AAA Aeroelastic Prediction Workshop

Structural Dynamics Modeling for HIRENASD

Presented by:

Carol D. Wieseman

Aeroelasticity Branch, NASA Langley Research Center

On behalf of the AePW Organizing Committee

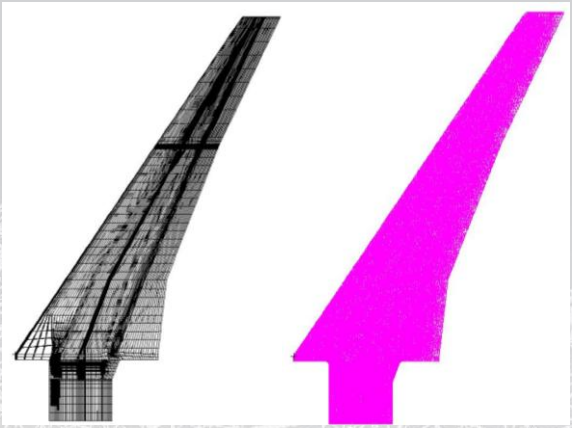
Principal contributors

- Carol Wieseman, NASA
- Jack Castro, MSC
- Alexander Boucke, Aachen University
- Jennifer Heeg, NASA
- Ruben Moreno, Gulfstream

OUTLINE

- Motivation
- Wind-tunnel model
- FEM Description
- Validation of FEM
- Summary

BACK STORY



- JUNE 2011
  - Wing-only wind tunnel models
    - Cantilevered
    - Extended inboard wing section
    - 2nd Bending Mode frequency approximately 86 Hz
  - Experimental frequencies approximately 78-80 Hz

  - Frequency discrepancy
  - Mode shapes? How do they compare?
  - What FEM should we use for AEPW?

ACKNOWLEDGEMENTS

- Original HEX and TET model were developed by Aachen University
  - http://heinrich.lufmech.rwth-aachen.de/en/hollow-wing-body-geometry
  - Based on design, construction and dynamic qualification tests by A. Dafnis, M. Kämpchen, H. Korsch at ILB, RWTH Aachen University
  - Original FE discretisation was delivered by L. Reimer at CATS, RWTH Aachen University according to the design data

- The weight distribution for non-structural mass (instrumentation/wiring) was provided by by A. Boucke, ITAM GmbH/RWTH Aachen University based on beam model

- Published references:

1. Dynamic qualification of the HIRENASD elastic wing model, Korsch, H. ; Dafnis, A.; Reimerdes, H.-G. Source: Aerospace Science and Technology, v 13, n 2-3, p 130-138, March 2009
2. Computational Analysis of High Reynolds Number Aero-structural Dynamics (HIRENASD) Experiments, Lars Reimer, Alexander Boucke, Josef Ballmann, and Marek Behr, IFASD-2009-130

Structural Dynamics Model Development Effort

- Finite element model modifications from June 2011 to Nov 2011 (final FEM)
  - Receipt of Tetrahedral Model with the missing parts
  - Inclusion of instrumentation
  - Inclusion of full balance model (inclusion of modelcart)
  - Modification of bolt connections of anregung to wing
  - Modification of OML
- Experimental Data Reduction of Air-off Data Sets
  - In tunnel excitation of using root exciters
  - Uncertainty characterization on frequencies and mode shapes
  - Accelerometers used
- Comparison of Modal Data (freqs & mode shapes via MAC)
  - June 2011 FEM
  - Experimental Data
  - Nov 2011 final FEM
- FEM deemed acceptable and uploaded to Website
  - Final FEM provided and the output from Nastran provided
  - Interpolation of modeshapes using JAMSHID's to the AEPW provided CFD Grids
  - Subset of modeshape deflections at 144 points on the wing and locations provided

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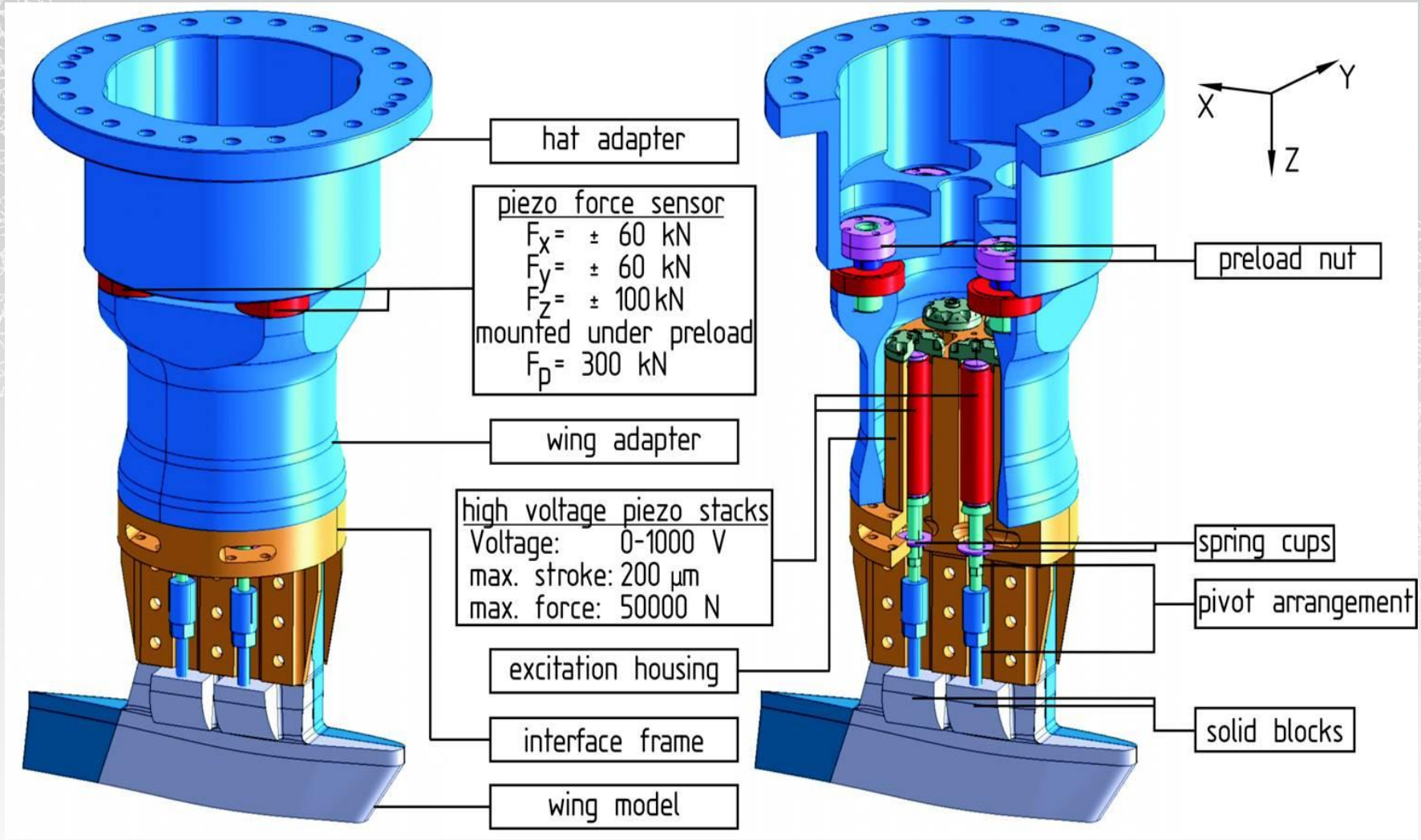
Wind Tunnel Model Mounted in ETS

Wind Tunnel Balance and Vibration Excitation Mech.



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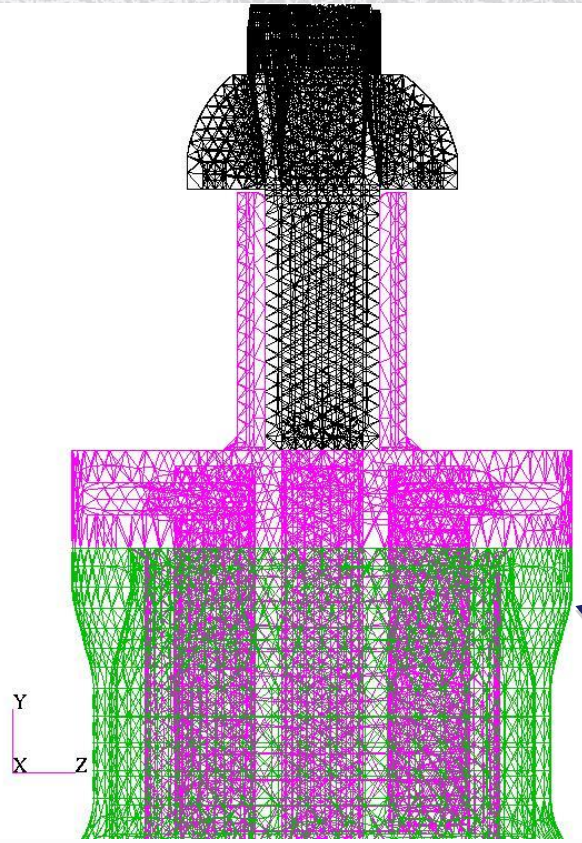
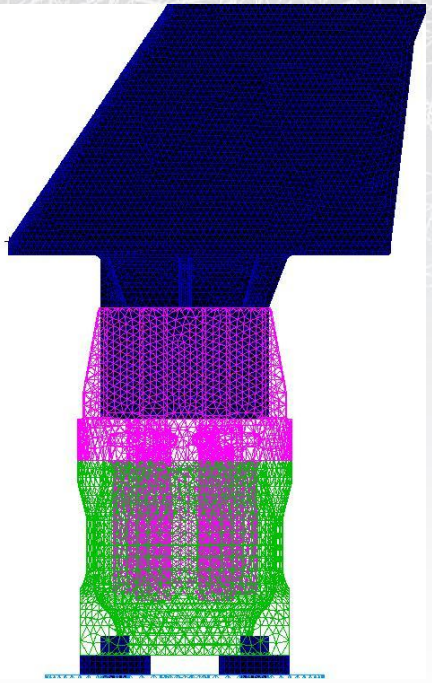
Tetrahedral Element Model

