7-10-2018

Finite Element Study of Acoustic Mode Force Transmission in a Loaded, Structural-Acoustical Tire Model

Rui Cao
Purdue University, cao101@purdue.edu

J Stuart Bolton
Purdue University, bolton@purdue.edu

Cao, Rui and Bolton, J Stuart, "Finite Element Study of Acoustic Mode Force Transmission in a Loaded, Structural-Acoustical Tire Model" (2018). *Publications of the Ray W. Herrick Laboratories.* Paper 175.
https://docs.lib.purdue.edu/herrick/175

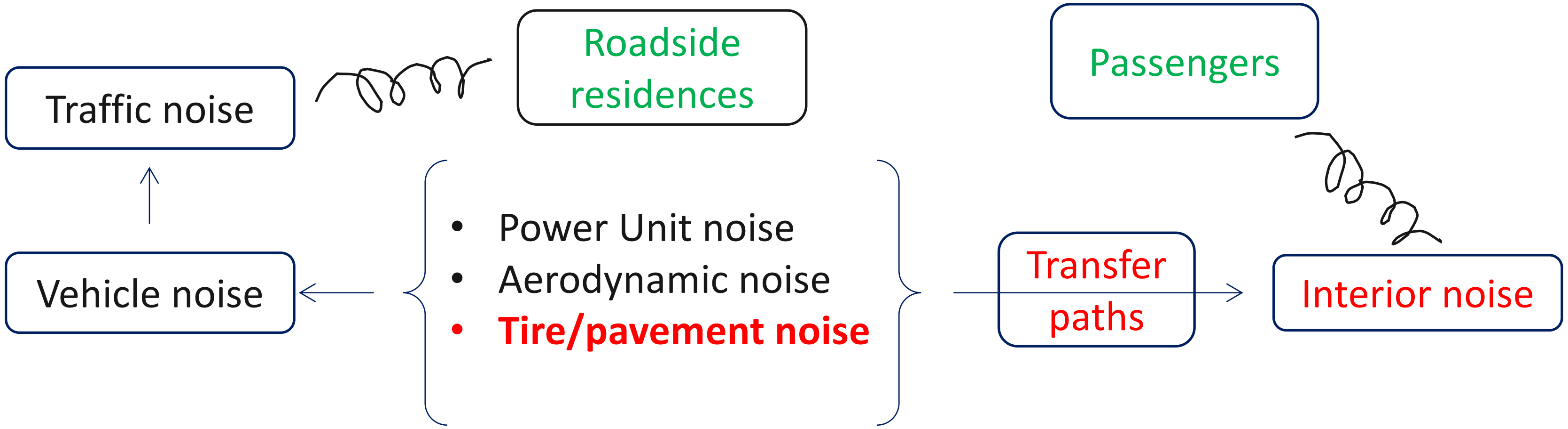
Force transmission characteristics for a loaded structural-acoustic tire model

Ray W. Herrick Laboratories,
Purdue University, USA
Rui Cao and J. Stuart Bolton
07/10 2018

ICSV25
25th International Congress on Sound and Vibration
8-12 July 2018 HIROSHIMA CALLING

Herrick Laboratories
PURDUE UNIVERSITY

I. Introduction



Traffic noise

Roadside residences

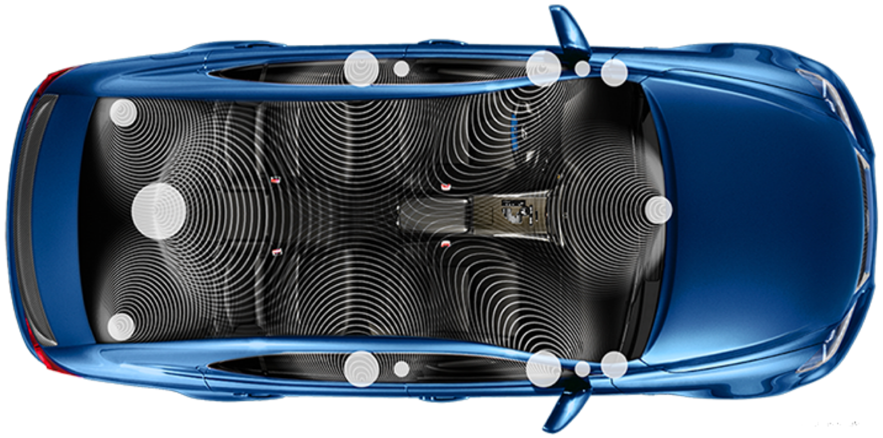
Passengers

Vehicle noise

- Power Unit noise
- Aerodynamic noise
- **Tire/pavement noise**

Transfer paths

Interior noise

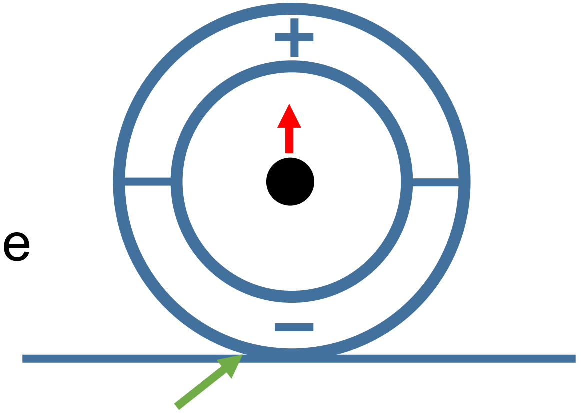


I. Introduction

- High frequency interior noise is mostly airborne and usually is not associated with structural vibration from road excitation. However, low frequency noise, has a strong association with structural vibration and can be perceived by the passengers.
- A major component of structure-borne noise comes from the tire's acoustic cavity mode near 200 Hz

Why do two tires of same size and geometry, from different manufacturers, have very different responses, in terms of cavity noise perception?

- Study force transmission from contact patch excitation to rim center
- How the cavity resonance may affect force transmission
- Ways of identifying bad tires/good tires, in terms of structure-borne noise



II. Finite element tire model

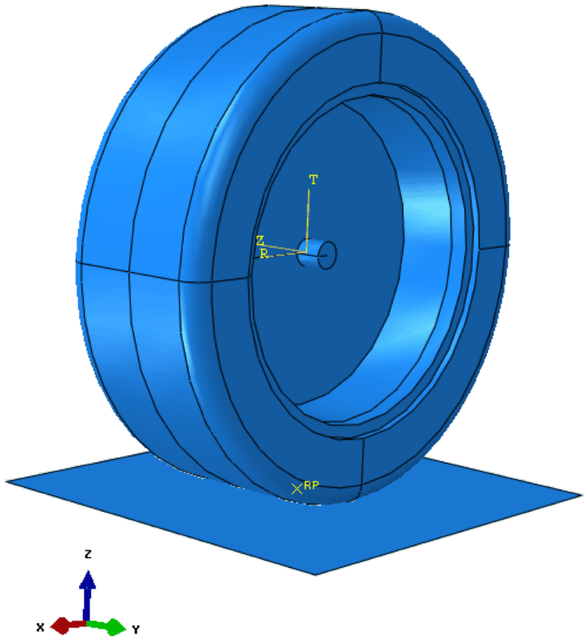
A Finite Element structural-acoustical tire model was created to investigate the tire cavity-induced structure-borne noise

- Create realistic tire-road contact patch
- Point excitation at the contact patch edge
- Calculate dispersion relation in tire tread to identify vibration modes, as from test results
- Calculate force transmission from excitation location to the rim center, to act as input for full vehicle analysis
- Comparison study to identify the influencing factors

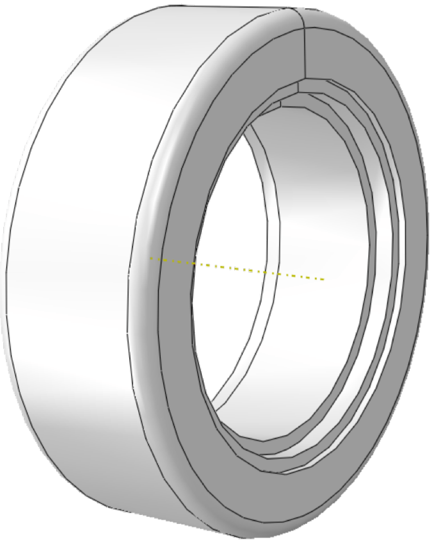
II. Finite element tire model

All modeling was performed in Abaqus 6.13

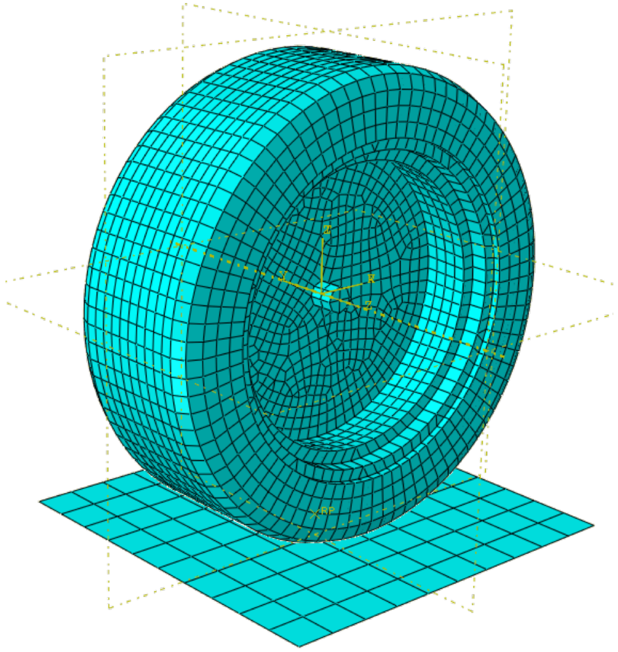
Assembled model



Air cavity model



Meshed assembled model



A 245/40R20 tire was used for dimension

II. Finite element tire model

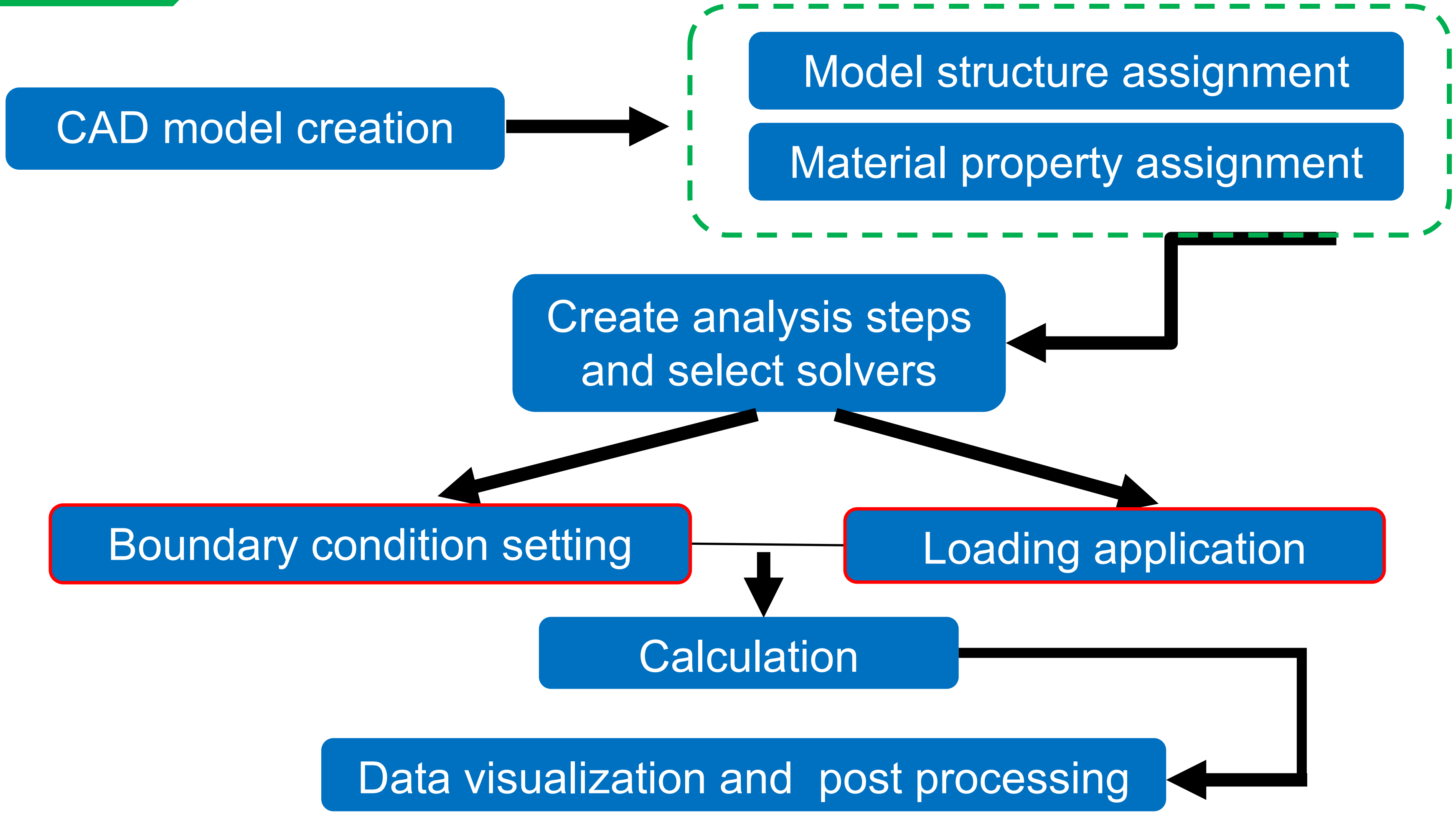
All parts are using homogeneous material

Part	Density [kg/m^3]	Modulus [Pa]	Thickness [mm]	Poisson's ratio
Rim	2700	7×10^{12}	10	0.3
Tread	1200	7.5×10^{8}	10	0.45
Sidewall	800	5×10^{7}	8	0.45
Air	1.204	149180	N/A	N/A

- ❖ Material properties were simplified and approximated
- ❖ Rim was set to be very stiff, so it's resonances were above the frequency of interest in this study
- ❖ Air bulk modulus was given at 97 ˚F

