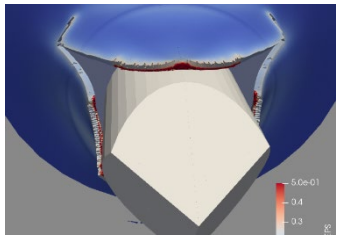
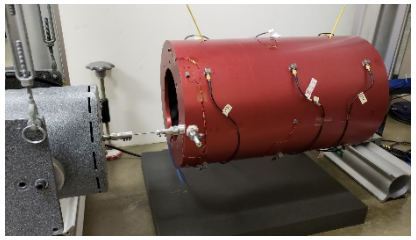
Nonlinear Dynamic Analysis of a Finger-Like Mechanism for Morphing Wings





Students:

Aabhas Singh & Kayla Wielgus

Mentors:

Robert Kuether, Ignazio Dimino, Matthew Allen

SAND2020-7662 PE

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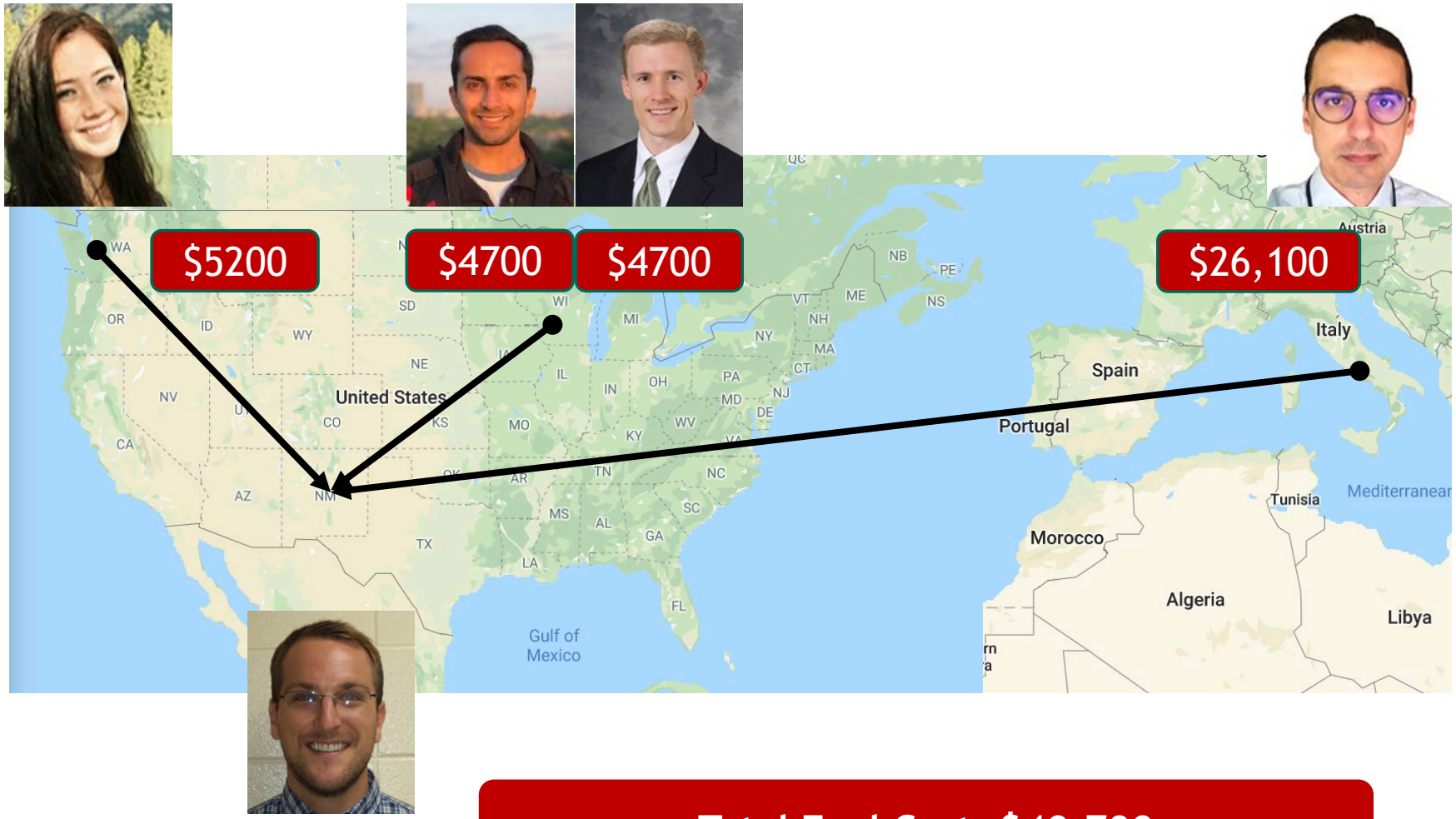
Fuel Cost if NOMAD was in Albuquerque

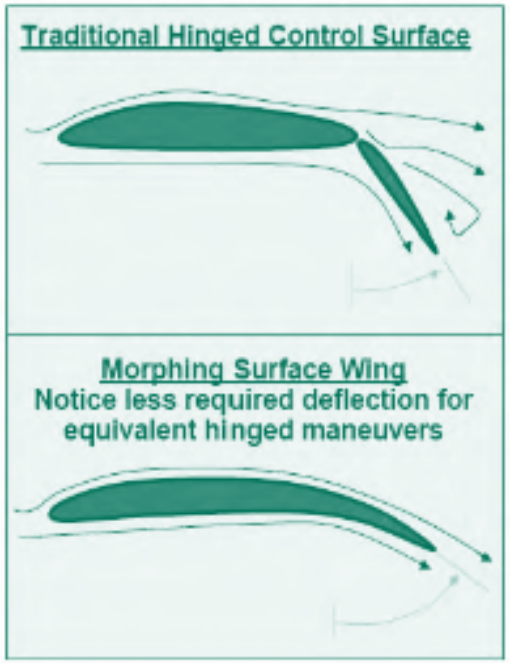


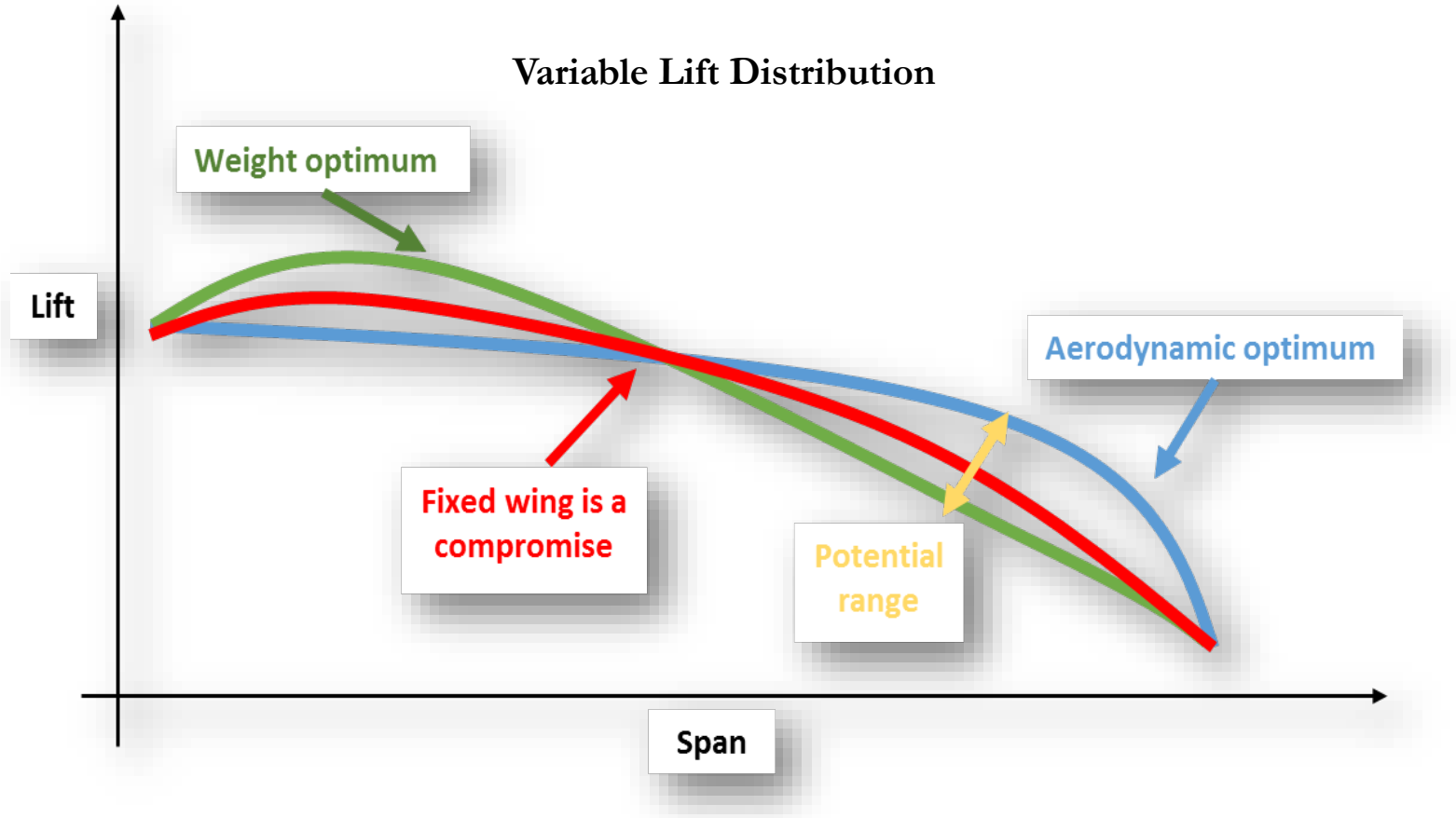
Jet Fuel Avg. 2019 PPG	$1.88
Aircraft Avg. MPGGE	0.43

