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FSI & Flutter Analysis of a Solar Powered HALE UAV

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CAL POLY POMONA

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Mechanical & Aerospace Engineering
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ANSYS®

Introduction

- Problem Statement
- Model Set-up
- Free Vibration Analysis
- Forced Vibration Analysis
- Fluid Structure Interaction (FSI)
- Flutter Analysis
- Conclusions
- Future Work

Problem Statement

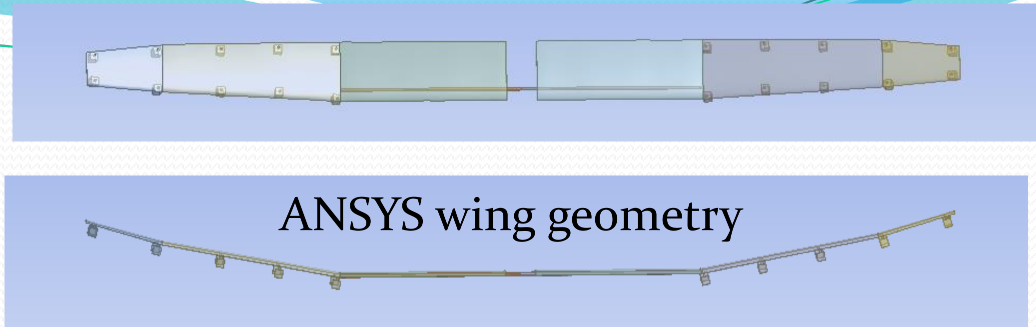
- Achieving a 24/7 HALE (High Altitude Long Endurance) UAV Solar drone
  - Can be used for defense services to gather intel or to perform stealth reconnaissance
  - Can be used for agricultural GPS related studies to enhance water resource management
- Use of embedded actuators in wing of UAV to aid in the flight
  - Solar Panels are installed on the airfoils to power the aircraft using super capacitors to store and power the battery during the day time
  - Vibration based generators (embedded actuators) can be used to power the aircraft by utilizing the vibrational motion of the airfoil, those vibrations can be forced or unforced for e.g. buffeting or using shakers to induce controlled vibrations on the airfoil

Problem Statement

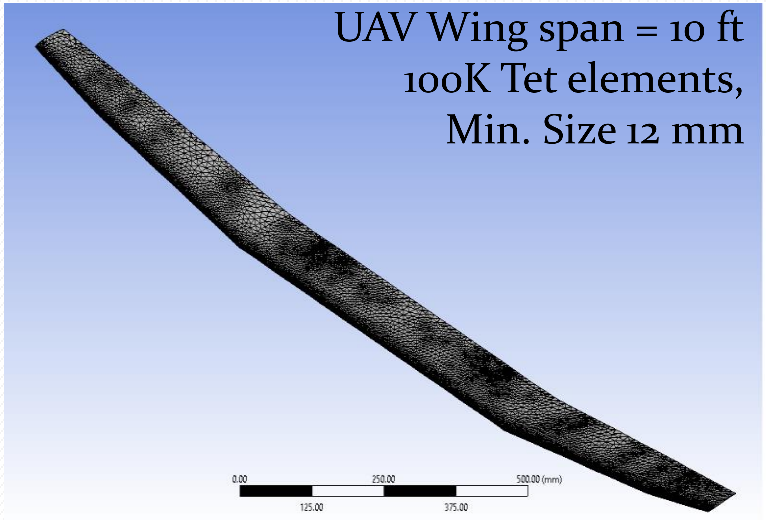
- UAV using solar cells assisted with embedded actuators (vibration generators) enabling 24/7 flight times
- The vibration generators can be positioned inside the wing at various locations to be excited by gusts and control surface pulses to produce structural vibrations to produce power to the aircraft storage devices
- In order to aid the further design of UAV with embedded actuators, a FEM based flutter analysis study has been carried out and is presented in this paper
- This current Mech Aero 2015 presentation refers to the work of
  - Anderson et al., July 2015
  - Singh, et al. 2015
  - Anderson et al. 2016
  - Anderson et al. Sep. 2015

Model Set-up

- Geometry and Mesh



ANSYS wing geometry

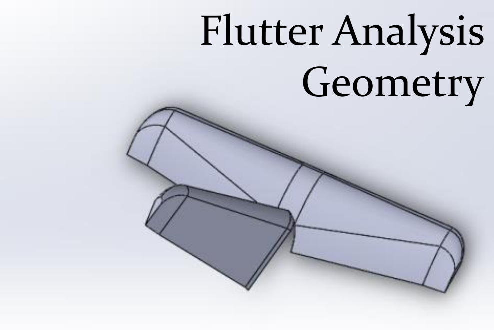


UAV Wing span = 10 ft
100K Tet elements,
Min. Size 12 mm

UAV & undergraduate team

Elevator

Rudder



Flutter Analysis Geometry

Free Vibration Analysis

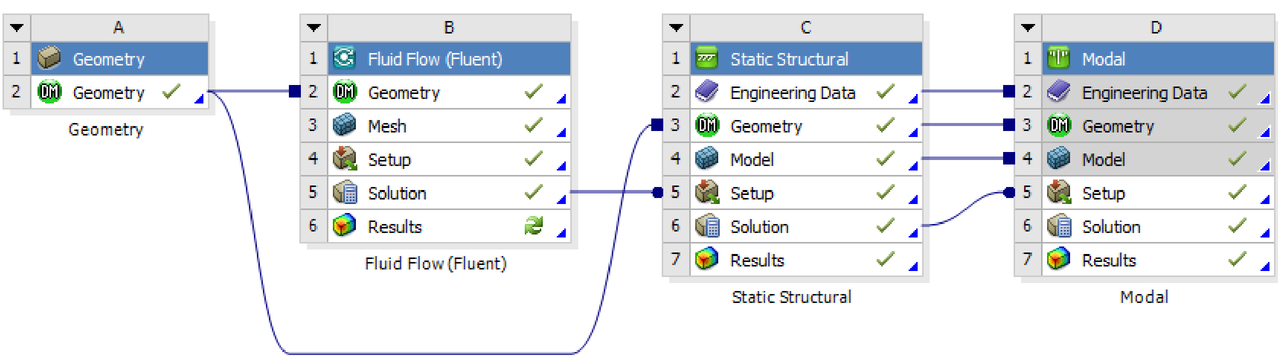
- ANSYS Model Set-up

Properties of Outline Row 4: Mylar

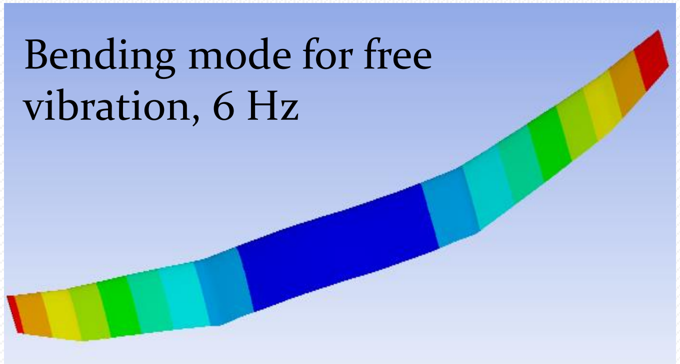
	A	B	C	D	E
1	Property	Value	Unit		
2	Density	1.39	g cm^-3		
3	Isotropic Elasticity				
4	Derive from	Young's Modulus...			
5	Young's Modulus	2800	MPa		
6	Poisson's Ratio	0.37			
7	Bulk Modulus	3.5897E+09	Pa		
8	Shear Modulus	1.0219E+09	Pa		