III. Analysis process

Overview



CAD model creation

Model structure assignment

Material property assignment

Create analysis steps and select solvers

Boundary condition setting

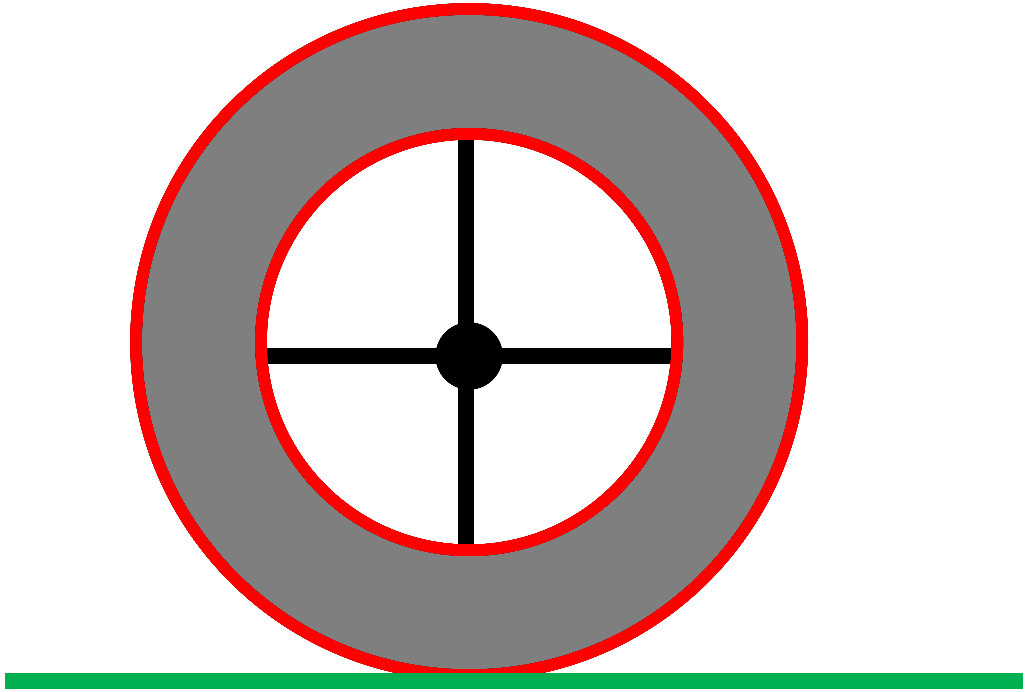
Loading application

Calculation

Data visualization and post processing

III. Analysis process

Boundary conditions



Continuity boundary

Tread – Air Cavity

Sidewall – Air Cavity

Rim – Air Cavity

"TIE" function was applied to enforce the two surfaces stay in contact at all times

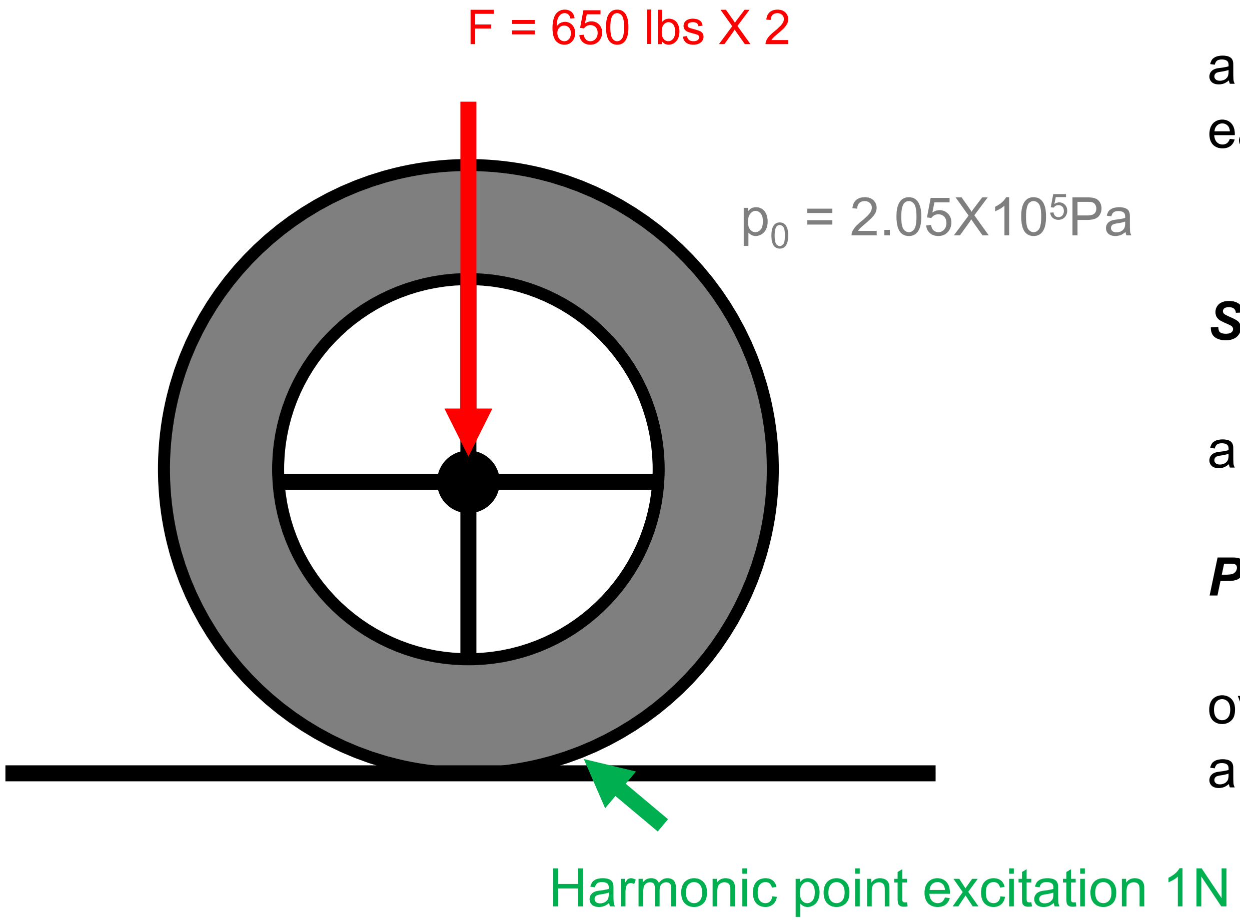
Contact boundary:

Tread surface – rigid ground

Ground is considered rigid in the normal direction; a small friction coefficient is added to increase solution robustness (prevent tire sliding horizontally as the contact starts)

III. Analysis process

Excitations



Vertical static loads

1300 lbs (approximately 6000 N) applied at the rim center – with 650 lbs on each side

Static inflation pressure

A $2.05X10^5$ Pa inflation pressure was applied to all tire interior cavity surfaces

Point harmonic excitation

A 1 N point harmonic point excitation over the investigated frequency range was applied at the contact patch leading edge

III. Analysis process

Analysis Steps

Initial step – fix rim center

Step 1 – Tire inflation

- rim center is still fixed

Step 2 – Apply vertical load

- rim center is released
- require adaptive mesh of the air cavity

Step 3 – Modal analysis

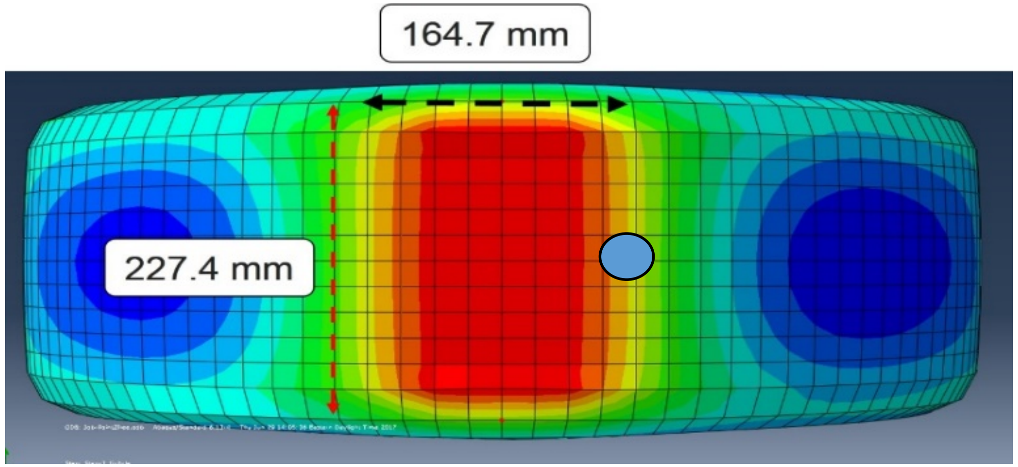
- extract modes from 10 Hz to 320 Hz

Step 4 – Forced response calculation

- direct approach
- 0.5 Hz increment

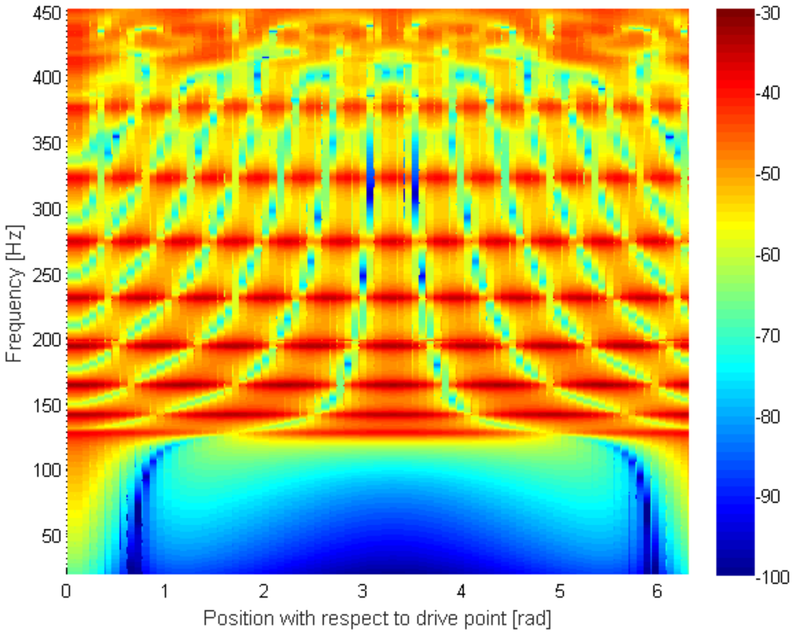
IV. Data visualization and comparison study

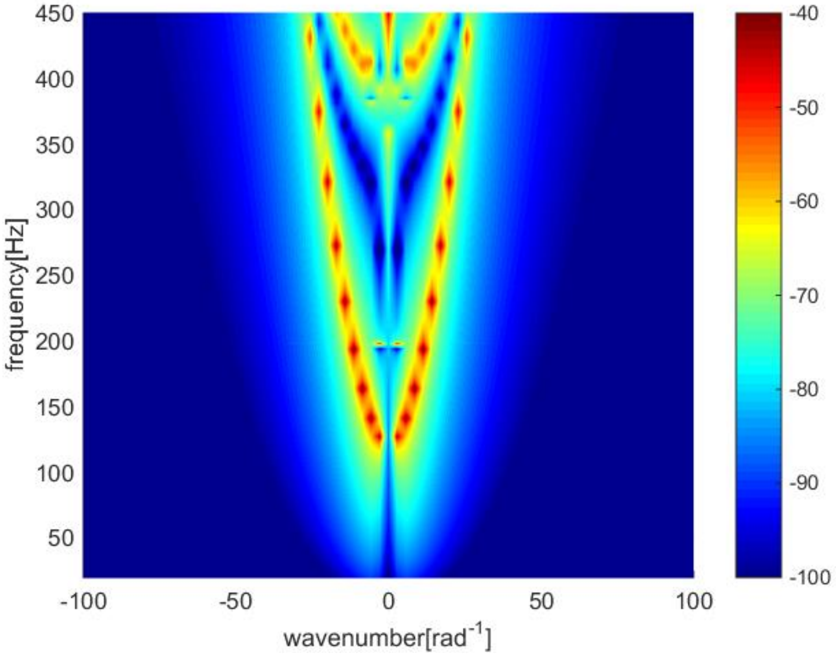
- What to expect from the results
  - ➢ Surface velocity of the tire tread – identify vibration modes
  - ➢ Dispersion relation of the tire tread – identify wave types
  - ➢ Rim center acceleration – force transmissibility study
  - ➢ Cavity and structural mode shapes



Contact patch area

IV. Data visualization and comparison study

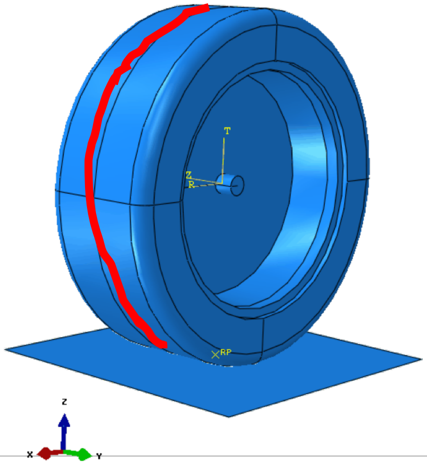




Drive point

Spatial Surface velocity
- unloaded tire

Velocity was measured at points along the tire tread centerline

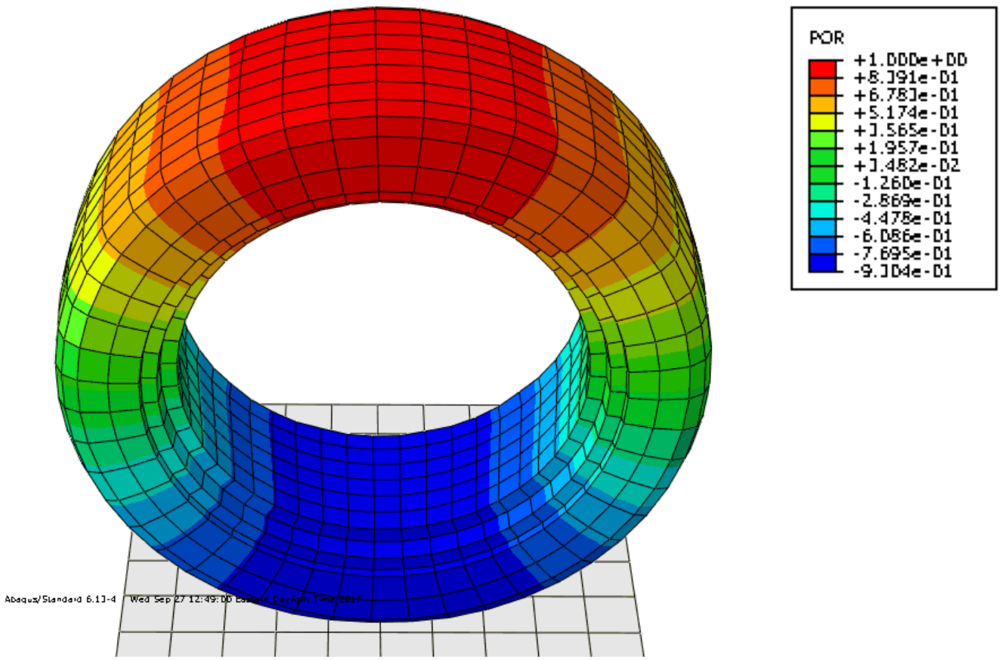


Dispersion relations
- unloaded tire

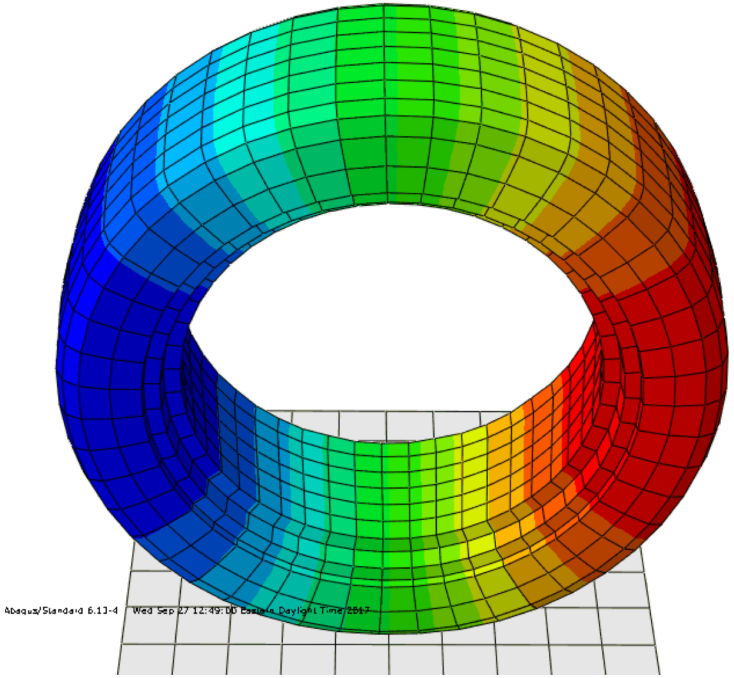
Dispersion was based on the wavenumber decomposition of the surface mobility data