https://www.eia.gov/
https://afdc.energy.gov/data/10311
Maps.google.com

Total Fuel Cost: $40,700

Hinged Wings – A Compromise





Morphing Wings – Nature Motivated

Nature inspires

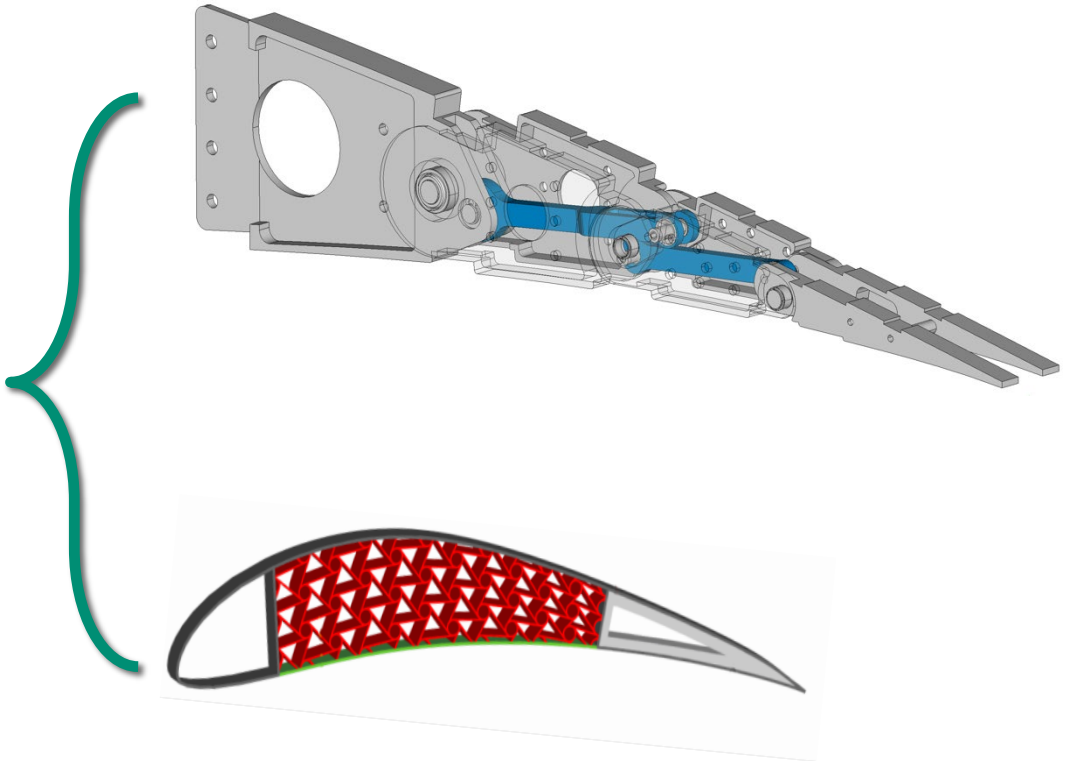
Actual A/C devices

Morphing Wings – Not just a Concept

They are flexible, shape-changing and bio-inspired high-lift devices:

- ✓ Reduced fuel consumption
- ✓ Reduced airframe noise

https://www.youtube.com/watch?v=bC5BUuDFhmg

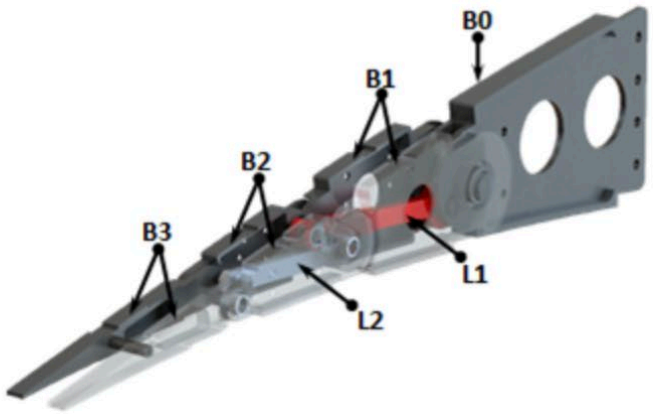


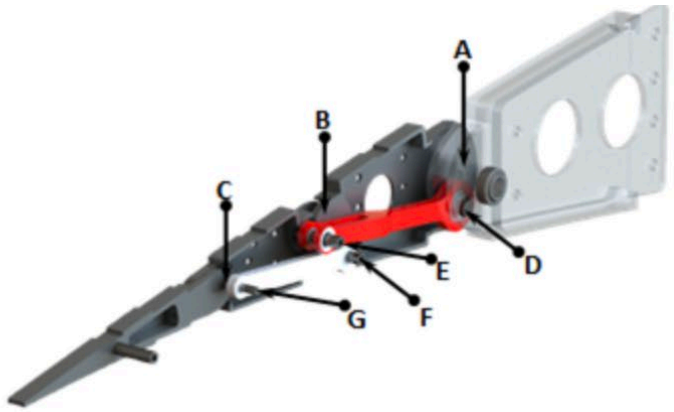
Kinematic Systems

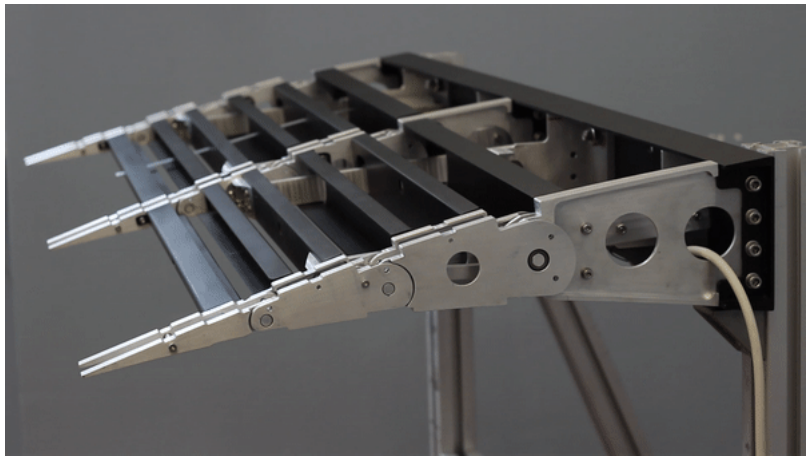
Compliant

Kinematic Finger Like Mechanisms

Finger – Like Mechanisms consists of different blocks (connected by hinges and links) moving with a pre-defined mechanical law and driven by load-bearing actuators





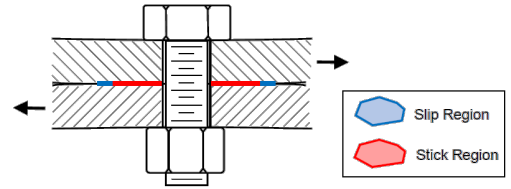


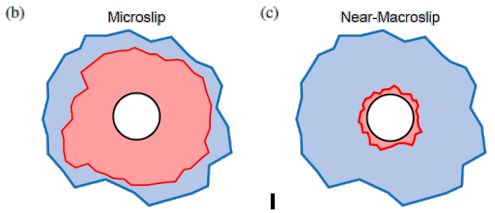
Several connected components exhibit frictional nonlinearity at the interfaces

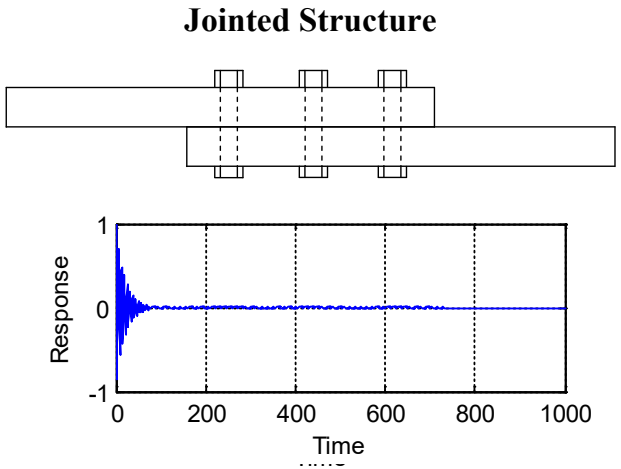
Importance of Modeling Frictional Interfaces

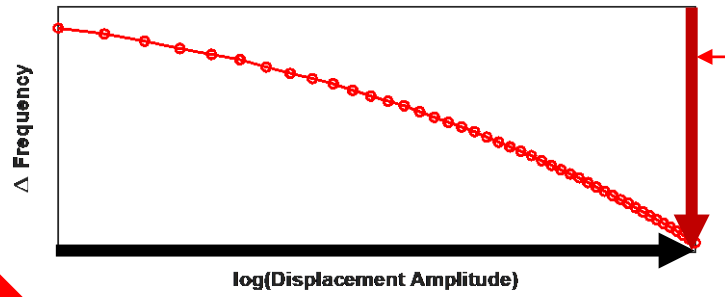
Well tightened bolts still exhibit regions of slip at the edge of contact