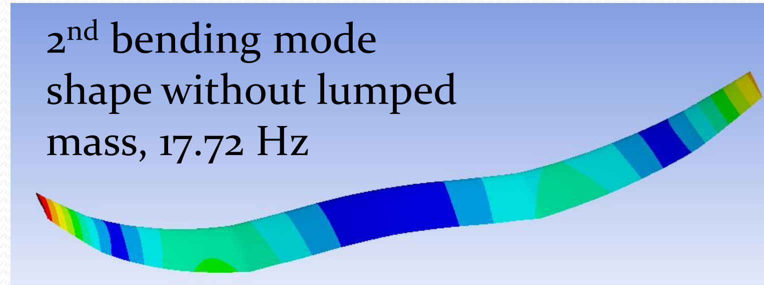
Table 1 Elastic properties for Mylar

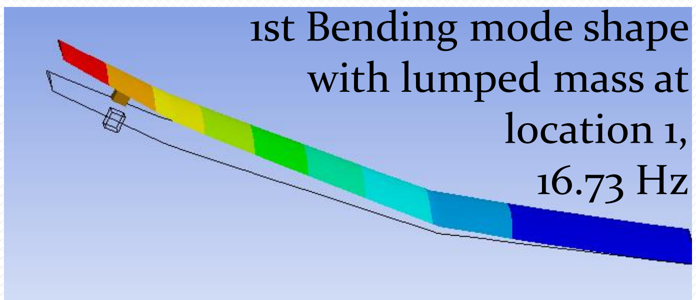
Property	Value
Density	1.39 g/cm^3
Young's Modulus	2800 MPa
Poisson's Ratio	0.37
Bulk Modulus	3.5897×10^9 Pa
Shear Modulus	1.0219×10^9 Pa

