A Principal Component Analysis (PCA) Decomposition Based Validation Metric for Use with Full Field Measurement Situations

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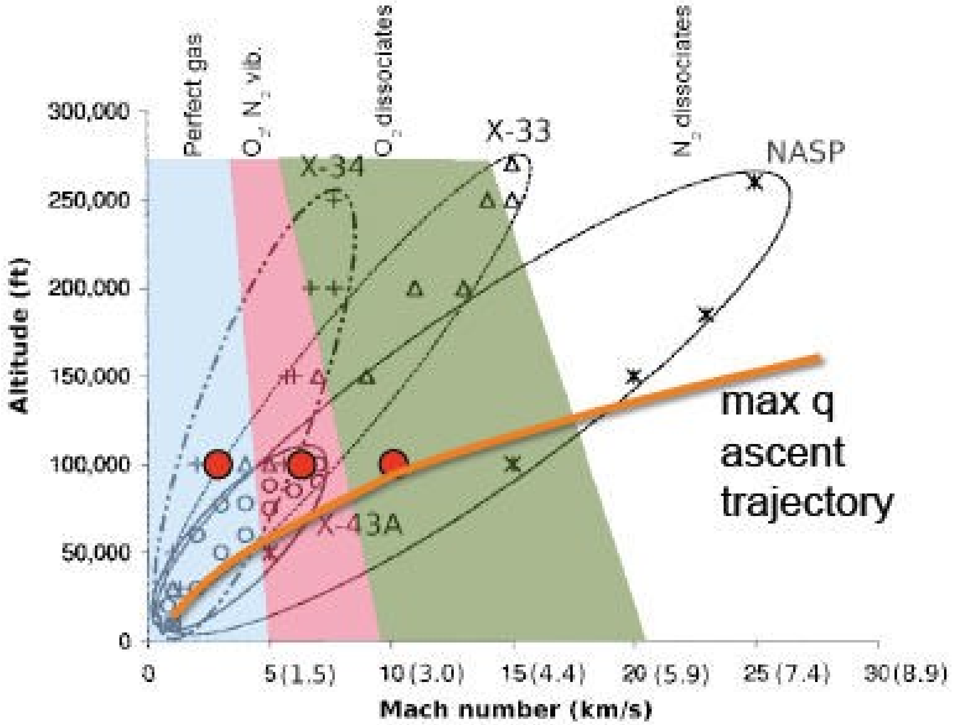
Introduction

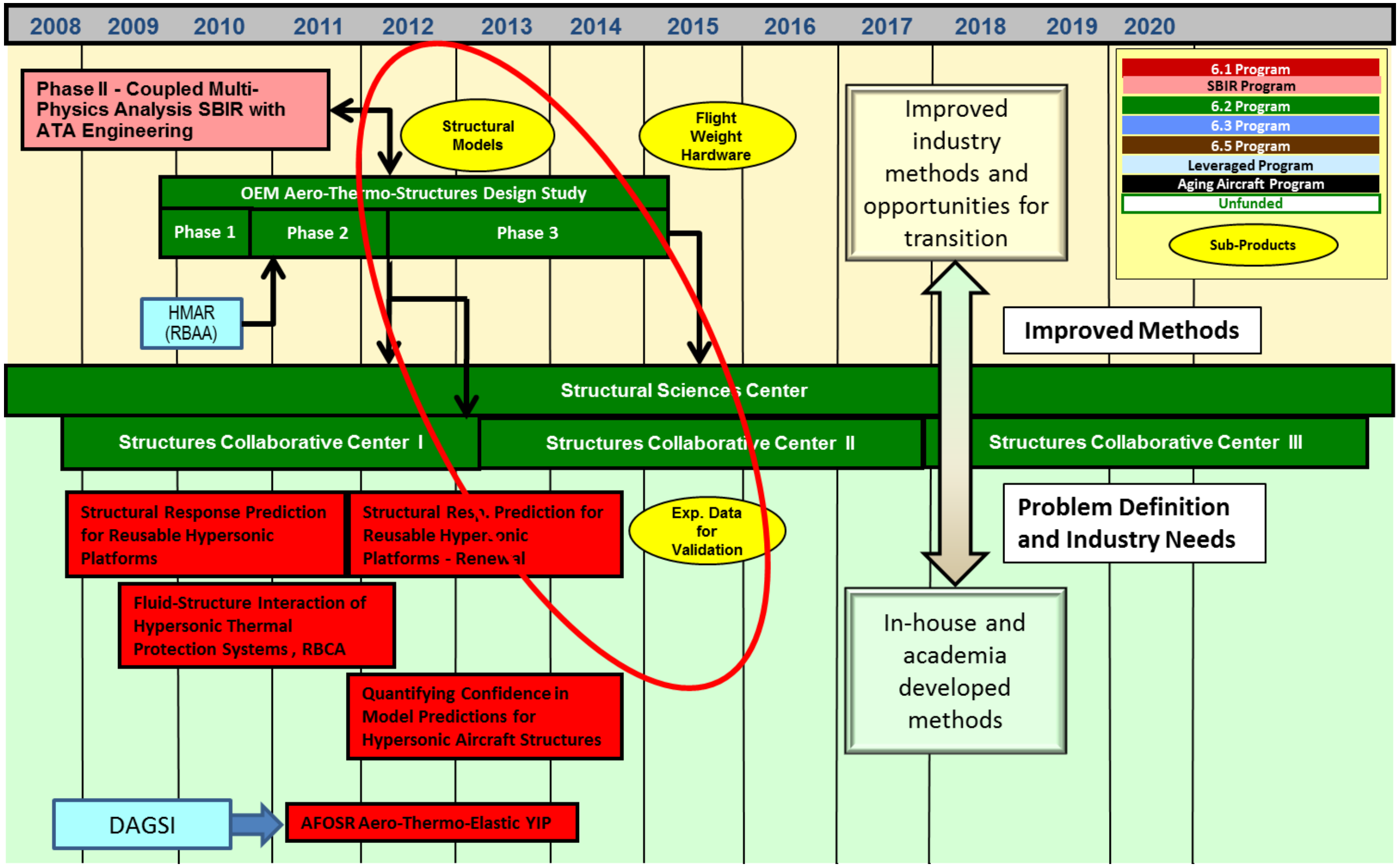
- Hypersonic Vehicle Technology Development Program
  - Senior Collaborator with AFRL-SSC (Structural Sciences Center)
  - Hot structure (no ablation), reusable vehicle
  - Extreme environment, nonlinear coupled response problem
  - Minimal testing prior to first flight – analytical certification
  - Includes refined modeling methodology (coupled, nonlinear)
  - Includes modeling of linear and nonlinear systems
    - High fidelity models and reduced order models (ROMs)
  - Verification and Validation (V&V) of computational model
    - Digital Twin -> virtual vehicle -> computational model
  - Validation Metrics
    - Compliant with V&V Guidelines
    - Incorporate full-field simulation and measurement experiments
    - Minimal overlap of validation and application domain
    - Acceptance by OEM industry partners

