Verification of NACA-4197 algorithm for composite rocket fins using scanning Laser Doppler Vibrometry

Project Proposal for ME5304

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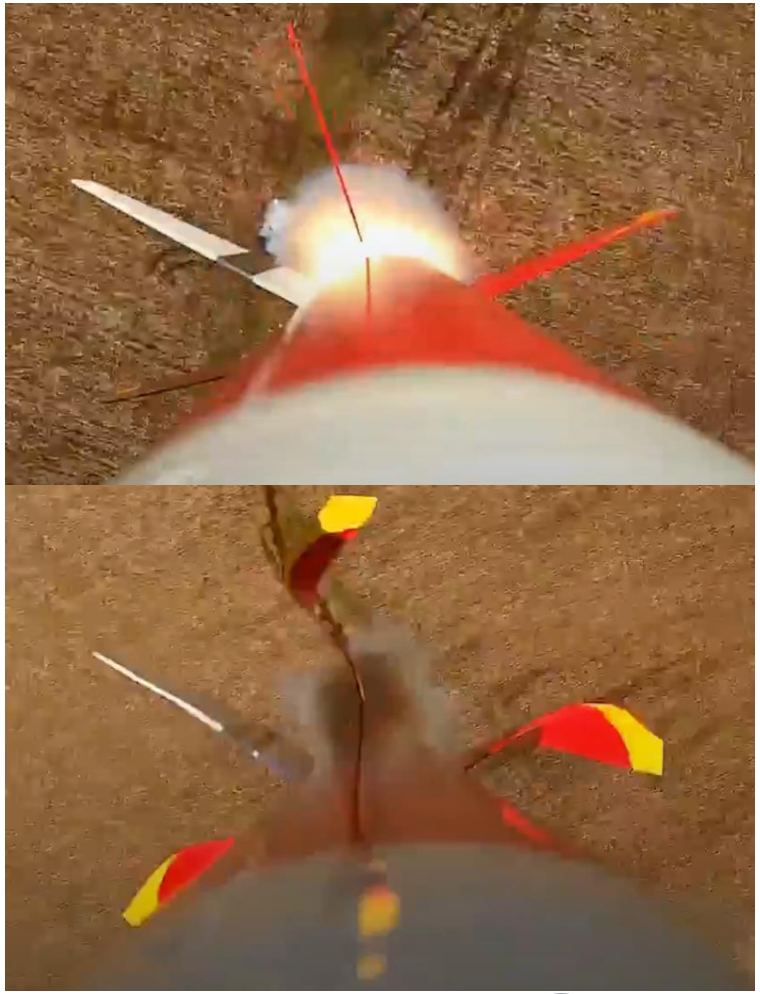
David Strom

3/5/2025

Motivation

- Aeroelastic flutter and aeroelastic divergence are one of the leading causes of fin failure in rocketry
- Strength-to-weight trades favor fiberglass composite fin materials
- Composites are very difficult to analyze with traditional methods



Motivation

- High Power Rocket Club projects overwhelmingly use composite fins
- Handmade composite layups are fundamentally inconsistent in density and strength
- Use SLDV measurements and a high-fidelity model to validate a low-fidelity model in a novel use case

Problem Overview – NACA TN 4197

TECHNICAL NOTE 4197

SUMMARY OF FLUTTER EXPERIENCES AS A GUIDE TO

THE PRELIMINARY DESIGN OF LIFTING

SURFACES ON MISSILES[1]

By Dennis J. Martin

SUMMARY

A limited review is made of some experiences in the flight testing of missiles and of wing flutter investigations that may be of interest in missile design. Several types of flutter which may be of concern in missile studies are briefly described. Crude criteria are presented for two of the most common types of flutter to permit a rapid estimate to be made of the probability of the occurrence of flutter. Many of the details of the flutter picture have been omitted, and only the broader elements have been retained so as to give the designer an overall view of the subject.

WPI

Problem Overview – NACA TN 4197

Flutter Velocity

Shear modulus

$$\left(\frac{V_f}{a}\right)^2 = \frac{G_E}{\frac{39.3A^3}{\left(\frac{t}{c}\right)^3 (A + 2)} \left(\frac{\lambda + 1}{2}\right)\left(\frac{p}{p_0}\right)}$$

Air pressure

Sea level pressure

Speed of sound

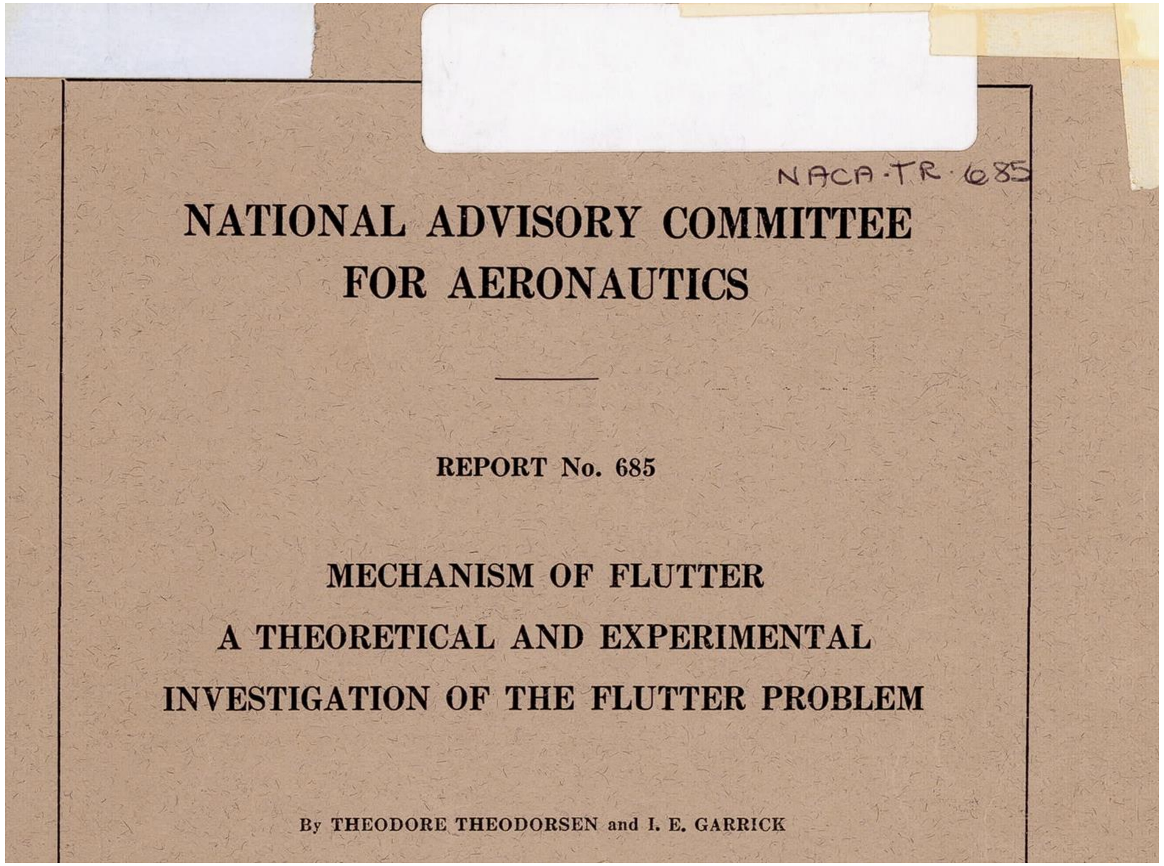
Thickness

Aspect Ratio

Fin taper ratio

Chord Length

Problem Overview – NACA TN 685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NATIONAL ADVISORY COMMITTEE
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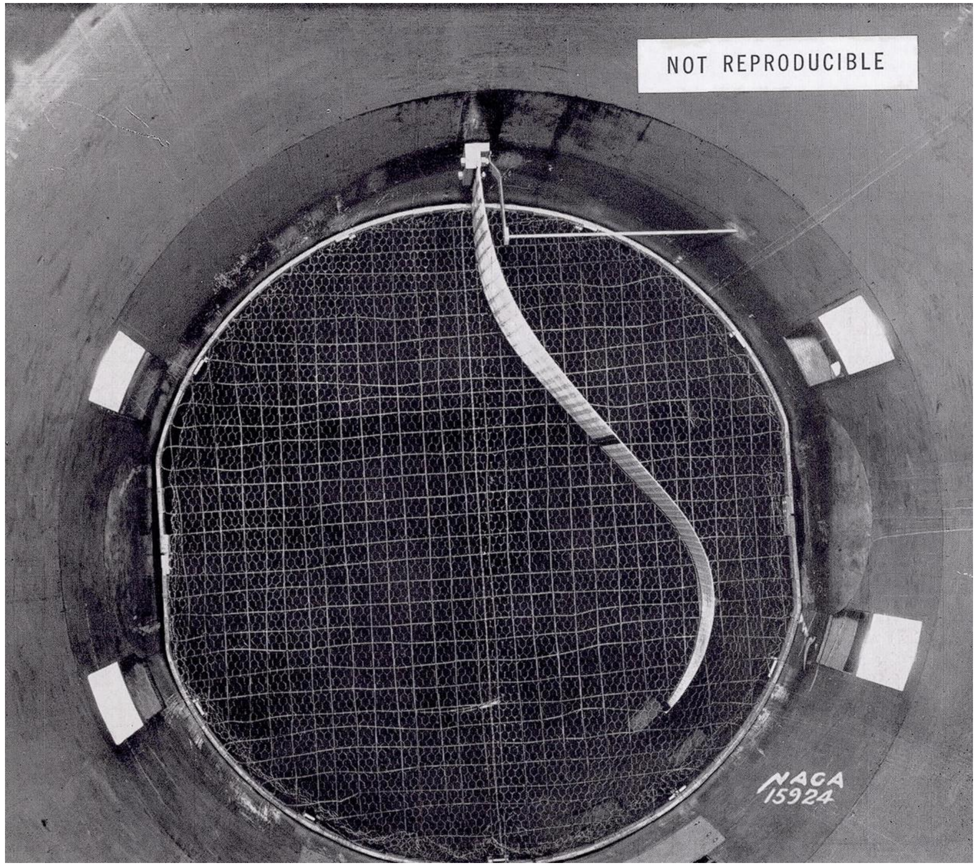
REPORT No. 685

MECHANISM OF FLUTTER

A THEORETICAL AND EXPERIMENTAL
INVESTIGATION OF THE FLUTTER PROBLEM

By THEODORE THEODORSEN and I. E. GARRICK



Problem Overview – NACA TN 685

form convenient for further studies. The paper attempts to facilitate the judgment of flutter problems by a systematic survey of the theoretical effects of the various parameters. A large number of experiments were conducted on cantilever wings, with and without ailerons, in the N. A. C. A. high-speed wind tunnel for the purpose of verifying the theory and to study its adaptability to three-dimensional problems. The experiments included studies

with the theory. In fact, it is shown that there exists a rather remarkable agreement between theoretical and experimental results. A simple method is presented for

WPI

Problem Overview

Flutter frequency.—The flutter frequency is shown in graph I–F. It is seen, for instance, that for small values of ω_h/ω_α, the flutter frequency is around 60 percent of the torsional frequency ω_α; for higher values of the flexural frequency, the flutter frequency approaches or exceeds the torsional. This graph is primarily of interest in connection with experimental flutter research.