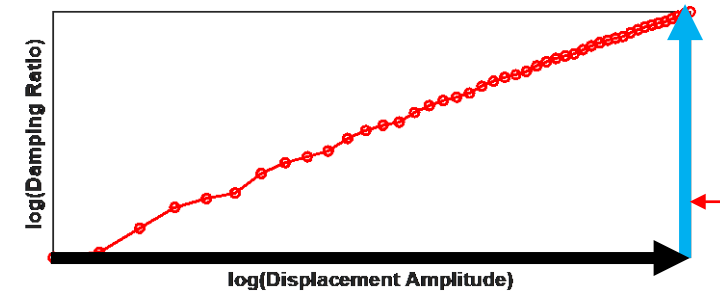
- Microslip/Macroslip
- Introduces hysteresis and amplitude dependent behavior

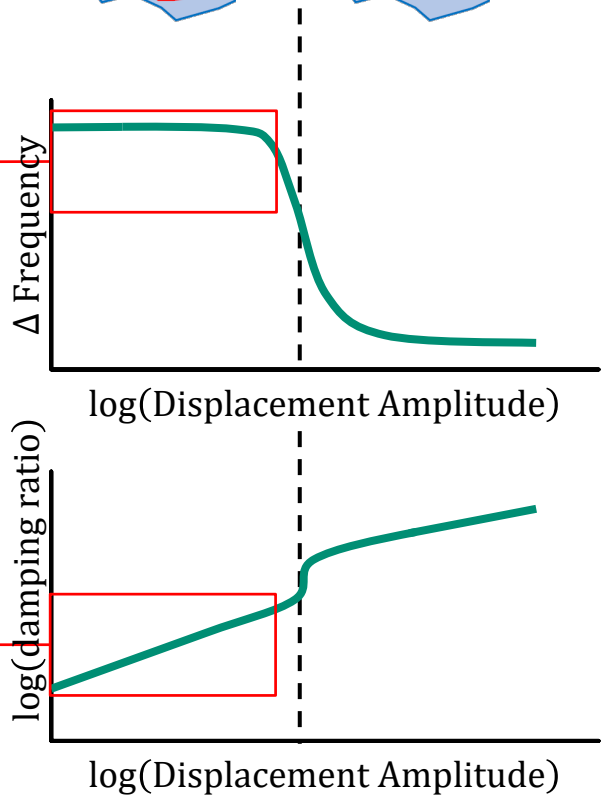




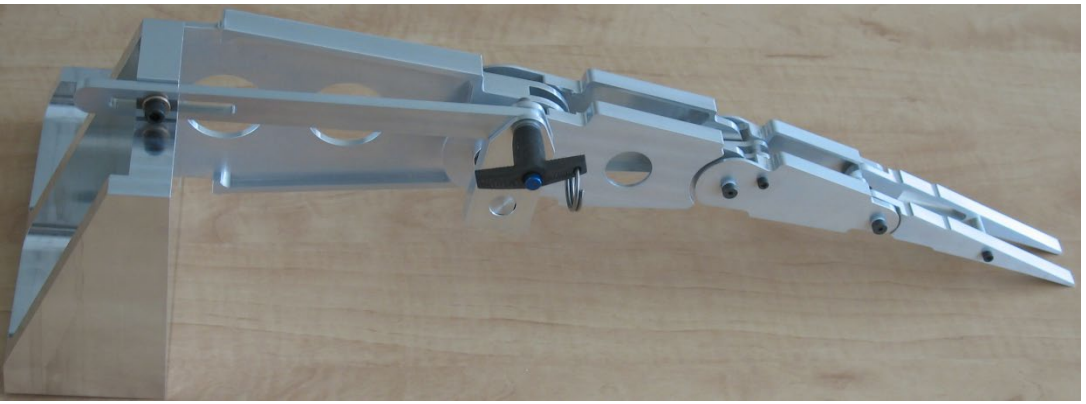


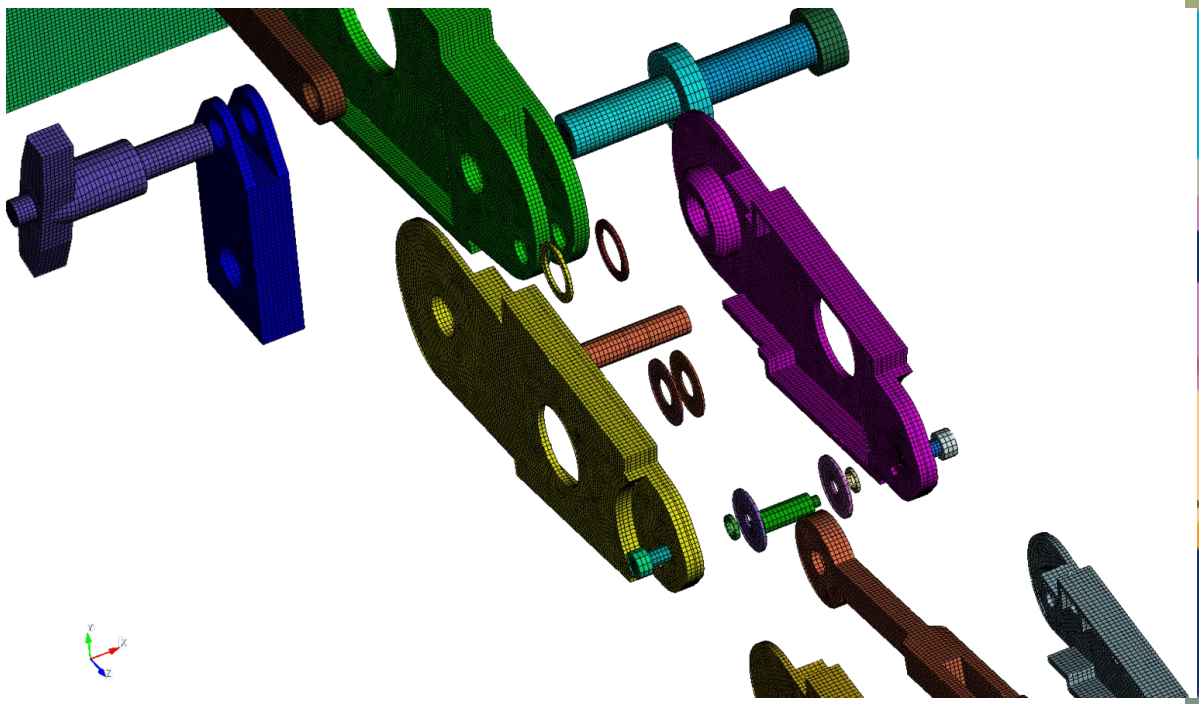






Project Objective





Develop a nonlinear finite element model of an industrial structure to better understand the nonlinear damping and frequency behavior

Full – Order Modeling with Quasi-Static Modal Analysis

The Quasi-Static Modal Analysis Process

QSMA of a Full-Order Model

Nonlinear Preload Analysis — SM

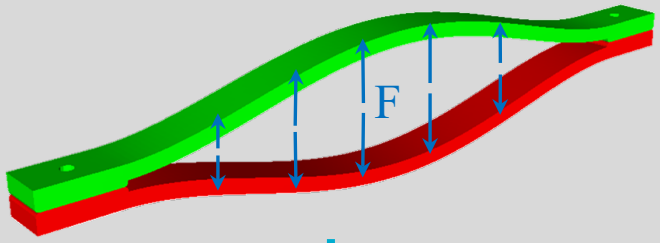
$$Kx + f_{NL}(x,\theta) = f_{pre}$$

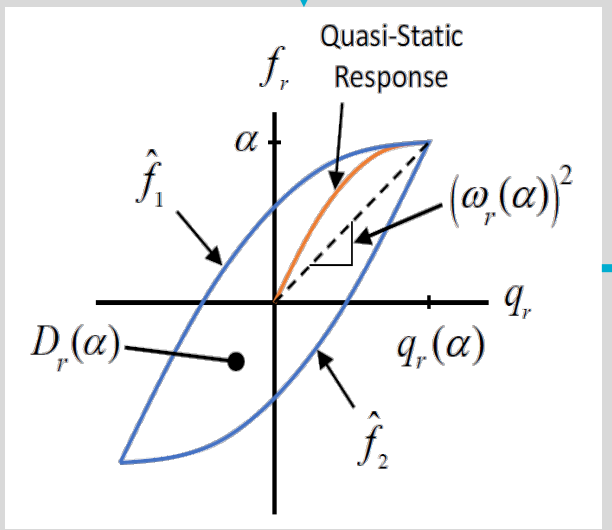
Linearized Modal Analysis — SD

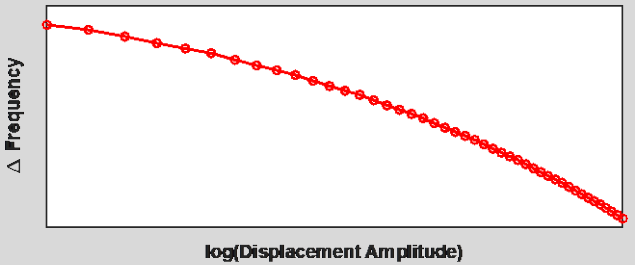
$$\left(K + \left.\frac{df_{nl}(x,\theta)}{dx}\right|_{x=x_{pre}} - \omega_r^2 M\right)\phi_r = 0$$

