



Distributed strain sensing for the Integrated Adaptive Wing Technology Maturation wind tunnel model

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Outline

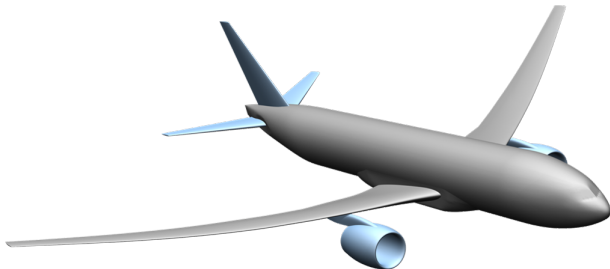
(1) **Introduction**

- a) Integrated Adaptive Wing Technology Maturation (IAWTM) project
- b) Distributed strain sensing using fiber Bragg gratings

(2) **IAWTM wind tunnel model**

(3) **Distributed strain sensing work in support of IAWTM**

(4) **Future work**



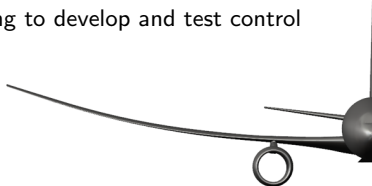


Introduction



IAWTM project overview

- (1) NASA Advanced Air Transport Technology (AATT) project
 - Higher Aspect Ratio Optimal Wing technical challenge: Enable a 1.5-2X increase in the aspect ratio of a lightweight wing with safe flight control and structures
- (2) Cooperative agreement between NASA and Boeing to develop and test control technologies to meet multiple objectives:
 - Drag optimization
 - Maneuver load alleviation
 - Gust load alleviation
 - Flutter suppression
- (3) Purpose: decrease cost of vehicle operation by reducing induced drag and structural weight penalties normally associated with a high-aspect ratio wing





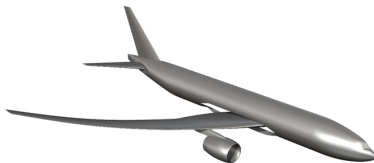
IAWTM project overview, cont.

(4) IAWTM vehicle

- Aspect ratio 13.5 wing of a modern transport configuration based on the Common Research Model (CRM)
- Aspect ratio is a 1.5X increase over the nominal aspect ratio 9 CRM wing

(5) Analysis and testing

- Full-scale analysis
 - Evaluation of performance using a high fidelity 6DOF simulation and development of multi-objective control law
- Model-scale testing
 - Wind tunnel test to be conducted at the NASA Langley Transonic Dynamics Tunnel (TDT) in 2020





Distributed strain sensing using fiber Bragg gratings

- (1) Fiber optic strain sensing using fiber Bragg gratings (FBGs) enables low mass and volume distributed sensing capability
- (2) System characteristics for wavelength division multiplexing (WDM) strain sensing using a Micron Optics si155
 - a) Tens of FBGs on a single fiber, each of which can be used as a strain sensor
 - b) Up to four fibers can be measured simultaneously
 - c) On each fiber, FBGs etched with unique nominal Bragg wavelengths (wavelength selective mirrors)
 - d) Fiber diameter: 195 μm
 - e) Sampling rate: 1,000 samples/second
 - f) Measurement latency: ≈ 0.65 ms

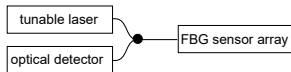
Micron Optics si155



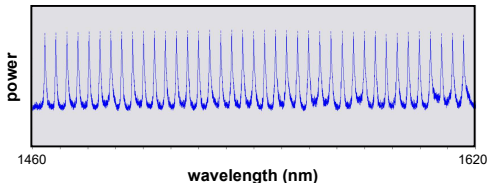
Distributed strain sensing using fiber Bragg gratings, cont.