$$\frac{\omega_h}{\omega_\alpha}$$

First bending frequency

First torsional frequency

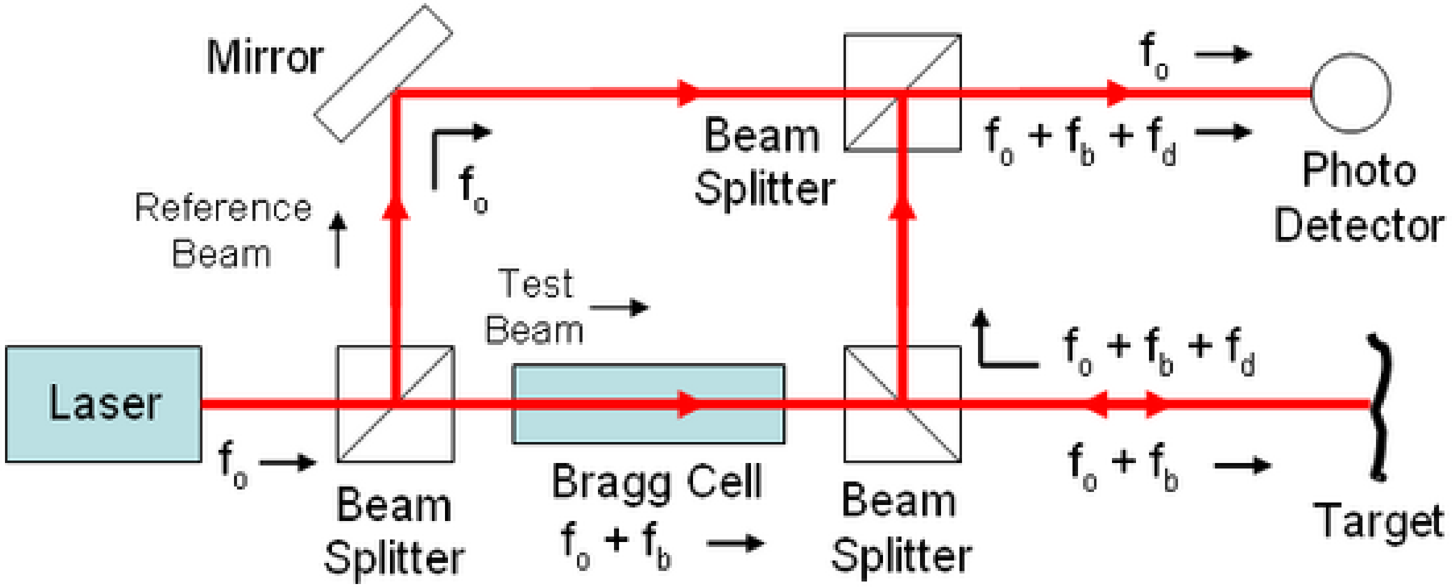
Methodology & Background for SLDV

$$f_{beat} = f_B - \Delta f(t)$$

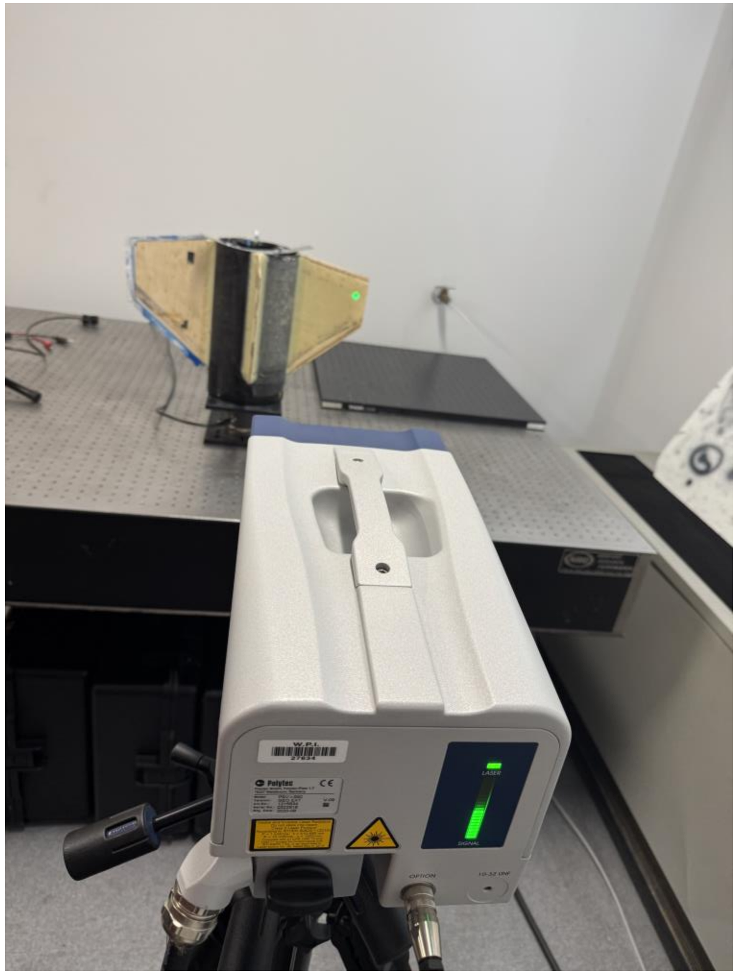
$$\Delta f(t) = 2\frac{v(t)}{\lambda}$$

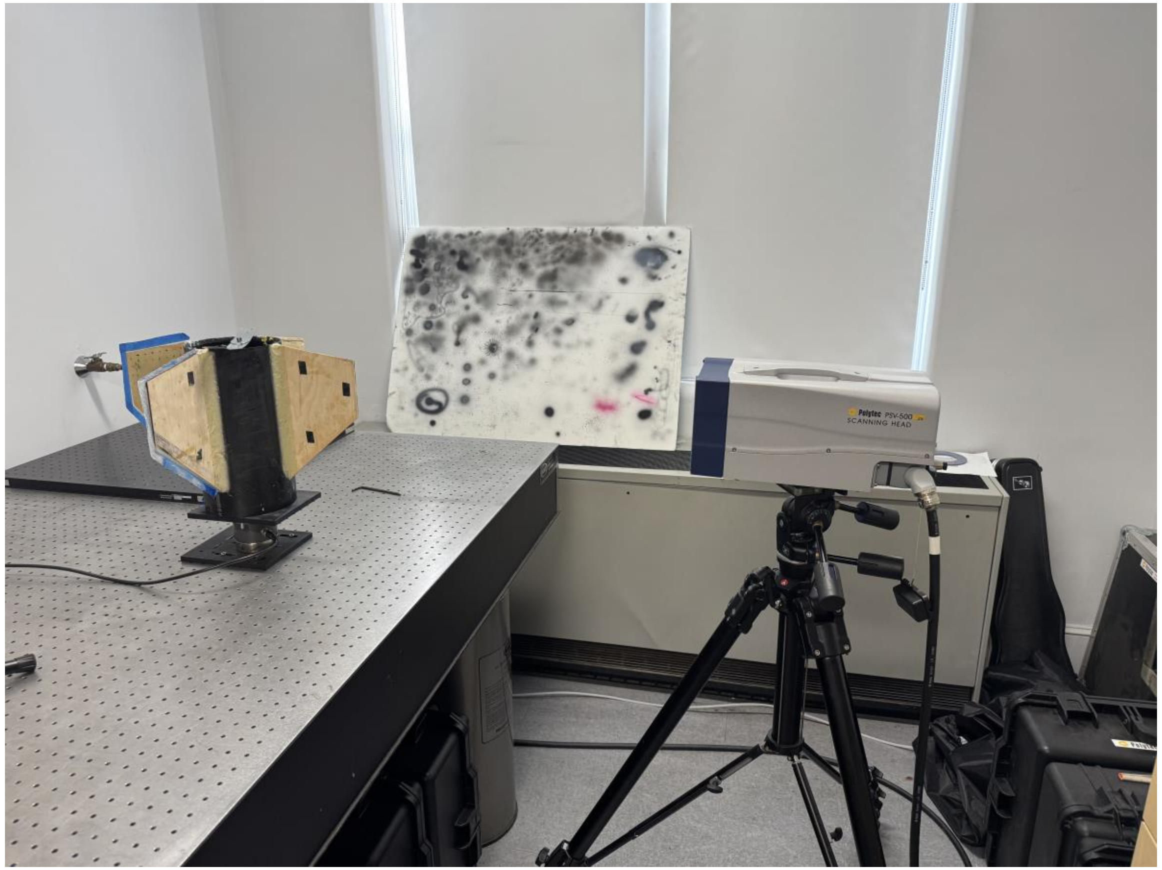
$$v(t) = \lambda\frac{\Delta f(t)}{2}$$

$$x(t) = \int v(\tau)d\tau$$