Wing: black and/or dark blue
Exciter (anregung): pink

Modelcart not included in figures

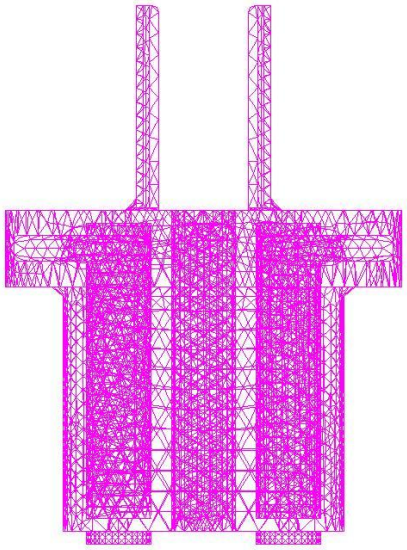


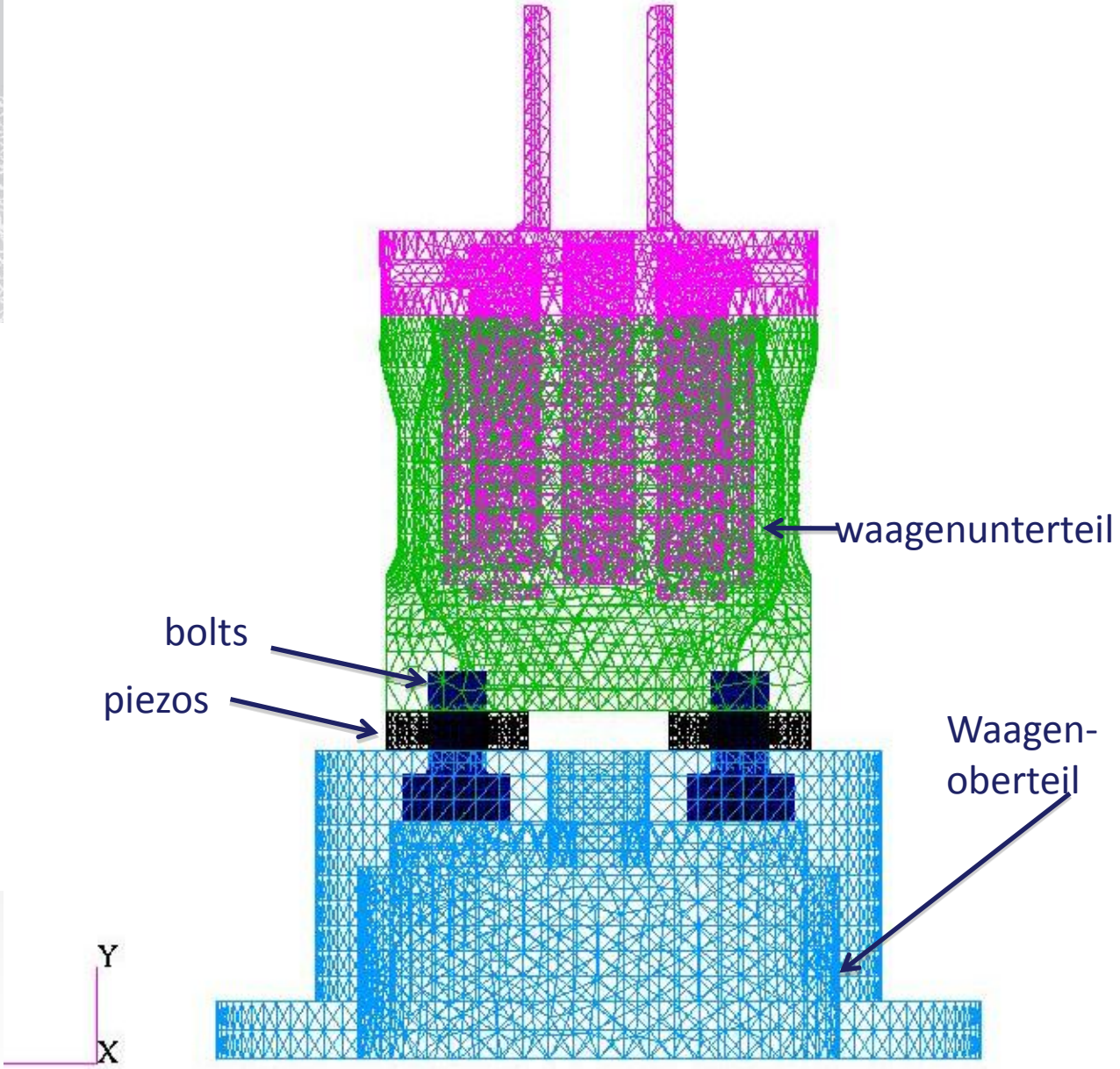
Waagen-
unterteil



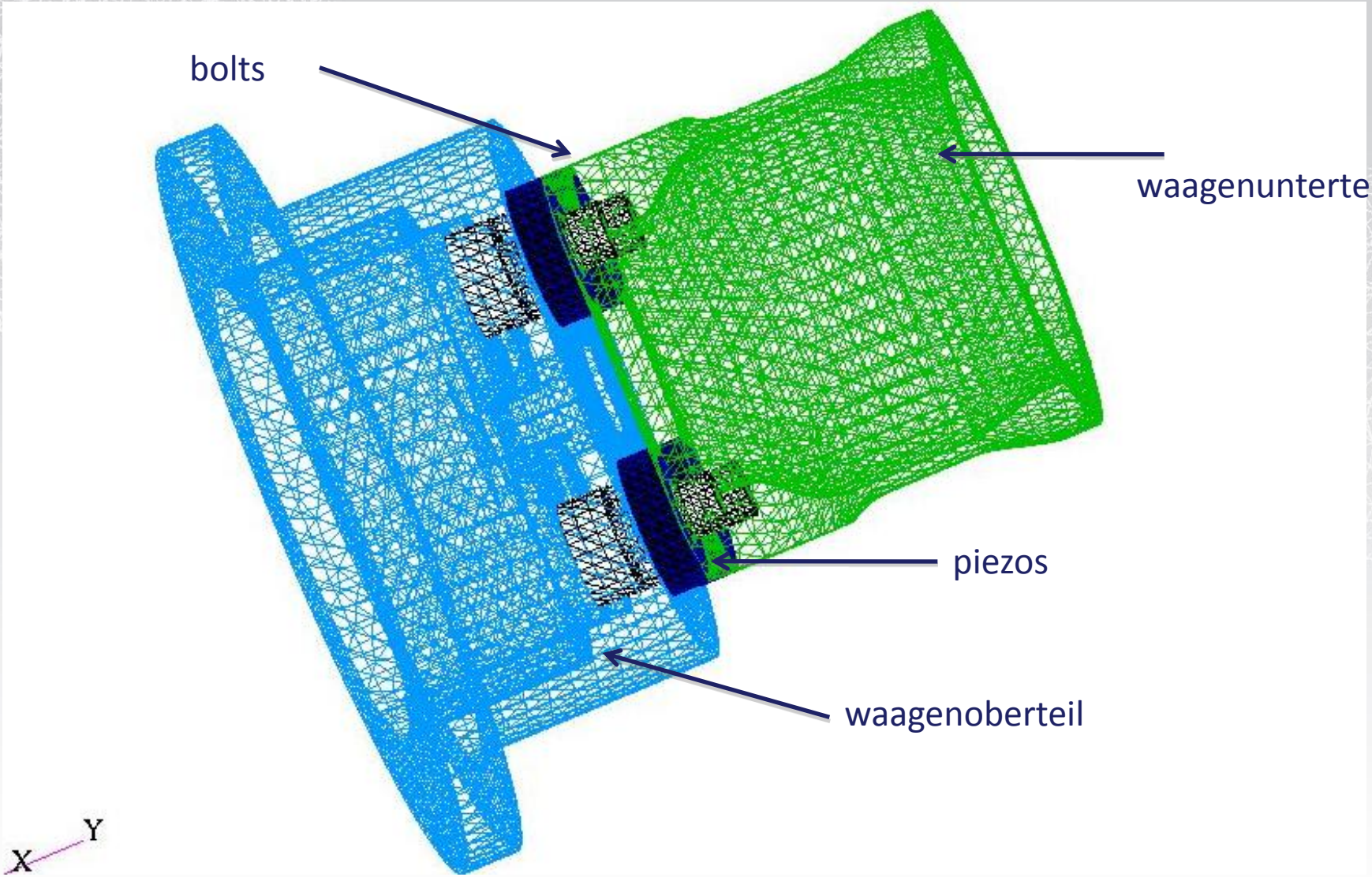
Tetrahedral Element Model

ANREGUNG (exciter)

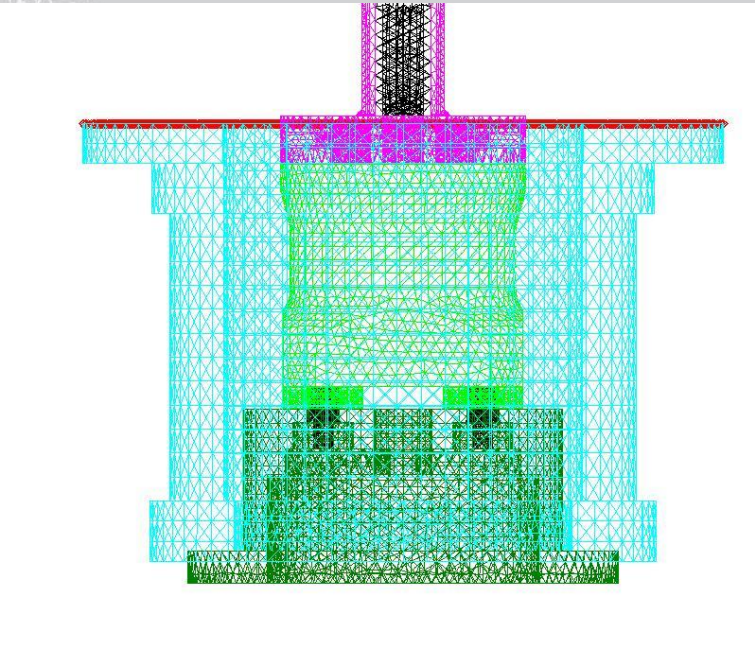




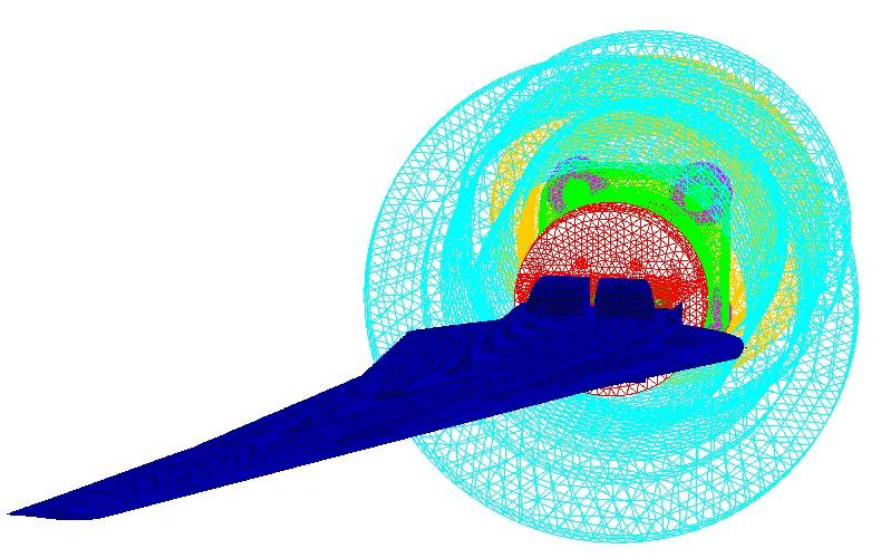
BALANCE



FEM including Model Cart



Cyan is the model cart
Green are the waagenoberteil and waagenunterteil
The red grids are the locations of the SPC constraint boundary conditions



Modifications of FEM

- Start with the full Tetrahedral element FEM that includes a CAD-based model of each part
- Modify the Tet model that includes the full model of the wing, balance, exciter, and model cart
  - Add instrumentation using CONMs and spidering
  - Remove common grid point connections between exciter and wing at the base of the wing (bottom of U)
  - Remove common grid points connections at top and bottom of wing where anregung is connected to wing
  - Add constraints in bolted connection regions to connect anregung to wing
  - Project surface grids points to match the IGES OML definition

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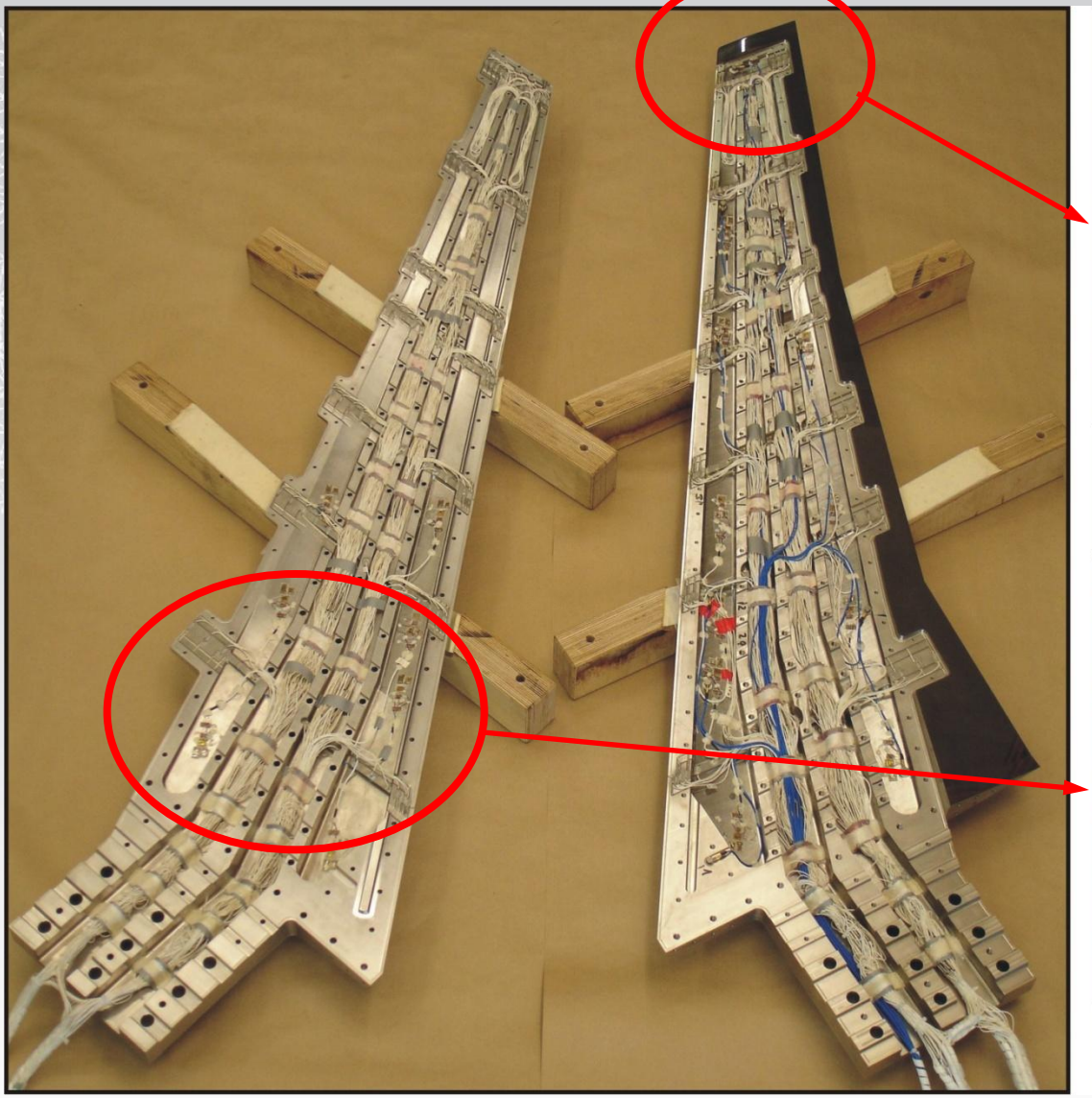
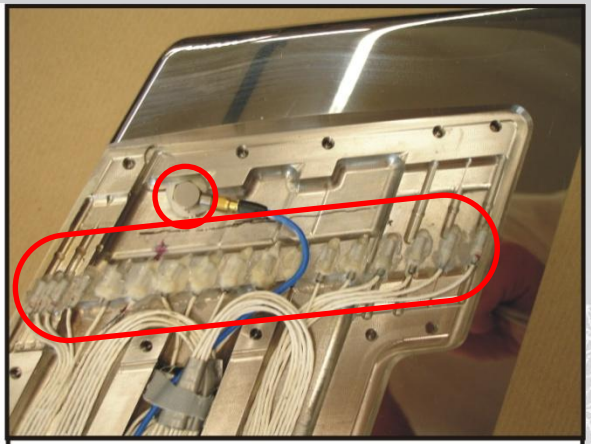
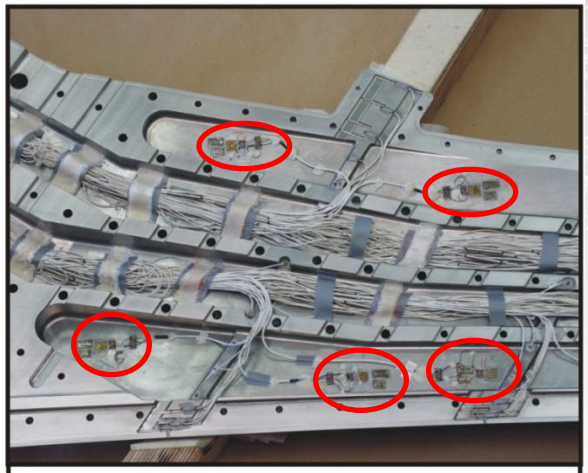
Measuring Equipment