IV. Data visualization and comparison study

Vertical cavity mode (pressure distribution)



Horizontal cavity mode (pressure distribution)



- Deformation causes cavity resonance split
- One occurs below undeformed cavity resonance (horizontal)
- One occurs above undeformed cavity resonance (vertical)

Undeformed resonance: 200.1 Hz; vertical mode: 201.4 Hz; horizontal mode: 199.3 Hz

IV. Data visualization and comparison study

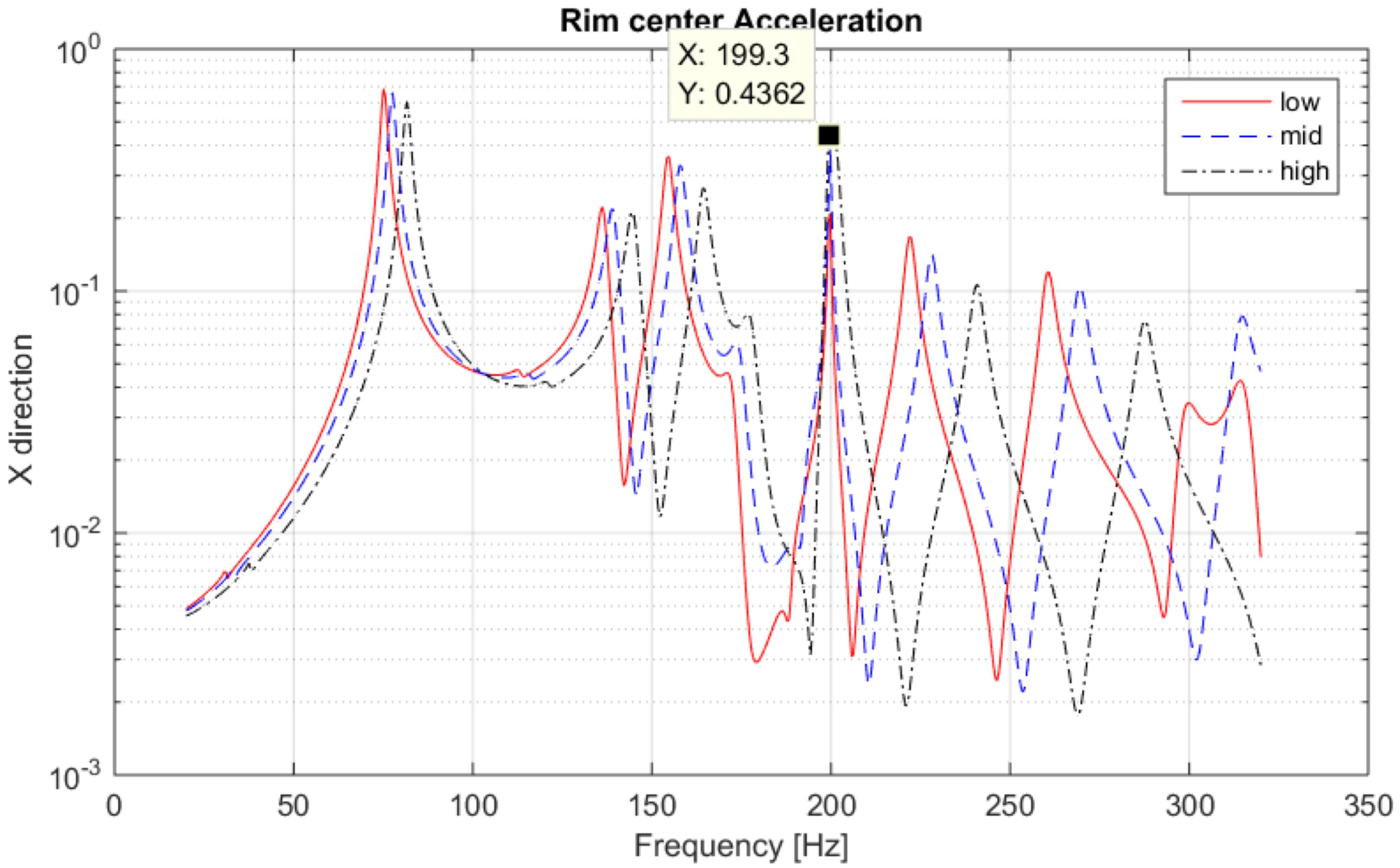
For GY245/40R20 tire, the material property of the tread was modified to be soft (low stiffness), medium (medium stiffness) and stiff (high stiffness) to align the ***vertical cavity resonance*** to either the symmetric circumferential 8th mode or the asymmetric circumferential 9th mode of the treadband.

Status	**Modulus**	**Alignment**
Soft	$4.5e^8$	9th mode
Medium	$6.0e^8$	In between
Stiff	$10.0e^8$	8th mode

Point excitation located at the contact patch on the tread centerline, toward the rim center. Most forcing component is in the vertical direction (+Z)