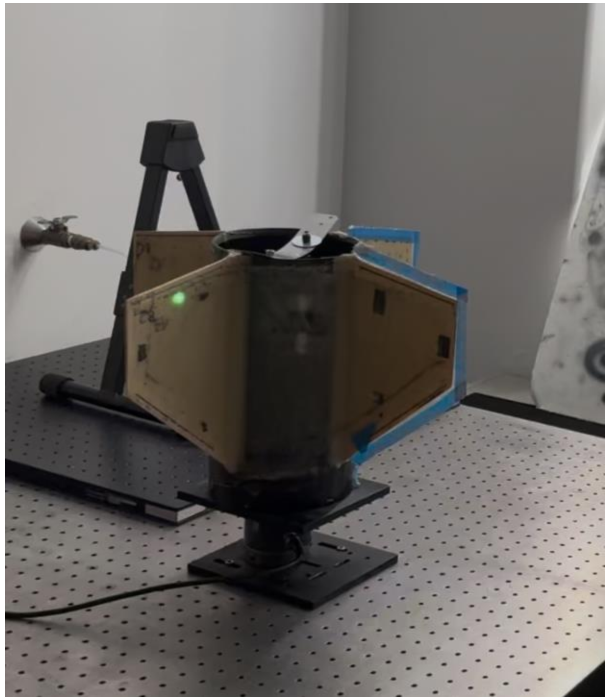


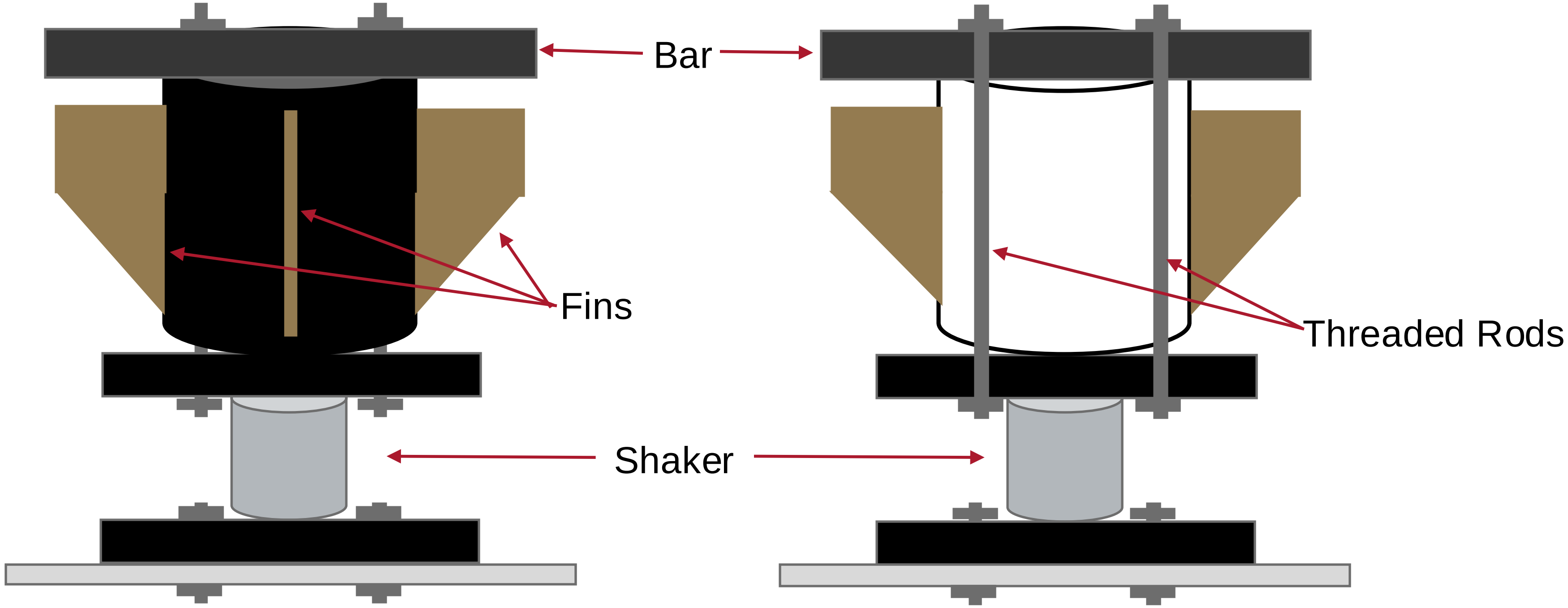
SLDV In Practice



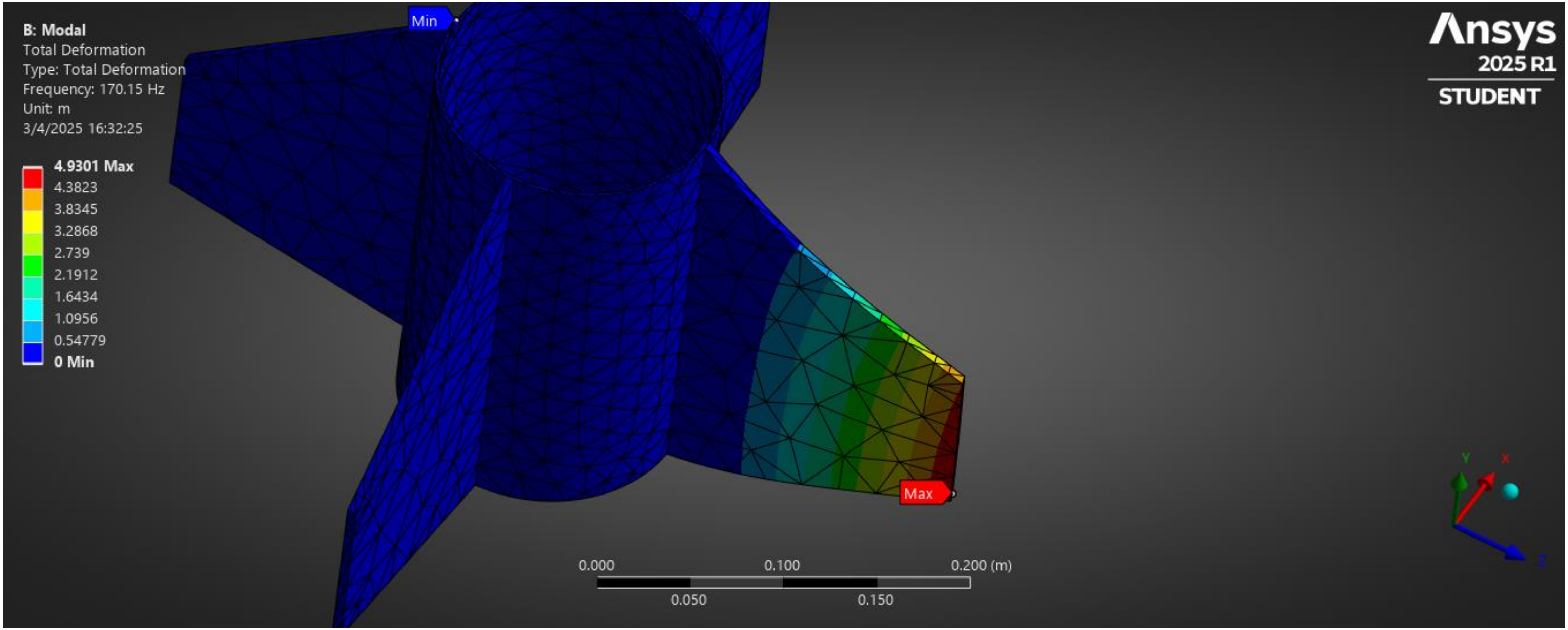


Securing of the Fin Can





Simulated Results (FG – 170Hz, Wood – 232Hz)



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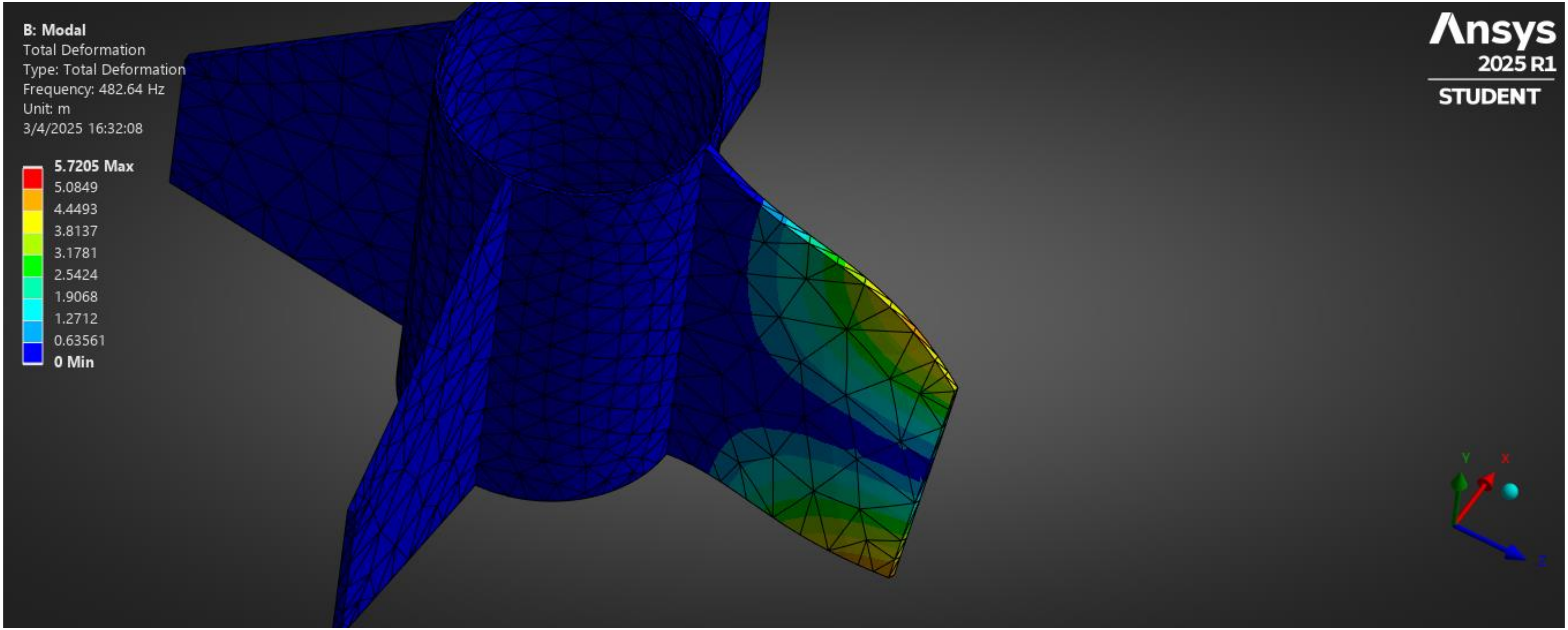
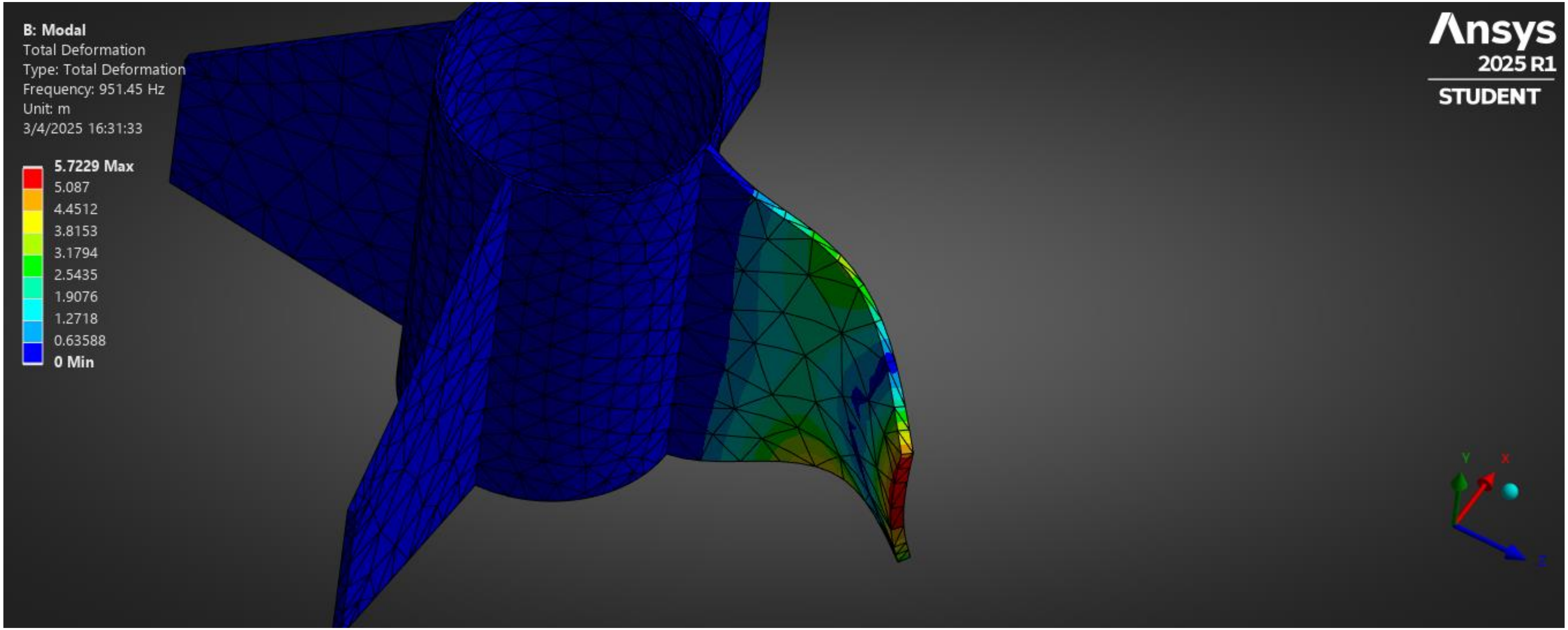
Simulated Results (FG – 482Hz, Wood – 620Hz)

