Rapid State Space Modeling Tool for Rectangular Wing Aeroservoelastic Studies

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Outline

- Overview & Motivation
- Aeroservoelastic tool
- Verification and Validation studies
- State Space Model Development and Results
- Conclusions

Overview & Motivation

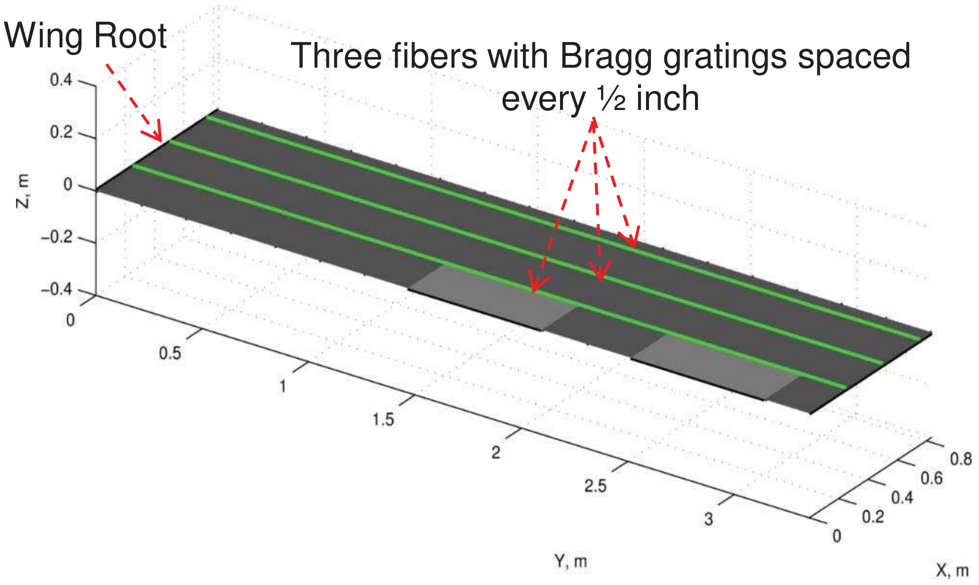
- Overview
  - Presentation of computational and experimental results from a recently developed rectangular wing aeroservoelastic modeling tool
- Motivation
  - Compare tool to independently published work[2]
  - To support rapid investigation of aeroservoelastic phenomena in a medium-fidelity tool
    - Also novel sensors such as fiber optics
  - Provide a rapid aeroservoelastic design platform which can serve students of aeroservoelasticity

[2] SConyers, H. J., Dowell, E. H., and Hall, K. C., Aeroservoelastic Studies of a Rectangular Wing with a Hole: Correlation of Theory and Experiment," 2010 Aerospace Systems Conference

Background

- In previous work[1], tool used to model a clamped wing structure with two control surfaces and fiber optic sensor feedback used for flutter suppression

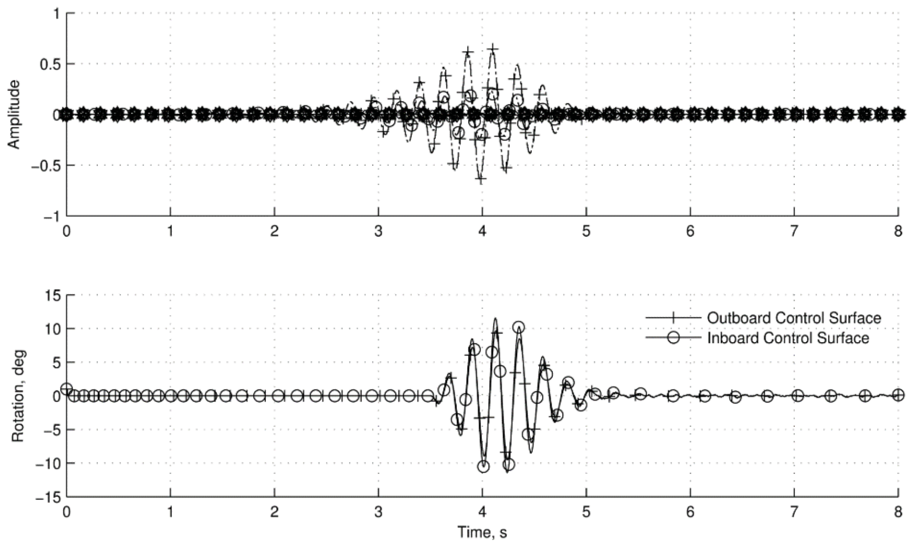
Computational Wing Model



Wing Root

Three fibers with Bragg gratings spaced every ½ inch

Active Flutter Suppression



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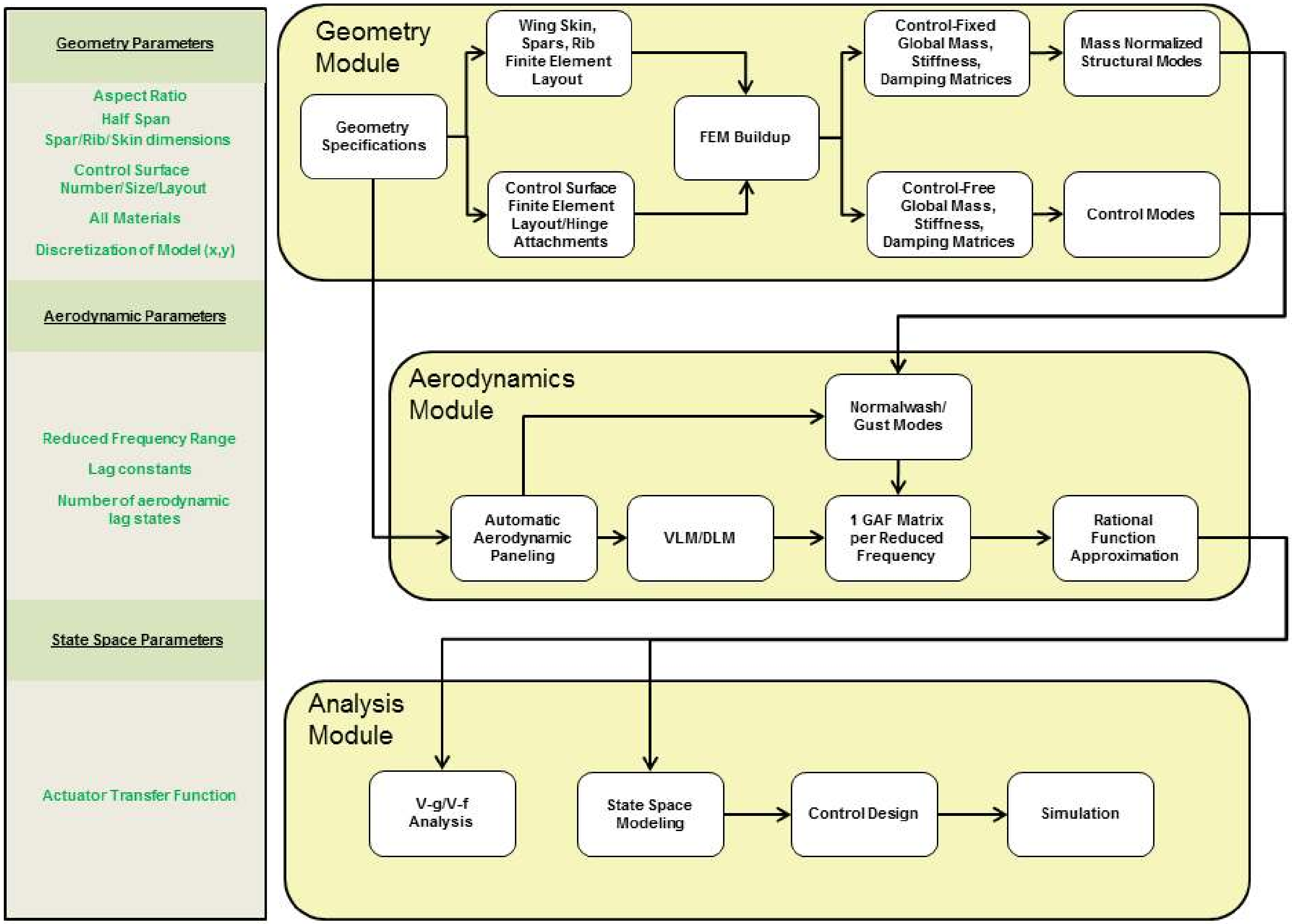
[1] Suh, P. M., and Mavris, D. N., Modal Filtering for Control of Flexible Aircraft, AIAA 2013-1741

Aeroservoelastic Tool Overview

- Tool allows the user to quickly move from inputs like aspect ratio, control surface count, and half span to a linear time invariant state space model which can be used for control
  - A few seconds of real time computation
  - Most important structural and aerodynamic properties are parametric

Tool for Rectangular Wing Aeroservoelastic Design in MATLAB



Geometry Parameters

Aspect Ratio
Half Span
Spar/Rib/Skin dimensions
Control Surface Number/Size/Layout
All Materials
Discretization of Model (x,y)

Aerodynamic Parameters

Reduced Frequency Range
Lag constants
Number of aerodynamic lag states

State Space Parameters

Actuator Transfer Function

Geometry Module

- Geometry Specifications
- Wing Skin, Spars, Rib Finite Element Layout
- Control Surface Finite Element Layout/Hinge Attachments
- FEM Buildup
- Control-Fixed Global Mass, Stiffness, Damping Matrices
- Control-Free Global Mass, Stiffness, Damping Matrices
- Mass Normalized Structural Modes
- Control Modes

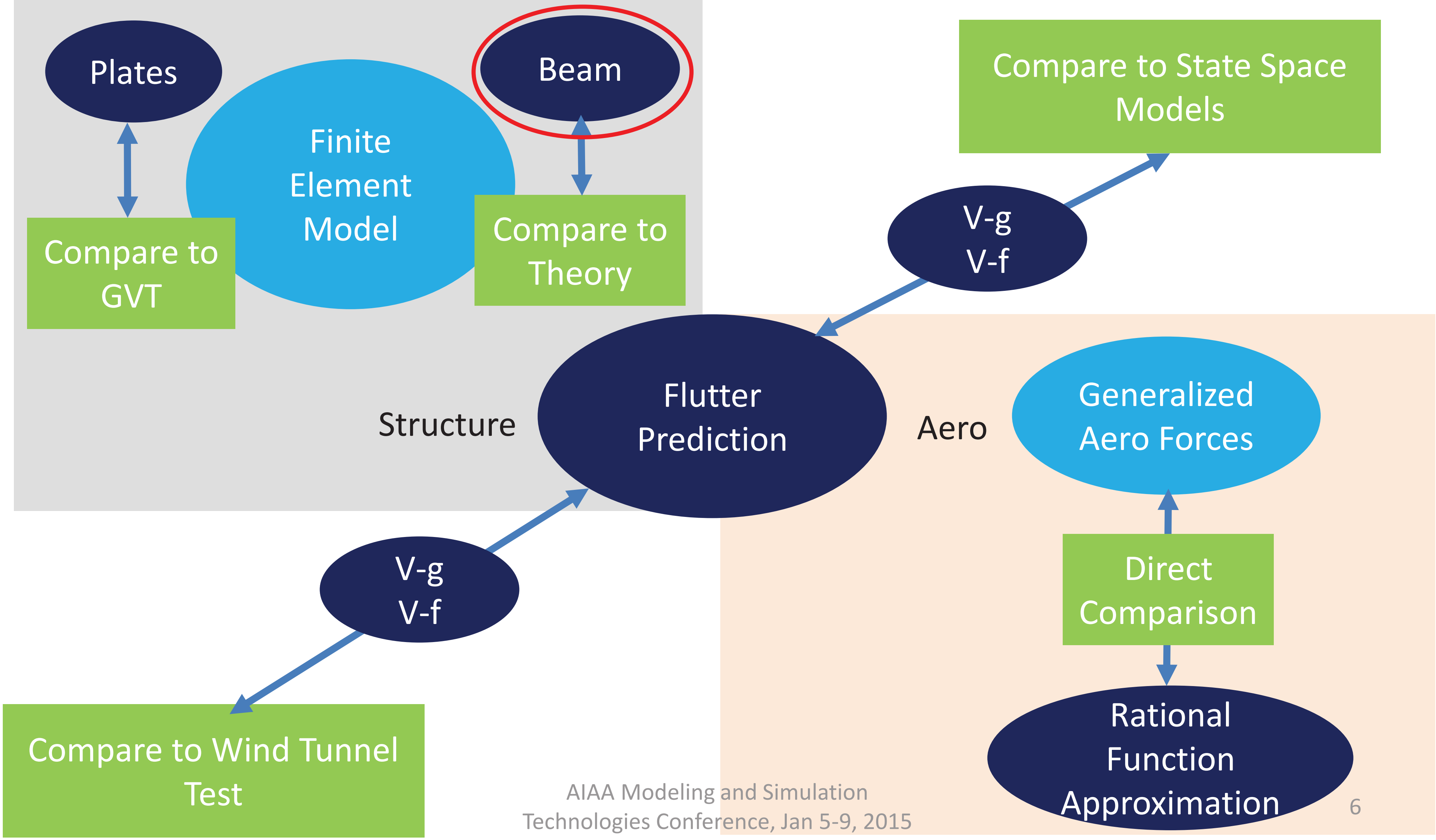
Aerodynamics Module

- Normalwash/ Gust Modes
- Automatic Aerodynamic Paneling
- VLM/DLM
- 1 GAF Matrix per Reduced Frequency
- Rational Function Approximation

