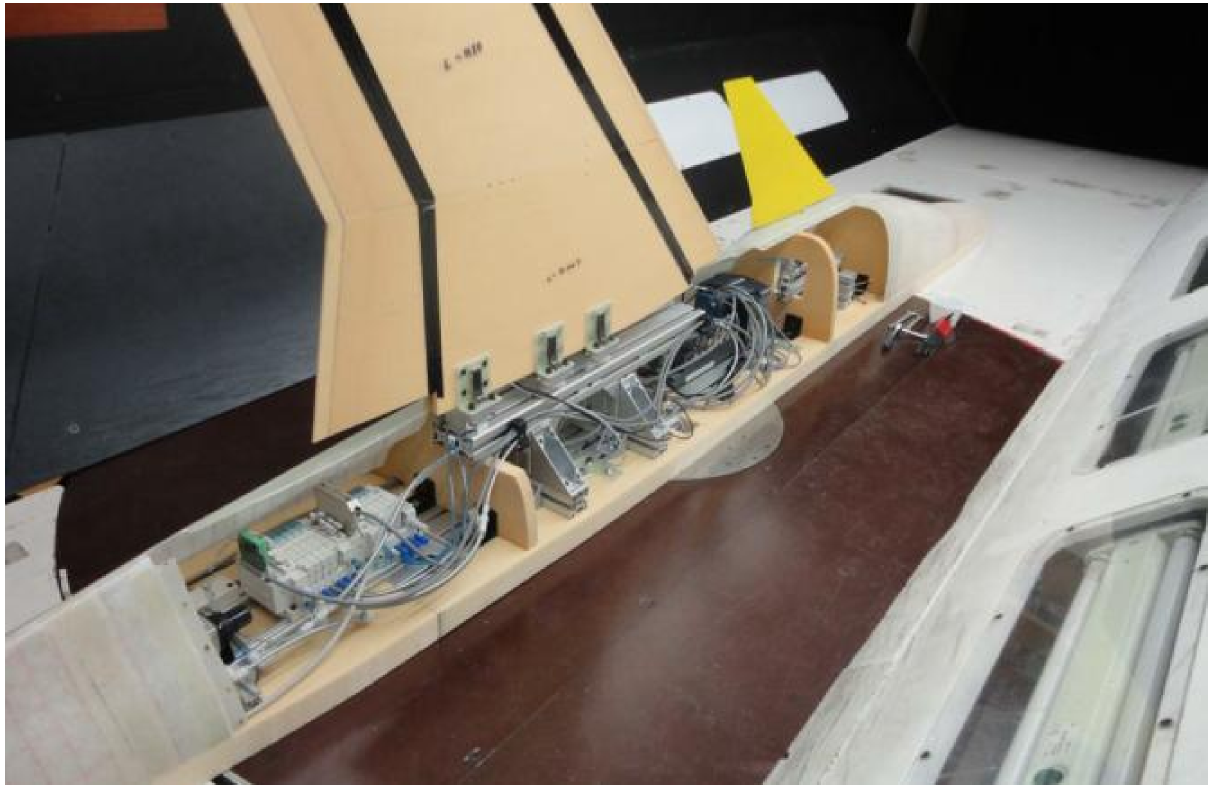
1 945 934 points



4 264 161 points

MODELLING ASPECTS *COMPLEX HARDWARE MODEL*

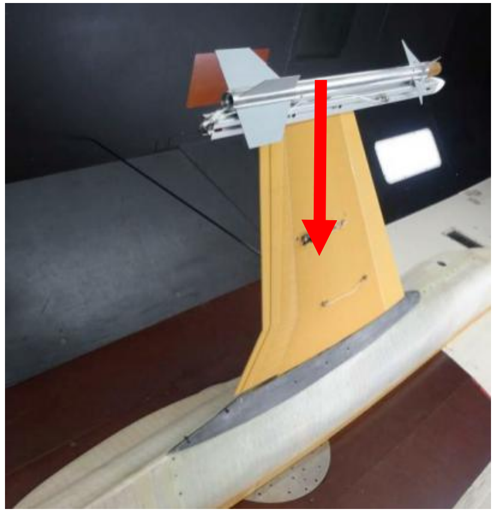
- Model, designed and constructed by KTH, Prof. Ulf Ringertz and team, floor mounted with all equipment inside fuselage
- Complex pylon design for mimicking real A/C suspension (sway brace)



MODELLING ASPECTS

GRAVITATIONAL FORCES

- For configurations with underwing external stores the floor mounted WT model will give rise to a static deformation

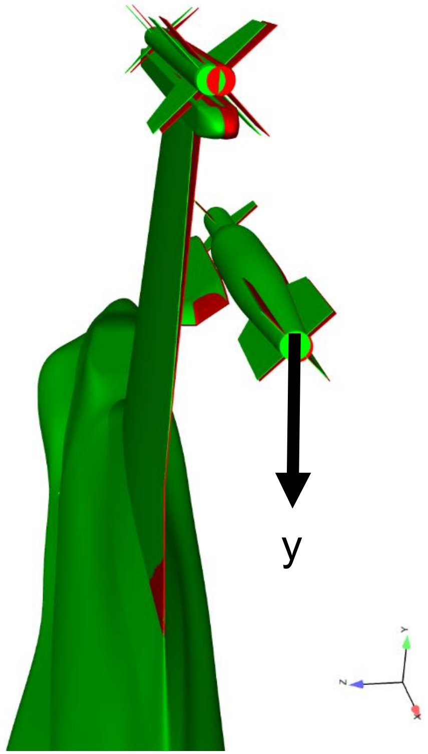


CONTENTS

VALIDATION

GRAVITATIONAL FORCES

- Effect of gravity on WT model including GBU - validation for Y-direction



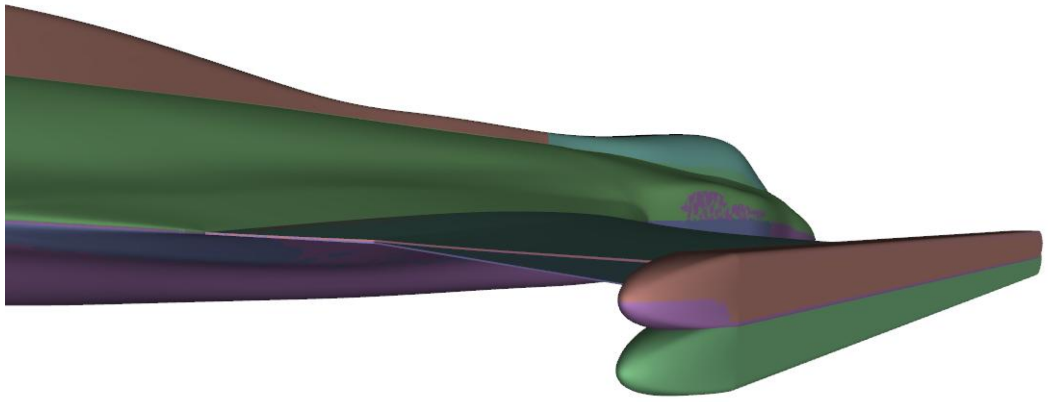
Deformation due to gravitational forces in y direction

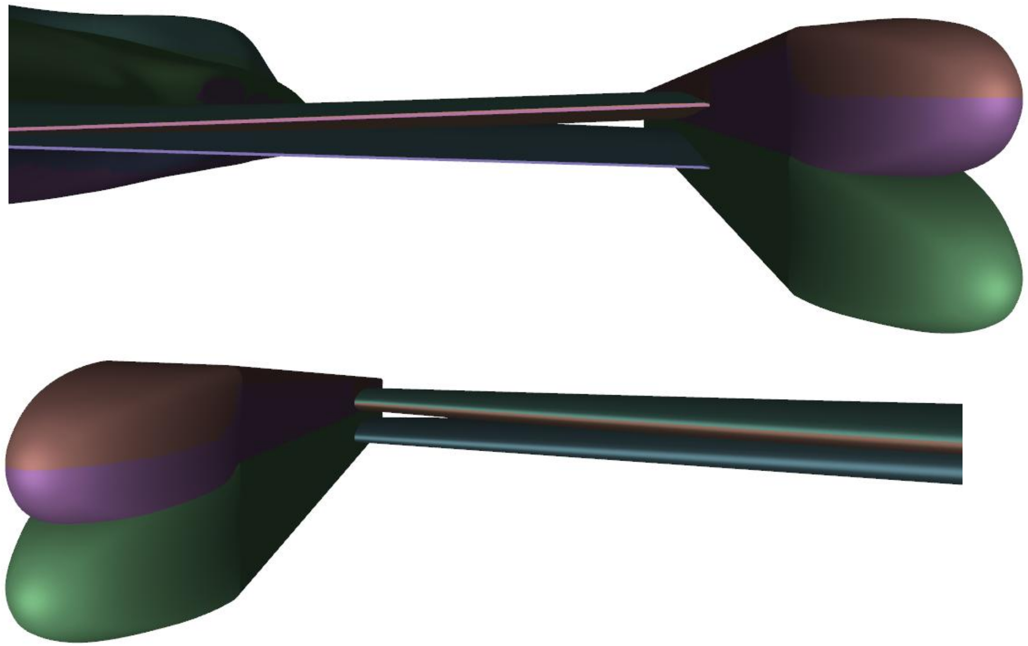
	Extdyn (G-set)		**Nastran**	
	Min disp [mm]	Max disp [mm]	Min disp [mm]	Max disp [mm]
X	-0.26	0.48	N/A	N/A
Y	-0.92	3.92	-0.92	3.92
Z	-0.079	11.2	-0.079	11.2