- WDM operation
 - (1) Tunable laser directs incident light along fiber core towards FBG sensor array in a wavenumber sweep
 - (2) Incident light interacts with FBGs, leading to some reflection to the optical detector and some transmission down the fiber
 - (3) Reflectivity measured using the optical detector as a function of wavelength
 - (4) Peak (Bragg wavelength) shifts due to axial strain are measured and transmitted digitally via a UDP or TCP connection

System setup



Typical reflection spectrum, 39 FBGs



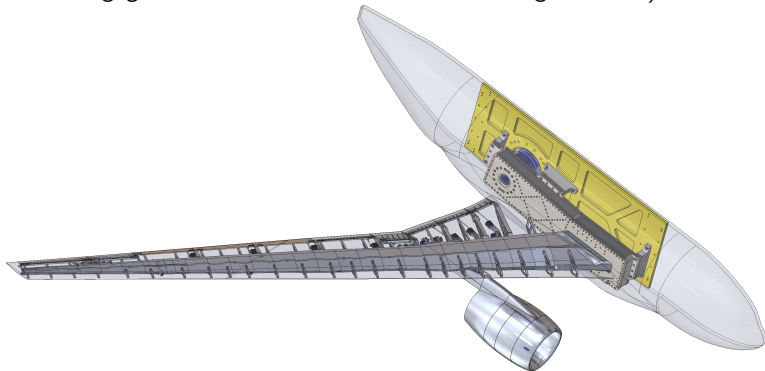


IAWTM wind tunnel model



Wind tunnel model overview

- Semi-span dynamically scaled wing for testing at NASA Transonic Dynamics Tunnel (TDT) in 2020
 - Spar-pod construction (aluminum spar, carbon fiber skins) with flow-through engine nacelle and non-metric fuselage
 - 10 active control surfaces and large number of sensors (accelerometers, strain gages, distributed strain sensors, balance, gust sniffer)

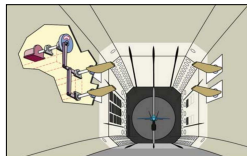




Active control testing objectives

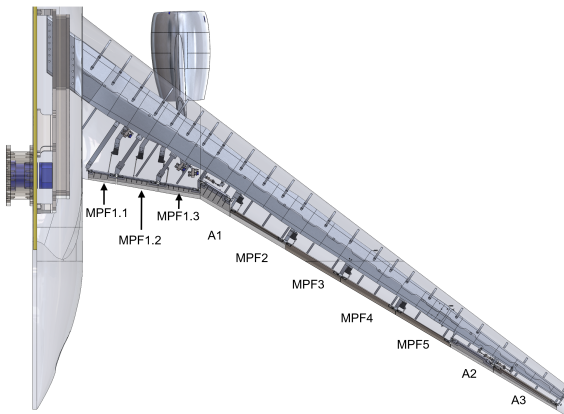
- (1) Drag optimization at off nominal conditions
 - Drag measured with balance
- (2) Maneuver load alleviation
 - Load reduction measured with model strain sensors and balance
- (3) Gust load alleviation
 - Excitation provided by TDT airstream oscillation system (AOS)
 - Upstream vane sensor to serve as surrogate LIDAR gust detector for predictive gust load alleviation
- (4) Modal and flutter suppression
 - Modal suppression important at all operating conditions due to low structural stiffness and damping
 - Active controller implemented using dSPACE hardware/software
 - Flutter suppression

TDT AOS



Control surfaces

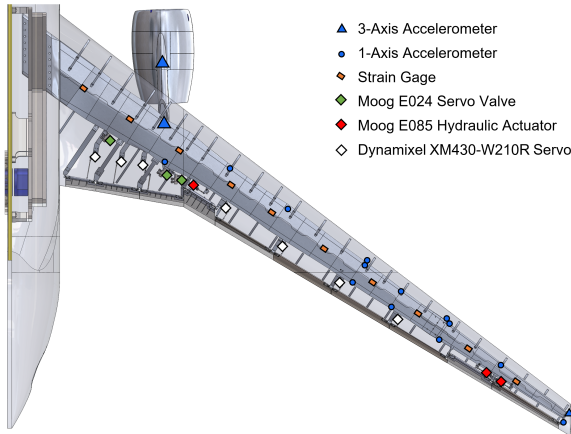
- 10 trailing edge distributed control surfaces
 - 3 hydraulically actuated ailerons (faster response)
 - 7 electric servo actuated mini plain flaps (slower response)