Analysis Module

- V-g/V-f Analysis
- State Space Modeling
- Control Design
- Simulation

Graphical Path of Verification and Validation of Tool



Plates

Compare to GVT

Finite Element Model

Beam

Compare to Theory

Structure

Flutter Prediction

Aero

Compare to State Space Models

V-g
V-f

Generalized Aero Forces

Direct Comparison

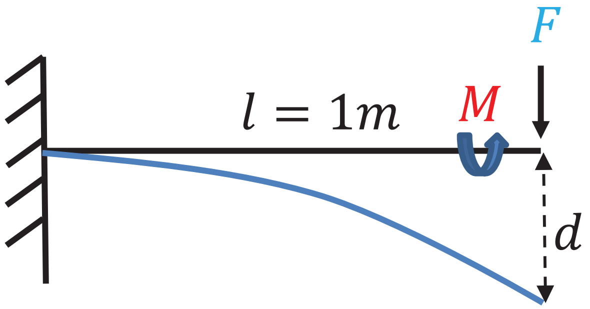
Rational Function Approximation

V-g
V-f

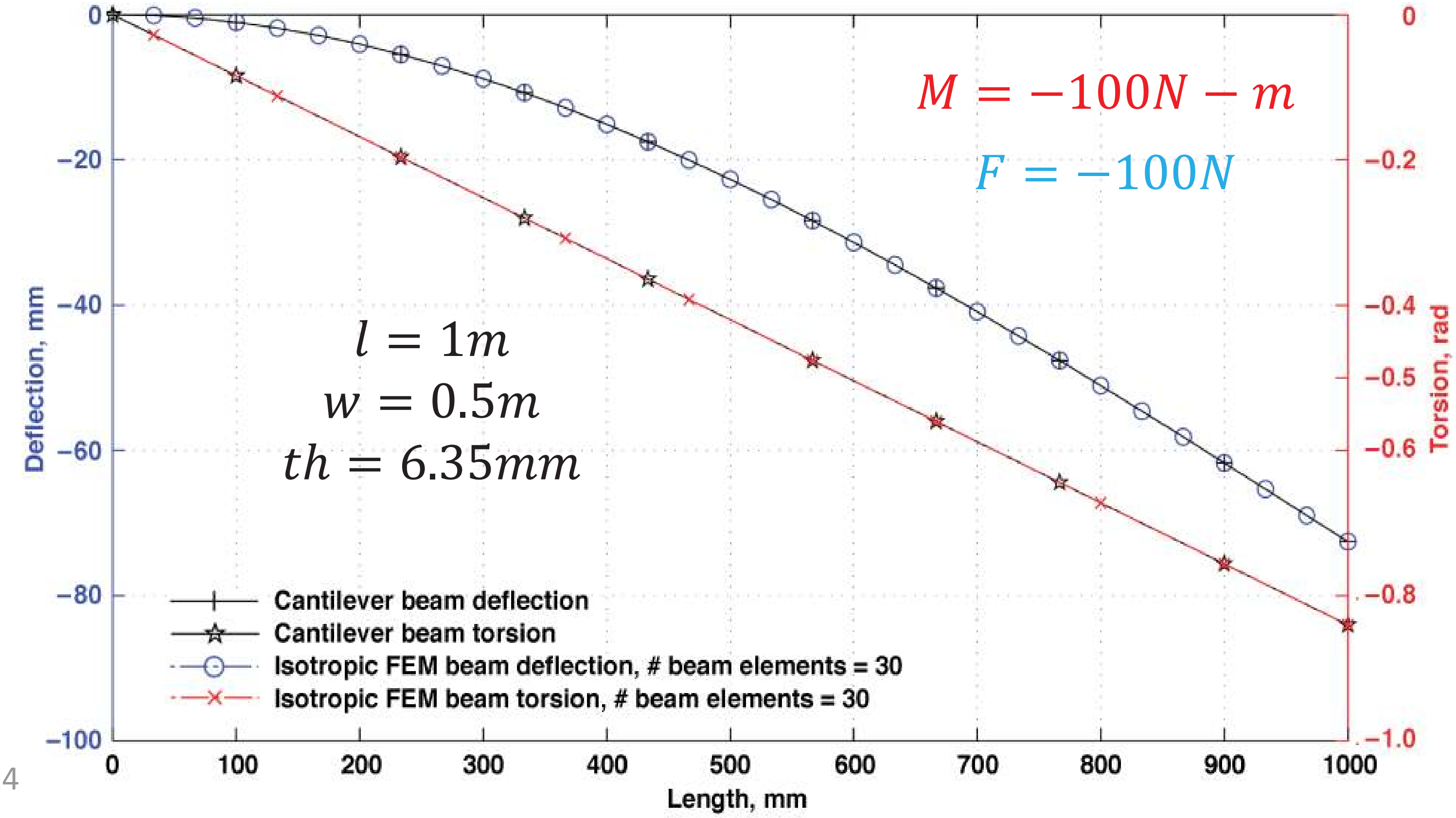
Compare to Wind Tunnel Test

Beam Model Verification

- Beams used to model wing structure
  - FEM with 30 elements compared to theory show good matches in bending and torsion



Cantilever Theory versus FEM Beam Model: Deflection and Twist



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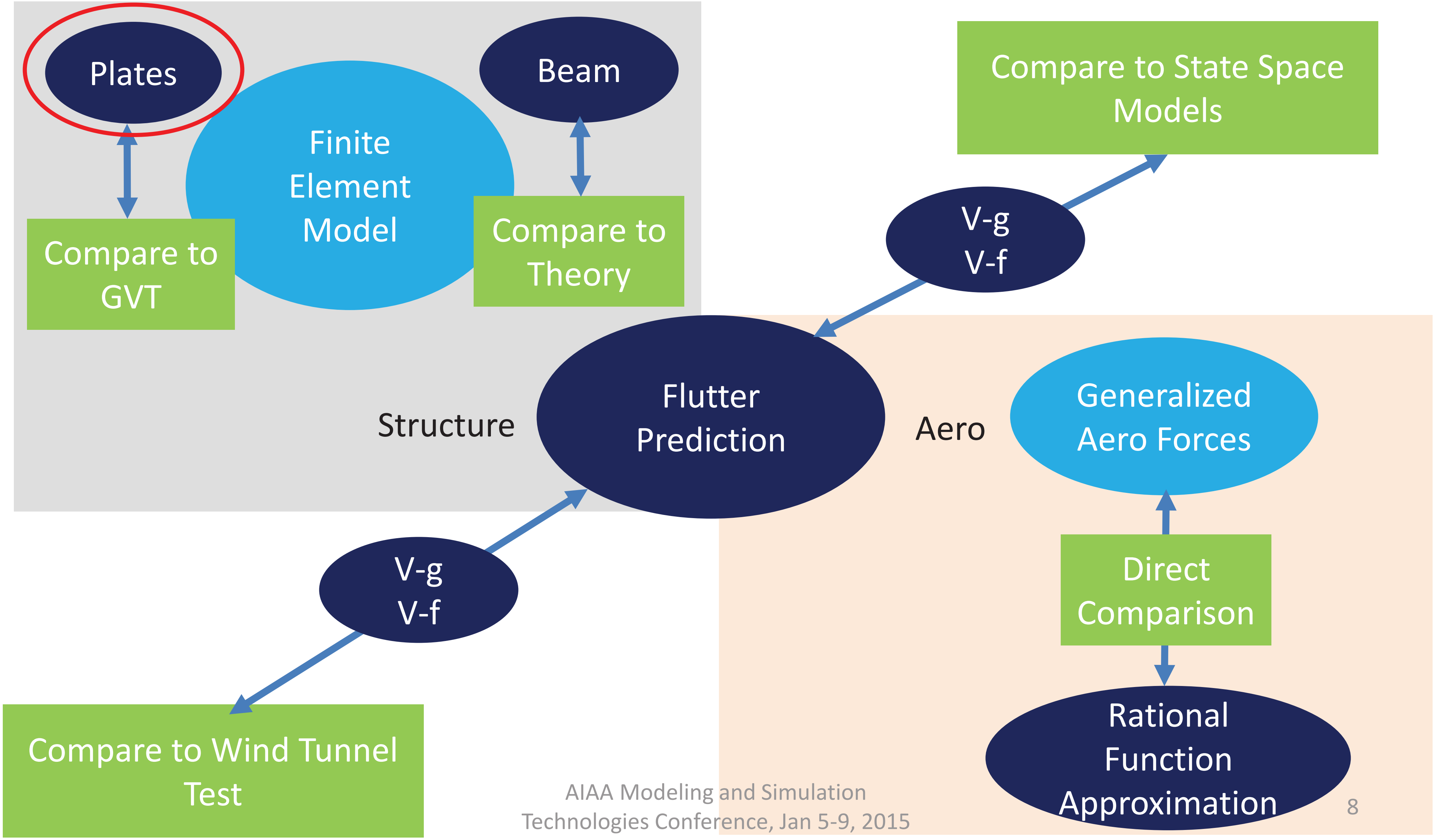


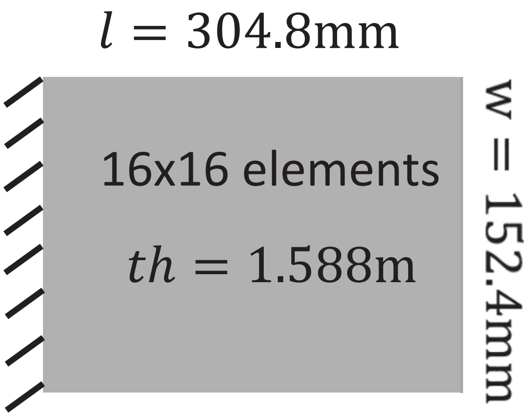
[2] SConyers, H. J., Dowell, E. H., and Hall, K. C., Aeroservoelastic Studies of a Rectangular Wing with a Hole: Correlation of Theory and Experiment," 2010 Aerospace Systems Conference

Plate FEM Validation

- Ground Vibration Test (GVT) on a article used for validation of plate FEM
- Plate FEM Discretized with 16x16 12 DOF isotropic plate elements
- Experiment shows good correlation with ANSYS and tool

GVT on Article (with a hole for a different test)

Computational Model



$l = 304.8\text{mm}$

clamped

16x16 elements

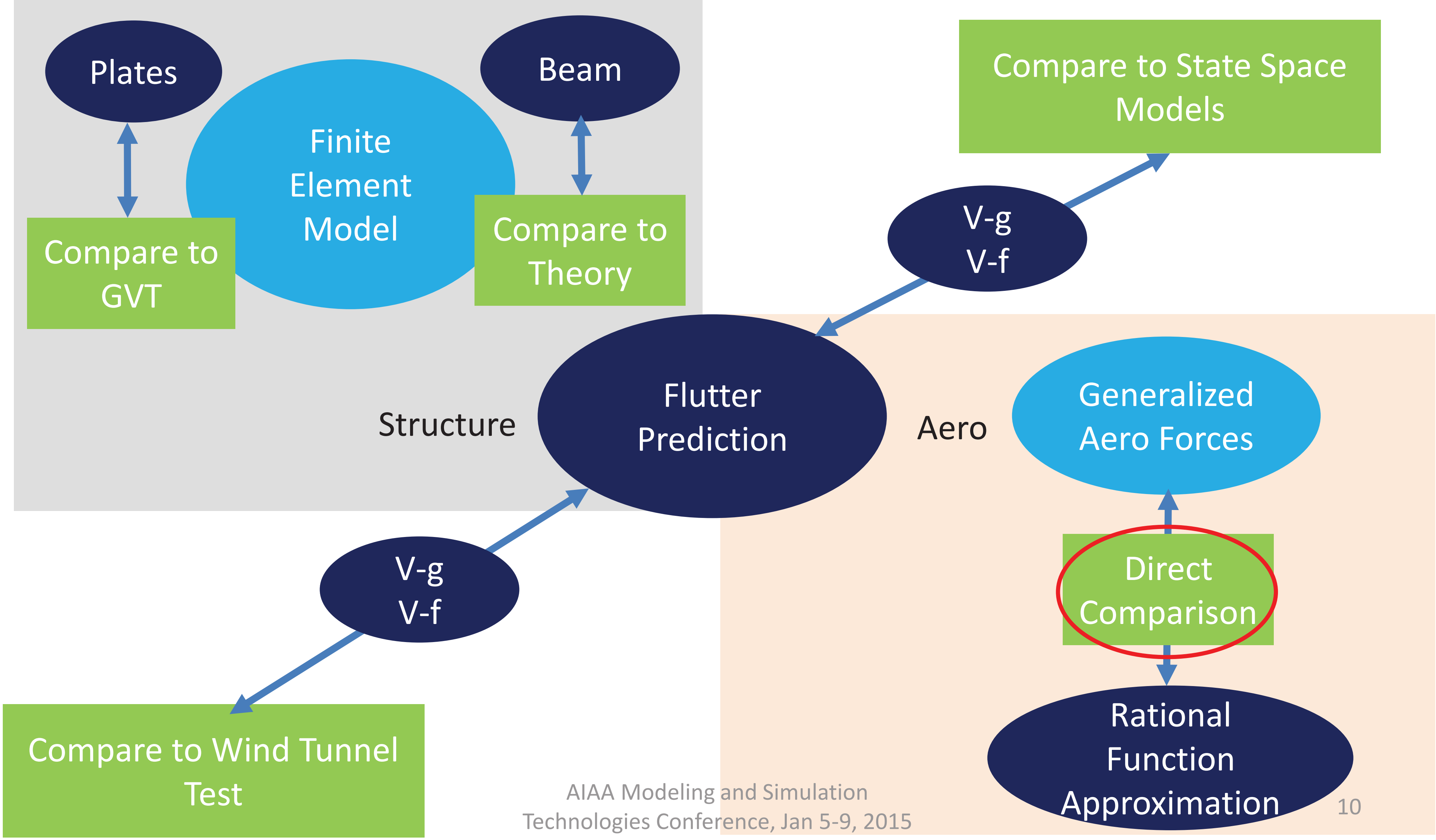
$th = 1.588\text{m}$

w = 152.4mm

Experimental Data[2]