VALIDATION

STATIC DEFORMATION

- Comparison with existing modal approach and new non-modal approach (direct coupling Nastran)
  - Rigid (green - on pylon)
  - static aeroelastic shape (brown - on pylon) for modal approach
  - static aeroelastic shape (purple - on pylon) for non-modal approach





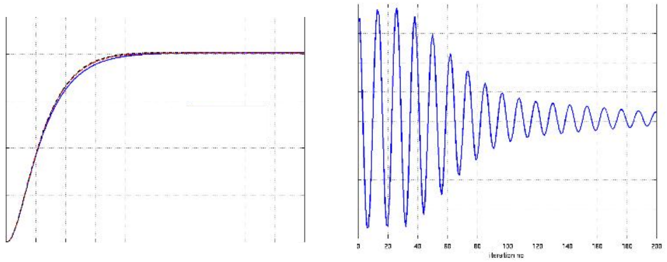
CONTENTS

RESULTS

SIMULATION / PREDICTION

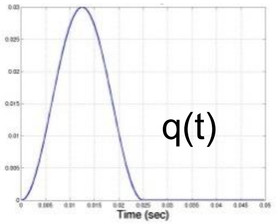
- Coupled analysis (modal & non-modal formulation)
  - Static (critical damping = 1 used)
  - Dynamic (zero or structural damping used)

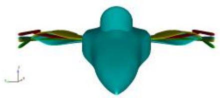
Simulations



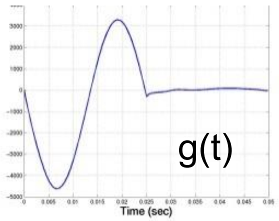
- Prescribed motion for generating GAF(ω) from CFD
  (Standard flutter analysis subsequently used)

perturbation



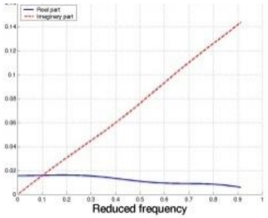


response



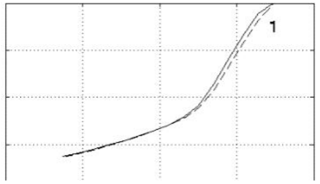
FFT

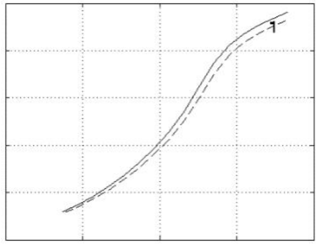
GAF(ω)



$$\mathbf{GAF}(\omega) = \hat{g}(\omega) / \hat{q}(\omega)$$

Predictions





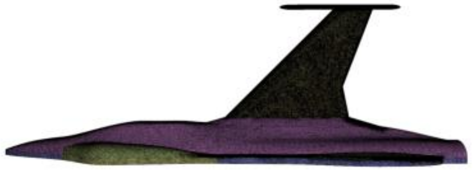
Speed

RESULTS

CONFIGURATIONS / CASES

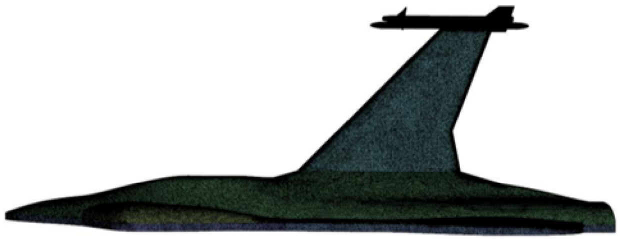
- Several configurations tested in the wind tunnel
- A selection of results presented here:
  - **Case 1**: config1_00 (no wing tip missile, no GBU)
  - **Case 2**: config2_0F (wing tip missile CG forward, no under wing store)
  - **Case 7**: config7_FR (wing tip missile CG rearward, GBU CG forward)

1

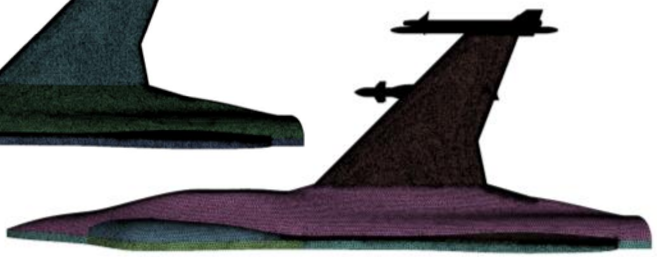


Case 1 mainly used for static aeroelastic analysis

2



7

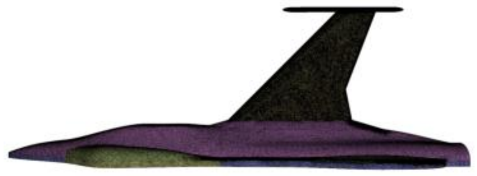


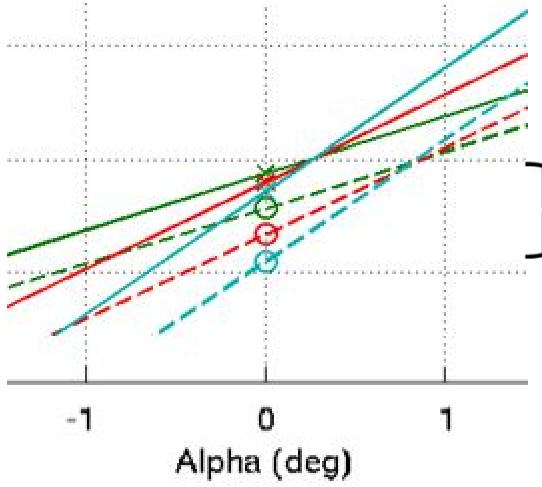
Case 2 and 7 is mainly for dynamic analysis

RESULTS

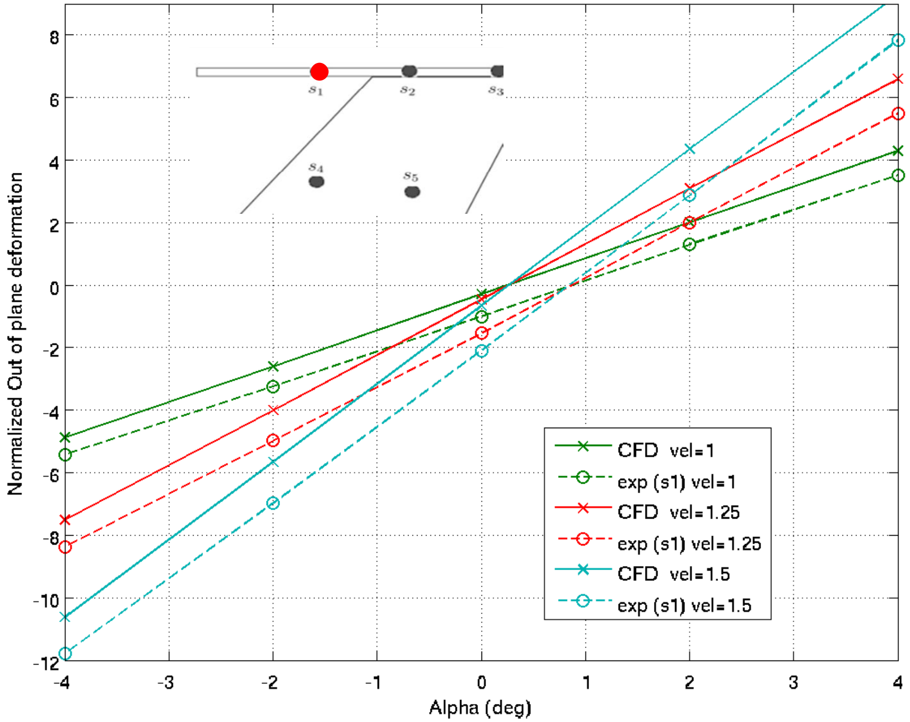
STATIC DEFORMATION - CASE 1

- Good correlation with exp . data but a small offset observed
- Investigations made regarding
  - Wind tunnel effects (not causing offset)
  - Viscosity, Euler/NS (not “causing” offset)
- Conclusions: The asymmetry found in WT not reproducible in analysis