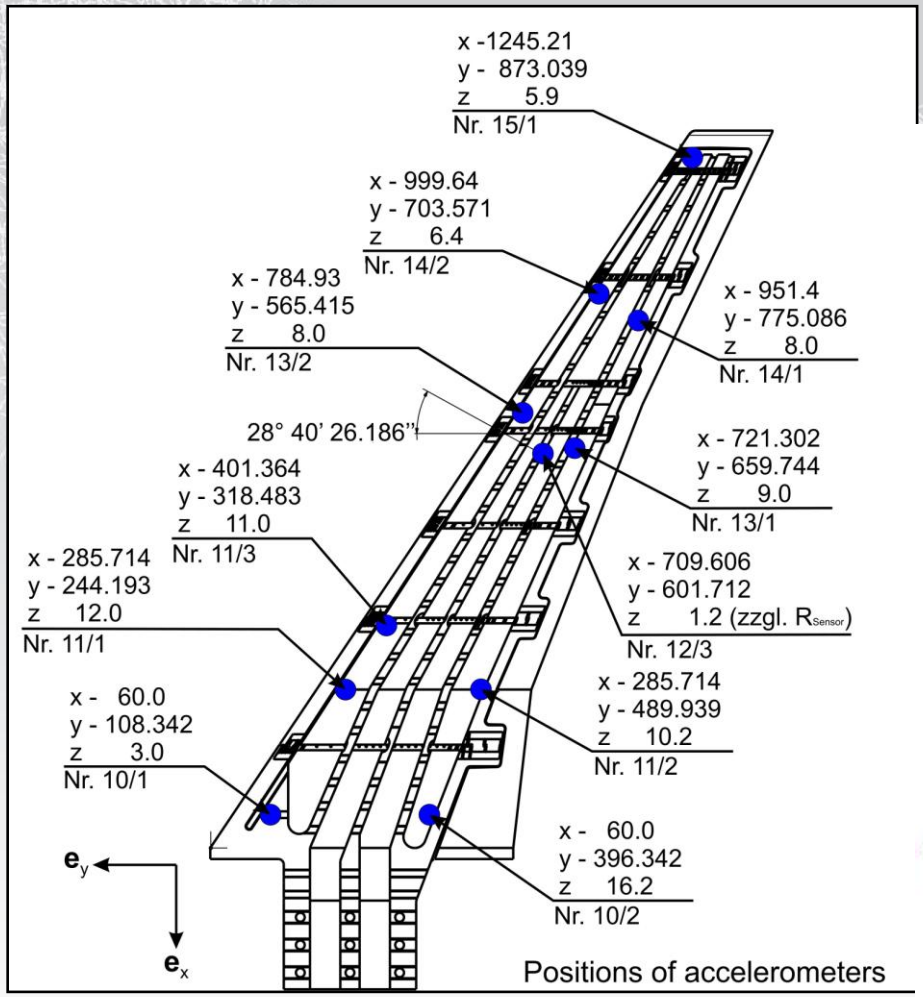
In-situ pressure sensors and accelerometers

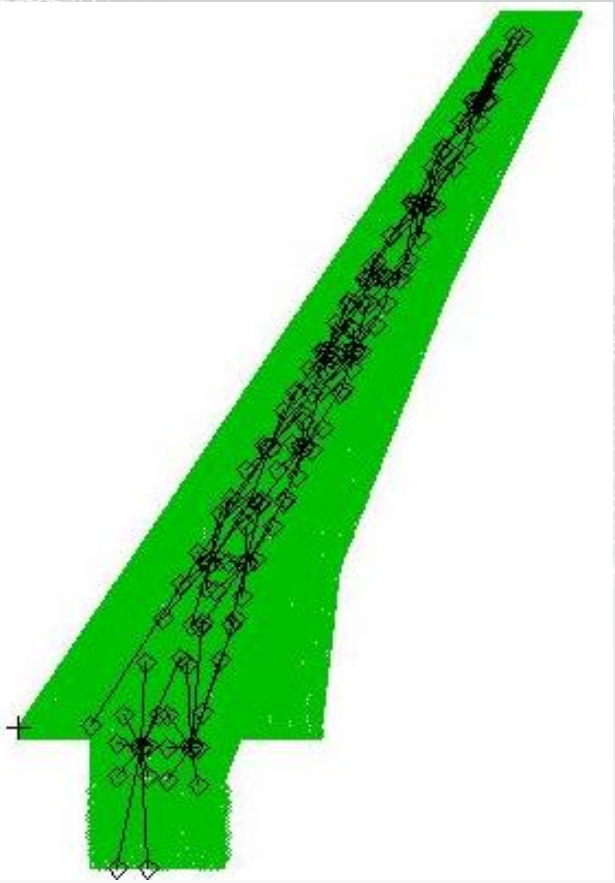


Strain gauges

Instrumentation weight within the wing that is being added to the FEM

Wiring


x -1245.21
y - 873.039
z 5.9
Nr. 15/1
x - 999.64
y - 703.571
z 6.4
Nr. 14/2
x - 784.93
y - 565.415
z 8.0
Nr. 13/2
x - 951.4
y - 775.086
z 8.0
Nr. 14/1
28° 40' 26.186"
x - 721.302
y - 659.744
z 9.0
Nr. 13/1
x - 401.364
y - 318.483
z 11.0
Nr. 11/3
x - 285.714
y - 244.193
z 12.0
Nr. 11/1
x - 709.606
y - 601.712
z 1.2 (zzgl. R_{Sensor})
Nr. 12/3
x - 285.714
y - 489.939
z 10.2
Nr. 11/2
x - 60.0
y - 108.342
z 3.0
Nr. 10/1
x - 60.0
y - 396.342
z 16.2
Nr. 10/2
e_y
e_x
Positions of accelerometers



Modifications of FEM

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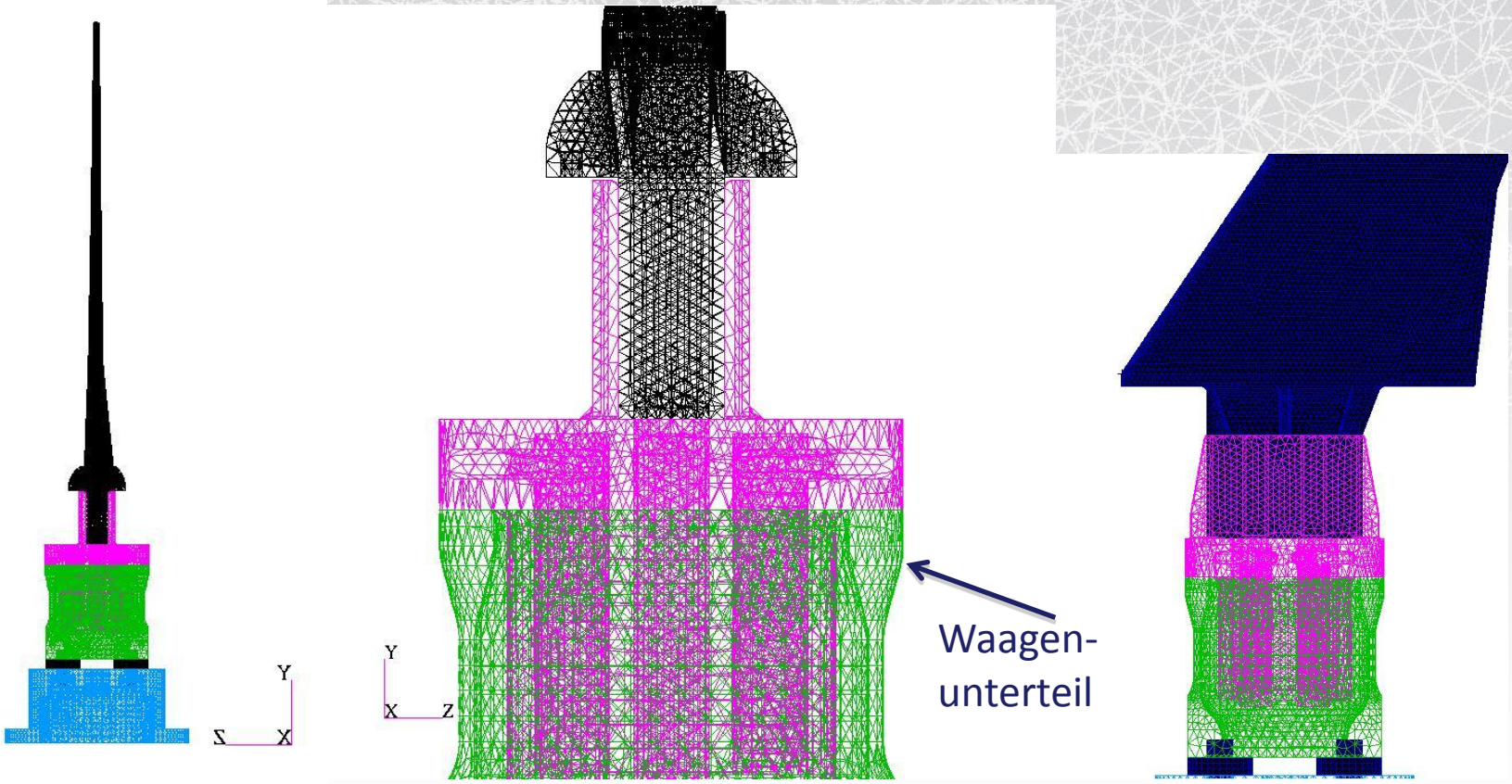
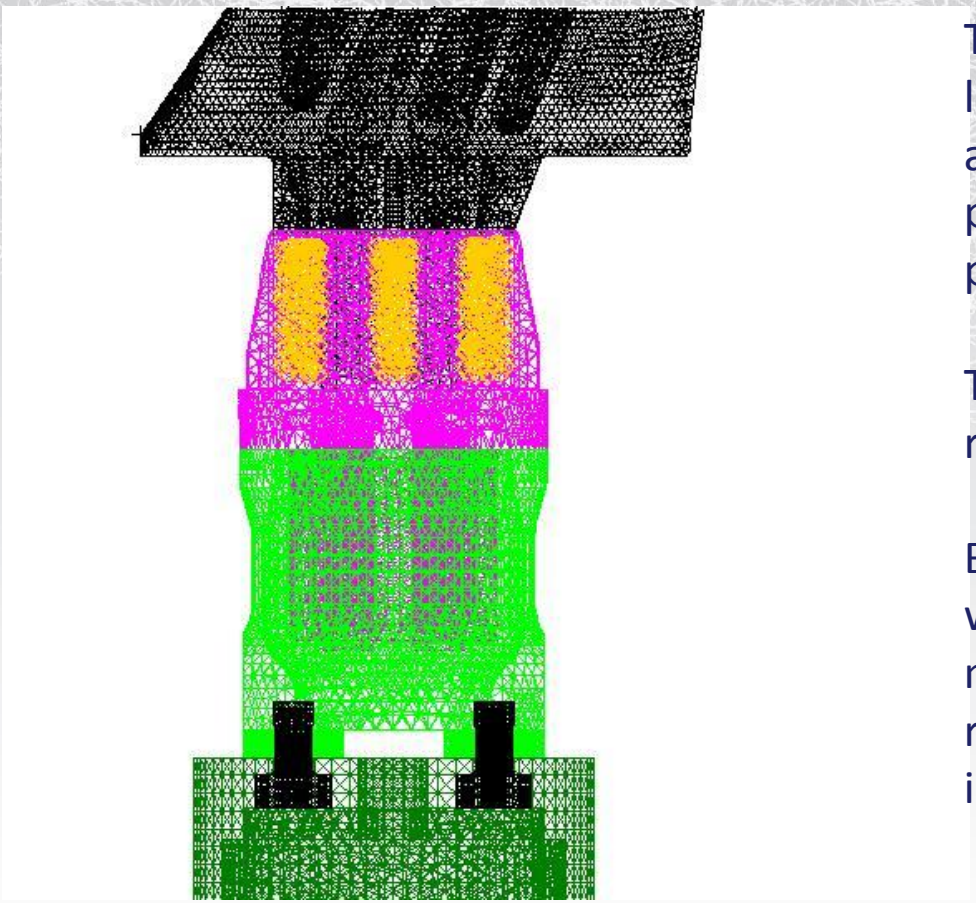
Tetrahedral Element Model

Wing: black and/or dark blue
Exciter (anregung): pink



FEM plots showing the bolted regions



The Yellow are the RBE which link the grids on the fluegel Tet and the anregung that were previously the same grid points.

The ETW Model cart has been removed from this figure.

Both TET models with and without the model cart were modified to have this bolt region connected using RBE instead of common grids.

Modifications of FEM

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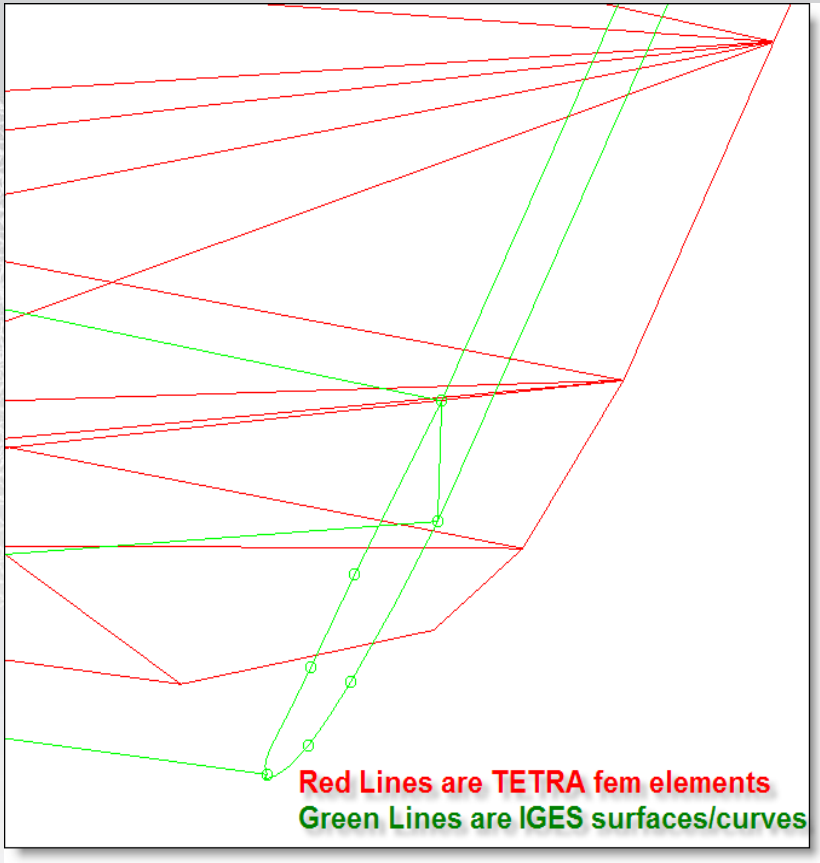
OML projection issue

- The FEM OML does NOT match the IGES OML
- FEM OML grids were transformed from present location to an OML defined by the IGES surface. Thanks Jack Castro for doing this for us.