	ANSYS Frequencies, Hz	Tool FEM Frequencies, Hz	Conyers et al. GVT, Hz
Mode # 1	3.99	3.99	4.13
Mode # 2	16.96	16.97	17.24
Mode # 3	24.86	24.89	24.38
Mode # 4	55.33	55.40	54.25
Mode # 5	69.84	69.92	69.00

Graphical Path of Verification and Validation of Tool



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V-f

Generalized Aero Forces

Direct Comparison

Rational Function Approximation

V-g
V-f

Compare to Wind Tunnel Test

RFA Verification

- Generalized aerodynamic forces (GAF) computed for plate
- Roger’s rational function approximation (RFA) used to fit GAF coefficients
  - 4 lag states
- Least squares error for bending and twist coefficients

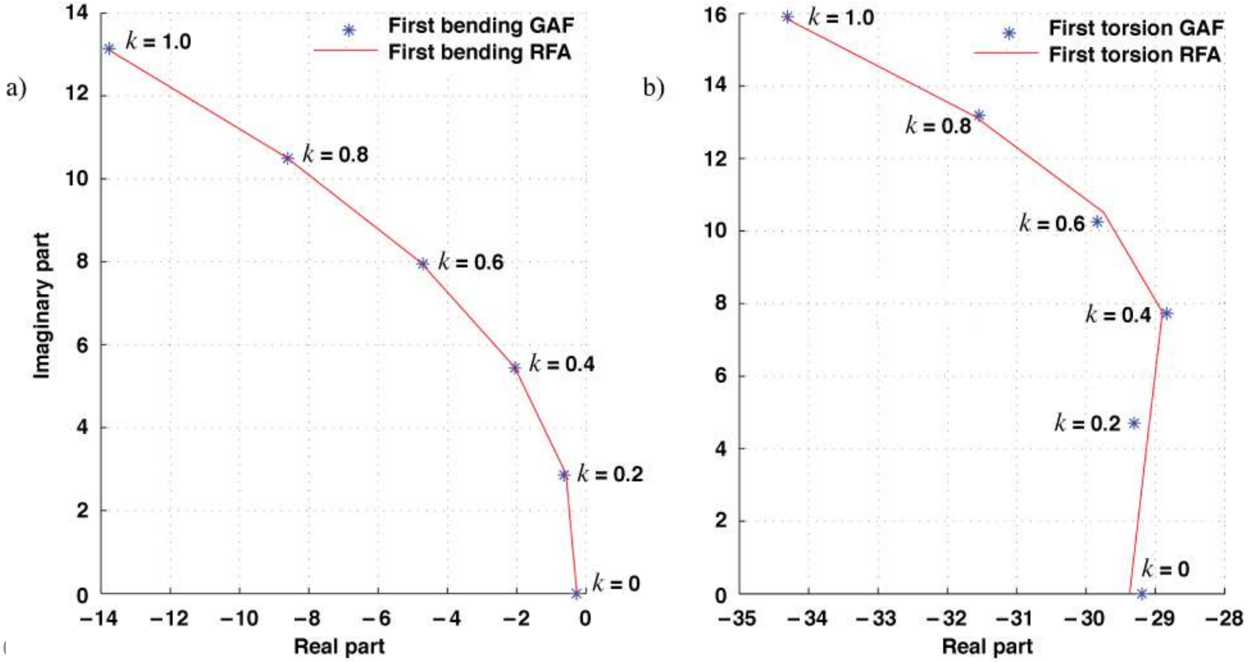
Generalized Aerodynamic Force

$$Q(\hat{\imath}k) = {Z_f}^T D(\hat{\imath}k)^{-1} A_p W_{c.p.}$$

Rational Function Approximation of GAF

$$\hat{Q}(\bar{s}) = A_0 + \bar{s}A_1 + \bar{s}^2 A_2 + \sum_{l=1}^{L} \frac{\bar{s}}{\bar{s} + \beta_l} A_{2+l}$$

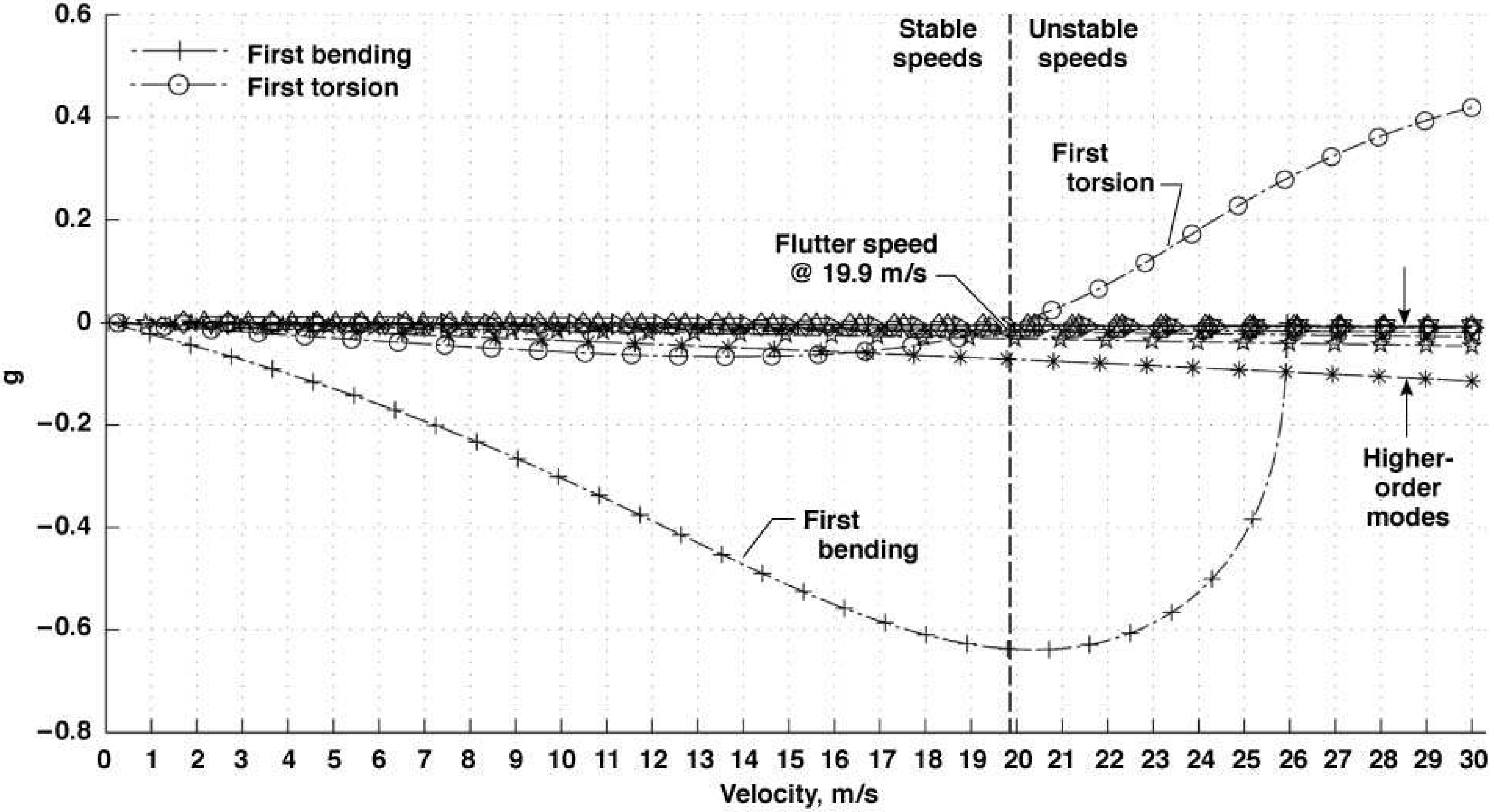
Comparison of GAF and RFA Curve Fits



V-g Analysis using RFA

- The test plate article flutter speed was predicted to be 19.9 m/s
  - traditional bending/torsion flutter mode

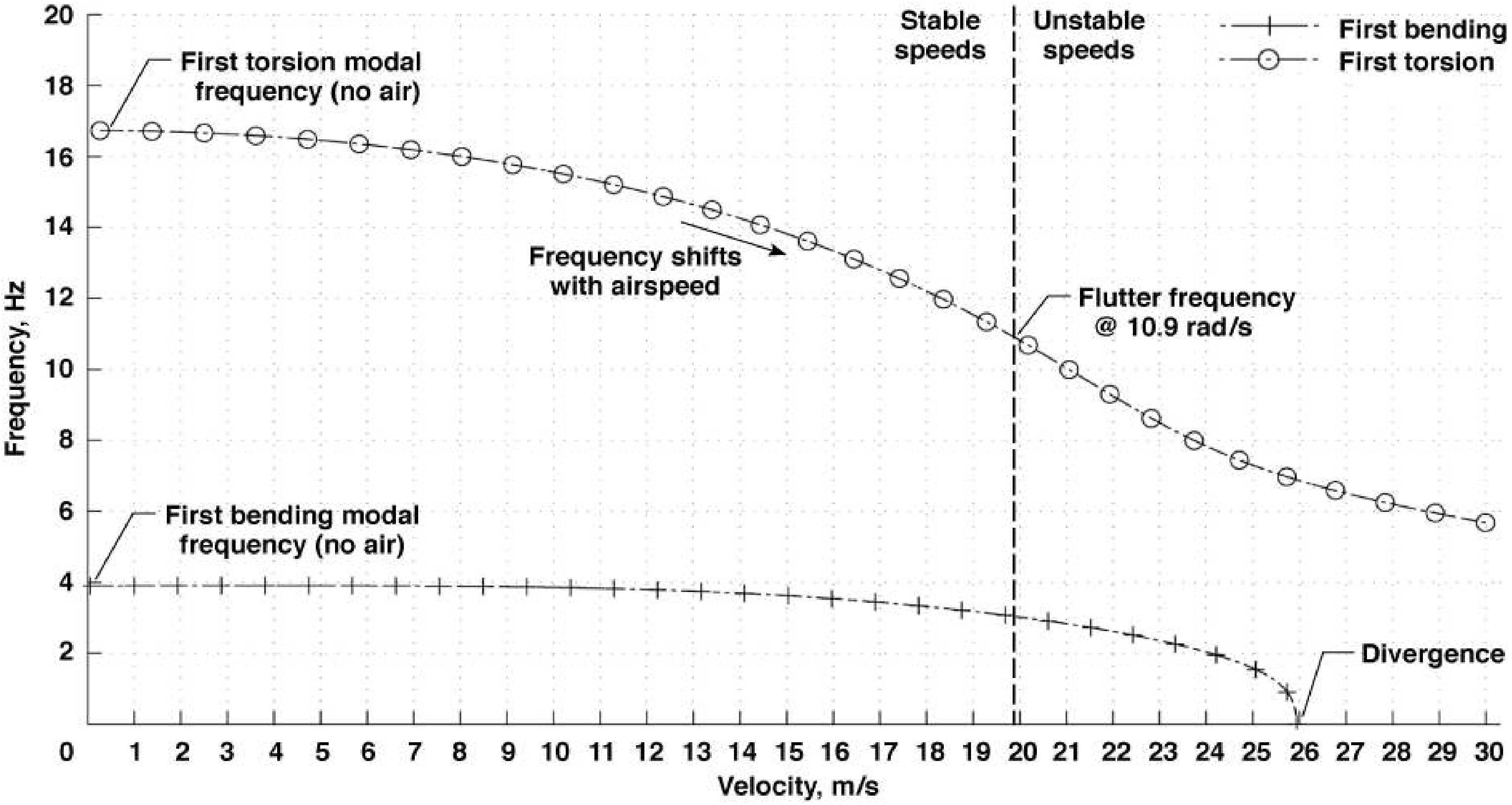
V-g Analysis on Computational Plate Article



V-f Analysis using RFA

- The test plate article flutter frequency was predicted to be 10.9 rad/s
  - Torsional mode shifts closer to bending mode
  - Characteristic of a one side clamped plate flutter mode