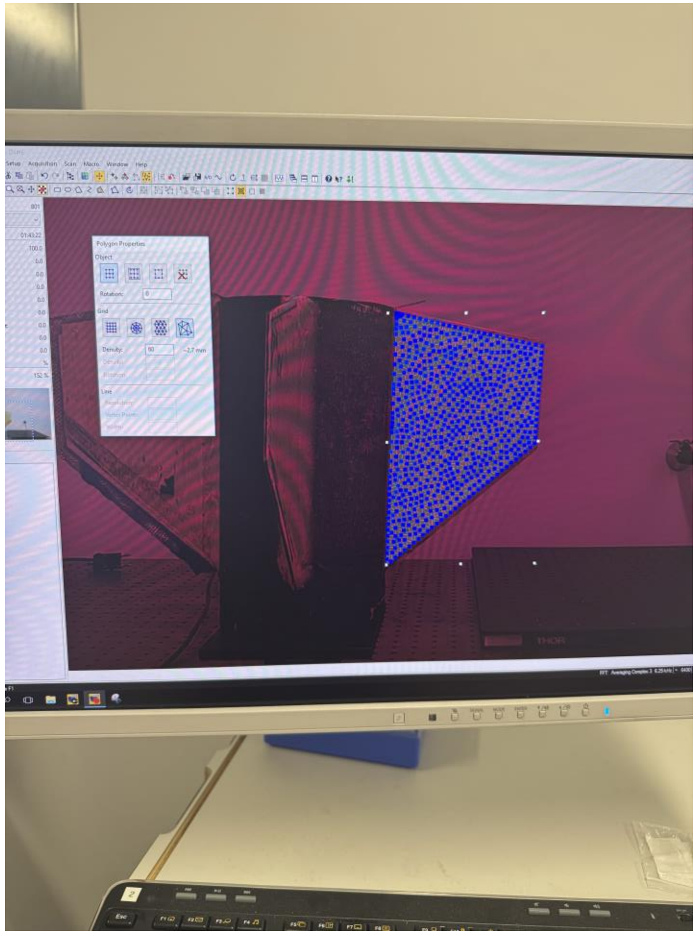


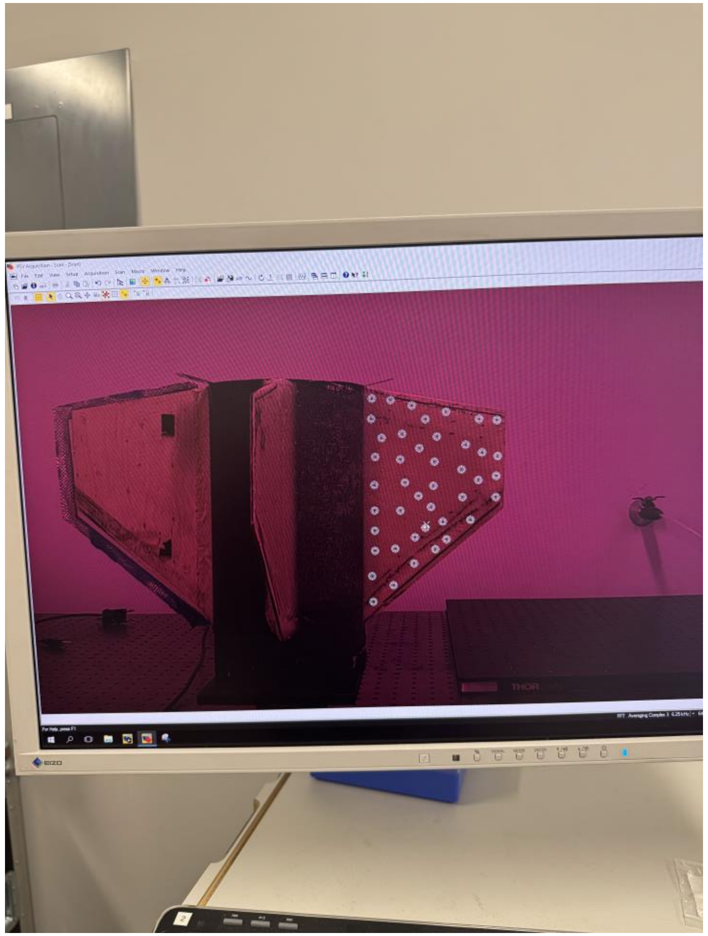
Simulated Results (FG – 951Hz, Wood – 1270Hz)



WPI

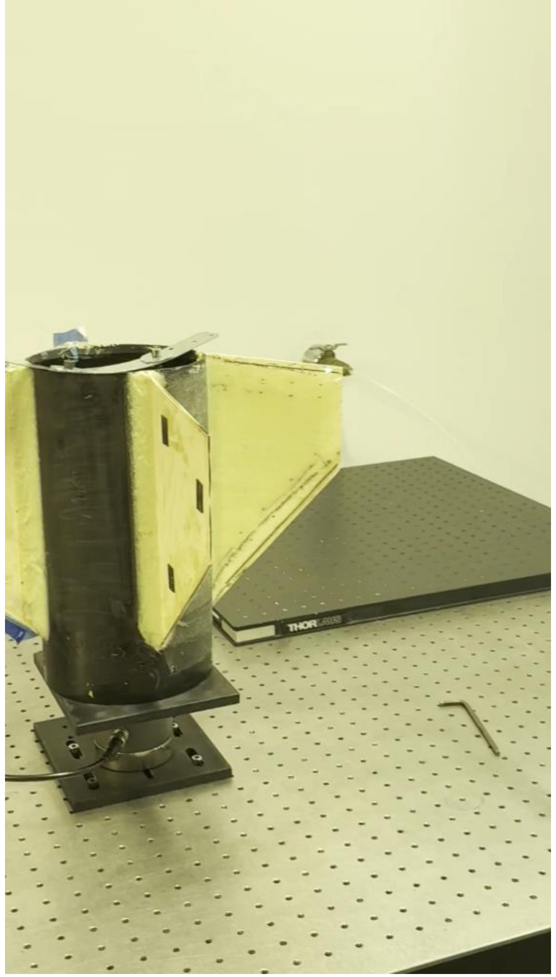
SLDV Scans



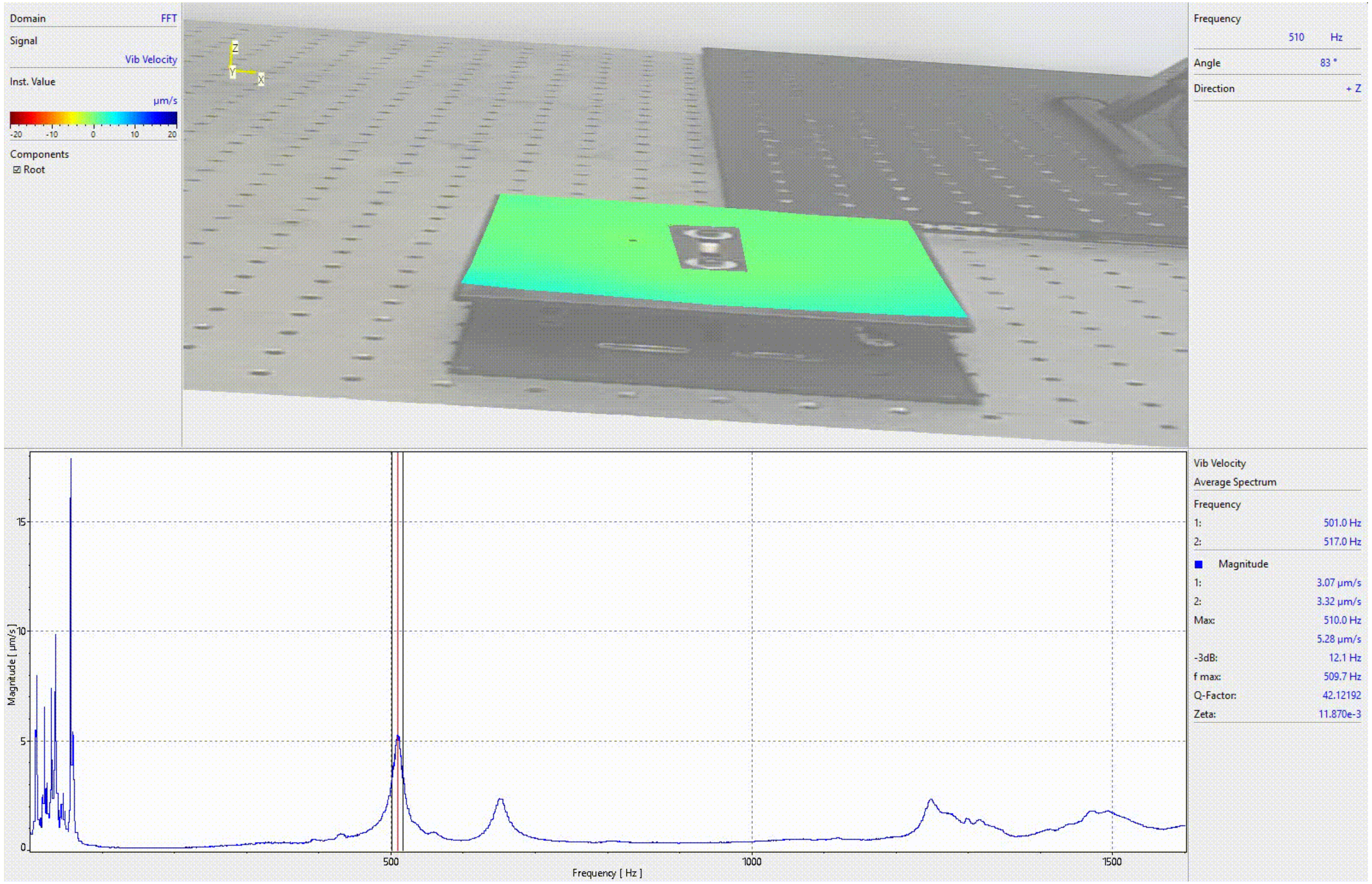


- We focused the SLDV across the fin & created an outline of the wing profile within the PSV software
- Generated a mesh (1028 Points per Fin)
- FFT scan from 1 Hz – 800 Hz; 3 Point Averaging

Scan Running



Scan of Piezoelectric Plate (510 Hz)



Fully Finished Fin vs Half Finished Fin

Fully Finished Fin

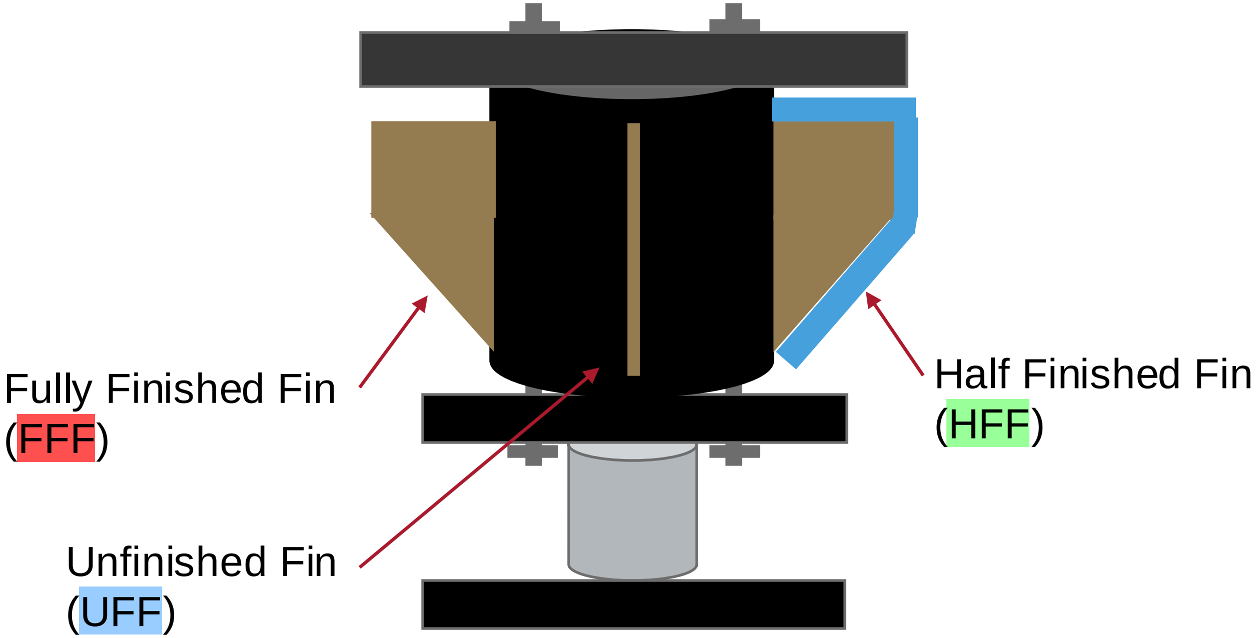
1/8” plywood with 4 sheets of fiberglass on both sides