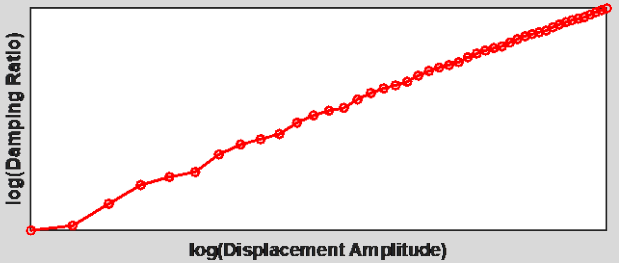
Modal Force Application — SM

$$Kx + f_{nl}(x,\theta) = f_{pre} + M\phi_r\alpha$$









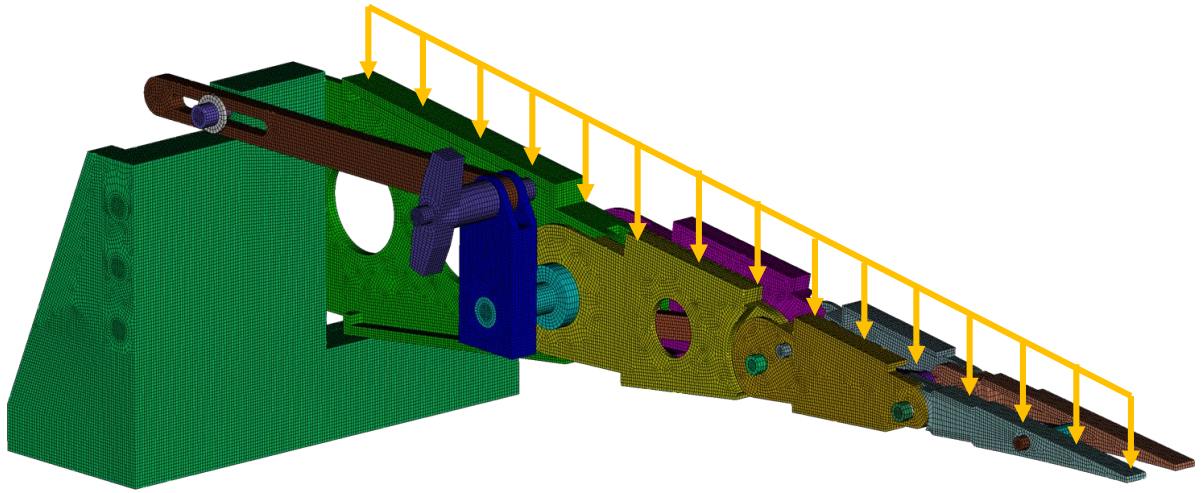
Dynamic analysis of a structure is computationally expensive so we use a static analysis

- ~10x increase in speed for a quasi-static case (seconds) vs. static response case (hours)
- Dynamic simulation could take upwards of weeks

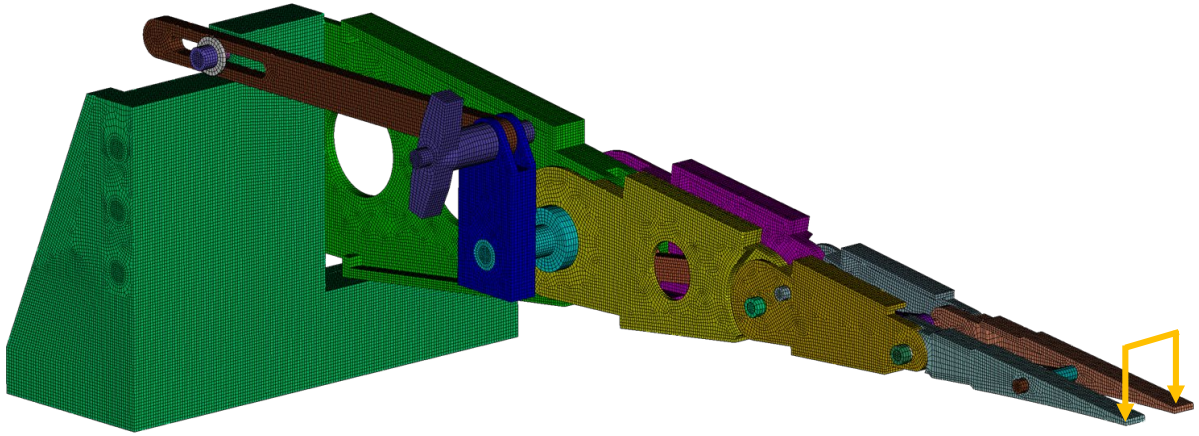
R. M. Lacayo and M. S. Allen, "Updating Structural Models Containing Nonlinear Iwan Joints Using Quasi-Static Modal Analysis," *Mechanical Systems and Signal Processing*, vol 118, pp. 133-157, 2019