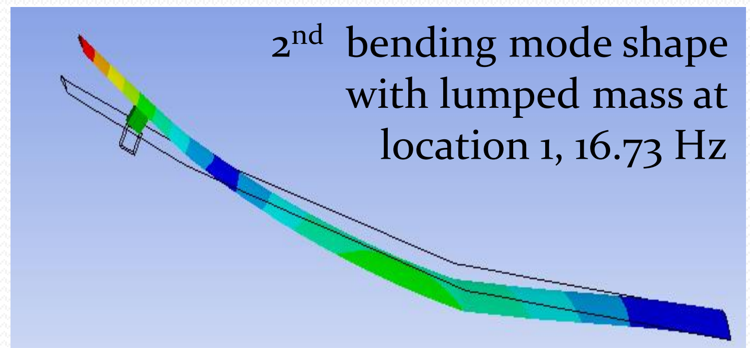


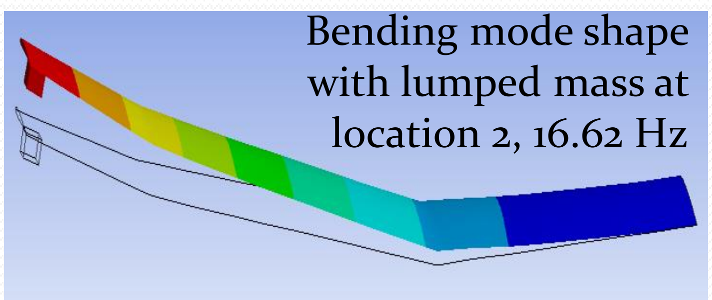
Free Vibration Analysis

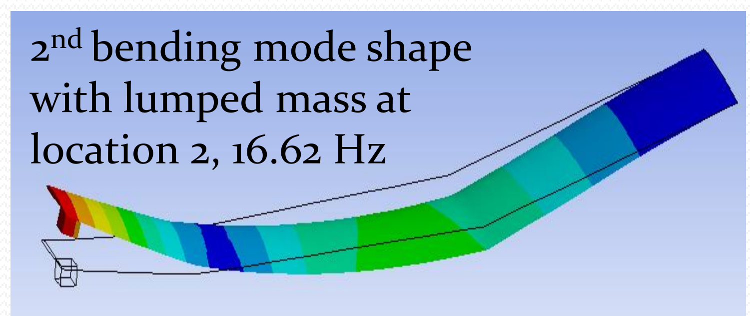




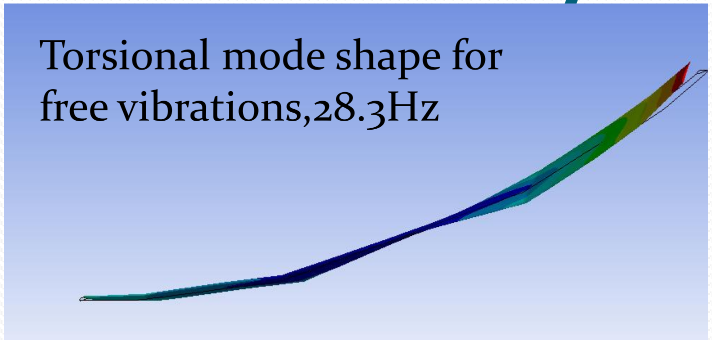


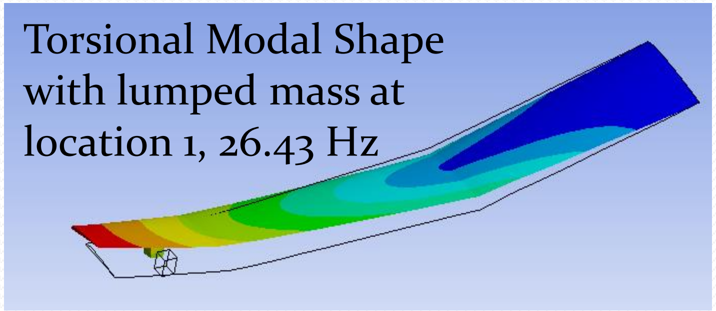


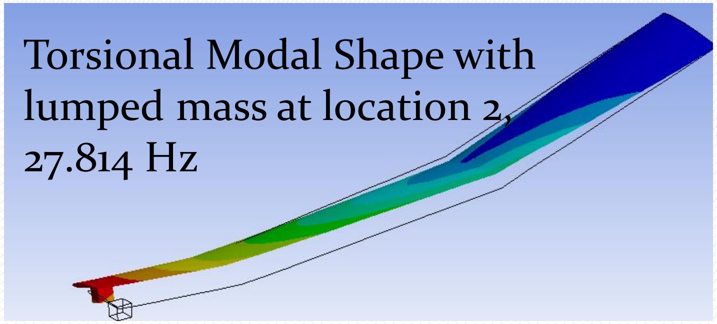




Free Vibration Analysis

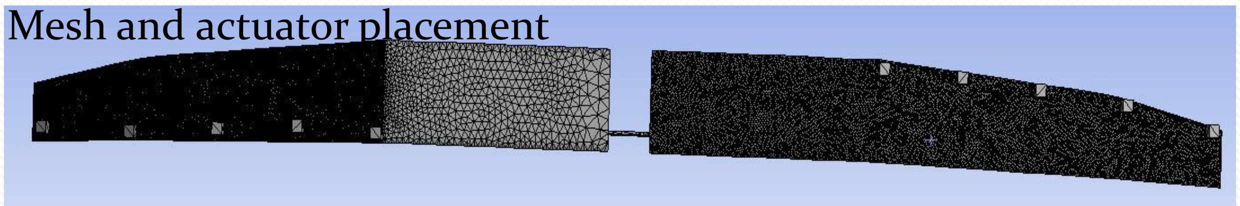


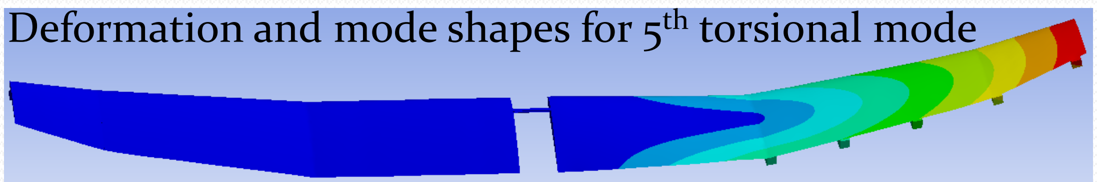




Forced Vibration Analysis

- Configuration scenario I for actuators


Mesh and actuator placement


Deformation and mode shapes for 5th torsional mode

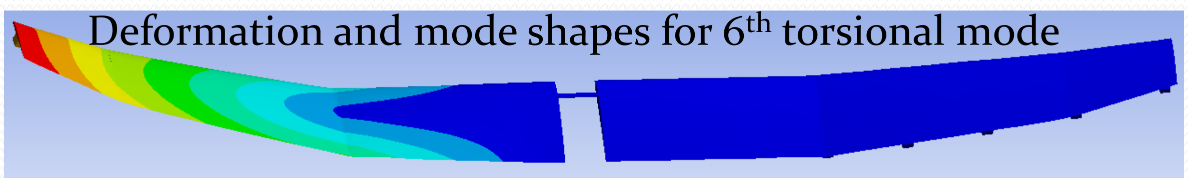

Deformation and mode shapes for 6th torsional mode

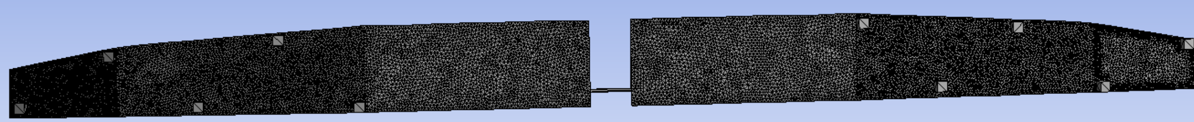
Table 1 Asymmetric excitation first case study

Mode	Frequency (Hz)	Max. Deflection (mm)
1	11.81	62.853
2	11.822	62.896
3	58.045	78.066
4	58.161	78.289
5	93.707	71.617
6	95.121	72.751
7	149.18	85.073
8	149.6	86.696
9	233.59	108.38
10	239.9	109.27

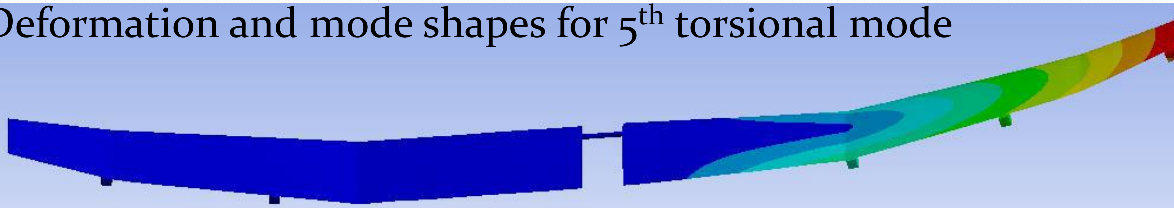
Forced Vibration Analysis

- Configuration scenario II for actuators

Mesh and actuator placement



Deformation and mode shapes for 5th torsional mode



Deformation and mode shapes for 6th torsional mode

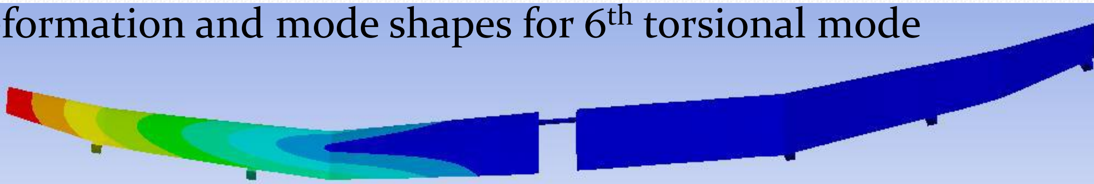


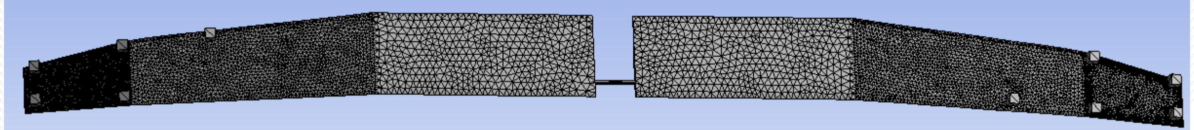
Table 2 Asymmetric excitation second case study

Mode	Frequency (Hz)	Max. Deflection (mm)
1	11.756	37.328
2	11.762	37.333
3	57.834	46.537
4	57.84	46.274
5	94.109	42.878
6	94.419	42.784
7	148.61	52.168
8	148.72	49.879
9	231.09	66.448
10	231.35	72.89

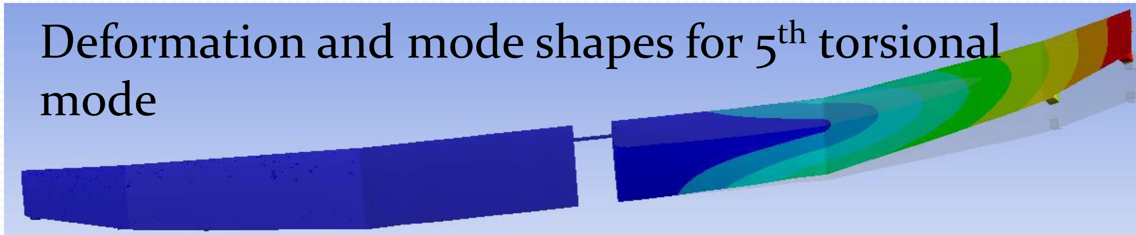
Forced Vibration Analysis

- Configuration scenario III for actuators

Mesh and actuator placement



Deformation and mode shapes for 5th torsional mode



Deformation and mode shapes for 6th torsional mode

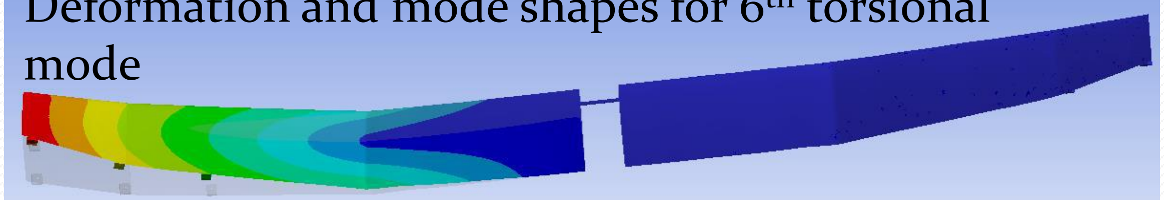


Table 3 Asymmetric excitation second case study

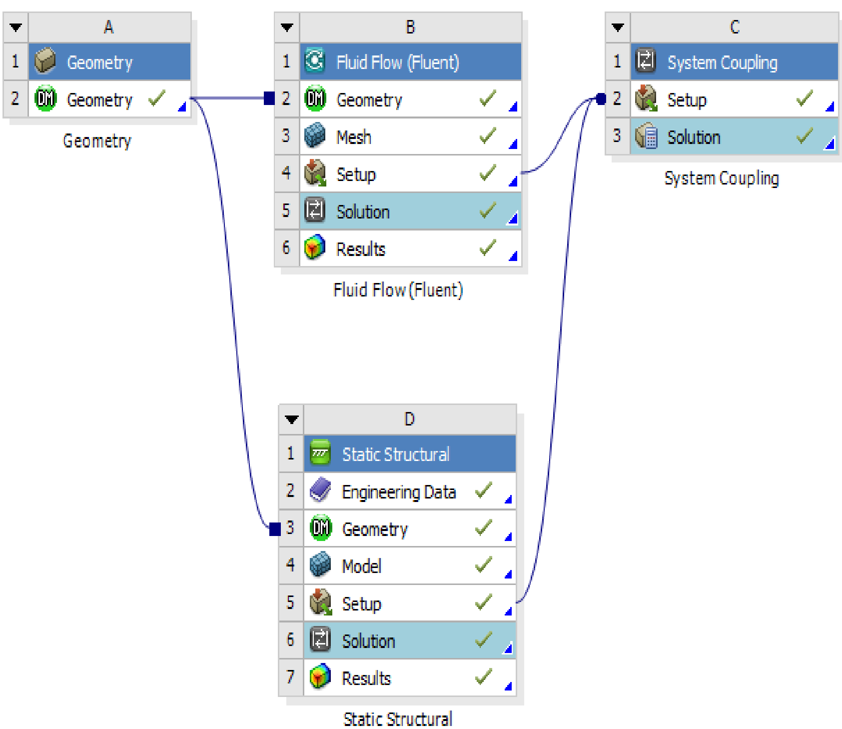
Mode	Frequency (Hz)	Max. Deflection (mm)
1	11.538	61.575
2	11.539	61.567
3	57.395	74.413
4	57.457	74.181
5	92.282	70.407
6	92.514	70.099
7	146.28	80.522
8	146.64	79.700
9	222.67	115.63
10	227.11	121.51