Half Finished Fin

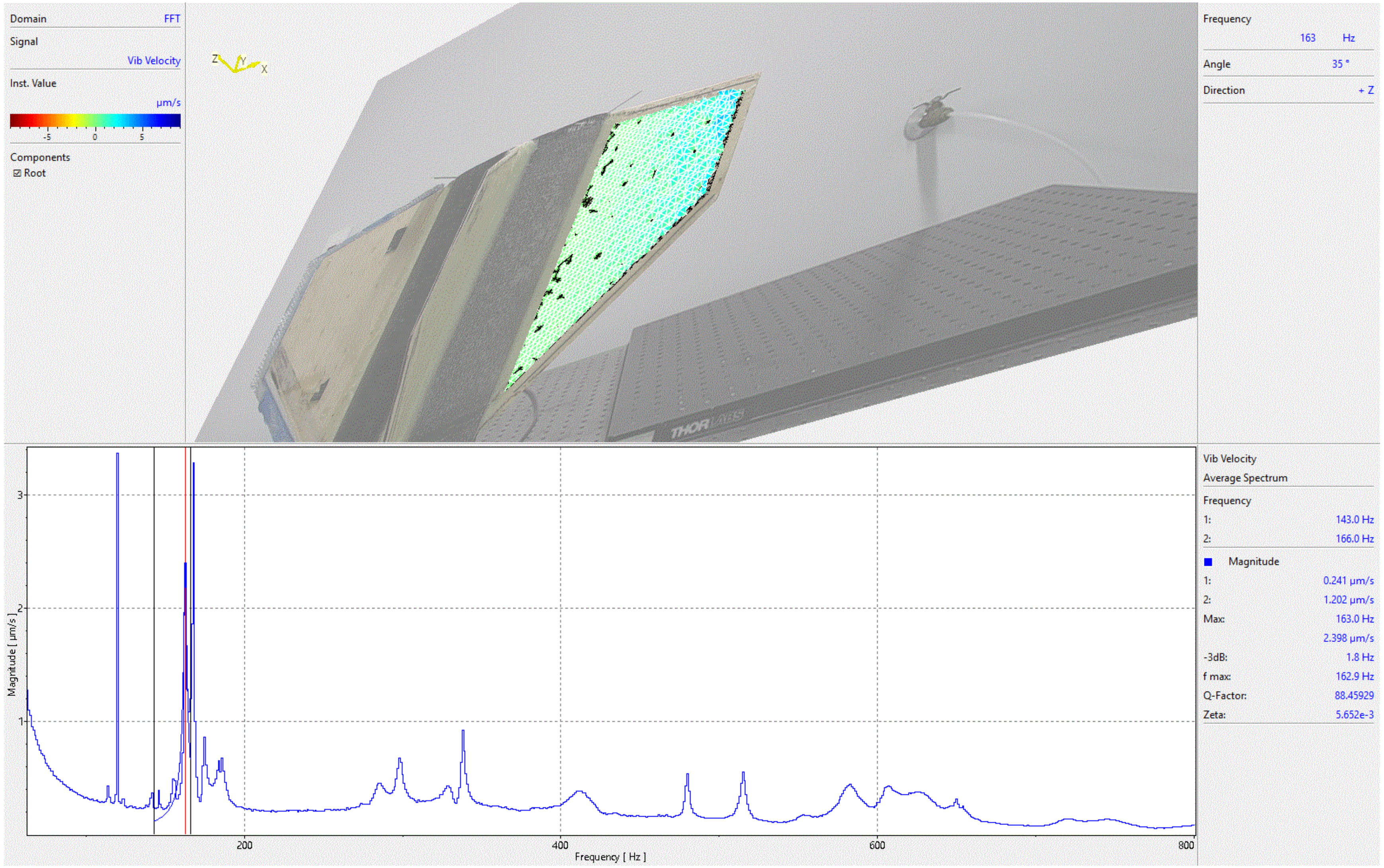
1/8” plywood with 4 sheets of fiberglass on one side, not trimmed to size

Unfinished Fin

1/8” plywood with 4 sheets of fiberglass on one side

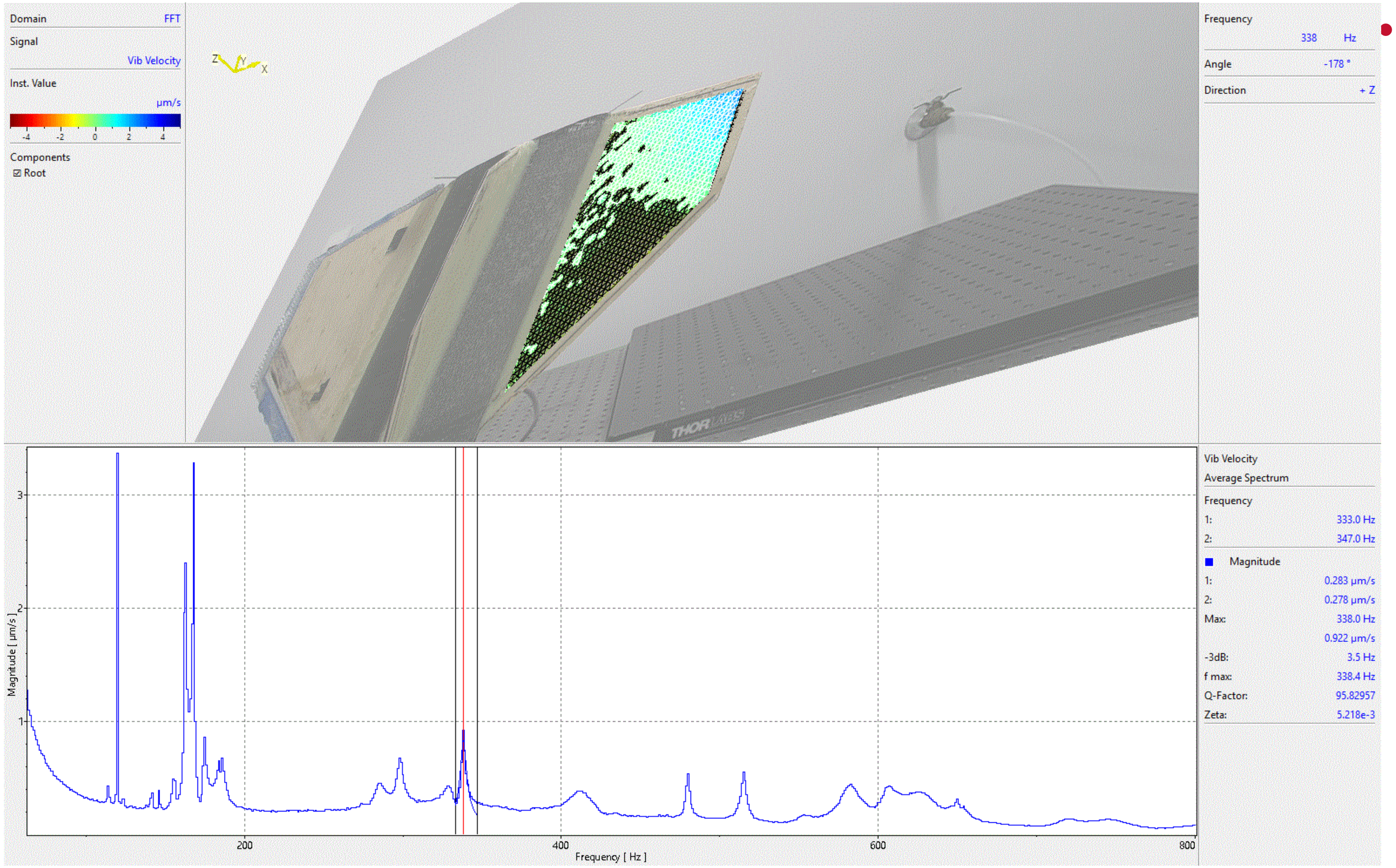


FFF Data (163Hz)



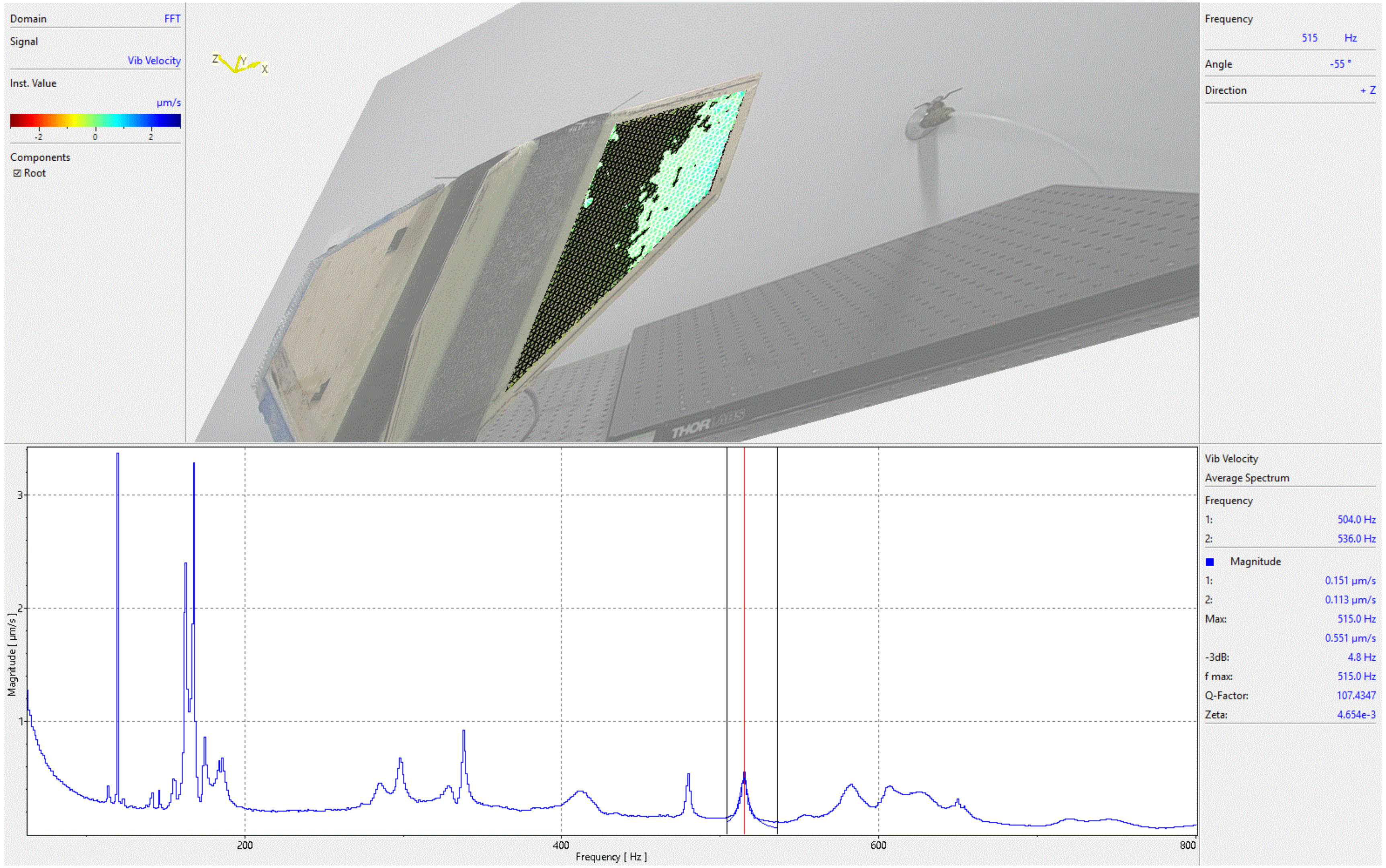
- FFF in first bending mode (small amplitude)

FFF Data (338Hz)



