Operational Modal Analysis for Aircraft and Spacecraft Structures

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Steven Pauwels – Jan Debille – LMS International

LMS ENGINEERING INNOVATION

Overview

- Introducing LMS
- Why Operational Modal Analysis ?
- What is Operational Modal Analysis ?
- LMS PolyMAX Parameter Estimation
- Applications & Case Studies
- Conclusions

LMS, 25 years of engineering innovation
Market leadership in noise & vibration engineering

A future built on strong fundamentals

- Driven by a compelling vision
- The industry largest R&D commitment to Engineering Innovation
- Talented people, 650 professionals committed to customers' success
- More than 3000 manufacturing companies actively use LMS products and services
- Strong financial track record of double digit profitable growth
- 20 offices worldwide

2005 25 years of Engineering Innovation

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LMS, delivering a next generation portfolio for functional performance engineering

LMS Tec.Manager

Test and Simulation
Data Management

LMS Engineering

Process Integration & Engineering Services

LMS Test.Lab

Market Leader Physical Test

LMS Virtual.Lab

Technology Leader Virtual Simulation

Modal analysis on operational data
Why?

- Real operating conditions $\neq$ laboratory conditions
  - non-linearities
  - “Structural” changes
  - environmental influences

- Practical reasons
  - Inability to measure input forces

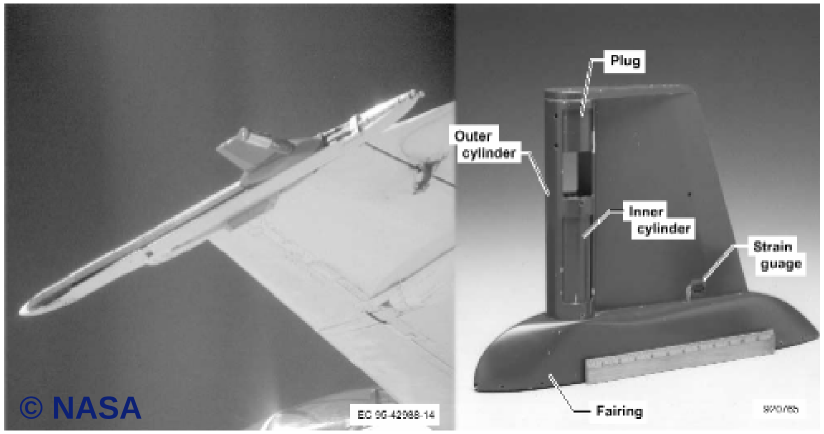
- Health monitoring / damage detection

- Extended use of available data

Operational Modal Analysis
In-operation Testing

- Input - output (FRF) data
  - Require special setups for forced excitation
    - Rotating wing-tip vanes
    - Electromagnetic bearings
    - Low-frequency exciters
    - Drop-weights
    - Unbalance shakers
    - Pyrotechnics
    - Control Surface Input
  - Testing complexity
  - Data quality (*undesired* ambient sources)

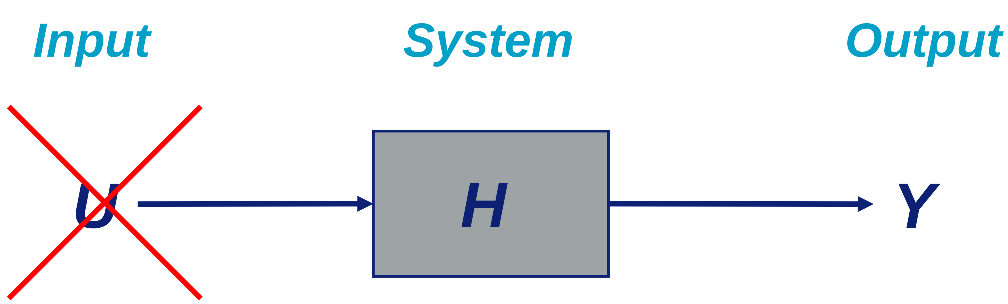
- Output-only data
  - *Desired* (but unknown) ambient sources



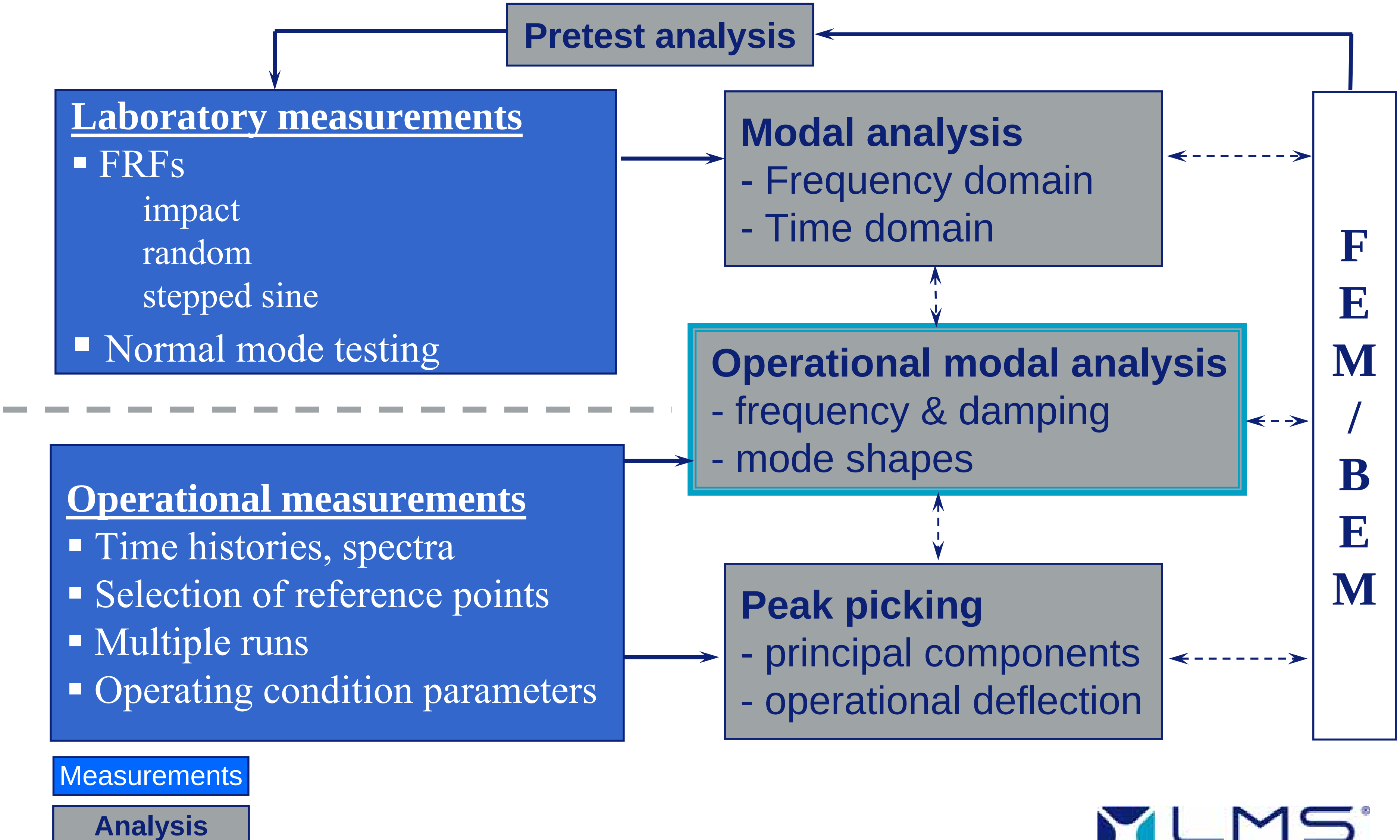
What is Operational Modal Analysis

- Identification of modal parameters from data measured on a structure during operational conditions.
  - Eigenfrequency
  - Damping
  - Mode shape

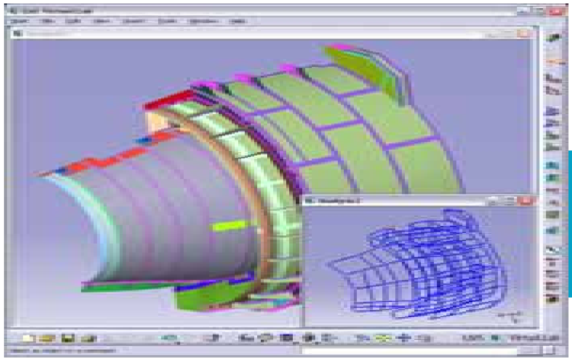
- Operational modal analysis = identifying *H*
  - Based on *Y*
  - Without knowing *U*



What is operational modal analysis?
Complementary to experimental modal analysis



Operational Modal Parameter Estimation Challenges



- Complexity of tested structures
  - Large number of data points, ie. aircraft, satellites
  - Larger frequency bands
  - In-situ vehicles, ie. full scale, trimmed structures, in-flight aircraft
- With regards to product development testing
  - Reduced testing time
  - More product variants
  - Reliable accuracy adequate for use with FE applications
- Expertise of the users
  - Less experienced personnel
  - Less consistency between operators