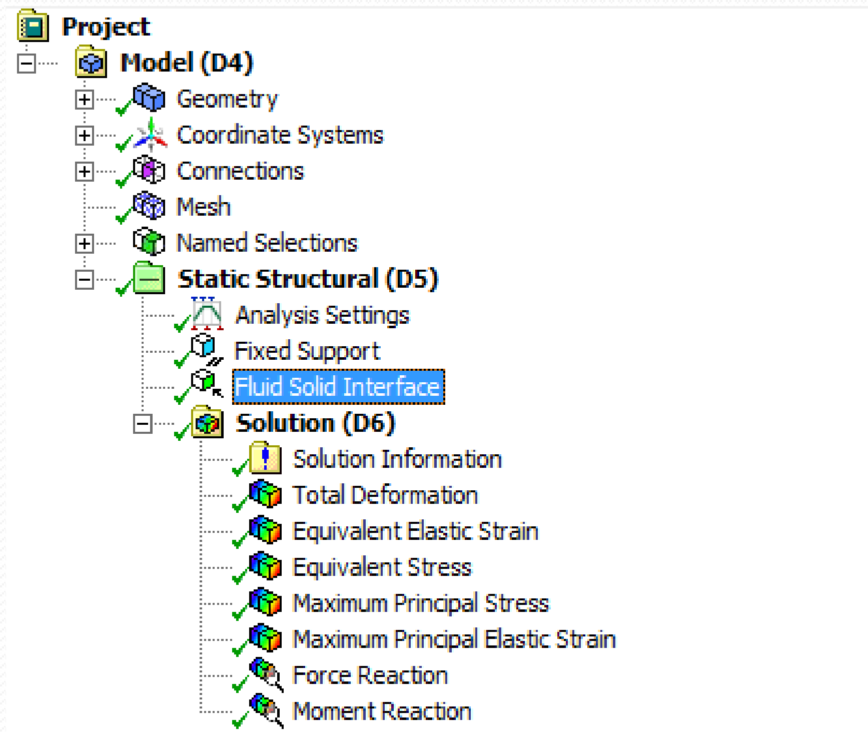
Forced Vibration Analysis

- The results from the embedded actuator forced vibration study indicate that for the first asymmetric loading case in which five actuators each having 5 N force (generators) were located on the leading edge of the left wing and five generators were placed on the trailing edge of the right wing of the airfoil, the first, second and third modal frequencies are 11.81 Hz, 11.822 Hz, and 58.045 Hz corresponding to maximum deflections of 62.853 mm, 62.896 mm, and 78.066 mm, respectively
- For the second asymmetric loading case whereby five actuators were staggered spatially on the left wing and five generators were staggered spatially on right wing of the airfoil, the first, second and third modal frequencies are 11.756 Hz, 11.762 Hz, and 57.834 Hz corresponding to maximum deflections of 37.328 mm, 37.333 mm, and 46.537 mm, respectively
- For the third asymmetric loading case where five actuators were staggered arranged spatially concentrated near the outboard region on the left wing and five generators were arranged spatially concentrated in the vicinity of the outboard area of the right wing of the airfoil, the first three modal frequencies are 11.538 Hz, 11.539 Hz, and 57.395 Hz corresponding to maximum deflections of 61.575 mm, 61.567 mm and 74.413 mm, respectively
- Hence, it is clear that the architectural layout and placement of the embedded actuators has a profound effect on the vibrational characteristics of the UAV airfoil

