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Prediction of Split in Fundamental Air-Cavity Mode of Loaded Tires based on Experimental Observations and Computational Simulations

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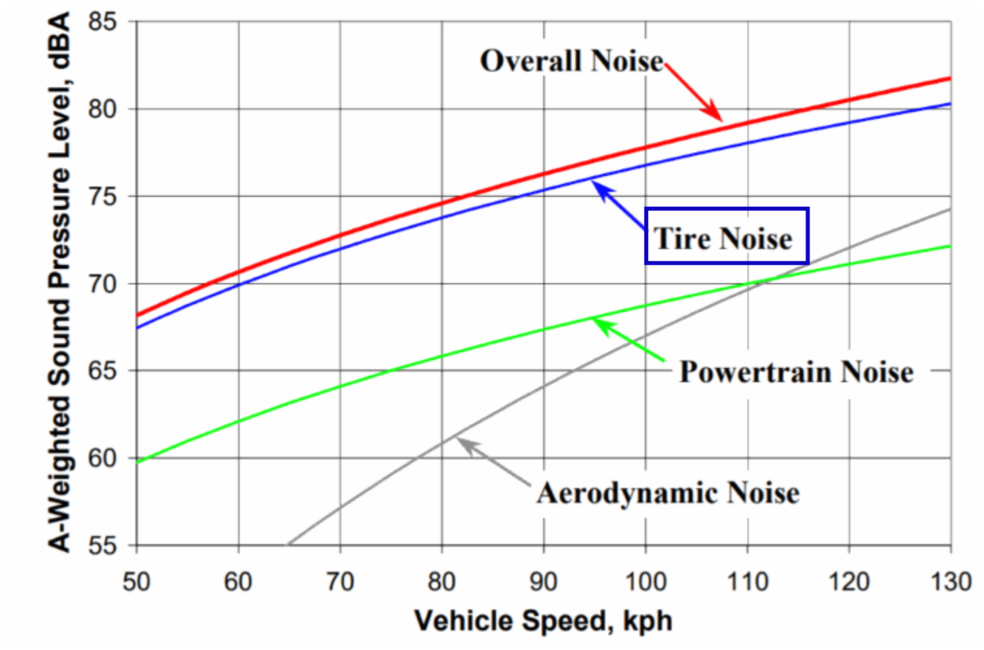
INCE USA

Contents

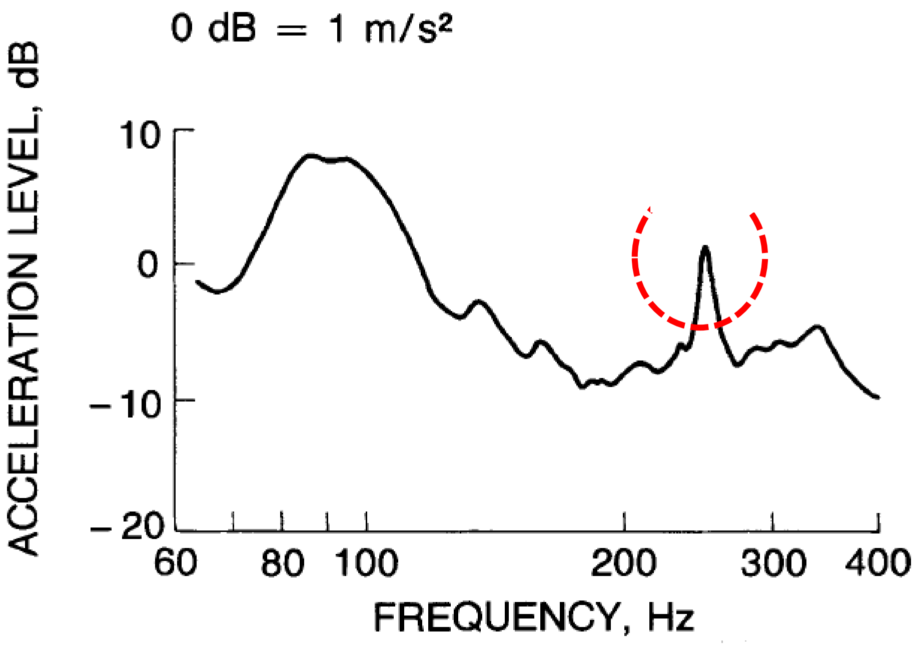
Introduction

Background (1/3)

- Tire/road noise can be a dominant source of cabin and pass-by noise for Electric Vehicles
- Tire's cavity mode at around 200 Hz can contribute to vehicle interior noise due to dynamic forces transmitted through the suspension to interior in the low frequency range



Tire/road noise, Purdue & U of Central Florida [1]