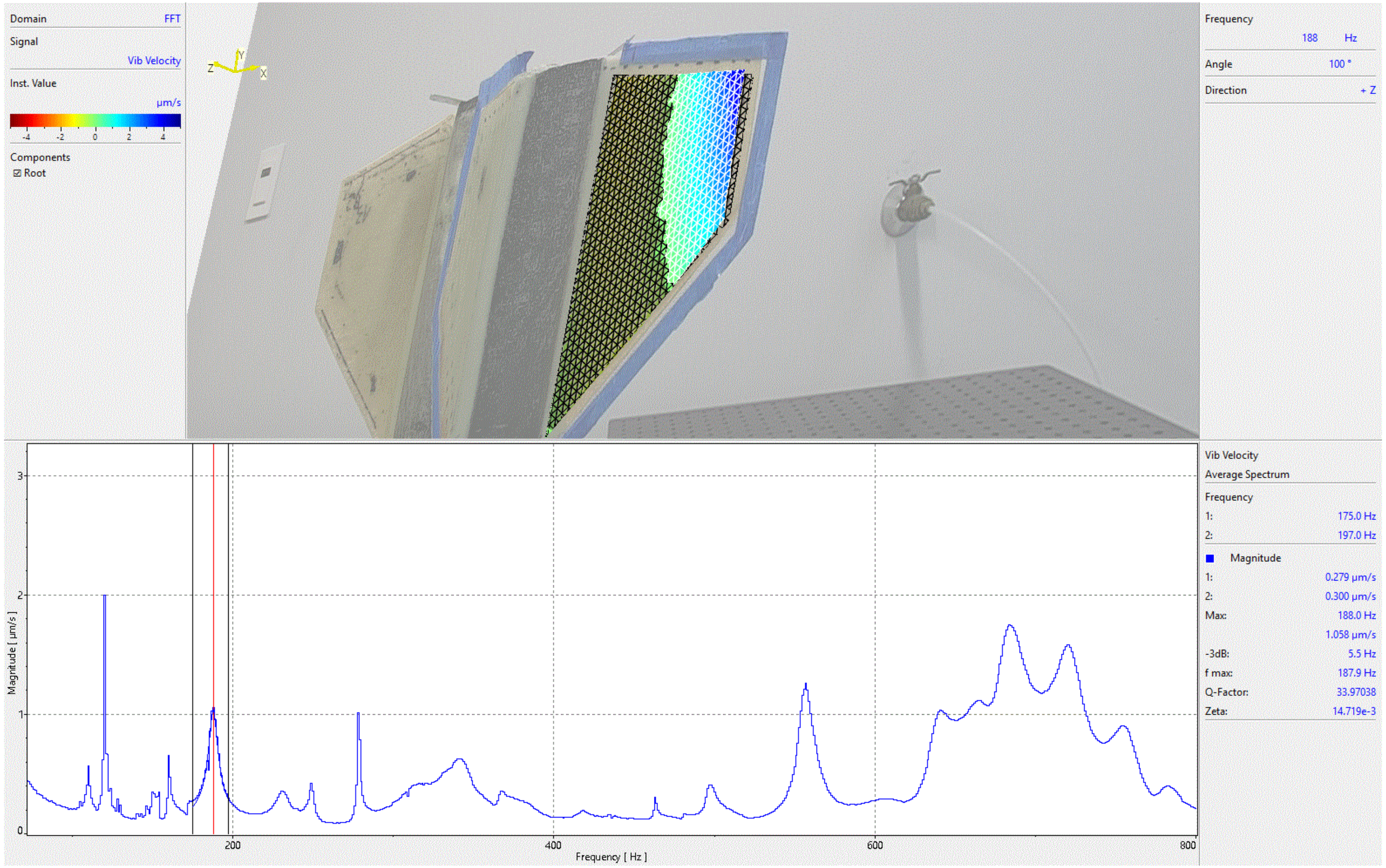
- FFF in first torsion mode (small amplitude)

FFF Data (515Hz)



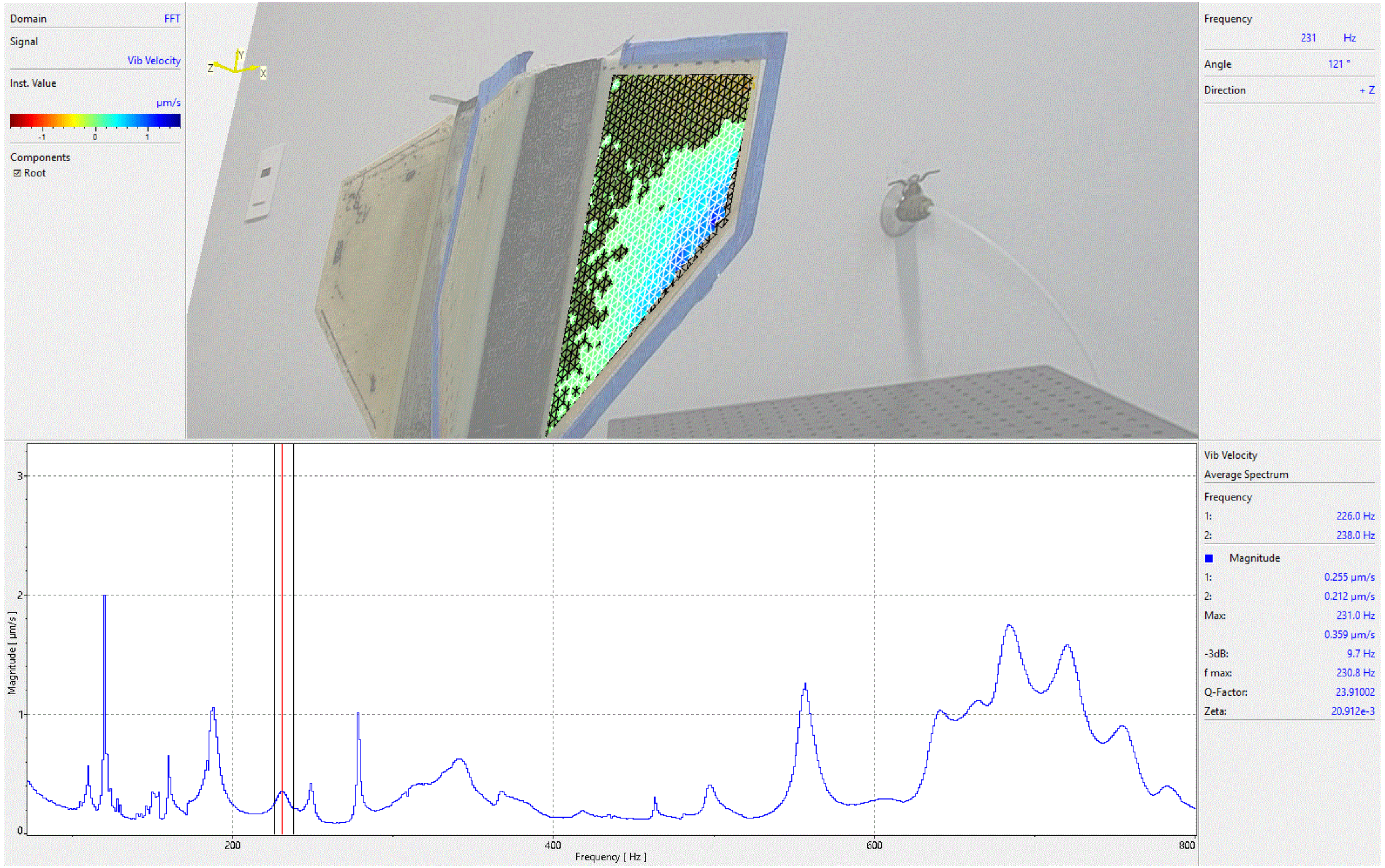
- FFF in second bending mode (small amplitude)

HFF Data (188Hz)



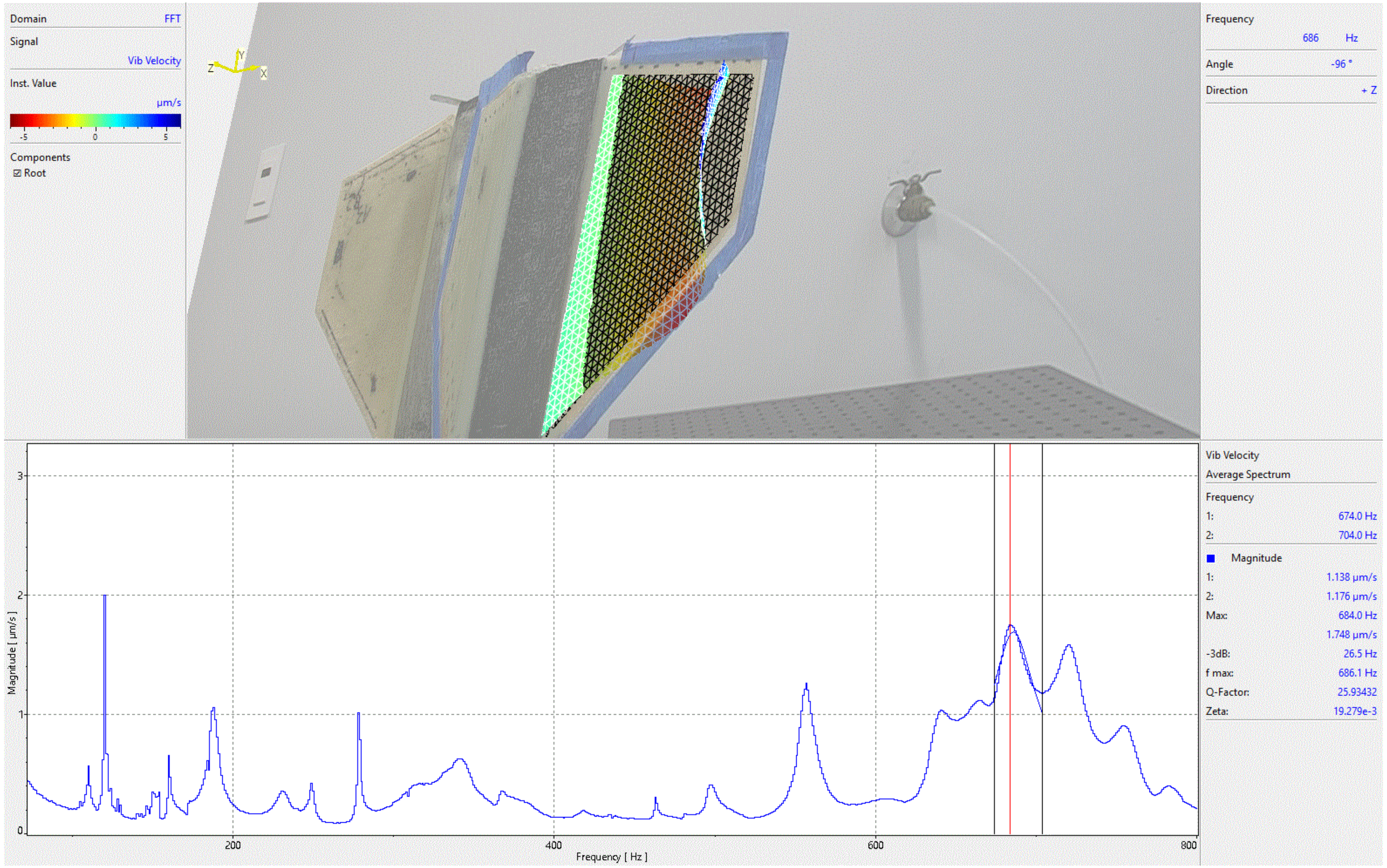
- HFF in second bending mode (small amplitude)

HFF Data (231Hz)



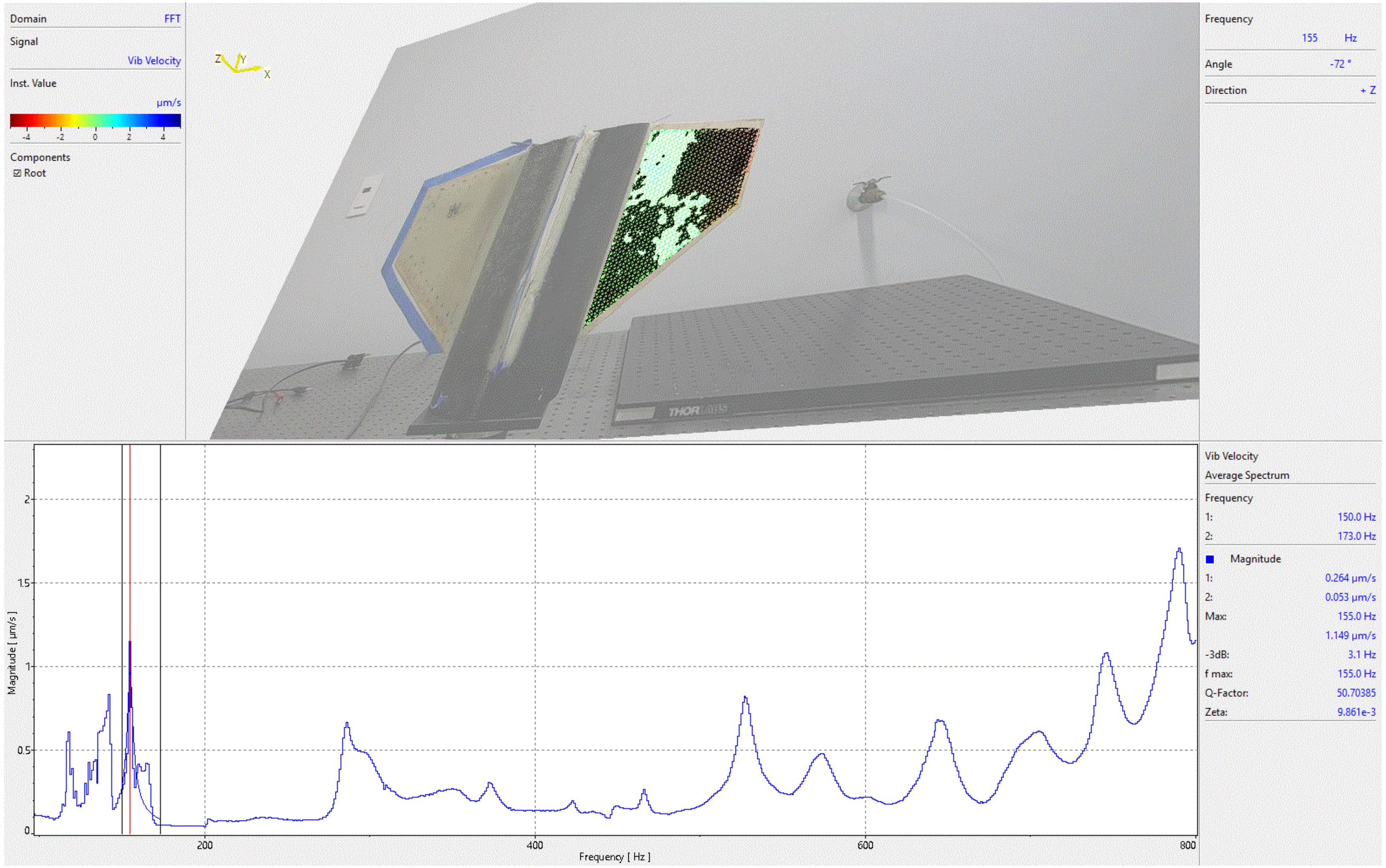
- HFF in first torsional mode (small amplitude)