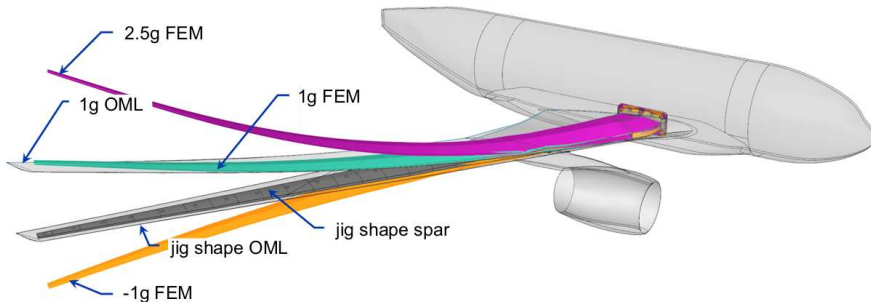
Point sensors

- 3 triaxial and 13 single axis accelerometers, 10 full-bridge strain gages, Q-flex inclinometer, 8 balance-based loads, gust vane sensor



Static aeroelastic wing deformation

- Model spar designed as an equivalent beam to approximate desired running stiffness
- Equivalent beam deformations (FEM) for several critical flight conditions illustrate representative static aeroelastic deformation of the model

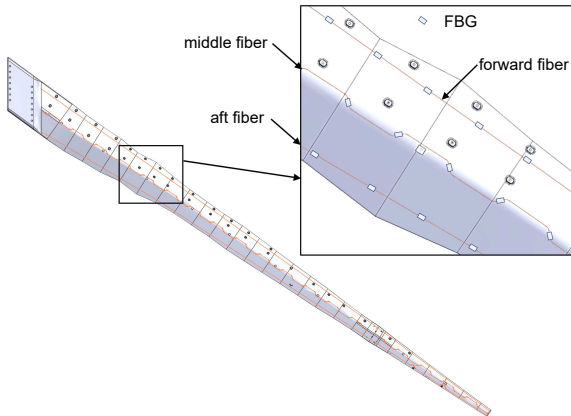




Distributed strain sensing work in support of IAWTM

Wind tunnel model fiber optic sensors

- Three fibers bonded into channels on the spar upper surface, each with 40 FBGs
- FBGs on forward and aft fibers oriented spanwise (sensitive to out-of-plane bending) and FBGs on middle fiber oriented 45 deg to spanwise direction (more sensitive to local twist rate)





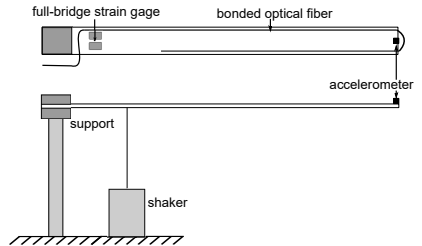
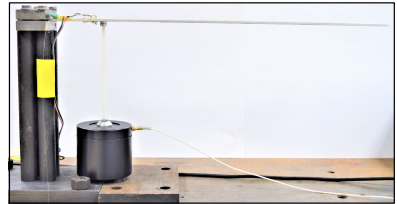
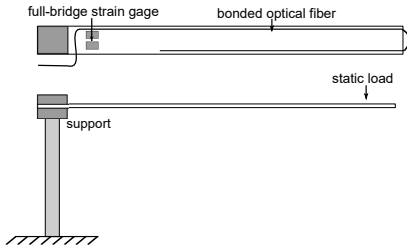
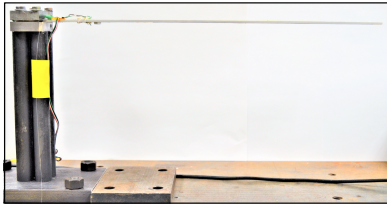
Shape sensing from measured strain

Clamped-free body

- Several methods available to estimate deformation from strain – here, the Newmark- β integration method is used
 - An integration matrix, W , can be defined such that out-of-plane deflection is given by $w = W^2 w''$, where the curvature, w'' , is proportional to the measured longitudinal surface strain
 - Important considerations include kinematic boundary conditions and interior interpolation

Benchtop testing

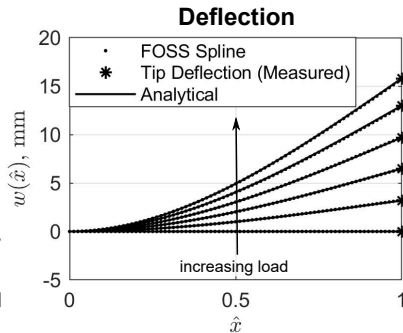
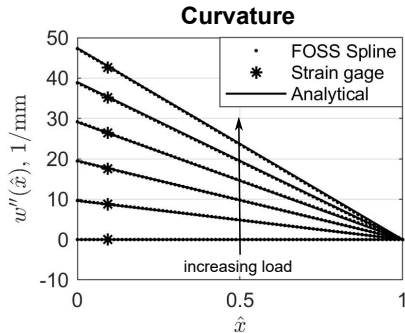
Clamped-free beam