V-f Analysis on Computational Plate Article



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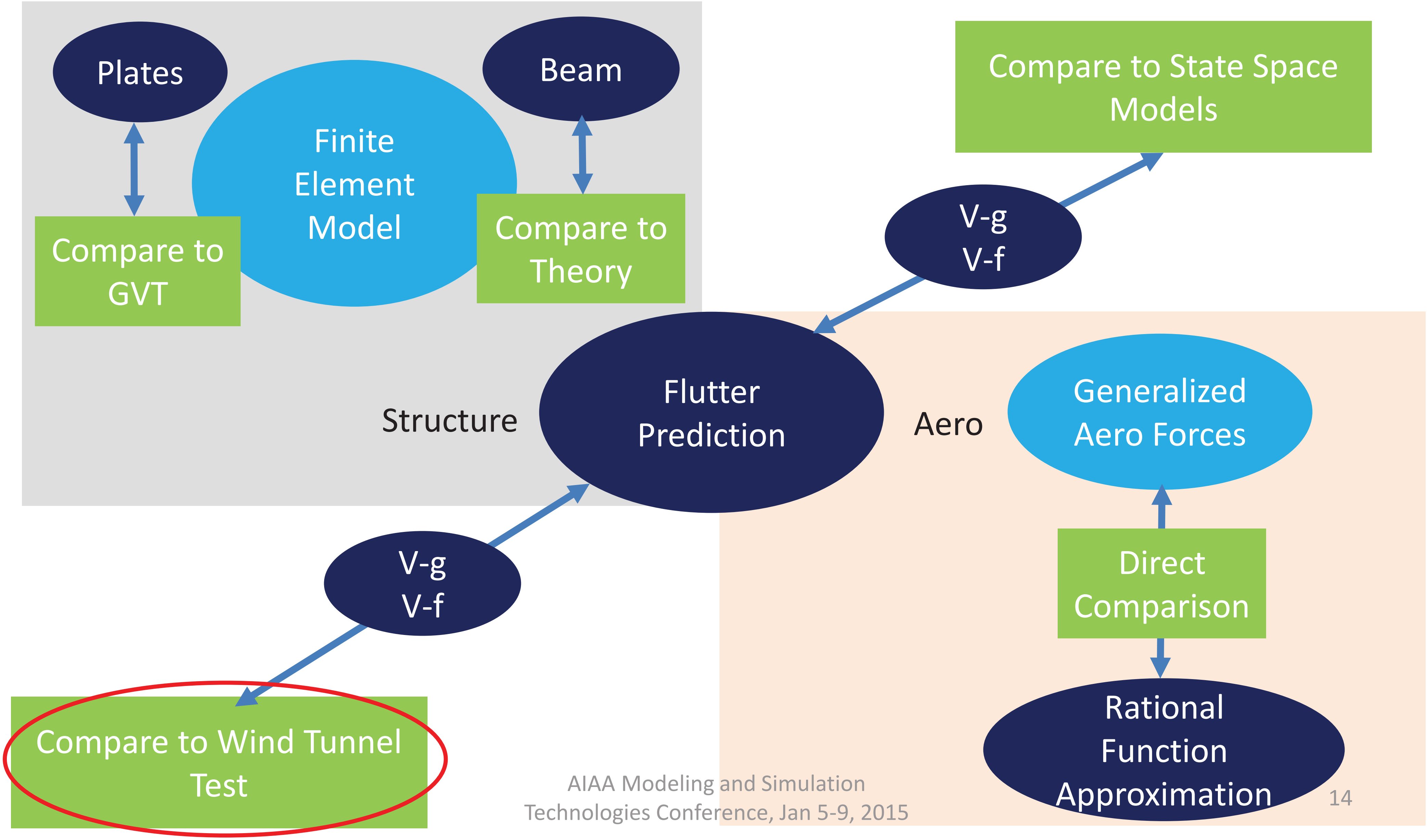

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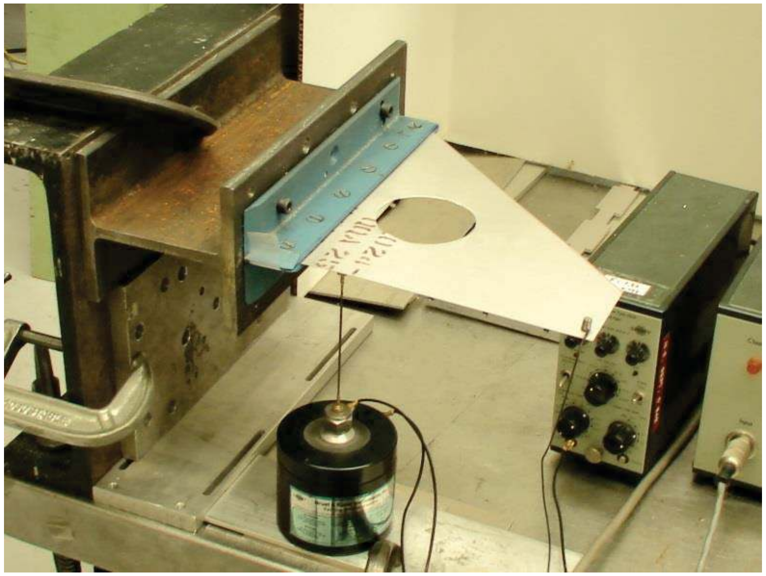
Flutter Validation Experimental Study

- A wind tunnel investigation was completed at Duke University in previous work
  - Tool flutter speed shows good correlation with Conyers et al.'s flutter code
    - Differences may be due to use of more aero panels in the tool
  - Wind tunnel results were comparably close

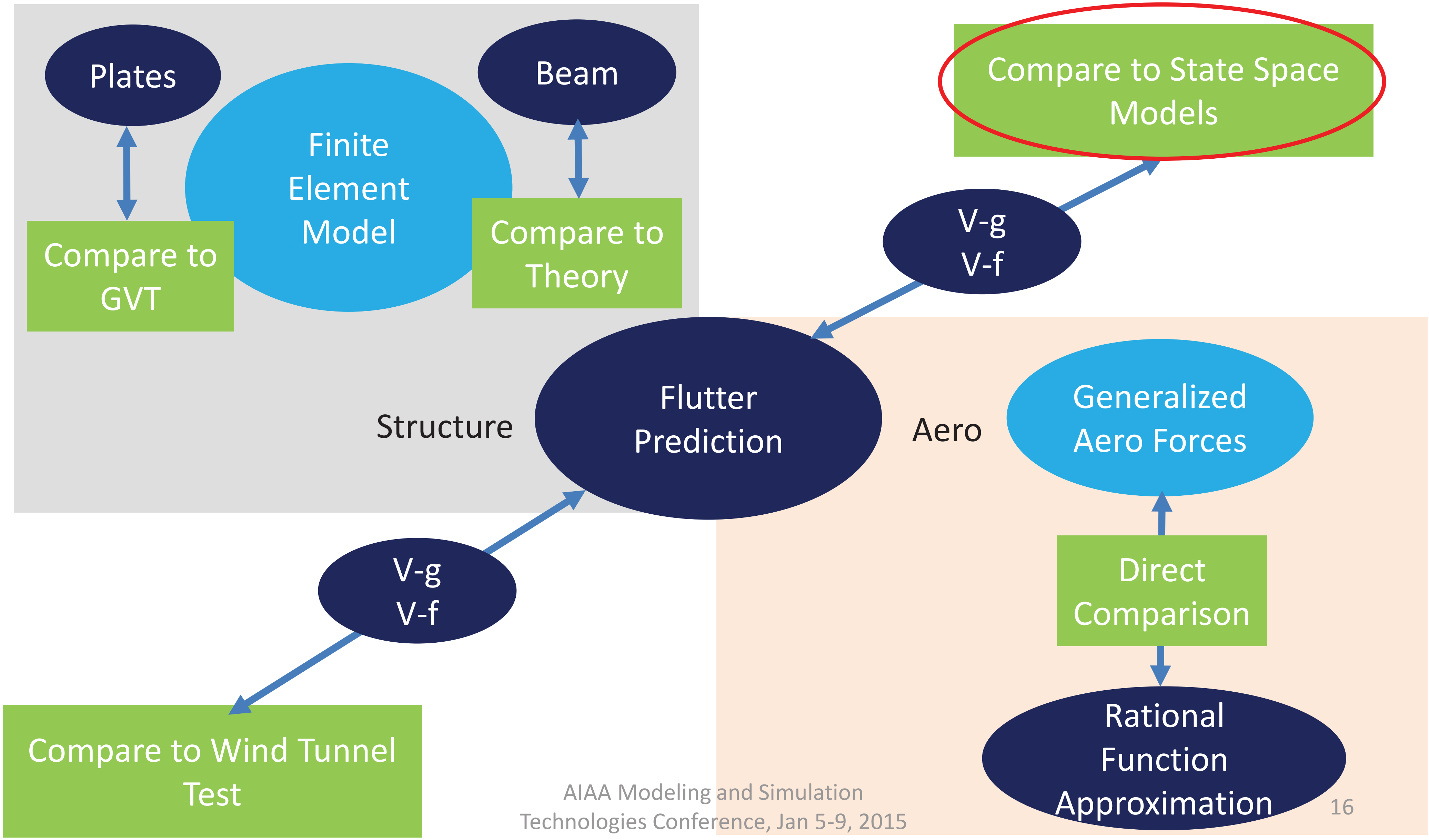
Configuration for Wind Tunnel Test at Duke (different article shown than flat plate)



Experimental Data[2]

	Conyers et al. Flutter Code[3]	Tool Flutter Code	Conyers et al. Wind Tunnel Results[3]
Flutter speed , m/s	20.8	19.9	20.05
Flutter frequency, Hz	10.3	10.9	11.50

Graphical Path of Verification and Validation of Tool



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V-g
V-f

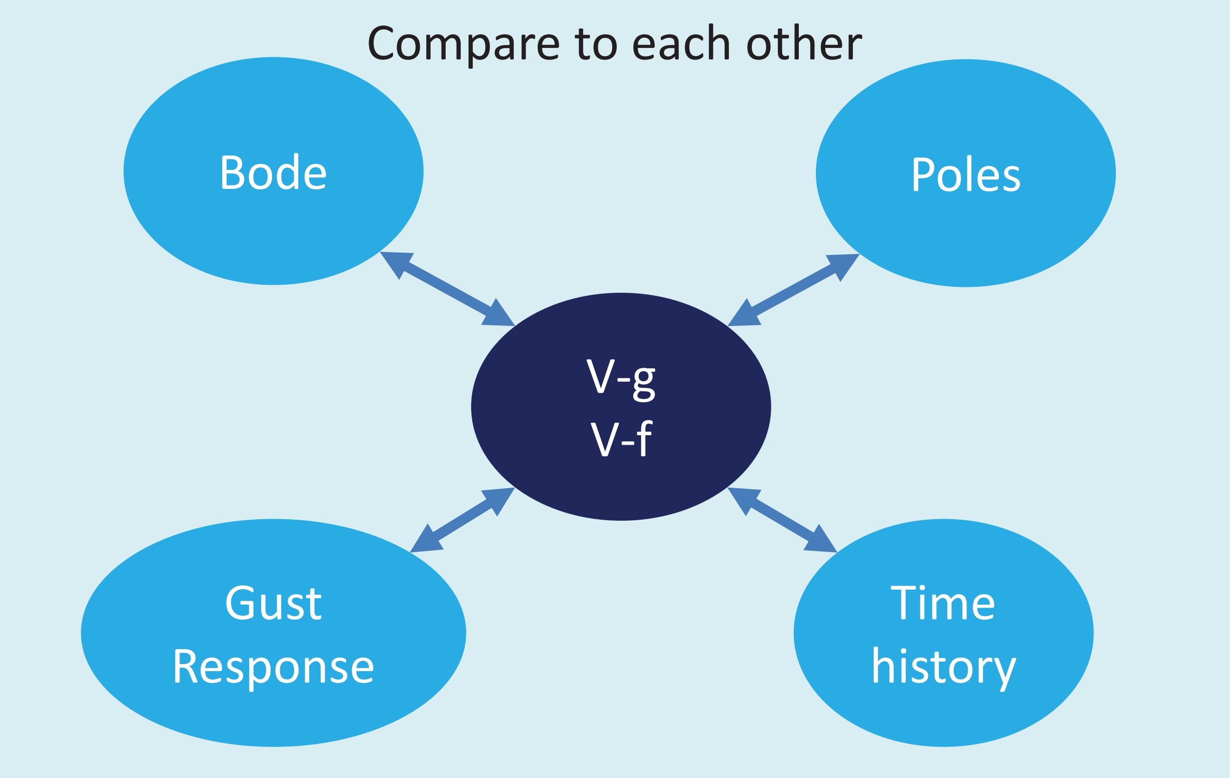
Compare to State Space Models

V-g
V-f

Compare to Wind Tunnel Test

State Space Model Verification

- We verify that the state space models correlate with what was predicted from the V-g and V-f analyses


Compare to each other

Bode

Poles

V-g
V-f

Gust Response

Time history

State Space Model Architecture

- Components of state space models
  - FEM mass, stiffness, damping and modal matrices
  - Rational function approximation coefficients
  - Actuator dynamic models
  - Flight condition

State Space Model Architecture

Modal displacement

Modal velocity

Aero lag states

$$\dot{x} = \begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \vdots \\ \dot{x}_6 \end{Bmatrix} = \begin{bmatrix} 0 & I & 0 & \cdots & 0 \\ -\widehat{M}^{-1}(\widehat{K} & \hat{C} & \bar{q}I & \cdots & \bar{q}I) \\ 0 & A_3 & -\beta_1(\frac{2V_\infty}{\bar{c}}) & 0 & 0 \\ \vdots & \vdots & 0 & \ddots & 0 \\ 0 & A_6 & 0 & 0 & -\beta_4(\frac{2V_\infty}{\bar{c}}) \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_6 \end{Bmatrix}$$

