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A Laboratory Procedure for Measuring the Dispersion Characteristics of Loaded Tires

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A LABORATORY PROCEDURE FOR MEASURING THE DISPERSION CHARACTERISTICS OF LOADED TIRES

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SCHOOL OF MECHANICAL ENGINEERING

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PURDUE MECHANICAL ENGINEERING

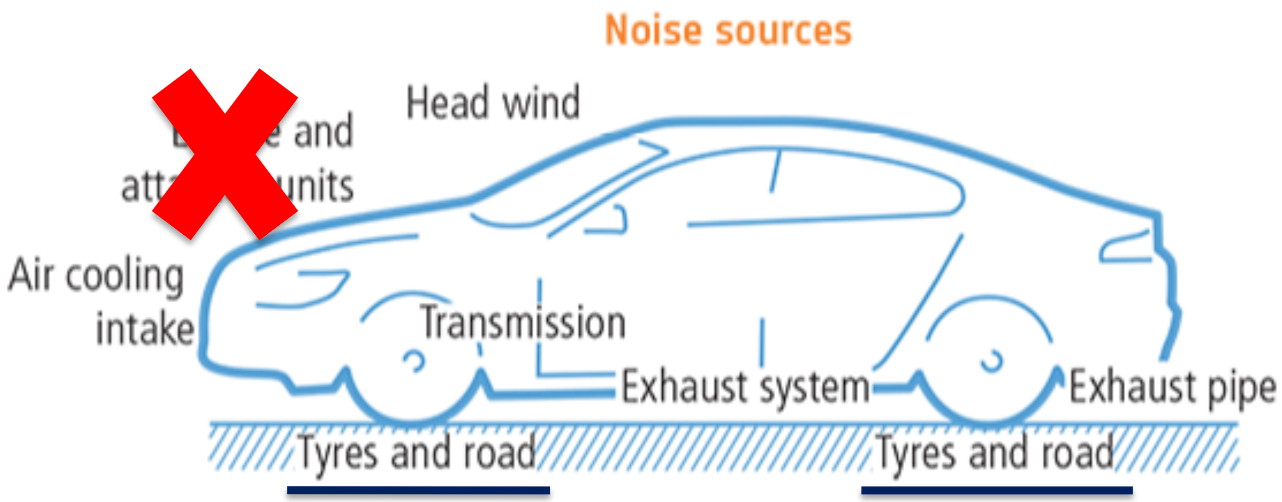
RAY W. HERRICK LABORATORIES

Content

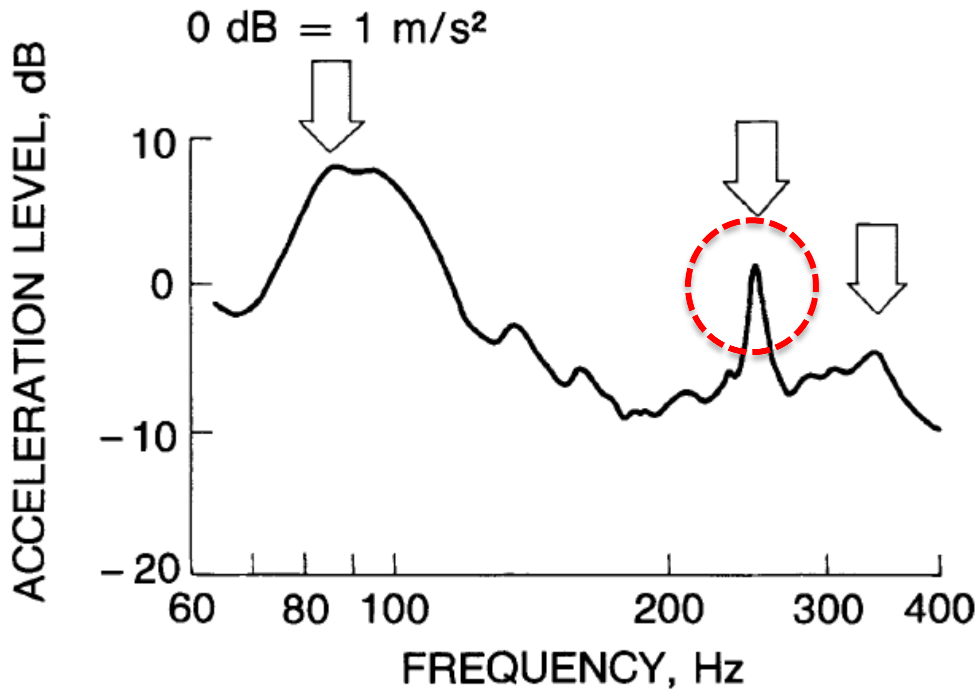
Background and Objective

Research background (1/2)

- Tire/road noise is becoming more significant with the advent of Electric Vehicles (EVs)
- Acoustic cavity mode usually happens around at 200 Hz depending on the size of tire and inflation
- It has been identified as a key contributor to cabin noise and transmitted force in a suspension system



Source : Bruel and Kjaer website

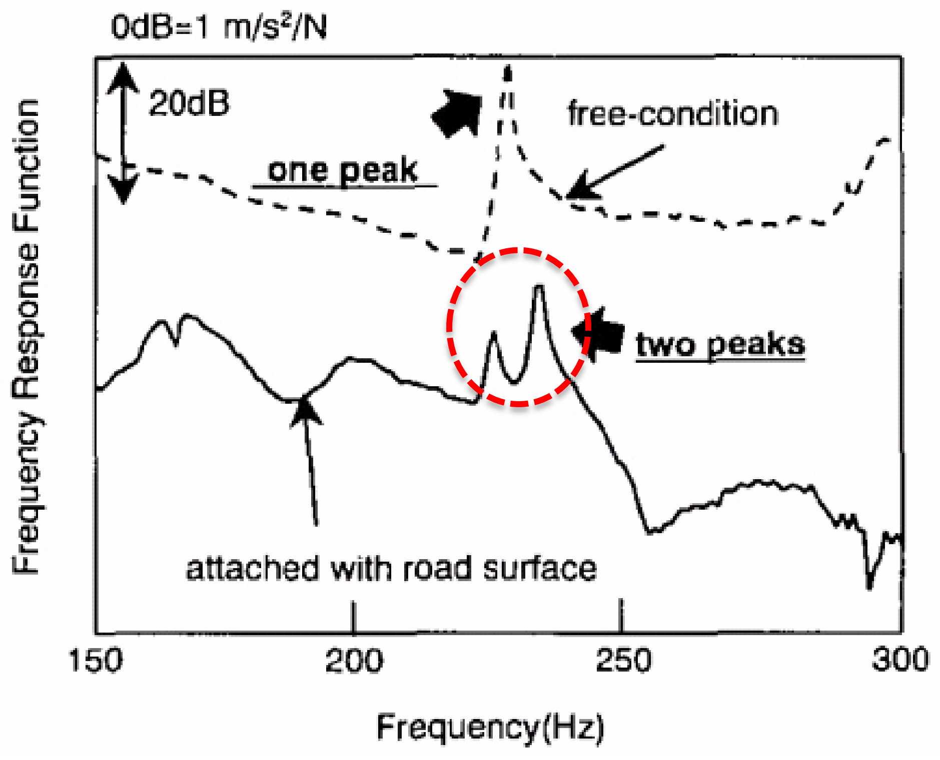


Source : Sakata and et al. (1990) [1]

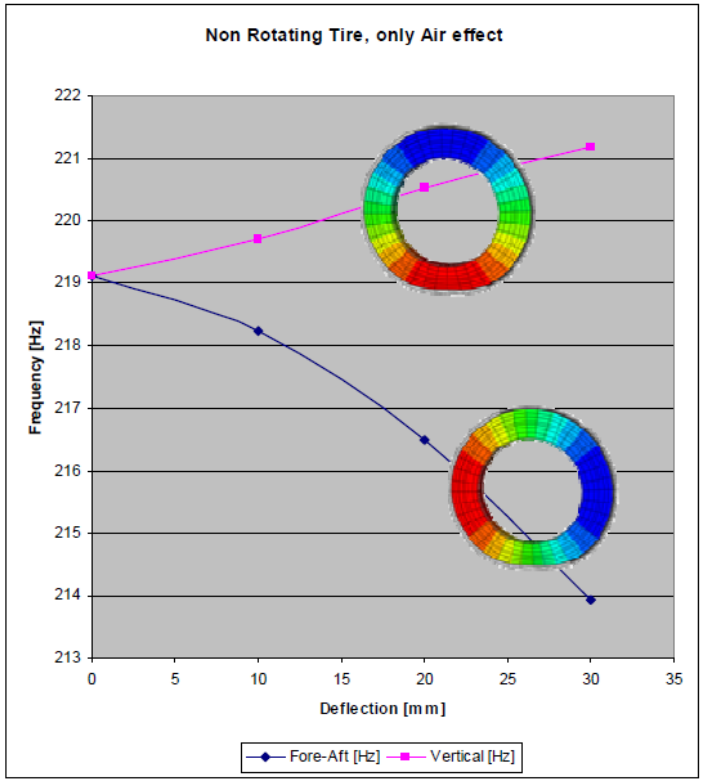
Background and Objective

Research background (2/2)

- Deformed tire can break geometrical symmetry, which produce two acoustic modes [2]
- Need to identify **'Frequency-split'** of the cavity mode for deformed tires experimentally



Source : Yamauchi and Akiyoshi (2002) [3]



Source : Ch. Bederna and E.-U. Saemann (2009) [4]

Background and Objective

Research objective

- **Test rig** should be designed to observe the **dispersion behavior** of **deformed tires** when measured with laser doppler vibrometer (LDV): i.e., type and speeds of waves in the coupled, stationary tires

Conventional test rig

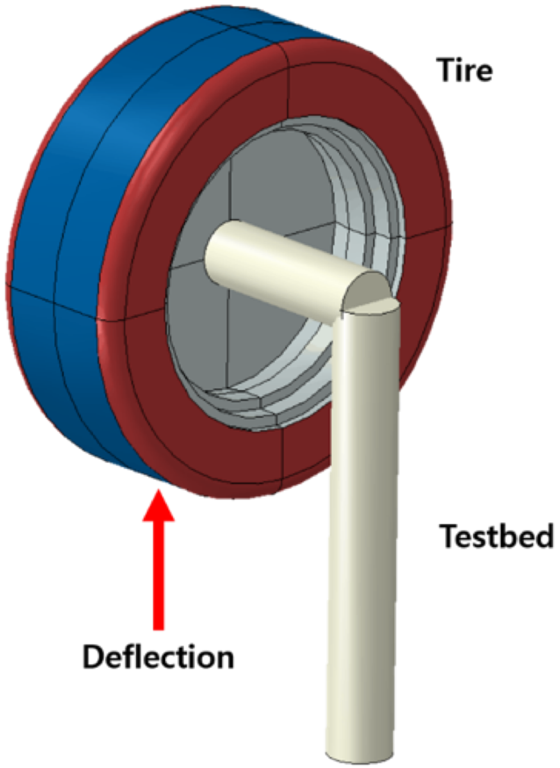
Design requirements

1. Avoid structural resonance between **200 and 300 Hz**
2. Capability of deforming on tires with a specific load
3. Economical, compact and robust structure