Application to the Morphing Wing

Gravity Load – Test Condition



Tip Load – Representative Operative Condition



Apply QSMA to get frequency and damping curves for these two preload methods

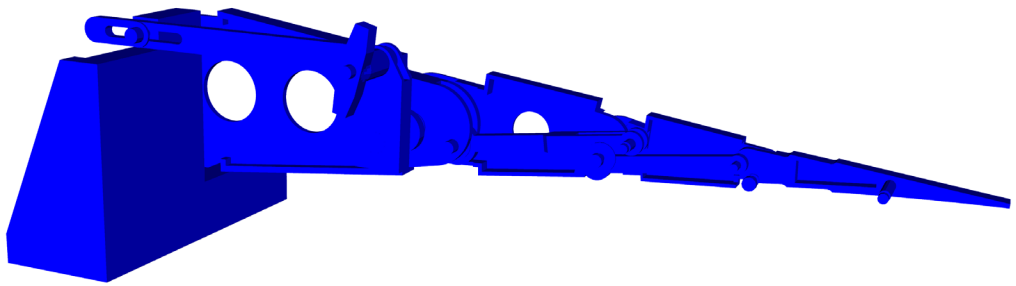
Apply Preload on the Structure

Nonlinear Preload Analysis

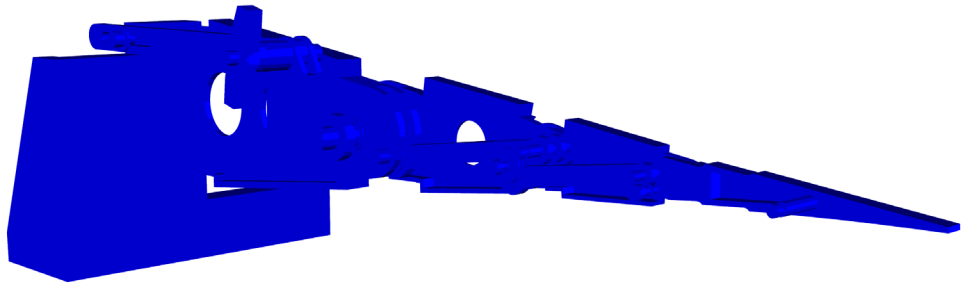
$Kx + f_{NL}(x, \theta) = f_{pre}$

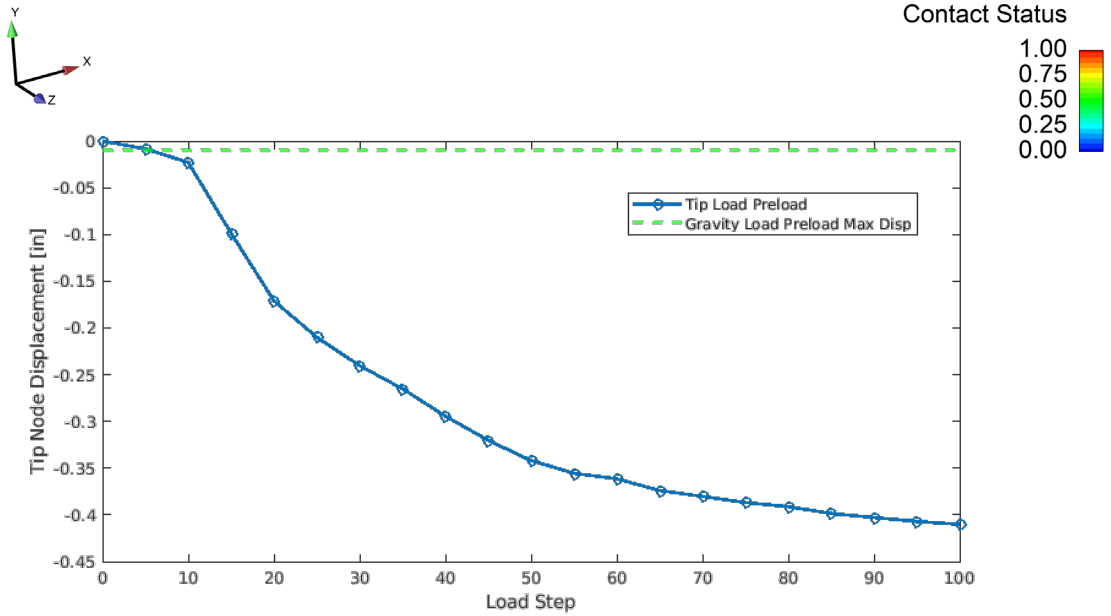
SM

Gravity Load



Tip Load





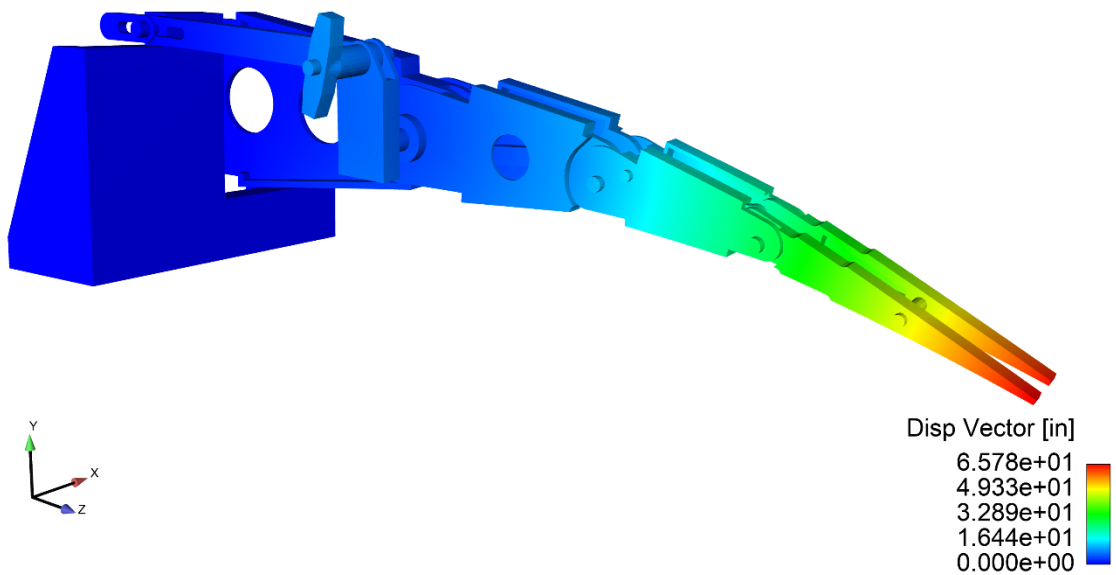
Mode Of Interest

SD

Linearized Modal Analysis

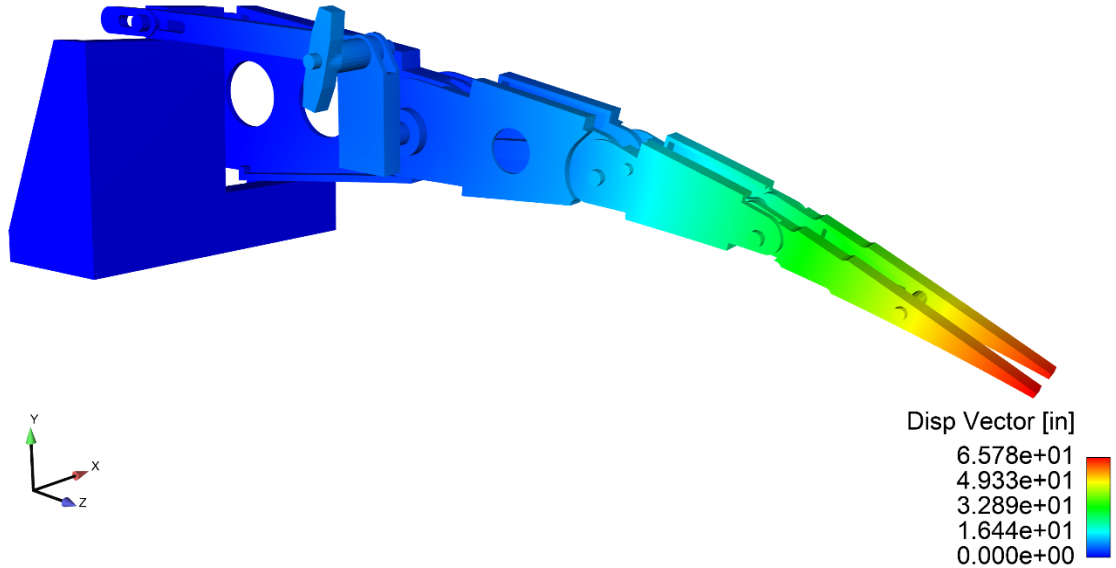
$$\left(K + \left.\frac{df_{nl}(x,\theta)}{dx}\right|_{x=x_{pre}} - \omega_r^2 M\right)\phi_r = 0$$