Control states

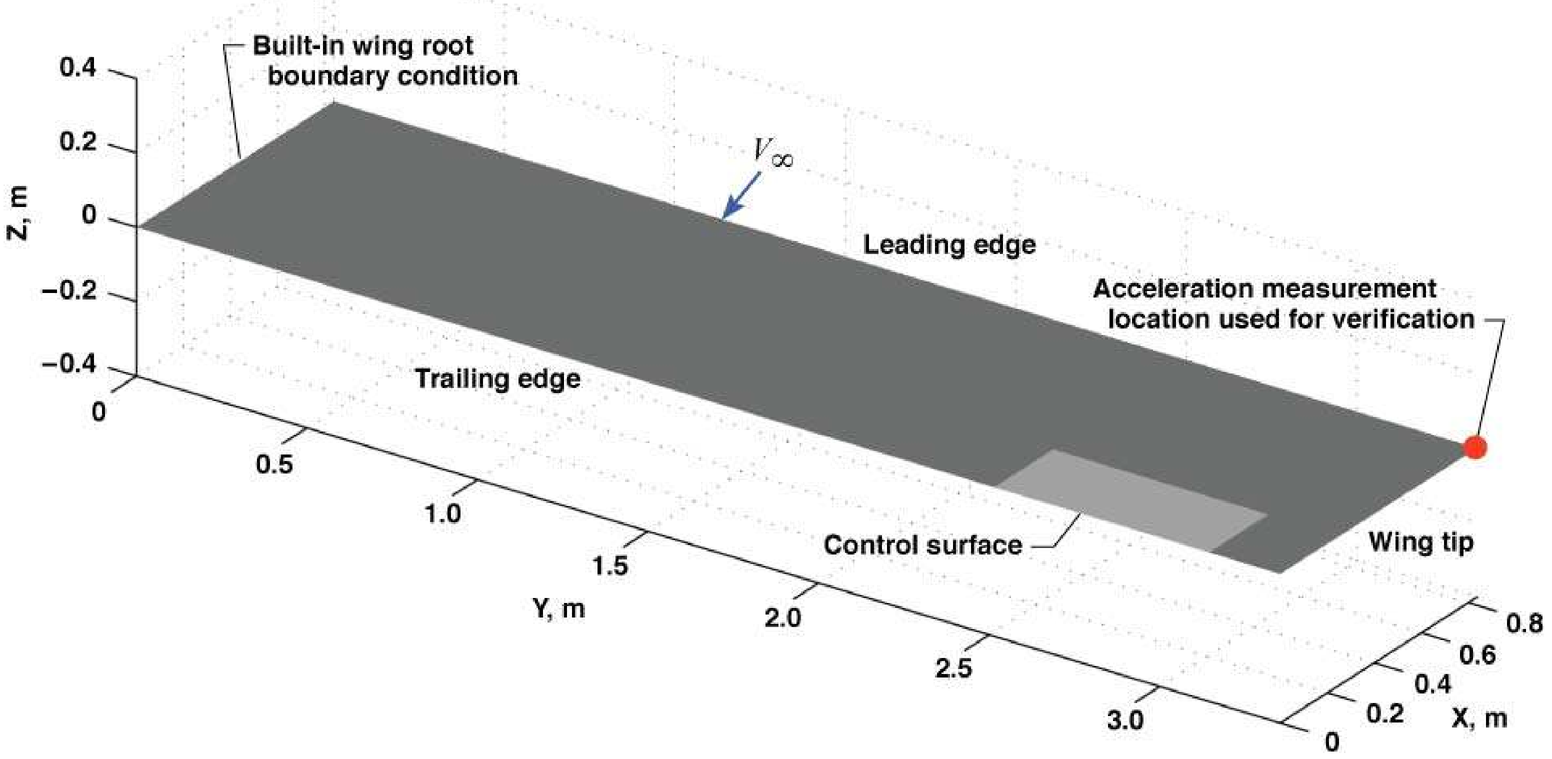
Gust states

$$+ \begin{bmatrix} 0 & 0 & 0 \\ -\widehat{M}^{-1}(\widehat{K}_c & \hat{C}_c & \widehat{M}_c) \\ 0 & A_{c1} & 0 \\ \vdots & \vdots & \vdots \\ 0 & A_{c4} & 0 \end{bmatrix} \begin{Bmatrix} u_c \\ \dot{u}_c \\ \ddot{u}_c \end{Bmatrix} + \frac{1}{V_\infty} \begin{bmatrix} 0 & 0 \\ -\widehat{M}^{-1}(\widehat{K}_g & \hat{C}_g) \\ 0 & A_{g1} \\ \vdots & \vdots \\ 0 & A_{g4} \end{bmatrix} \begin{Bmatrix} w_g \\ \dot{w}_g \end{Bmatrix}$$

Analytical Model with Control Surfaces

- Verification of state space models is completed for a wing model with
  - internal aluminum beam spar and rib structure
  - aluminum skin
  - a control surface and a leading edge accelerometer

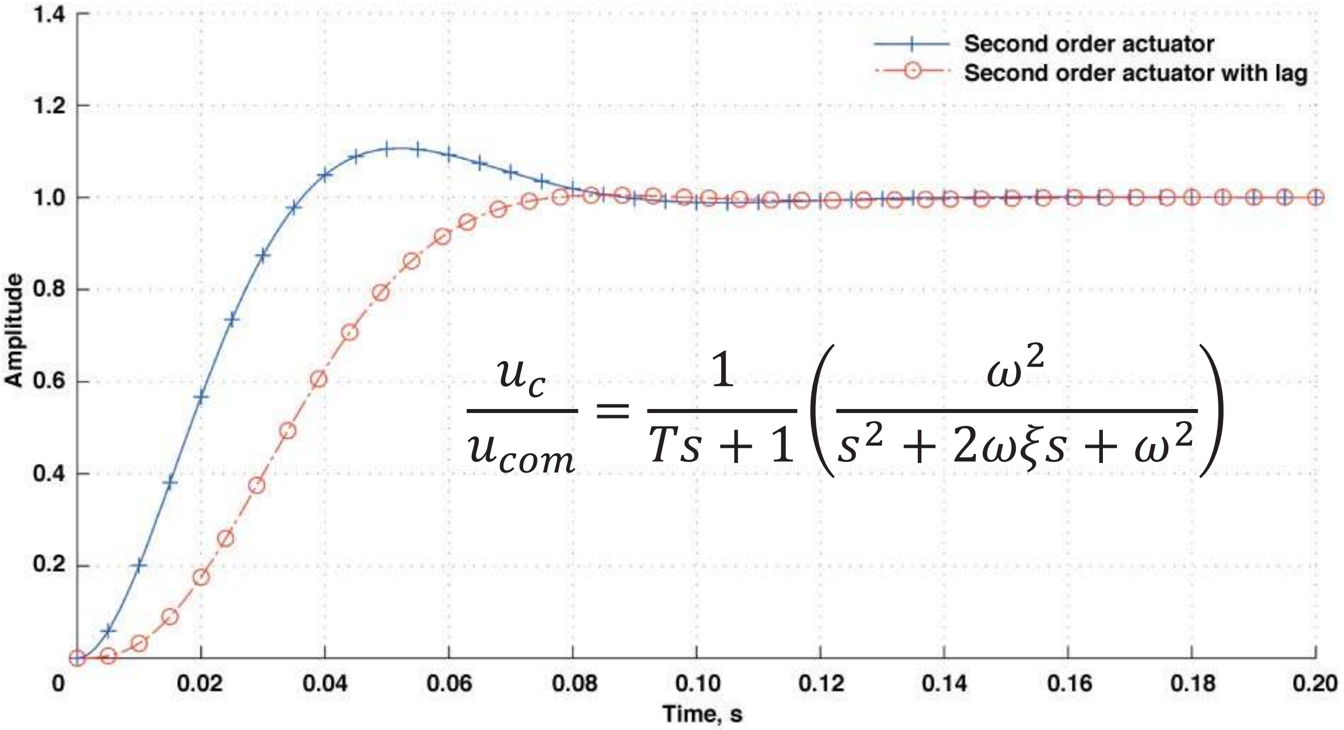
Analytical Model with One Control Surface and a Leading Edge Accelerometer



Actuator Dynamics

- Actuators are modeled as 3rd order transfer functions
  - 1st order command lag
  - 2nd order actuator dynamics

Actuator Model with and without command lag

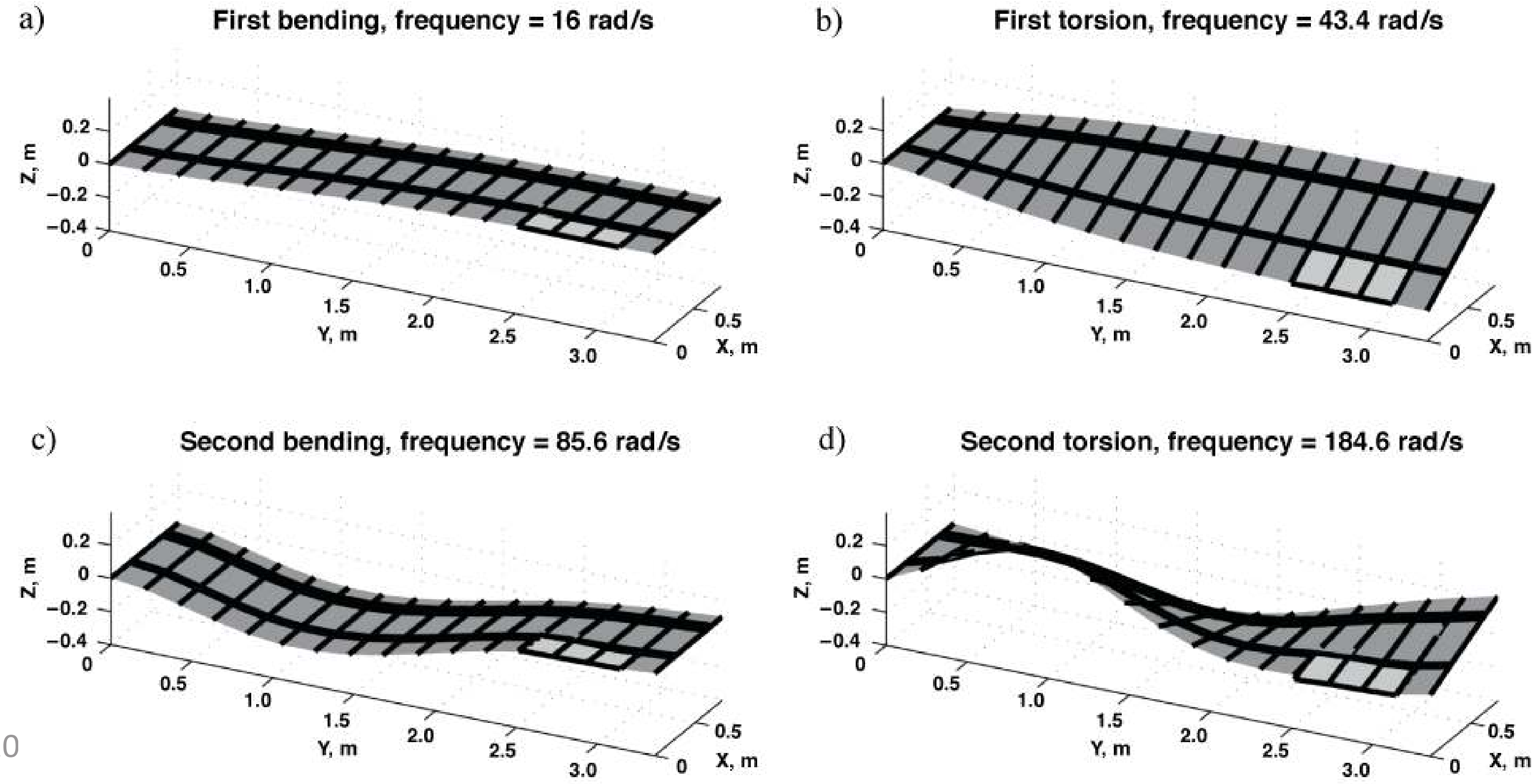


$$\frac{u_c}{u_{com}} = \frac{1}{Ts+1}\left(\frac{\omega^2}{s^2+2\omega\xi s+\omega^2}\right)$$

Analytical Wing Mode Shapes

- Mass normalized mode shapes are computed with high torsional spring stiffness in connected control surfaces
- Control modes are computed with low torsional spring stiffness and a prescribed 1 deg. rotation boundary condition