Offset at α=0°

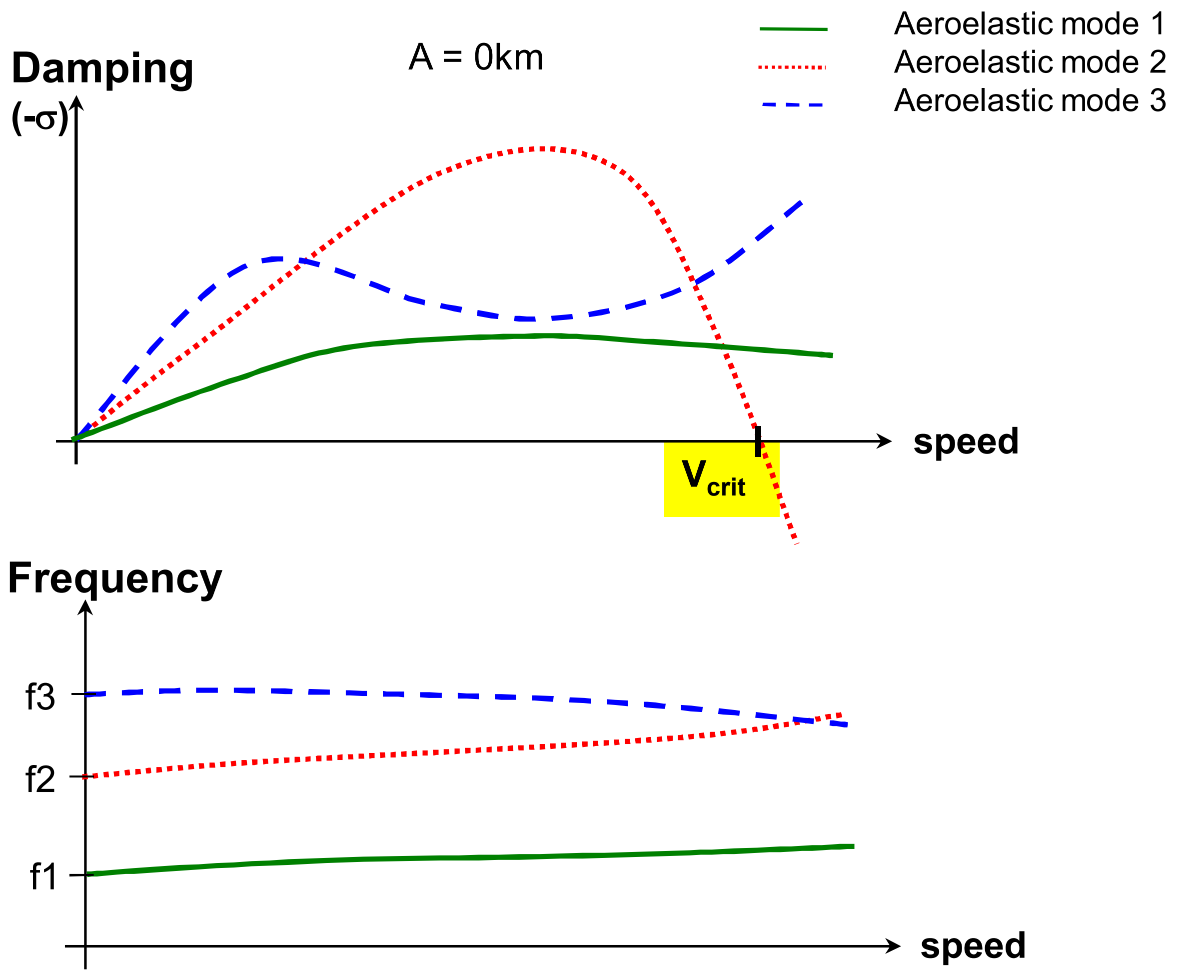


RESULTS

DYNAMIC PREDICTIONS

Main objective for dynamic ***predictions***

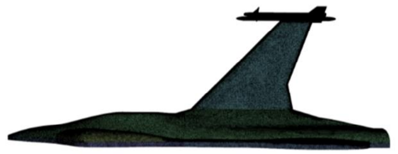
- Damping and frequency
  - as a function of speed
- Predict flutter speed

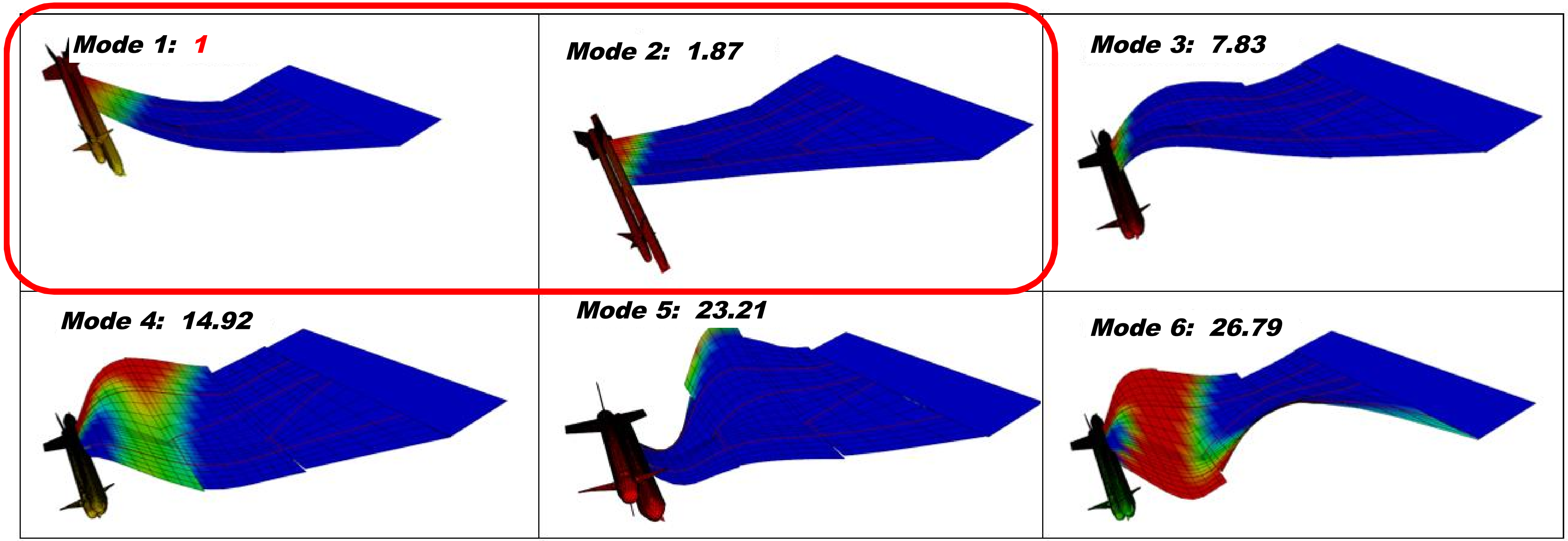


RESULTS

FLUTTER MECHANISM - CASE 2

- Only modes 1 (bending) and 2 (torsion) couple and give flutter

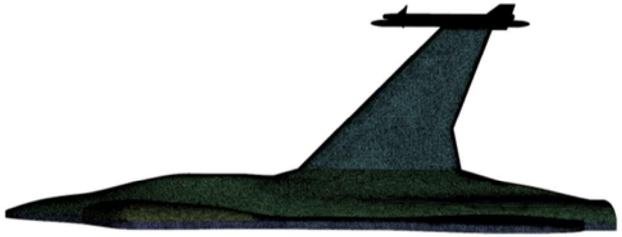




RESULTS

FLUTTER PREDICTION - CASE 2

- Model: Wing tip missile
- Method: Medium Fidelity: Modal approach (5 modes)
- Frequencies: from GVT in wind tunnel (modes 1-3)
- Structural damping: g1=1, g2=1.3



Increasing model fidelity →

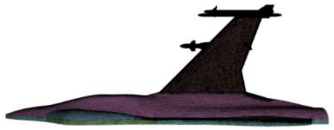
	FE baseline	WT frequencies (WTF)	WTF & struct damping*	Experiment
Flutter speed	1.03	0.96	0.98	1
Flutter frequency	1.06	1.01	1.00	1