IV. Data visualization and comparison study

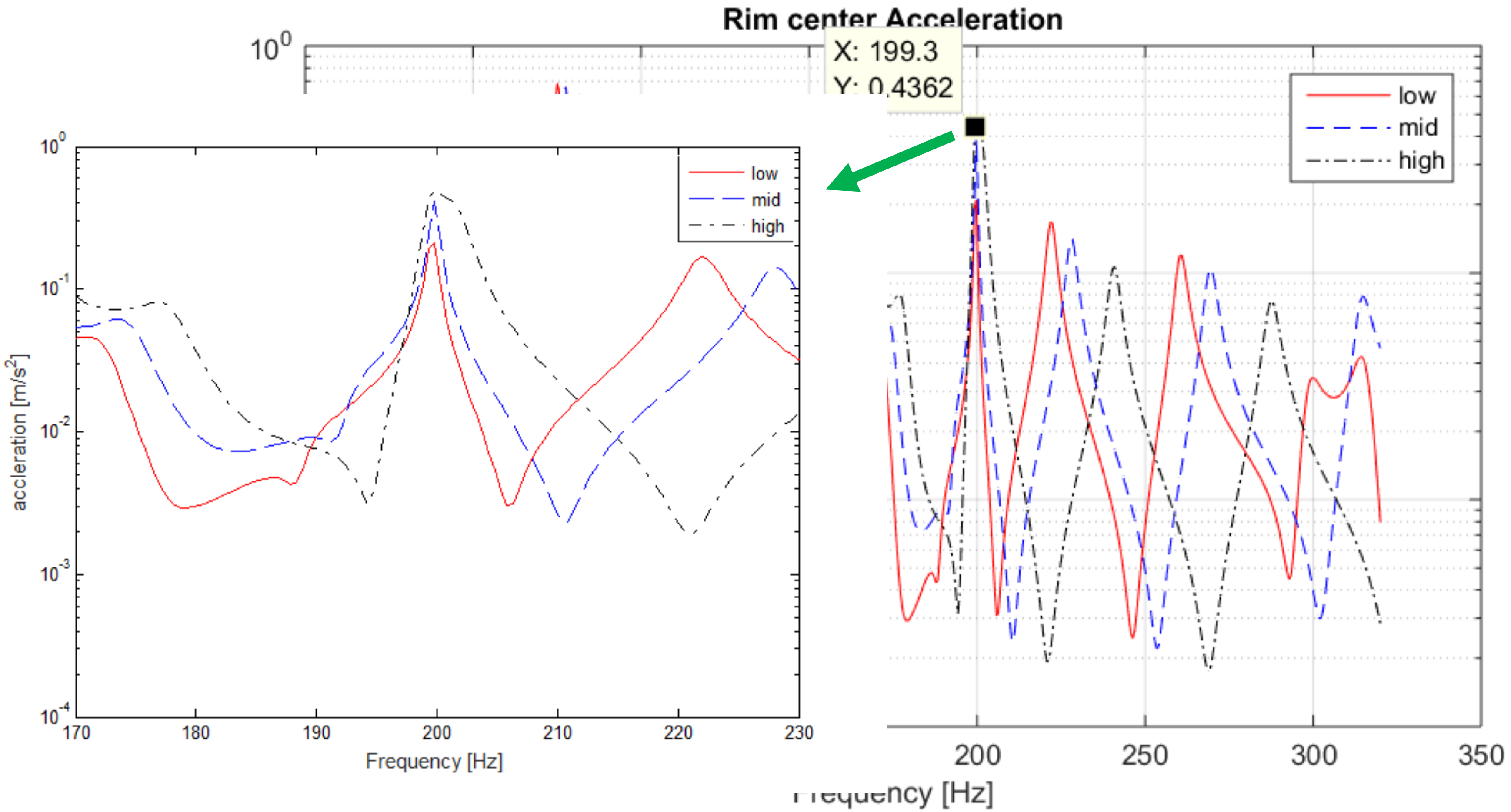
Rim center acceleration comparison



Peak at frequency corresponding to horizontal acoustic cavity mode

IV. Data visualization and comparison study

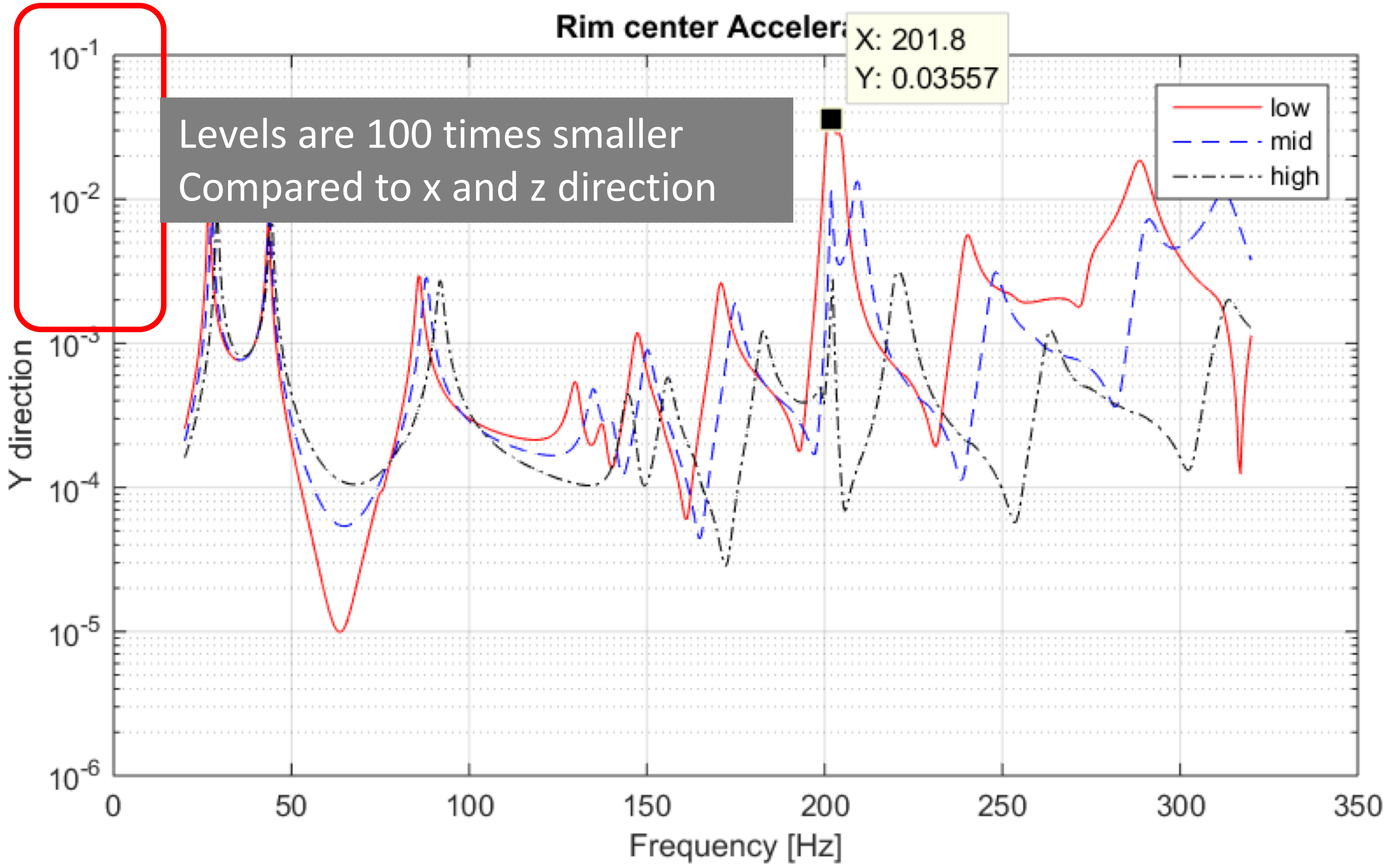
Rim center acceleration comparison



Peak at frequency corresponding to horizontal acoustic cavity mode

IV. Data visualization and comparison study

Rim center acceleration comparison

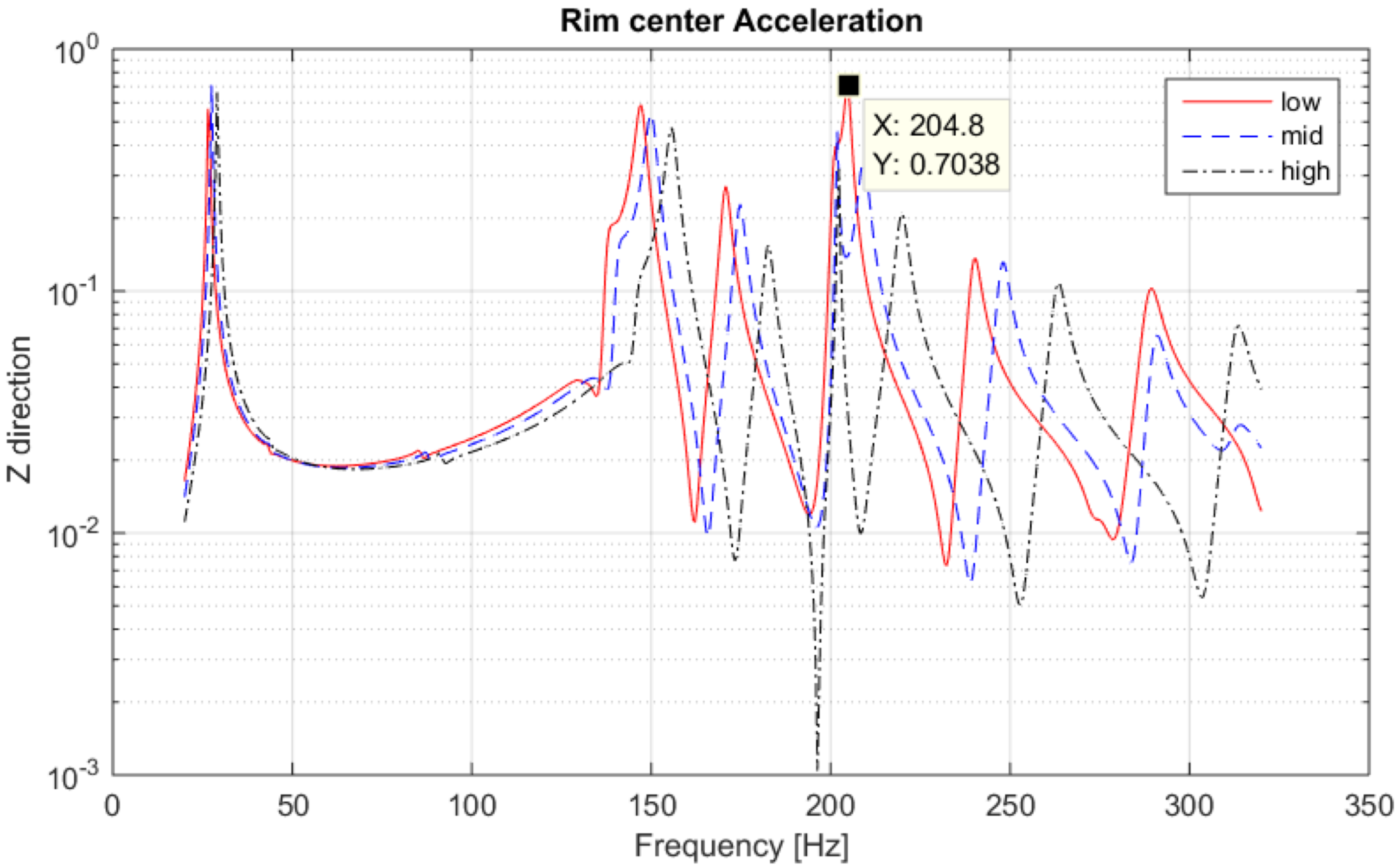


Levels are 100 times smaller
Compared to x and z direction

Very low levels in the y-direction – some axial component due to the rim profile

IV. Data visualization and comparison study

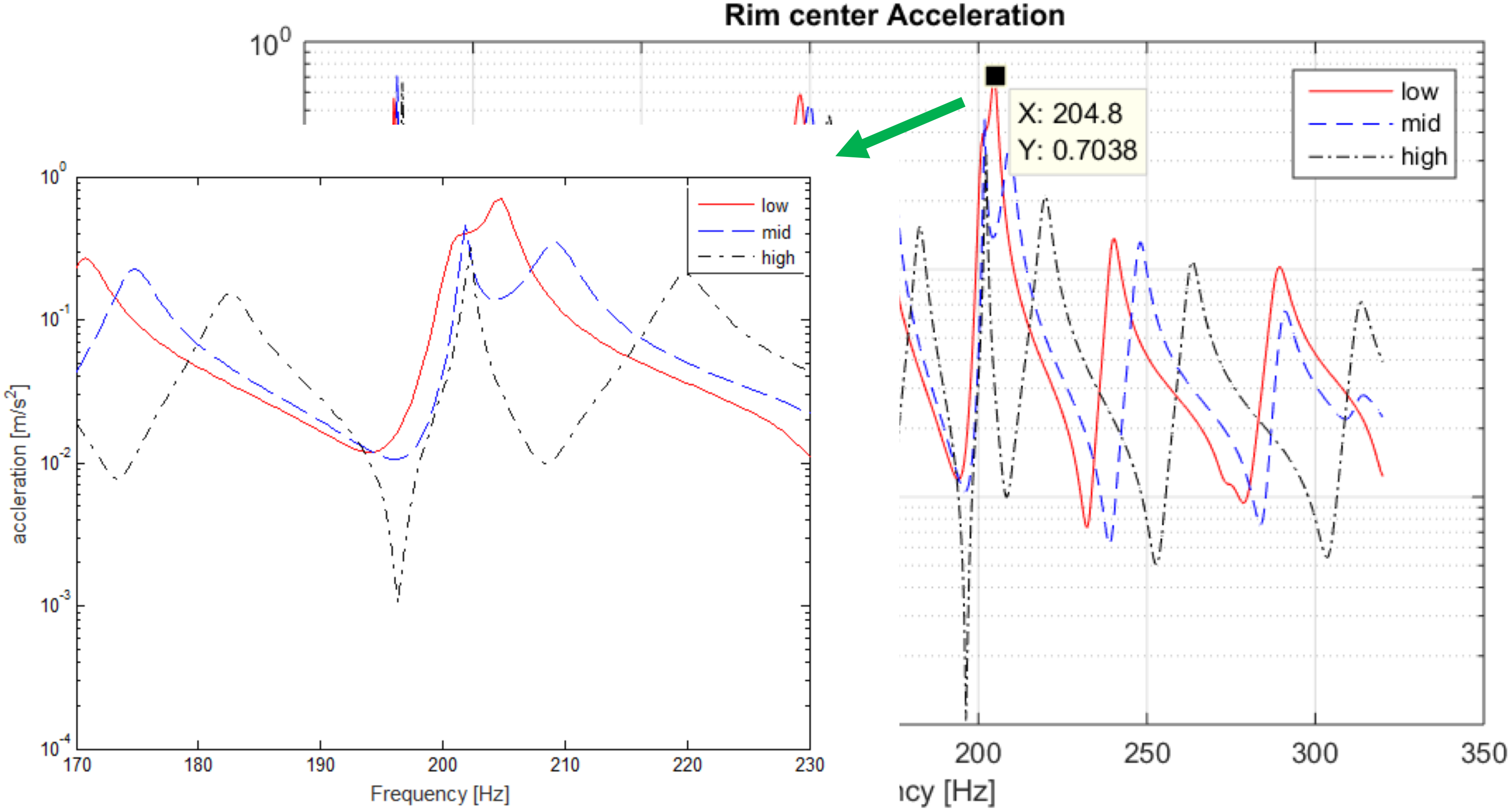
Rim center acceleration comparison



Peak at frequency corresponding to vertical acoustic cavity mode

IV. Data visualization and comparison study

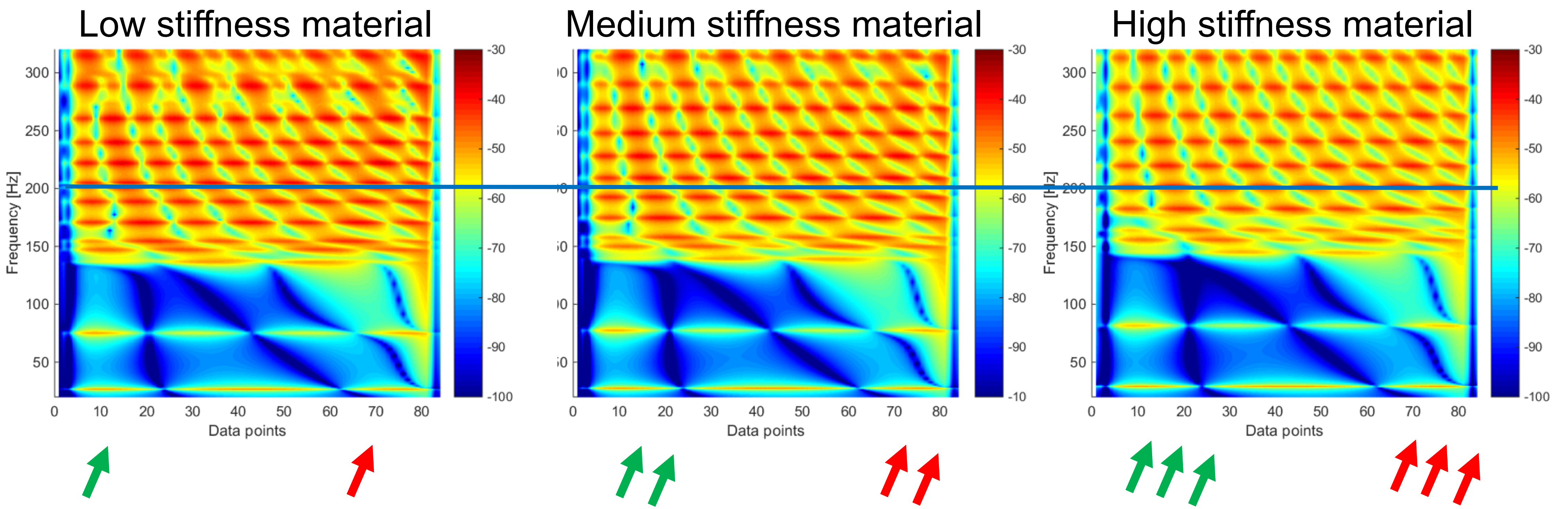
Rim center acceleration comparison



Peak at frequency corresponding to vertical acoustic cavity mode

IV. Data visualization and comparison study

Spatial mobility comparison



Stiffness Spatial pattern Stiffness Spatial pattern Stiffness Spatial pattern

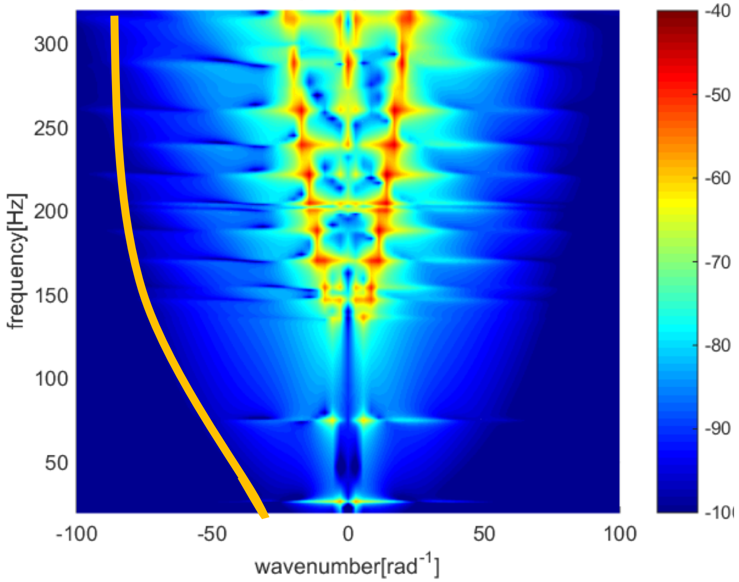
As stiffness increase, the spatial patterns move toward high frequency region

- Low stiffness – cavity mode matches 9th structural mode
- High stiffness – cavity mode matches 8th structural mode