HFF Data (684Hz)



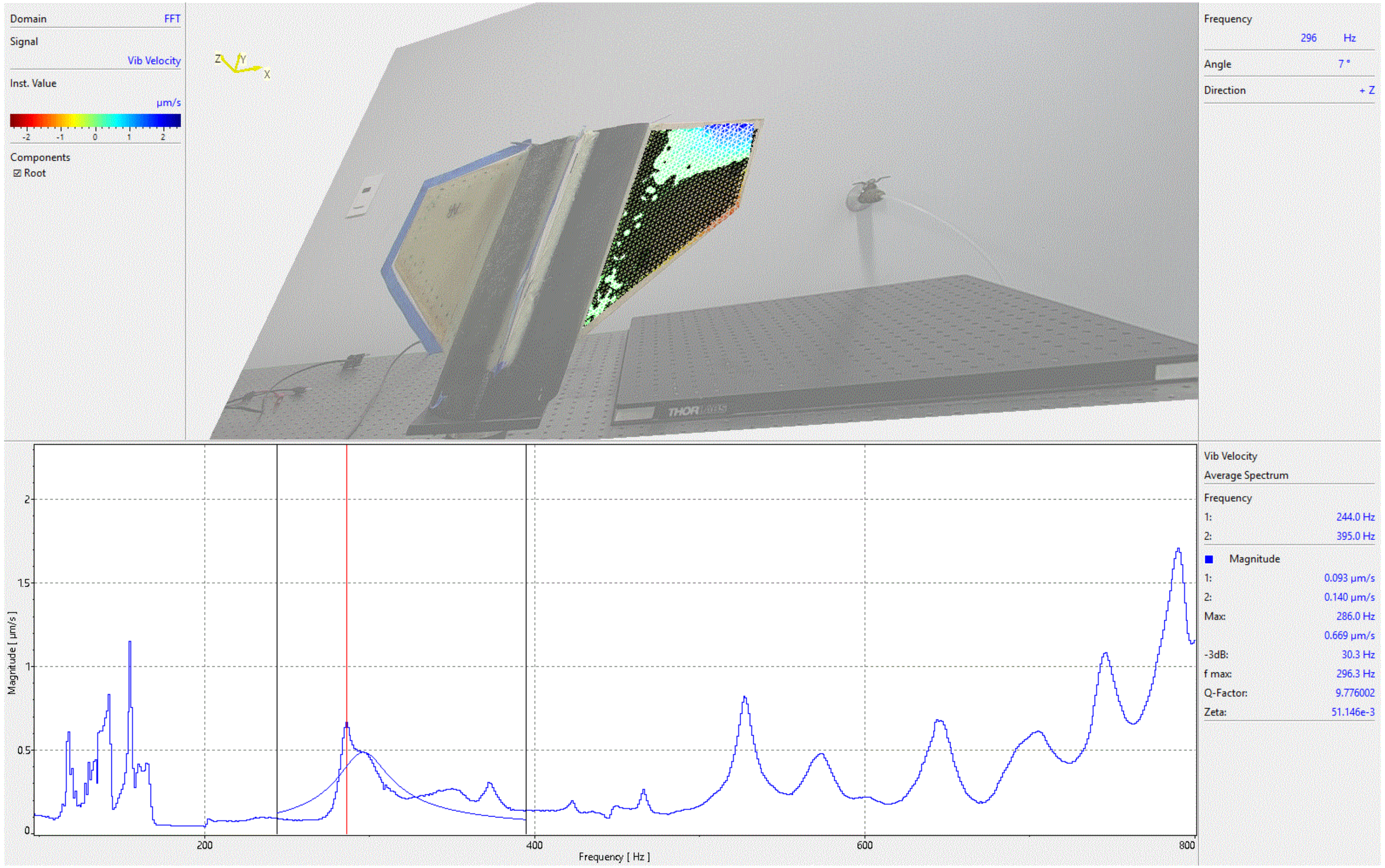
- HFF in second bending mode (large amplitude)

UFF Data (155Hz)



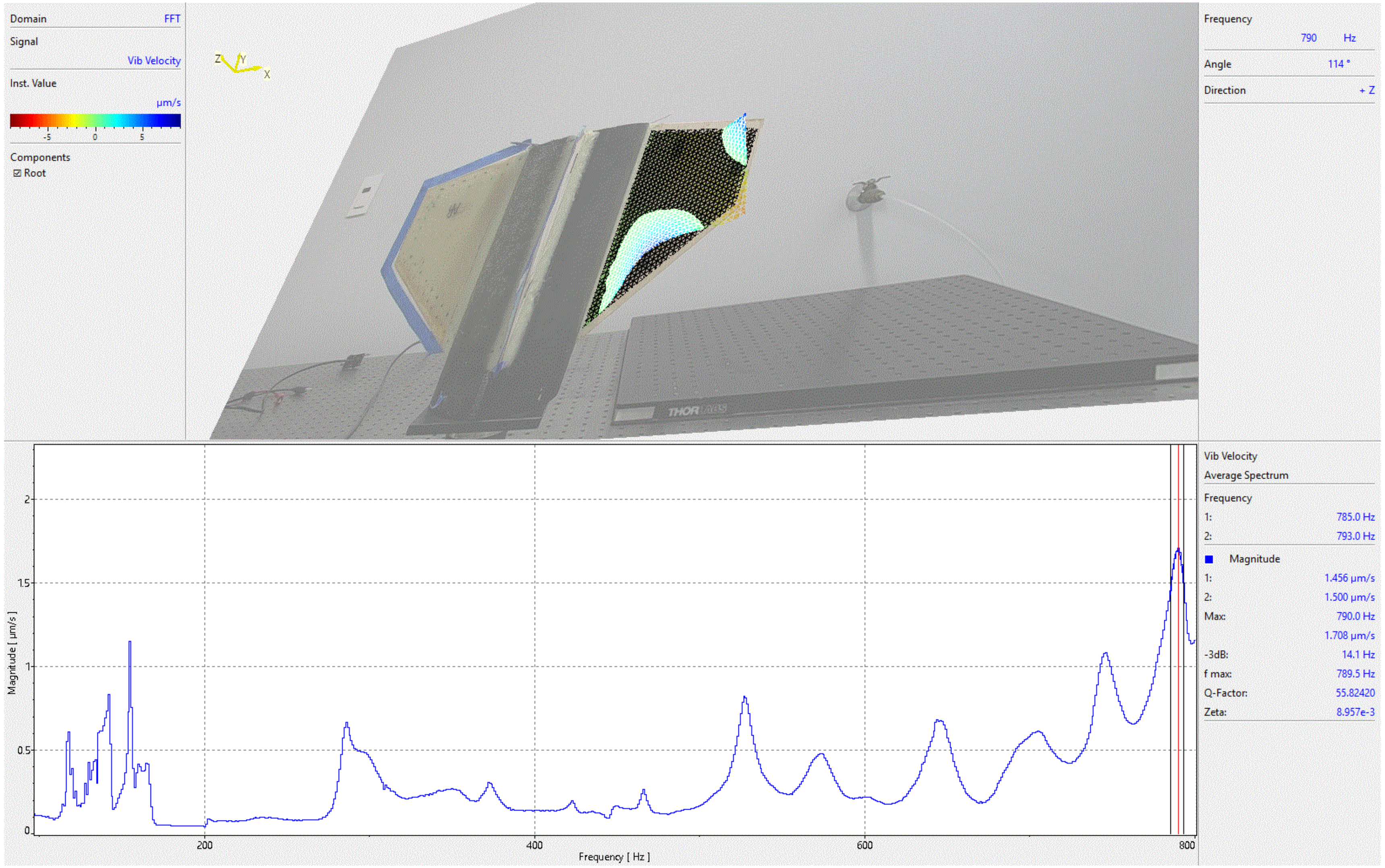
- UFF in second bending mode (small amplitude)

UFF Data (286Hz)



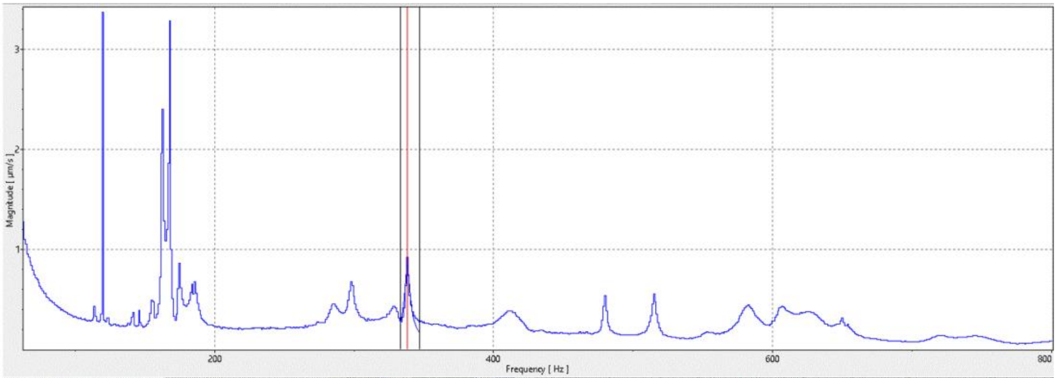
- UFF in first torsional mode (small amplitude)

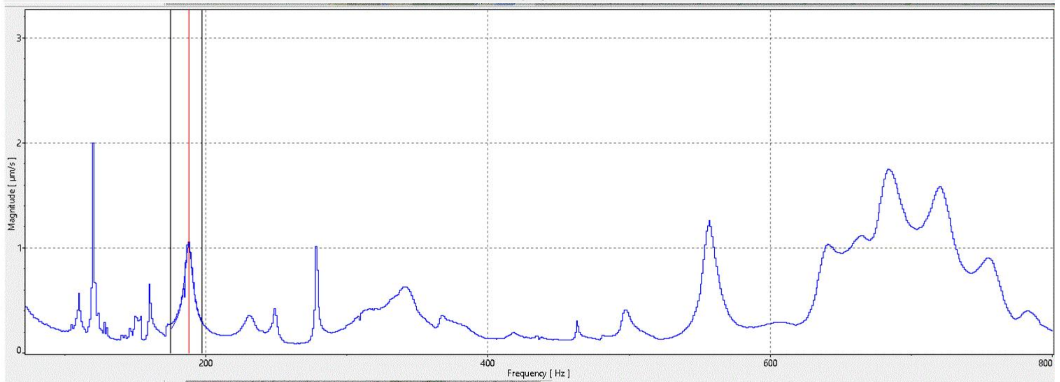
UFF Data (790Hz)