Static shape sensing

Clamped-free beam



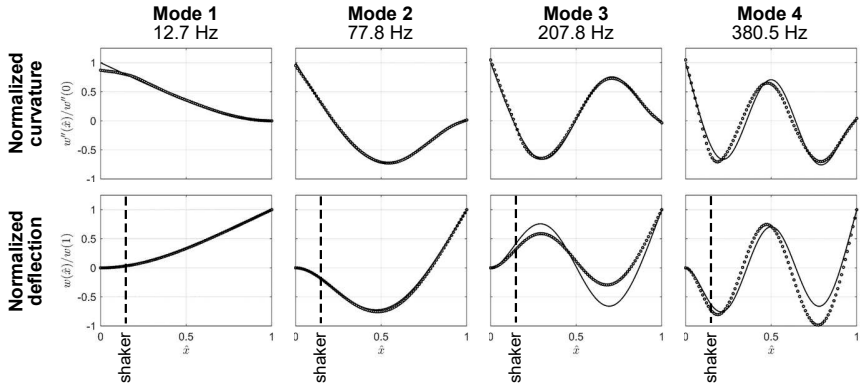
Max absolute error in deflection estimate: $\max \left| \frac{w_{\text{foss}} - w_{\text{measured}}}{w_{\text{measured}}} \right| = 0.90\%$



Dynamic shape sensing

Clamped-free beam

- Markers correspond to distributed strain measurement spline and solid lines correspond to Euler-Bernoulli beam theory

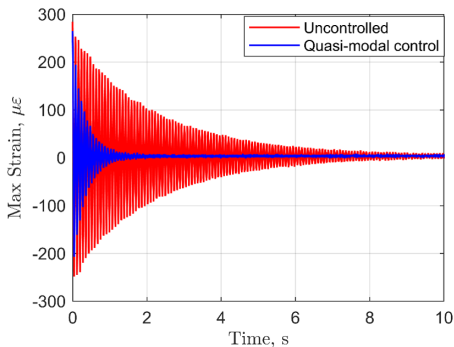




Quasi-modal vibration suppression with FBG feedback

Clamped-free beam

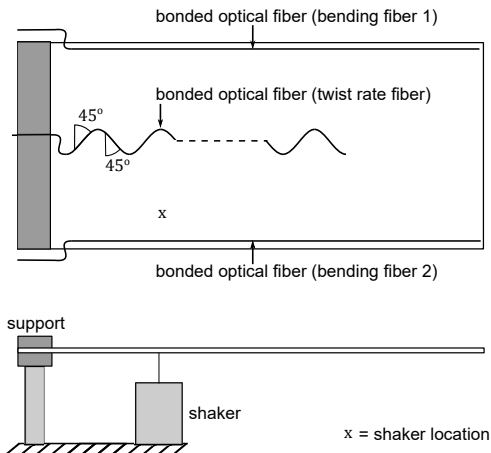
- Shaker used for vibration suppression of initial tip deflection
- Under control, 6.8X increased damping
 - Estimated damping ratios: $\hat{\zeta}_{\text{uncontrolled}} = 0.65\%$ and $\hat{\zeta}_{\text{controlled}} = 4.42\%$





Benchtop testing

Clamped-free plate





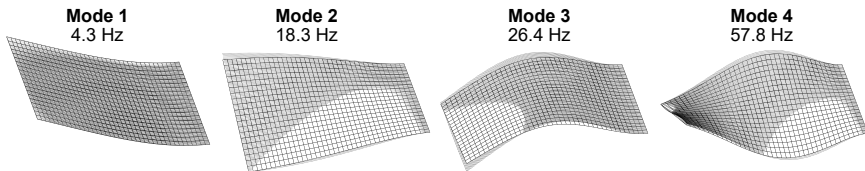
Dynamic shape sensing

Clamped-free plate

- Plate deflection based on linear interpolation between forward and aft bending fibers

$$w(\hat{x}, \hat{y}) = \hat{y} \cdot w_{\text{LE}}(\hat{x}) + (1 - \hat{y}) \cdot w_{\text{TE}}(\hat{x})$$