Fluid Structure Interaction (FSI) Analysis

- ANSYS 2-way FSI Set-up

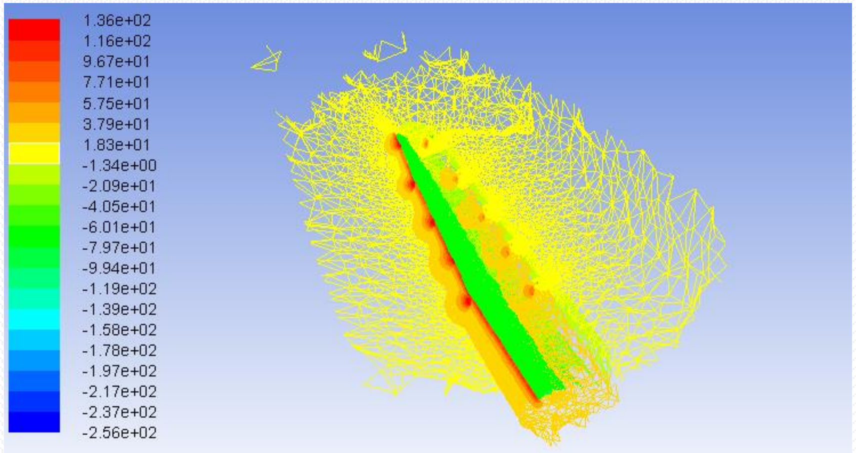


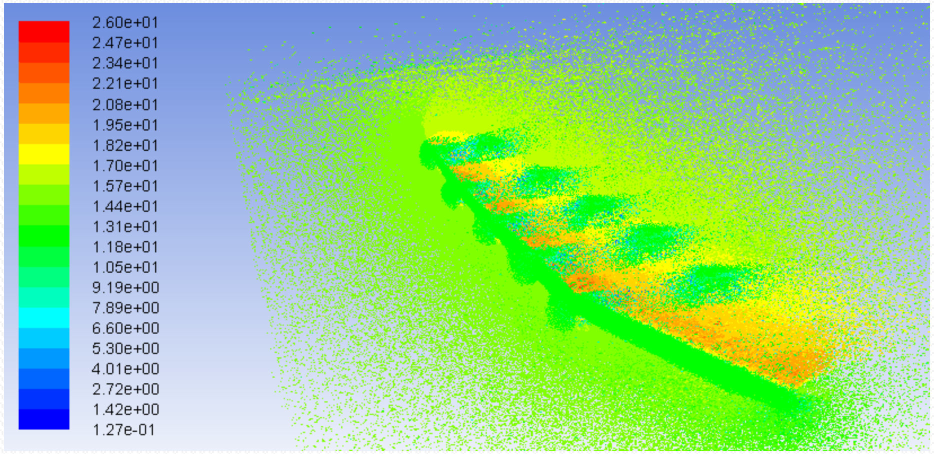


FSI Analysis

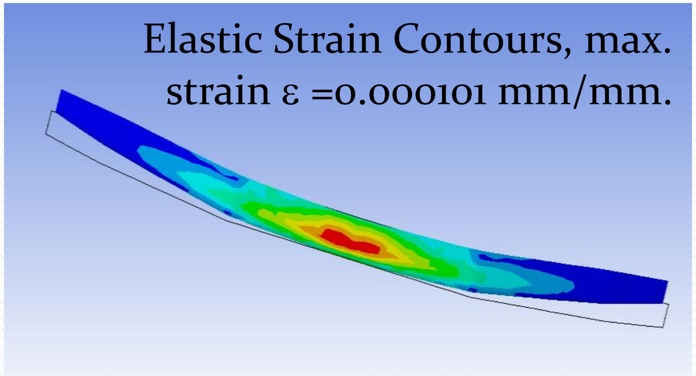
Pressure Field

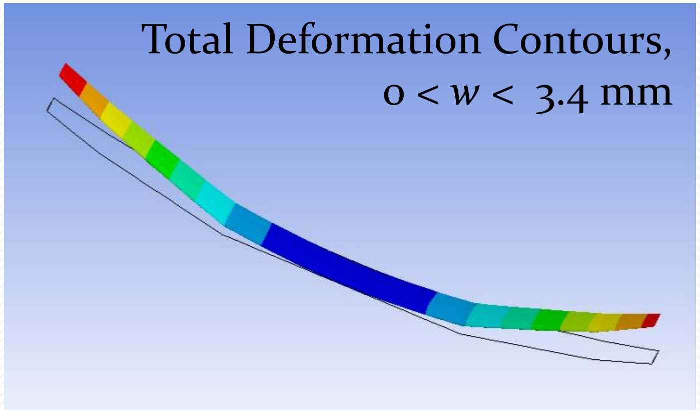
Velocity Field

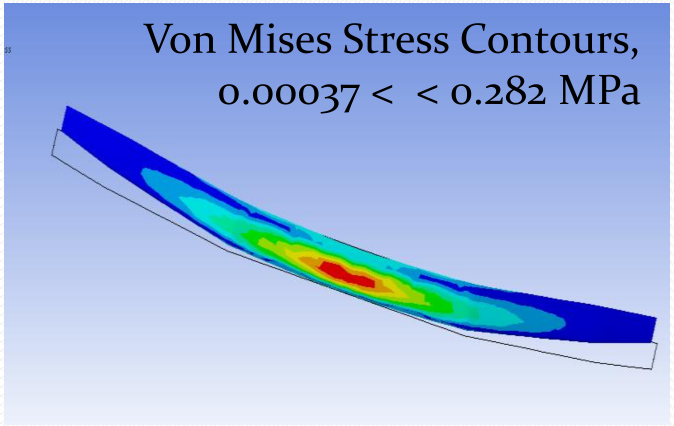


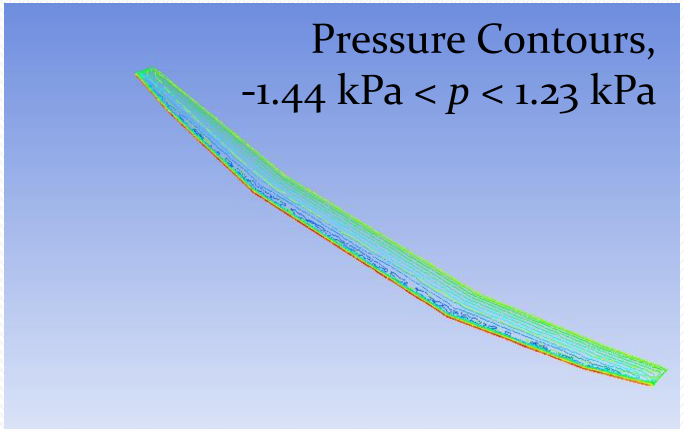


FSI Analysis

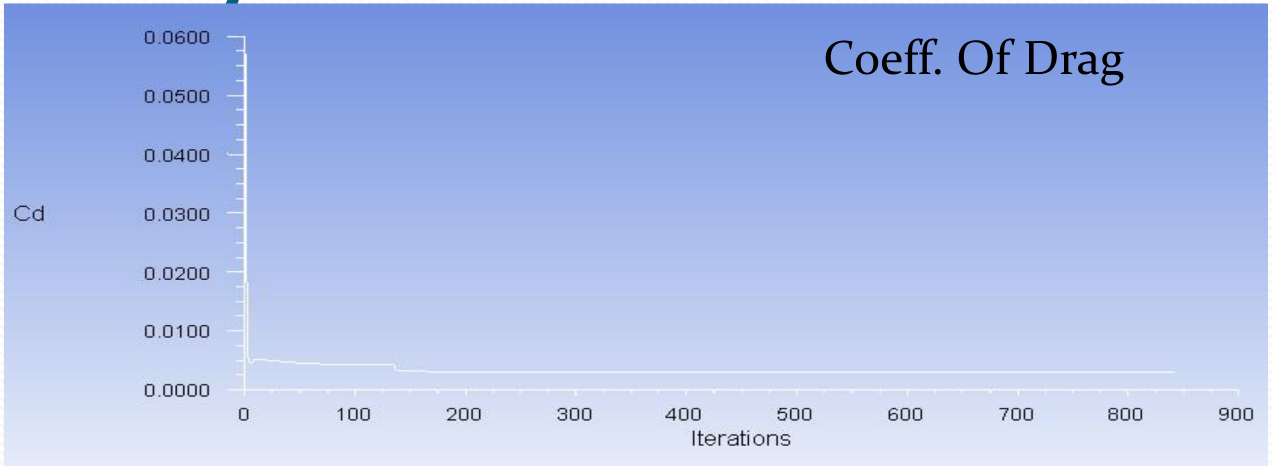


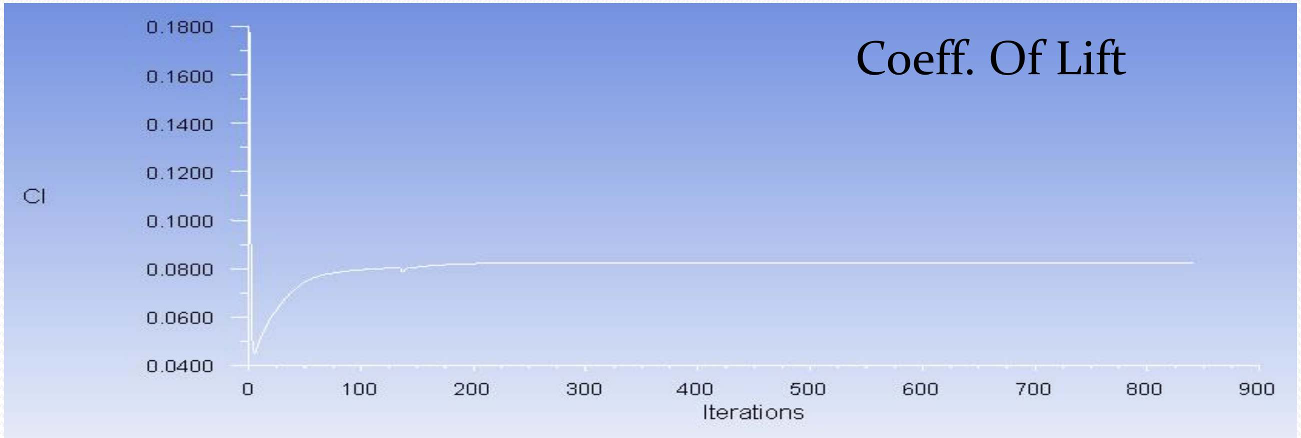






FSI Analysis





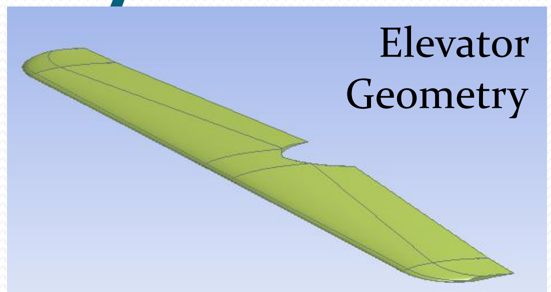
FSI Analysis

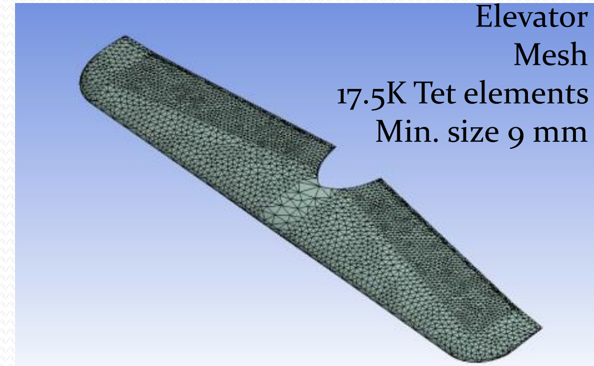
Table 4 Aerodynamic force results from FSI analysis