AFRL-SSC Hypersonic Vehicle Technology Development

- Digital Twin Concept: Analytical Certification of Air/Space Vehicles
  - AFRL, Structural Sciences Center
  - 2025 Target Date
  - Hypersonic (Mach 5-7)
  - Hot Structure, Reusable
  - Extreme Loads
    - Structure
    - Acoustic
    - Thermal
    - Fluid Flow
    - Coupled Analysis



AFRL-SSC Program Roadmap



2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

Phase II - Coupled Multi-Physics Analysis SBIR with ATA Engineering

Structural Models

Flight Weight Hardware

OEM Aero-Thermo-Structures Design Study

Phase 1

Phase 2

Phase 3

HMAR (RBAA)

Improved industry methods and opportunities for transition

6.1 Program
SBIR Program
6.2 Program
6.3 Program
6.5 Program
Leveraged Program
Aging Aircraft Program
Unfunded
Sub-Products

Improved Methods

Structural Sciences Center

Structures Collaborative Center I

Structures Collaborative Center II

Structures Collaborative Center III

Problem Definition and Industry Needs

Structural Response Prediction for Reusable Hypersonic Platforms

Structural Resp. Prediction for Reusable Hypersonic Platforms - Renewal

Exp. Data for Validation

Fluid-Structure Interaction of Hypersonic Thermal Protection Systems, RBCA

In-house and academia developed methods

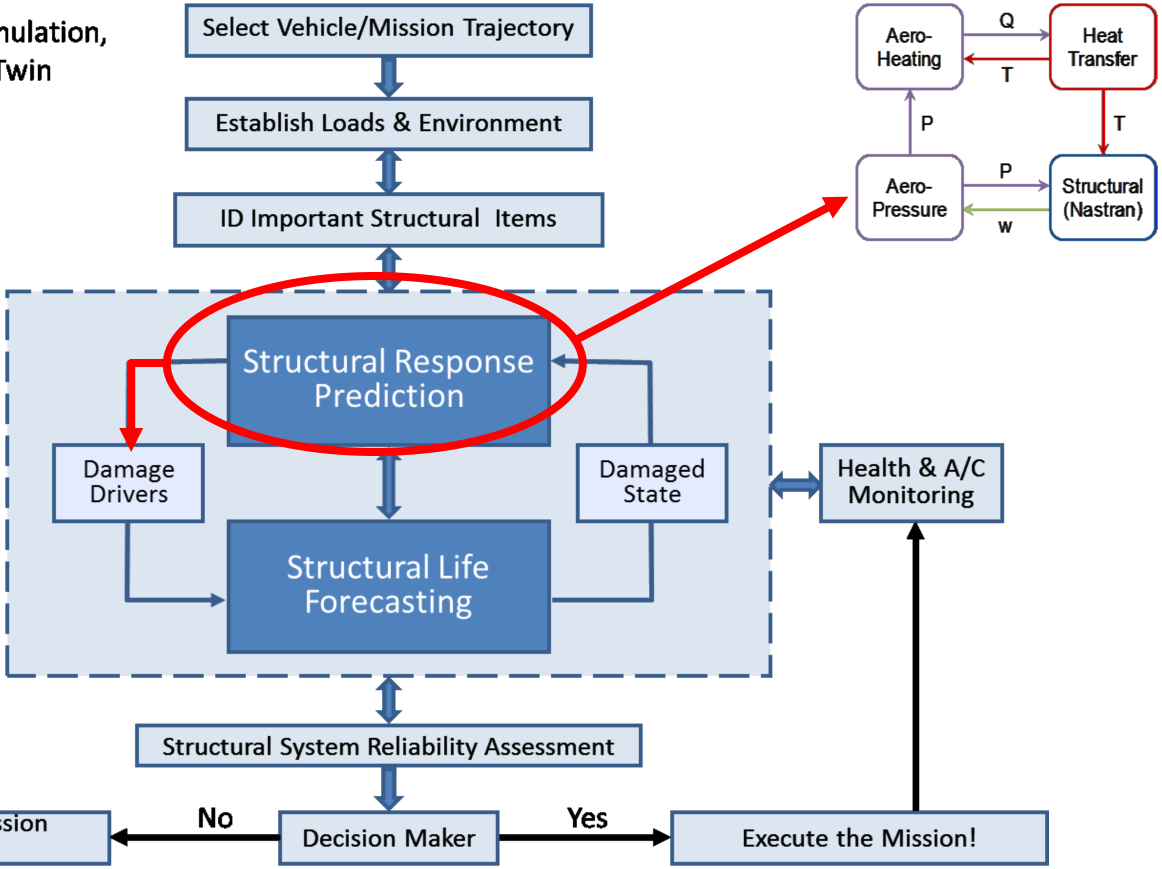
Quantifying Confidence in Model Predictions for Hypersonic Aircraft Structures

DAGSI

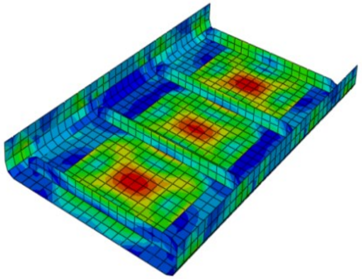
AFOSR Aero-Thermo-Elastic YIP

Computational Model - Digital Twin Concept

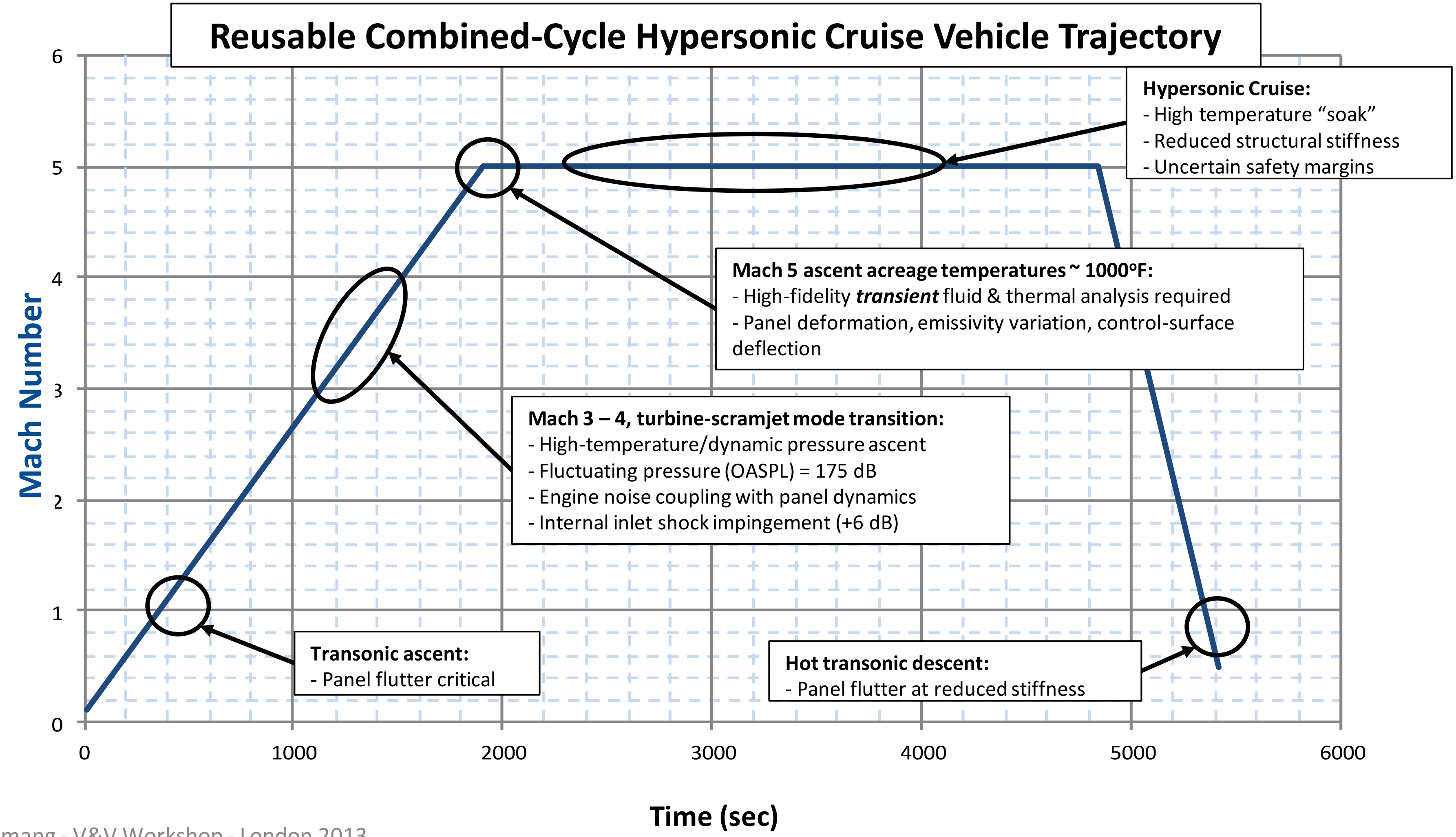
Full-Trajectory Simulation, i.e., a Digital Twin