Grid Projection to IGES Surface for HIRENASD model

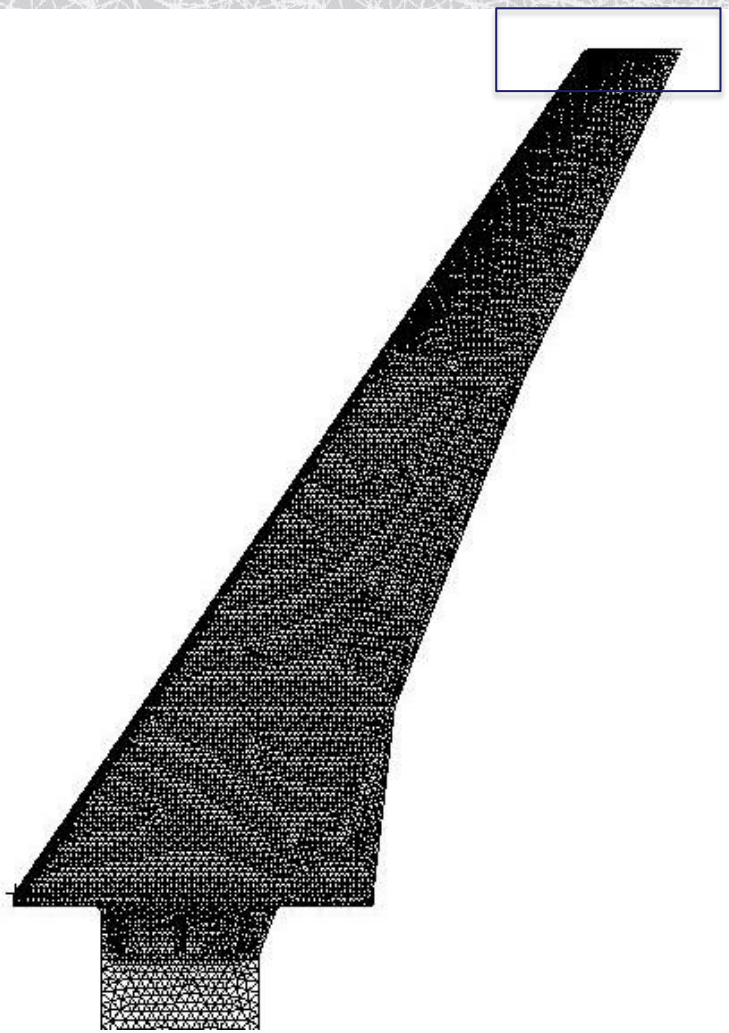
- Problem: Geometry used to tetmesh the hirenasd model not the same as the IGES geometry used for the CFD gridding
- Solution: Project the wetted surface tet nodes to the IGES surfaces using a perpendicular projection to closest surface (used PATRAN: Modify/Node/Project function)
- Difficulties
  - A few interior nodes were included and projected. These were identified and moved back to original locations
  - Inconsistent definition of “trailing edge” in the FEM model vs. the IGES geometry (no resolution to this issue)

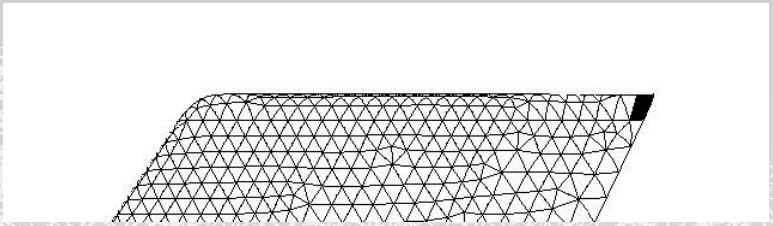
Tip Trailing Edge Detail View

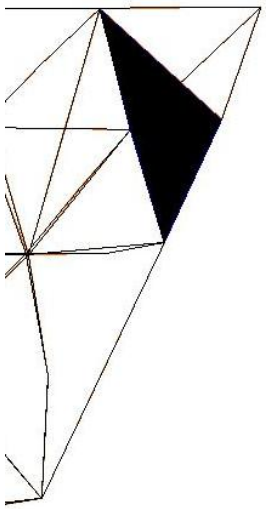


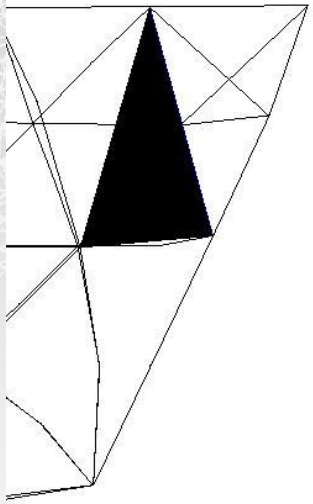
Trailing edge has no thickness in FEM model but has finite thickness in IGES model

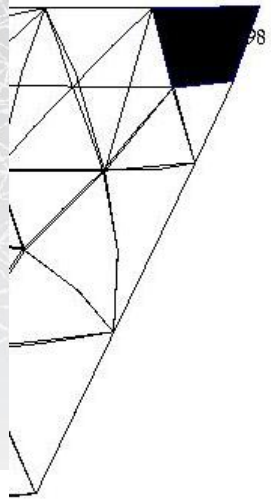
OML projection to IGES file











OUTLINE

- Motivation
- Wind-tunnel model
- Validation of FEM
- Summary

Validation of FEM

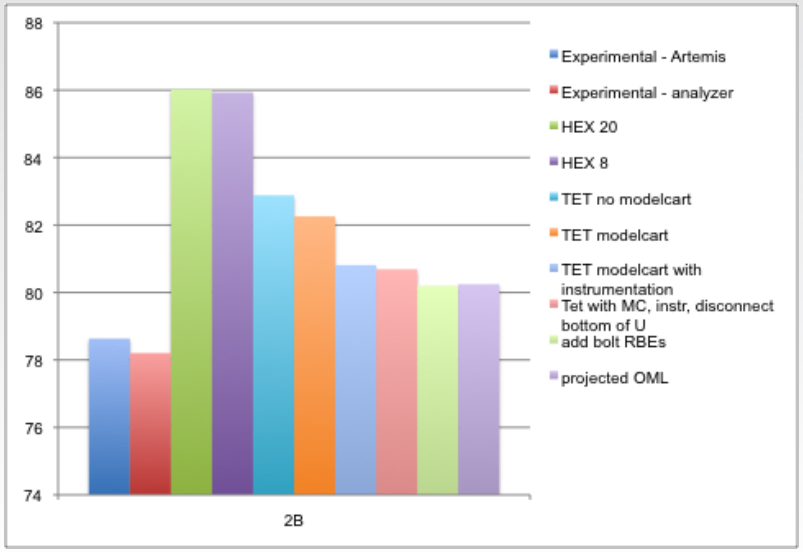
- Comparisons with experimental data
  - Frequencies
  - Modal Assurance Criteria
  - Leading & Trailing Edge Deflections
  - Twist distribution
  - Node lines
  - Displacements at accelerometer locations

- The following results are prior to the projection of the grid points onto the IGES surface modification; the difference in the mode shapes before and after IGES projection are minimal and quantified on a slide at the end of the modal comparison plots.

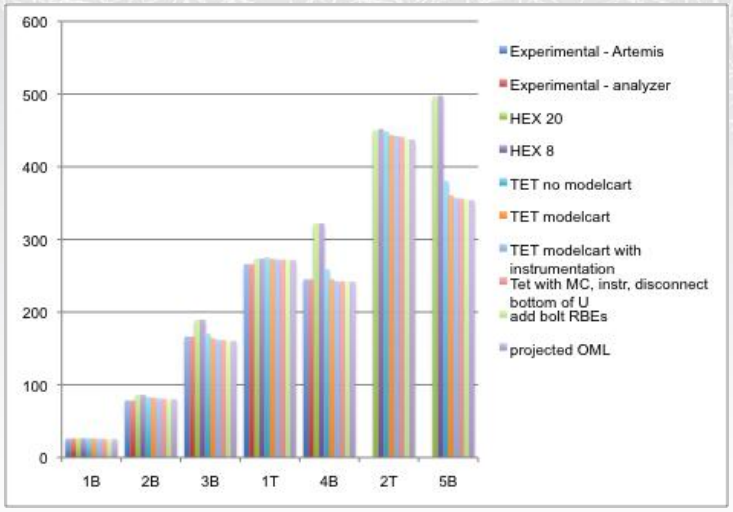
COMPARISON OF MODAL FREQUENCIES

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10
	EXPERIMENTAL WIND-OFF		WING-ONLY		Add Exciter	Add Model-cart	Add Instr.	Tet with MC, instr,		
	Experimental - Artemis	Experimental - analyzer	HEX 20	HEX 8	TET no modelcart		instrumentation	disconnect bottom of U	add bolt RBEs	projected OML
1B	26.015	26.250	26.541	26.534	26.249	26.217	25.618	25.604	25.542	25.550
2B	78.635	78.203	86.019	85.932	82.881	82.257	80.812	80.688	80.199	80.245
1FA			156.938	157.237	117.465	110.904	108.626	106.998	106.242	106.193
3B	166.250	166.250	189.311	189.434	170.083	163.745	161.770	161.441	160.381	160.349
4B	245.002	245.000	321.774	321.985	259.317	244.899	242.520	242.364	241.942	241.995
1T	265.855	265.781	272.859	273.443	275.120	273.055	272.295	272.182	271.718	271.844
2T			450.506	451.811	448.517	443.496	442.291	441.178	437.122	437.830
5B			496.680	497.795	380.224	360.338	356.863	356.332	354.341	354.155
2FA			422.976	423.259	280.260	256.158	252.790	252.651	252.361	252.225
3T			622.407	625.227						569.737
3FA					499.387	454.750	450.171	446.396	444.318	443.805
6B										497.802
3T										569.737
7TB										643.234

Comparison of 2B frequencies

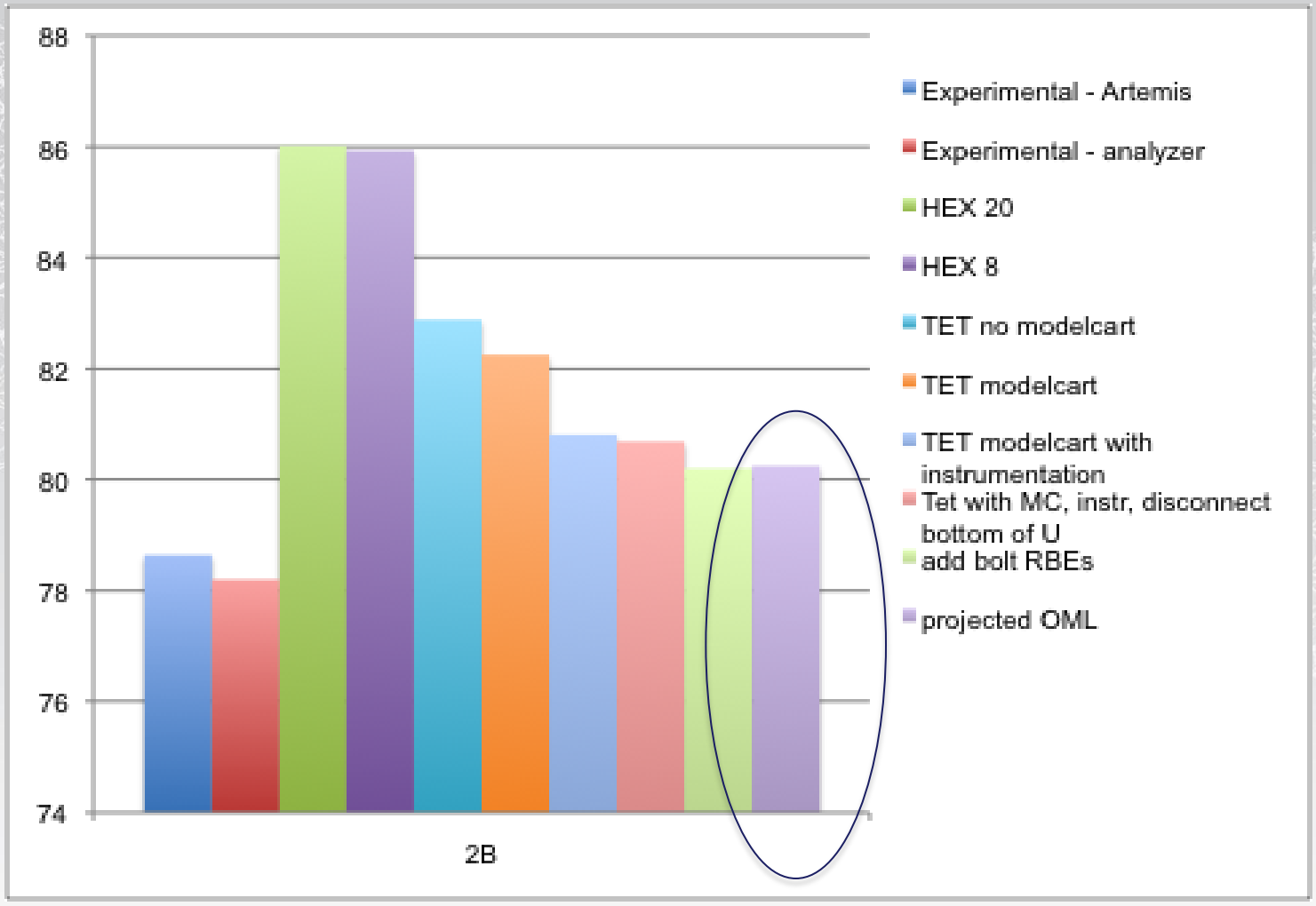


Comparison of Modal frequencies (omit FA modes)