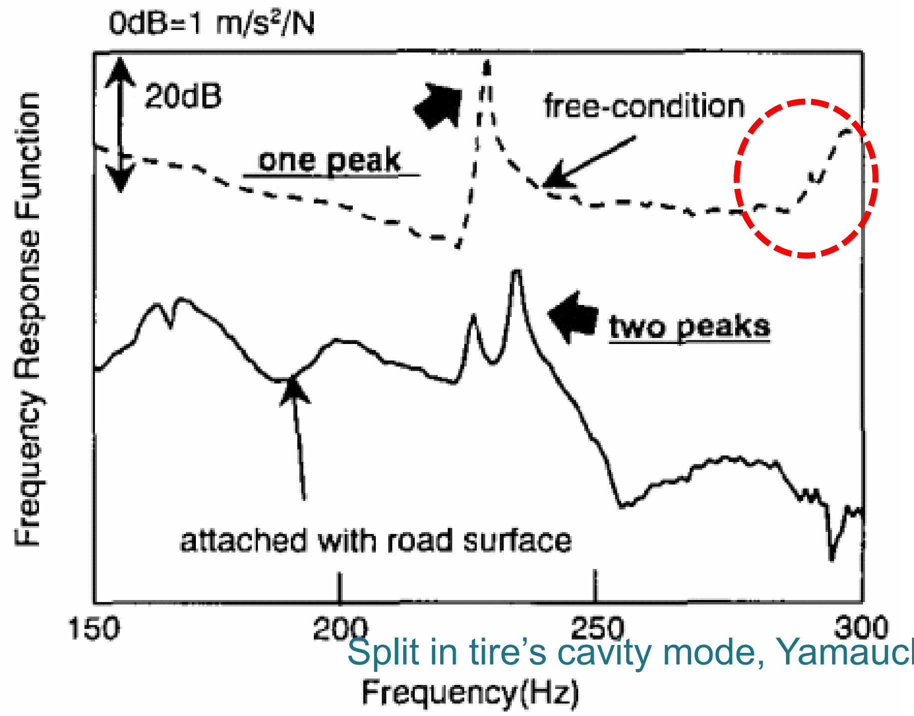


Tire's cavity mode, Sakata and et al [2]

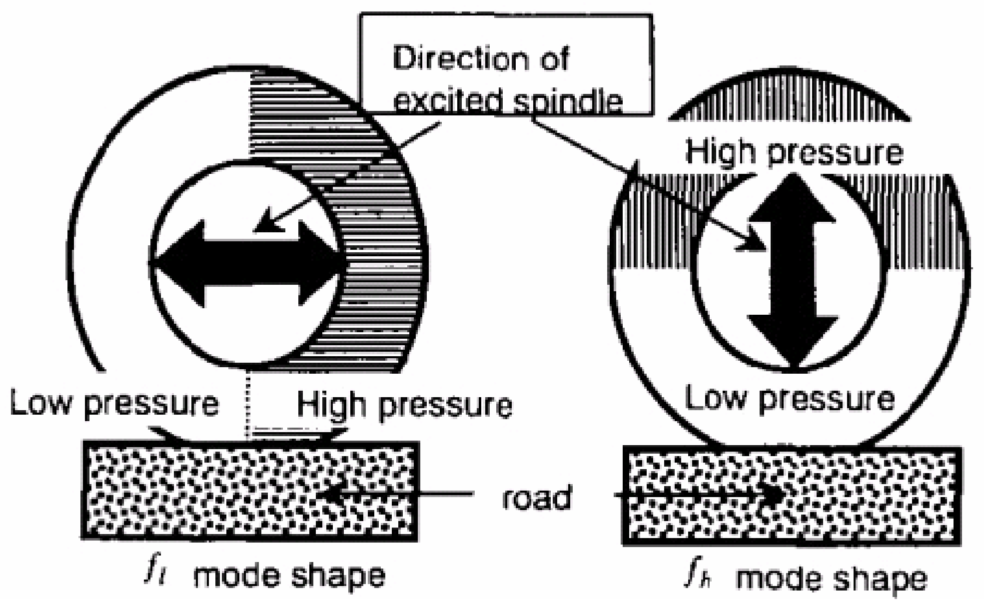
Introduction

Background (2/3)

- ❑ Loading breaks tire's geometrical symmetry, which splits acoustic cavity mode
- ❑ Need to identify 'Frequency-split' of the cavity mode for loaded tires quantitatively



Split in tire's cavity mode, Yamauchi and Akiyoshi [3]

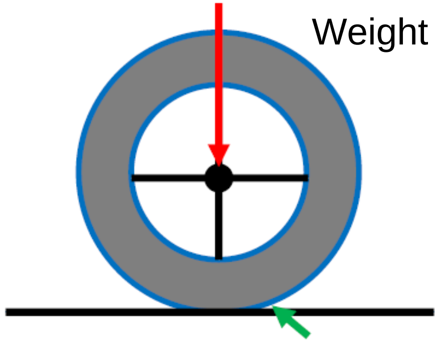


Two acoustic modes for loaded tire [3]