NASP-era Ramp Panel Heat Shield Presented in 2009 Review



Hypersonic Vehicle - Notional Trajectory



Reusable Combined-Cycle Hypersonic Cruise Vehicle Trajectory

Hypersonic Cruise:
- High temperature "soak"
- Reduced structural stiffness
- Uncertain safety margins

Mach 5 ascent acreage temperatures ~ 1000ºF:
- High-fidelity ***transient*** fluid & thermal analysis required
- Panel deformation, emissivity variation, control-surface deflection

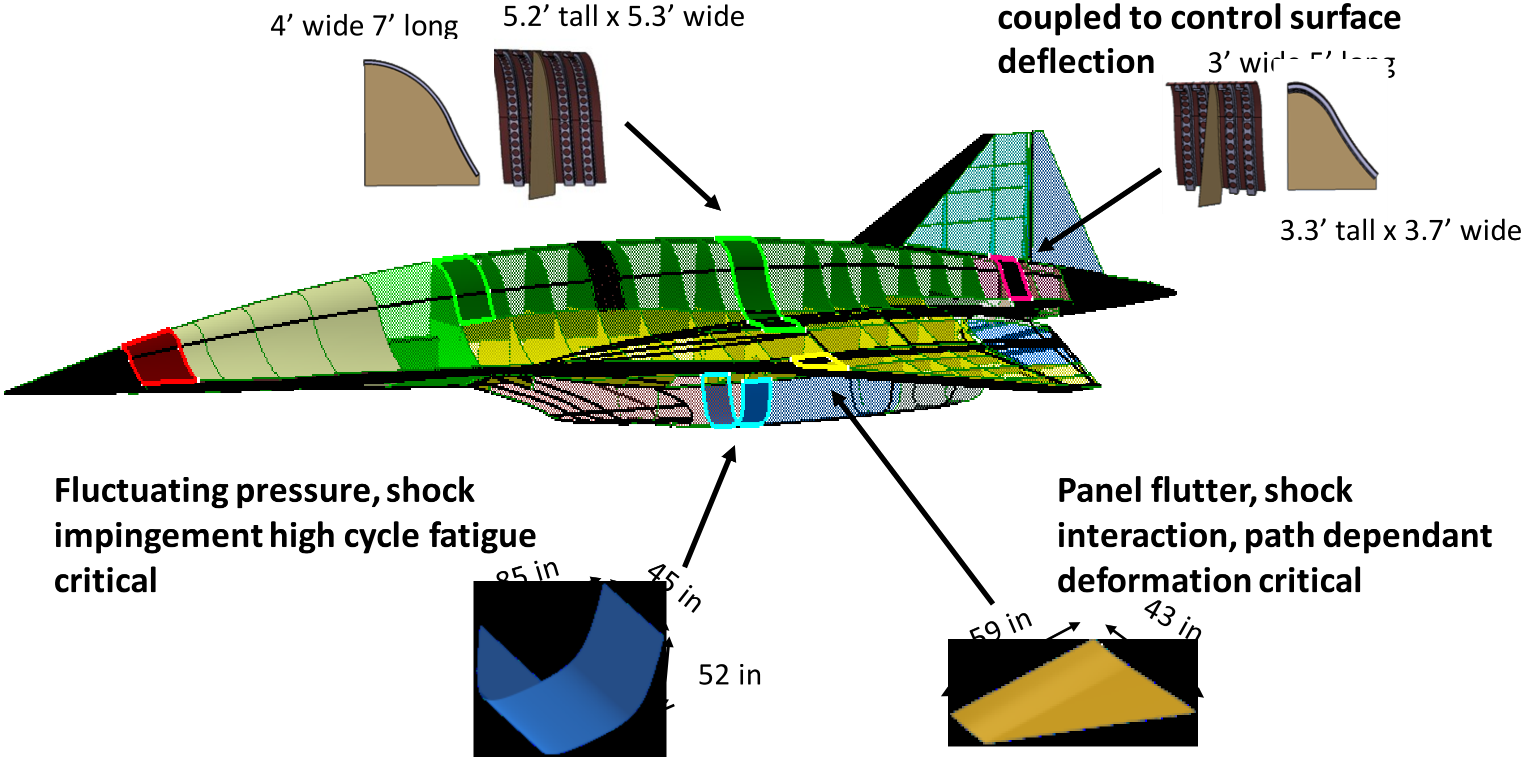
Mach 3 – 4, turbine-scramjet mode transition:
- High-temperature/dynamic pressure ascent
- Fluctuating pressure (OASPL) = 175 dB
- Engine noise coupling with panel dynamics
- Internal inlet shock impingement (+6 dB)

Transonic ascent:
- Panel flutter critical

Hot transonic descent:
- Panel flutter at reduced stiffness

Representative Structure from Phase II

Reusable Combined-Cycle Hypersonic Cruise Vehicle Structure



Fuel-laden transient thermal gradients, local buckling critical

High-temperature local buckling critical coupled to control surface deflection

Fluctuating pressure, shock impingement high cycle fatigue critical

Panel flutter, shock interaction, path dependant deformation critical

Publications - *B. J. Zuchowski* , “Investigation of Shortfalls in Hypersonic Vehicle Combined Environment Analysis Capability,” AIAA-2011-2013.