Analytical Wing Modal Analysis


a) First bending, frequency = 16 rad/s

b) First torsion, frequency = 43.4 rad/s

c) Second bending, frequency = 85.6 rad/s

d) Second torsion, frequency = 184.6 rad/s

State Space Model Verification

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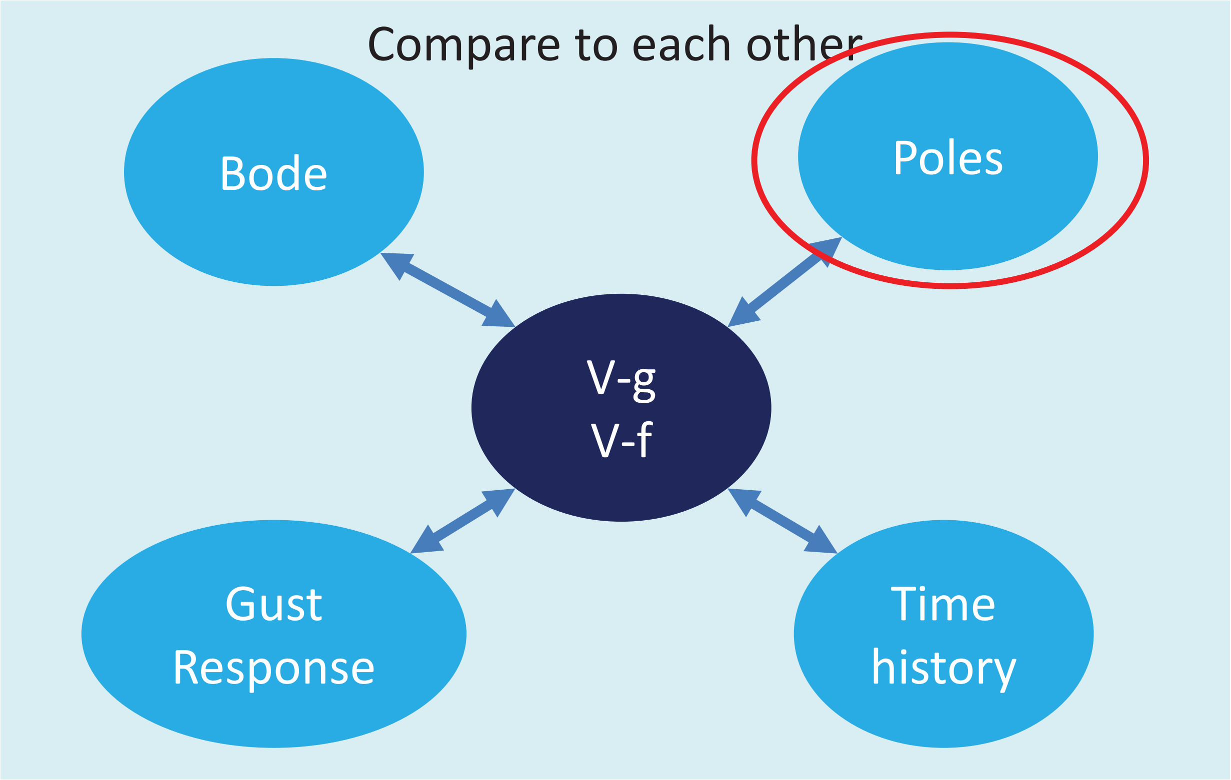

Compare to each other

Bode

Poles

V-g
V-f

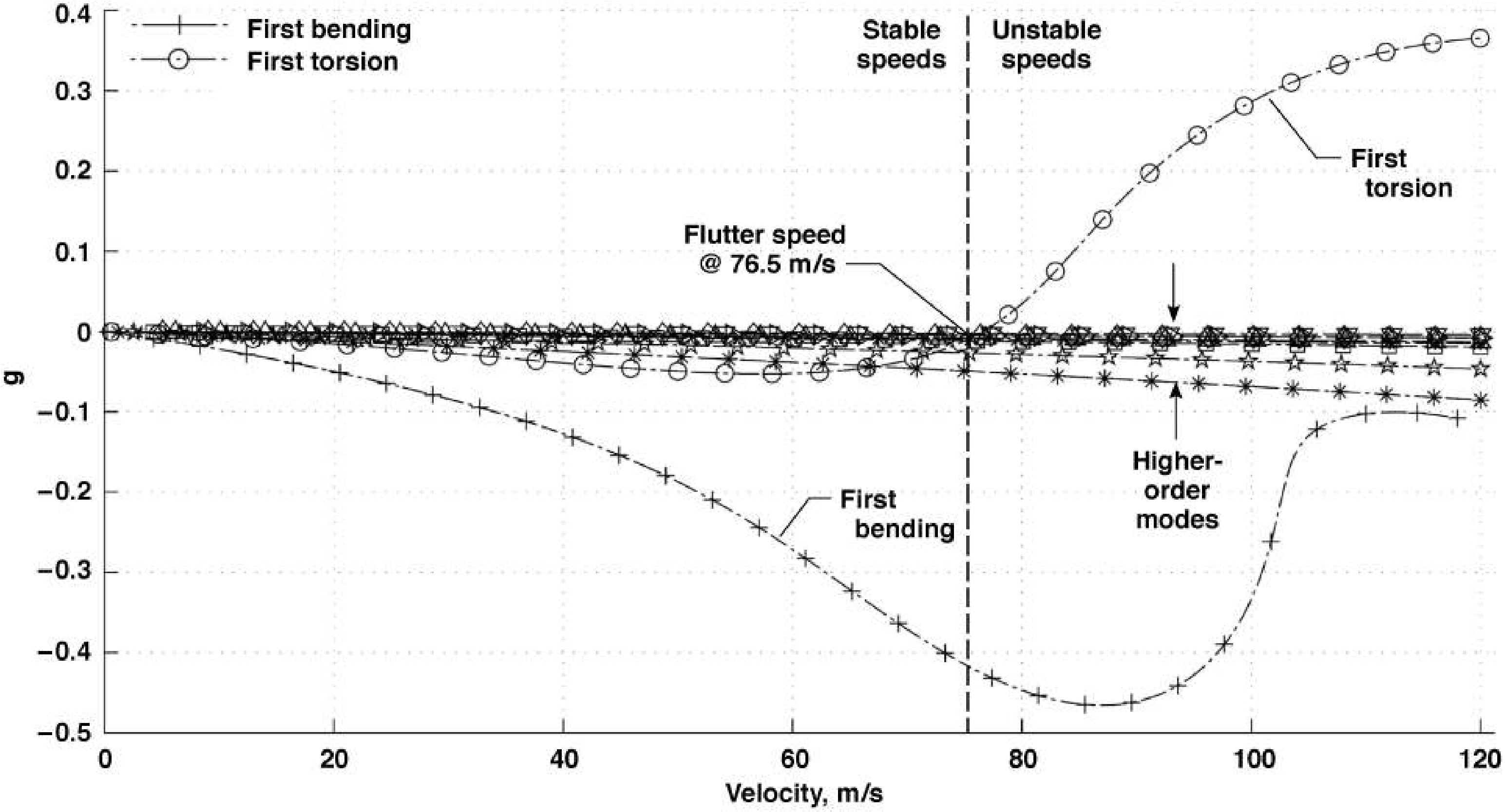
Gust Response

Time history

V-g Analysis with RFA

- V-g analysis of wing shows a traditional bending/torsion flutter mode appearing at 76.5 m/s

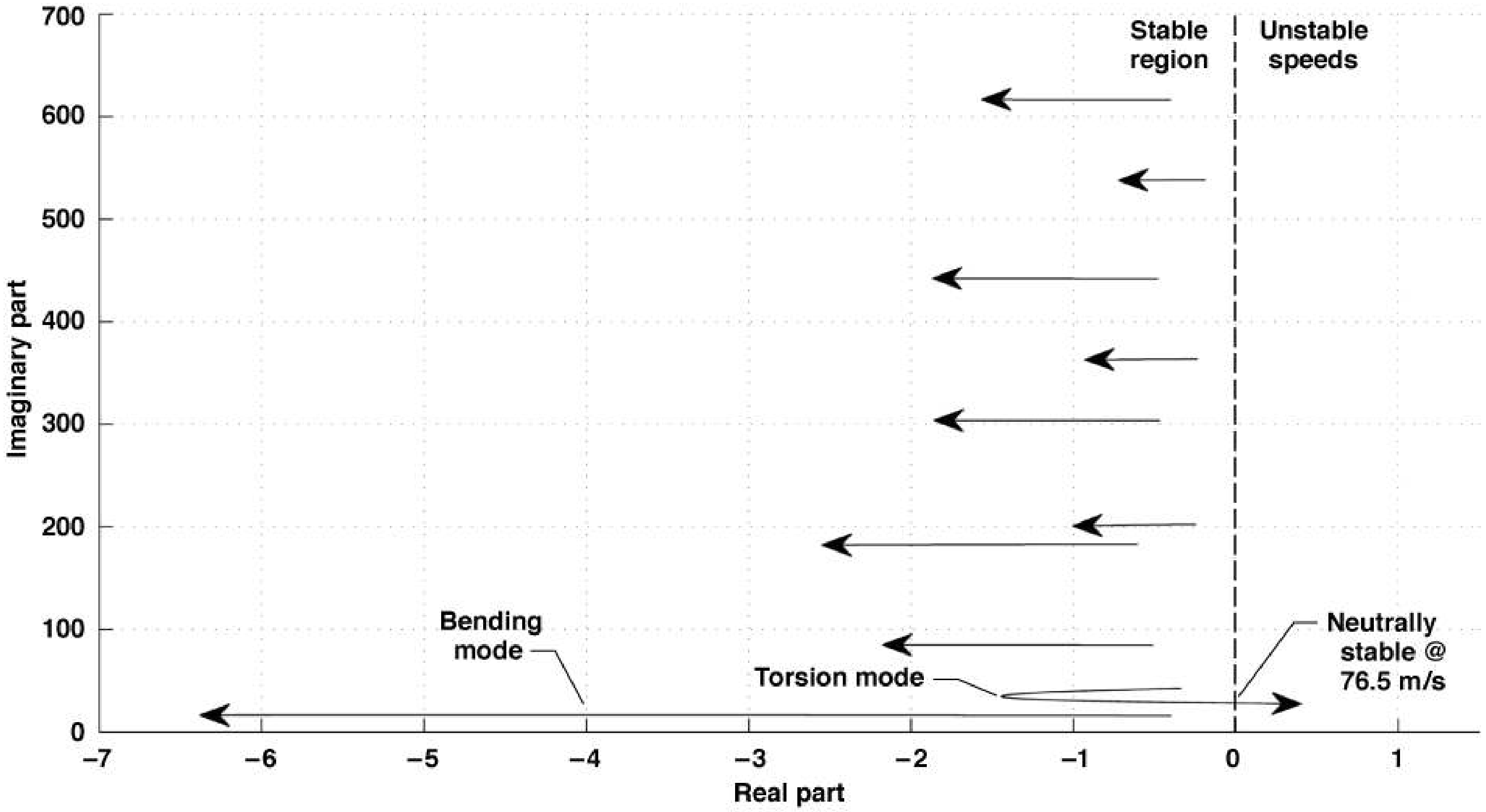
V-g Analysis of Analytical Wing Model



Wing Model Pole Migration

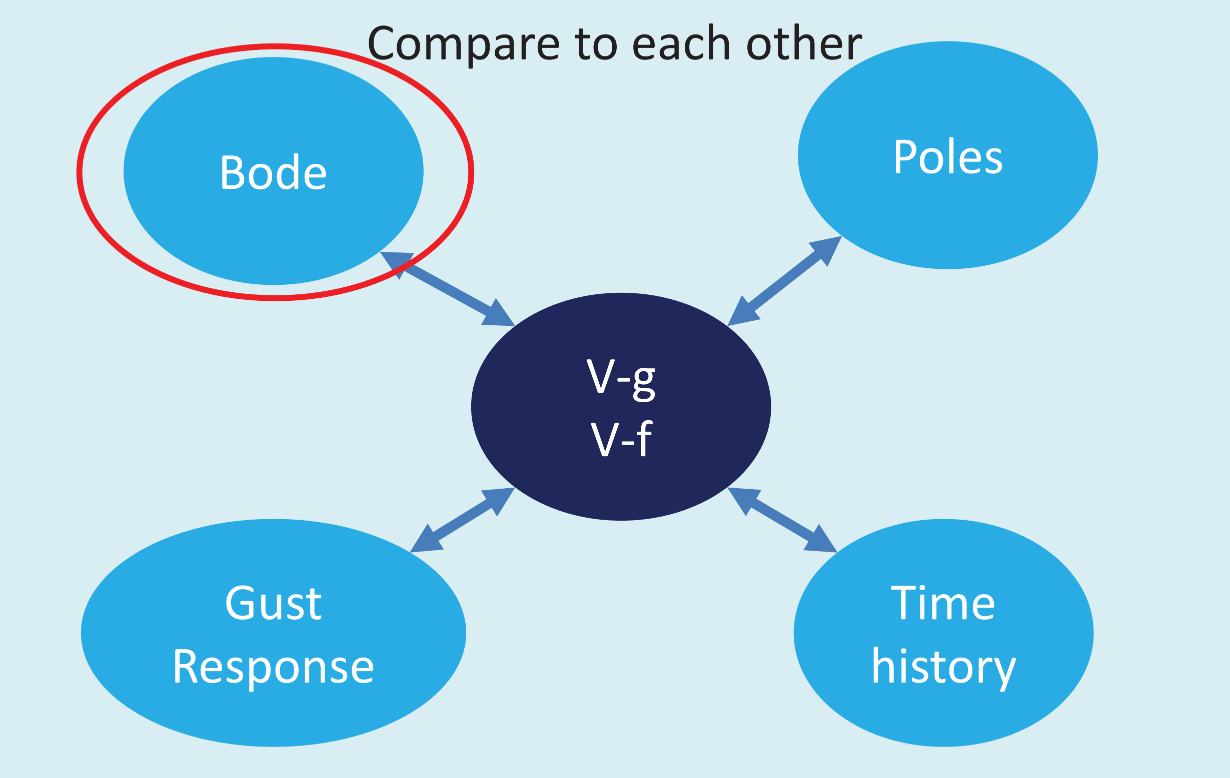
- The bending mode becomes more stable
- The torsion mode becomes neutrally stable at 76.5 m/s
- Flutter speed is the same as predicted in the V-g analysis