Accurate, efficient and reliable analysis of complex datasets with minimal user interaction

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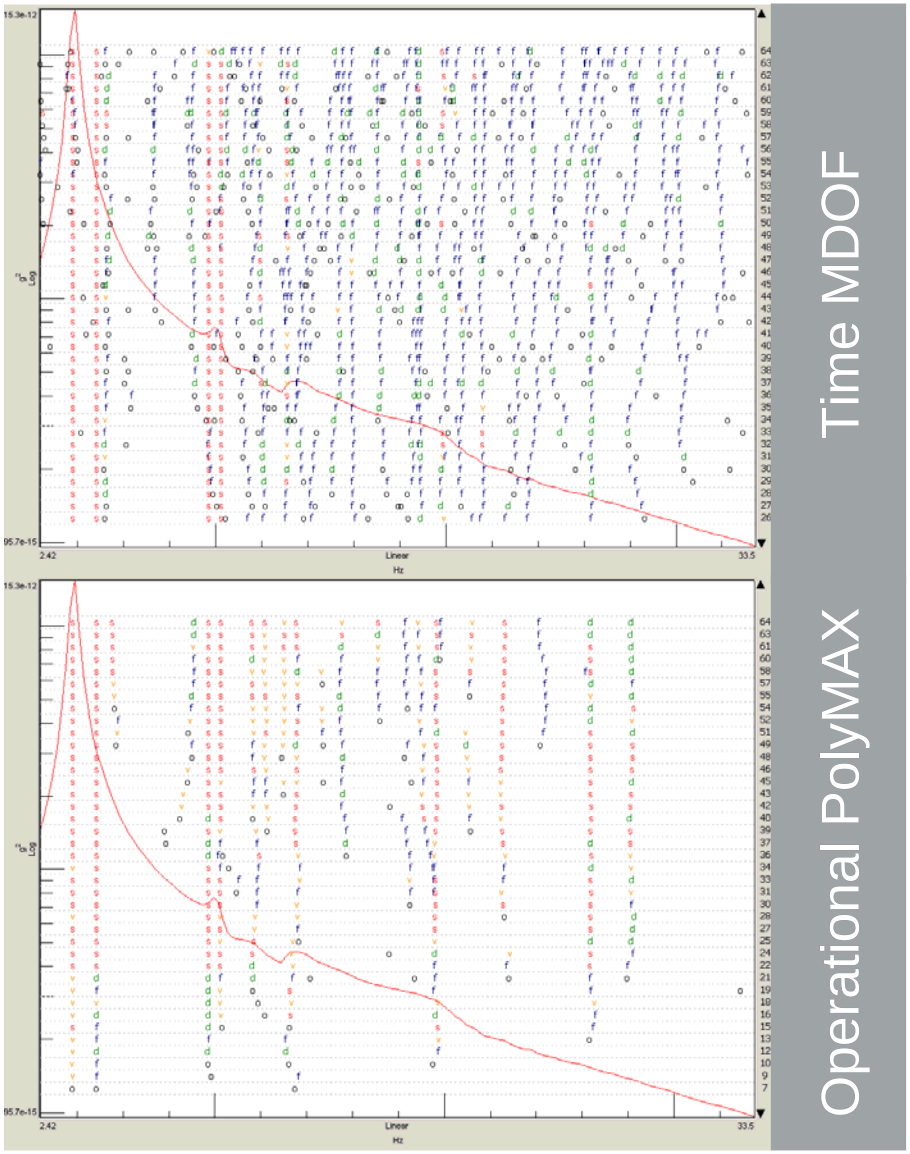
Operational Modal Parameter Estimation
Operational LMS PolyMAX



- Same method as classical modal
  - Frequency domain method
- General purpose method
  - High or low damped structures
  - High modal density
  - Large bandwith
  - Noisy data
- Extremely clear stabilization diagrams
- Consistent, user-independent results

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Operational Modal Parameter Estimation
Operational LMS PolyMAX

- (Half) Spectra Parametrization (cfr FRF)

$$S_{yy}^{+}(j\omega) = \sum_{i=1}^{n} \frac{\{v_i\} < g_i >}{j\omega - \lambda_i} + \frac{\{v_i^*\} < g_i^* >}{j\omega - \lambda_i^*} + \frac{[LR]}{j\omega} + j\omega [UR]$$

- Z-domain transformation

$$\omega \quad => \quad z = e^{j\omega\Delta t}$$

- Right-Matrix fraction model

$$[S(\omega)] = [B(\omega)][A(\omega)]^{-1} \quad = " \frac{[\beta_p] z^p + [\beta_{p-1}] z^{p-1} + \ldots + [\beta_0] z^0}{[\alpha_p] z^p + [\alpha_{p-1}] z^{p-1} + \ldots + [\alpha_0] z^0} "$$

$[\alpha_r]$ $\rightarrow$ Poles

$[\beta_r]$ $\rightarrow$ Mode shapes

Technical Details Reference: ***IMAC 2004 Technical Paper***
http://www.lmspolymax.com

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Operational Modal Parameter Estimation
Time MDOF vs Operational LMS PolyMAX

Balanced Realization (Time MDOF)

- For smaller models (multiple runs)
- High computational load
- High damping a problem
- High modal density
- Not for broadband analysis
- Unclear stabilization diagram
- Possibly inconsistent results

+ One step Poles & Modes
+ Many references possible

Operational LMS PolyMAX

+ Large number of responses
+ Fast, efficient computation
+ High damping no problem
+ High modal density
+ Broadband analysis
+ Crystal-clear stabilization diagram
+ Consistent, repeatable results

- Poles & modes in 2 steps
- Few references, otherwise poor results

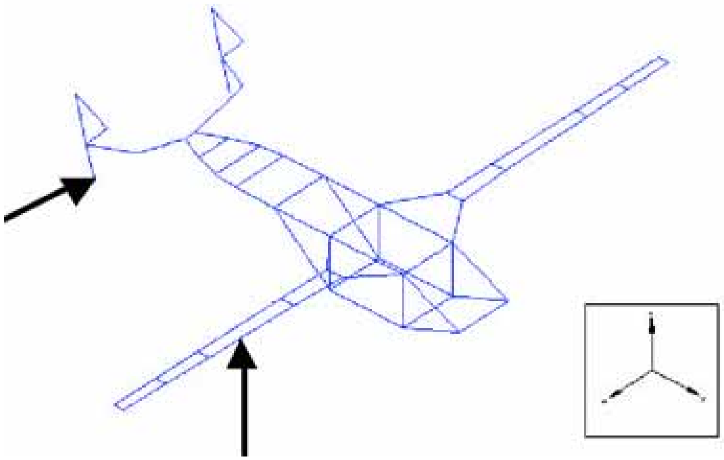
Operational Modal Analysis
Case Studies

Application example
Aircraft in-flight testing

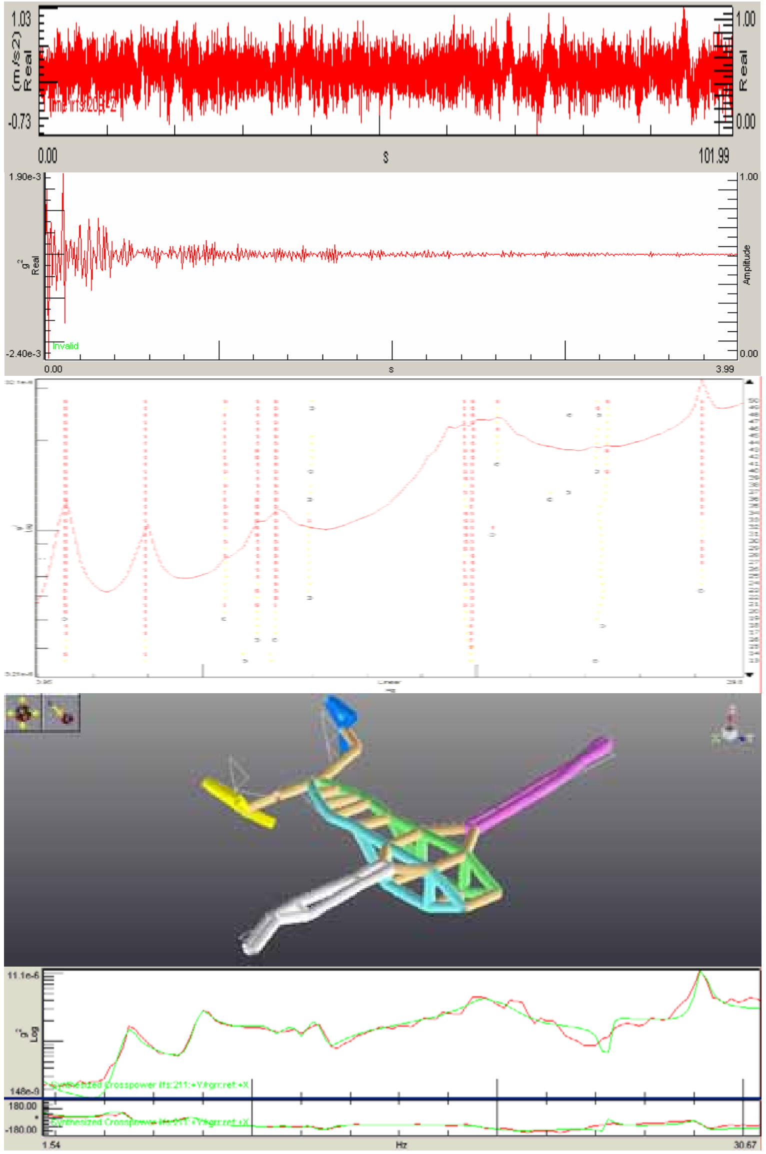
- Test setup
  - 5 flights
  - 30 responses / flight
  - 2 reference points