Levels of Experiments for Validation

- The lowest levels of the required physical experimentation are exploratory (discovery) experiments which are designed to assist in determining which physics models are most appropriate for the system in light of the required environments. Experiments at this level for materials, and a limited subset of components, have already been planned and have begun.
- The next level of physical experimentation includes calibration experiments, which are designed to develop correct model order, verify the parameters in the models, and assist in the quantification of uncertainty associated with the probably environment(s), model(s) and also with the physical experiment(s).
- Another possible level of physical experimentation includes qualification (certification) experiments which are physical experiments required to measure whether certification/qualification standards are met, if these standards exist.
- The final level of experimentation includes validation experiments which are designed to compare results between the analytical model predictions and the measured data.

Major Validation Challenges/Issues

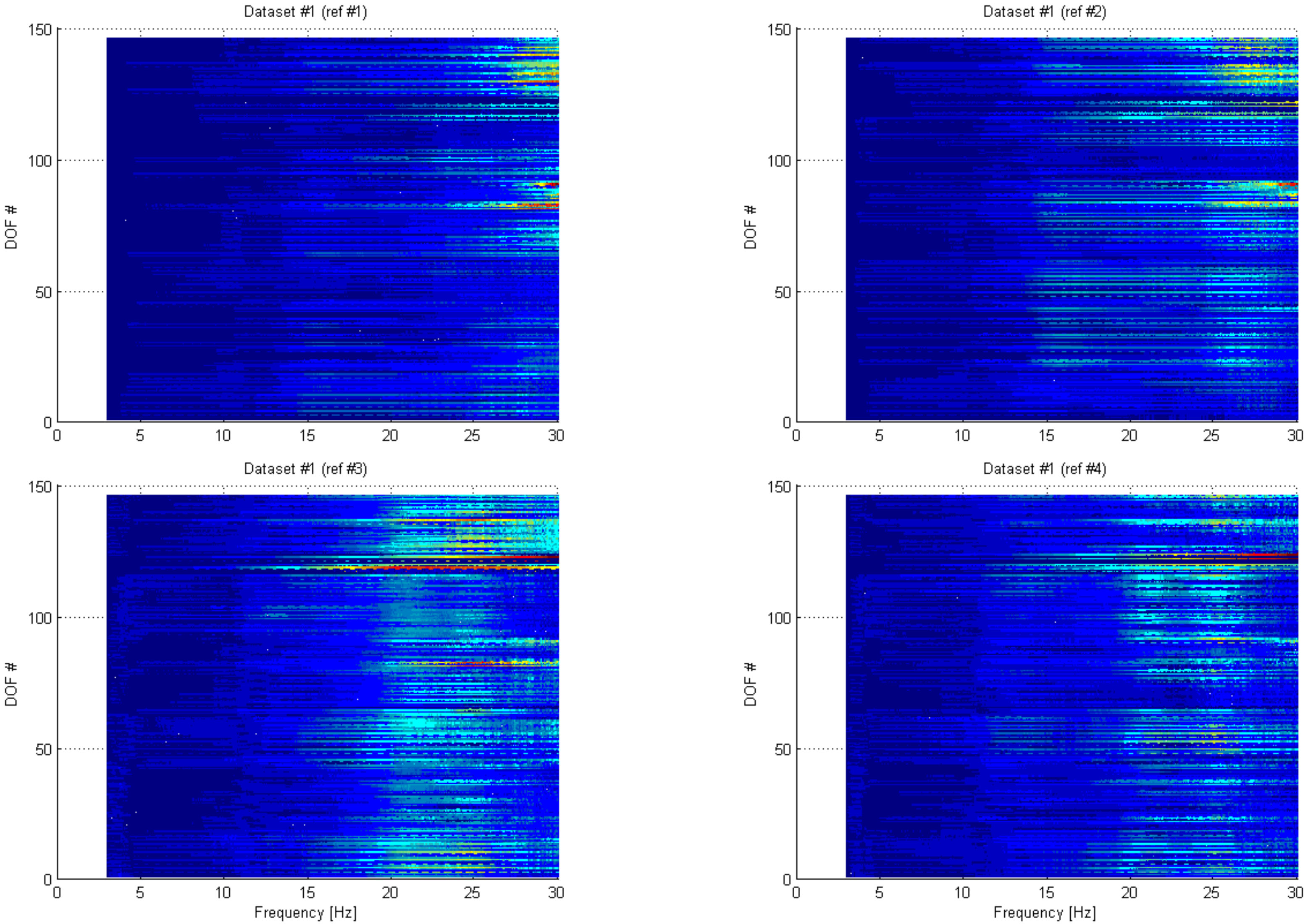
- The major challenges/issues to the validation of the hypersonic vehicle include:
  - Appropriate use of data mining
  - Limits imposed by the use of existing test facilities
  - Resolving blind epistemic uncertainty (accounting for what is not known) versus recognized epistemic uncertainty.
  - Identification of appropriate inputs and physics
  - Proper use of expert panel elicitation
  - Identification of validation metrics and methods
  - Focus on quantification of margins and uncertainties (QMU)
  - Changing the modeling-testing culture

PCA-SVD Validation Metric

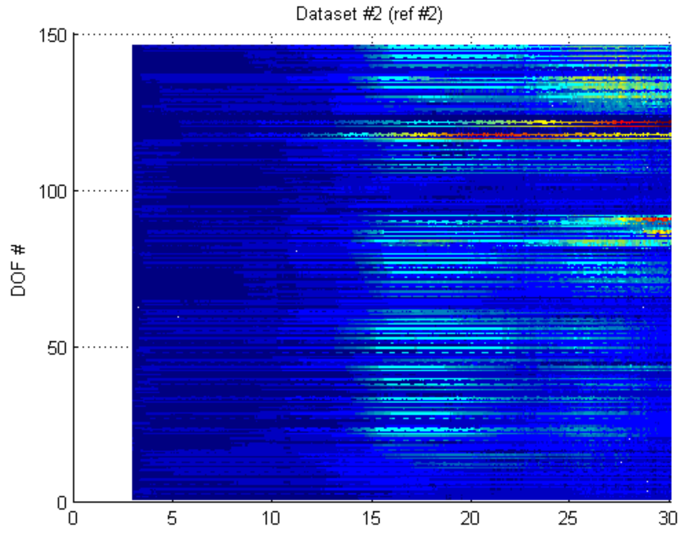
$$[\,B\,]_{N_L \times N_S} = [\,U\,]_{N_L \times N_S} \lceil\, S \,\rfloor_{N_S \times N_S} [\,V\,]^H_{N_S \times N_S}$$