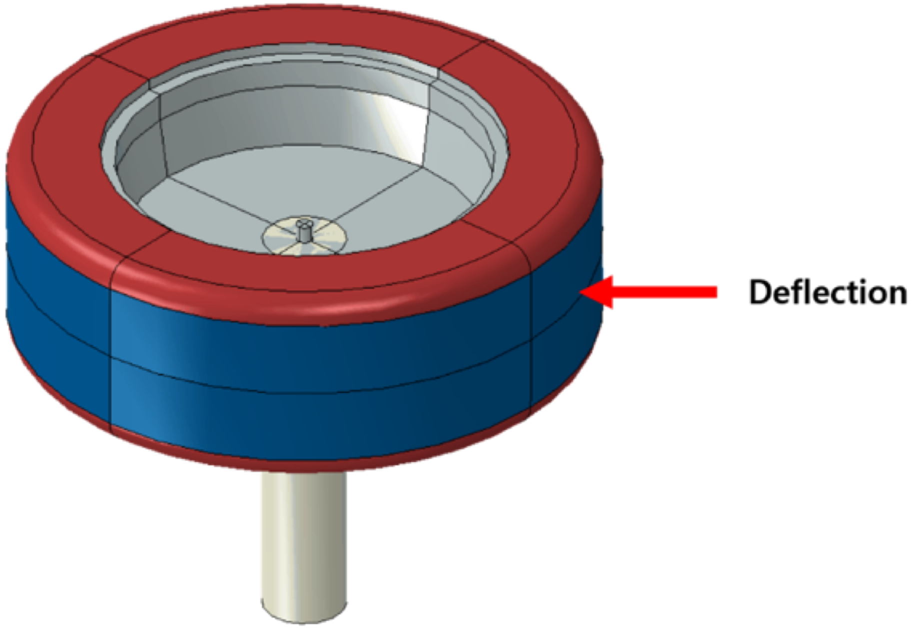
Design of Test Rig

Conceptual design

- Horizontally positioned tire is beneficial since higher natural frequency comes from short vertical support that can be achieved with a light-weight structure



(a) Vertically positioned tire

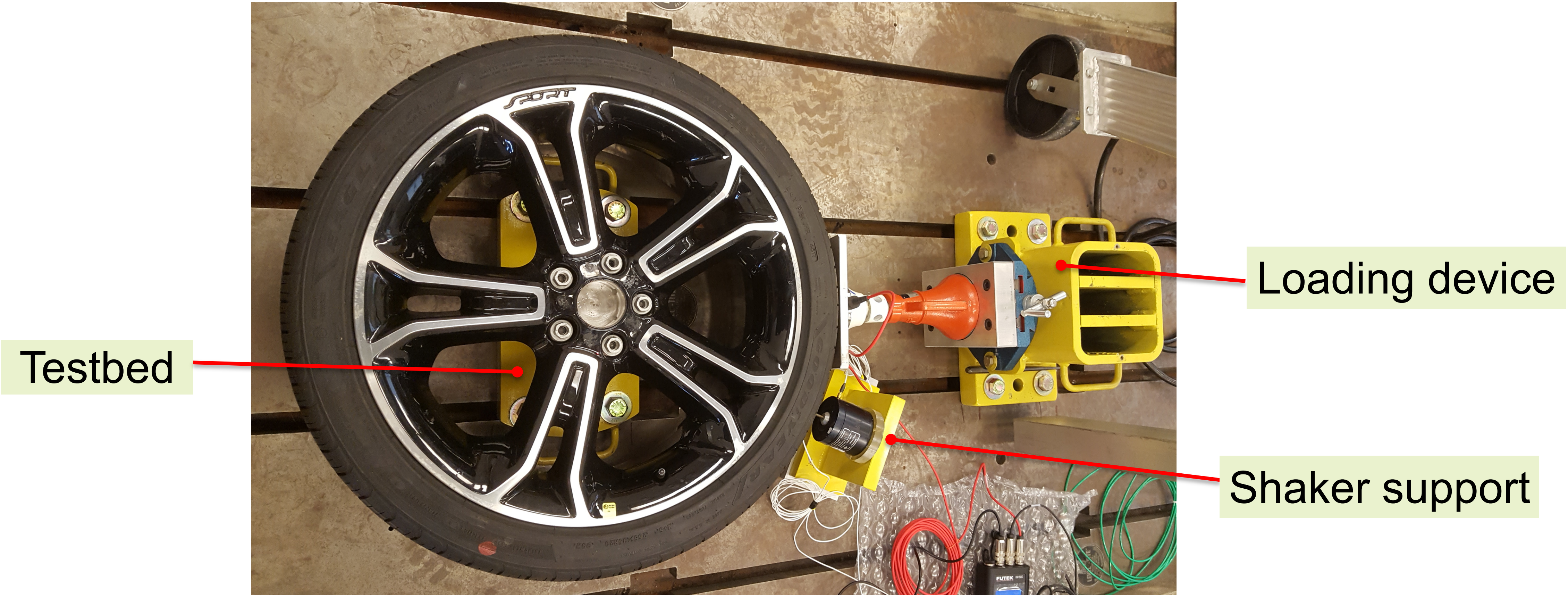


(b) Horizontally positioned tire

Design of Test Rig

Physical overview

- Test rig consists of testbed, loading device, and shaker support

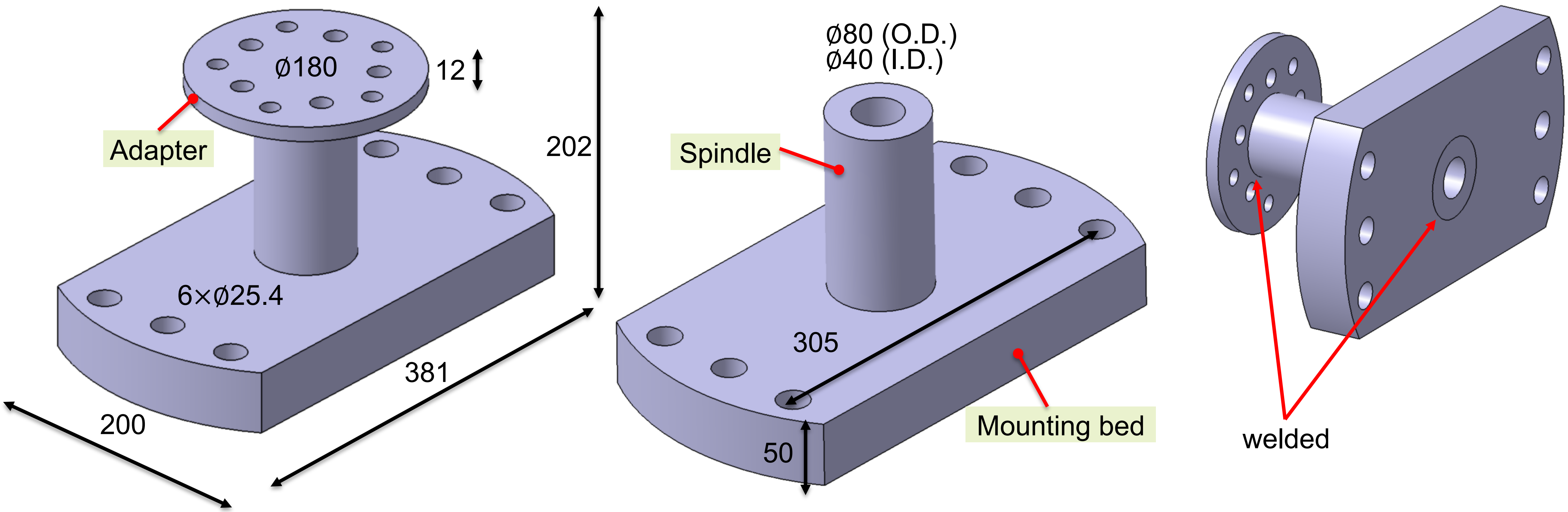


Design of Test Rig

Testbed

- Mounted on commercial steel floor with T slot
- Adapter is compatible with two different bolt radii

36.8 kg (carbon steel), Unit [mm]