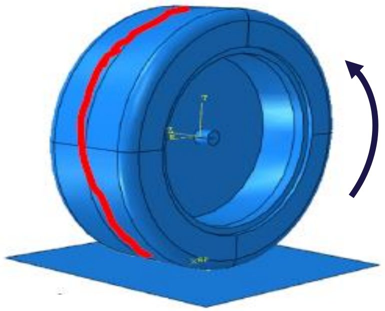
Introduction

Background (3/3)

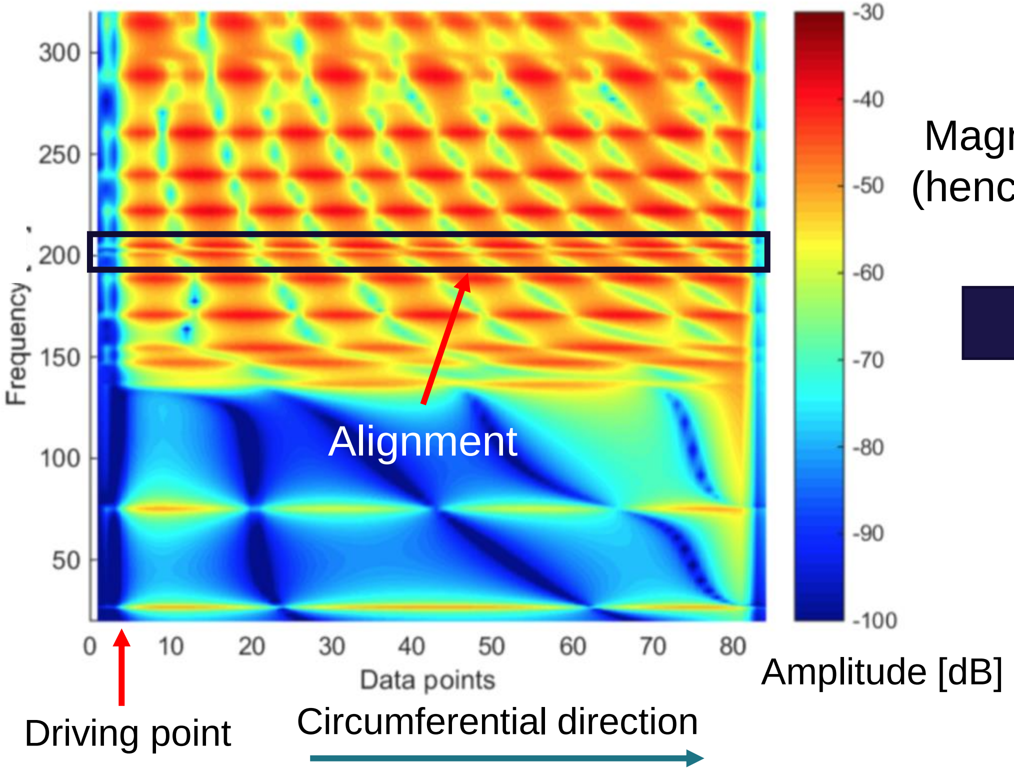
- ❑ Alignment between structural modes and cavity modes result in amplified force at the hub
- ❑ Identify mechanism of force generation and ultimately avoid any coupling between these two features



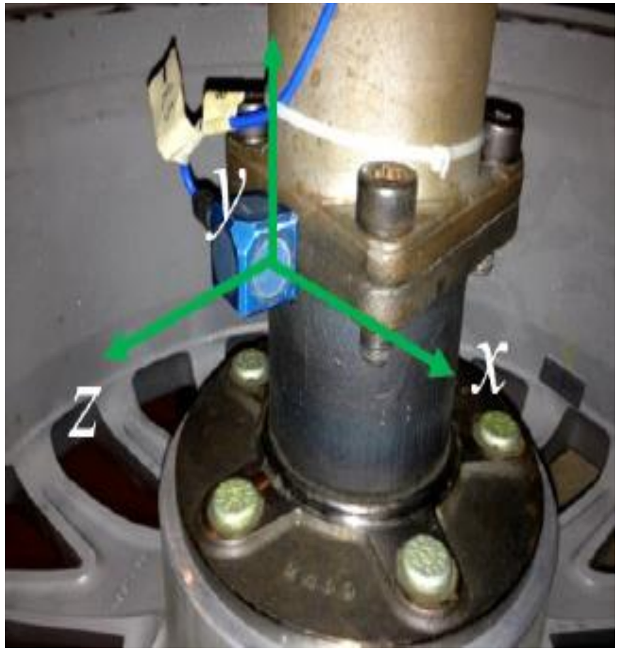
0 [0°] through 106 pts [360°]