- Different conditions:
  - Taxi
  - Climbing
  - Level flight (3 altitudes, 4 air speeds)
  - Steady turn
  - Descend

- Objectives
  - Compare with GVT results
  - Tracking of frequency and damping



Aircraft in-flight testing
Analysis procedure



Flight data

↓

Correlation functions

↓

Modal parameter estimation

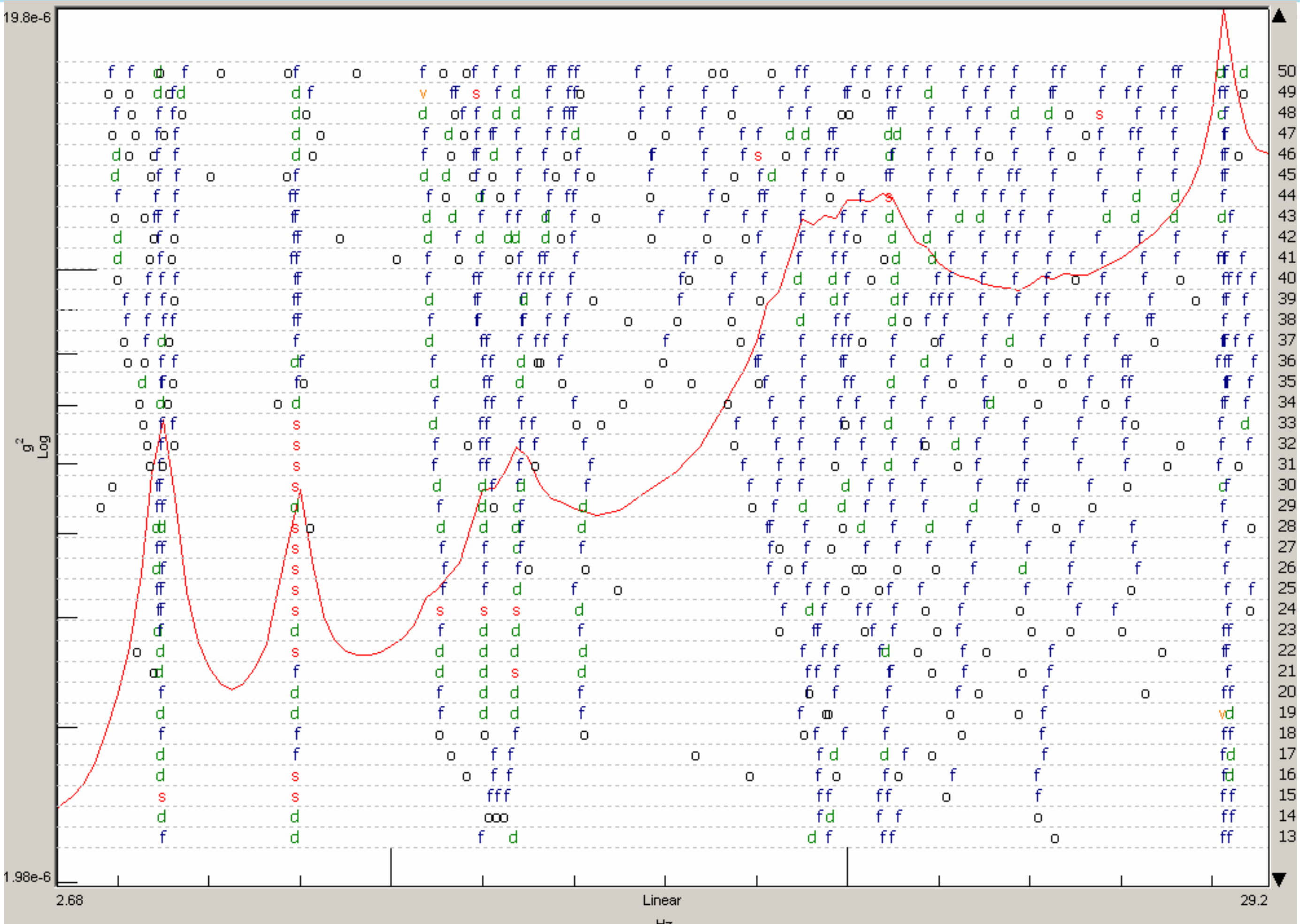
↓

Modal model

↓

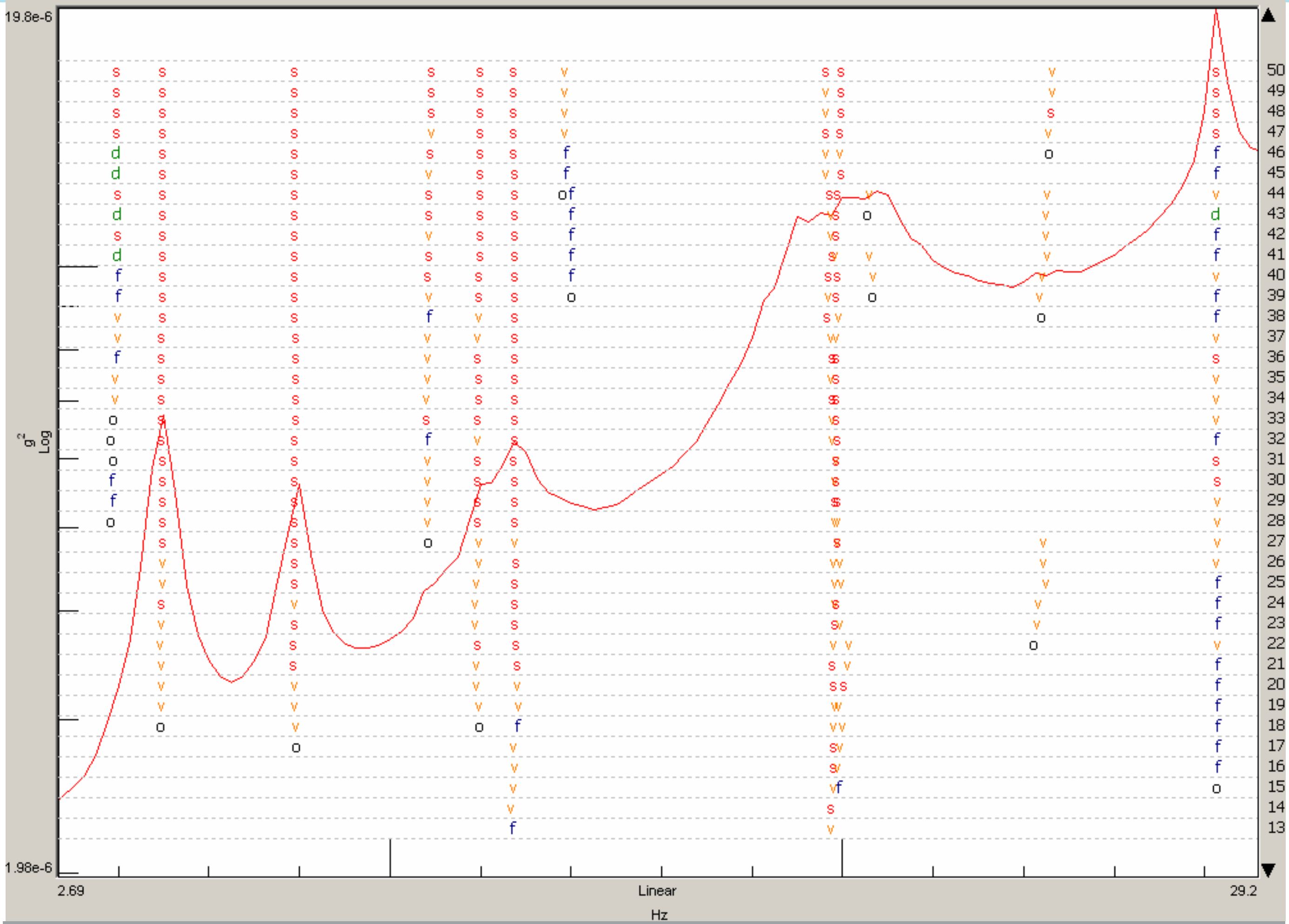
Model Validation

Aircraft in-flight testing
Stabilization diagram



Time MDOF (Balanced Realization)