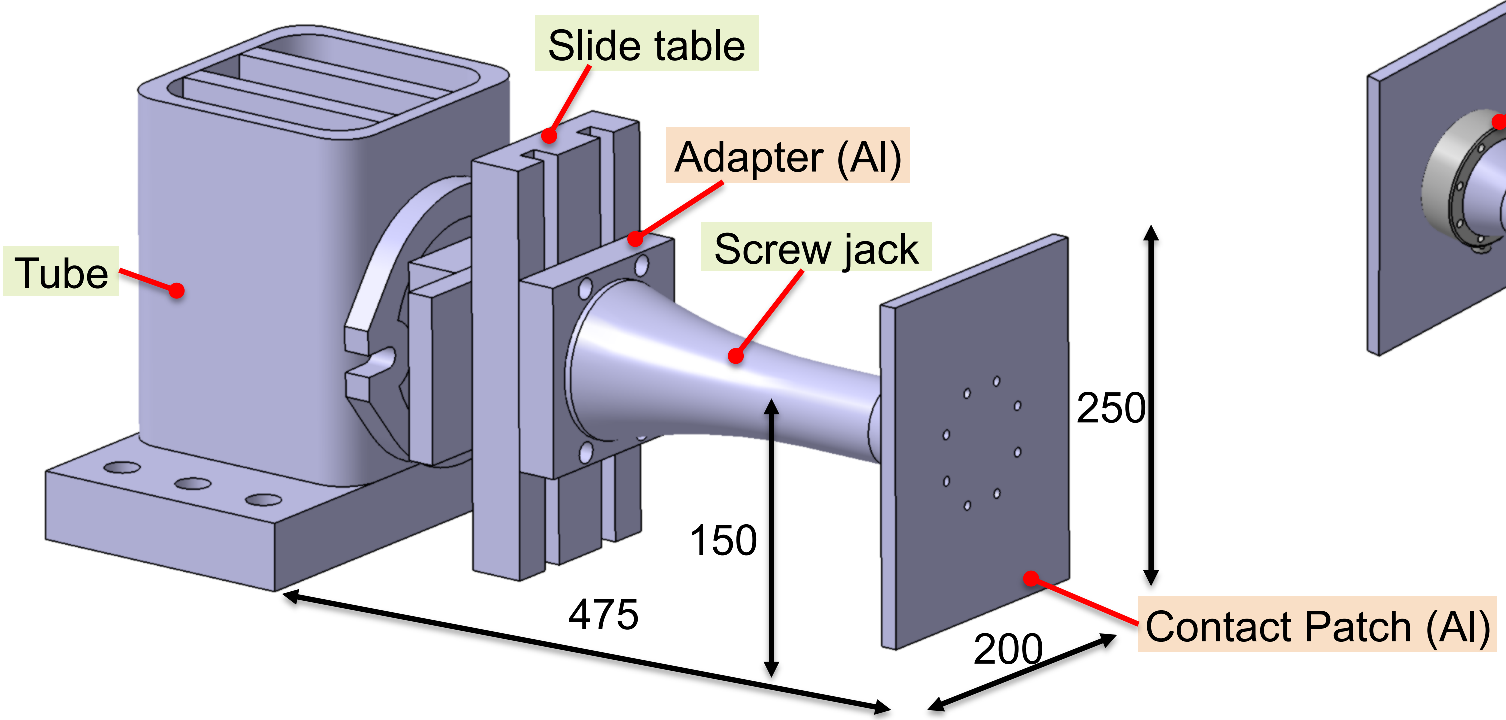


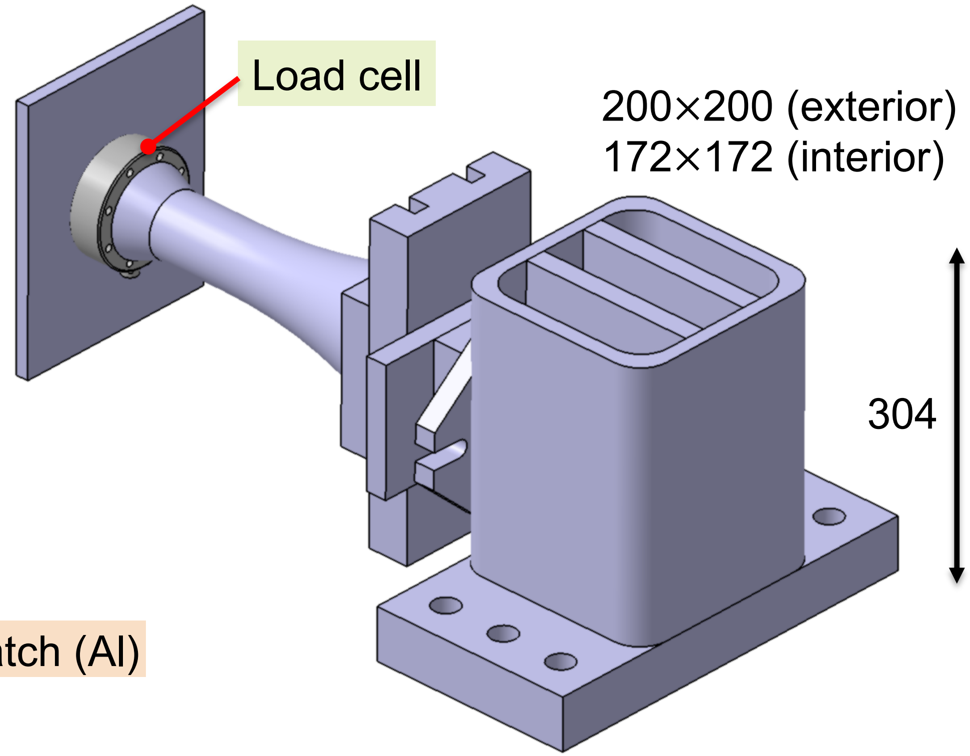
Design of Test Rig

Loading device

- Equipped with a slide table to adjust height
- Impose deformation on the tire using screw jack and patch

61.2 kg (carbon steel & Al), Unit [mm]



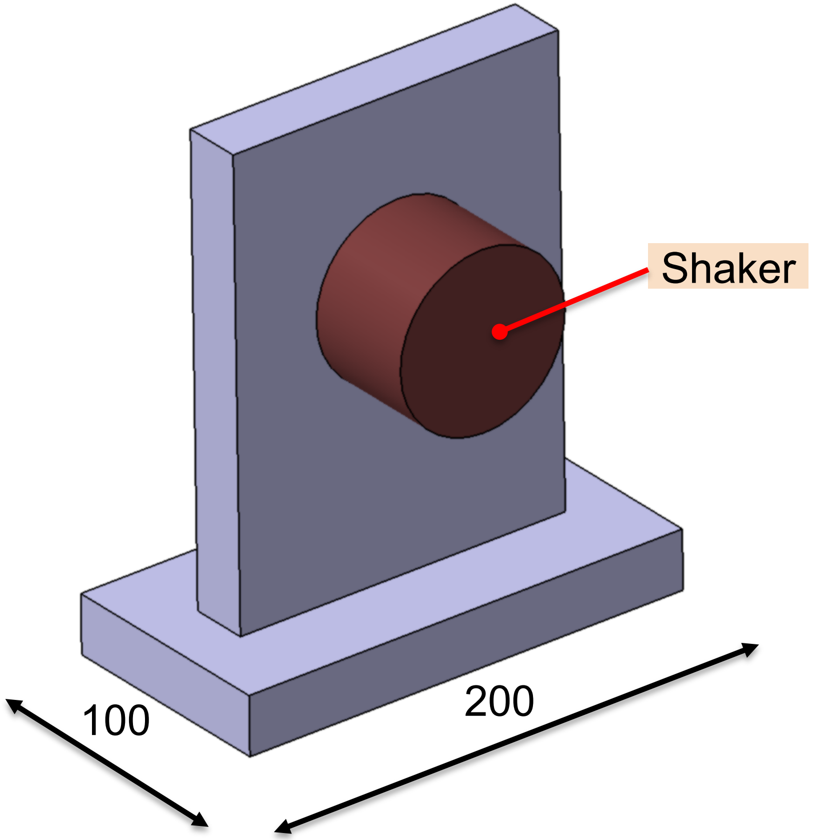


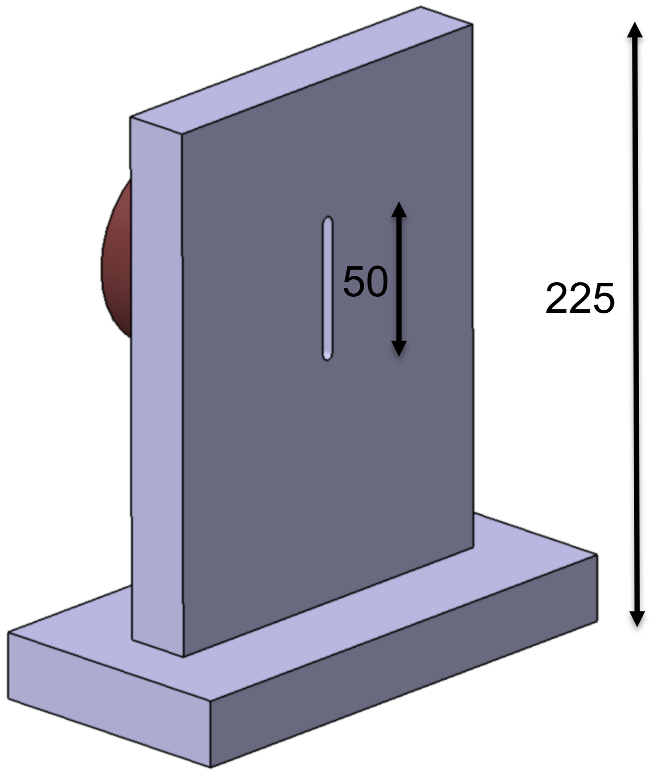
Design of Test Rig

Shaker support

- Compatible with mini shaker (B&K 4810)
- Adjustable height by incorporating a long slot

4.5 kg (Al), Unit [mm]





Modal Analysis

Verification for cantilever beam

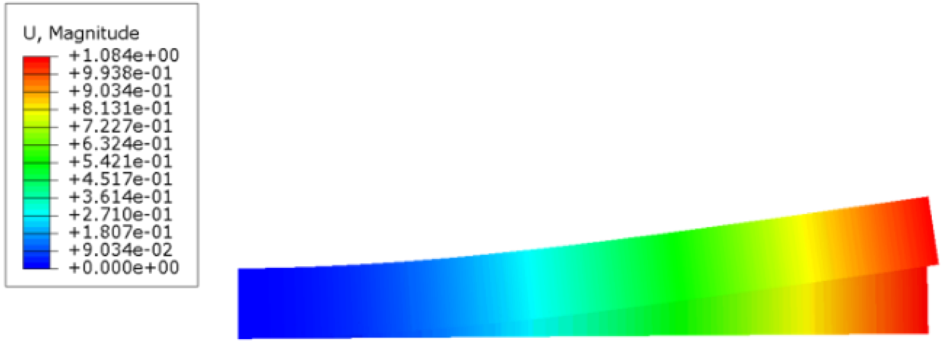
- Preliminary study on reliability of simulation software, Abaqus 2018
- Simulation results conform to the analytical calculation [5]

1(L)×0.1(W)×0.1(H), steel

$$f_1 = \frac{1.875^2}{2\pi L^2}\sqrt{\frac{EI}{\rho A}} = 80 \text{ Hz}$$

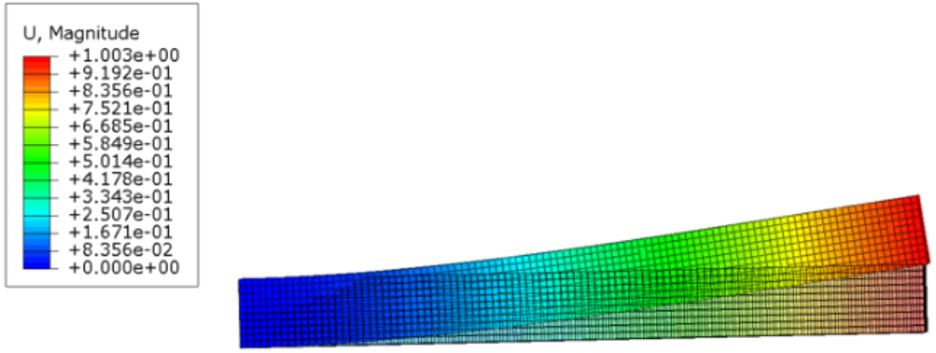
(refer to Appendix)