Tread centerline mobility



Magnify axle force (hence cabin noise)



Rui Cao [4]

Introduction

Objective

- The objective is to observe the split in tire's cavity mode in an experimental and numerical way for a set of loaded tires under static condition
- Secondly, the relation between load level and amount of split needs to be verified

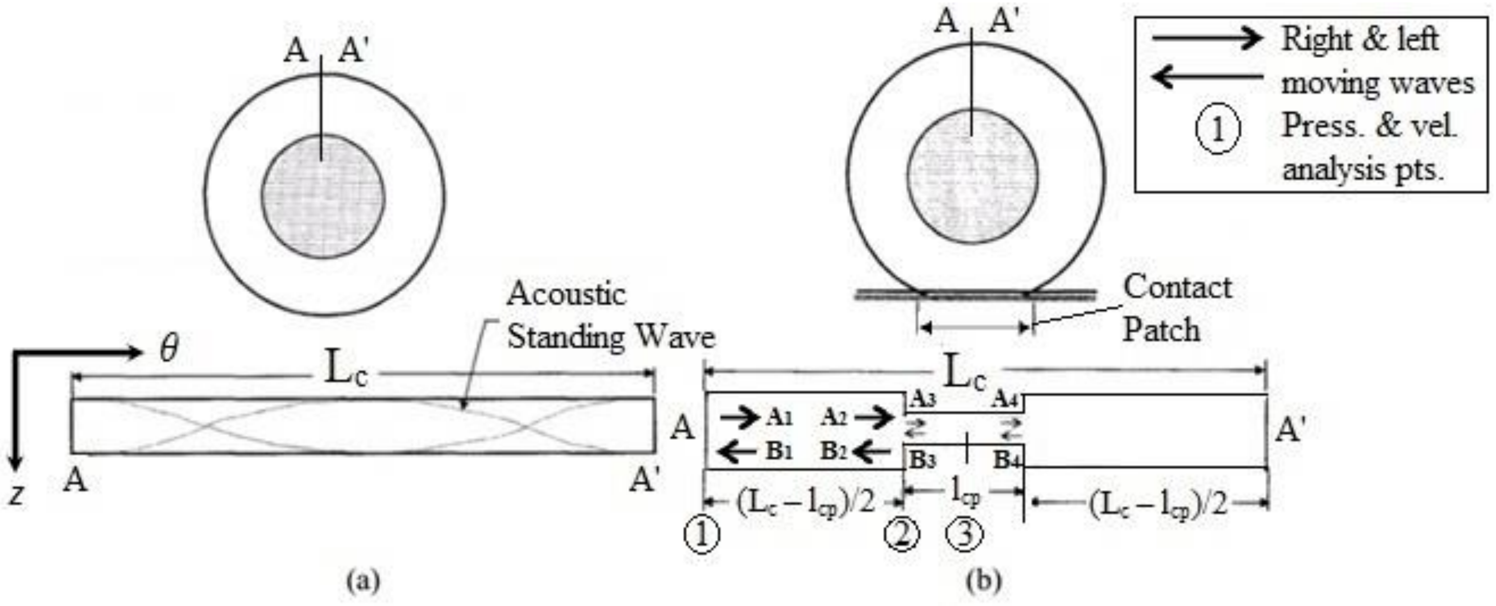
List of Test Tire

No.	Rim	Width	Aspect ratio	Inflation	Rated load	Remark
1	16 inch	225 mm	75	0.45 MPa	7430 N	Truck tire
2	17 inch	235 mm	55	0.24 MPa	4954 N	
3	18 inch	235 mm	50	0.24 MPa	5496 N	
4	19 inch	235 mm	55	0.23 MPa	5986 N	
5	20 inch	265 mm	35	0.24 MPa	4812 N	

Analytical Approach

Loaded tire model by Thompson

- Unwrapped torus model such that acoustic standing wave is formed along the length of waveguide
- The narrowed channel near the contact patch due to a load causes additional mode to appear
- The natural frequencies of two acoustic modes can be predicted by applying proper boundary conditions to the pressure and particle velocity



Loaded tire model adopted from Thompson [5]