Pole Migration of State Space Model from 20 – 78 m/s



State Space Model Verification

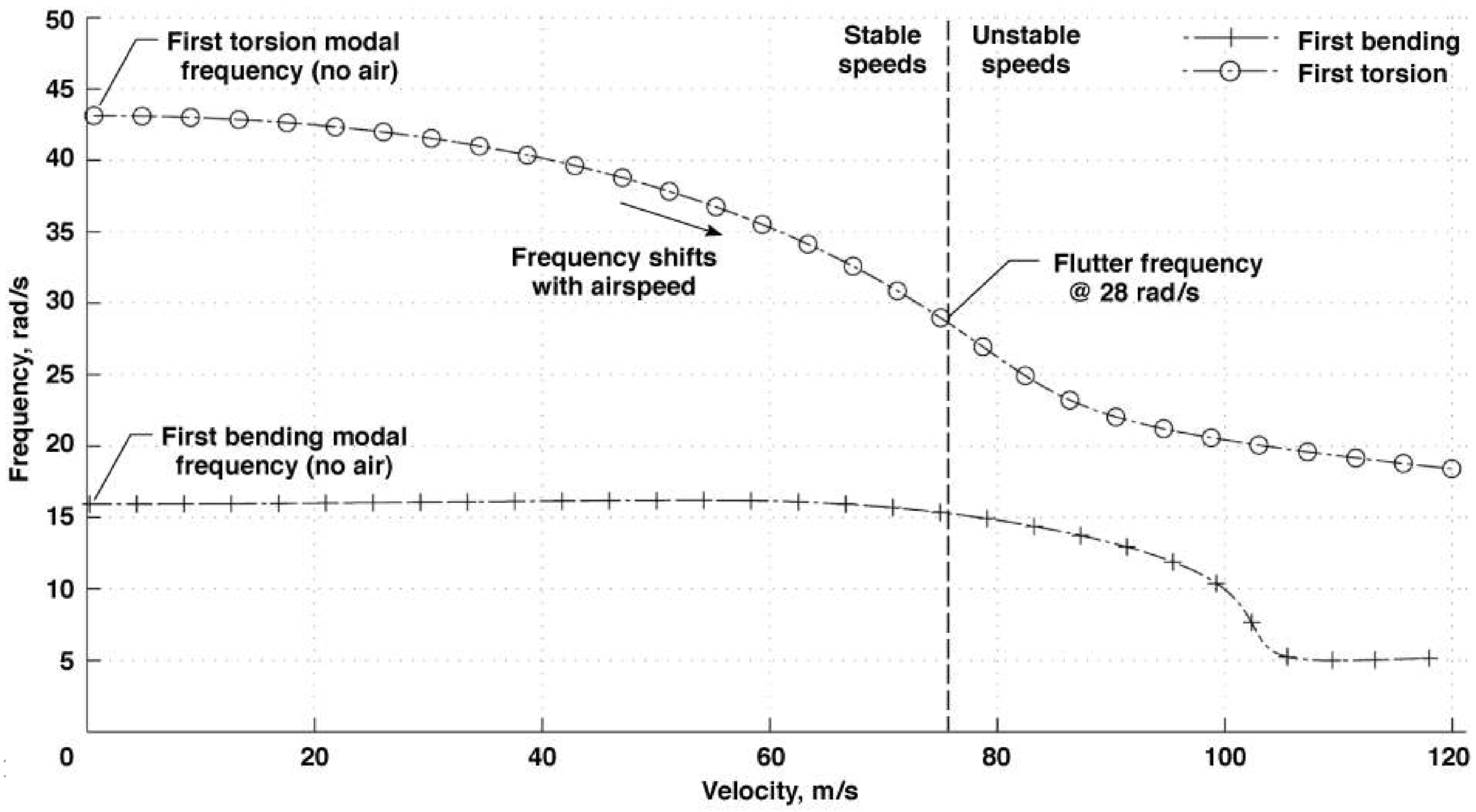
- We verify that the state space models correlate with what was predicted from the V-g and V-f analyses


Compare to each other

V-f Analysis

- Frequency analysis shows the flutter frequency at 28 rad/s

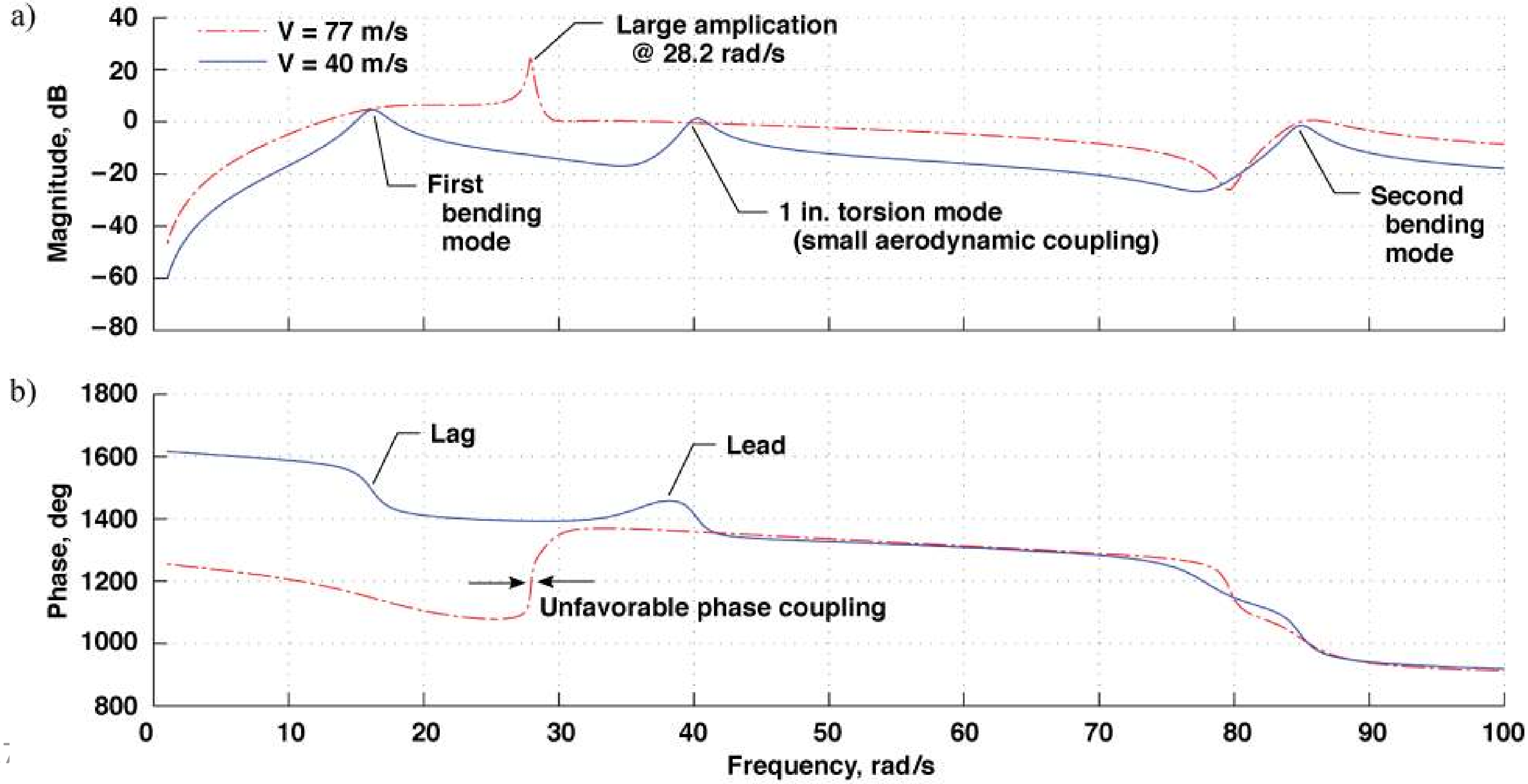
V-f Analysis of Analytical Wing Model



Bode Plot of State Space Model

- At speed below flutter speed, amplitudes of two distinct modes visible
- At flutter speed only flutter mode is visible
- Frequency is the same as predicted from the V-f analysis

Bode Plot of Surface to Leading Edge Accelerometer



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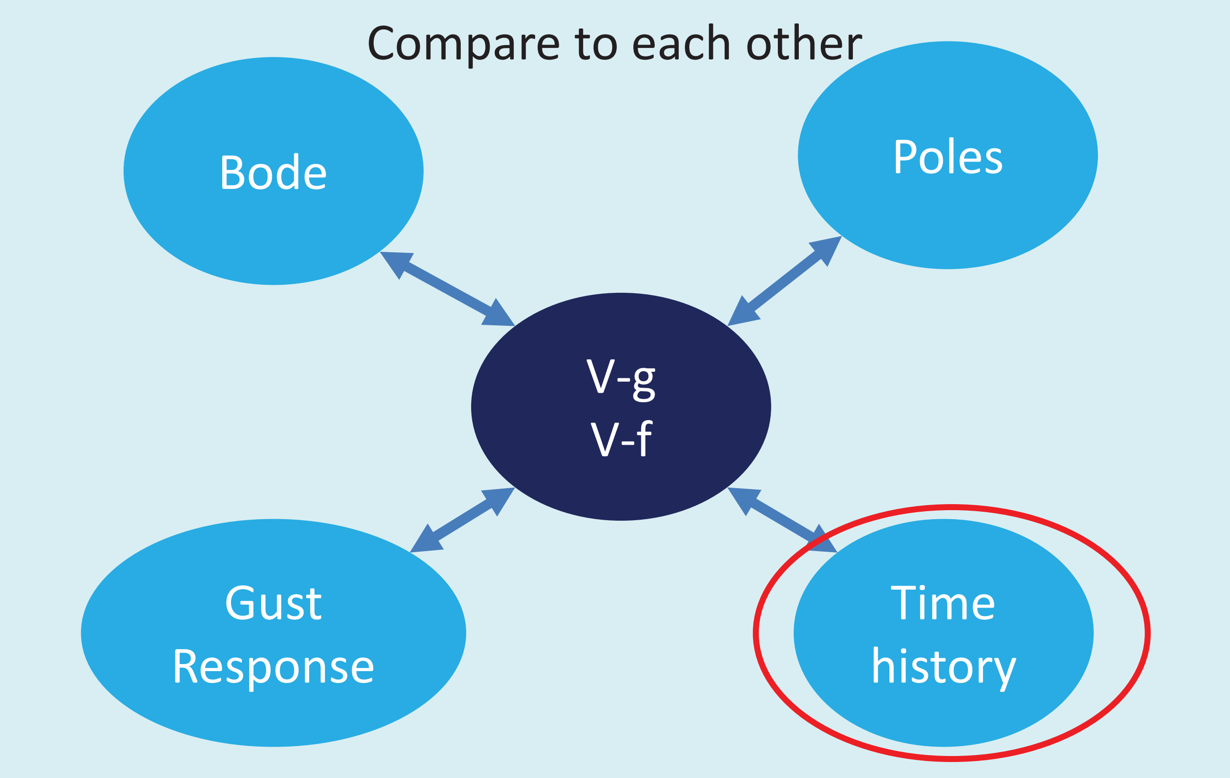