80 Hz



(a) 1-D mesh

80 Hz

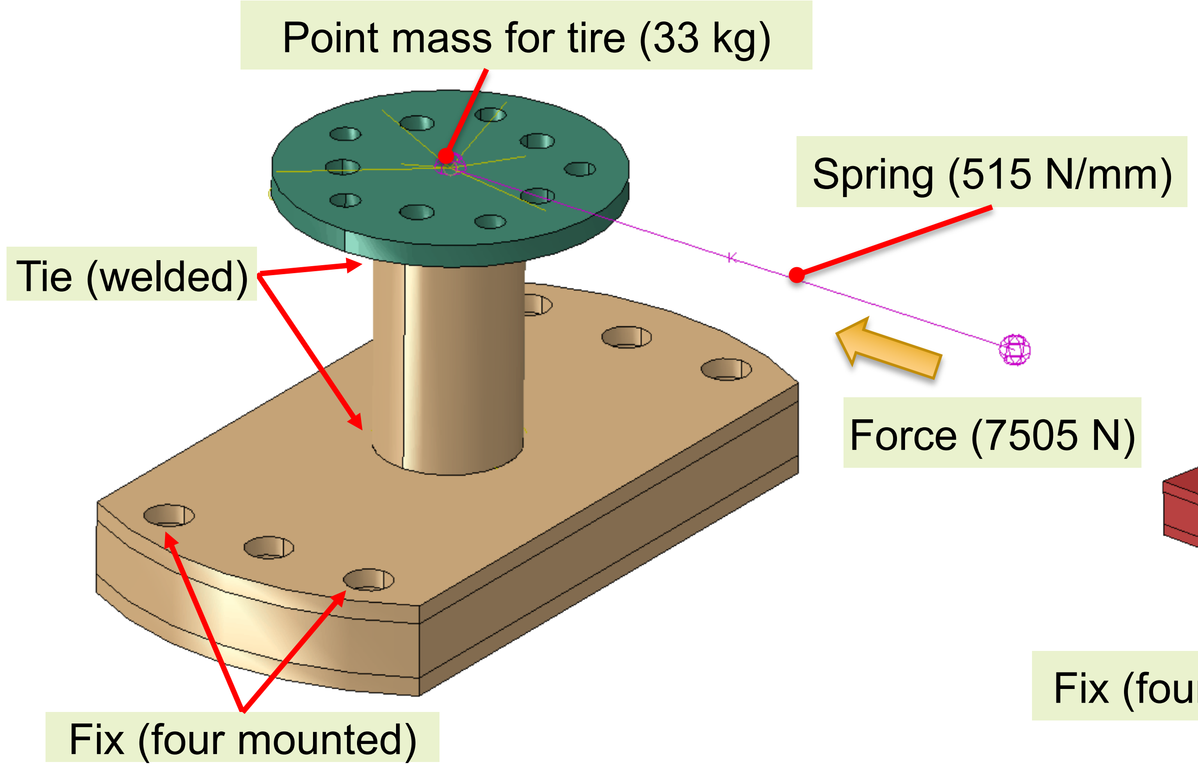


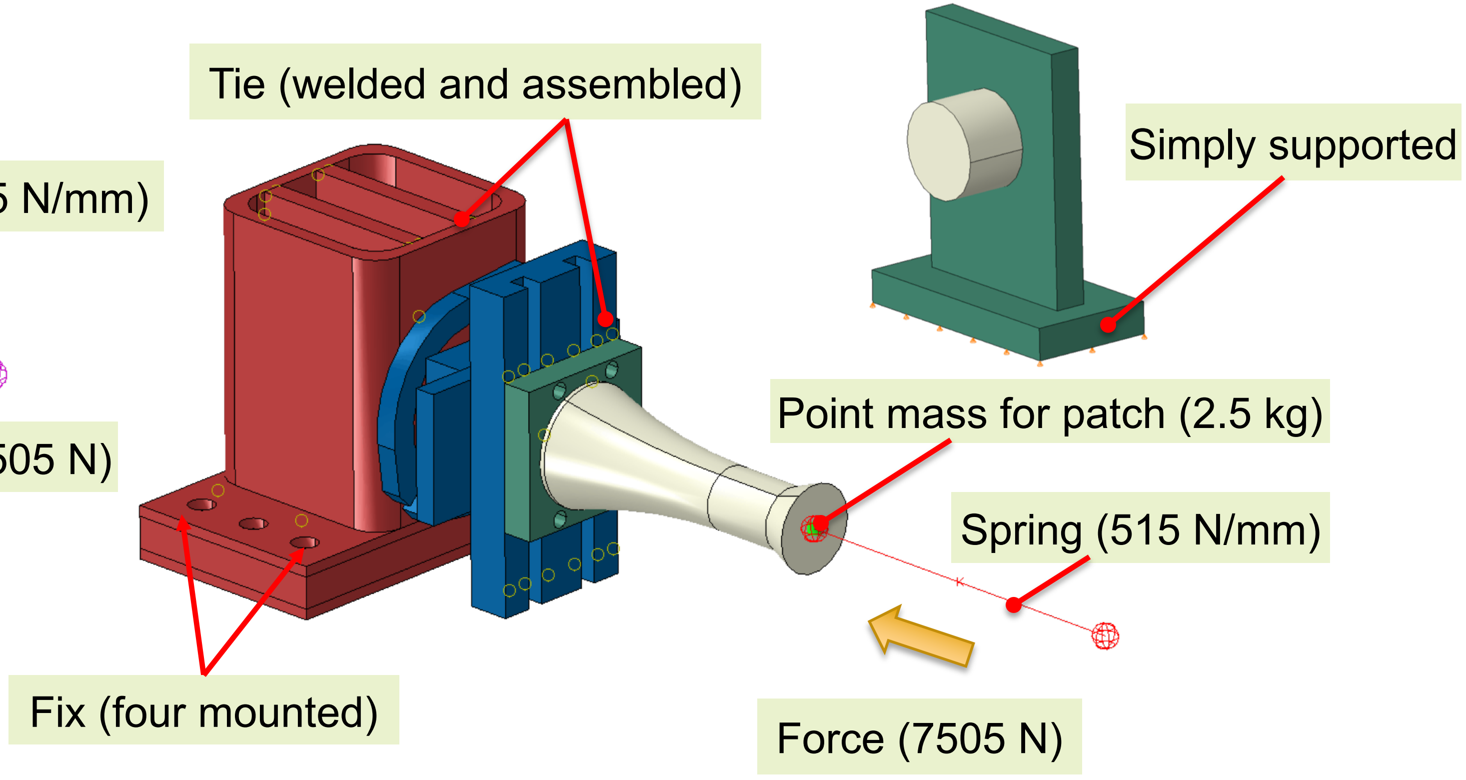
(b) 3-D mesh

Modal Analysis

Boundary and load

- Tie condition is applied for welding and assembly with fixed mounting
- Tire is modeled as a combination of point mass, spring, and static force to simulate deflection