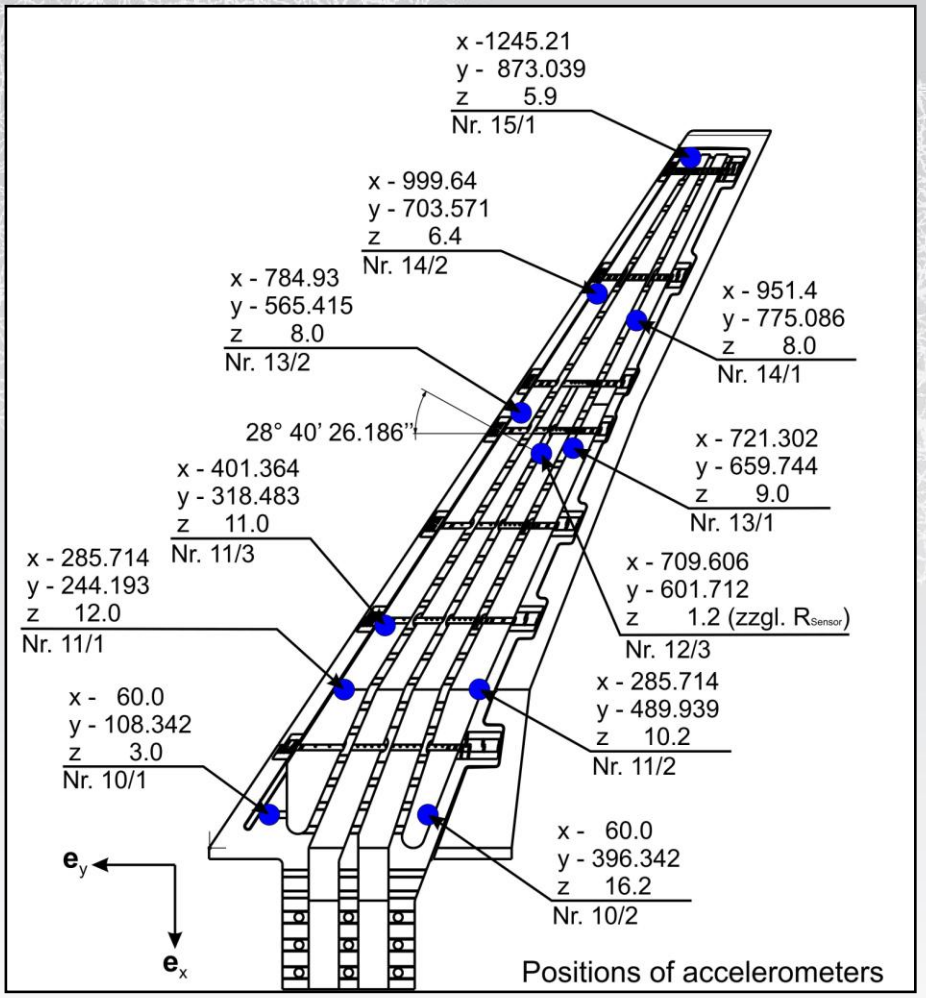


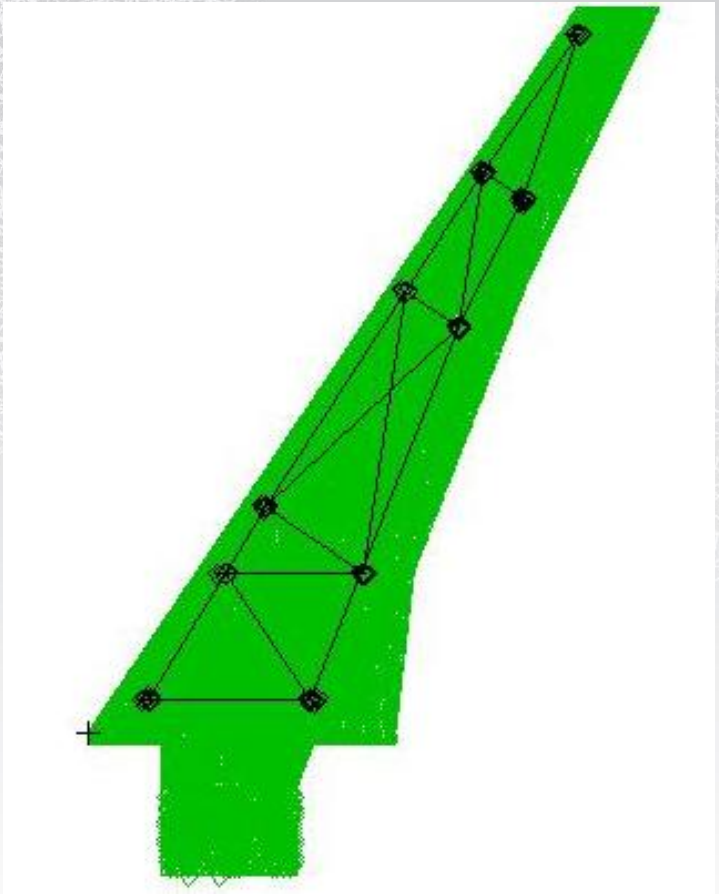
Artemis Data are provided by Boucke

COMPARISON OF MODAL FREQUENCIES



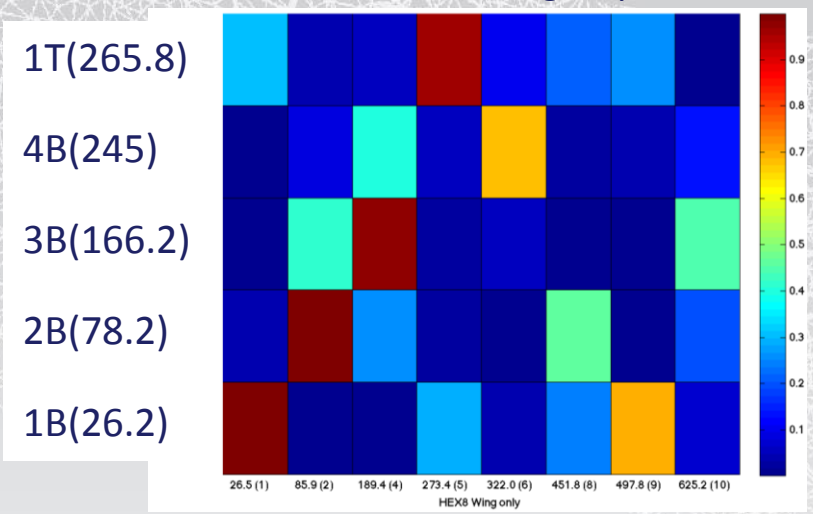
Accelerometer Locations



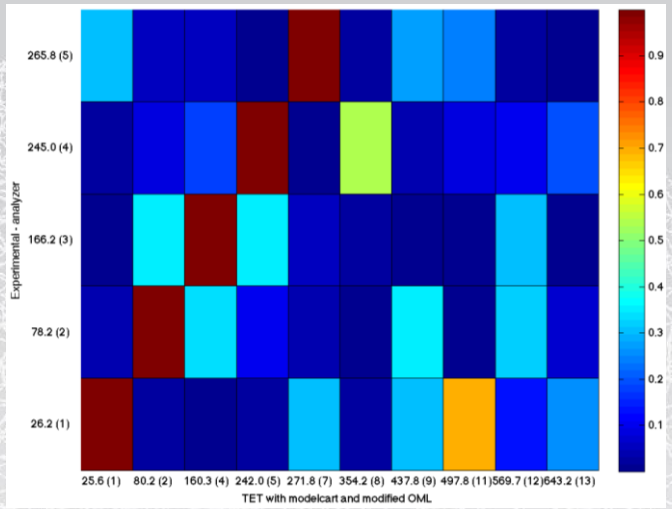


Modal Assurance Criteria

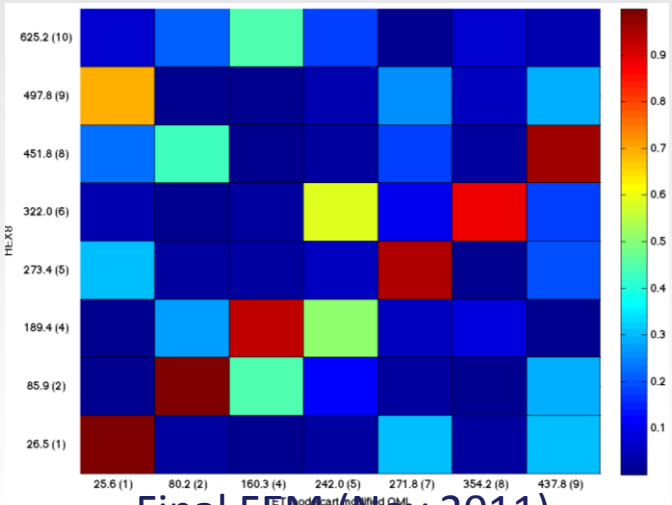
Comparison of Experimental with Hex8 wing only



Comparison of Experimental with TET10 mode with modified OML

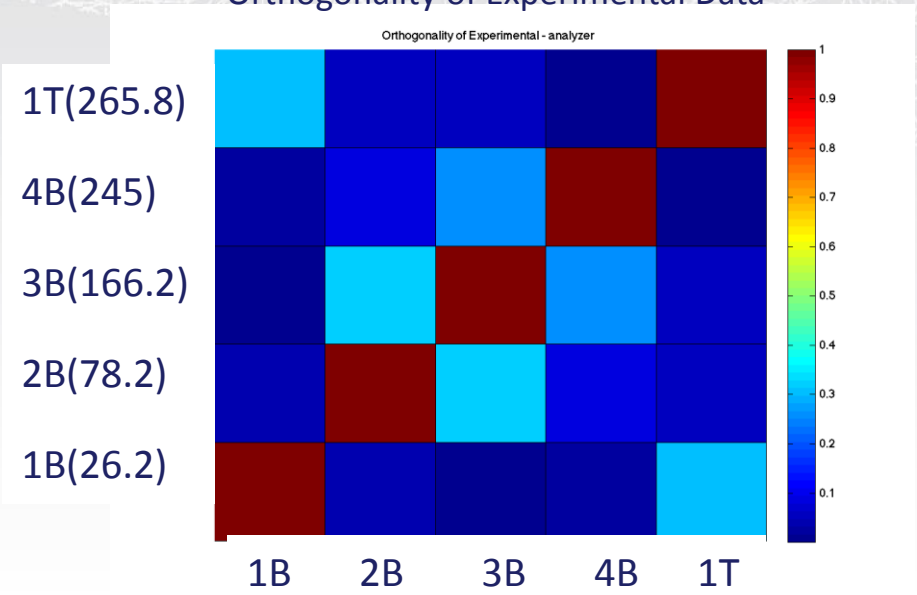


Comparison of HEX8 wing only and TET10 model with modified OML



HEX 8 (Wing Only)

Orthogonality of Experimental Data



Final FEM (Nov 2011)

Wing Leading Edge Deflection Comparisons 2nd bending mode

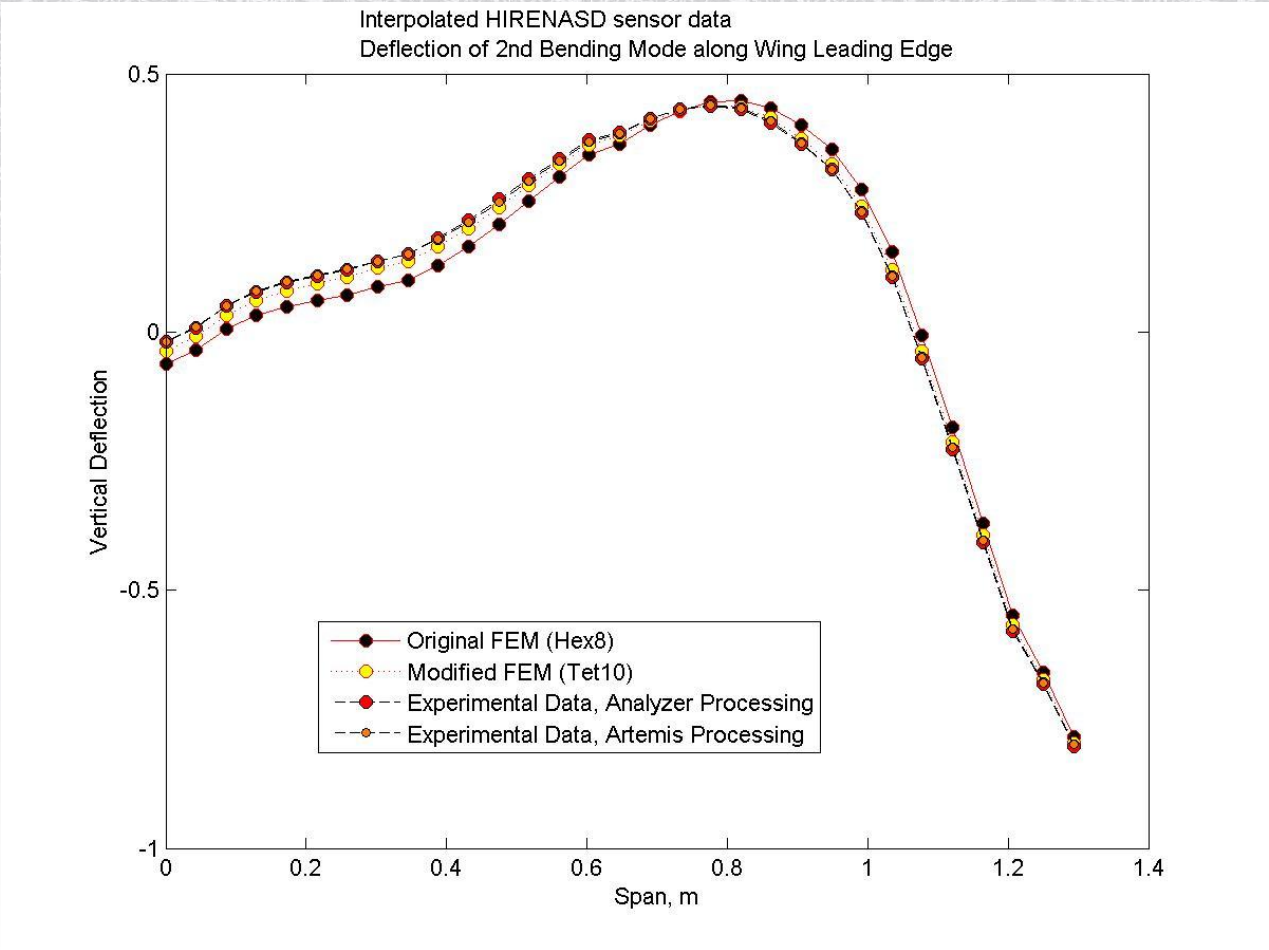
In order to compare the span-wise deflection, the flow-wise twist angle, and the node lines, the data from 9 sensor locations is extrapolated & interpolated to a uniformly spaced grid, using the matlab griddata function

Data:

9 accelerometers

Node lines:

Deflection crosses 0



Wing Trailing Edge Deflection Comparisons 2nd bending mode

In order to compare the span-wise deflection, the flow-wise twist angle, and the node lines, the data from 9 sensor locations is extrapolated & interpolated to a uniformly spaced grid, using the matlab griddata function