IV. Data visualization and comparison study

Dispersion comparison

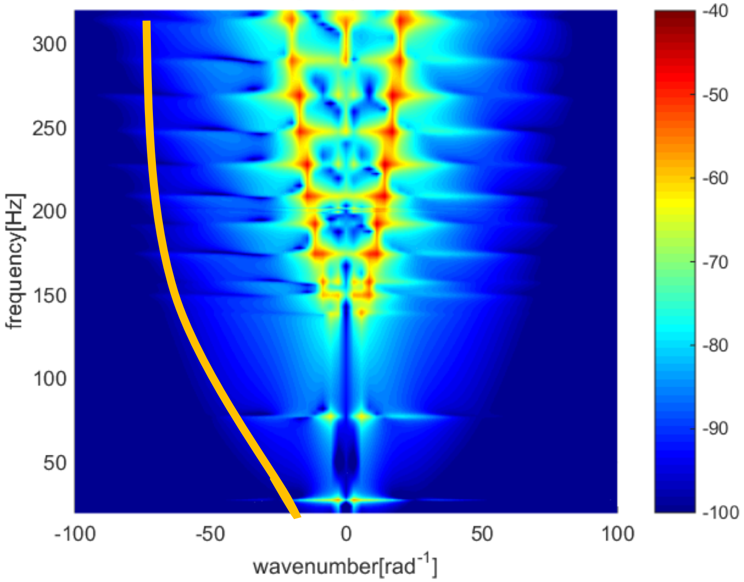
Low stiffness material



↑ Stiffness

↑ Wave speed

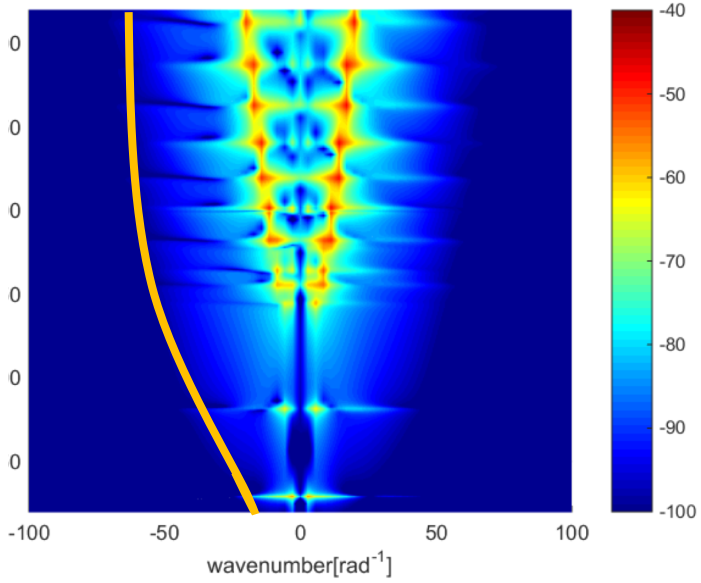
Medium stiffness material



↑↑ Stiffness

↑↑ Wave speed

High stiffness material



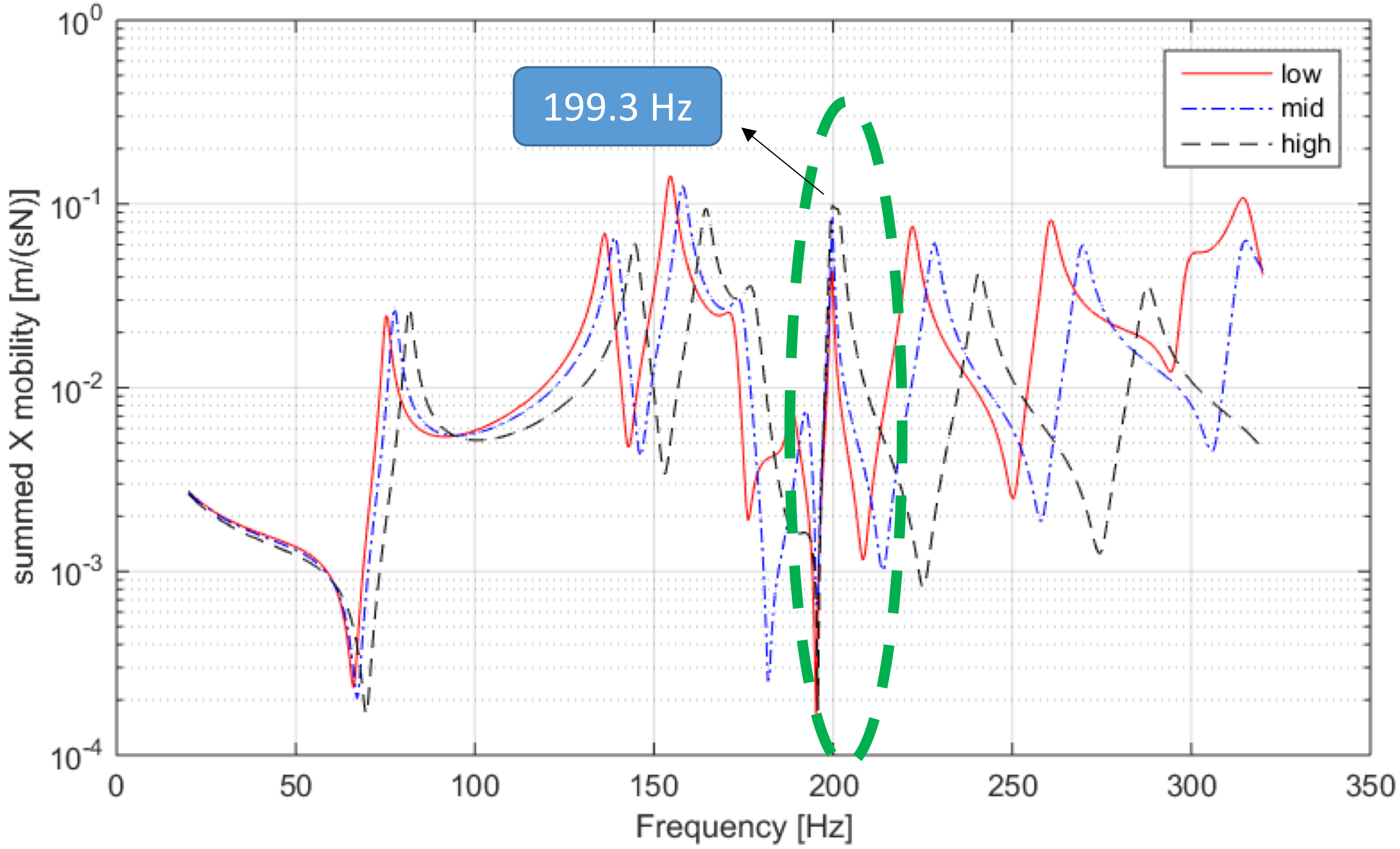
↑↑↑ Stiffness

↑↑↑ Wave speed

As stiffness increase, the dispersion curve becomes narrower, indicating faster waves