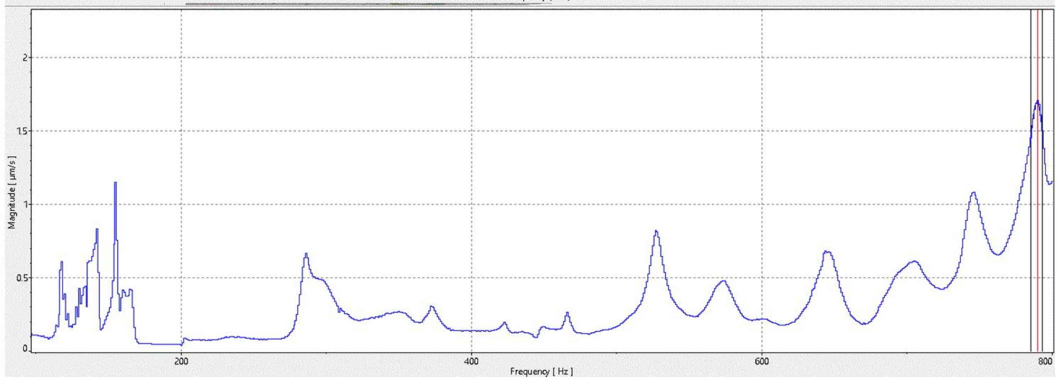


- UFF in mixed bending mode (large amplitude)

FFT Spectrum Comparison

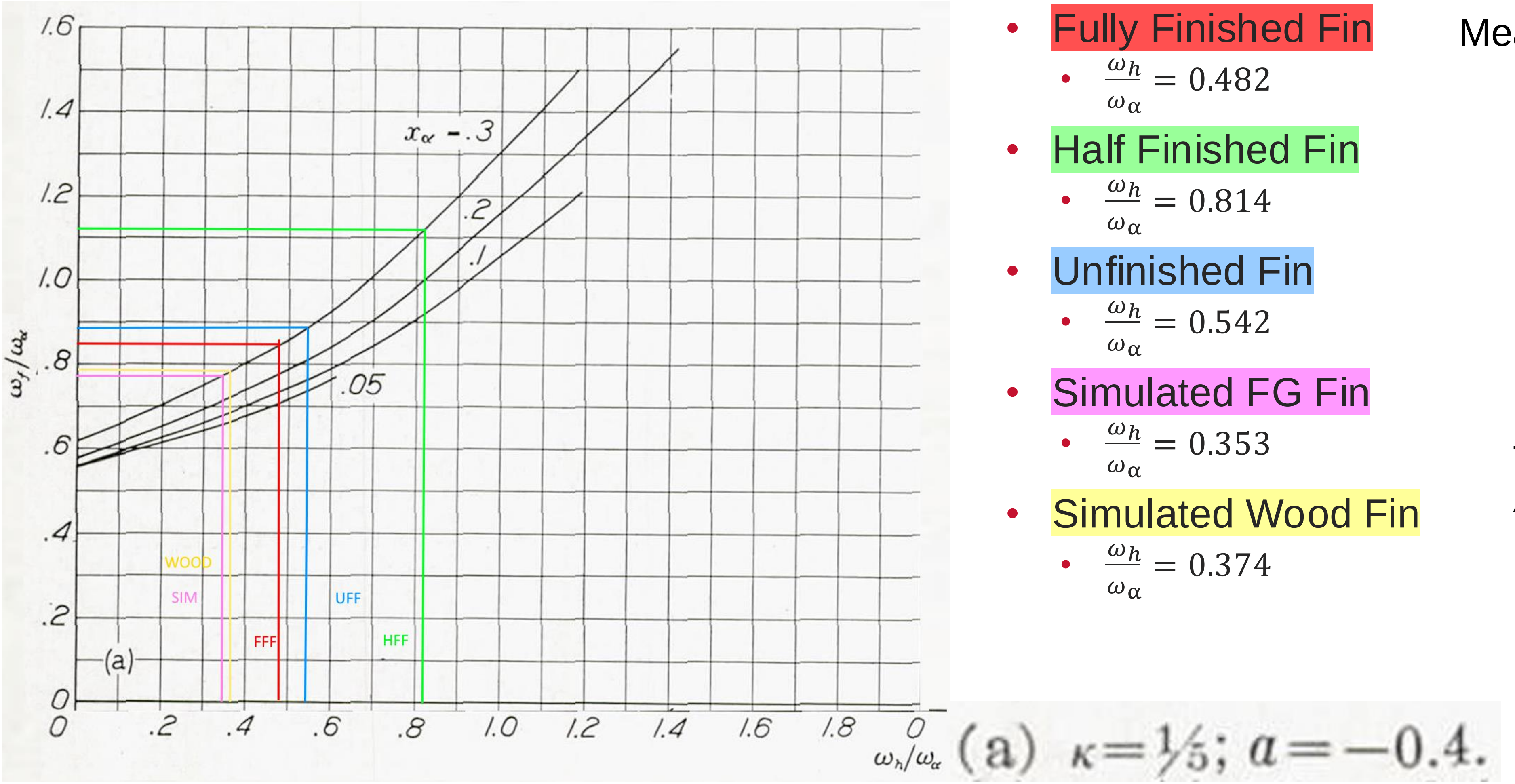






- Fully Finished Fin
  - Very strong resonant frequencies in the low (sub-200Hz) range
  - $\frac{\omega_h}{\omega_\alpha} = 0.482$
- Half Finished Fin
  - Equally strong resonance in low (sub-200Hz) and medium (600Hz+) ranges
  - $\frac{\omega_h}{\omega_\alpha} = 0.814$
- Unfinished Fin
  - Significantly stronger resonance in medium (600Hz+) range
  - $\frac{\omega_h}{\omega_\alpha} = 0.542$

Fin Flutter Math



- Fully Finished Fin
  - $\frac{\omega_h}{\omega_\alpha} = 0.482$
- Half Finished Fin
  - $\frac{\omega_h}{\omega_\alpha} = 0.814$
- Unfinished Fin
  - $\frac{\omega_h}{\omega_\alpha} = 0.542$
- Simulated FG Fin
  - $\frac{\omega_h}{\omega_\alpha} = 0.353$
- Simulated Wood Fin
  - $\frac{\omega_h}{\omega_\alpha} = 0.374$

Measured:

- $\kappa \approx 1/4$ (Wing density)
- $a \approx -0.5$ (Location of neutral axis)
- $x_a \approx 0.3$ (Location of center of gravity from neutral axis)

Approximating:

- $\kappa \approx 1/5$
- $a \approx -0.4$
- $x_a \approx 0.3$

$\frac{\omega_f}{\omega_\alpha} \approx$ 0.85, 1.11, 0.89, 0.77, 0.79

$\frac{\omega_f}{2pi} = f_f \approx$ 287Hz, 256Hz, 254Hz, 371Hz, 489Hz

Fin Flutter Math

$$X = \frac{{r_\alpha}^2}{\kappa} * \left(\frac{\omega_\alpha}{\omega}\right)^2$$

$$v = \frac{r_\alpha \omega_\alpha b}{\sqrt{\kappa}} * \frac{1}{k} * \frac{1}{\sqrt{X}}$$

$v =$ 940, 839, 832, 1214, 1602 [ft/s]

- Fully Finished Fin
  - $\frac{\omega_h}{\omega_\alpha} = 0.482$
  - $\omega_\alpha = 2213\, rad/s$
- Half Finished Fin
  - $\frac{\omega_h}{\omega_\alpha} = 0.814$
  - $\omega_\alpha = 1451\, rad/s$
- Unfinished Fin
  - $\frac{\omega_h}{\omega_\alpha} = 0.542$
  - $\omega_\alpha = 1796\, rad/s$
- Simulated FG Fin
  - $\frac{\omega_h}{\omega_\alpha} = 0.353$
  - $\omega_\alpha = 3028 \frac{rad}{s}$
- Simulated Wood Fin
  - $\frac{\omega_h}{\omega_\alpha} = 0.374$
  - $\omega_\alpha = 3895 \frac{rad}{s}$

Measured:

- $\kappa \approx 1/4$ (Wing density)
- $a \approx -0.5$ (Location of neutral axis)
- $x_a \approx 0.3$ (Location of center of gravity from neutral axis)

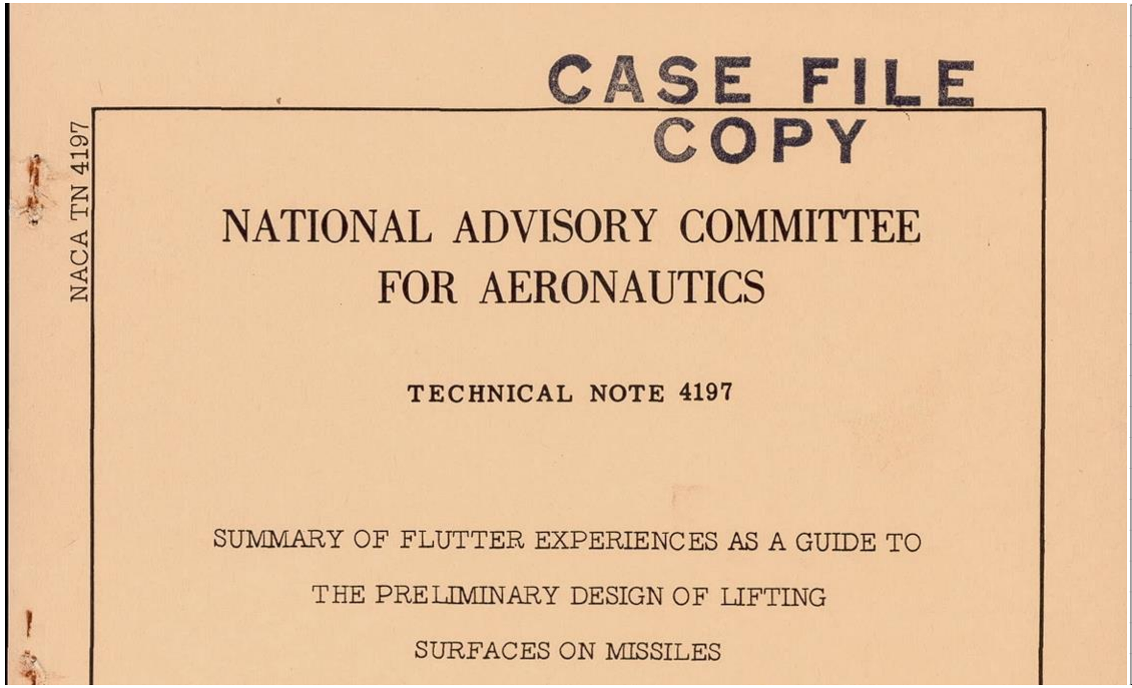
Approximating:

- $\kappa \approx 1/5$
- $a \approx -0.4$
- $x_a \approx 0.3$

Assuming:

- $\frac{1}{k} \approx 0.8$
- $r_a \approx 1/4$

Fin Flutter Alternative Analysis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TECHNICAL NOTE 4197
SUMMARY OF FLUTTER EXPERIENCES AS A GUIDE TO
THE PRELIMINARY DESIGN OF LIFTING
SURFACES ON MISSILES

Fin Geometry:	Tapered Swept Rect.	G10 Fiberglass	1/4'' thickness	1.5 mm Epoxy Layer		
Root Chord (Cr)	0.254	m		Speed of Sound (a)	332.5823	m/s
Tip Chord (Ct)	0.1016	m		Temperature (Tc)	2	C
Thickness (t)	0.00735	m		P/Po	0.784552	
Thickess Ratio (t/Cr)	0.028937008			Altitude	2000	m
Semi-Span Length (l)	0.1524	m				
				Flutter Velocity (Vf)	326.176	m/s
Aspect Ratio (A)	0.857142857				1043.763	ft/s
Area	0.02709672	m^2				
Taper Ratio (Lamda)	0.4					
Shear Modulus	1,300,000	Kpa				

$$v = 1043 \text{ [ft/s]}$$

Conclusions

$$v_{NACA-685/SLDV} = 940$$

$$v_{NACA-4197} = 1043$$

$$v_{NACA-685/ANSYS} = 1214$$

Thanks to

- Prof. Furlong
- Danny Ruiz-Cadalso
- Howard Zheng

Questions?