1. Horizontal mode

$$f_H = \frac{c}{L_c + (1-m)l_{cp}} \quad (1)$$

2. Vertical mode

$$f_V = \frac{c}{L_c - (1-m)l_{cp}} \quad (2)$$

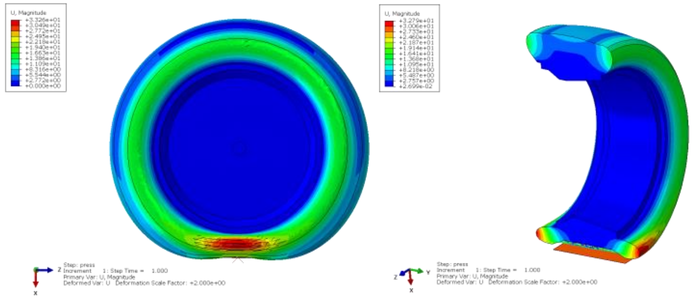
$$m = \frac{A_{Loaded}}{A_{Unloaded}}$$

Analytical Approach

Comparison of frequency split for the 18 inch tire (235/50/R18)

- To demonstrate the principle of physics described in Thompson's work
- The parameters (l_{cp}, m) can be obtained from static analysis
- The predicted natural frequencies of the two acoustic modes are close to values from test

c	L_c	l_{cp}	m	$f_{H\_Thompson}$	$f_{V\_Thompson}$	f_{H_test} (f_{H_FEM})	f_{V_test} (f_{V_FEM})
343 m/s	1.7 m	0.22 m	0.91	199.9 Hz	204.5 Hz	198.4 Hz (198.5 Hz)	205.2 Hz (205.5 Hz)
Speed of sound	Length of perimeter	Length of contact patch	Ratio of cross-sectional area between loaded and unloaded tire	Horizontal mode	Vertical mode	Horizontal mode	Vertical mode

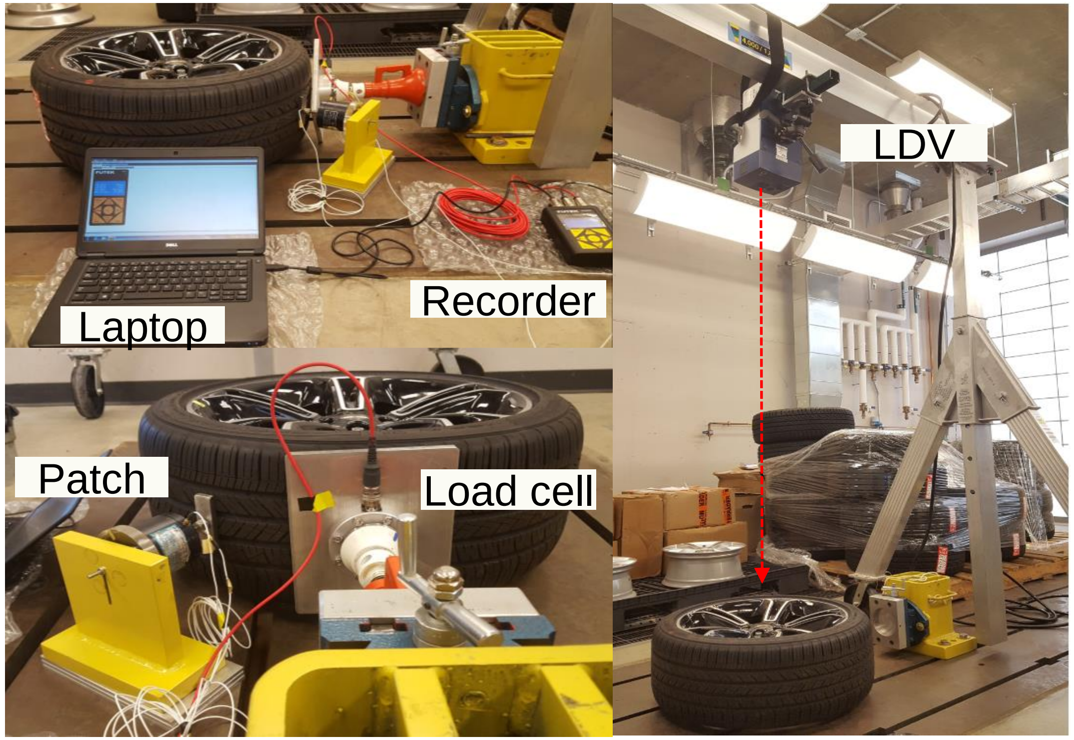


Static deformation implemented by Abaqus 2019

Experimental Approach

Procedure of test

- ❑ Each tire was mounted on the rig, dynamically rigid below 300 Hz
- ❑ Mobility data at 106 equally-spaced points along the sidewall were measured by using Laser-Doppler Vibrometer



Configuration of experiment [6]