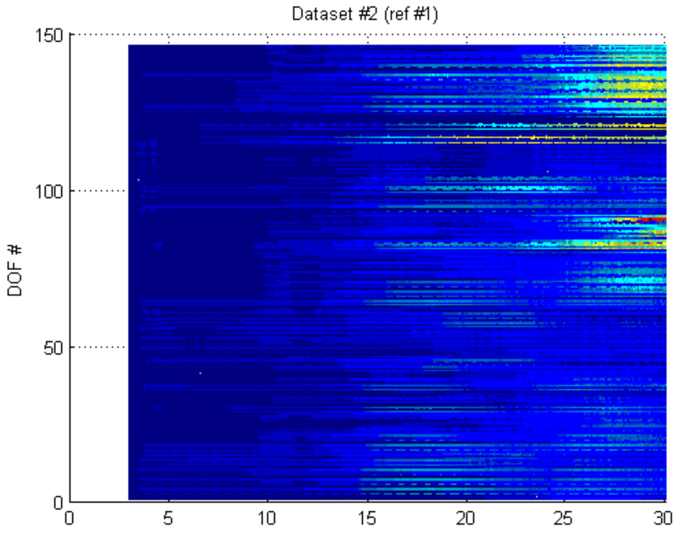
- In the above equation, the matrix [B] represents the data matrix that will be evaluated. In general, this matrix will be complex-valued and rectangular of size N_L by N_S (size of the long and short dimension of the data).
- The [U] matrix is the right singular vectors and the [V] matrix is the left singular vectors and both are complex-valued and unitary. The superscript T represents the transpose of the matrix and the superscript H represents the hermitian (conjugate transpose) of the matrix.
- The remaining [S] matrix is the singular value matrix which is diagonal, square and real-valued.
- As the [U] and [V] matrices are unitary, the magnitude characteristics of the data matrix [B] are captured in the singular values and with proper scaling have the same engineering units (EU) as the data matrix [B].