Aircraft in-flight testing
Stabilization diagram



LMS PolyMAX

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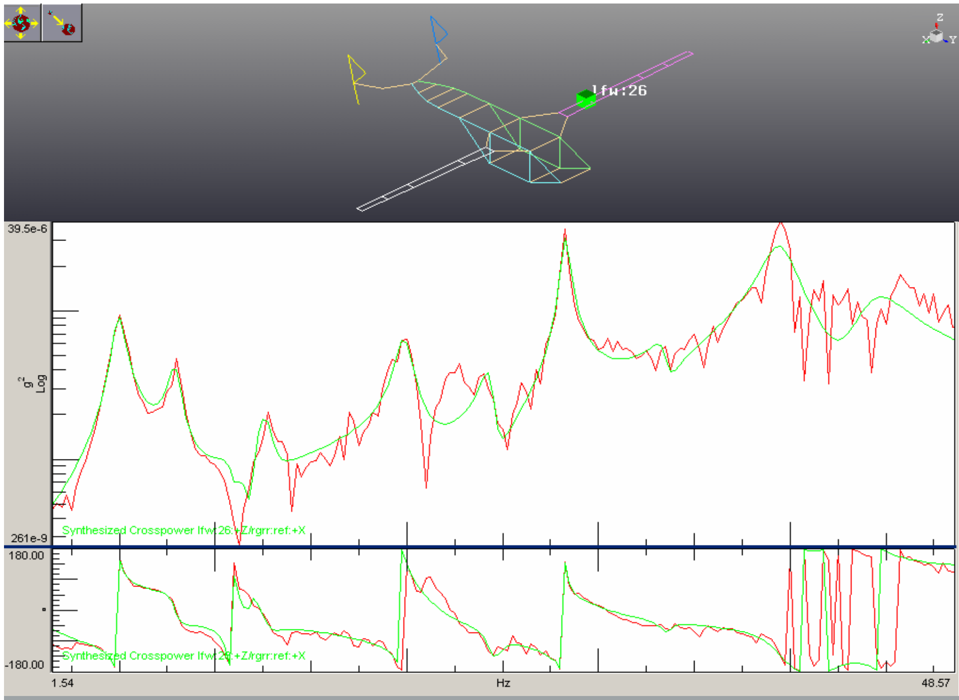
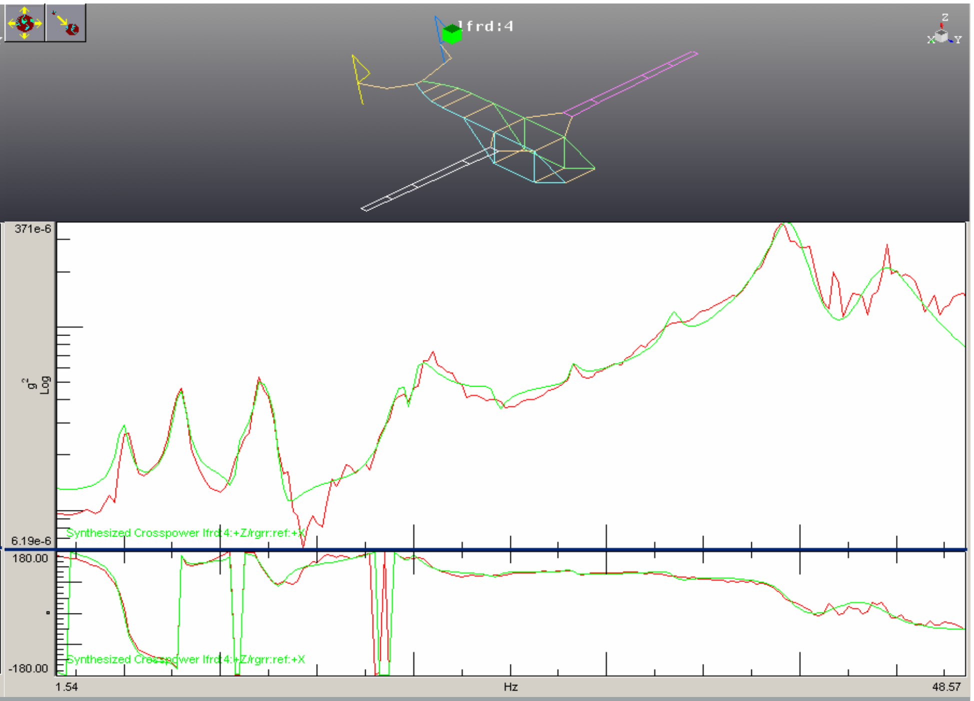
Aircraft In-flight Testing
Crosspower synthesis