Information about signal processing

Bandwidth	Sampling	Averaging	Window	Overlap
40 to 1000 Hz	0.15 Hz	5	Hann	50%

Experimental Approach

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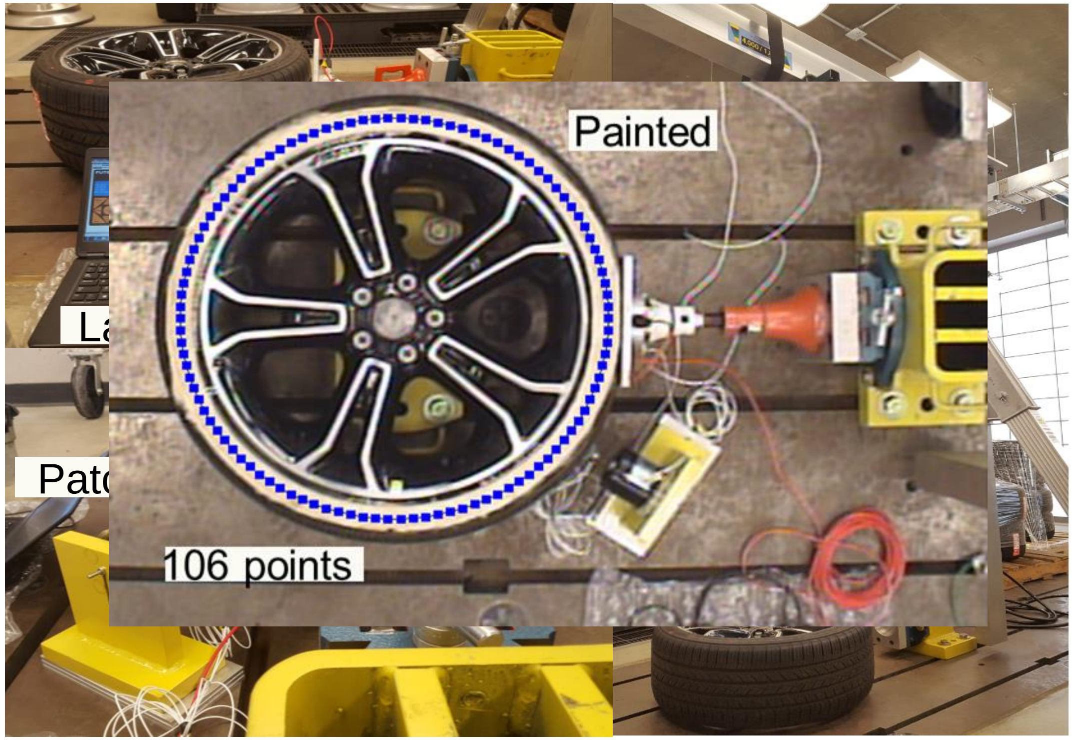


Configuration of experiment [6]