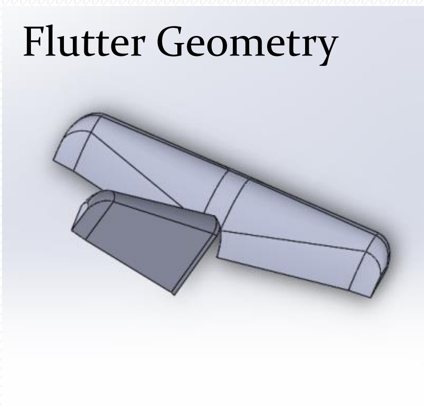
Parameter	Vale
Lift coeff.	0.077
Drag coeff.	0.0052
Lift /Drag coeff.	14.9
Drag force	11.74 N
Lift force	47.83 N
Center of press.	(-6.8, -10.09,1.669)
Press. moment	-50.96 in +x-dir.
Max. press. coeff.	0.98

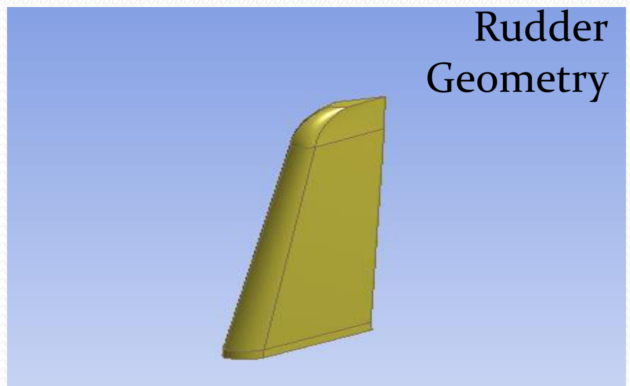
Flutter Analysis

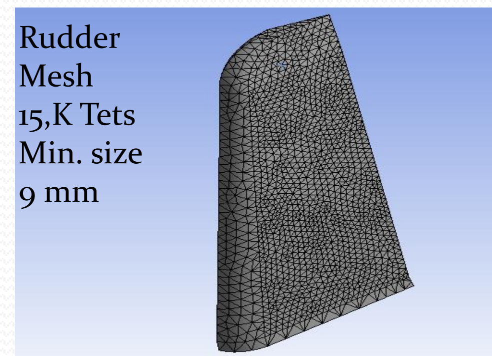
- Geometry/Mesh



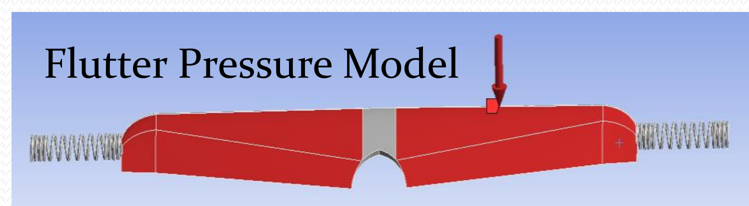








- The pressure profile is transferred from the CFD analysis of the elevator with angle of attack maintained at α=5°



Flutter Analysis

- Flutter Theory

Wing Bending-Torsion Flutter Predictions

This form calculates the frequency solution for a 2 DoF bending/torsion model of a straight, high aspect ratio wing.The geometry of the wing along with its natural frequency and mass components is required so that airflow forced frequency may be computed. The solution may be purely real, indicating a stable oscillating solutionor a complex root indicating an unstable solution.

Input Parameters
2 DoF Model Parameters

Wing Area(S)
0.045

Wing Mass(m)
0.486

Wing Polar Inertia (I_α)
7.05E-5

Distance to CG (x_{cg})
0.001

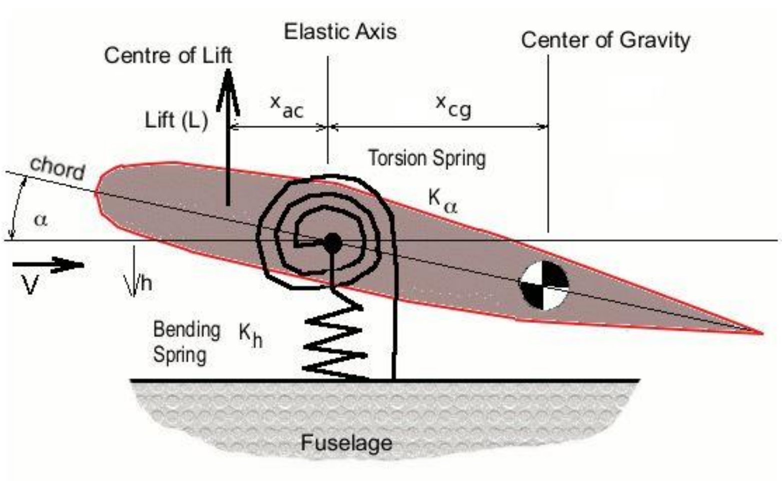
Distance to AC (x_{ac})
0.035

Bending Natural Frequency (Hz)
8

Torsion Natural Frequency (Hz)
60

Maximum Airspeed (V)
90

Air Density (ρ)
1.225



analyse reset

cf. https://sites.google.com/site/aerodynamics4students/table-of-contents/aeroelasticity

Flutter Analysis

- Flutter Theory

Bending :

$$-L - K_h h = m\ddot{h} + S_\alpha \ddot{\alpha}$$

Torsion :

$$LX_{AC} - K_\alpha \alpha = I_\alpha \ddot{\alpha} + S_\alpha \ddot{h}$$

where

$$I_\alpha = \int r^2 dm \equiv \text{wing polar inertia}$$

$$S_\alpha = \int r dm \approx X_{cg} m \equiv \text{coupling inertia}$$

Simple Harmonic Vibration :

$$h = h_o e^{i\omega t}, \alpha = \alpha_o e^{i\omega t}$$

Stiffness :

$$K_h = \omega_h^2 m, K_\alpha = \omega_\alpha^2 I_\alpha$$

Linear Aerodynamic Forcing Functions :

$$L = \frac{dC_L}{d\alpha} \alpha \frac{1}{2} \rho V^2 S = \frac{dC_L}{d\alpha} \alpha q S = \frac{dC_L}{d\alpha} \alpha_o q S e^{i\omega t}$$

assumes torsion effects dominate, and neglects any second order acoustic or compressibility effects

System of Equations :

$$-\frac{dC_L}{d\alpha} \alpha_o q S - K_h h_o = -m\omega^2 h_o - S_\alpha \omega^2 \alpha_o$$

$$\frac{dC_L}{d\alpha} \alpha_o q S X_{ac} - K_\alpha \alpha_o = -I_\alpha \omega^2 \alpha_o - S_\alpha \omega^2 h_o$$

Flutter Matrix Form :

$$\begin{bmatrix} m\omega^2 - K_h & S_\alpha \omega^2 - \frac{dC_L}{d\alpha} q S \\ S_\alpha \omega^2 & I_\alpha \omega^2 - K_\alpha + \frac{dC_L}{d\alpha} q S X_{ac} \end{bmatrix} \begin{Bmatrix} h_o \\ \alpha_0 \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix}$$