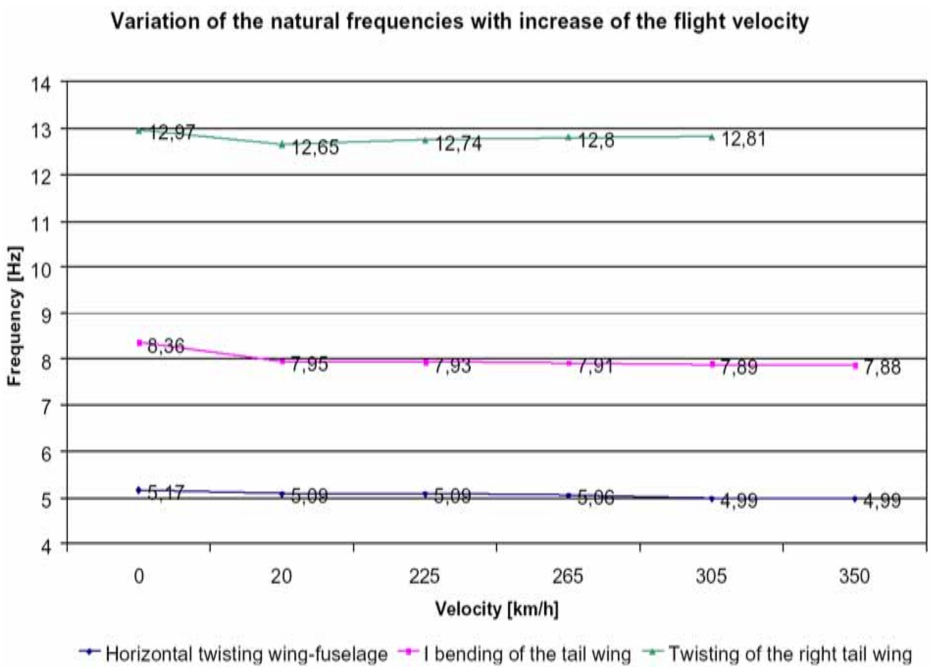


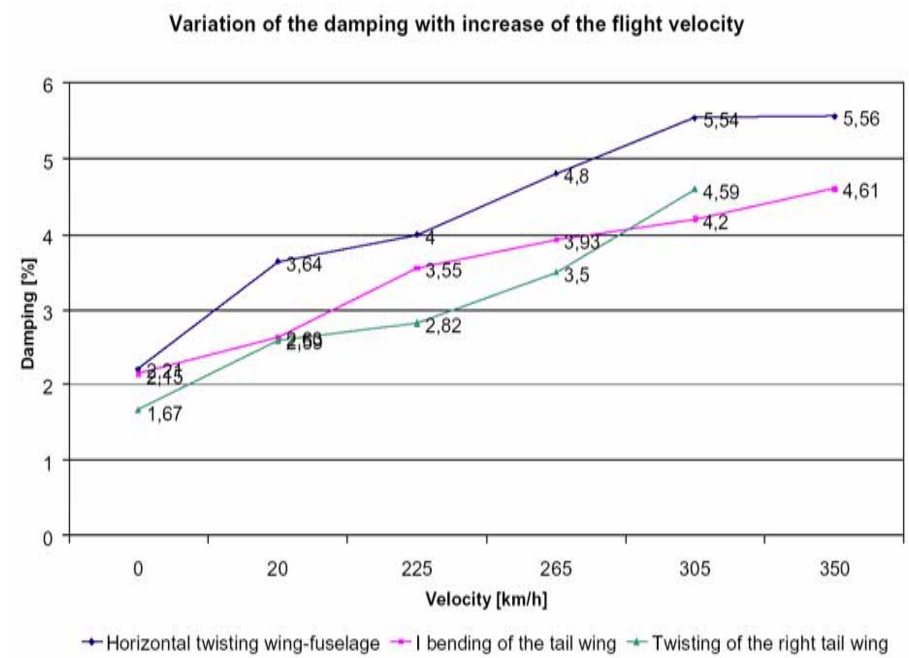
DOF on wing



DOF on tail

Aircraft In-flight Testing
Evolution of frequency & damping





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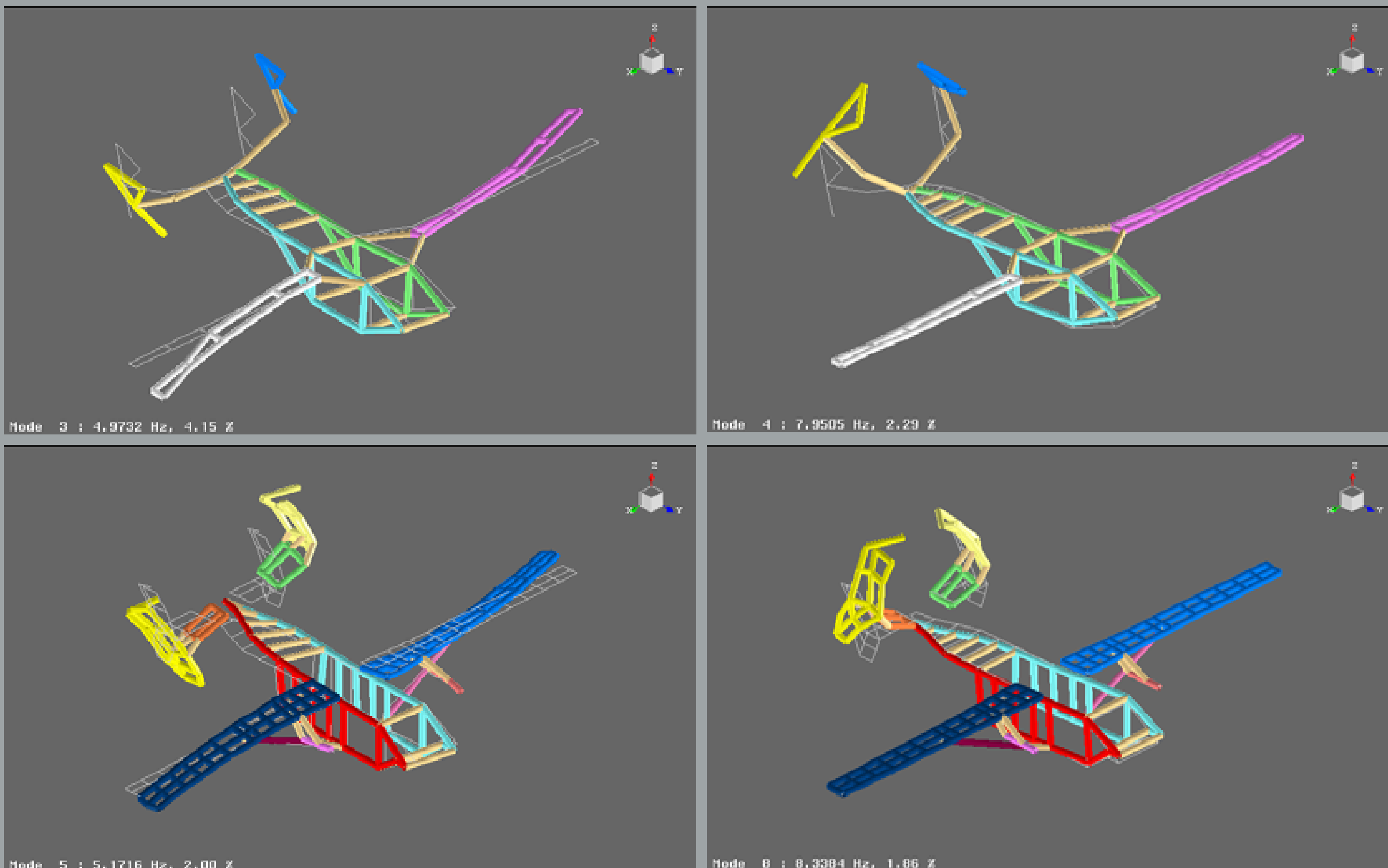
Aircraft In-flight Testing
Mode Shapes



Flight test

Ground Vibration test

ARIANE-5 Launcher

- Identify modal parameters
  - Launcher
  - Main constituents
- Using in-flight data
  - Practical, economical and safety reasons (no GVT)
  - Validation and updating of FE models
  - Influence of gradual mass decrease
  - Damping

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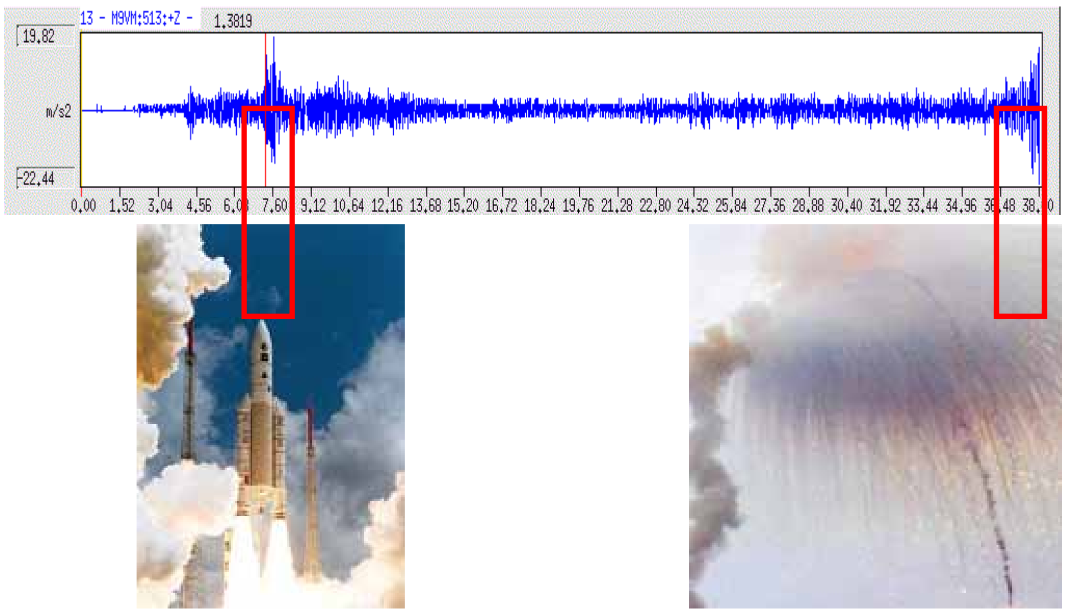
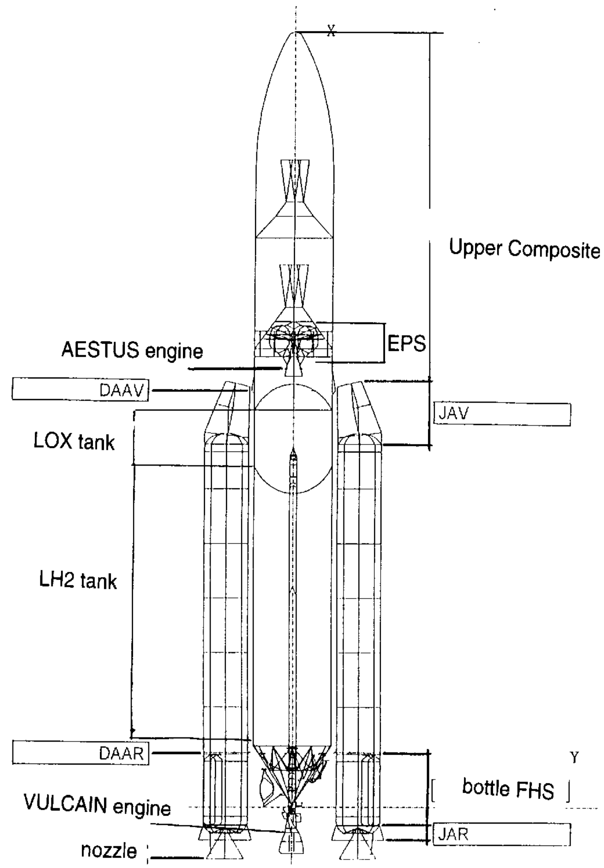
ARIANE-5 Launcher

- Flight 501
- +- 100 accelerations
  - booster segments, booster skirts, booster attachments
  - LH2 and LOX tanks in the main cryogenic stage
  - MMH and N204 tanks in the EPS stage
  - VULCAIN and AESTUS engines