Rectangular clamped-free plate mode shapes based on interpolated distributed strain measurements (grids) and finite element analysis (dots)



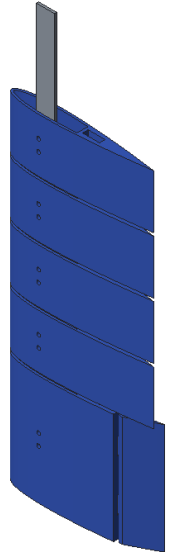
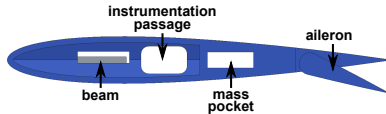


Future work



Low speed aeroelastic testing of partially 3d printed model

- Semi-span aeroelastic wing for testing in a low speed concept development wind tunnel
 - Spar-pod model (aluminum beam spar, 3d printed PLA pods) with distributed strain sensors instrumenting the spar
 - Rectangular planform, NACA 0012 airfoil

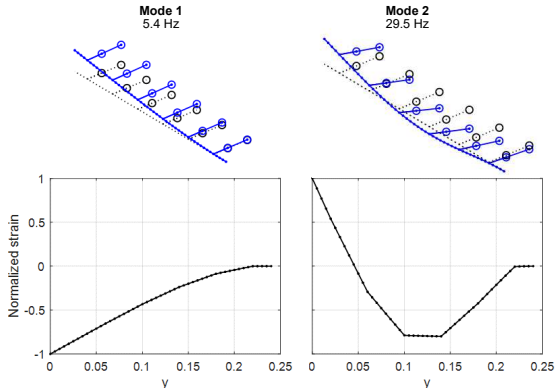




3d printed model

Structural dynamics

- NASTRAN model: clamped-free beam with rigidly attached concentrated masses for pods and trailing edge masses (control surface motion not modeled)
 - Strain distributions correspond to longitudinal strain along upper surface of spar centerline



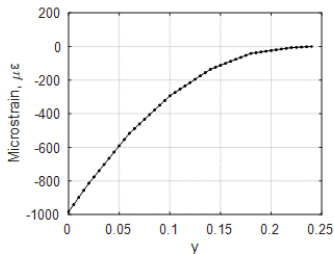


3d printed model

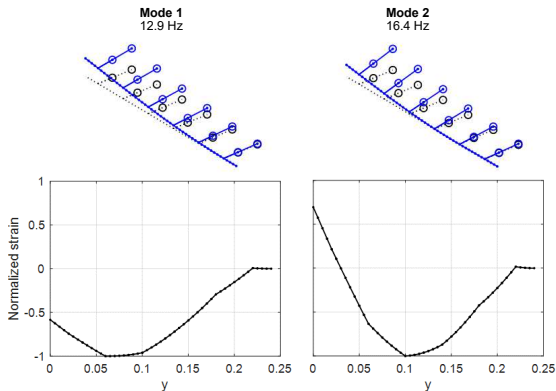
Aeroelastic analysis

- Strain distributions correspond to longitudinal strain along upper surface of spar centerline

Static strain distribution at 2 deg AoA



Mode shapes, frequencies, and strain distributions at flutter speed, 56.8 m/s





Summary

- Distributed strain sensing is a potential enabling sensor technology to support increased efficiency, highly flexible, wing designs
- Benchtop studies have been conducted to characterize system performance and shape sensing capability
- Proof-of-concept work has been conducted to demonstrate the use of real-time distributed strain measurements for feedback control
- Future work will focus on:
 - Real-time distributed strain measurements for wing shape estimation using a low speed aeroelastic model
 - Distributed strain feedback for static and dynamic aeroelastic control
 - IAWTM wind tunnel test in the NASA Langley TDT in 2020