Flutter Analysis

- Flutter Theory (continued)

Flutter Determinant :

$$\begin{vmatrix} m\omega^2 - K_h & S_\alpha\omega^2 - \frac{dC_L}{d\alpha}qS \\ S_\alpha\omega^2 & I_\alpha\omega^2 - K_\alpha + \frac{dC_L}{d\alpha}qSX_{ac} \end{vmatrix} = 0$$

$$\left(m\omega^2 - K_h\right)\left(I_\alpha\omega^2 - K_\alpha + \frac{dC_L}{d\alpha}qSX_{ac}\right) - \left(S_\alpha\omega^2 - \frac{dC_L}{d\alpha}qS\right)\left(S_\alpha\omega^2\right) = 0$$

gives solutions for ω which define the motion, these solutions mainly depend on the speed of the vehicle and hence are controlled by the value of the dynamic pressure q

Flutter Analysis

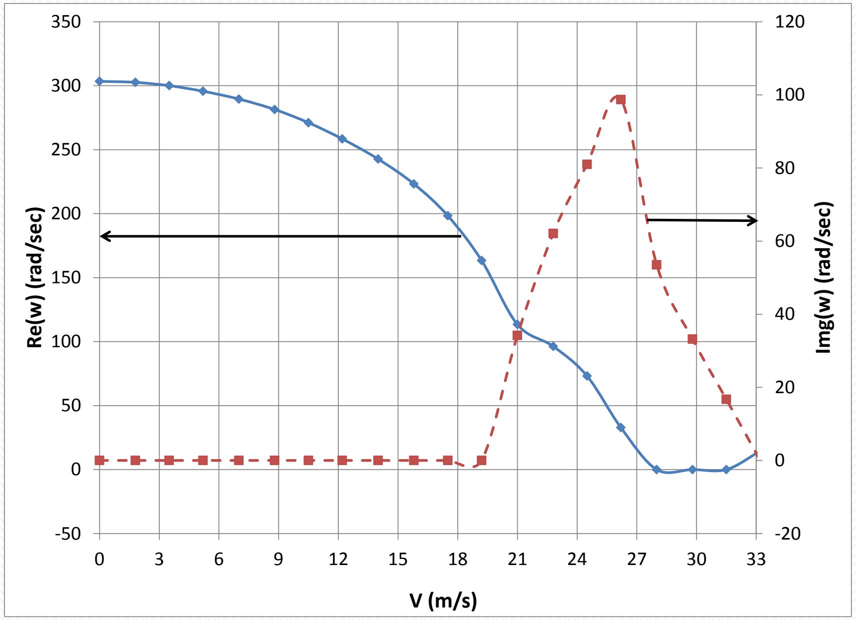
- Analytic Flutter Analysis Wing Bending-Torsional Predictions software of The University of Sydney http://aerodynamics.aeromech.usyd.edu.au/
  - Eccentricity, E = 0.001 m
  - Mass of the Elevator, m = 0.149 kg
  - Density of Air, ρ = 1.225 kg/m^3
  - Polar Moment of Inertia, J = 3.6E-5 kg/m^2
  - Axis Locations, A = -0.2
  - Semi chord of the Elevator, B = 0.06 m
  - Aerodynamic center, $B/2$ = 0.03
  - Elastic axis from the leading edge, $[(1+A)\ B]$ = 0.048 m
  - Center of gravity (C.G.) from the leading edge, $[(1+E)B]$ = 0.066
  - Distance between aerodynamic center and elastic axis, X_{ac} = 0.012 m
  - Distance between elastic axis and C.G., X_{cg} = 0.012 m
  - Reduced frequency k = 0.2 (Fung (1969))

Flutter Analysis

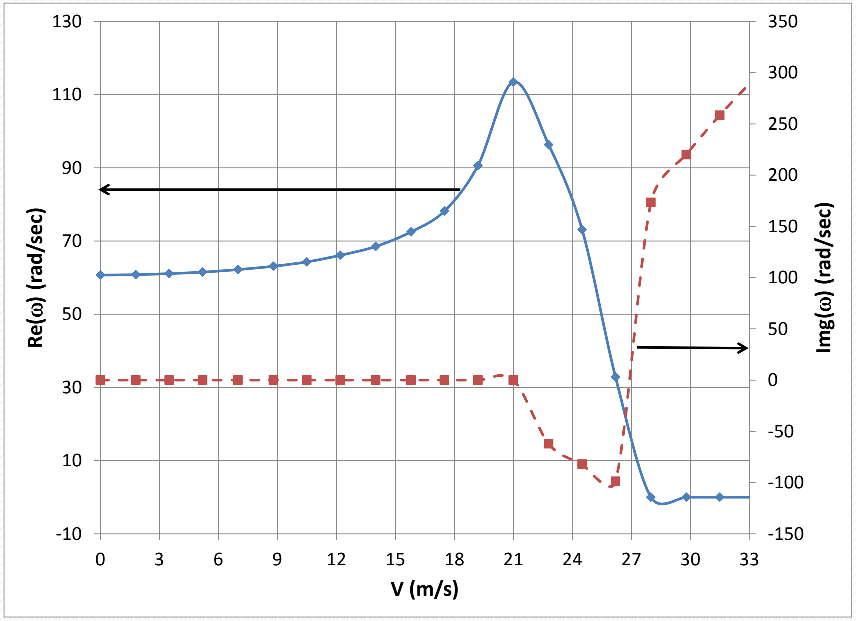
- Analytical Flutter Results for Elevator
- Flutter Determinant, $X = \frac{\omega_\alpha}{\omega} = 1.32$ (Bislinghoff et al. (1962))
- Critical flutter speed, $U_{cr} = \frac{b\omega_\alpha}{k\sqrt{X}} = 49.47$ m/s (Fung (1969))
- Divergence speed, V = 32.7 m/sec
- Eigenvalues for 1st and 2nd modes are plotted on next chart