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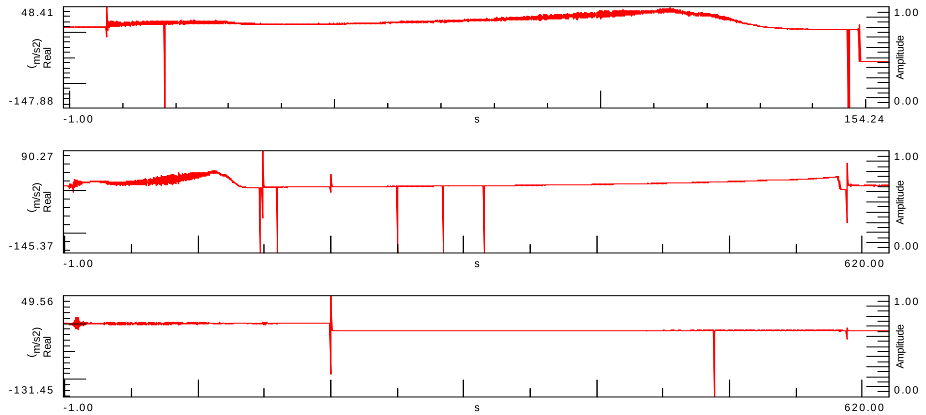
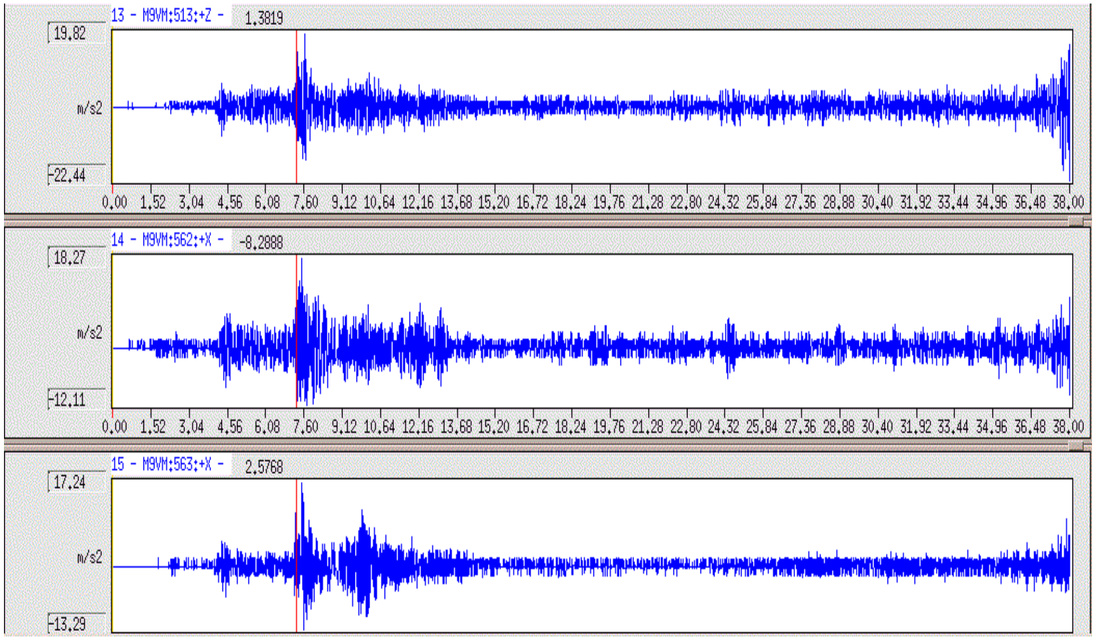
ARIANE-5 Launcher
Characteristics ARIANE-5 Flight Data

- Channels synchronized to common time t_0
- Non-equidistant
- Rounding errors, losses, …
- Different sample frequencies
- Static components
- Drop-outs, spikes
- ADC bit resolution

➔ Intensive data preparation





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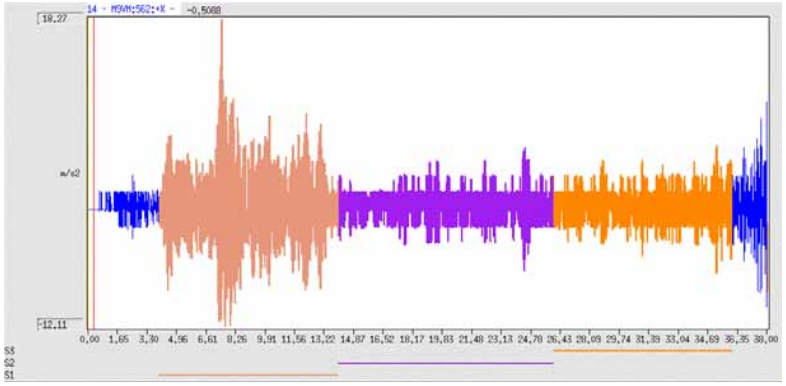
ARIANE-5 Launcher Analyses

- 8 signals measured at 4 fuel tanks in the EPS stage
  - Signals resampled at 93.4Hz
  - Analyses performed for 4 time data segments