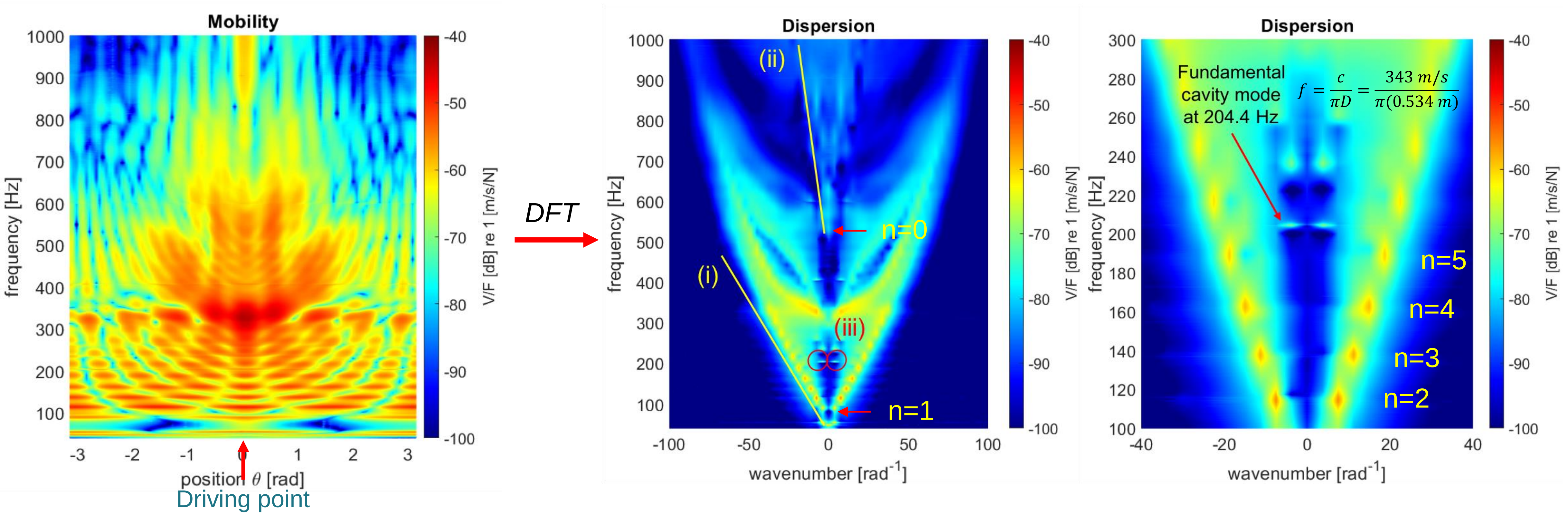
Information about signal processing

Bandwidth	Sampling	Averaging	Window	Overlap
40 to 1000 Hz	0.15 Hz	5	Hann	50%

Experimental Approach

Test set #1 : 225/75/R16, 65 psi, 7430 N

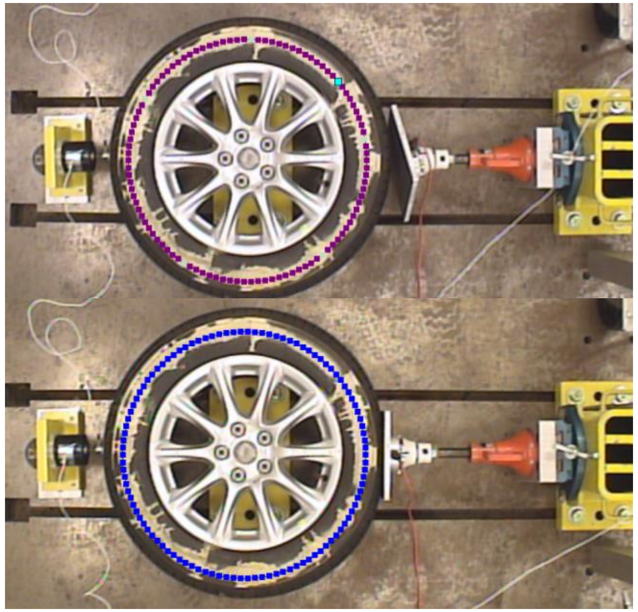
- Mobility, the ratio between surface velocity and input force, was measured with and without the load
- Dispersion curve could be obtained from Discrete Fourier Transform of the spatial data at each frequency
- Slow-traveling flexural (i), Fast-propagating longitudinal wave (ii), and Fundamental cavity mode (iii) were observed