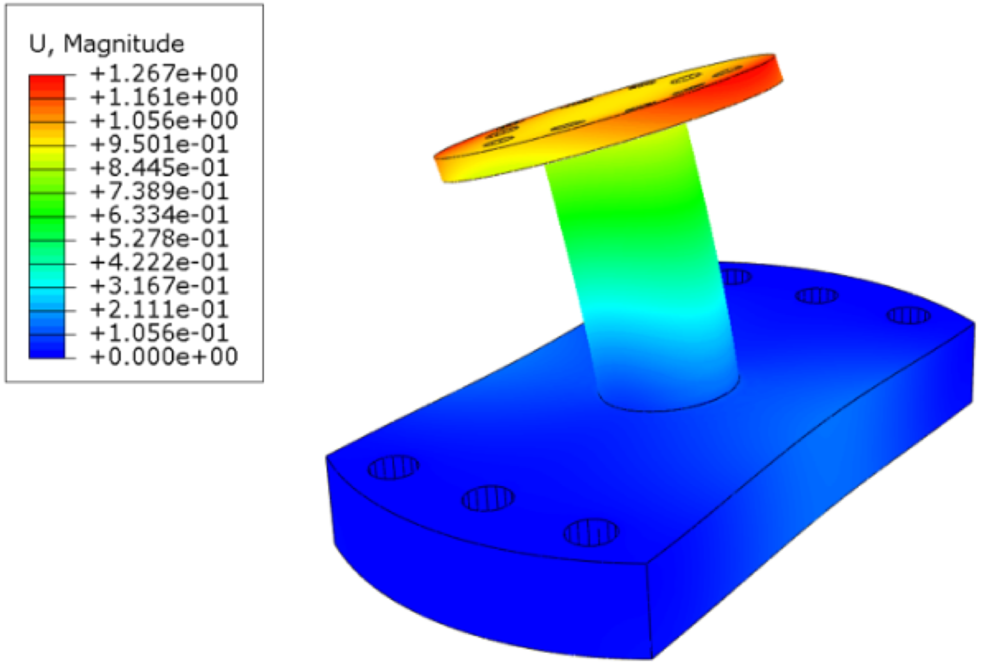
Modal Analysis

Simulation results

- Testbed

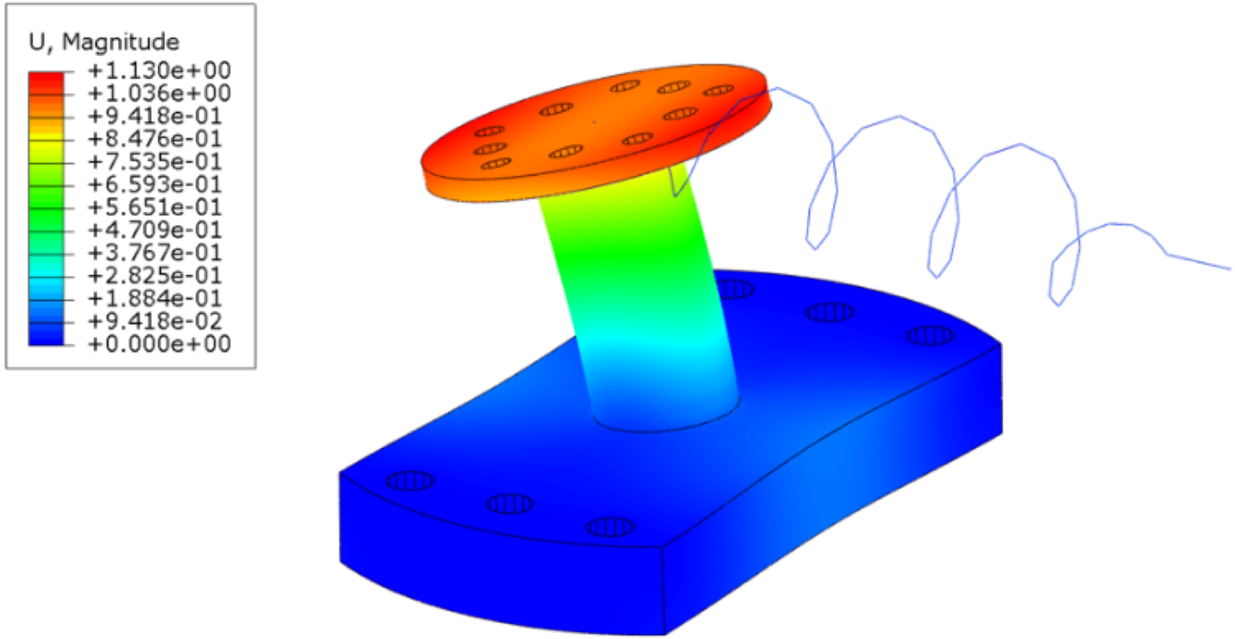
(a) without tire

900 Hz



(b) with tire

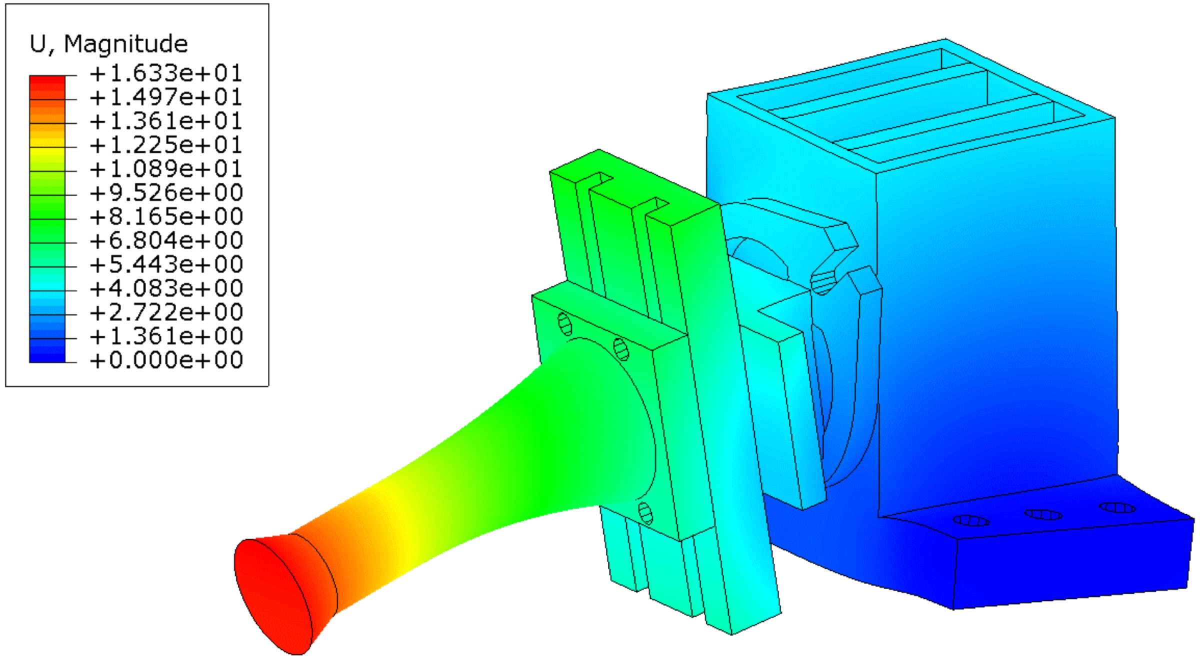
312 Hz



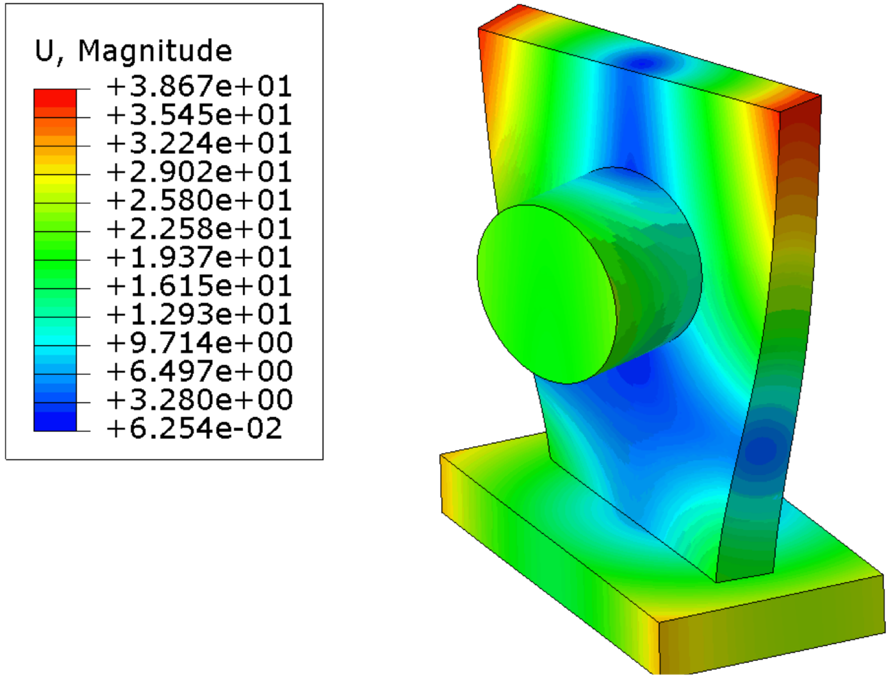
Simulation results

- Loading device & Shaker support

(c) Loading device **433 Hz**



(d) Shaker support **1670 Hz**

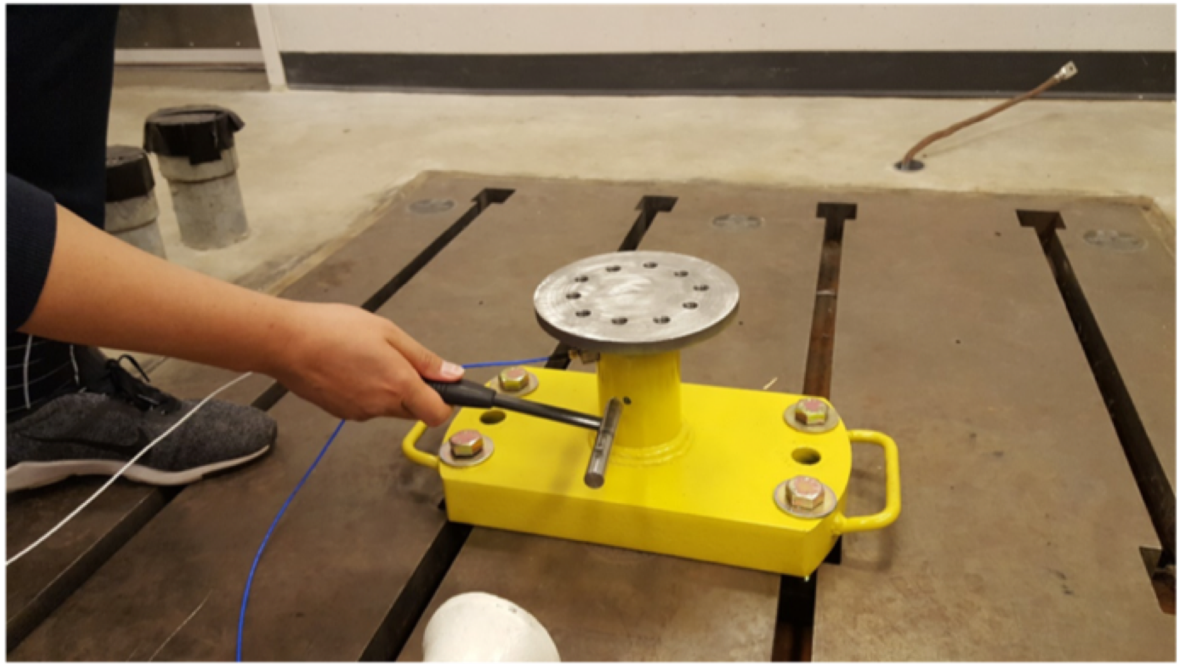


Impact Hammer Test

Test setup

- To confirm the results of numerical modal analysis
- Three-axis accelerometer is attached to a point where coherence factor is above 0.8

(a) without tire



(b) with tire under loaded

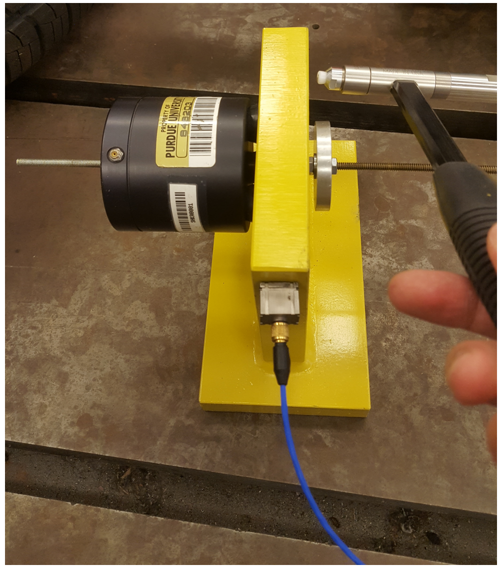
(refer to Appendix to see lists of measurement devices)

Impact Hammer Test

Test setup

- To confirm the results of numerical modal analysis
- Three-axis accelerometer is attached to a point where coherence factor is above 0.8