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9 accelerometers

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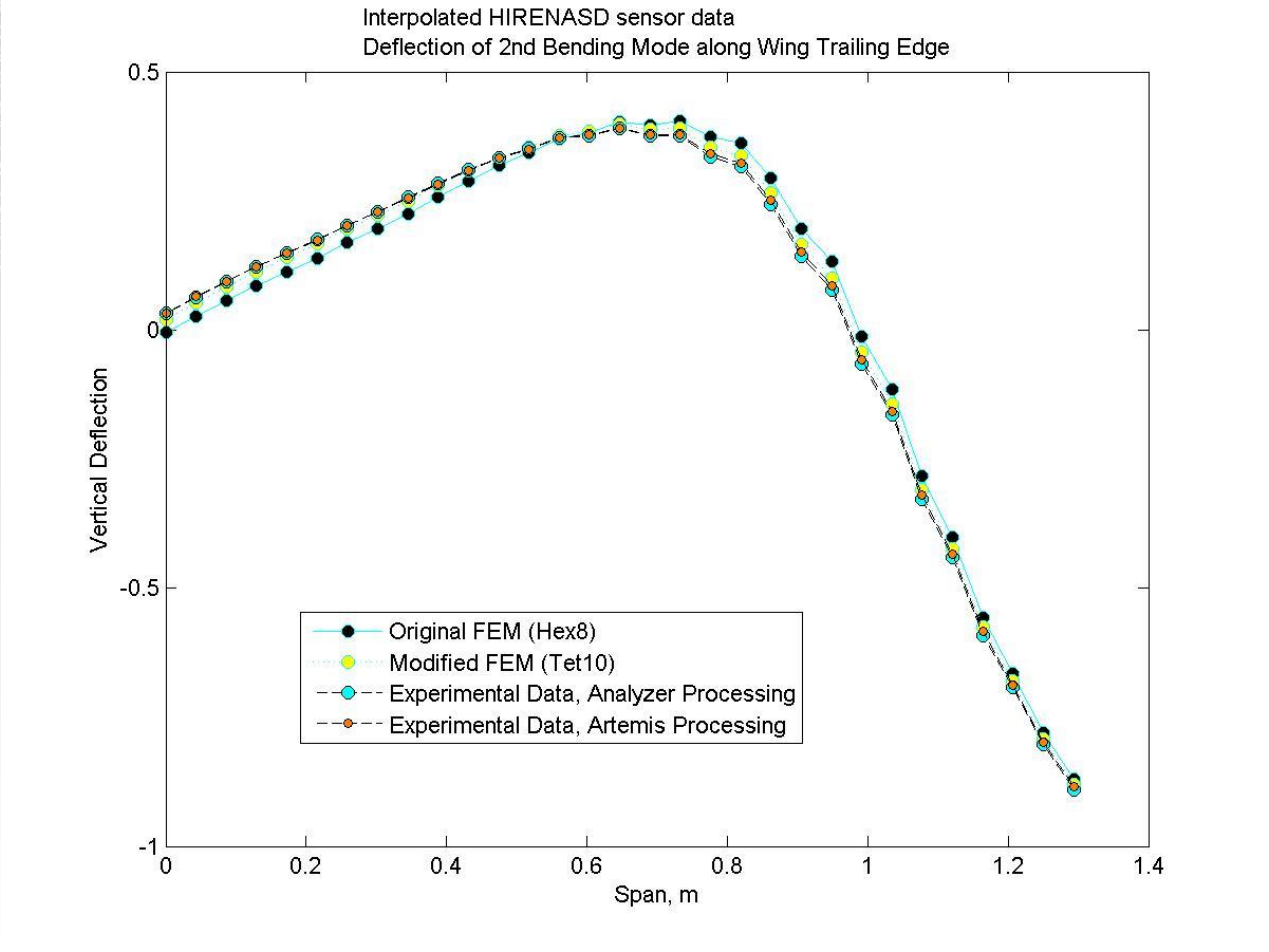
Deflection crosses 0



Wing Twist Angle Comparisons
2nd bending mode

In order to compare the span-wise deflection, the flow-wise twist angle, and the node lines, the data from 9 sensor locations is extrapolated & interpolated to a uniformly spaced grid, using the matlab griddata function

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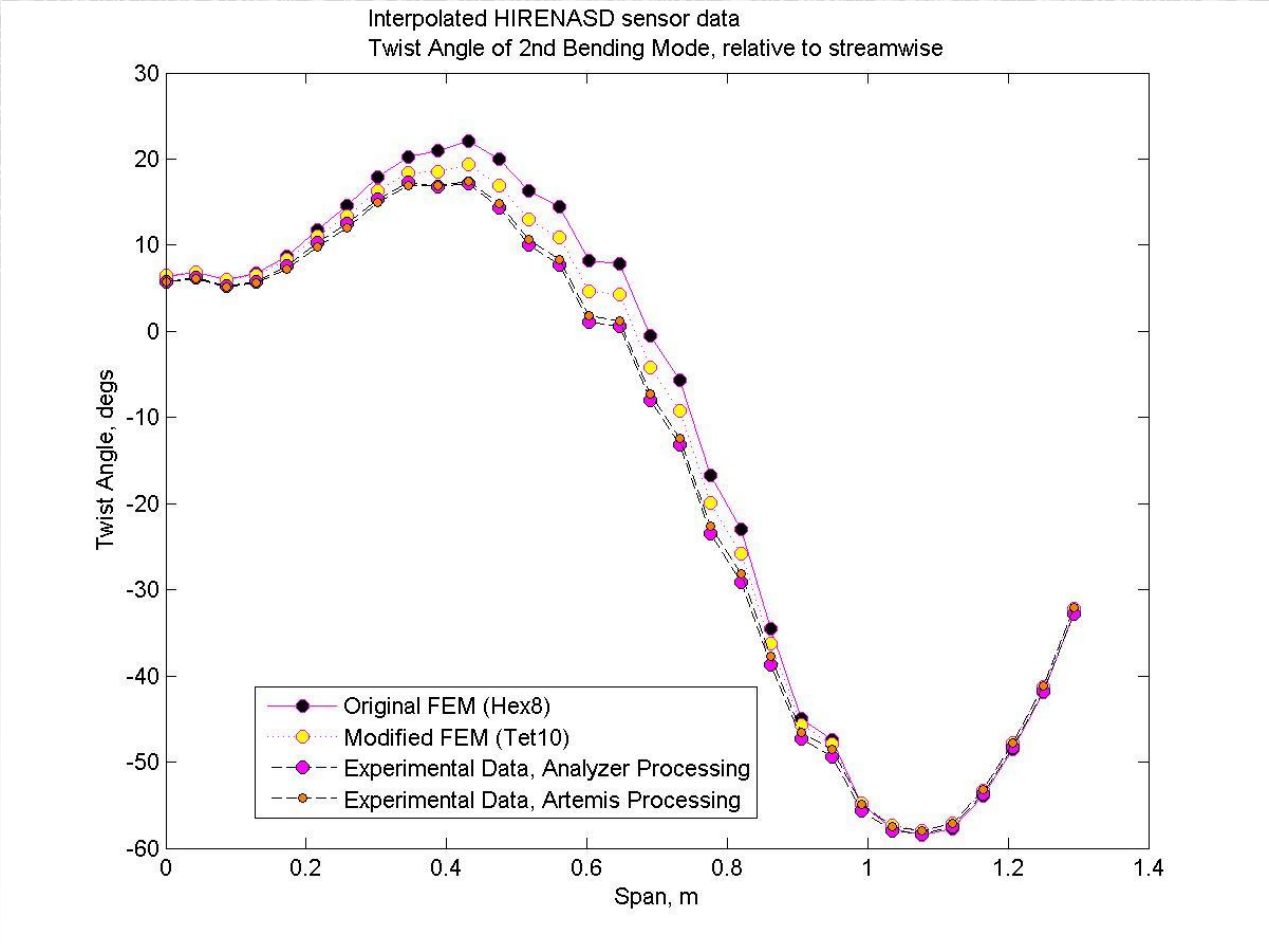
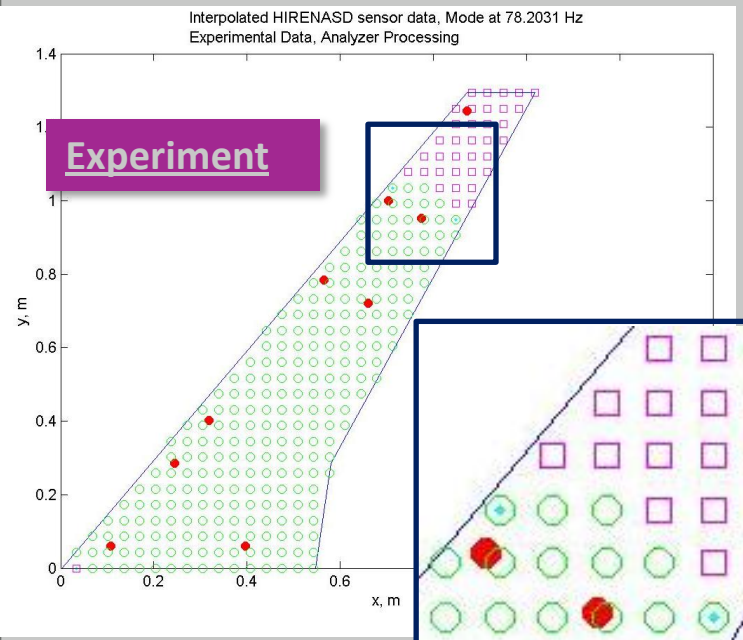
9 accelerometers

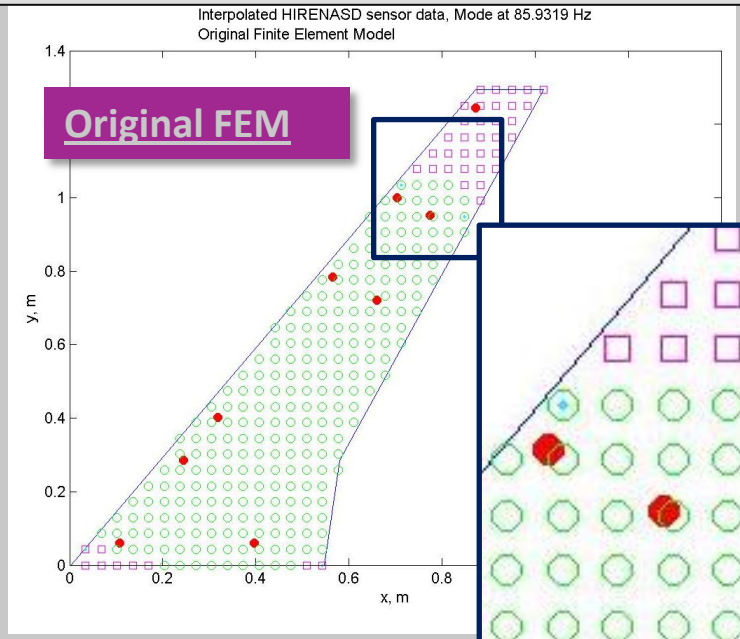
Node lines:
Deflection crosses 0

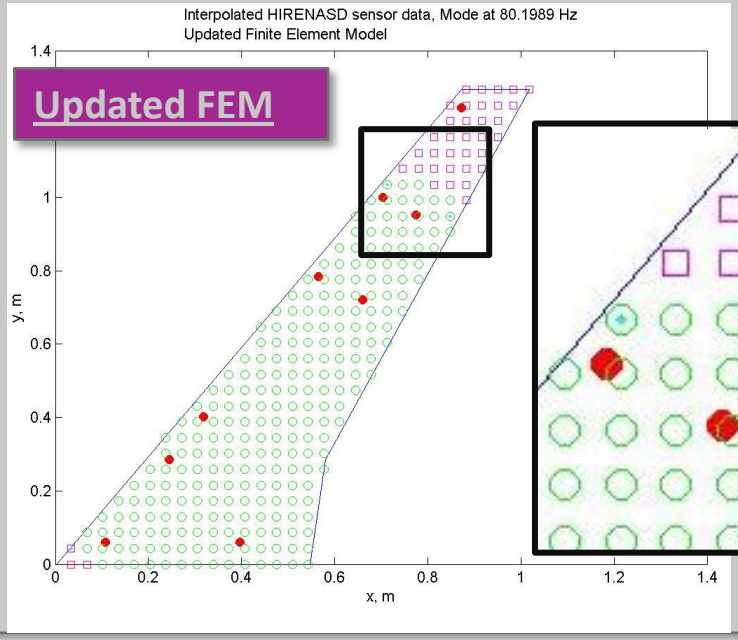


Node Line comparisons, 2nd bending mode

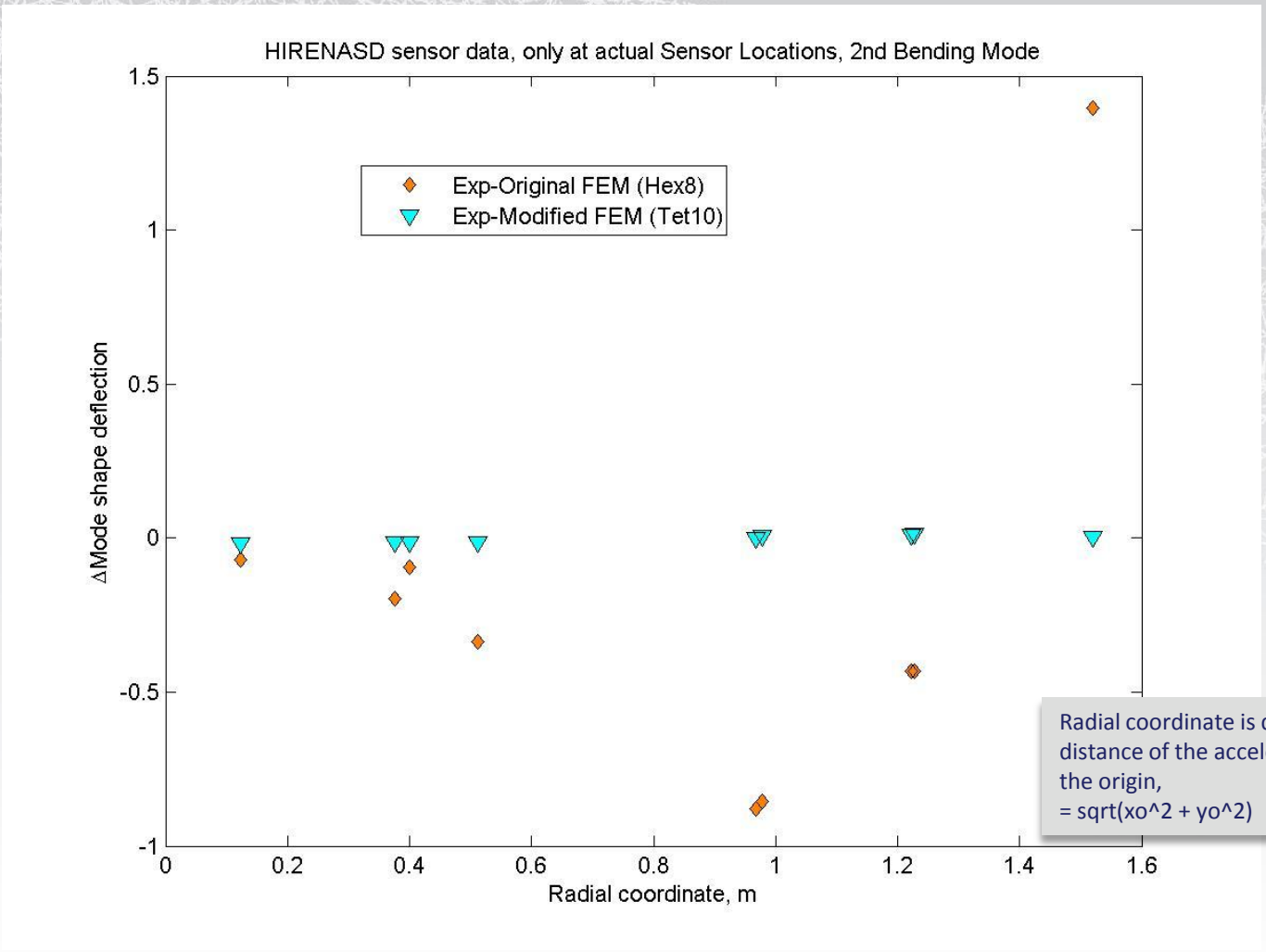
Data:
9 accelerometers (red circles)
Interpolated / extrapolated to uniformly spaced points using matlab griddata function
Node lines:
Lie between magenta squares (- values) and green circles (+ values)