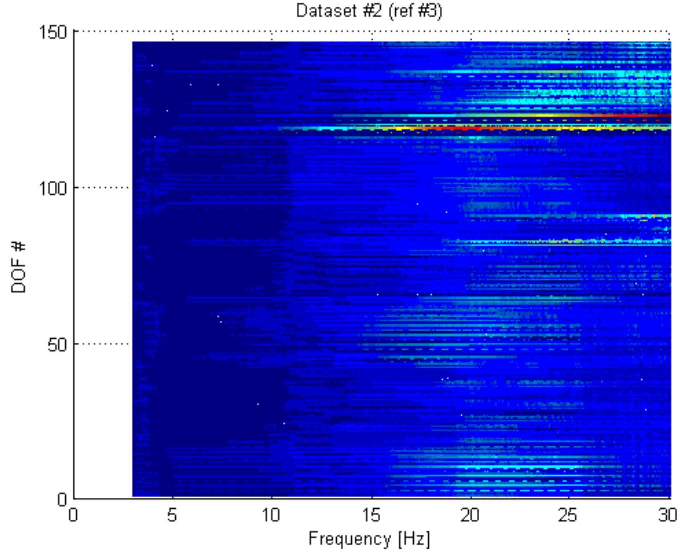
Automotive Example – Data Set #1

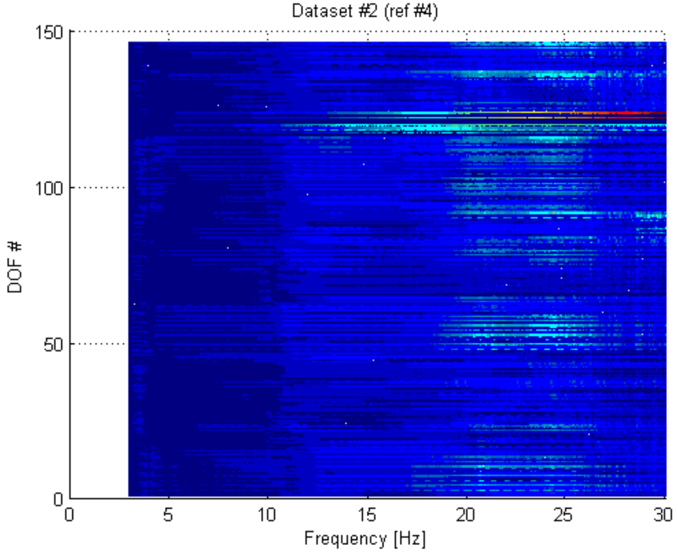


Automotive Example - Data Set #2

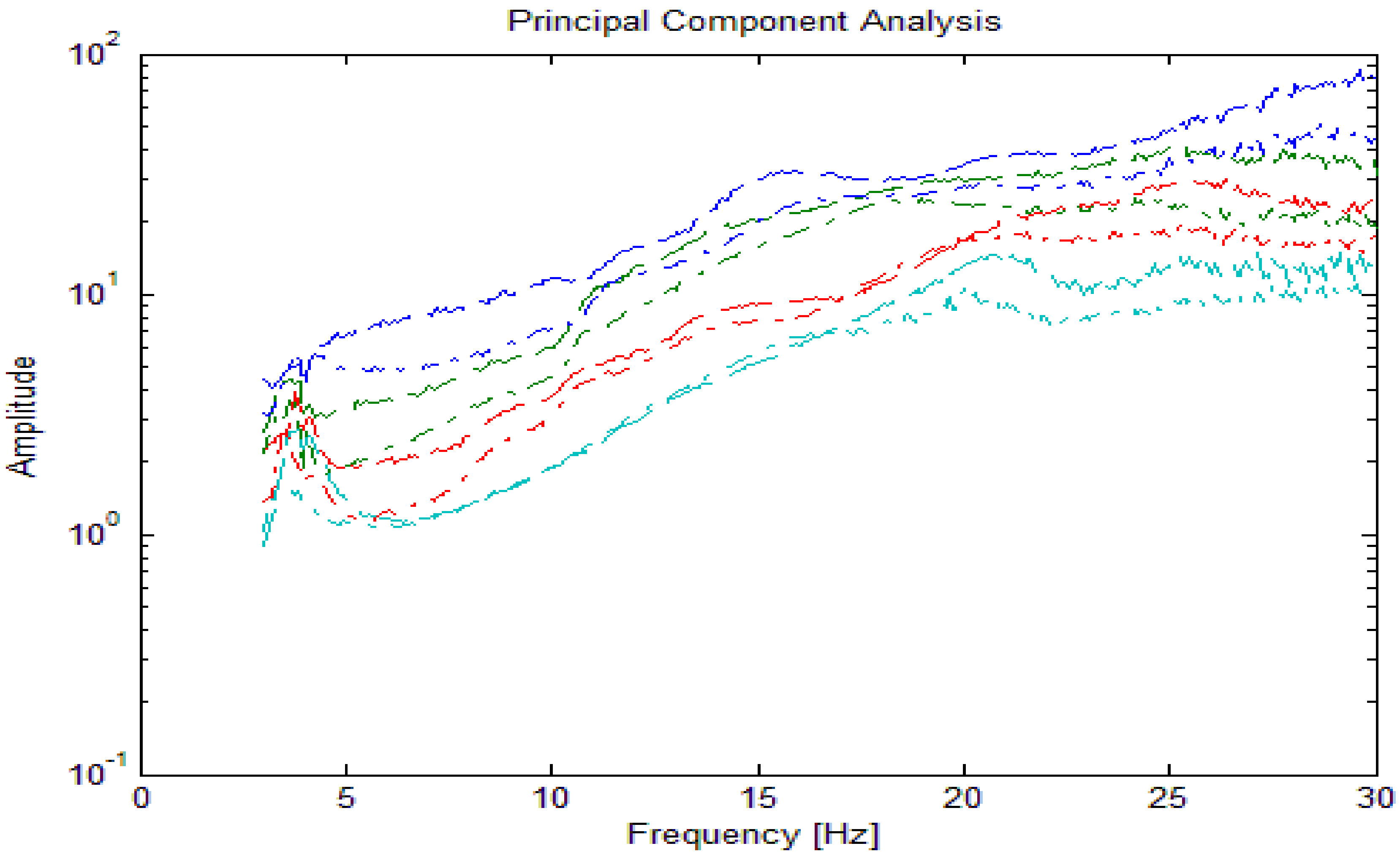




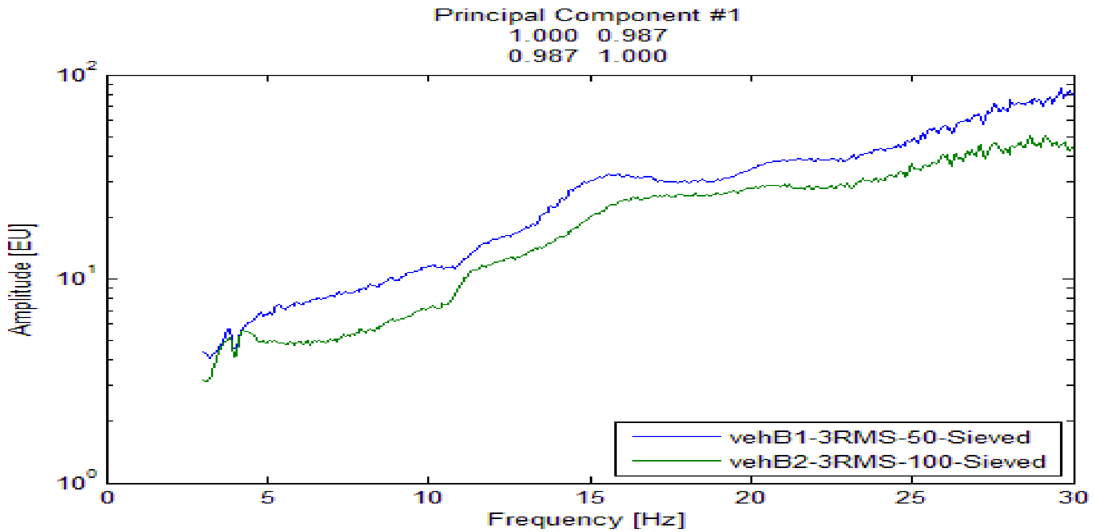


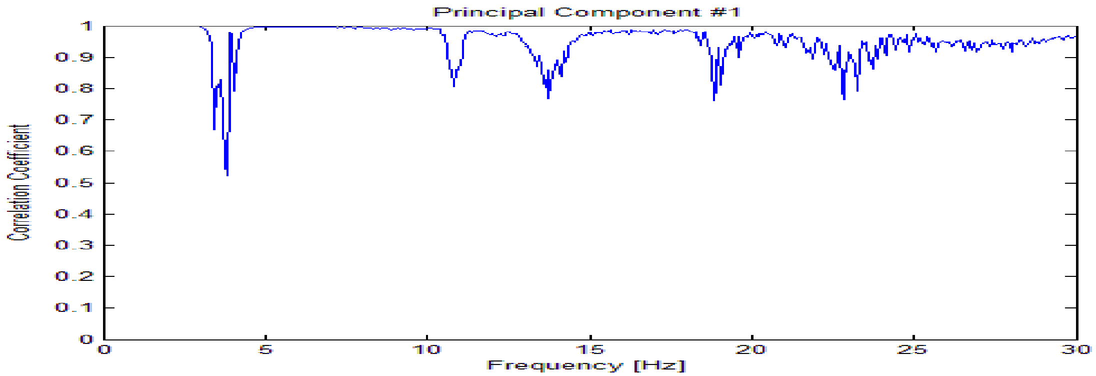


PCA-SVD of Datasets #1 and #2

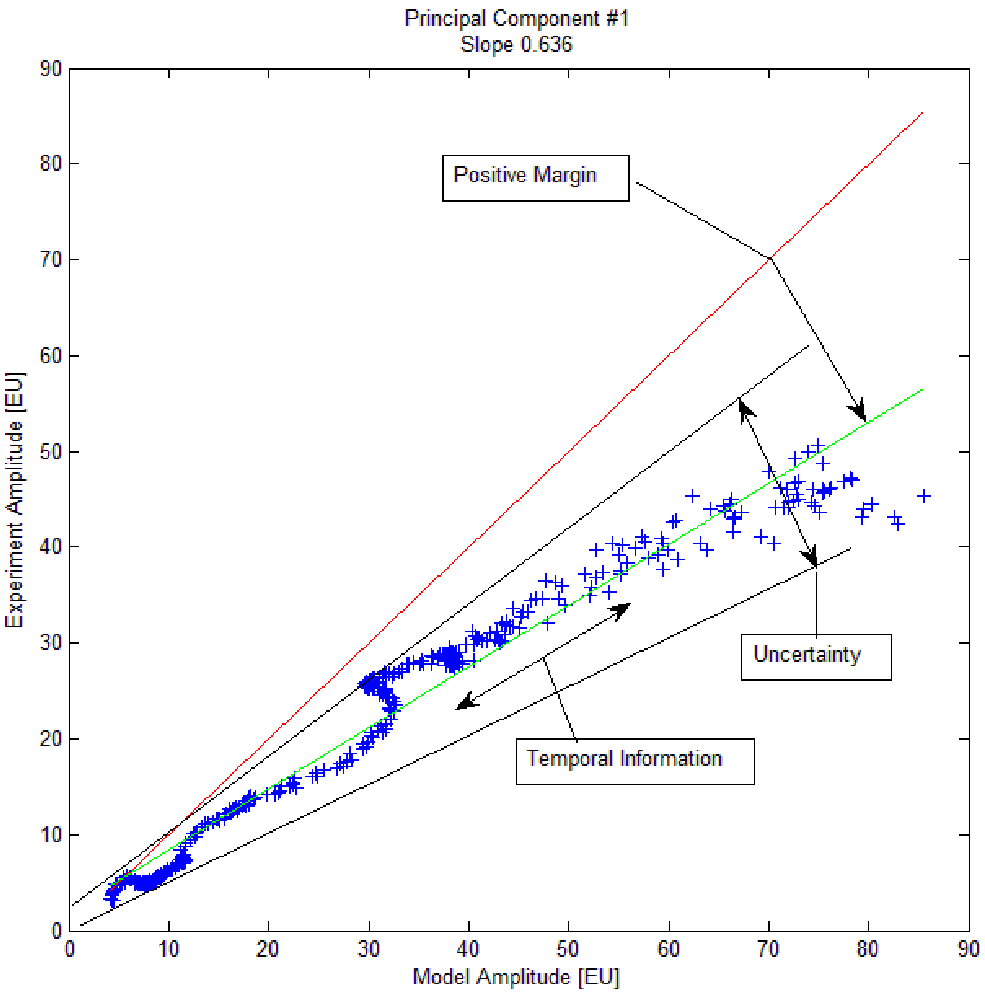


PCA-SVD Dominant Value and Vector Comparison

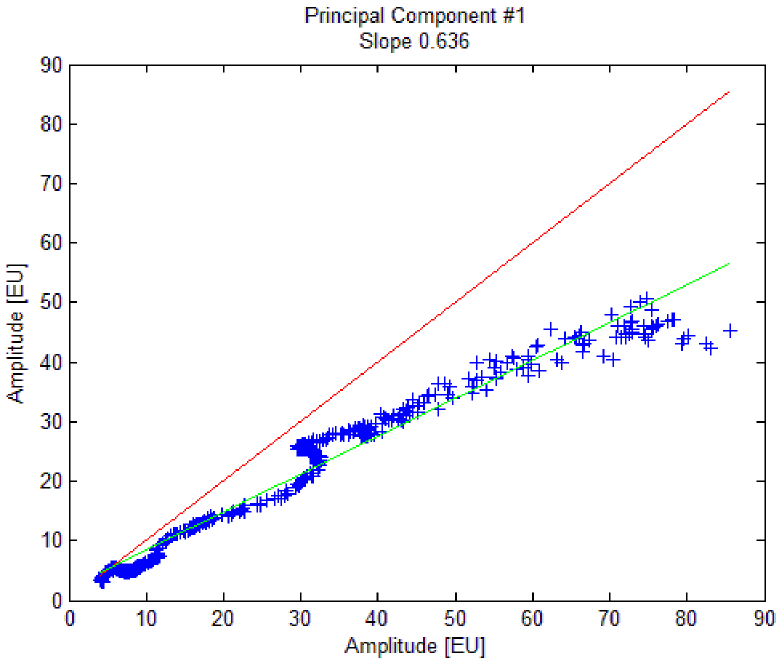




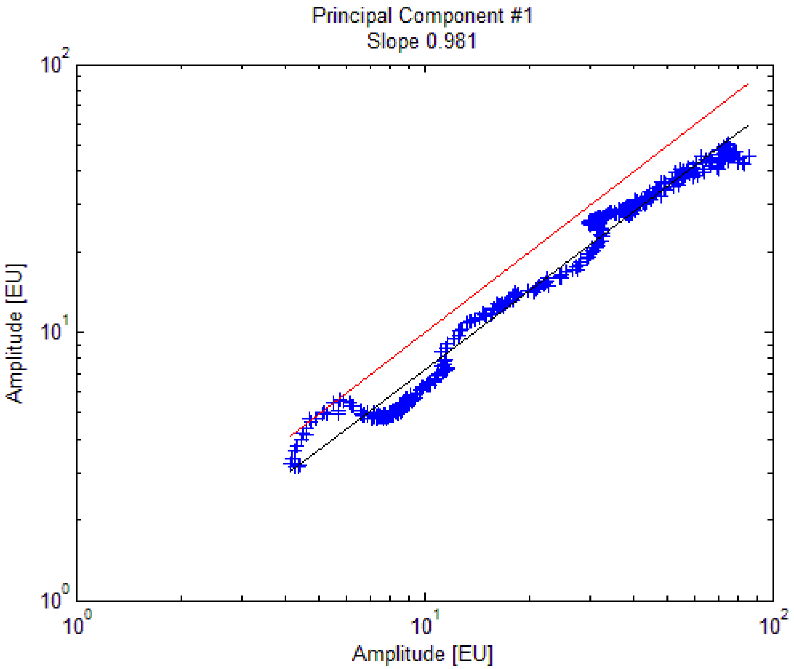
Validation Metric – Relationship to QMU



Validation Metric – Relationship to QMU



Principal Component #1
Slope 0.636



Principal Component #1
Slope 0.981

Current/Future Work

- Preparation for OEM Aero-Thermo-Structures Design Study experimental phase in Summer 2014
- Develop methods to handle mismatched DOFs between model simulation and experimental measurements