(c) shaker in support



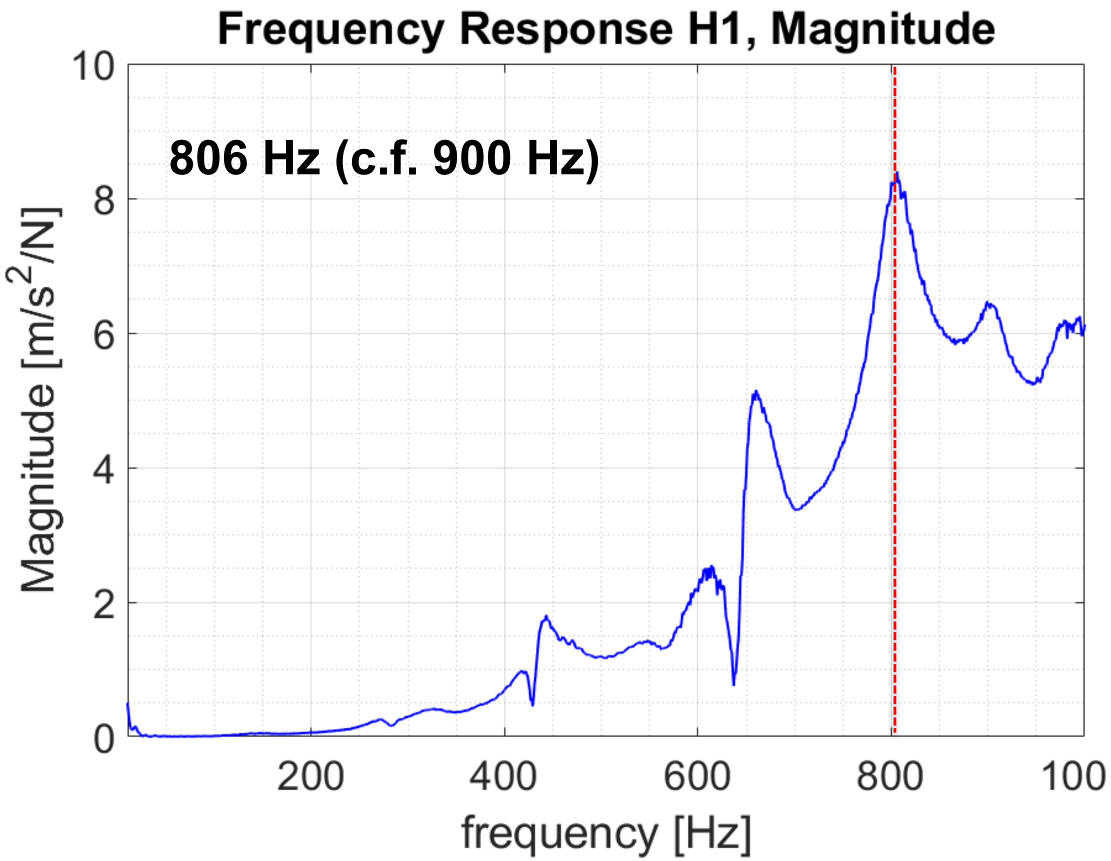
(refer to Appendix to see lists of measurement devices)

Impact Hammer Test

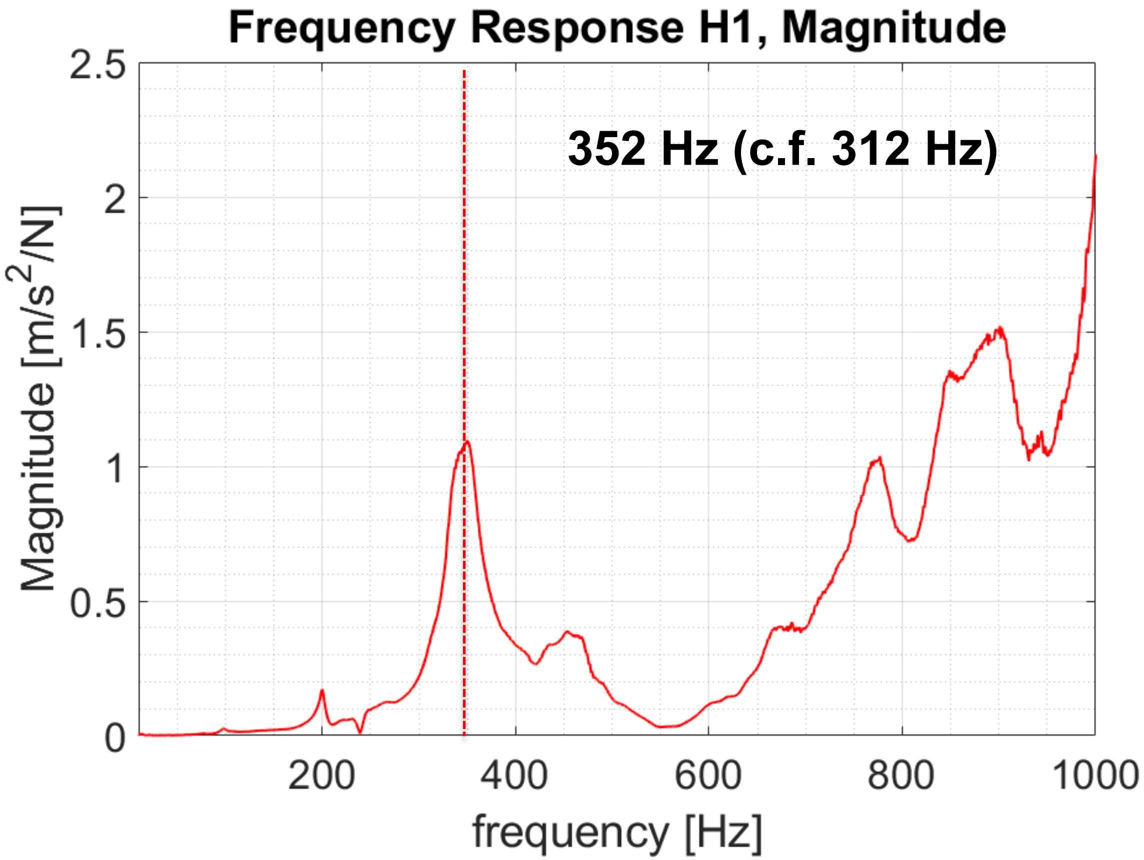
Results for testbed

- First natural frequency beyond 300 Hz for both cases, which conforms to numerical results

(a) without tire



(b) with tire

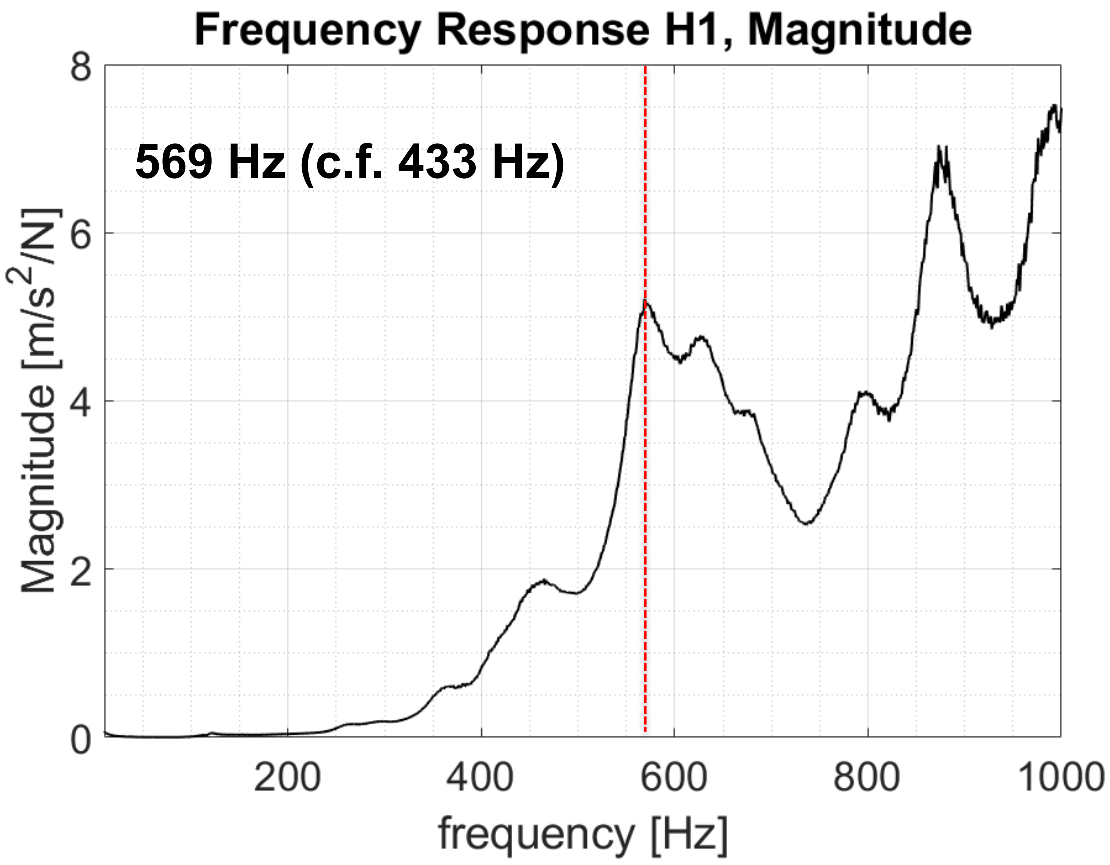


Impact Hammer Test

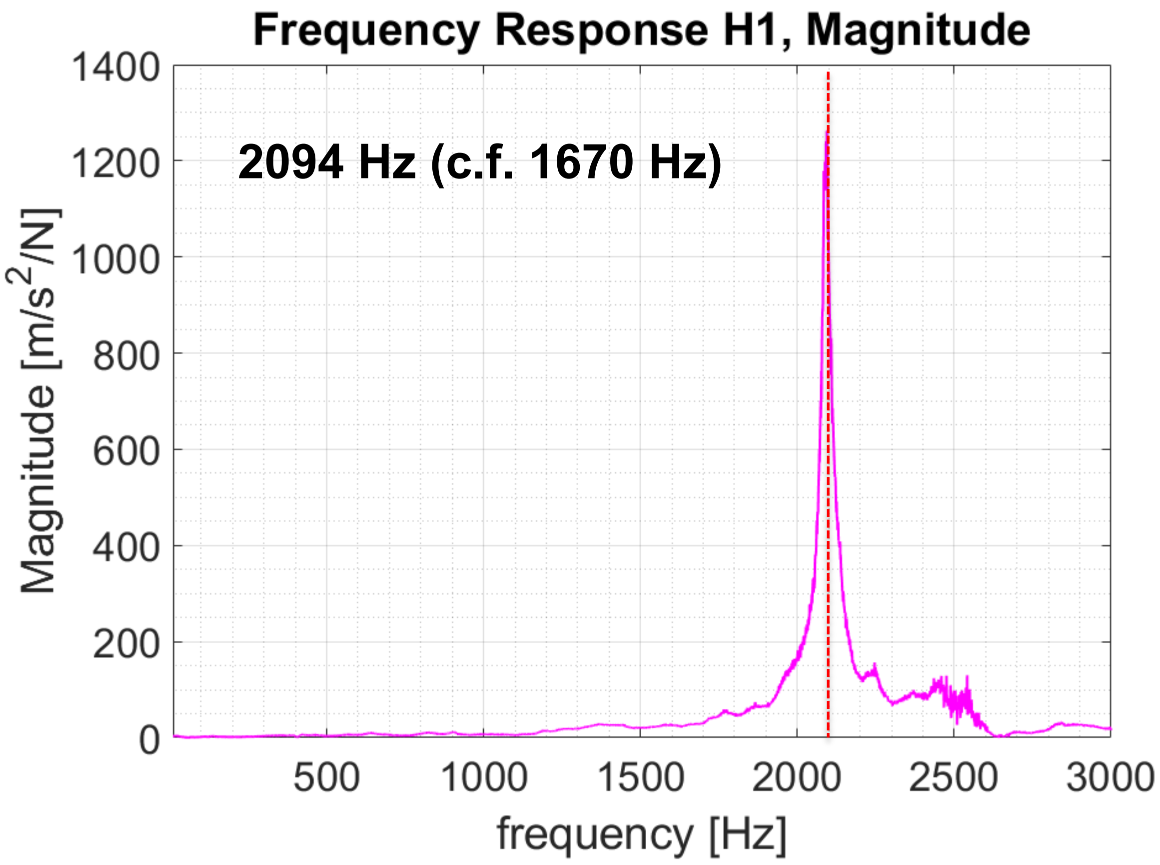
Results for loading device and shaker

- First natural frequency beyond 300 Hz for both cases, not perfectly matching prediction