IV. Data visualization and comparison study

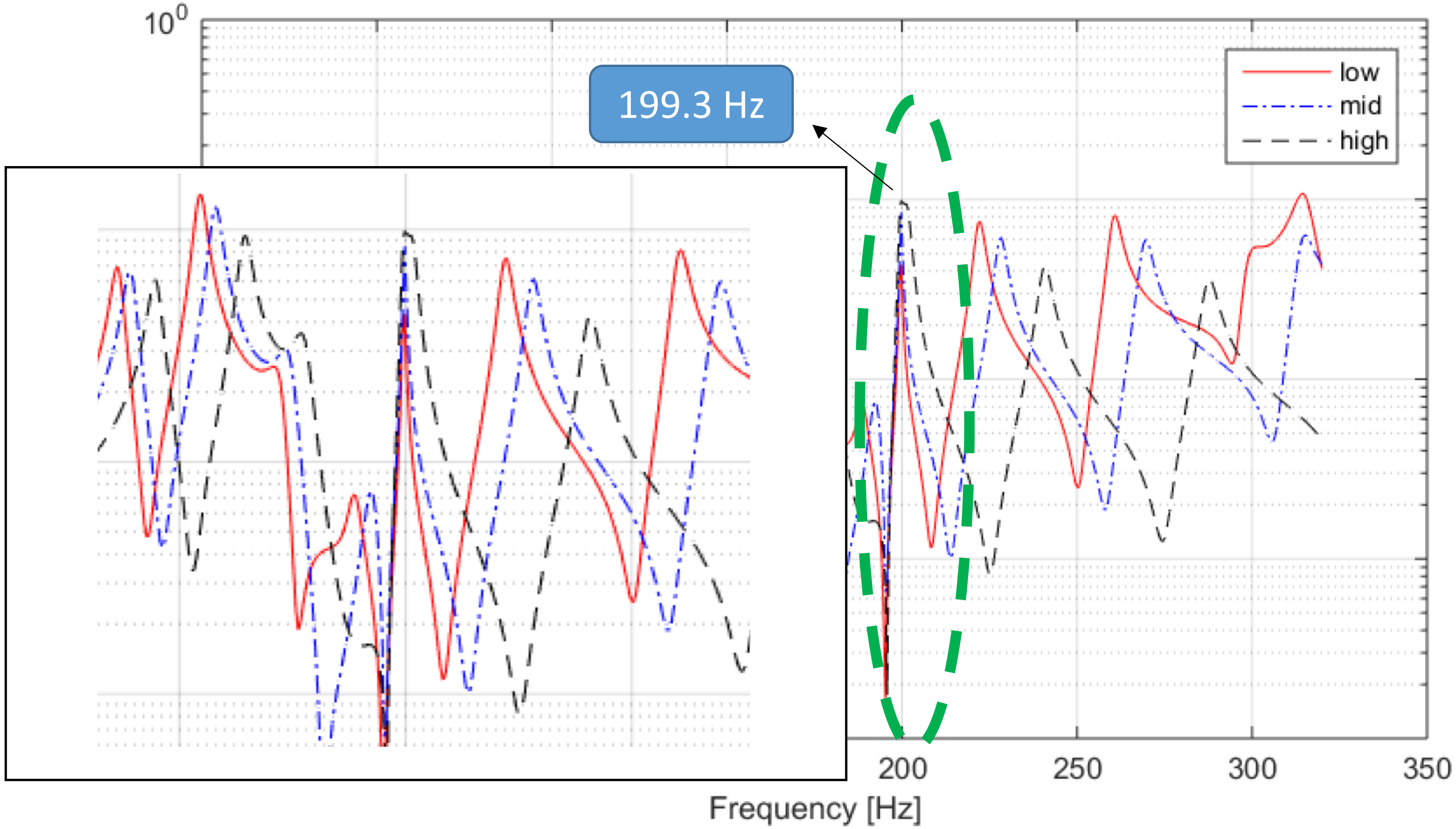
Resultant mobility in *X* direction



Resultant mobility – vector sum of mobility around tire in horizontal direction

IV. Data visualization and comparison study

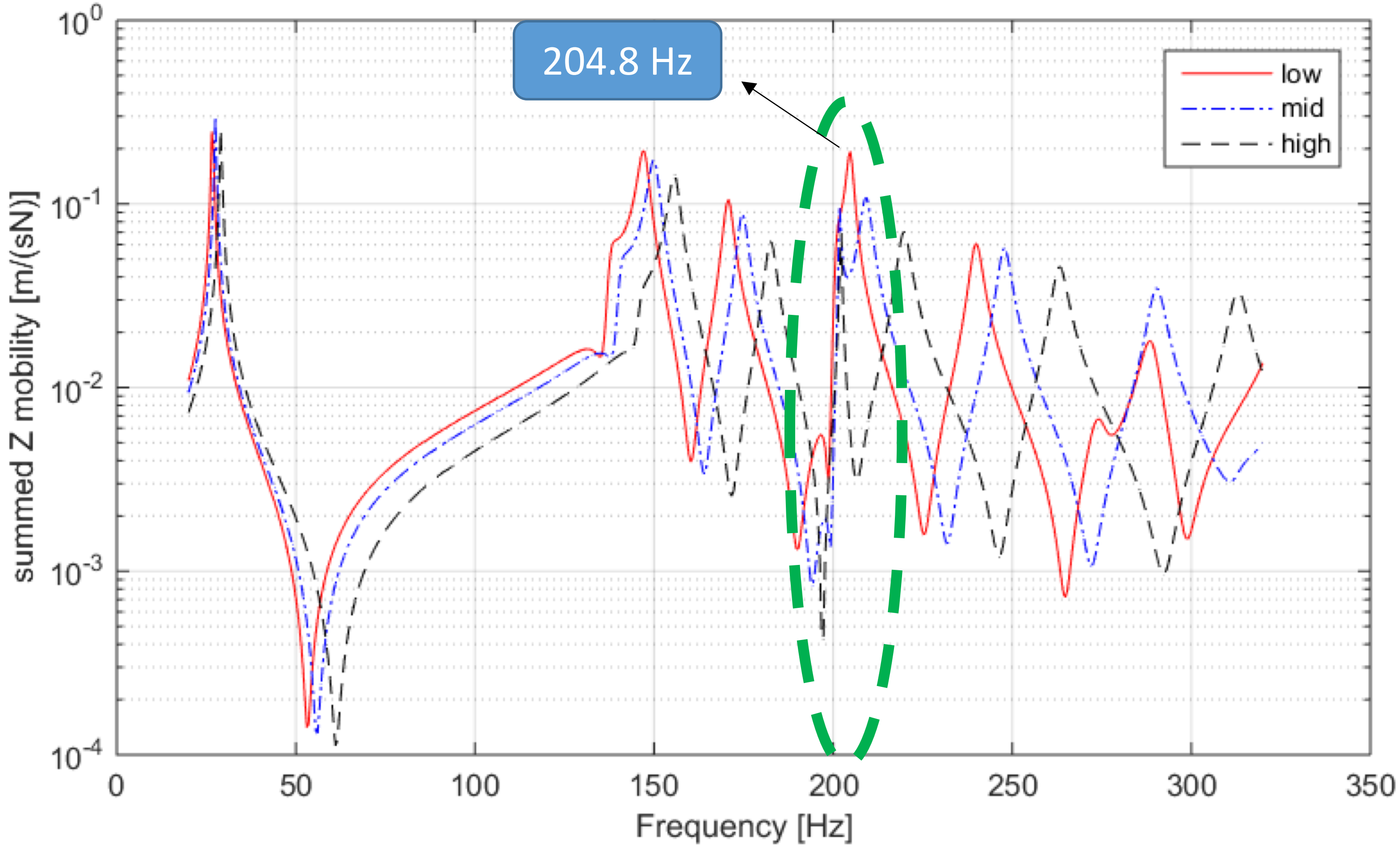
Resultant mobility in *X* direction



Resultant mobility – vector sum of mobility around tire in horizontal direction

IV. Data visualization and comparison study

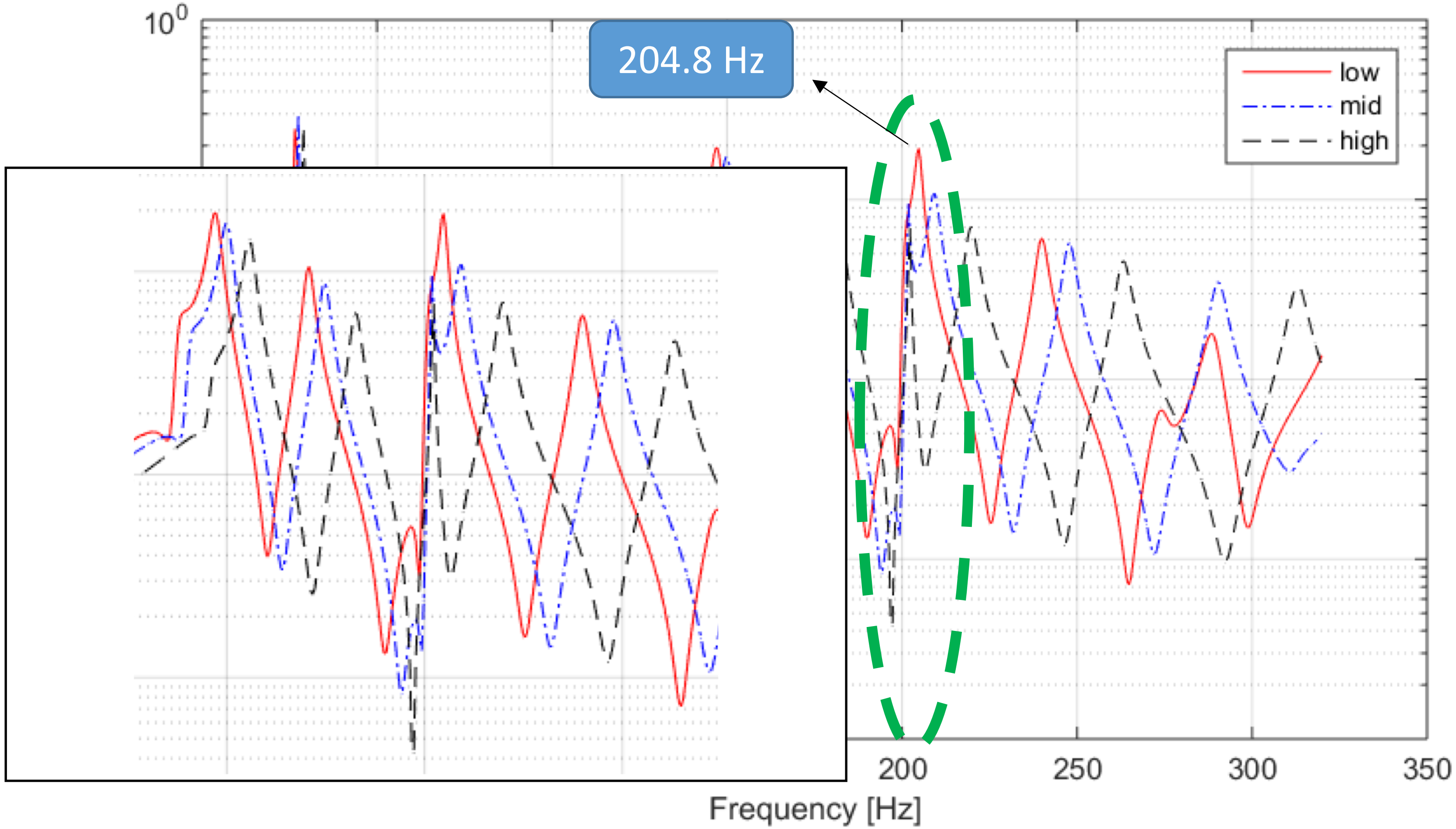
Resultant mobility in *Z* direction



Resultant mobility – vector sum of mobility around tire in vertical direction

IV. Data visualization and comparison study

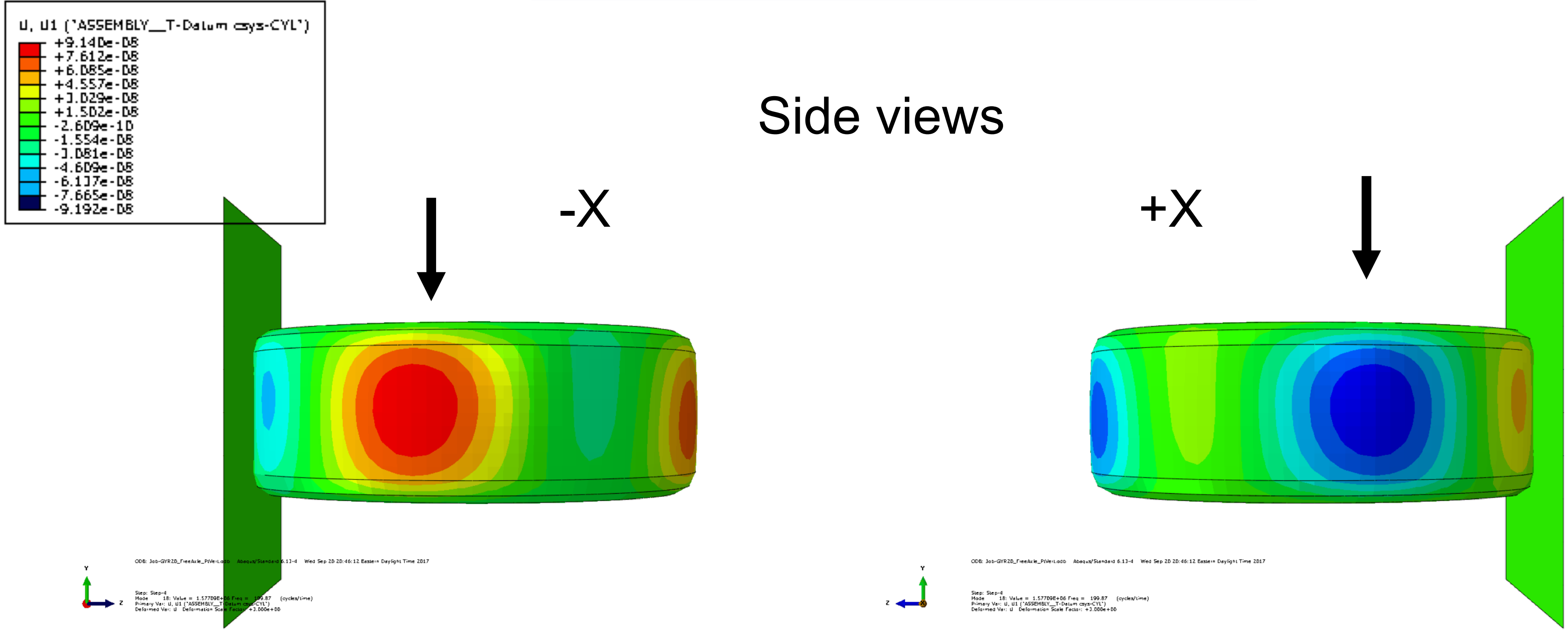
Resultant mobility in *Z* direction



Resultant mobility – vector sum of mobility around tire in vertical direction

V. Modal analysis

1st cavity mode - horizontal



Side views

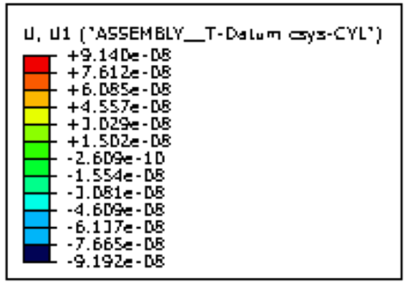
-X

+X

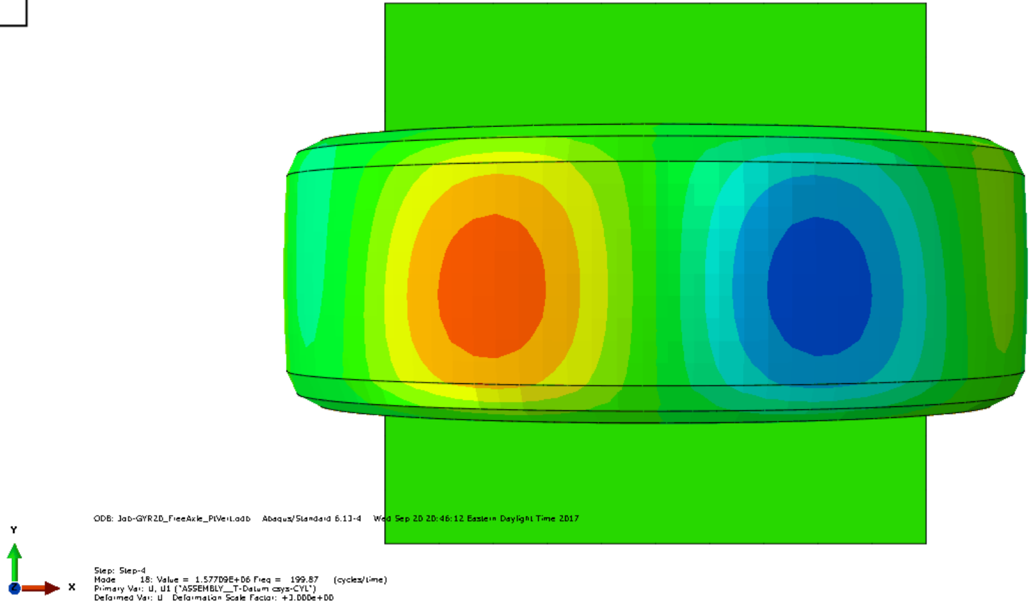
Radial displacement

V. Modal analysis

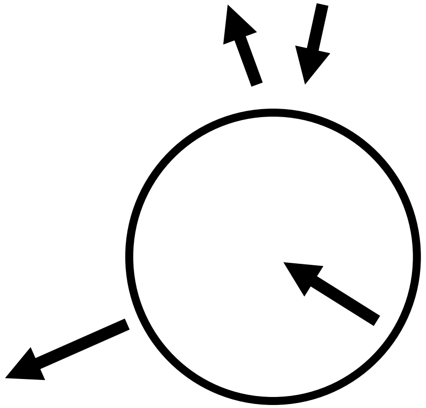
1^{st} cavity mode - horizontal



Top view

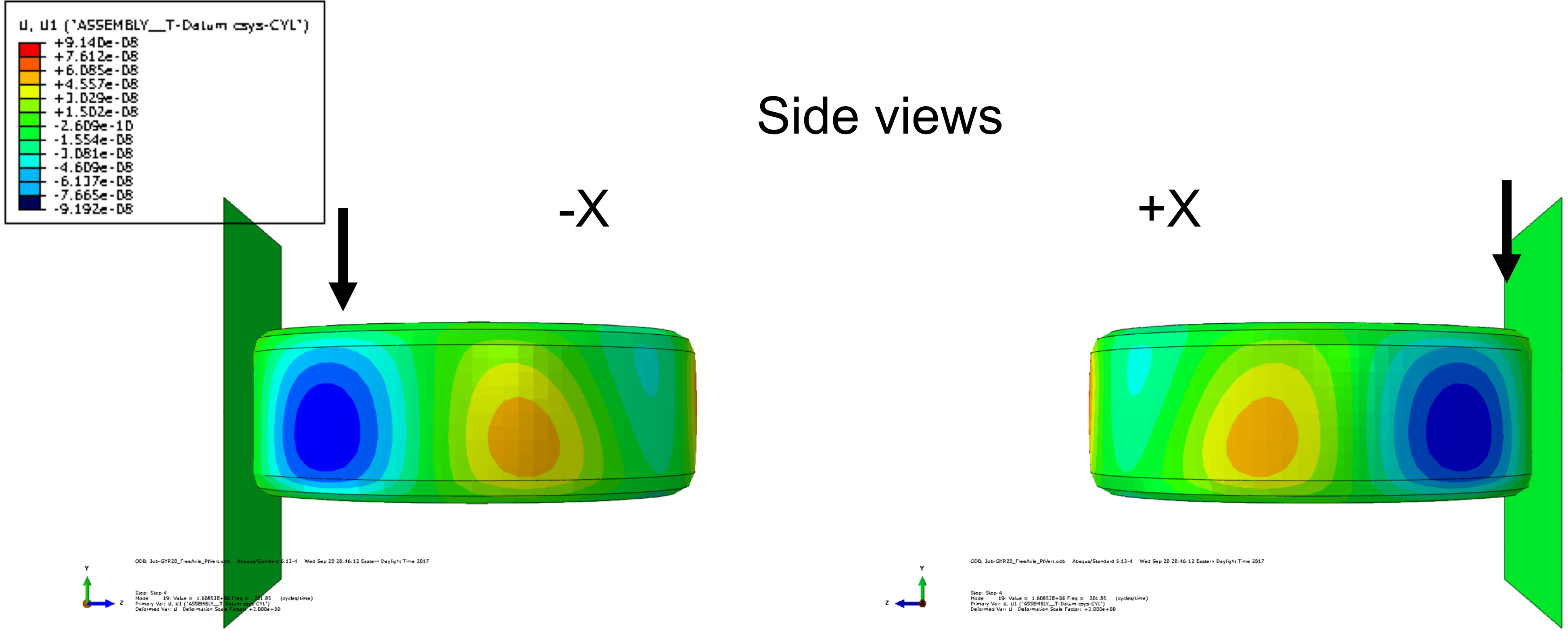


Vertical motion components were canceled, leaving only horizontal motions



V. Modal analysis

1st cavity mode - vertical



Side views

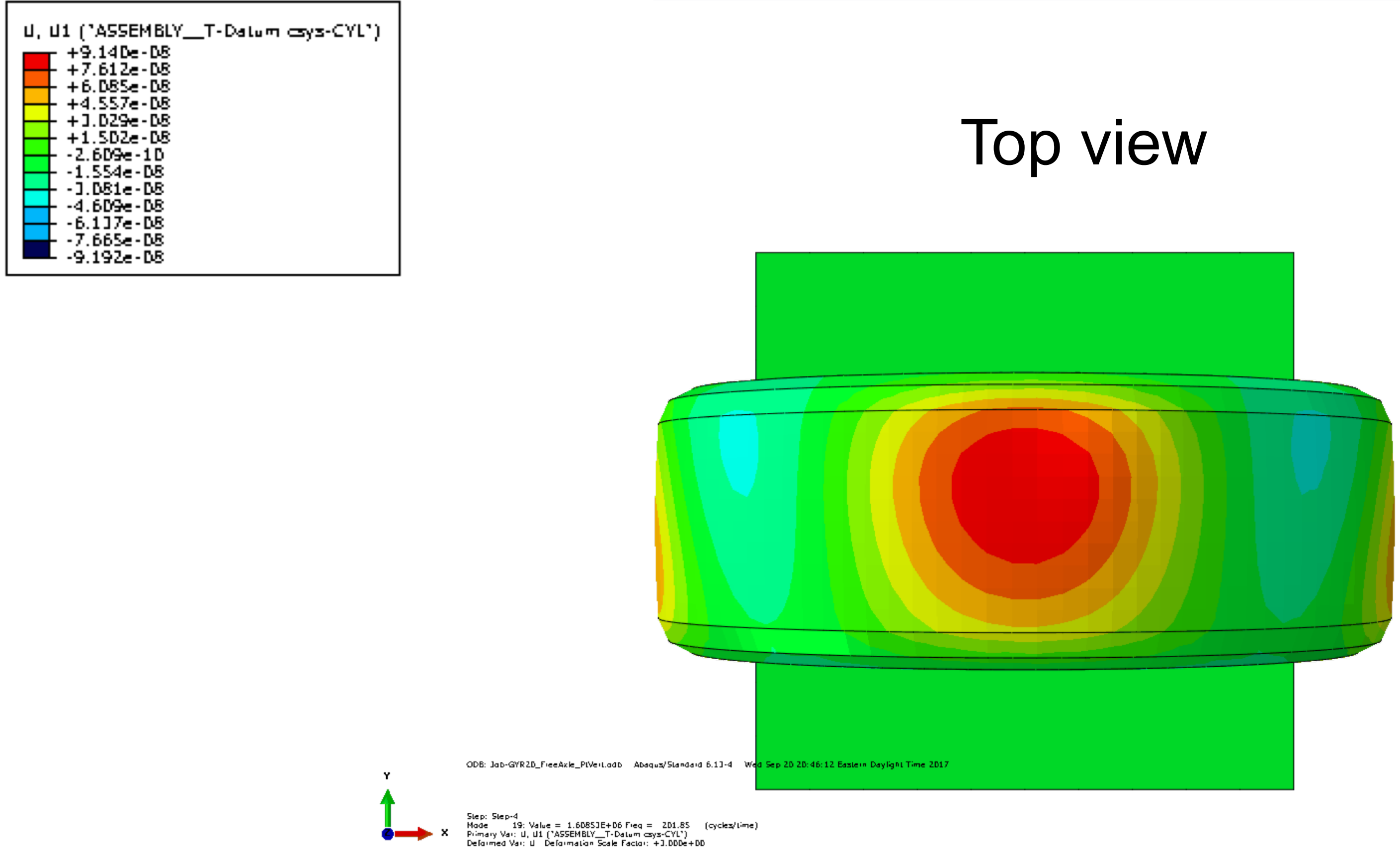
-X

+X

V. Modal analysis

1st cavity mode - vertical

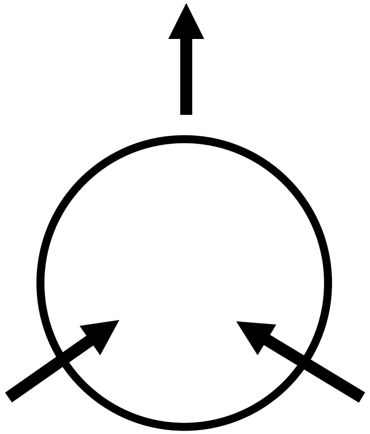
Top view



ODB: Job-GYR2D_FreeAxle_PtVert.odb Abaqus/Standard 6.13-4 Wed Sep 20 20:46:12 Eastern Daylight Time 2017