- Evaluate alternate metrics: methods commonly used in fingerprint, iris and facial biometric pattern recognition such as orthogonal polynomial moment descriptors (Mottershead, Patterson)

Summary

Based upon limited data set analysis to date:

- The PCA-SVD validation metric appears to give good results and is relatively easy to implement
- The PCA-SVD validation metric gives a clear indication of both margin and uncertainty, utilizing the dominant singular values
- The PCA-SVD gives a clear indication of spatial correlation, utilizing the singular vectors associated with the dominant singular values

Based upon current work:

- The PCA-SVD validation metric appears to be applicable to the case of mismatched DOFs

Questions/Comments?

Questions/Comments can be sent to the corresponding author:

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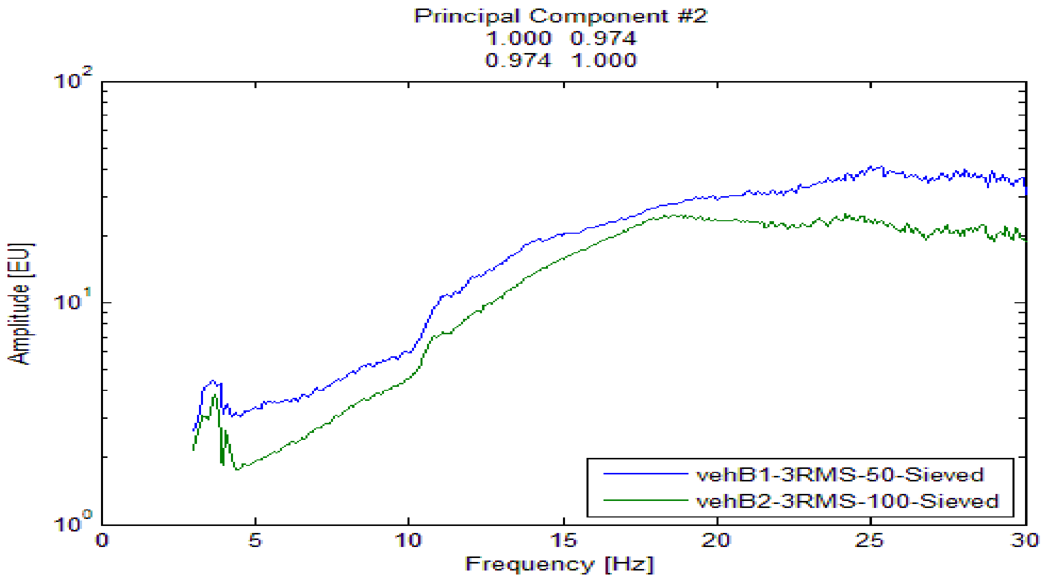
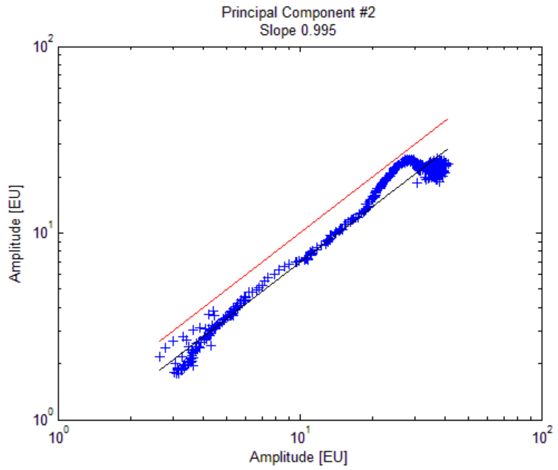
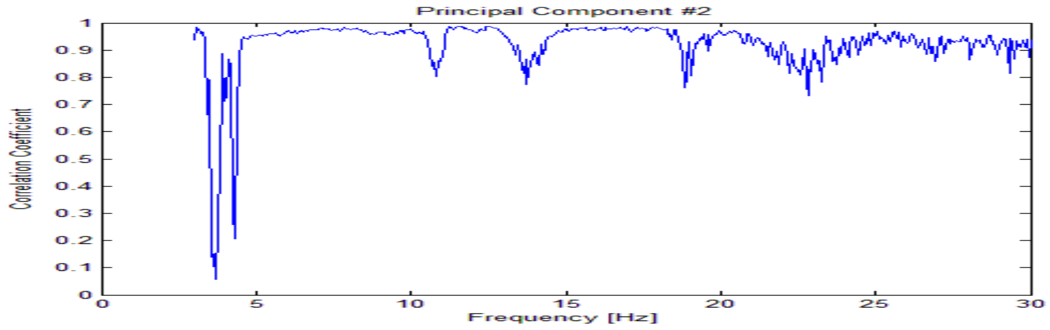
Validation Metric – Second Principal Component