(c) Loading device



(d) Shaker support



Impact Hammer Test

Summary

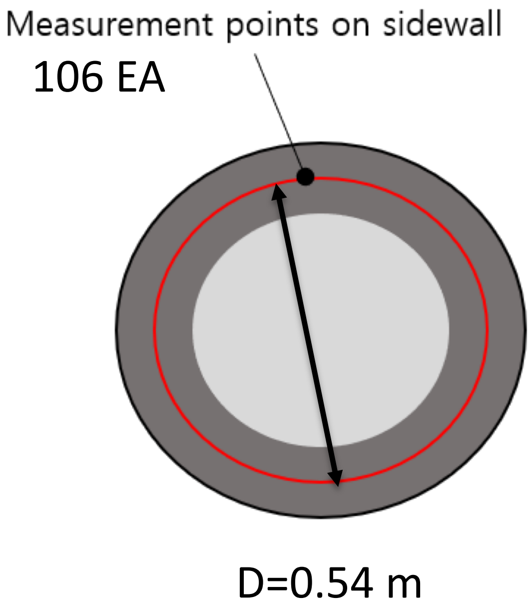
- Testbed has good agreement between numerical and experimental first natural frequency
- Loading device has a small discrepancy due to difficulty in fine modeling of moving slide and screw jack
- Shaker support matches reasonably well even though shaker modeling is challenging

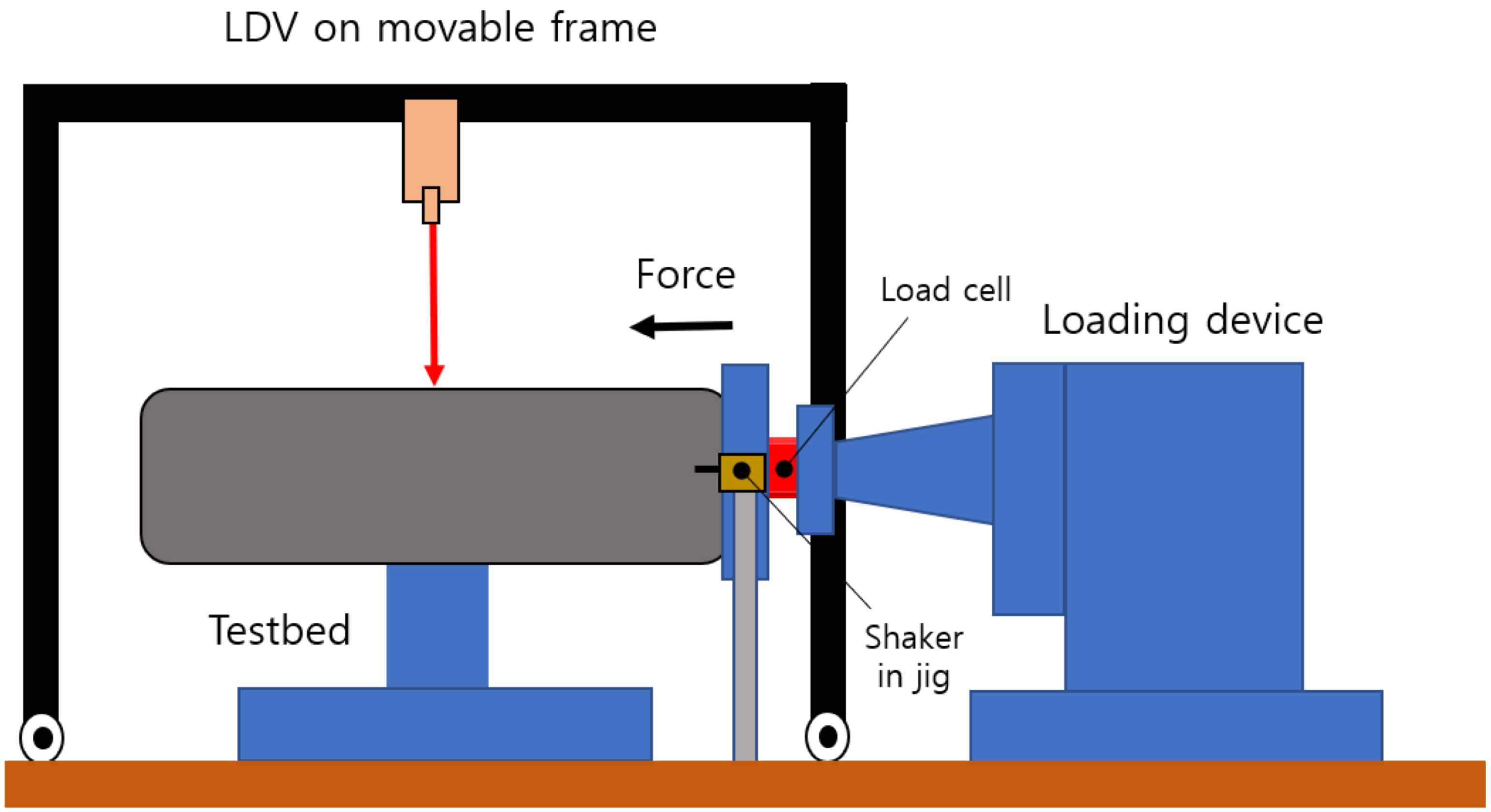
Description	FEM Mode	Test Mode
Testbed	900 Hz	806 Hz
Testbed with assembly	312 Hz	352 Hz
Loading device	433 Hz	569 Hz
Shaker support	1670 Hz	2094 Hz

Experiment with laser doppler vibrometer (LDV)

Schematic diagram

- Surface vibration on the sidewall under load can be detected from the top side

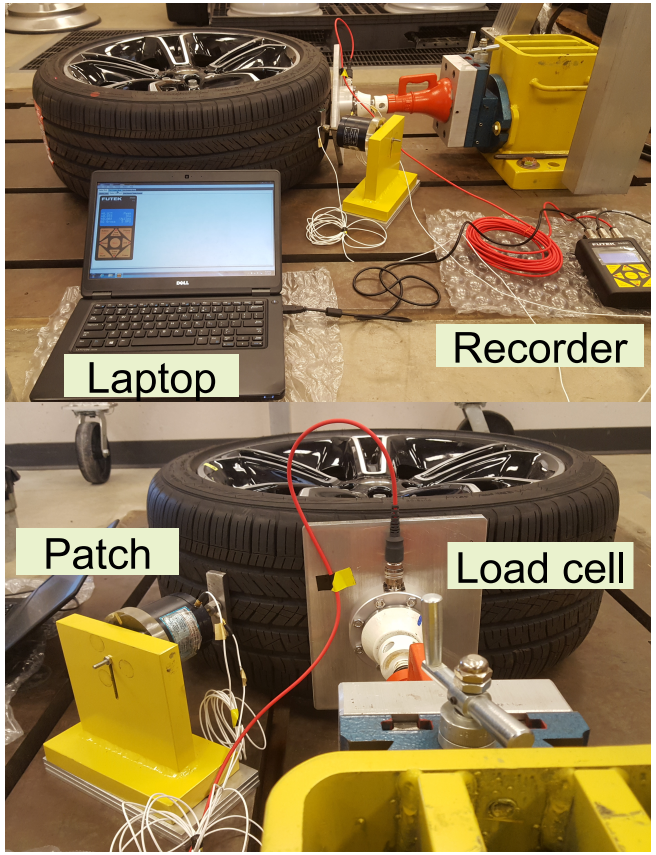


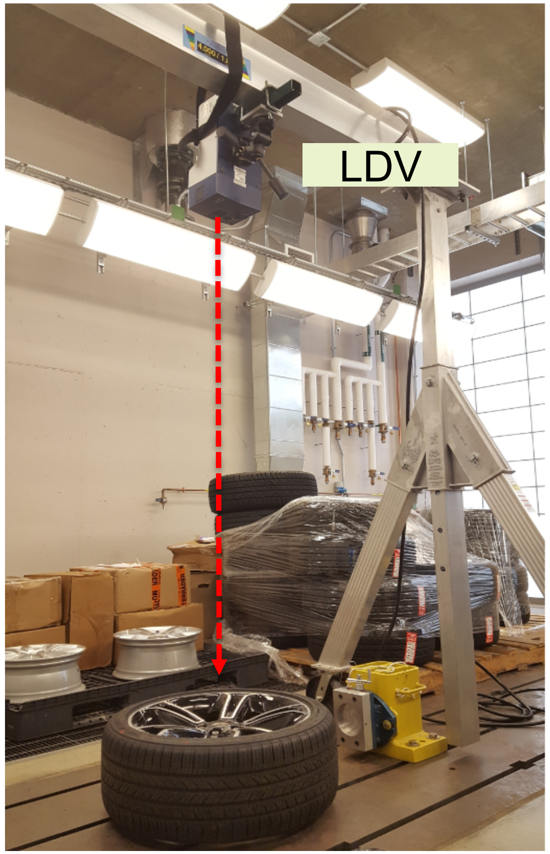


Experiment with laser doppler vibrometer (LDV)