164.5 Hz



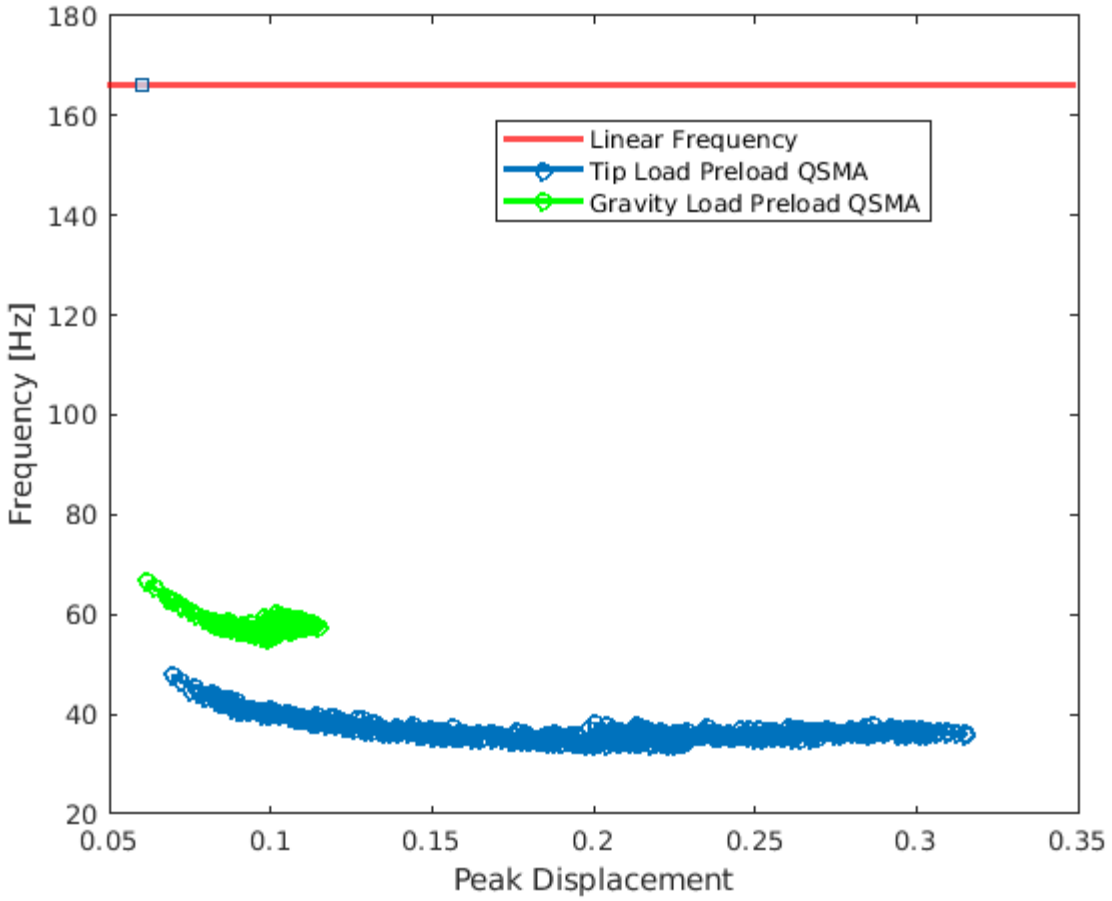
Gravity Load

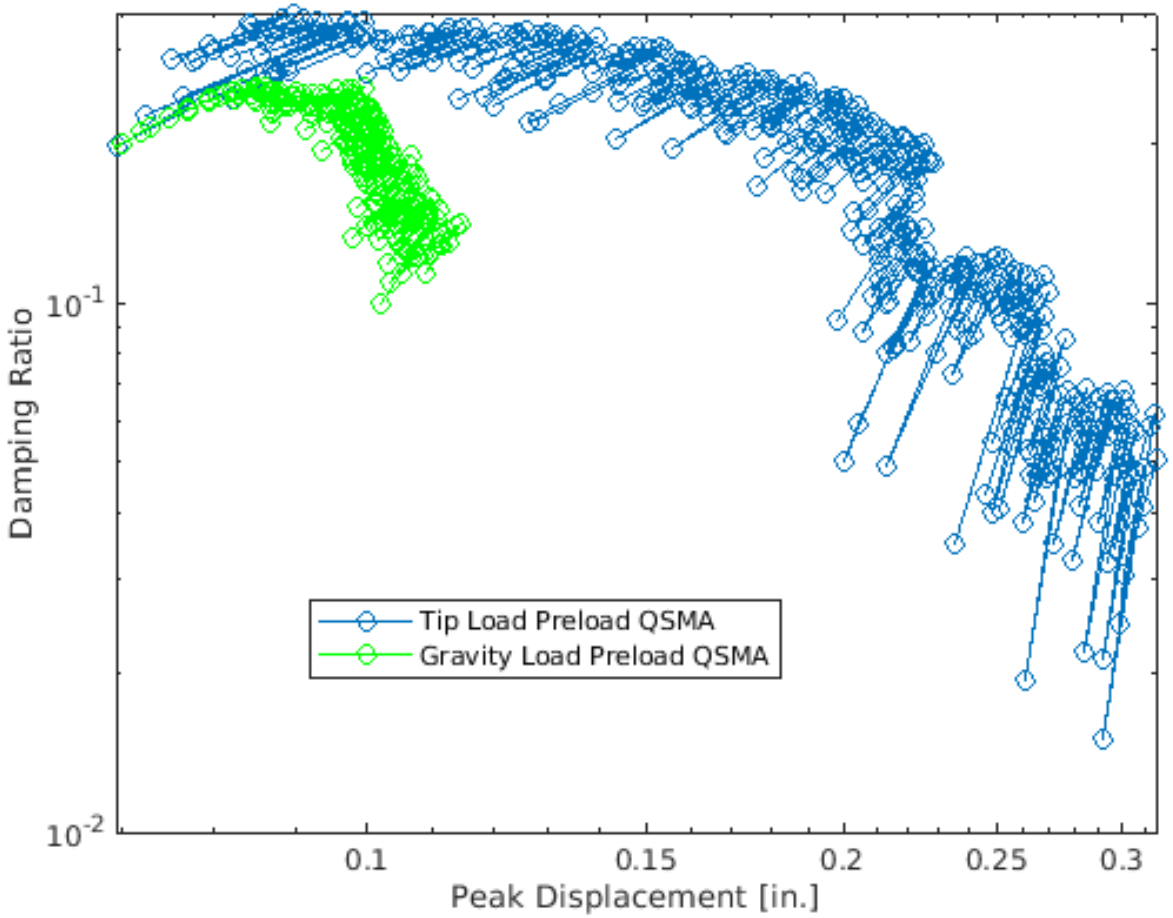
166.1 Hz



Tip Load

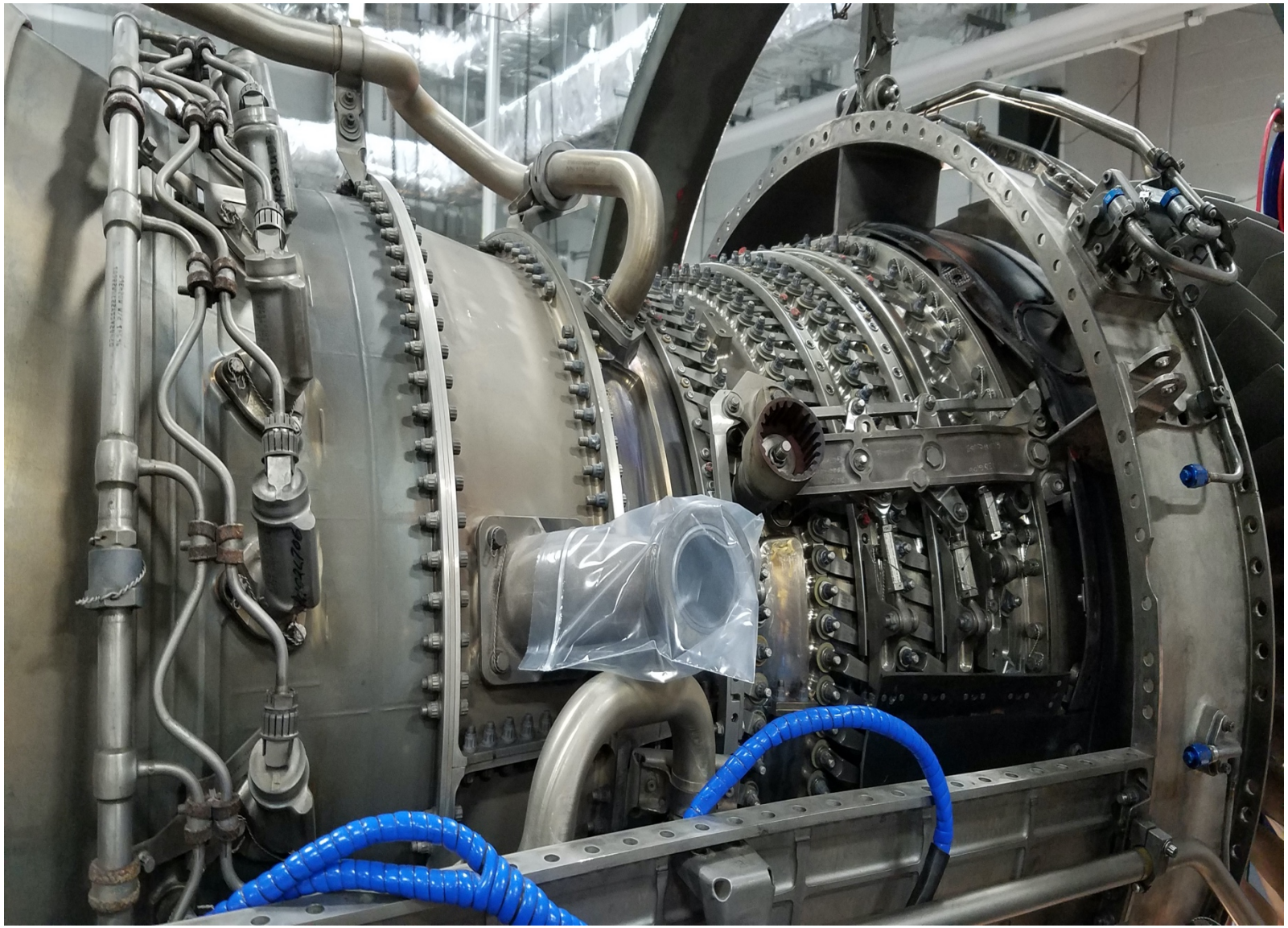
Gravity Load Vs. Tip Load QSMA

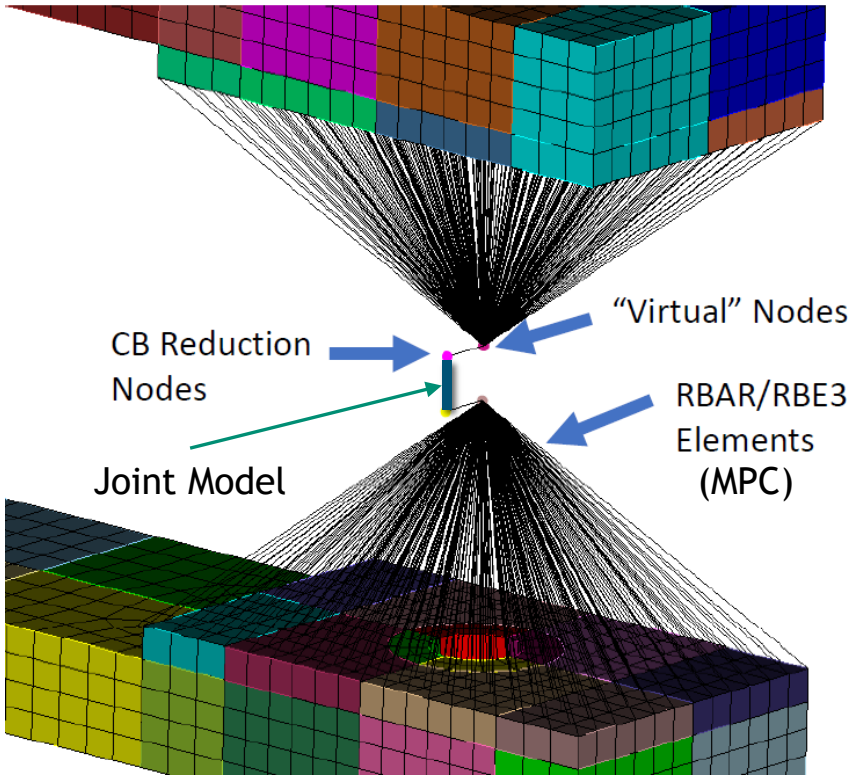




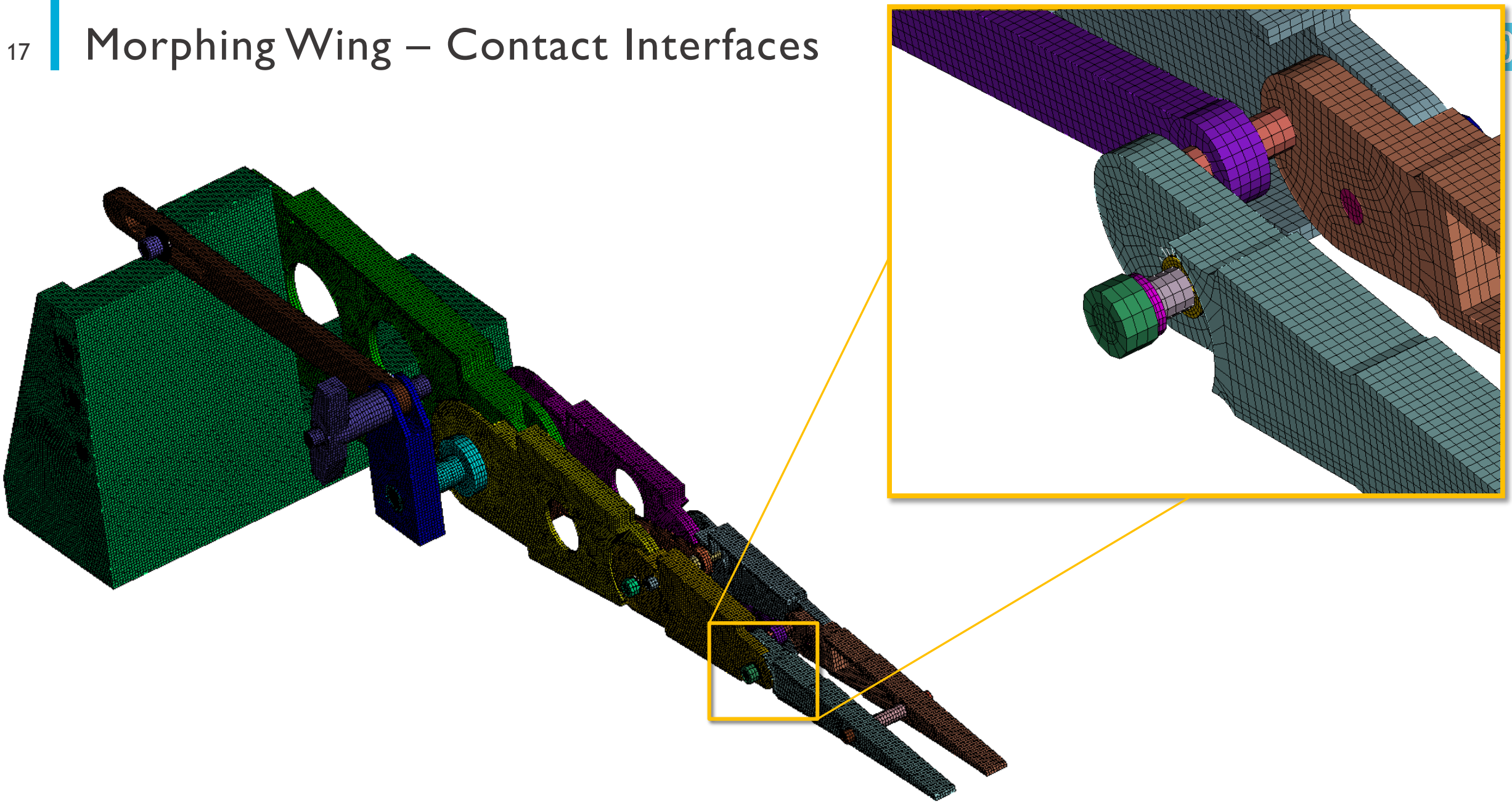
Interface Reduction using Multi-Point-Constraints