Direct comparison of Mode Shape Deflections at 9 Sensor Measurement Locations



Radial coordinate is defined as the distance of the accelerometer from the origin,
= sqrt(xo^2 + yo^2)

Differences before and after IGES projection
Modal Deflection of 2nd Bending Mode

Accelerometer #	Before projection	After projection	Difference
1	0.7024	0.7003	0.0021
2	-0.2048	-0.2053	0.0005
3	-0.2068	-0.2073	0.0005
4	-0.4356	-0.4354	0.0002
5	-0.4278	-0.4277	0.0001
6	-0.1809	-0.1807	0.0002
7	-0.1092	-0.1091	0.0001
8	-0.0393	-0.0393	0
9	-0.0541	-0.0543	0.0002

Structural Dynamics Model Development Effort

- Finite element model modifications from June 2011 to Nov 2011 (final FEM)
  - Receipt of Tetrahedral Model with the missing parts
  - Inclusion of instrumentation
  - Inclusion of full balance model
  - Modification of bolt connections of anregung to wing
  - Modification of OML
- Experimental Data Reduction of Air-off Data Sets (what data was used)
  - In tunnel excitation of using root exciters
  - Uncertainty characterization on frequencies and mode shapes
  - Accelerometers used
- Comparison of Modal Data (freqs & mode shapes via MAC)
  - June 2011 FEM
  - Experimental Data
  - Nov 2011 final FEM
- FEM deemed acceptable and uploaded to Website
  - Final FEM provided and the output from Nastran provided
  - Interpolation of modeshapes using JAMSHID's to the AEPW provided CFD Grids
  - Subset of modeshape deflections at 144 points on the wing and locations provided

Summary & Conclusions

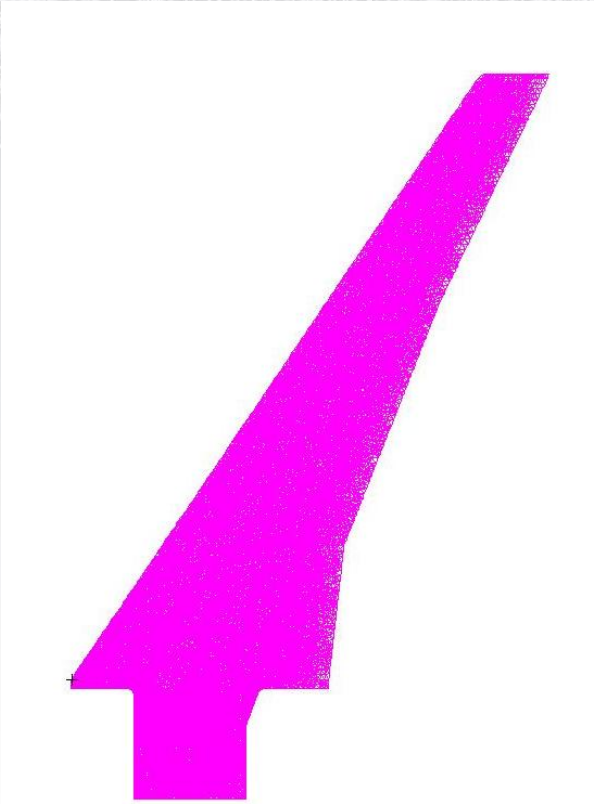
- The fundamental FEM that served as the baseline model for the modified FEM was generated using CAD files of the hardware
- Only modifications that make physical sense were incorporated into the FEM- no tweaking or tuning using experimental data was done in the modification
- The modified FEM appears to match the frequencies and 2nd bending mode shape better than the original FEM
- The mode shape has changed slightly

ADDITIONAL SLIDES

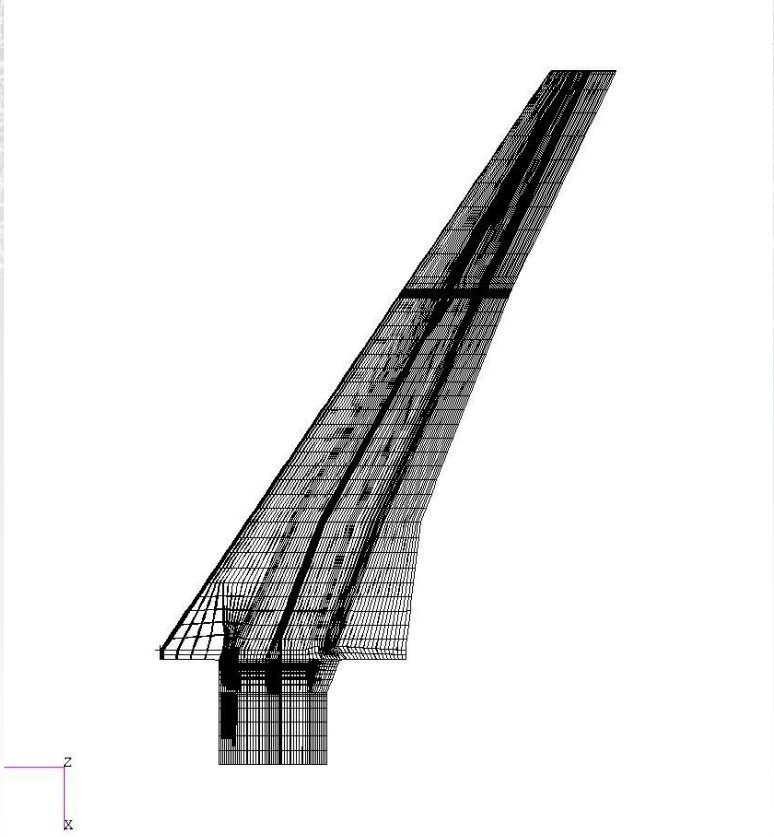
Models originally provided

Different coordinate systems
One in mm and the other in meters

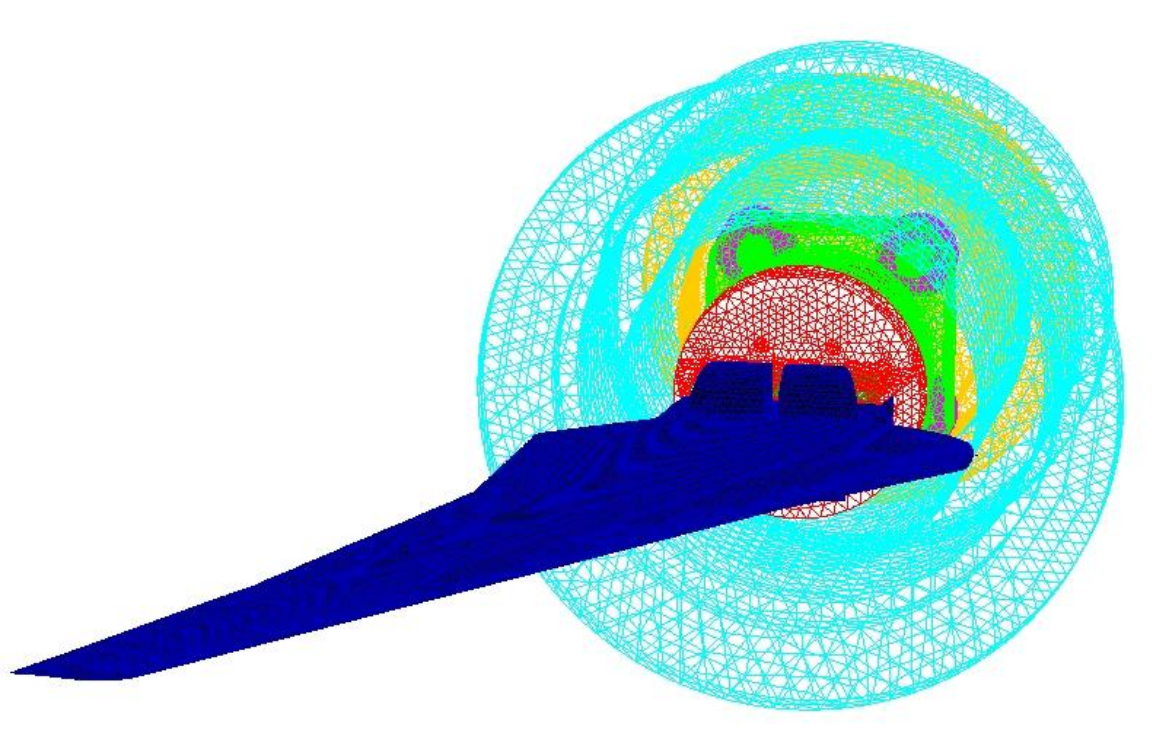
Unstr (Tetrahedral elements)



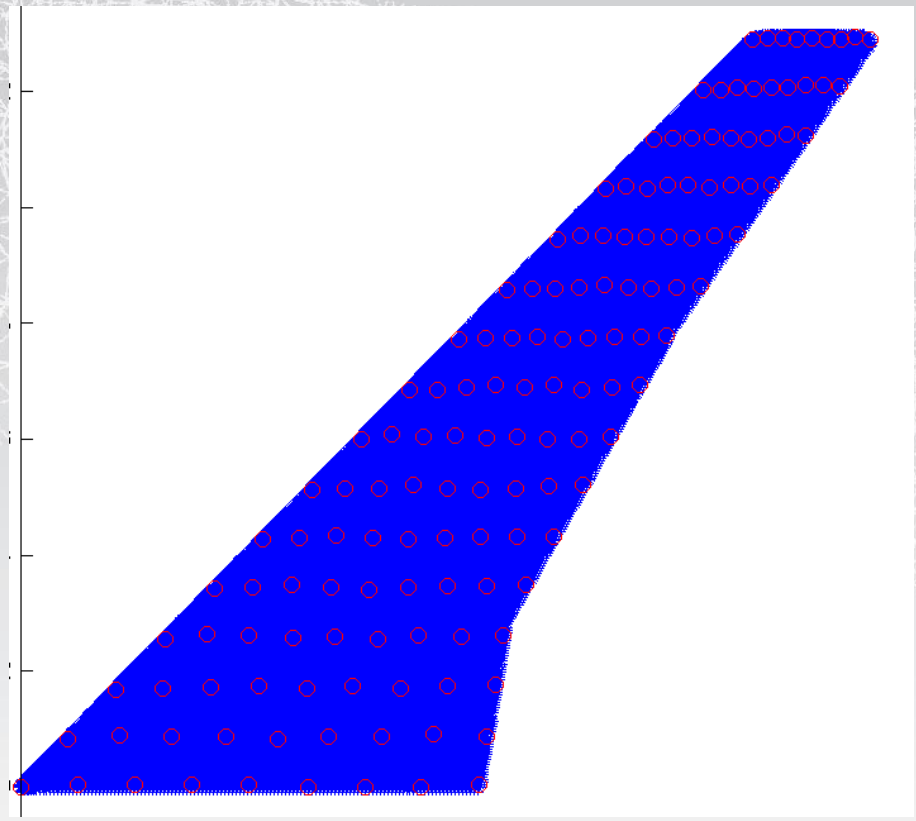
Str (HEXAHEDRAL elements)



Tetrahedral Element Model



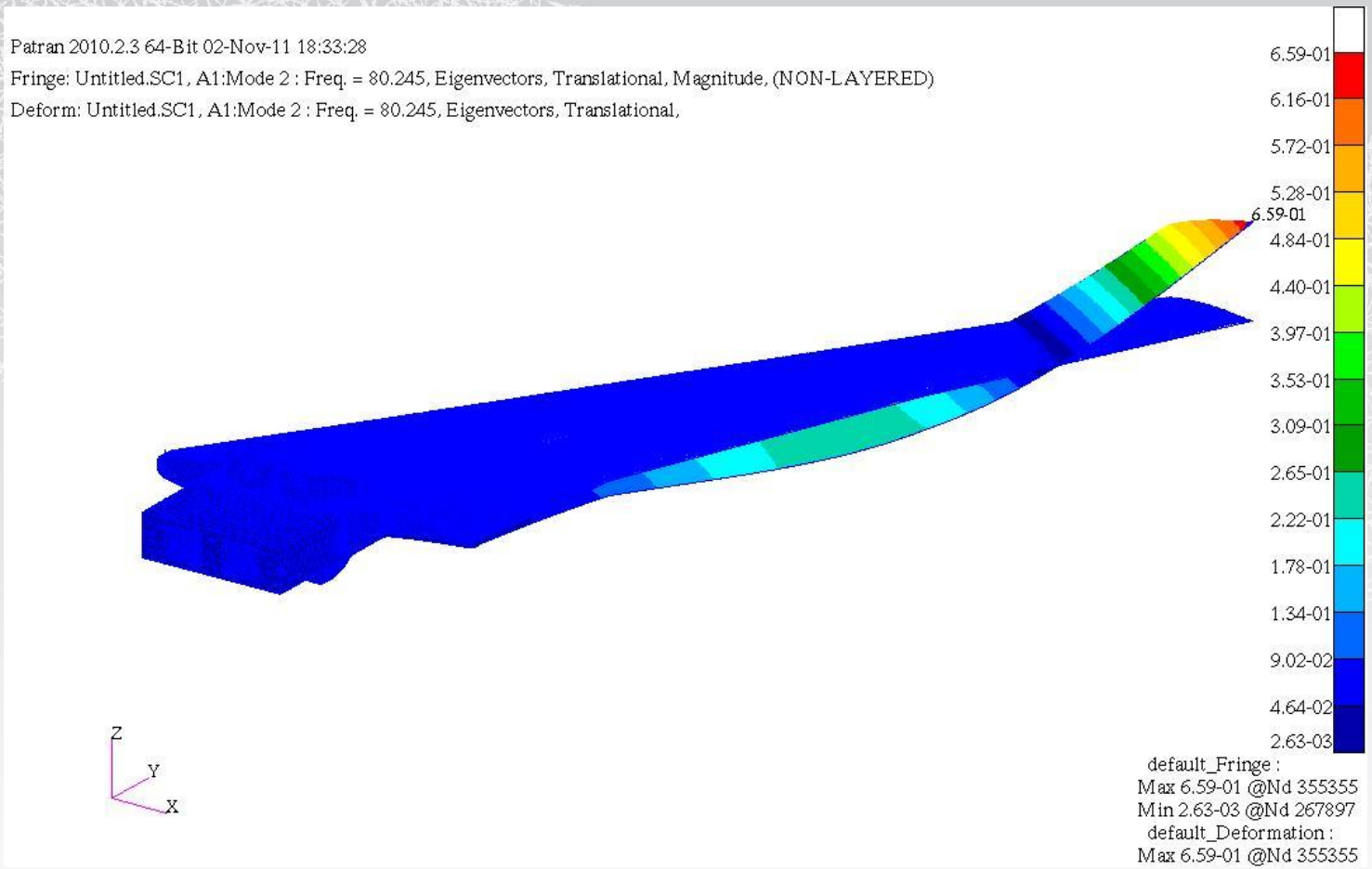
Subset of Modal Data Provided for Interpolation



9 chord locations
At 16 span stations
Upper surface – covering entire area of wing

Second Bending Mode of Final FEM (Nov 2011)

Final FEM
80.245 Hz



Rationale for using TET

- Started with HEX20
- Modified to HEX8
- No model cart available
- Interpolation Scheme used at NASA not work with TET only HEX
- Interpolation Scheme was modified to be able to interpolate TET models
- Uses all grids and mode shape deflections
- Enhanced to use subset and was reduced to using using the FLUEGEL TET group.