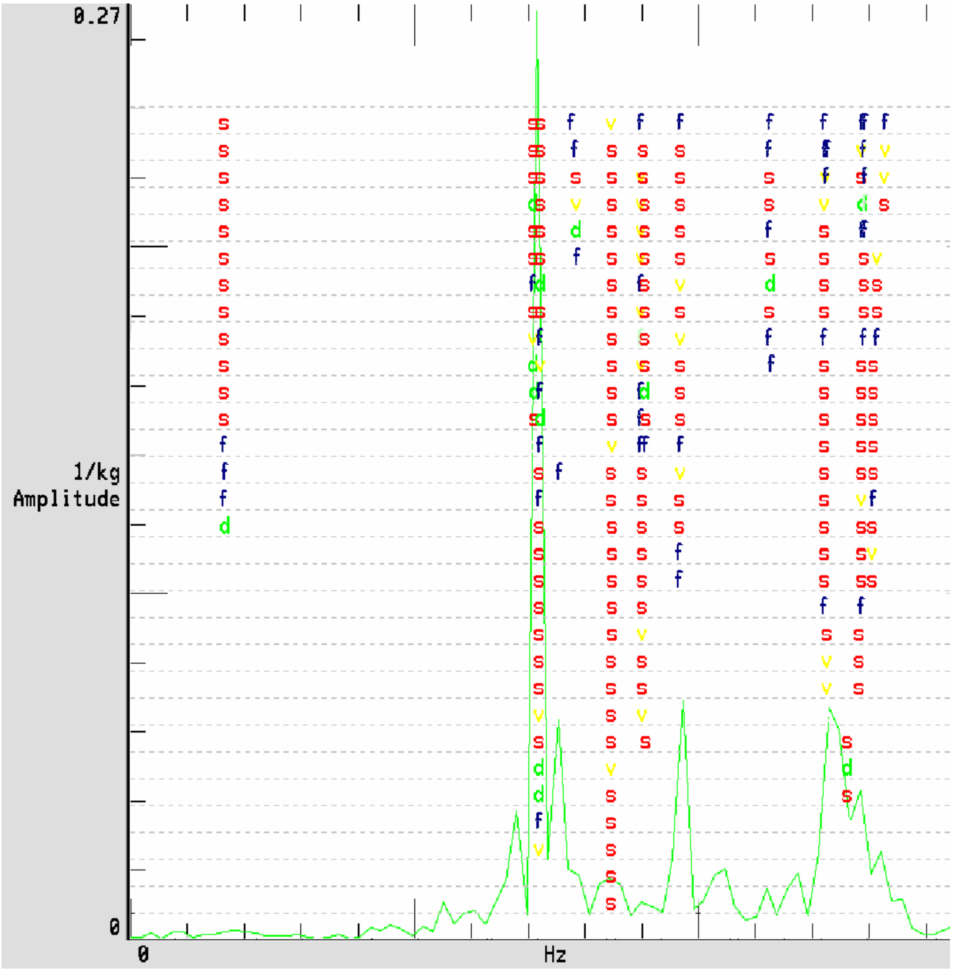


S1 : 4 - 14s

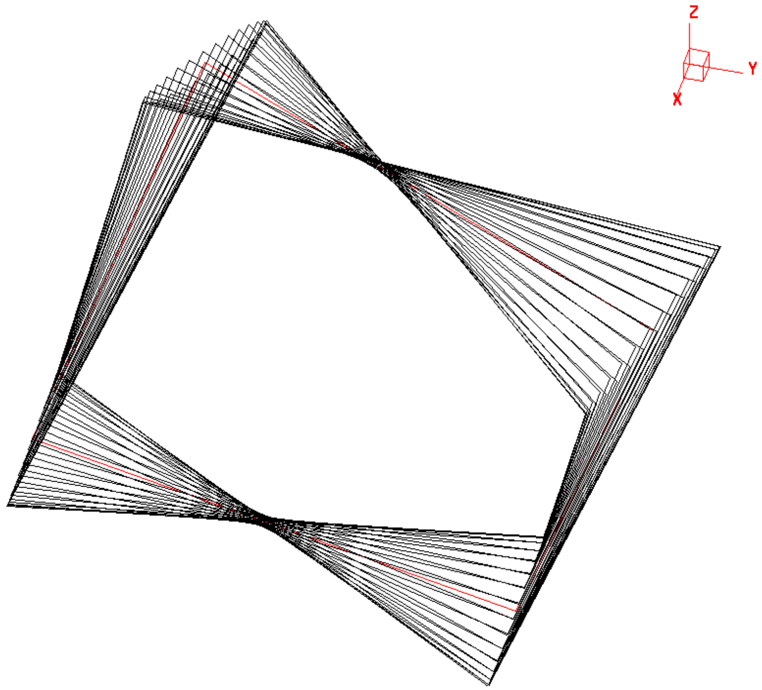
S2 : 14 - 26s

S3 : 26 - 36s

S4 : 4 - 36s

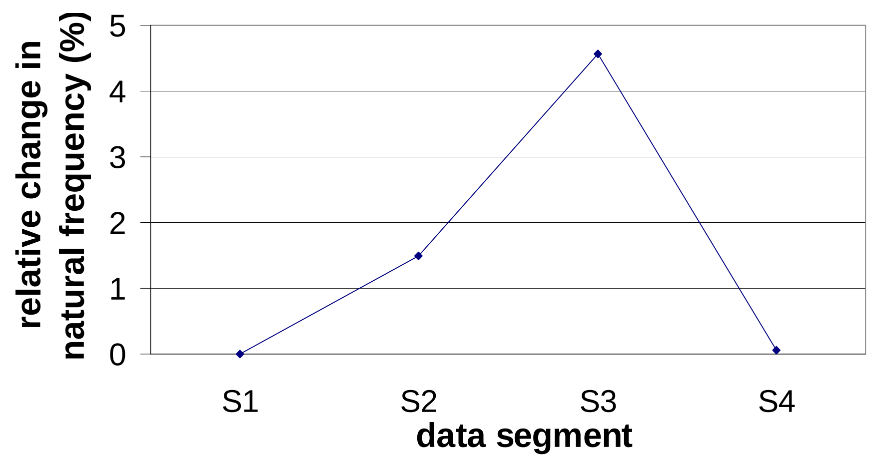


ARIANE-5 Launcher
Results



Fuel tanks suspension mode

Change of frequency vs time segment



S1 : 4 - 14s

S2 : 14 - 26s

S3 : 26 - 36s

S4 : 4 - 36s

Integral Sine Qualification Test
Operational Modal Analysis

Alenia SPAZIO

Integral

- Multi-shaker single axis qualification test
- 350 DOF's
- Range 5 - 100 Hz
- Repeated modes – symmetric setup
- Mode shapes from base-driven test

- Y-axis qualification sweep data

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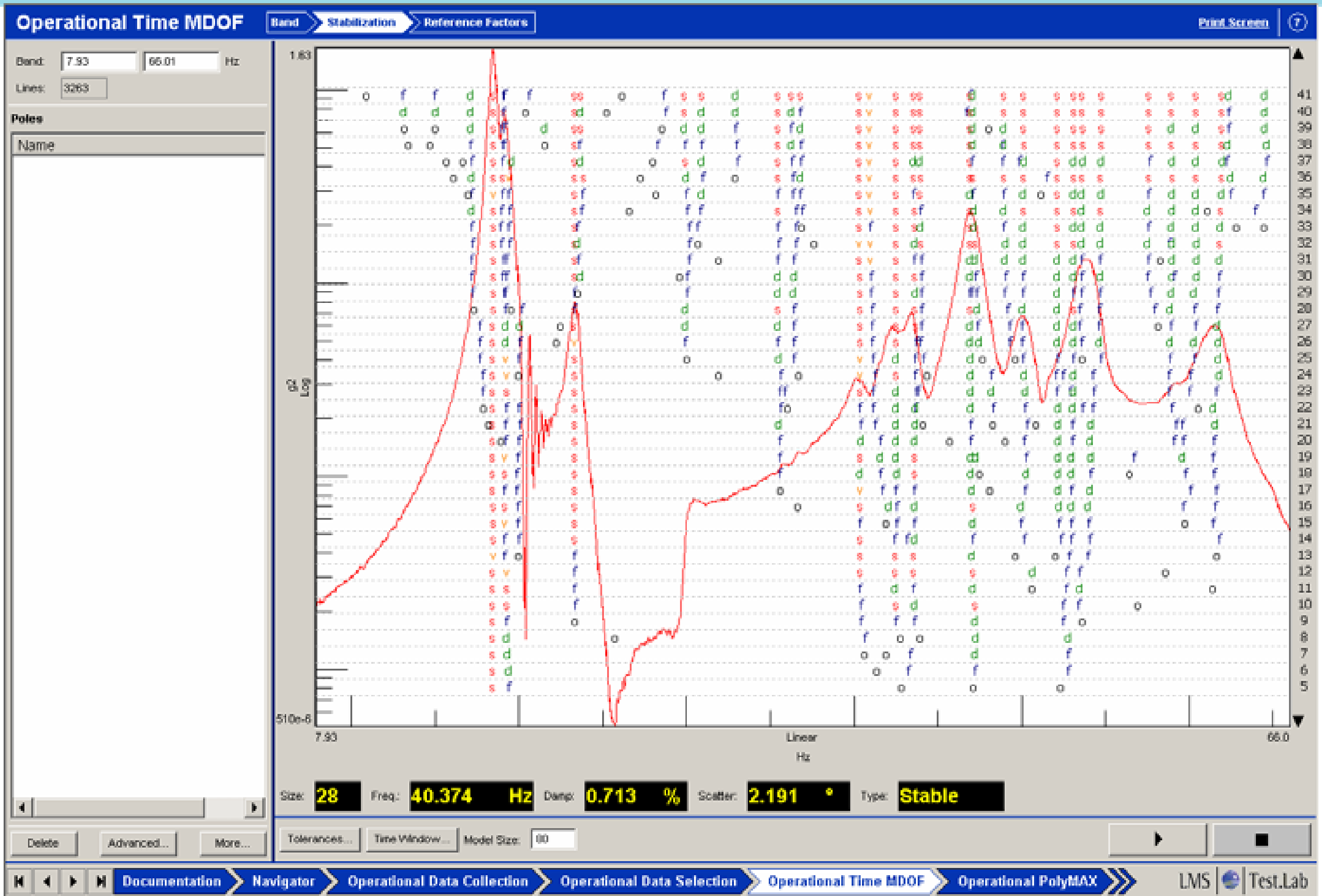
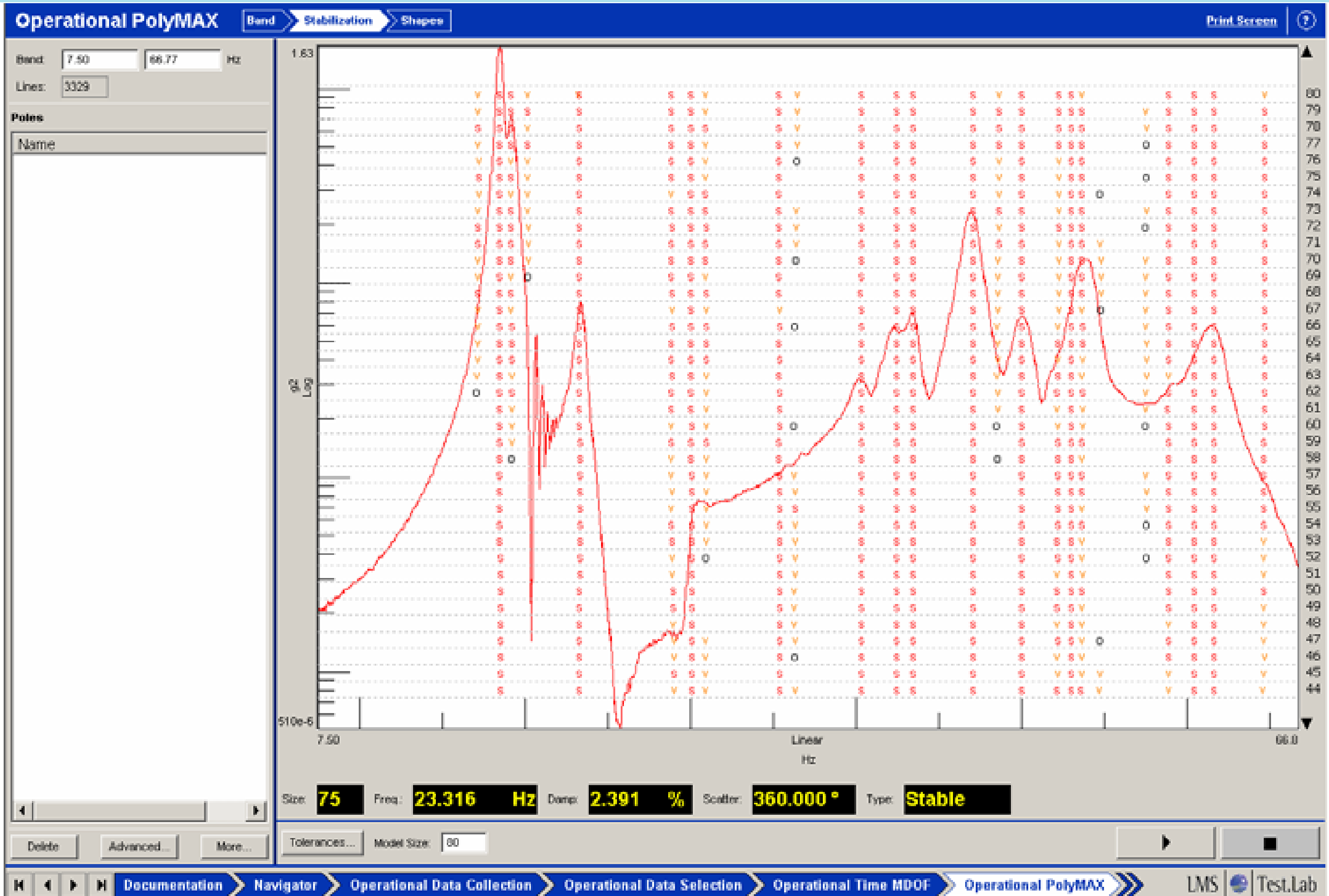
Integral Sine Qualification Test
Broadband / High-order Analysis