Modeling through Whole Joint Models





Morphing Wing – Contact Interfaces

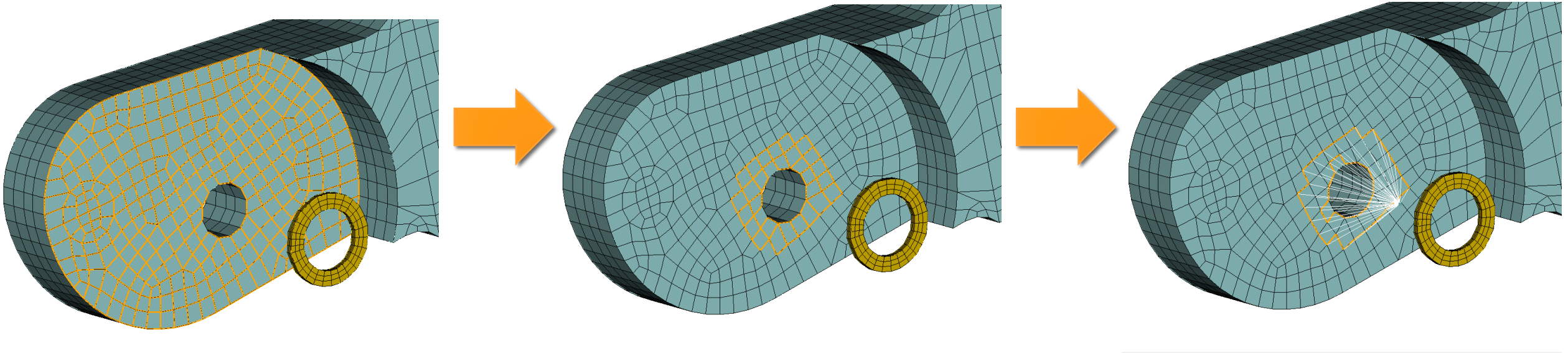


Morphing Wing – Spidering Process

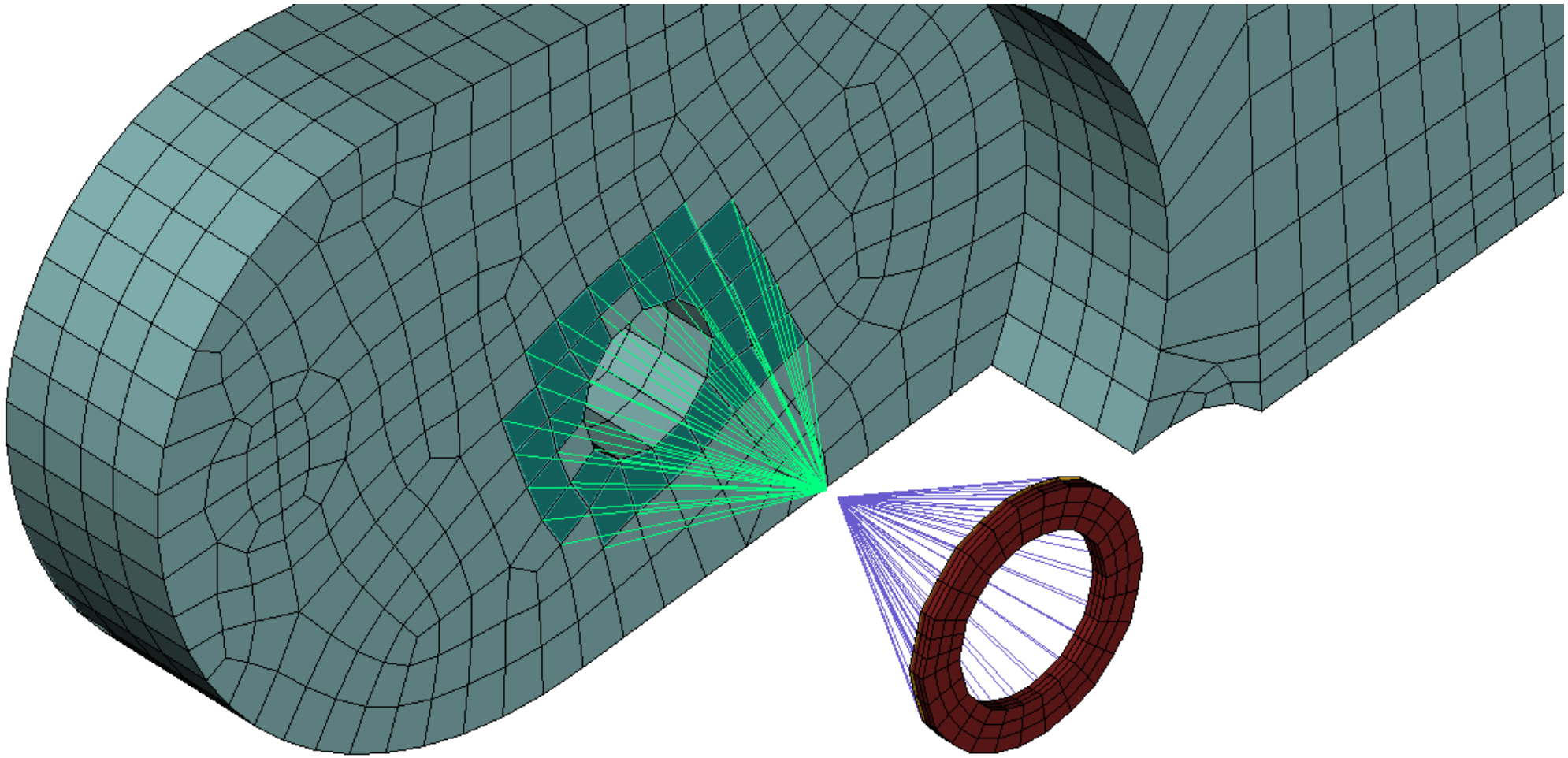
Original surface assigned for contact

Contact surface output from preload analysis

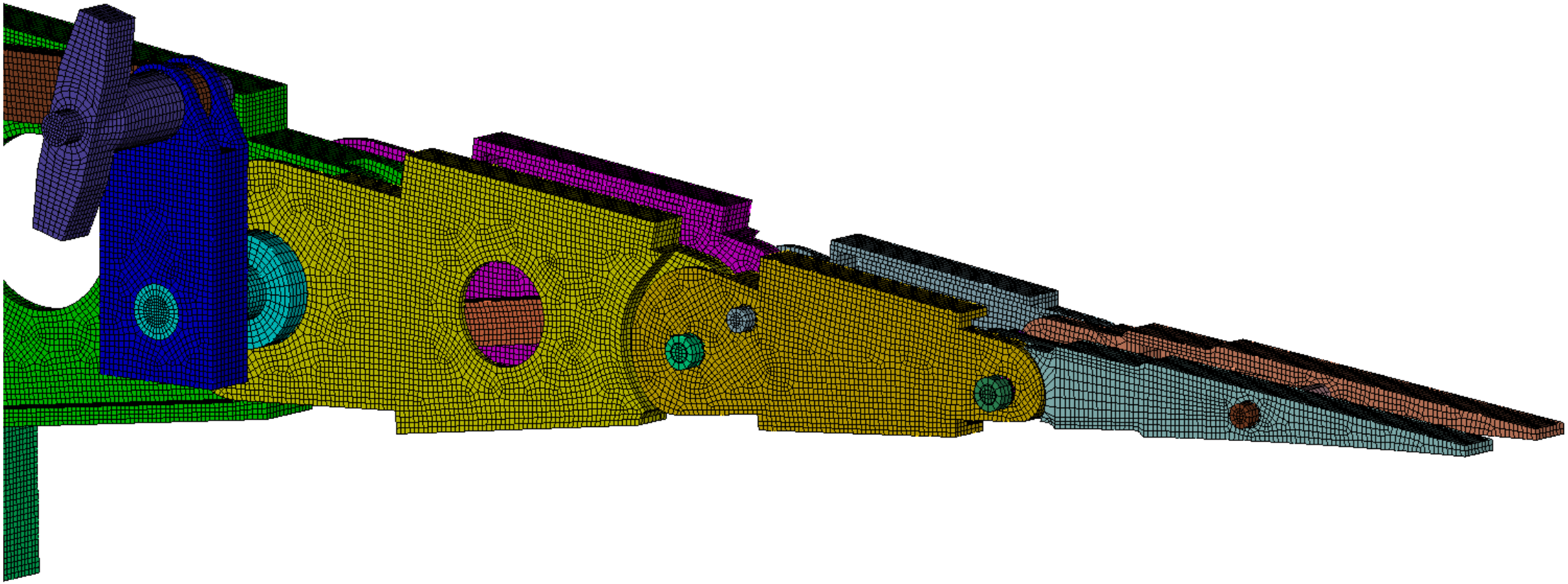
Spider created using nodes from preload contact surface