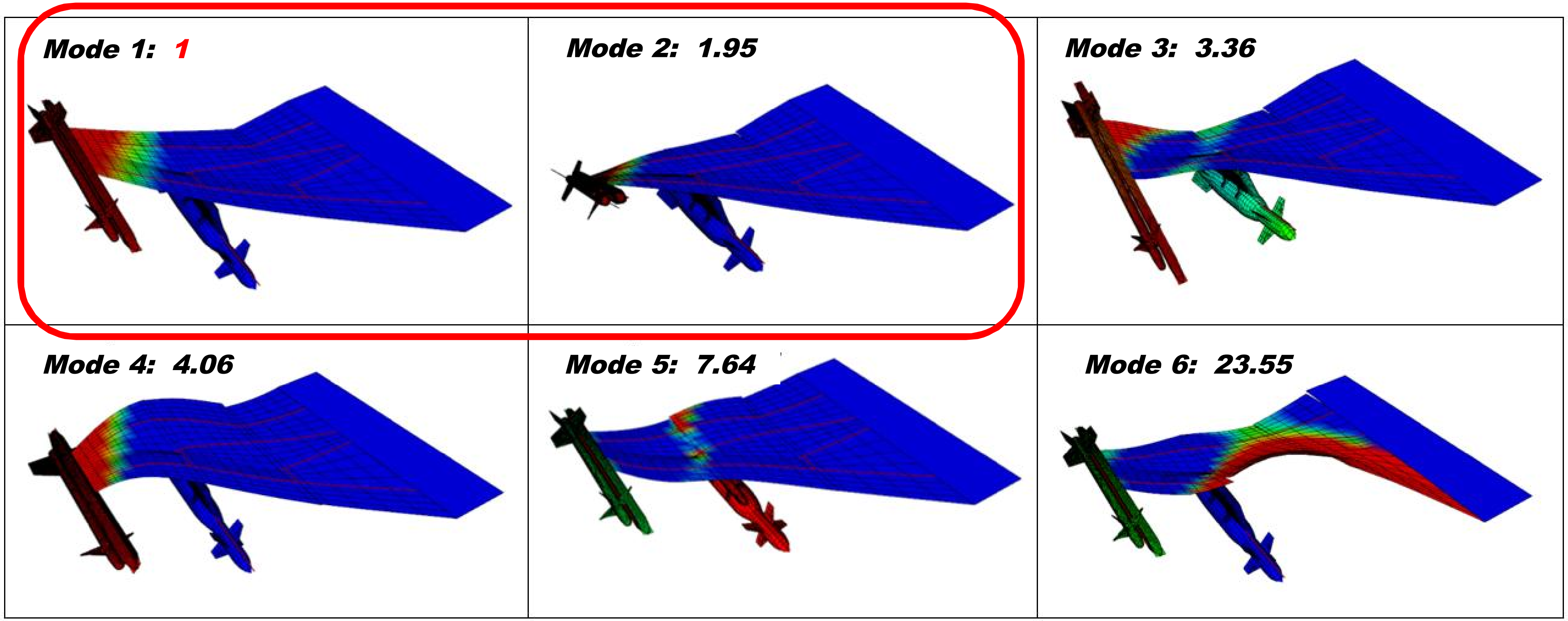
*) Modes 1 & 2

RESULTS

FLUTTER MECHANISM - CASE 7

- Only modes 1 (bending) and 2 (torsion) couple and give flutter

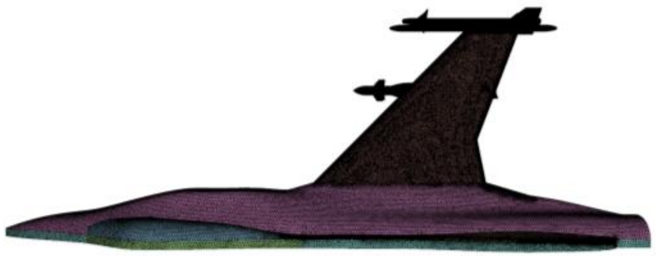




RESULTS

FLUTTER PREDICTION - CASE 7

– Model:	Wing tip missile + GBU (no sway brace)
– Method:	Medium Fidelity: Modal approach (5 modes)
– Frequencies:	from GVT in wind tunnel (modes 1-3)
– Structural damping:	g1=1, g2=0.91, g3=2.1



Increasing model fidelity →

	FE baseline	**WT frequencies* (WTF)**	**WTF & struct damping**	**WTF & struct damping & initial static deformation**	**Experiment**
Flutter speed	1.07	1.00	1.04	1.03	1
Flutter frequency	1.09	1.01	0.99	0.99	1

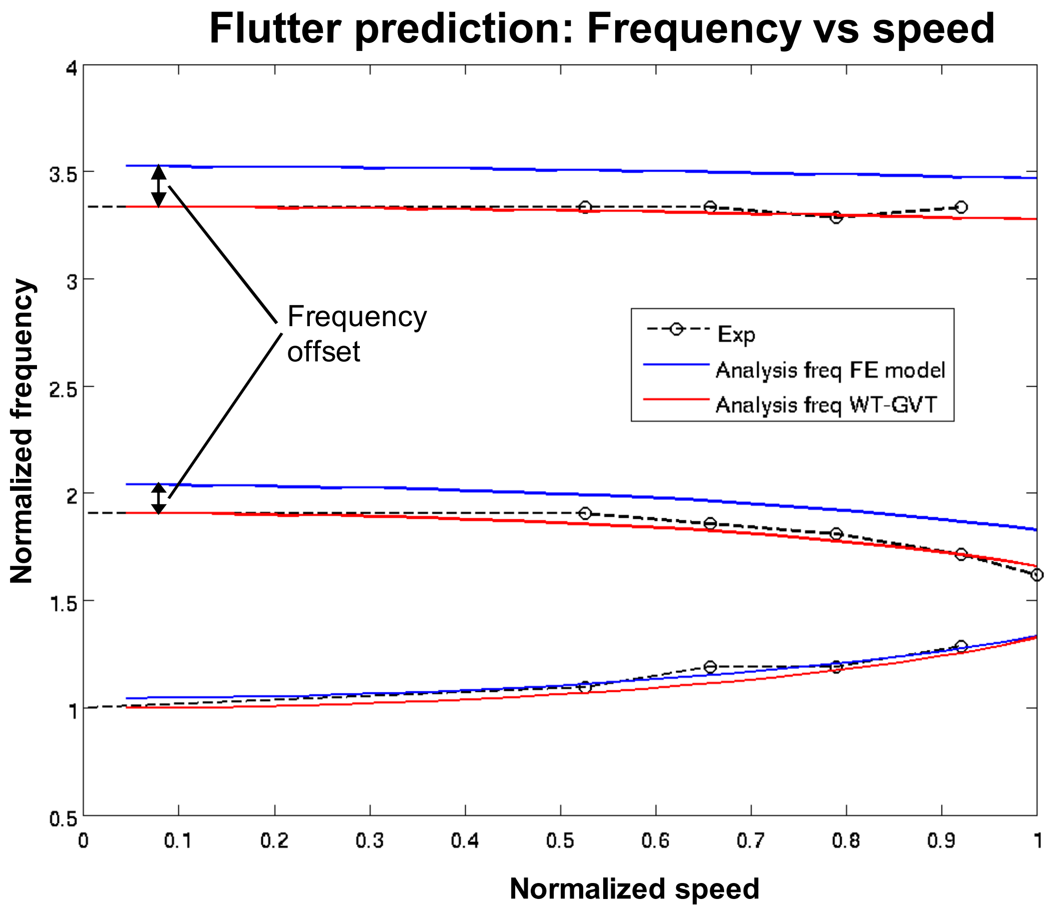
*) Modes 1-3

RESULTS

IMPORTANCE OF STRUCTURAL MODEL - CASE 7

- **Background**: FE model updated from GVT results
- **Problem**: Still differences can be found compared to measured natural frequencies of model in wind tunnel
- **Cause**: instrumentation such as accelerometers in wing tip pylon not accounted for
- **Effect**: Too high predicted flutter speed and flutter frequency

- **Lessons learnt**: Any small additional mass must be included in the FE model



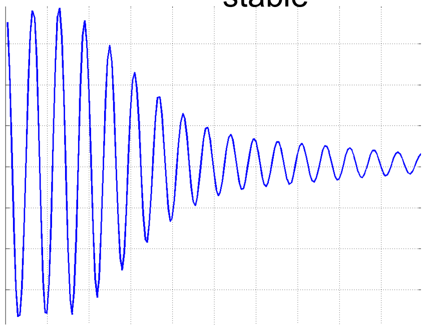
RESULTS

DYNAMIC SIMULATIONS

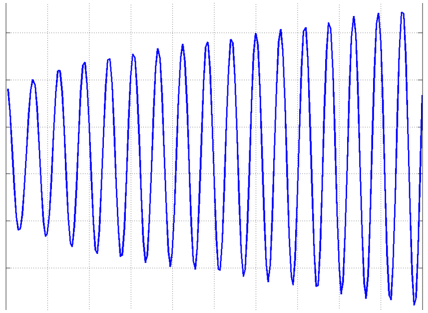
Two main objectives for dynamic ***simulations***

- Stability
  - “Easy” to include HiFi aerodynamics and structure
  - Very time consuming
  - Difficult to predict stability boundary

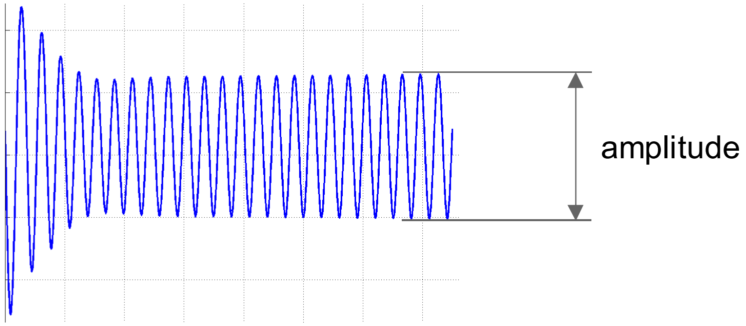
stable



unstable



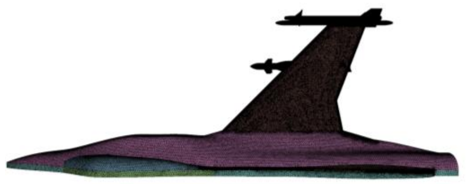
- Response (amplitude of oscillation)
  - Only of interest for constant amplitude cases e.g. LCO