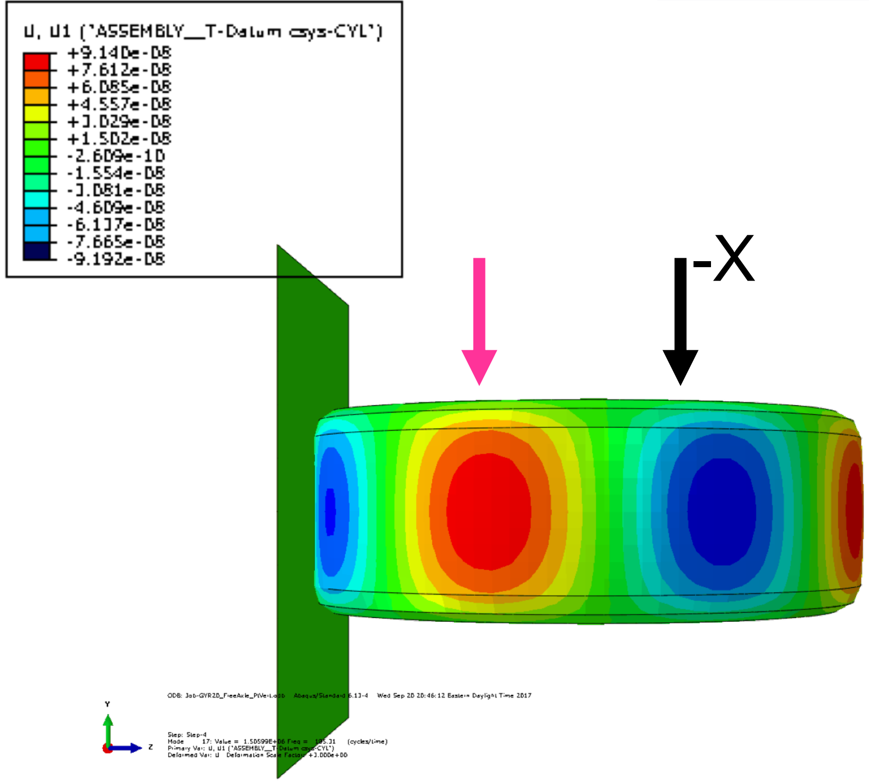
Step: Step-4
Mode 19: Value = 1.60853E+06 Freq = 201.85 (cycles/time)
Primary Var: U, U1 ('ASSEMBLY__T-Datum csys-CYL')
Deformed Var: U Deformation Scale Factor: +3.000e+00