Experimental Time Histories for MAC ,etc

- 304 (spreadsheet said 302)
  - Air off a=0 deg
  - Temp @23.5 RNL
  - Sheet says 26 Hz
  - Actually @78 Hz
  - 40% excitation strength

- 332 was wind-on – no excitation

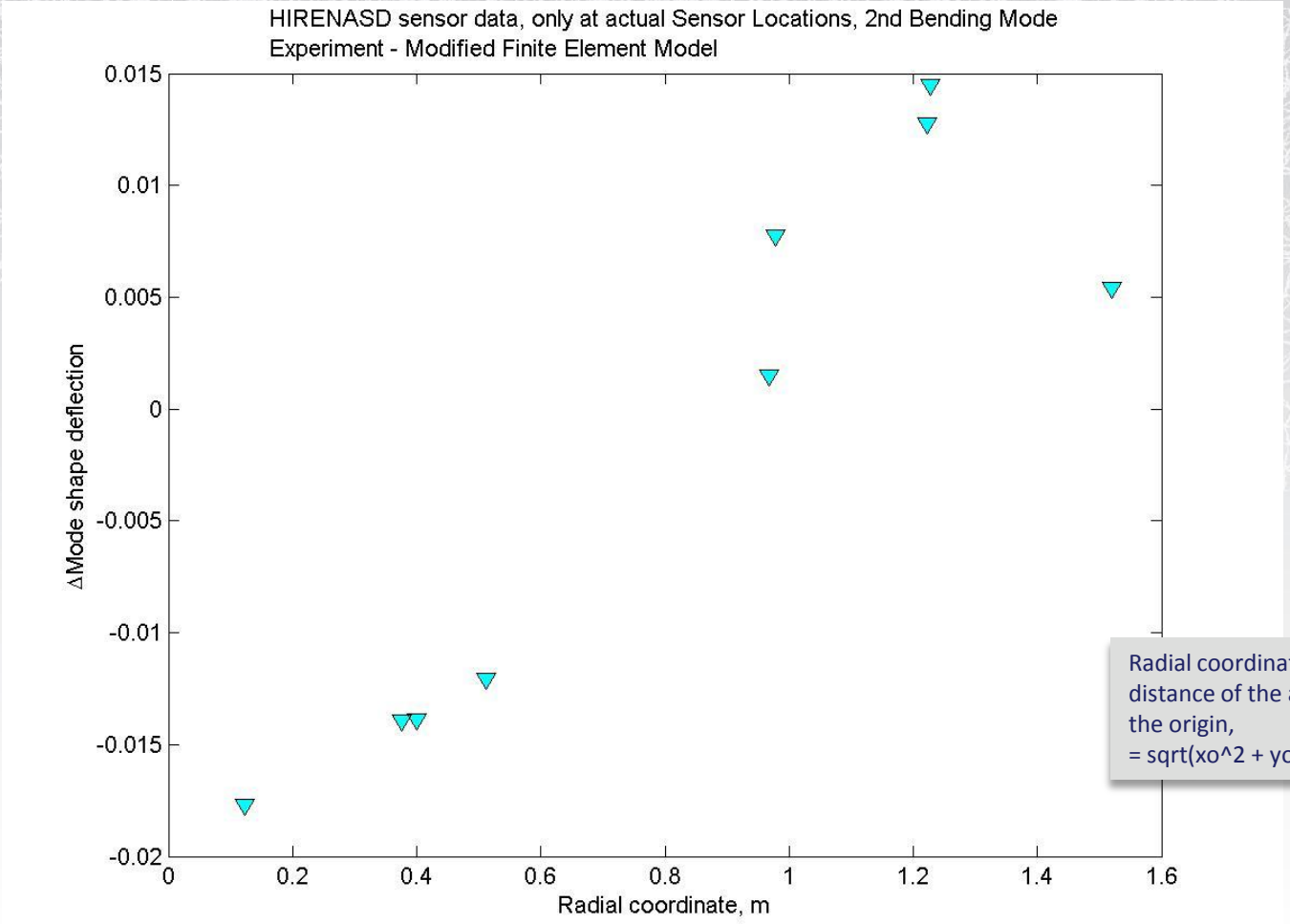
Methods to Extract the Mode shapes from the time histories

- Artemis – Boucke
- Analyzer – Do Frequency responses with respect to ACC15(1) and extract the magnitude and phase at the frequency desired.
- SVD – not included in this documentation

Original FEM

- HEX Model, on Website
- TET Model
- No balance, exciter or instrumentation
- Cantilevered at root

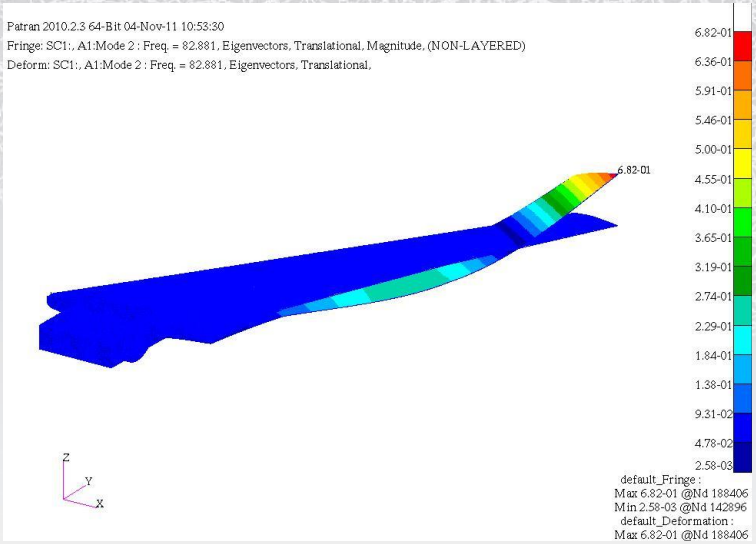
Direct comparison of Mode Shape Deflections at 9 Sensor Measurement Locations



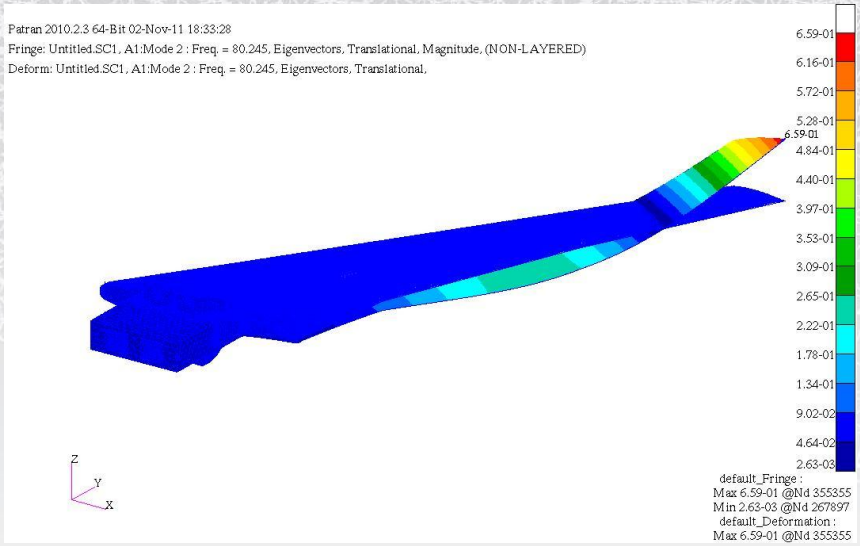
Radial coordinate is defined as the distance of the accelerometer from the origin,
= sqrt(xo^2 + yo^2)

Comparison of TET (no model cart) TET with modelcart

TET with Exciter (No Model Cart)
82.881 Hz

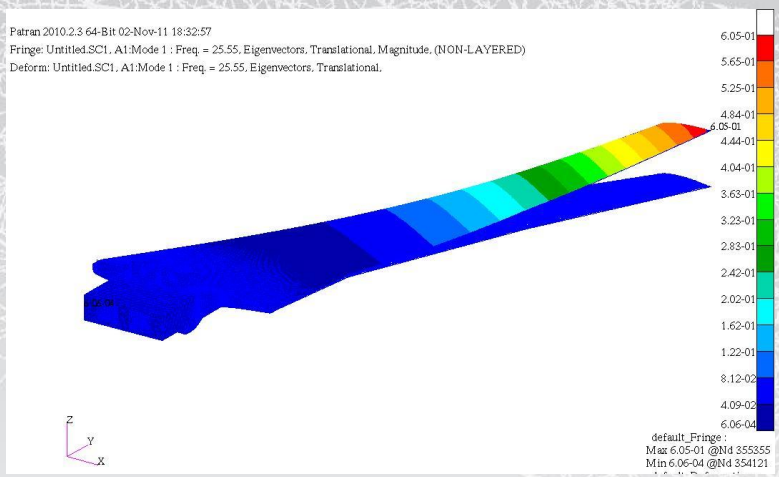


Final FEM
80.245 Hz

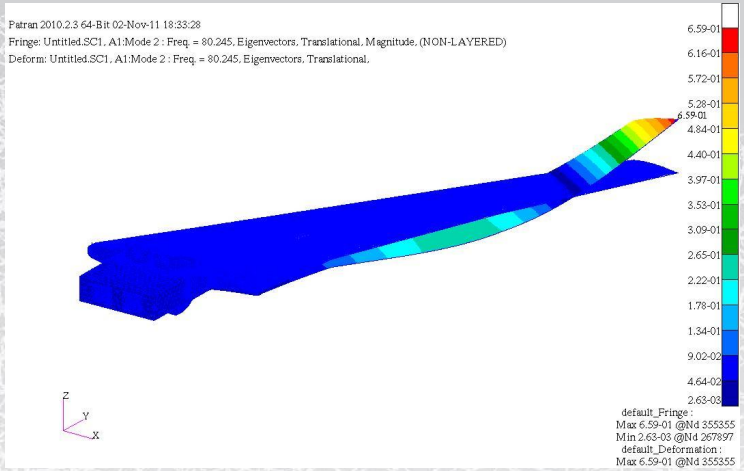


Final Modeshapes (displayed only on wing)

25.55 Hz



80.245 Hz



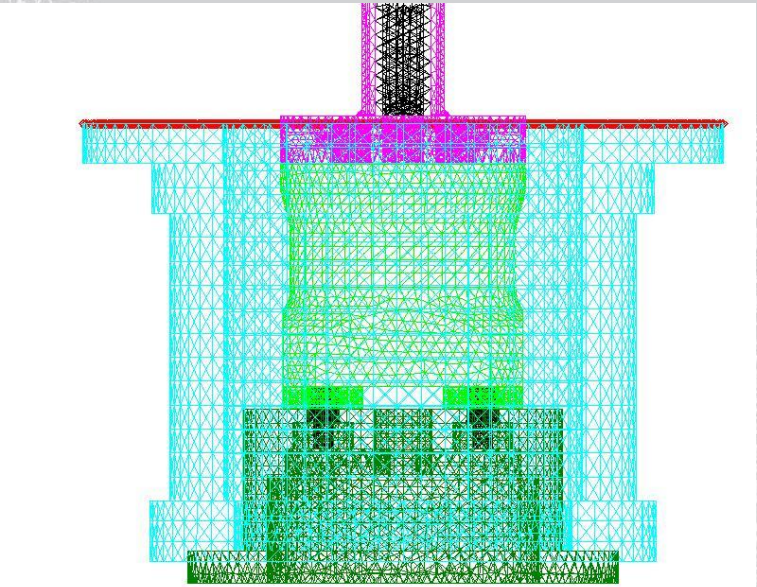
Modal Assurance Criteria (Theory)

- MAC(i,j) = (ms1{i}'*ms1{j})^2

- Where ms1{i}=ms{1}/norm(ms{1}) – normalized modeshape
- ms1{i} is a vector that is of length 9
- 9 accelerometers were used (one was bad)

- Used the deflection in the Z direction.

FEM including Model Cart



Cyan is the model cart
Green are the waagenoberteil and waagenunterteil
The red grids are the locations of the SPC constraint boundary conditions

FEM as provided connects the anregung and fluegel tet using common grid points surrounding the Wing root (bottom of U and the sides)

The grids were disconnected at the wing root (bottom of “U”) by renumbering the anregung grid points and regenerating the TET elements using the new grid points.

Grids at top and bottom of wing (sides in this figure) were disconnected in same manner and RBE elements were created that joined the grids at identical locations in the area covered by bolt region

Stereo Pattern Tracking (SPT) and Accelerometers

48 markers on the pressure side of wing model for SPT, spacial accuracy 0.1 mm

Positions of accelerometers In the upper (suction side) part of wing model