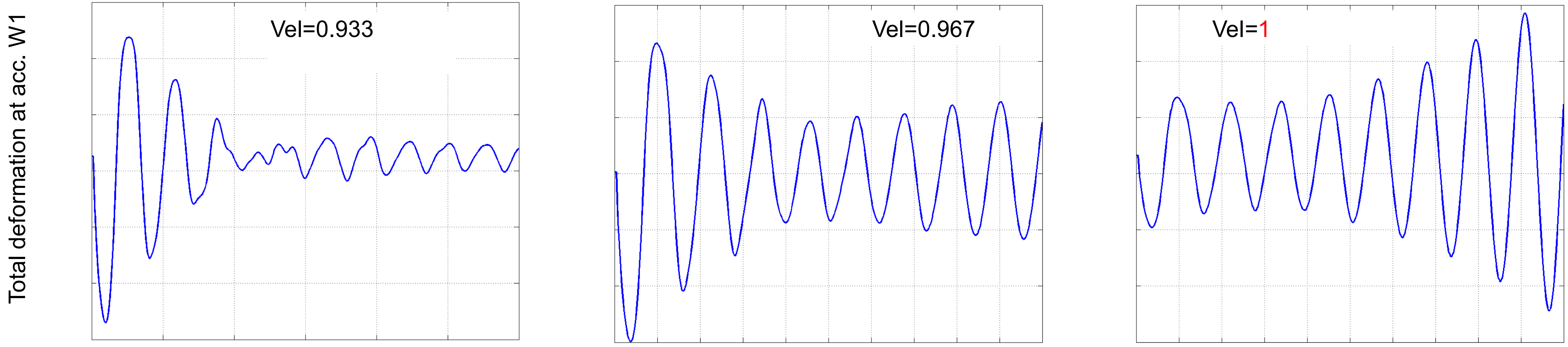


RESULTS

DYNAMIC SIMULATIONS - STABILITY (CASE 7)

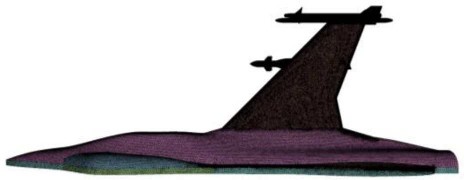
- CFD Model: GBU, no sway brace
- Method: Time domain simulation: **Modal approach (5 modes)**
- Frequencies: FE baseline
- Structural damping: No
- Normalization: Vel = $vel_{current}$ / vel_{case7}



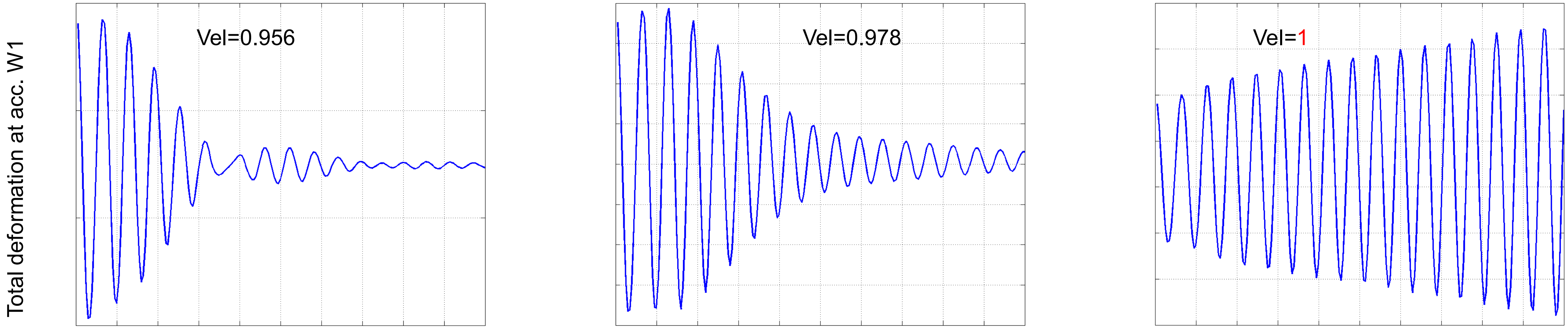


RESULTS

DYNAMIC SIMULATIONS - STABILITY *(CASE 7)*



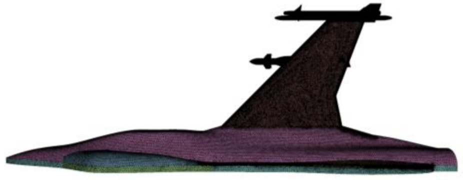
- CFD Model: GBU, no sway brace
- Method: Time domain simulation: **Non-modal approach**
- Frequencies: FE baseline
- Structural damping: No
- Normalization: $Vel = vel_{current} / vel_{case7}$



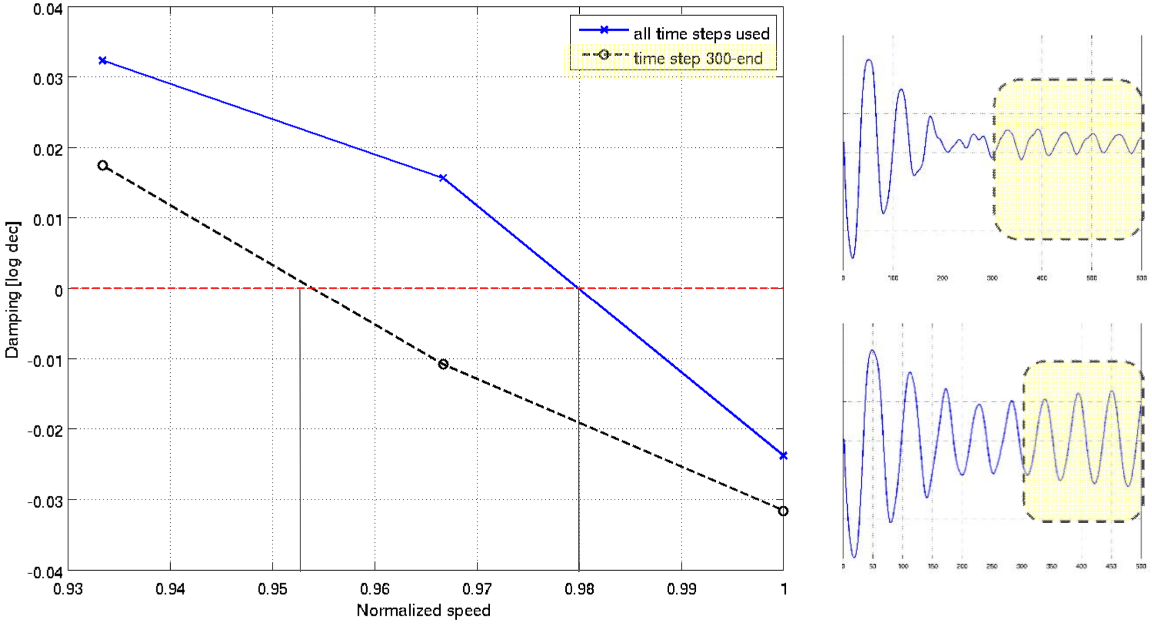
RESULTS

DYNAMIC SIMULATIONS - DAMPING *(CASE 7)*

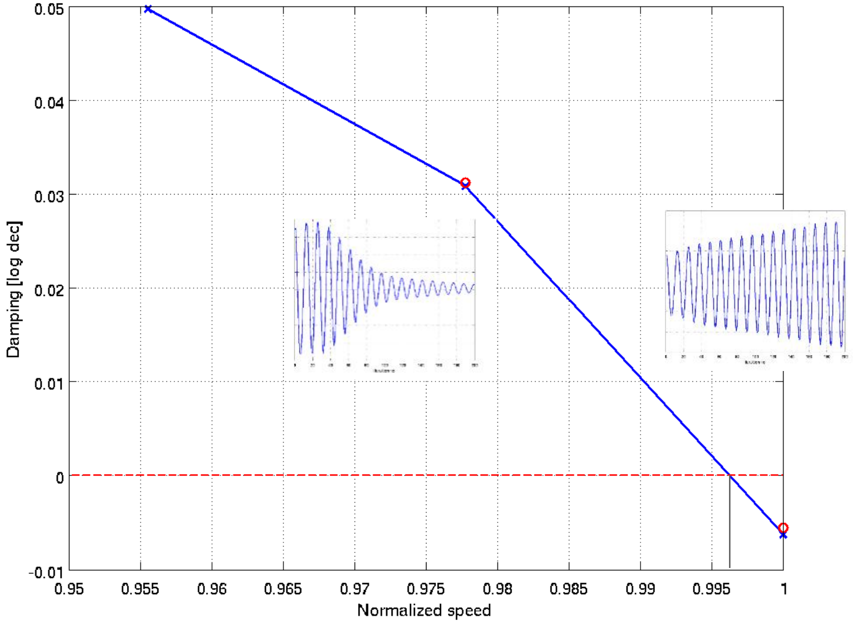
- Damping estimate from time history of accelerometer W1
- Sensitive physical quantity (difficult to estimate)
- Slightly higher V_{flut} for Non-modal approach