Horizontal motion components were canceled, leaving only vertical motion

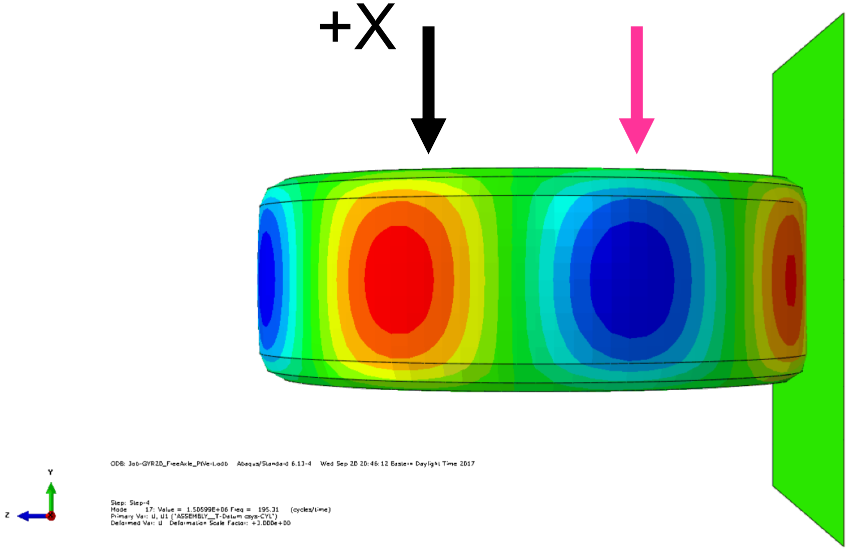


V. Modal analysis

8th structural mode

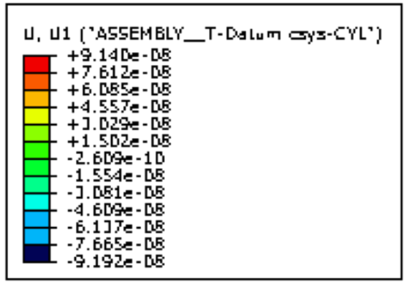


Side views

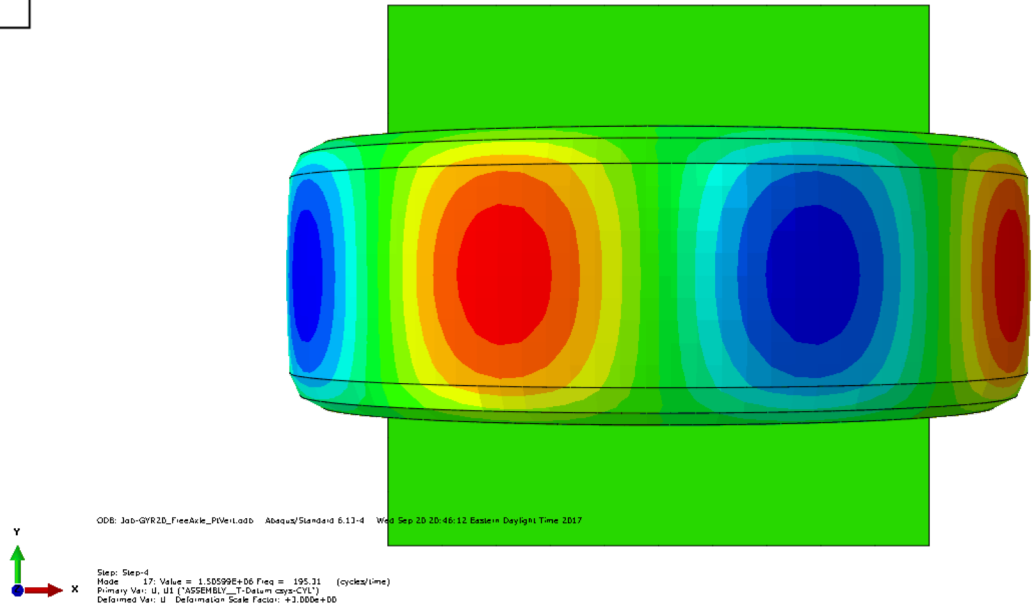


V. Modal analysis

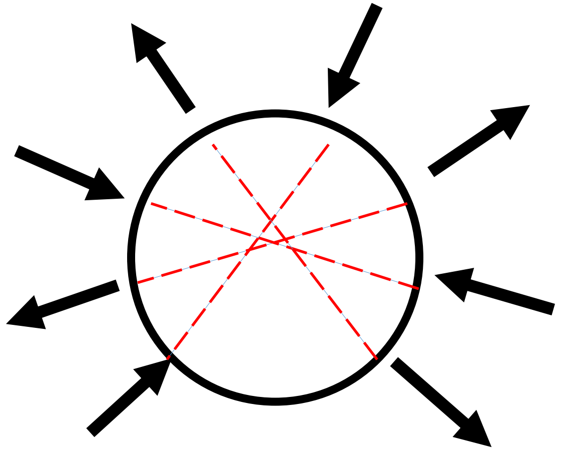
8th structural mode



Top view



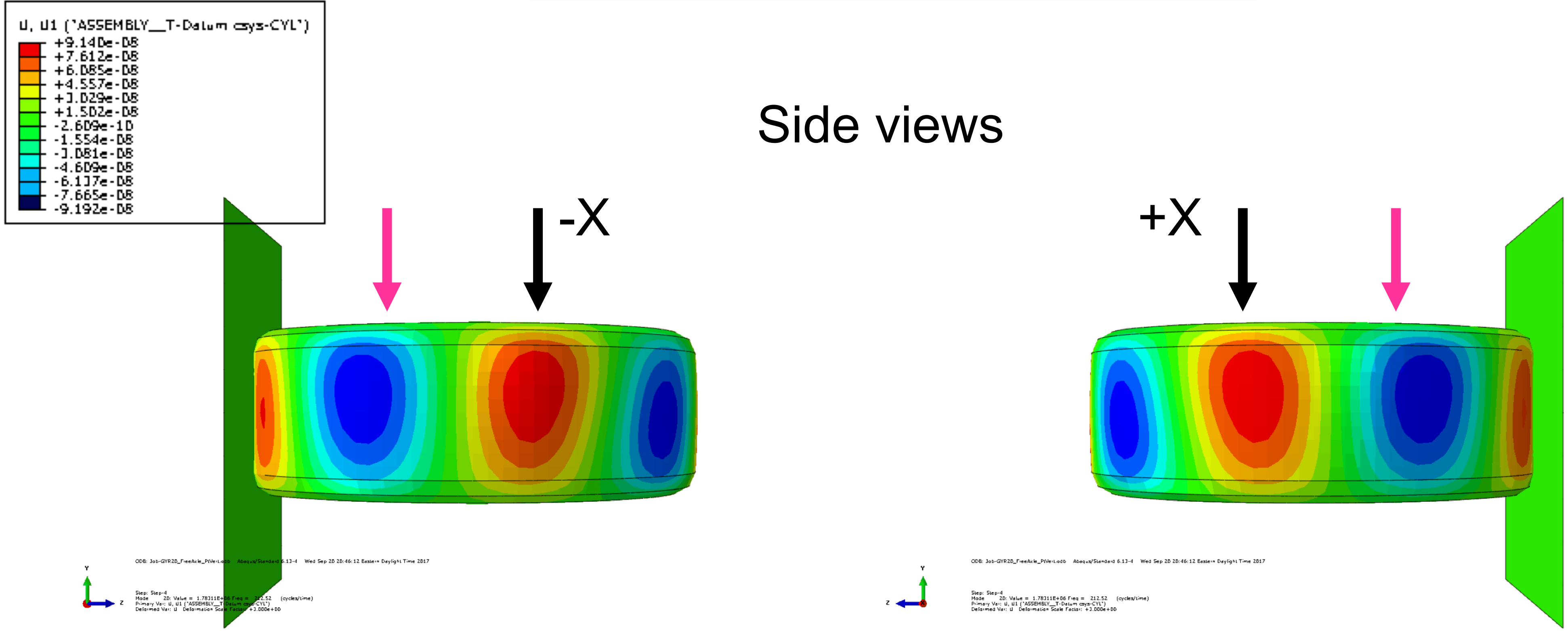
Motion on two sides cancel each other



V. Modal analysis

9th structural mode

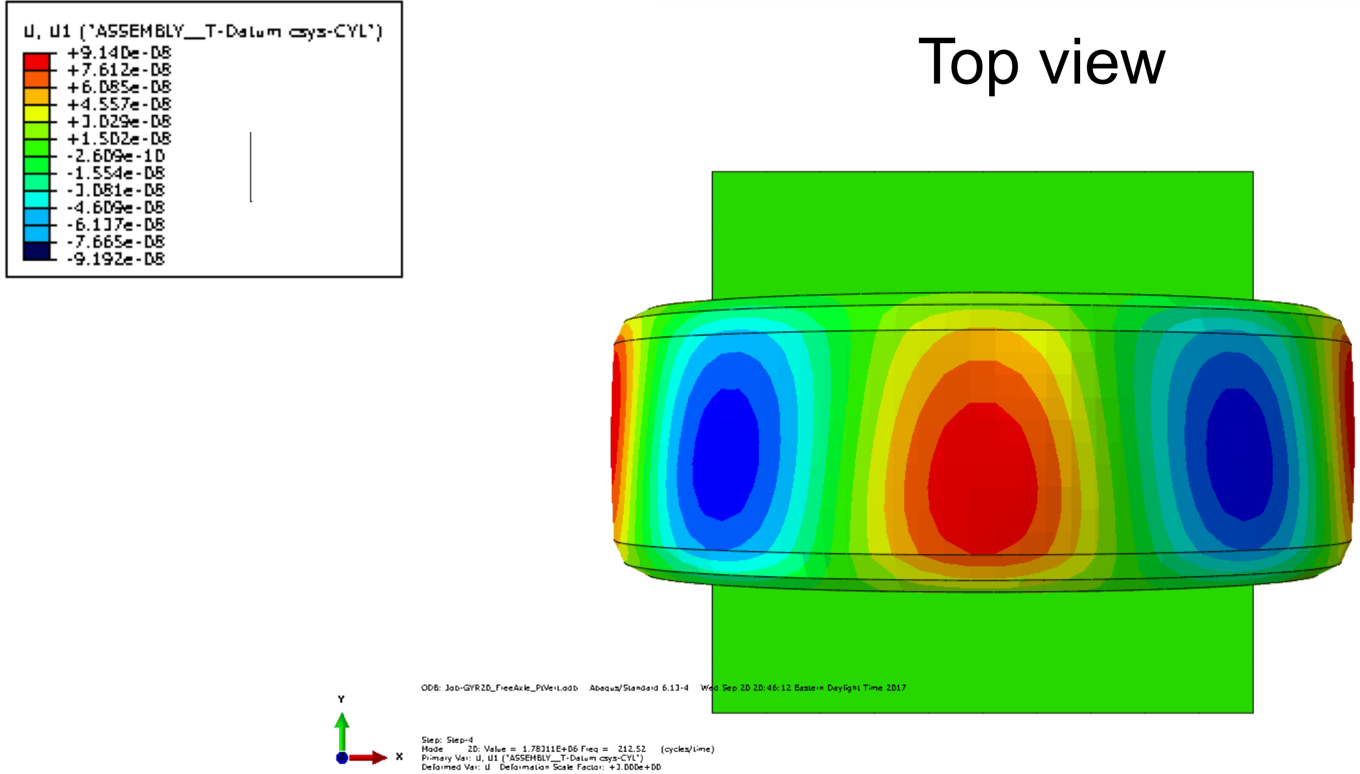
Side views



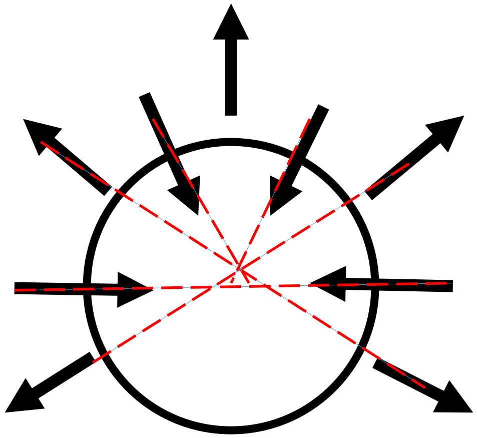
V. Modal analysis

9th structural mode

Top view



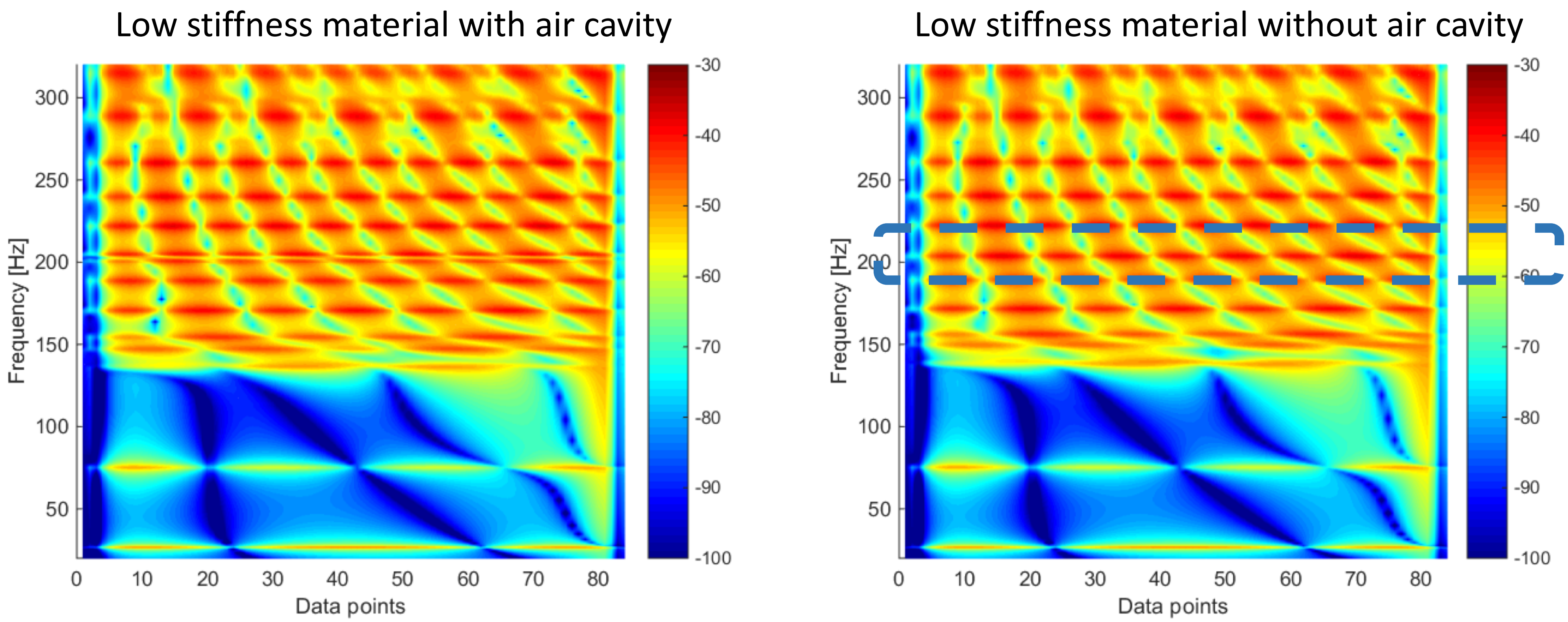
Motion on two sides cancel each other, except for the peak on top



When 9th circumferential structural mode has same frequency as the vertical cavity mode, large response is observed

VI. Compare with airless case

Compare with a model without air cavity

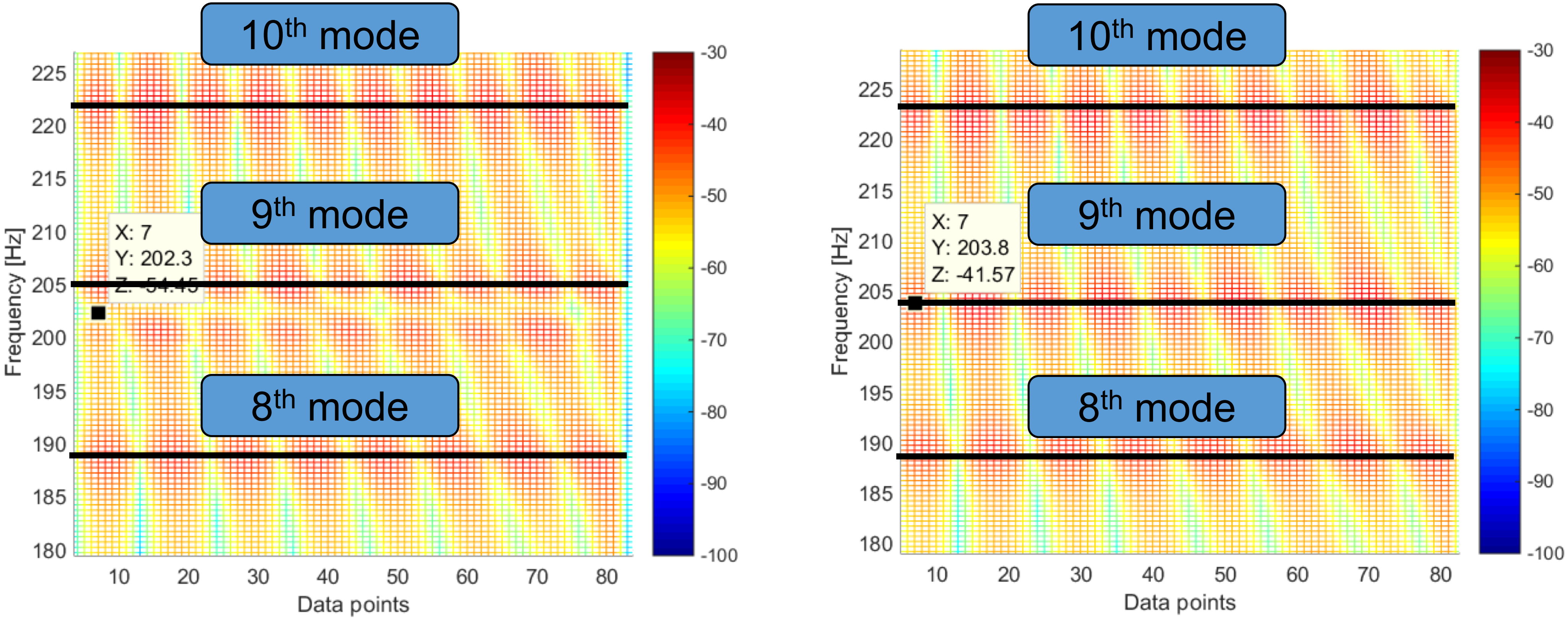


Low stiffness material with air cavity

Low stiffness material without air cavity

VI. Compare with airless case

Compare with a model without air cavity



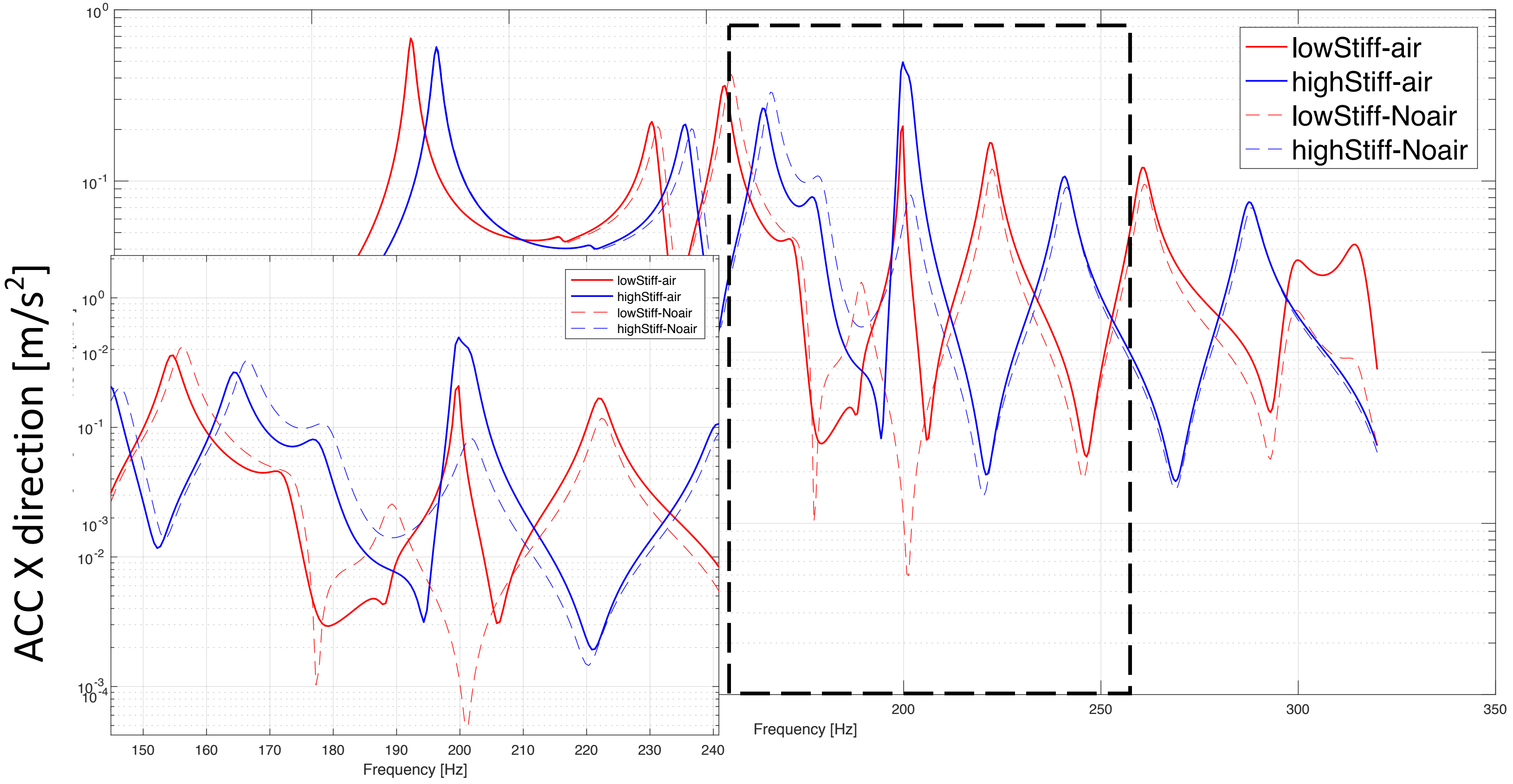
with air cavity

without air cavity

Zoom view of the cavity resonance frequency region

VI. Compare with airless case

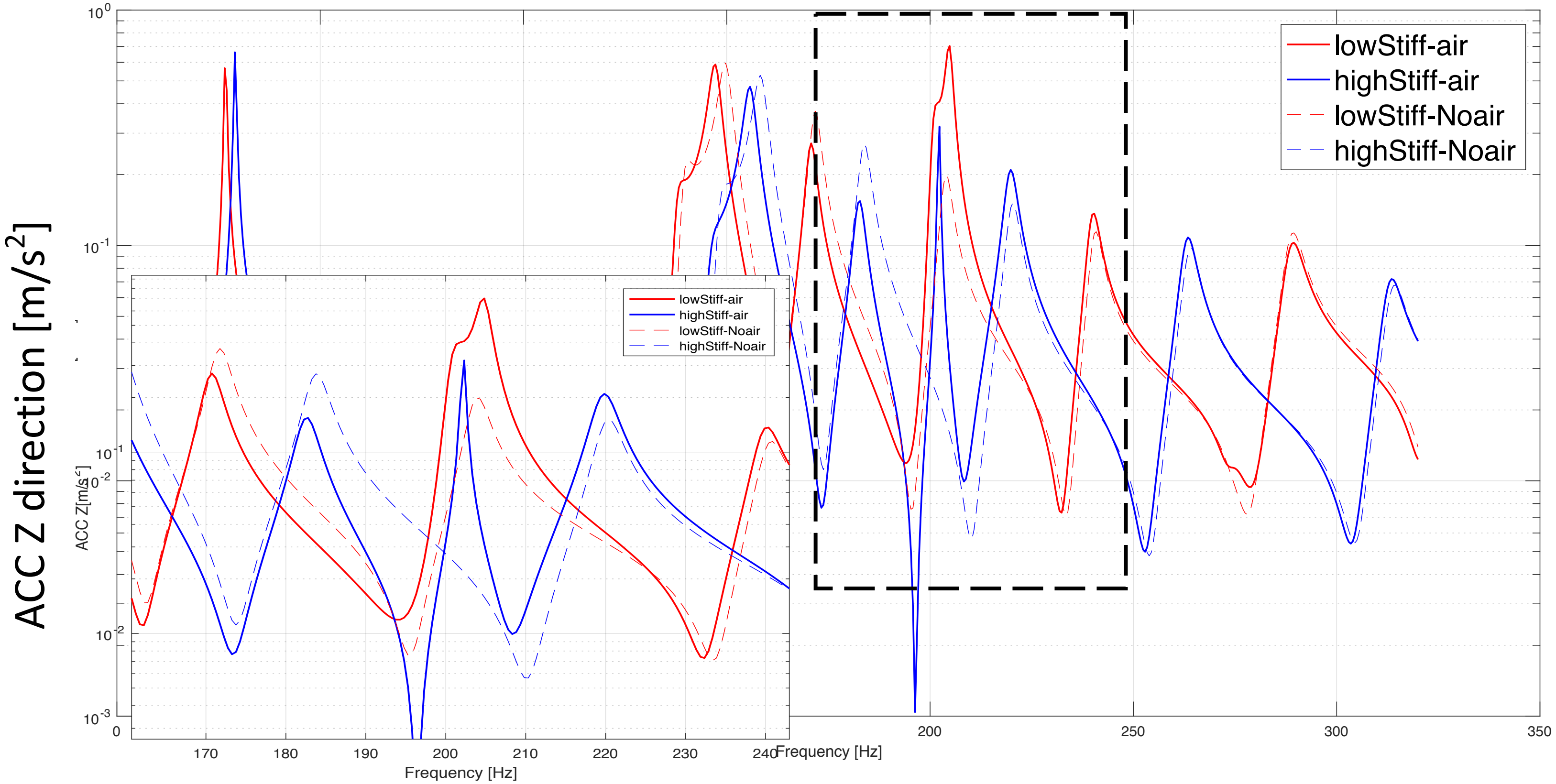
Compare with a model without air cavity



Without air – fore-aft motion is substantially reduced near 200 Hz

VI. Compare with airless case

Compare with a model without air cavity



Without air vertical motion is substantially reduced near 200 Hz

VII. Conclusion

Conclusion

- ❑ A finite element tire model was created, which simulated tire inflation, static loading toward a rigid surface and modal analysis.
- ❑ Reaction forces/acceleration at rim center were obtained, along with tread surface mobility and dispersion relations
- ❑ The coupling relation between cavity resonances and structural resonances were studied and odd-number structural modes were found to couple well with the vertical cavity mode due to similar mode shapes
- ❑ Force transmission was related to whether a net motion of the tire tread was created at a particular frequency
- ❑ A case without internal air cavity was simulated as an additional verification

Appendix

Reference

Rui Cao, J. Stuart Bolton, Force transmission characteristics for a loaded structural-acoustic tire model, *SAE International Journal of Passenger Cars-Mechanical Systems*, 2018 (under review)

Rui Cao, J. Stuart Bolton, Tire cavity induced structure-borne noise study with experimental verification, *INTER-NOISE and NOISE-CON Congress and Conference Proceedings* , 2018 (Conference submission)

Acknowledgement

Financial support provided by Ford Motor Company, Matt Black, contract monitor.