Time MDOF (Balanced Realization)

Integral Sine Qualification Test
Broadband / High-order Analysis



LMS Test.Lab PolyMAX

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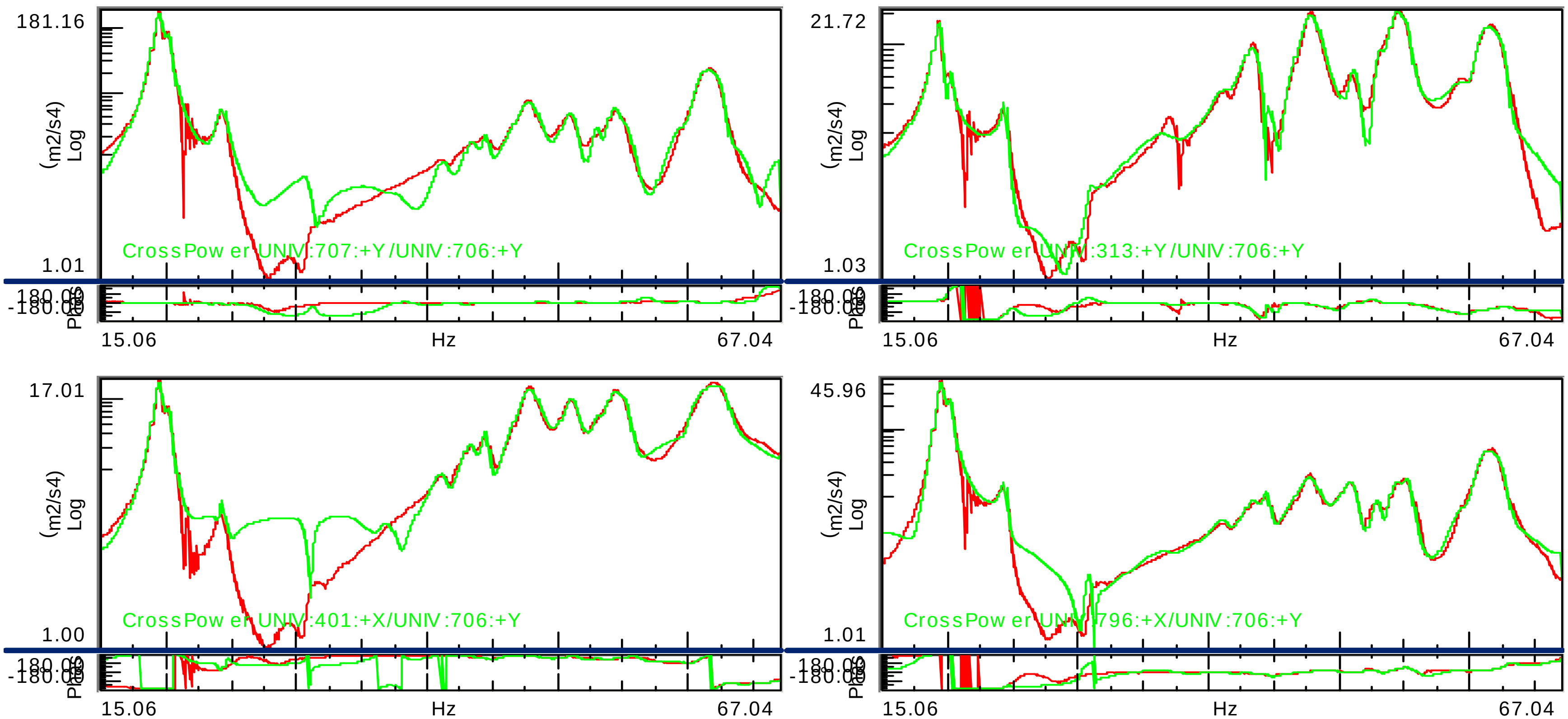
Integral Sine Qualification Test
Crosspower Synthesis

Payload module

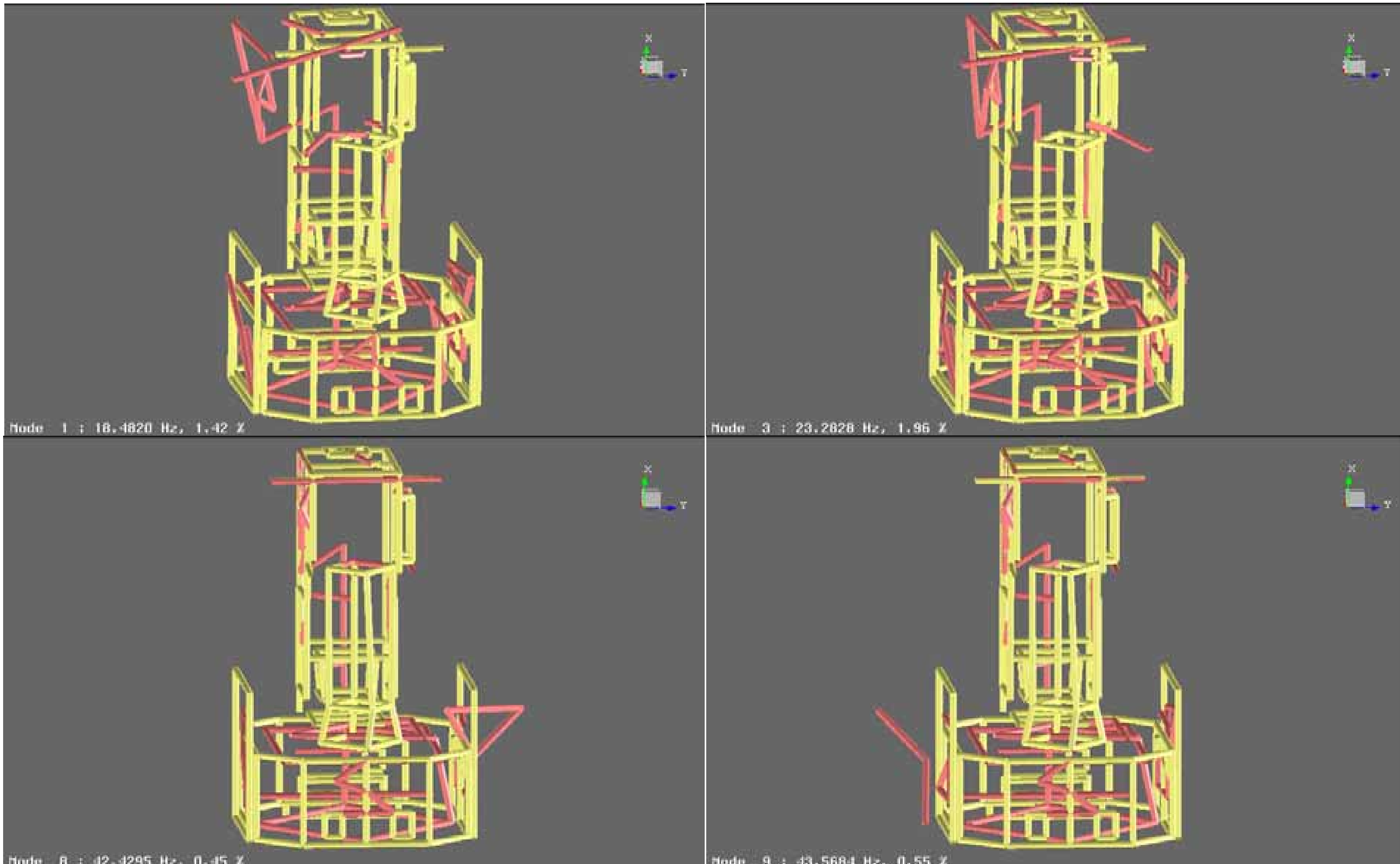
Solar Panel



Service module

Antenna

Integral Sine Qualification Test
Mode Shapes



Operational Modal Analysis
Conclusions

- Mature technology
  - Robust algorithms
  - Many relevant industrial applications
  - Complements Experimental Modal Analysis
  - Better exploitation of operational data
- Use PolyMAX to make OMA easy
  - Crystal-clear stabilization diagrams
  - User-independent results
- Applications include
  - Design verification / FE correlation
  - Trend analysis
  - Damage detection / Health monitoring

Thank you for your attention