Modal



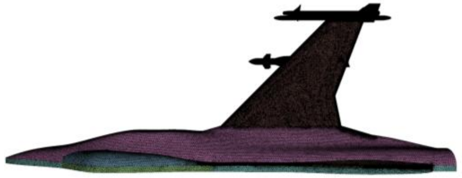
Non-modal

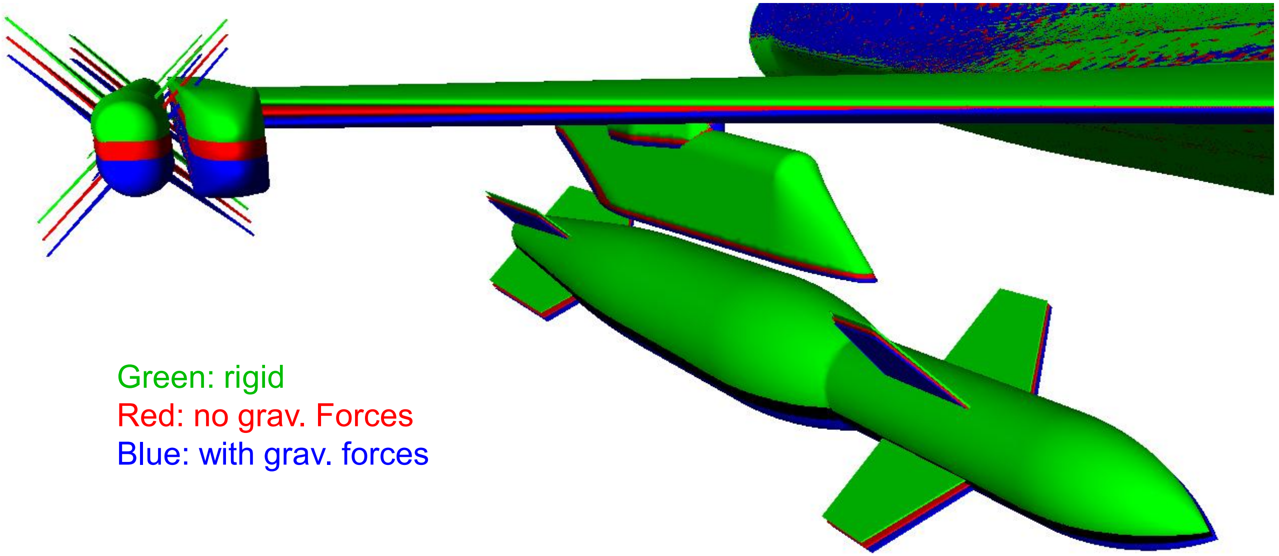


RESULTS

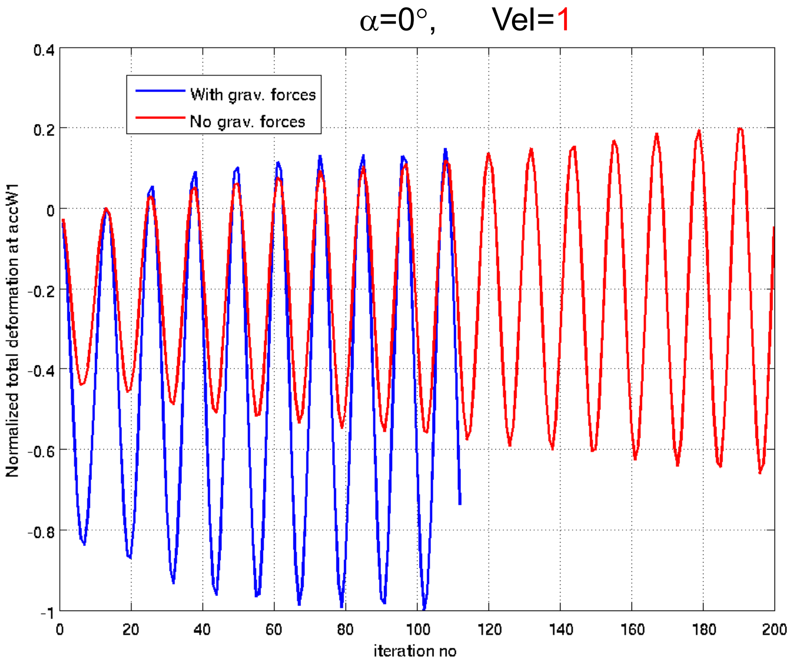
EFFECT OF GRAVITATIONAL FORCES – UNSTABLE CASE

- Large effect on static deformation (as expected)
- For dynamic simulations:
  - Small/no influence on stability characteristics
  - Amplitude is different if gravitational forces are included





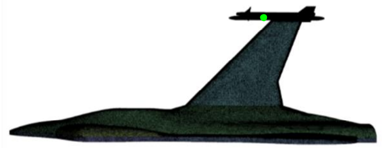
Green: rigid
Red: no grav. Forces
Blue: with grav. forces

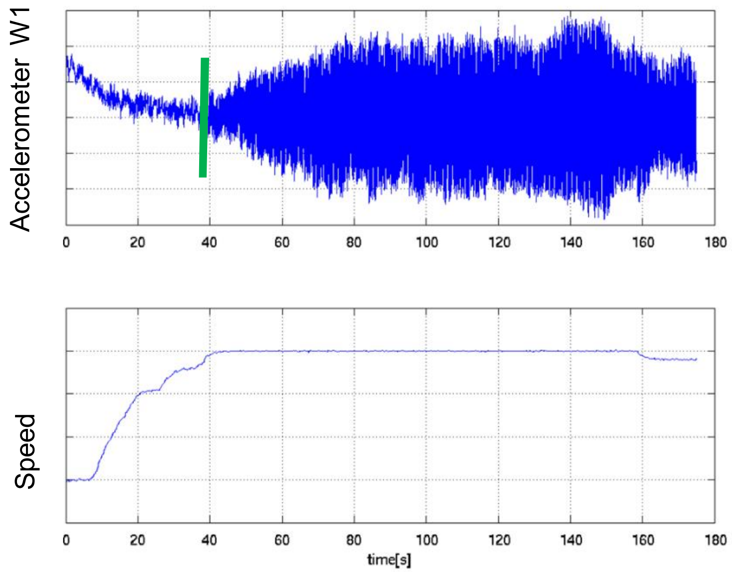


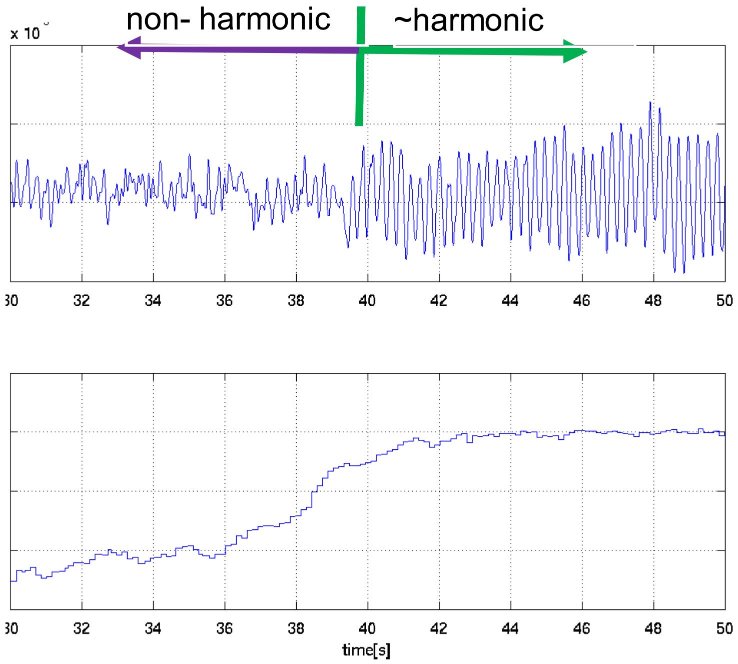
RESULTS

EXPERIMENTAL DATA (ISSA PROJECT)

- Three different configurations (complex model)
- Subcritical (with excitation) and flutter data
- Accelerometer data - uniaxial (W) and triaxial (WT)
- Optical deformation (QSYS)
- ***Unique aeroelastic data*** *(although only low speed)*