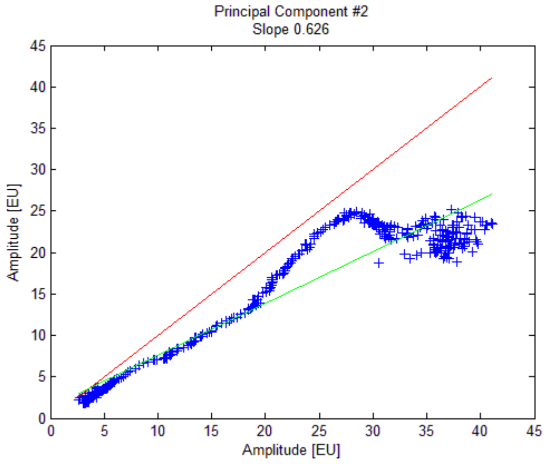
Principal Component #2
1.000 0.974
0.974 1.000



Principal Component #2
Slope 0.995

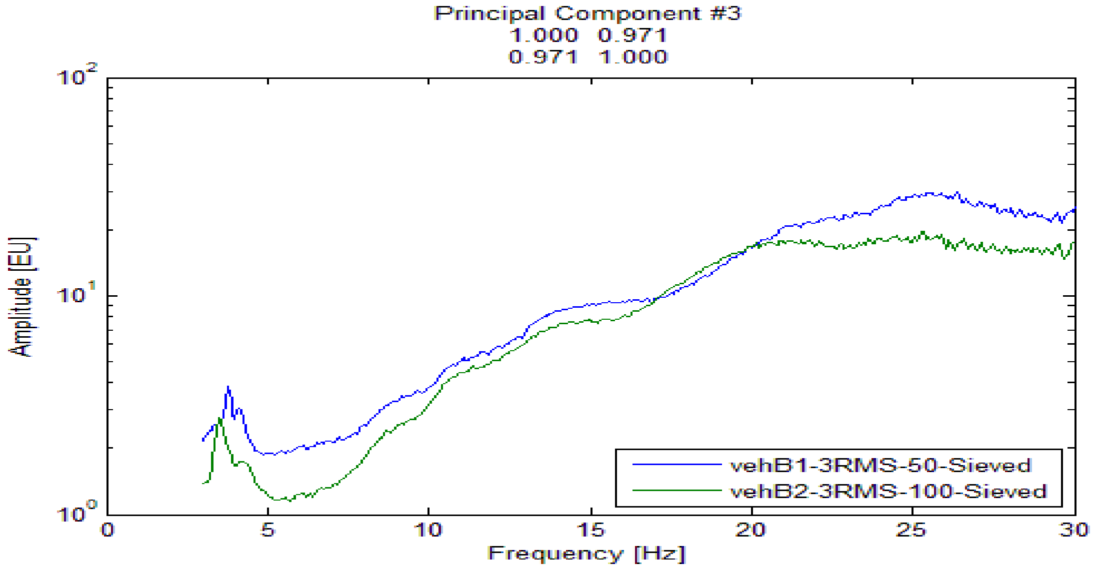


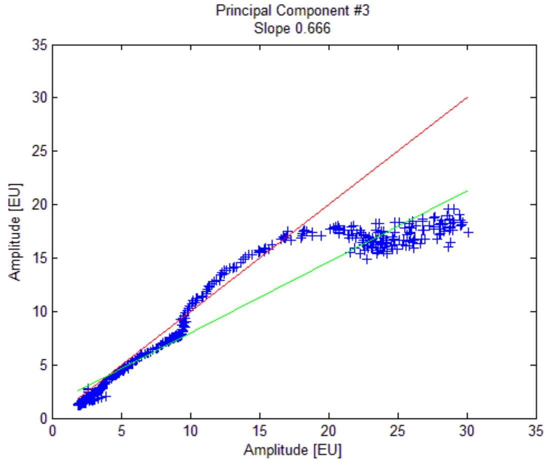
Principal Component #2

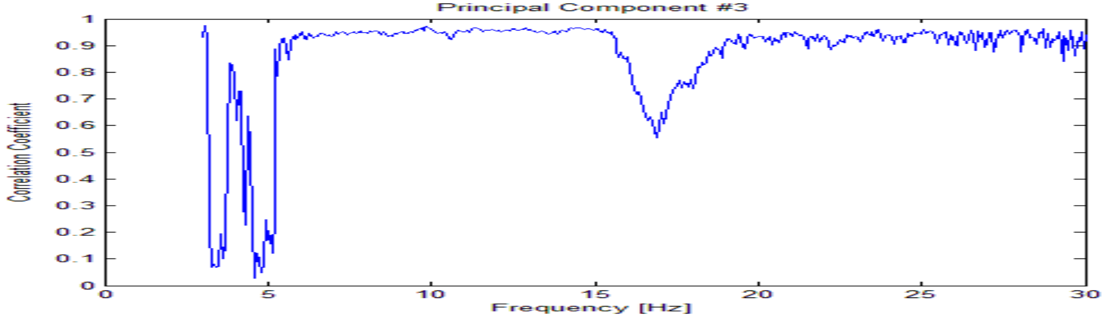


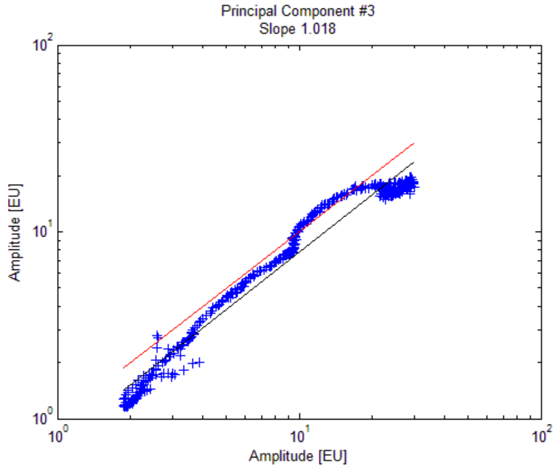
Principal Component #2
Slope 0.626

Validation Metric – Second Principal Component









Validation Metric – Fourth Principal Component