Morphing Wing – Spidering Process

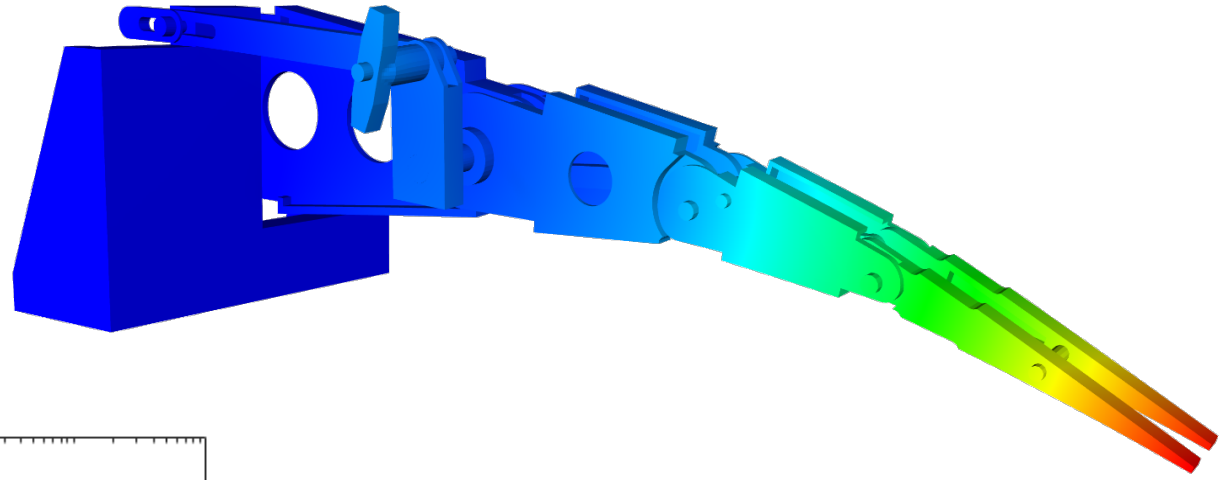


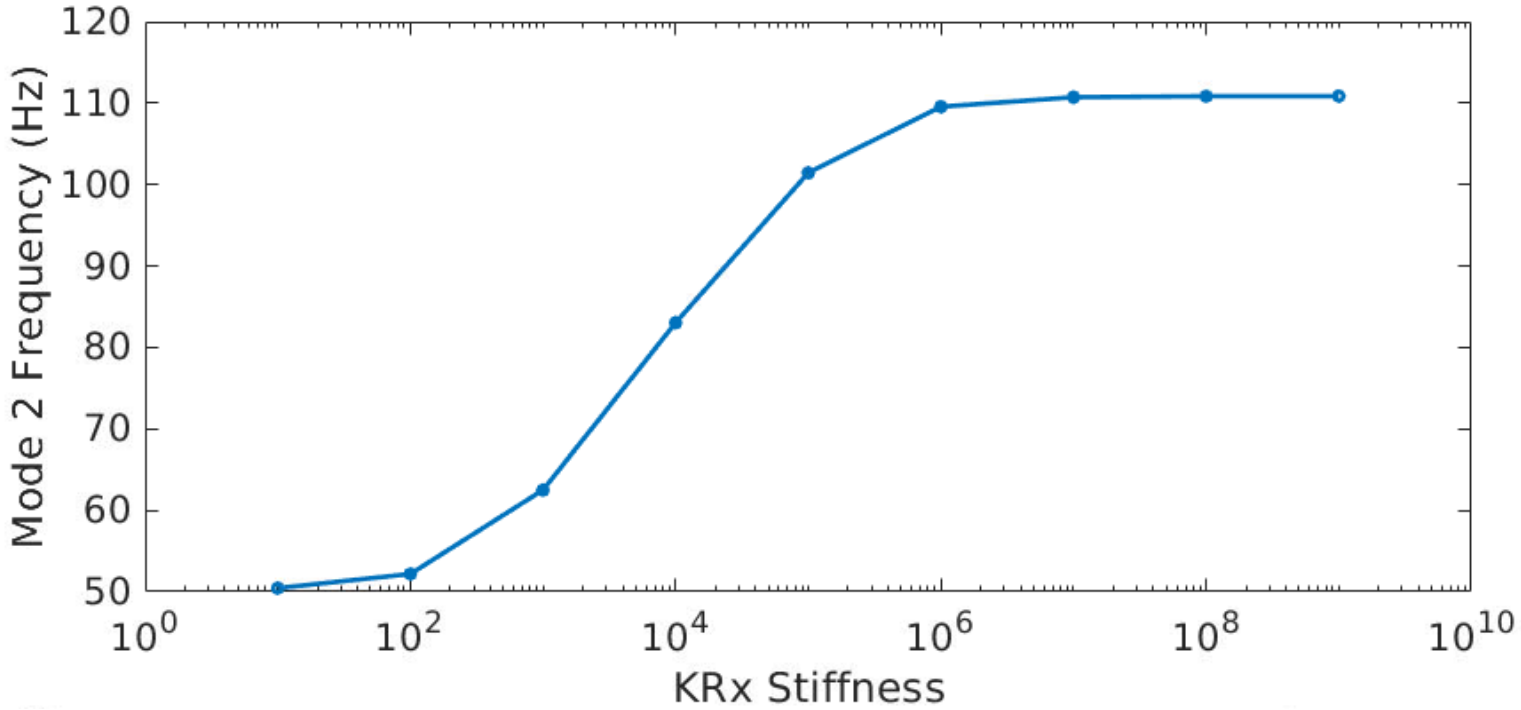
Morphing Wing – Full Model With Multi-Point Constraints Assigned



Rotational Stiffness Sensitivity Study

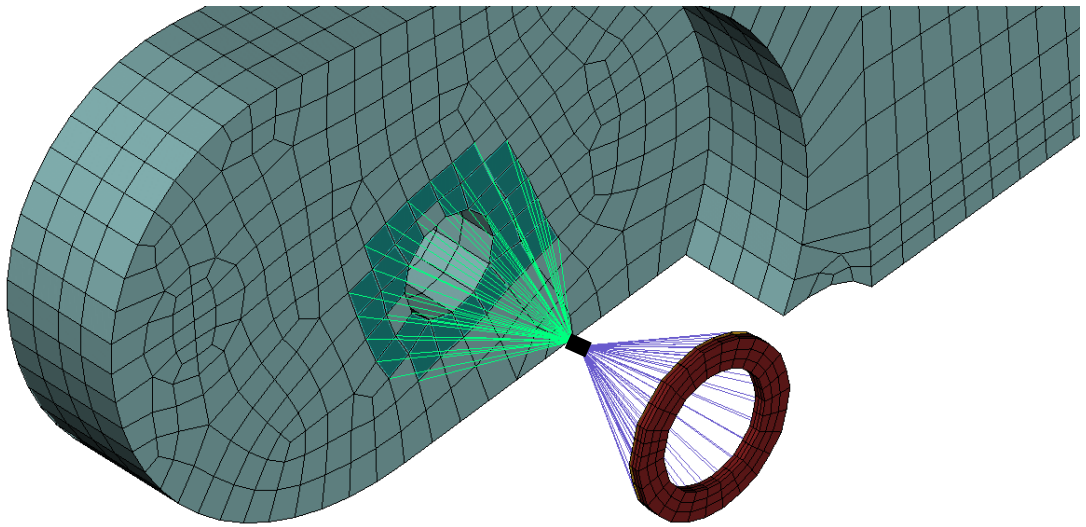
- Adjust rotational stiffness of the structure to see effect on the natural frequency of the 2nd Mode





Future Work

- Calibrate Reduced Order Model to match the linear natural frequencies about the preloaded state
- Apply nonlinear hysteretic elements and update to match the full order quasi-static frequency and damping curves
- Add hyper elastic compliant skin around the rib for a more realistic model
- Gauge additional reduction techniques on this industrial model



Joint model

Concluding Remarks

- Applied the QSMA framework on an industrial scale structure
  - Utilized two methods for preload (test vs. representative operative condition)
  - Both methods were able to generate quasi-static frequency and damping curves
- Developed a spidered reduced order model that can be updated to match the full order model
- These methods have been typically done on bolted connections vs. the pin/hole frictional connections for this model
- High fidelity nonlinear finite element models are key for future successful virtual testing demonstrations. They present several challenges to make advanced response predictions with confidence.

Acknowledgements

This research was conducted at the 2020 Nonlinear Mechanics and Dynamics Research Institute hosted by Sandia National Laboratories and the University of New Mexico.

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