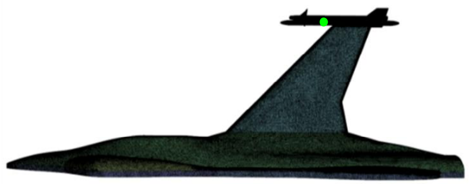




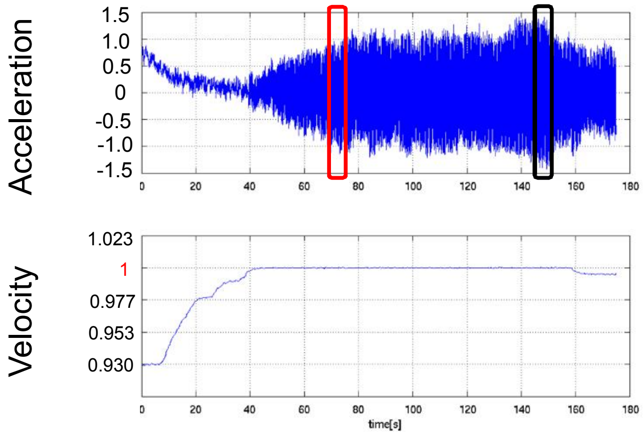
RESULTS

DYNAMIC SIMULATIONS - AMPLITUDE

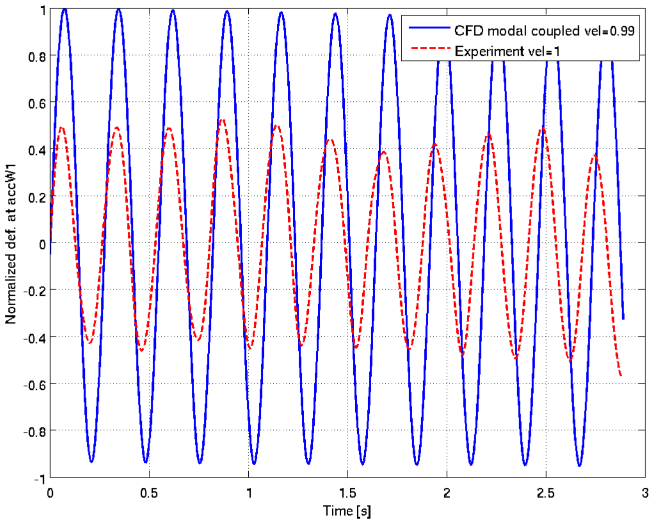
- Model: Wing tip missile
- Method: Modal approach (5 modes)
- Frequencies: from GVT in wind tunnel (modes 1-3)
- Structural damping: Yes



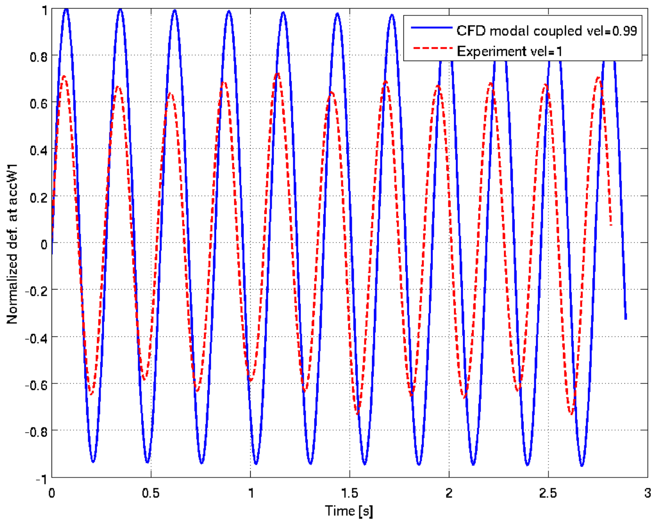
Experimental data (W1*)



Simulation vs experiment



Exp. time 70-75



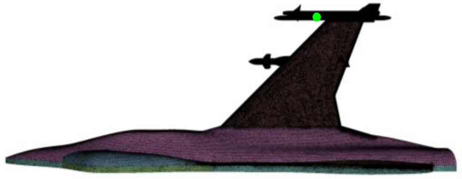
Exp. time 145-150

*)Uniaxial accelerometer

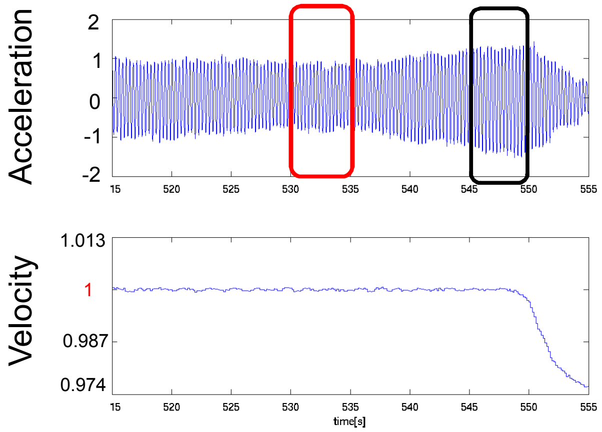
RESULTS

DYNAMIC SIMULATIONS - AMPLITUDE

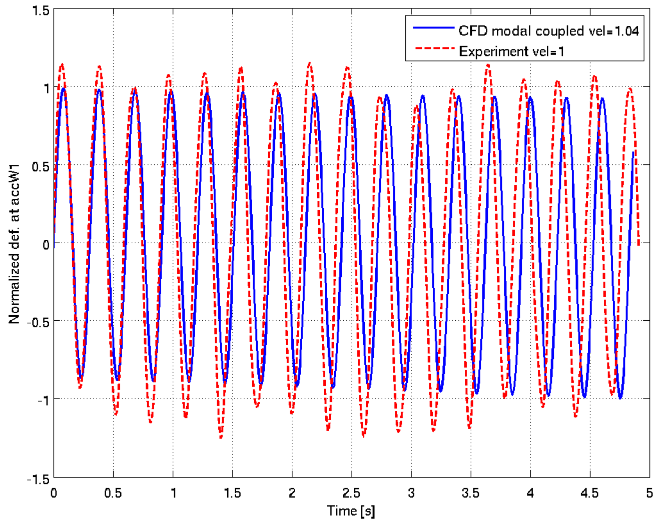
- Model: Wing tip missile + GBU
- Method: Modal approach (5 modes)
- Frequencies: from GVT in wind tunnel (modes 1-3)
- Structural damping: Yes



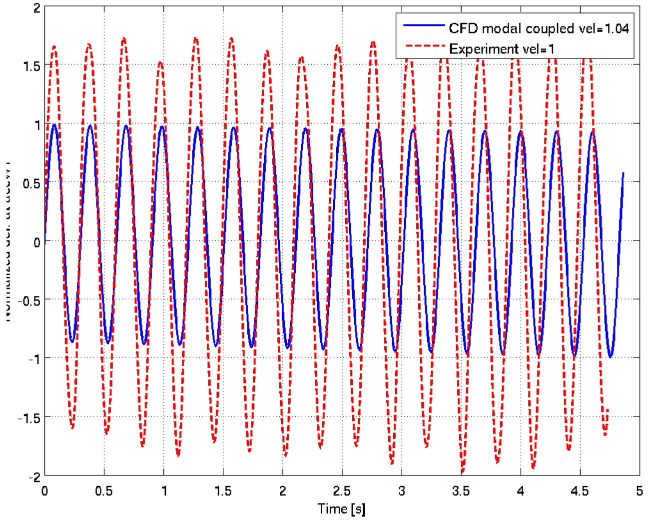
Experimental data (W1)



Simulation vs experiment



Exp. time 530-535



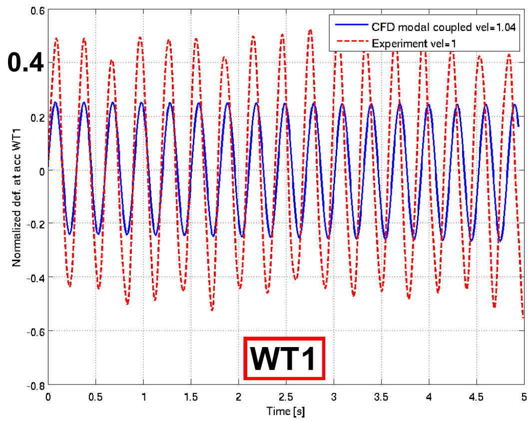
Exp. time 545-550

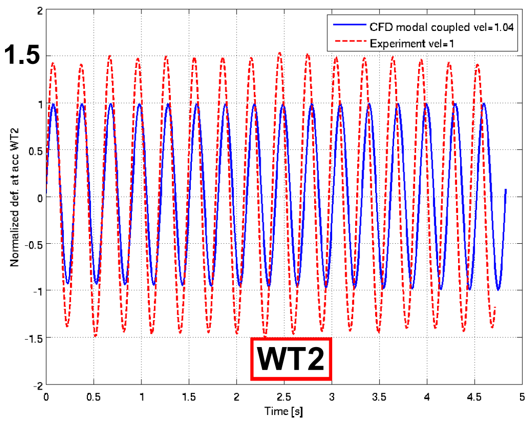
RESULTS

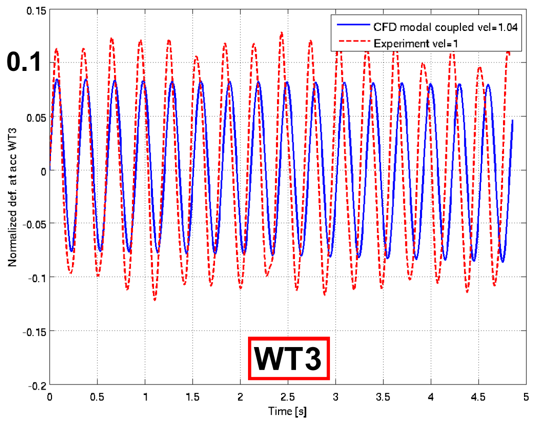
DYNAMIC SIMULATIONS - AMPLITUDE

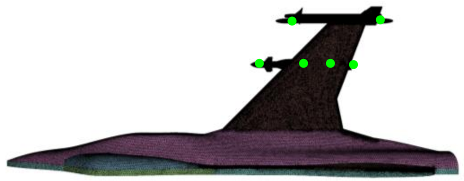
- Model: Wing tip missile + GBU, Method: Modal approach (5 modes)
- Experimental data: (***Triaxial acc. WT1 – WT6***)