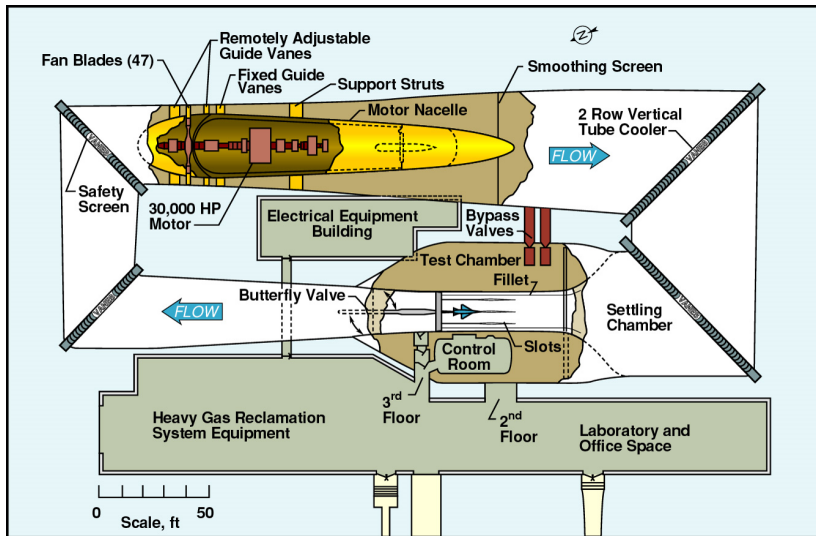
Questions?



Extra

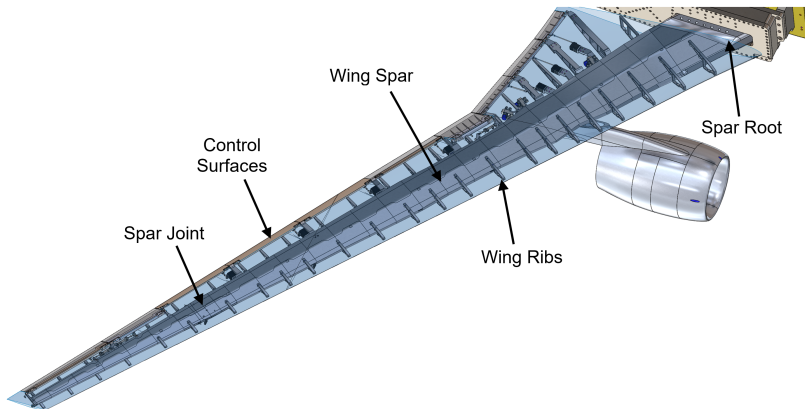


NASA Langley Transonic Dynamics Tunnel



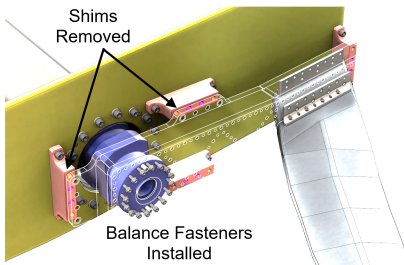


Wind tunnel model spar components

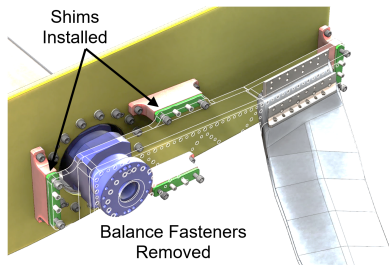


Balance adapter design

- To support both aerodynamic performance data acquisition using a balance and dynamic aeroelastic testing, a balance adapter will be used to engage/disengage the balance on the model load path



Balance in the Load Path

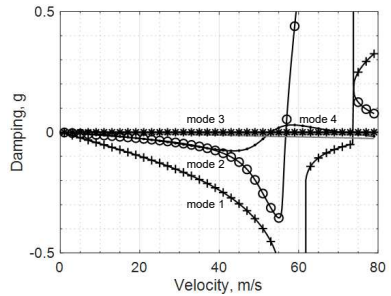
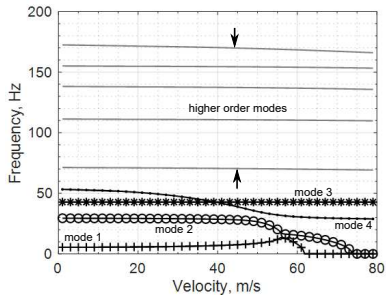


Bypassing the Balance



3d printed model

Aeroelastic analysis, v-g plot





3d printed model

Aeroelastic analysis, root locus