Compare to each other

Bode

Poles

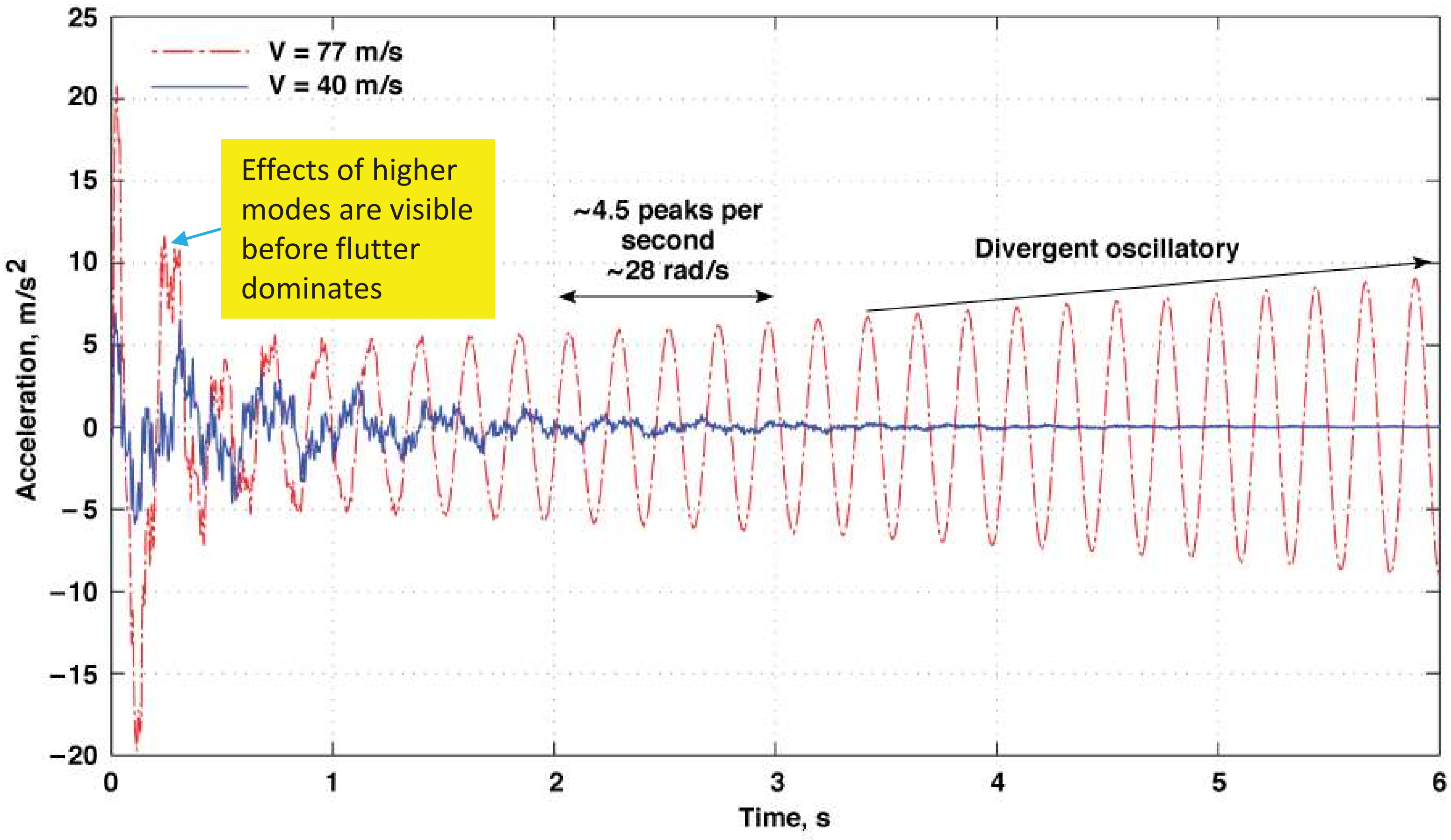
V-g
V-f

Gust Response

Time history

Impulse to State Space Model

- Flutter is apparent in model designed past flutter speed
  - Divergent oscillatory
- Model at lower speed is damped after impulse



Effects of higher modes are visible before flutter dominates

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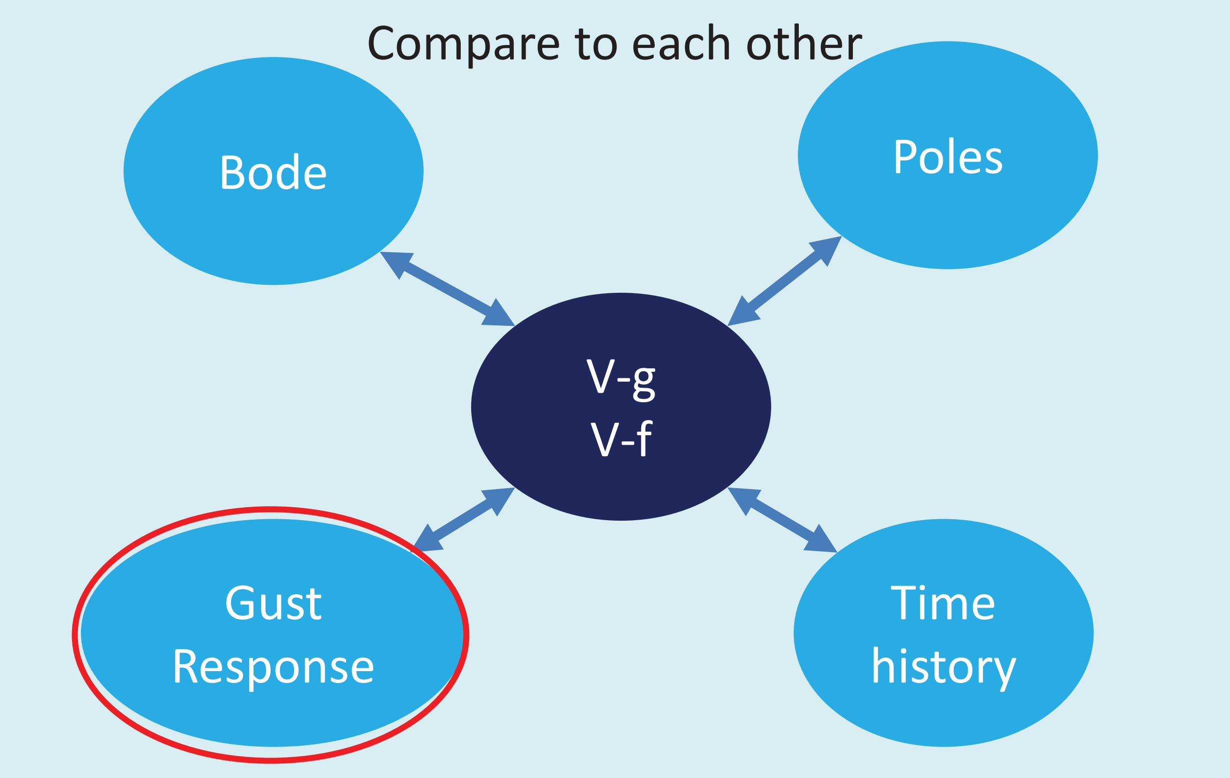
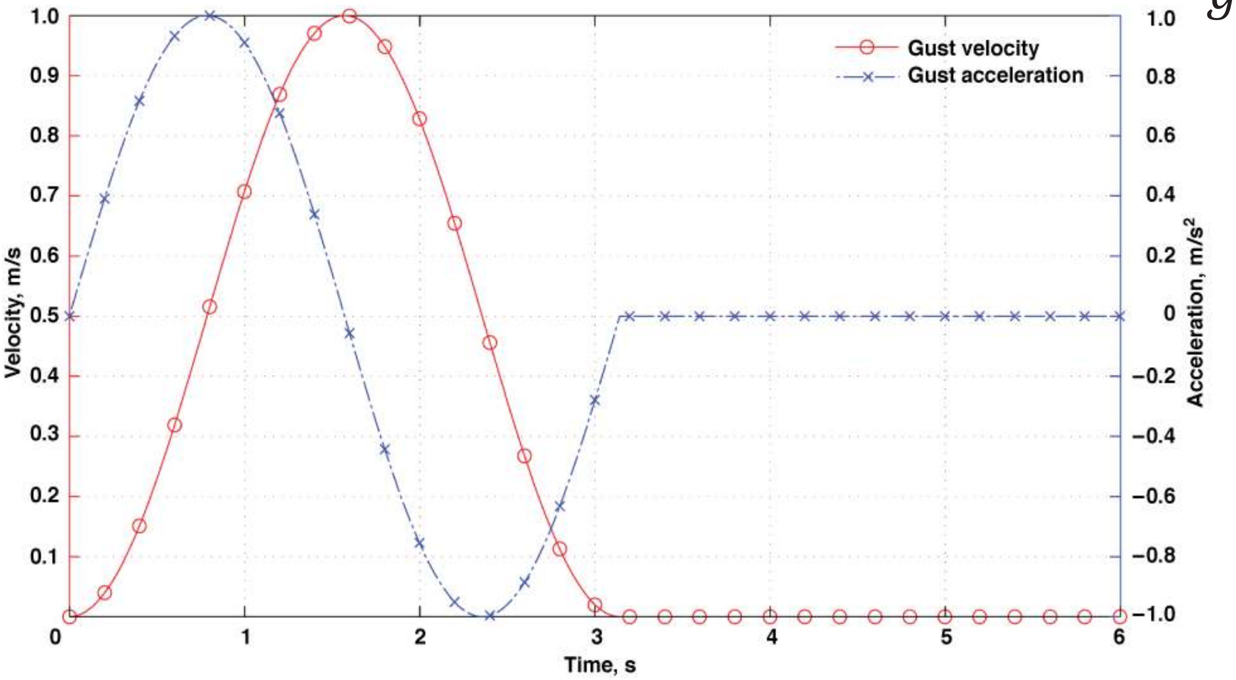


Compare to each other

1-cos Gust Model

- Gust inputs to structure are designed with gust modes and 1-cos gust input structure

1-cos Gust Input Model



Gust mode approximation

$$g_{wash} = -exp\left(\hat{\imath}\,\frac{2k}{\bar{c}}\left(x_{c.p.} - \bar{x}_{gust}\right)\right)$$

Gust velocity

$$w_g(t) = \frac{w_{g,max}}{2}\left(1 - \cos(Gt)\right)$$

Gust acceleration

$$\dot{w}_g(t) = \frac{w_{g,max}}{2}\,sin(Gt)\,G$$

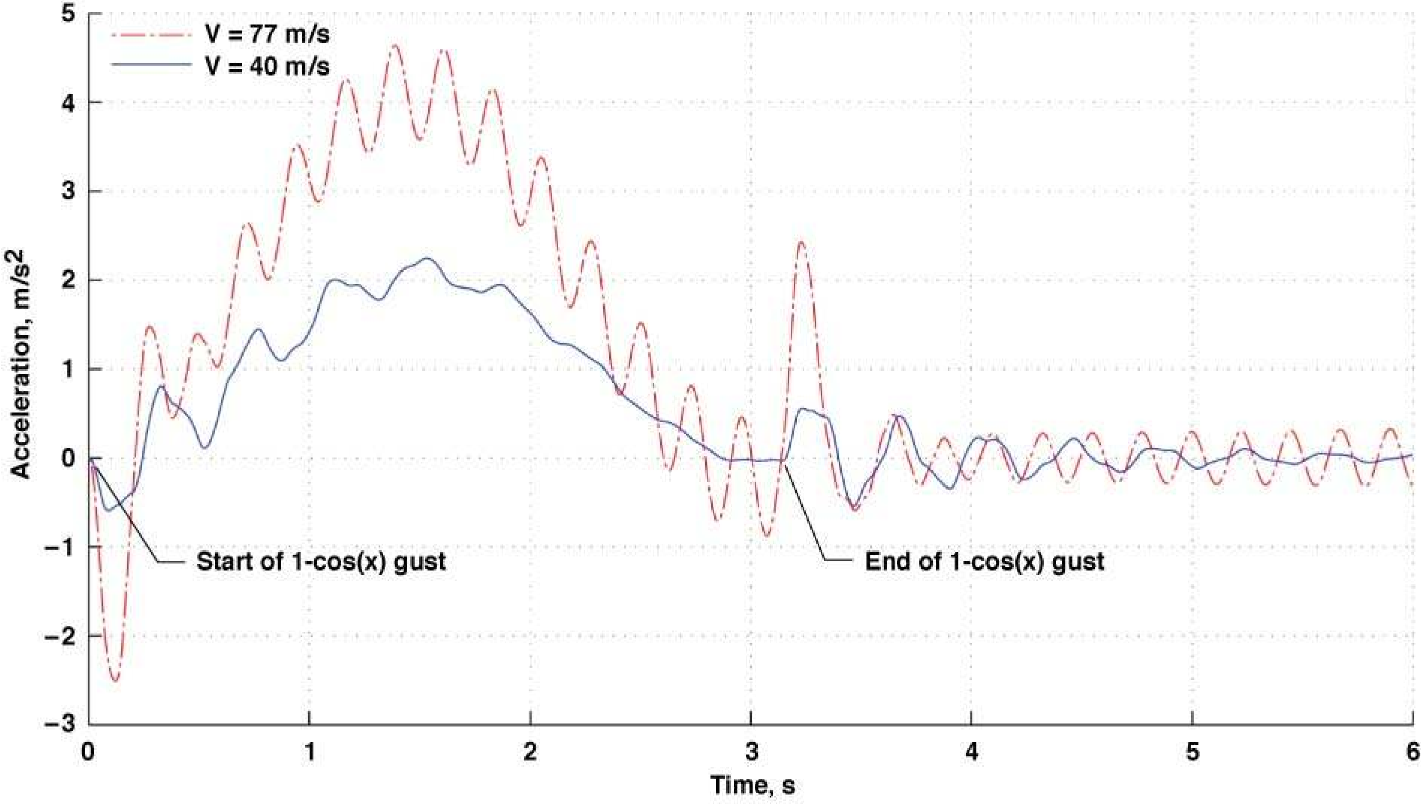
Gust frequency

$$G = 2\,\frac{\dot{w}_{g,max}}{w_{g,max}}$$

Gust Input to State Space Model

- The response of wing to 1-cos gust is expected
  - Low frequency gust response and high frequency oscillations from flutter are seen to be superimposed

Bode Plot of Surface to Leading Edge Accelerometer



Conclusions

- Several first step verification and validation studies were presented for a new aeroservoelastic tool
- More verification and validation is needed to assess the state space models including
  - An experimental flutter test and active flutter suppression
- This work further supports independent flutter analysis conducted by Dr. Conyers in his dissertation

Future Work

- Improvements will be made to include rigid body modes in the tool
- Input structure will be made more user friendly
- Would like to look into transitioning to use as an open tool for students

Questions?