=> Simulation follows amplitude variation (depending on location)

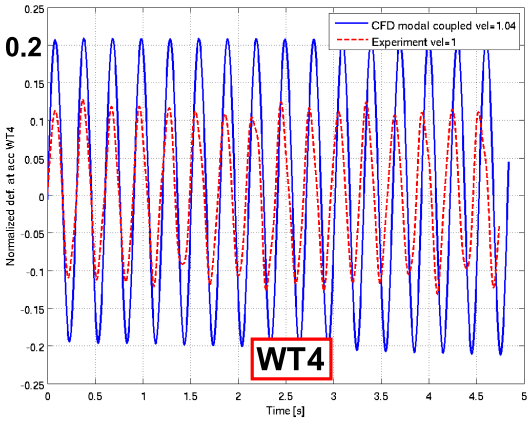


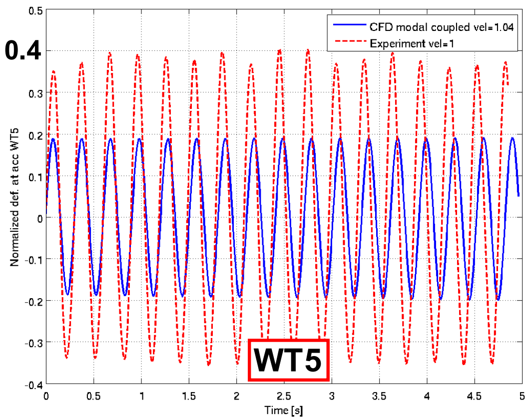


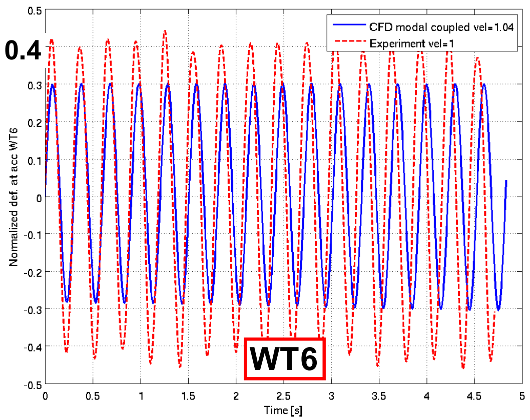


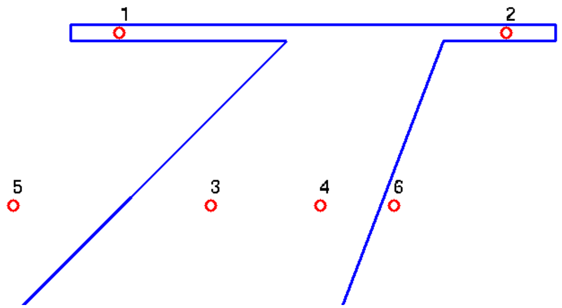


Exp. time 530-535







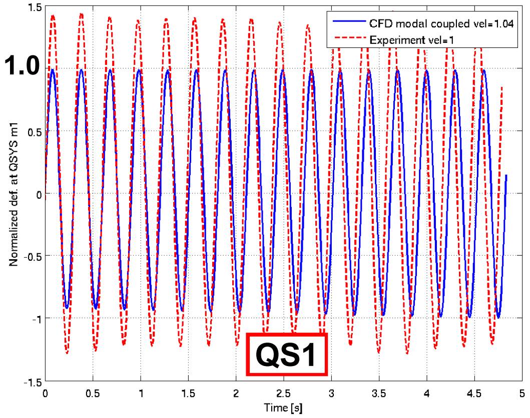


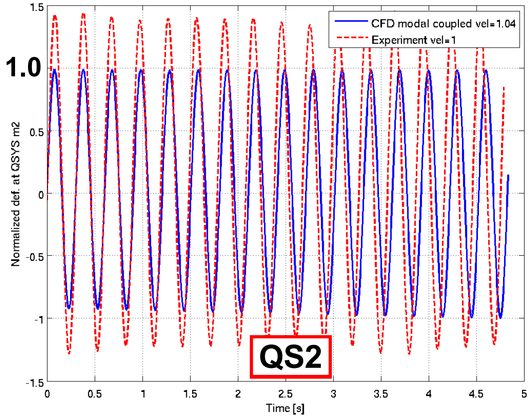
RESULTS

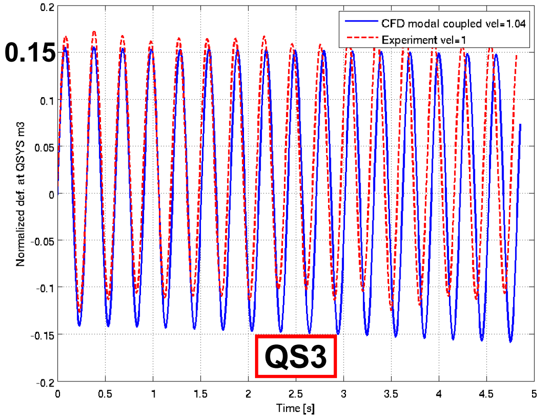
DYNAMIC SIMULATIONS - AMPLITUDE

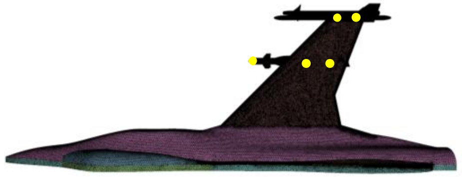
- Model: Wing tip missile + GBU, Method: Modal approach (5 modes)
- Experimental data: (***QSYS markers 1 – 7***)

=> Simulation follows amplitude variation (depending on location)

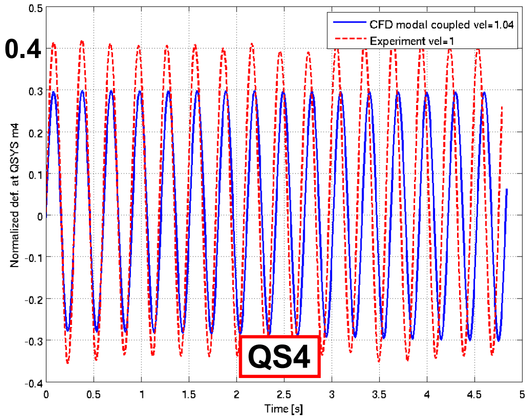


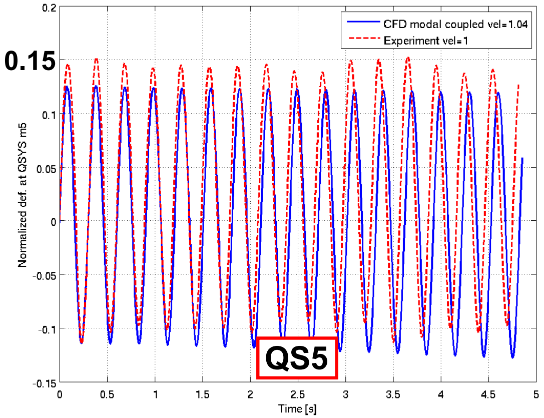


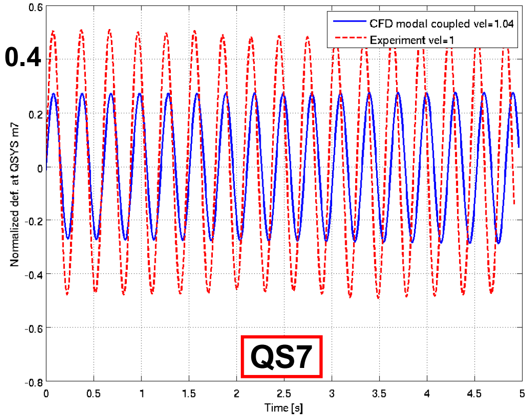


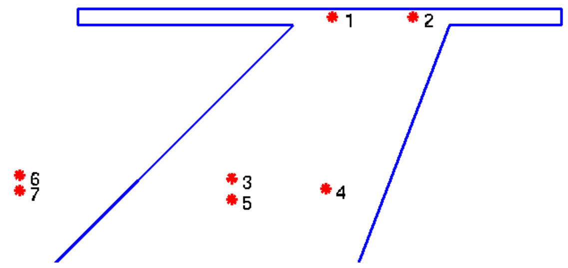


Exp. time 530-535









CONCLUSIONS

- New methods for non-linear aeroelastic analysis developed within NFFP5 and EDA R&D programs
  - Better handling of complex geometries
  - Non-modal coupling (platform for further development)
- In the EDA financed ISSA project
  - Unique aeroelastic experimental data
  - Complex Fighter model including external stores
  - Static deformation
  - Dynamic data (subcritcal as well as at flutter limit)
- Comparison with low speed WT data show:
  - Fairly good agreement for static deformation
  - Good agreement for flutter speed/frequency
  - OK agreement regarding dynamic amplitudes

QUESTIONS?

Thank you for your attention!