Test Apparatus

- Mobility data can be obtained by measuring surface velocity and force for the deformed tire
- Static force (7505 N) is maintained through monitoring a load cell





Experiment with laser doppler vibrometer (LDV)

Test Apparatus

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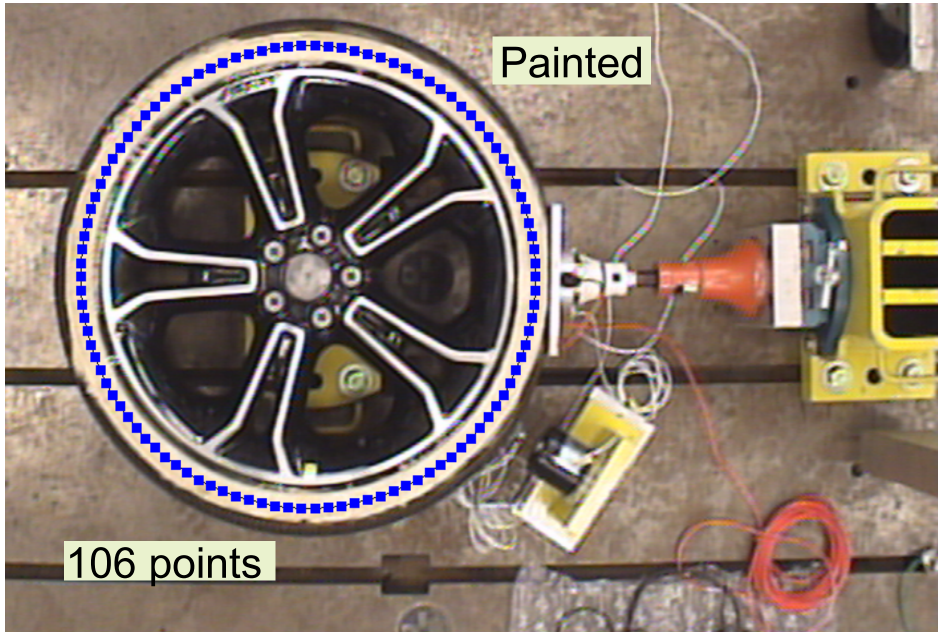
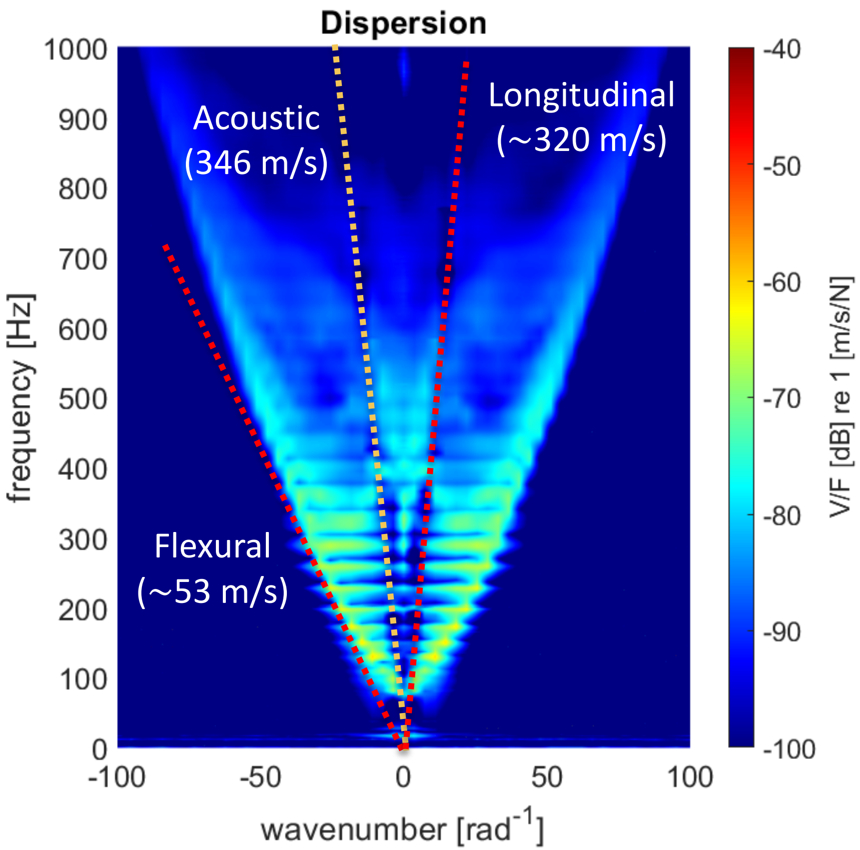


Experiment with laser doppler vibrometer (LDV)

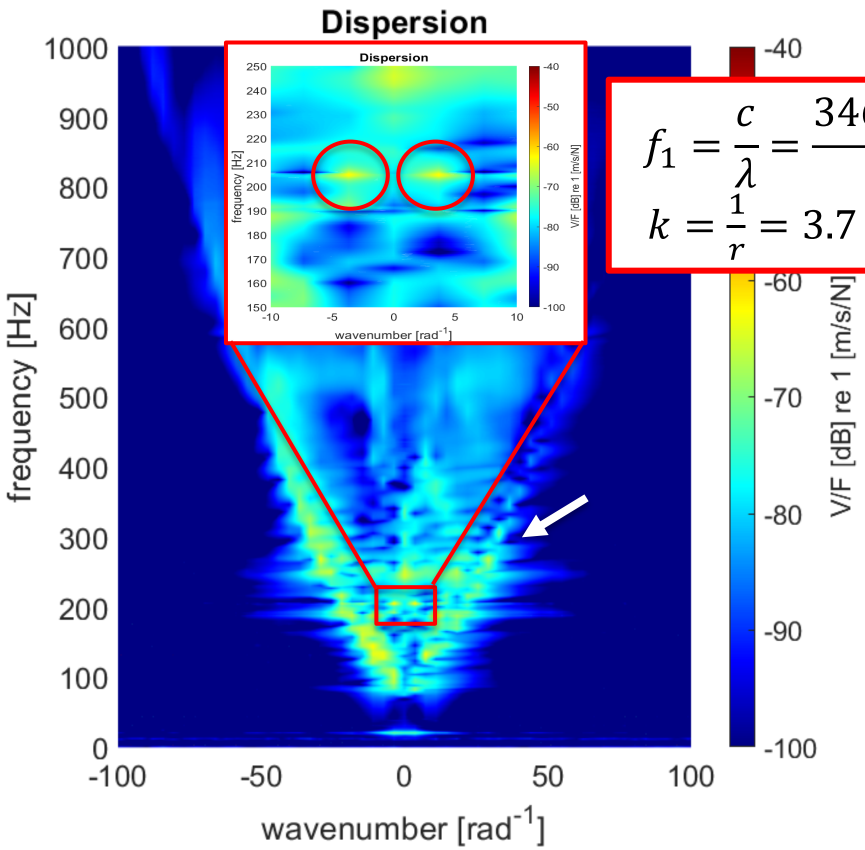
Example of measurement (20” tire)

- Dispersion curve is achieved by applying Fourier transform to spatial mobility

Unloaded



Loaded



$$f_1 = \frac{c}{\lambda} = \frac{346\ [m/s]}{2\pi r} = 204\ Hz$$

$$k = \frac{1}{r} = 3.7\ rad^{-1} \text{ (n=1)}$$

Conclusion

- Compact and cost efficient test rig was designed to measure dispersion characteristics of loaded tires
  - Allows height adjustment with force loading device
- Dynamically rigid behavior was achieved beyond 300 Hz, which was validated by both modal analysis and impact hammer test
  - More reliable to investigate frequency split in the first acoustic mode between 200 and 300 Hz
- Laser Doppler Vibrometer was used to observe dispersion characteristics of loaded tires combined with the test rig
  - Validated usefulness of the new test rig, generating meaningful results for the deformed tire
- Next steps are to quantify frequency split as function of load and deformation

Acknowledgement

- Ford Motor Company – Financial support / Tire & wheel sample provider
- Matthew Black – Main coordinator of this project
- Dan Haakenson – Technical advice and industrial feedback

THANK YOU

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[1] Sakata, T., Morimura, H. and Hideyuki, I. (1990) “ Effect of tire cavity resonance on vehicle road noise , ” *Tire Science and Technology*, Vol. **18(2)**, pp.68–79.

[2] Gunda, R., Gau, S. and Dohrmann, C. (2000) “Analytical Model of Tire Cavity Resonance and Coupled Tire/Cavity Modal Model, ” *Tire Science and Technology*, Vol. **30(1)**, pp.33–49.

[3] Yamauchi, H. and Akiyoshi, Y. (2002) “ Theoretical analysis of tire acoustic cavity noise and proposal of improvement technique, ” *JSAE Review*, Vol. **23**, pp.89–94.

[4] Bederna, C. and Saemann, E. (2009) “ Contributions to a better understanding of tire cavity noise, ” *NAG/DAGA 2009*, Rotterdam.

[5] B.A. Zai, and et al. (2011), “Structural Optimization of Cantilever Beam in Conjunction with Dynamic Analysis”, *Journal of the Korean Institute of Gas,* Vol. **15(5)**, pp.31-36.

Natural frequency of cantilever beam

- **1(L)×0.1(W)×0.1(H), steel**

Property	Value	Note
Young's modulus, E	210 GPa	
Moment of inertia, I	$8.33 \cdot 10^{-6}\ m^4$	$bh^3/_{12}$
Density, ρ	8000 kg/m^3	

$$f_1 = \frac{1.875^2}{2\pi L^2}\sqrt{\frac{EI}{\rho A}} = \frac{1.875^2}{2\pi(1\ m)^2}\sqrt{\frac{2\cdot 10^{11}\ N/m^2 \cdot 8.33\cdot 10^{-6}\ m^4}{8000\ kg/m^3 \cdot 0.01 m^2}} = 80\ \text{Hz}$$

Lists of equipment for tests

Impact Hammer Test

Type	Brand	Model	Remark
DAQ	B&K	3560-B-130	Frequency resolution, 1 Hz Five exponential averaging
Impact Hammer	PCB	086C03	Uniform window
Accelerometer	B&K	4506	Hanning window

LDV Test

Type	Brand	Model	Remark
LDV	Polytec	PSV-400	Frequency resolution, 0.156 Hz Five exponential averaging
Shaker	B&K	4810	White noise
Force transducer	PCB	208A3	Hanning window
Amplifier	QSC	1080	Max. force, 5 N
Analog filter	Wavetek	852	40 Hz ~ 1 kHz
Load Cell	Futek	LCF450	Max. force 8,829 N

Configuration of T slot