Flutter Analysis

Frequency for vs. flutter speed 1st Mode

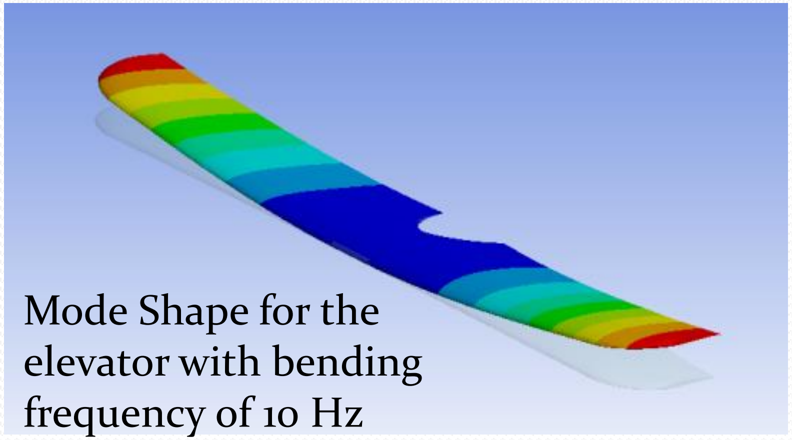


Frequency for vs. flutter speed 2nd Mode

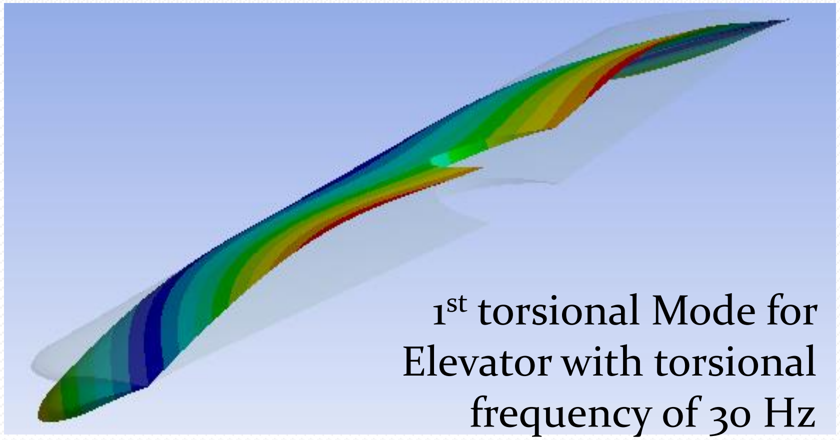


Flutter Analysis

- ANSYS Results



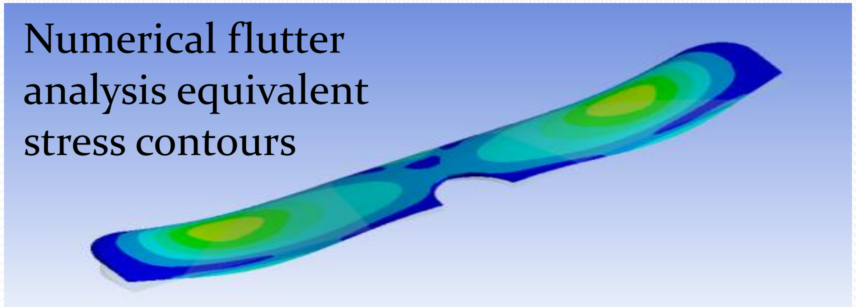
Mode Shape for the elevator with bending frequency of 10 Hz

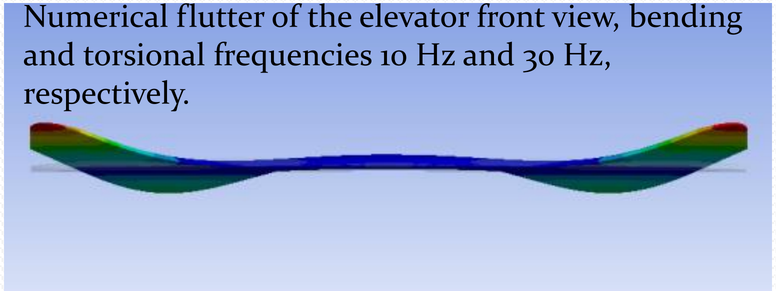


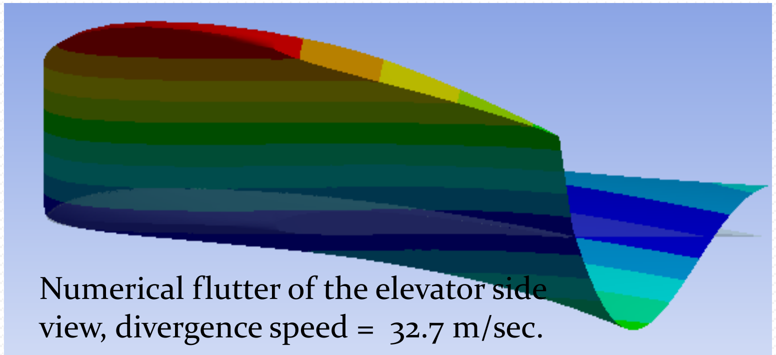
1st torsional Mode for Elevator with torsional frequency of 30 Hz

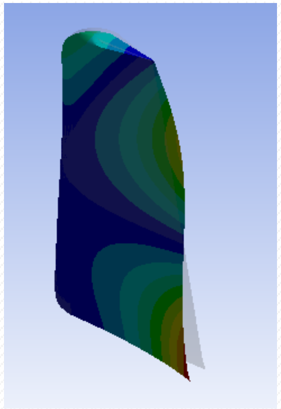
Flutter Analysis

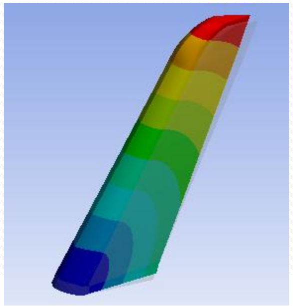
- ANSYS Results


Numerical flutter analysis equivalent stress contours


Numerical flutter of the elevator front view, bending and torsional frequencies 10 Hz and 30 Hz, respectively.


Numerical flutter of the elevator side view, divergence speed = 32.7 m/sec.


Numerical torsional mode for the rudder bending and torsional modes for the rudder were 60 Hz and 110 Hz, respectively


Numerical bending frequency of the rudder,
critical speed = 75 m/sec,
divergence speed = 65 m/sec

Flutter Analysis Results Summary

- Analytical flutter analysis is performed to verify the FEA results. The analytic flutter analysis gives the divergence speed to be 32.7 m/sec
- The numerical flutter analysis of the rudder shows the bending and torsional modes for the rudder were 60 Hz and 110 Hz, respectively
- The numerical flutter analysis of the rudder shows the maximum critical speed to be 75 m/sec and the divergence speed to be 65 m/sec

Conclusions

- Free vibrations performed on UAV airfiol to obtain natural frequencies
- Forced vibrations on UAV airfoil using differing configurations of embedded actuators in order to help define a control algorithm
- FSI analysis performed of UAV airfoil in order to bound the interaction of the UAV with its environmental surroundings
- Flutter Analysis perfromed on UAV elevator and rudder to understand possible failure modes
  - Analytic and numeric flutter analysis is in quantitative agreement

Future Work

- Fly UAV with instrumentation (accelerometers and strain gages) and correlate FEA model for Vibration and Flutter
- Finalize design of embedded actuators (MEMS, Vortex shedders, etc.)

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- Bisplinghoff, Raymond, and Holt Ashley. 1962. *Principles of Aeroelasticity*. New York: Wiley

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- "Flutter study of a high-altitude UAV using ANSYS" by Sukwinder Singh, Kevin R. Anderson, Steven K. Dobbs, Donald Edberg submitted to International Journal of Structural Mechanics and Finite Elements, *in review* September, 2015.

Conference Proceedings

- "Numerical and Theoretical Aeroelastic Flutter Analysis of a HALE UAV" by Kevin R. Anderson*, Sukwinder Singh*, Steve Dobbs**, and Don Edberg**, *Mechanical Engineering, **Aerospace Engineering, Cal Poly Pomona, accepted for presentation at 16th Intl. Conf. on Mechanical and Aerospace Engr. (ICMAE) Feb. 13, 2016, Convenient Grand Hotel, Bangkok, Thailand
- "Fluid-Structure Interaction (FSI) & Flutter Analysis of a Solar Powered UAV" by Dr. Prof. Kevin R. Anderson, Mr. Nouh Anies, Ms. Shilpa Ravichandra, Mr. Sukhwinder Singh Sandhu, Mechanical Engineering, Non-linear FEA/CFD Multiphysics Simulation Lab, Prof. Steve Dobbs, Dr. Prof. Donald Edberg, Aerospace Engineering, Cal Poly Pomona abstract accepted to the 3rd Intl. Mech-Aero Conference, San Francisco, CA, USA, Oct. 2015, Track 3-5 Airship Design and Development – Design.
- Vibration Analysis of a Solar Powered UAV" by Dr. Prof. Kevin R. Anderson, Mr. Nouh Anies, Ms. Shilpa Ravichandra, Mr. Sukhwinder Singh Sandhu, Mechanical Engineering, Non-linear FEA/CFD Multiphysics Simulation Lab, Prof. Steve Dobbs, Dr. Prof. Donald Edberg, Aerospace Engineering, Cal Poly Pomona, The 17th International Conference on Theoretical and Applied Mechanics (ICTAM), Los Angeles, CA, Sep. 28-29, 2015.

Webpages

- https://sites.google.com/site/aerodynamics4students/table-of-contents (last accessed 10/3/15)