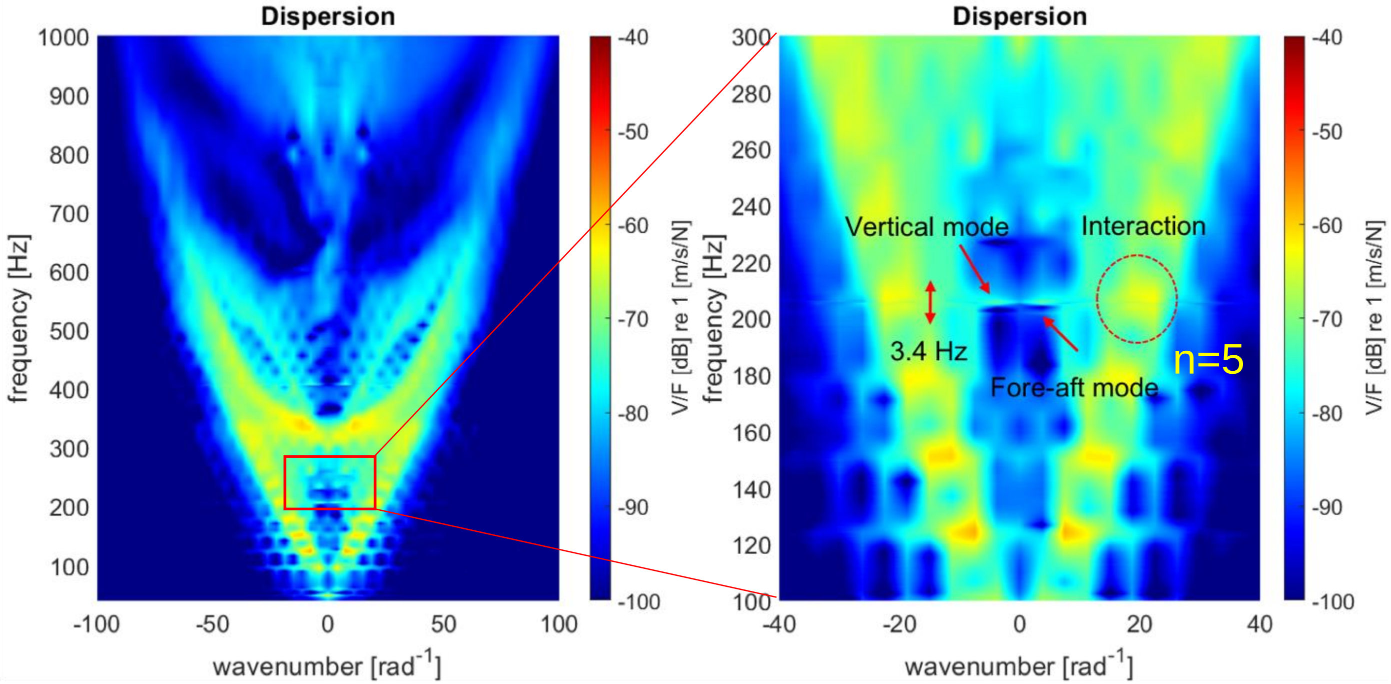
Experimental Approach

Test set #1 : 225/75/R16, 65 psi, 7430 N

- When tire is deformed, split in fundamental cavity mode can be found
- The upper resonance frequency is 205.3 Hz, related to the vertical mode
- The lower resonance frequency is 201.9 Hz, related to the fore-aft, horizontal mode
- Interaction between the fifth circumferential mode and two acoustic modes can amplify the response at the hub



Unloaded and loaded tire



Dispersion for loaded tire

Experimental Approach

Summarized results for five test tires

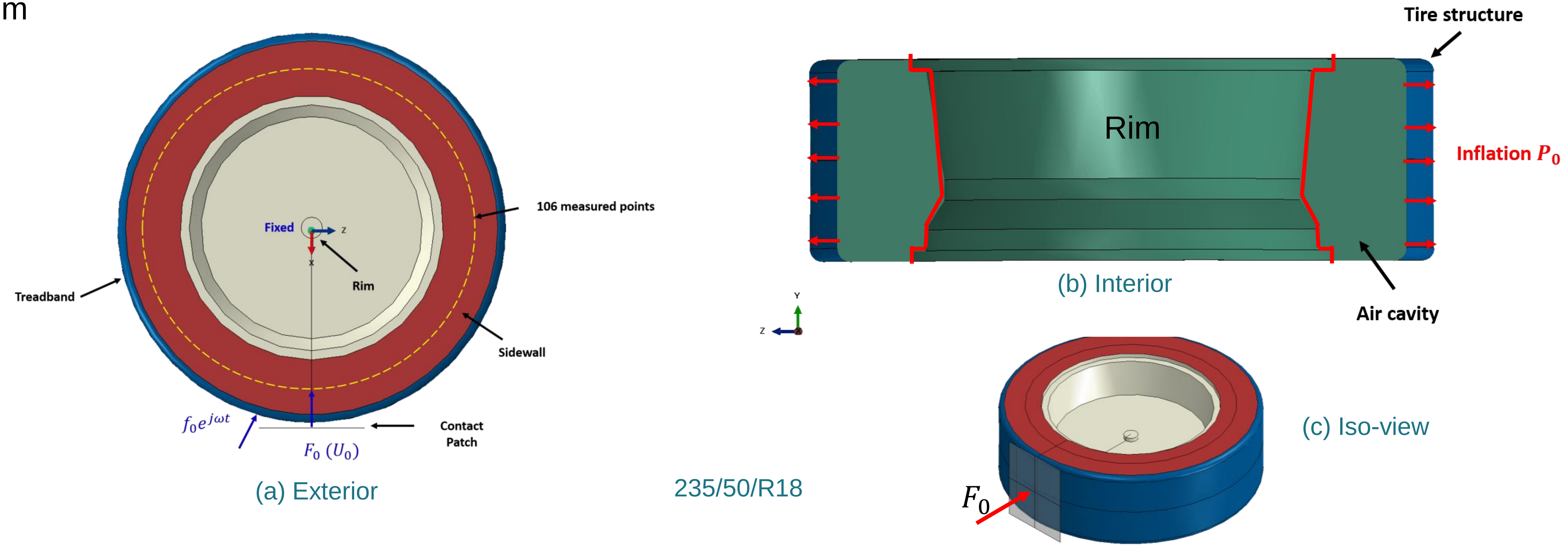
- ❑ The natural frequency of fundamental cavity mode generally decreased as the rim size goes up
- ❑ For the same tire, split expands with the increasing load
- ❑ The tire physical experimental parameters relate back well with the theoretical parameters (aspect ratio, load, mean diameter, stiffness) included in the Thompson's calculations

No.	Size	Aspect ratio	Cavity mode	Horizontal	Vertical	Split	Mean diameter	Rated load
1	16 inch	75	204.4 Hz	201.9 Hz	205.3 Hz	3.4 Hz	0.534 m	7430 N
2	17 inch	55	207.7 Hz	204.2 Hz	209.8 Hz	5.6 Hz	0.526 m	4954 N
3	18 inch	50	203 Hz	198.4 Hz	205.2 Hz	6.8 Hz	0.54 m	5496 N
4	19 inch	55	190 Hz	185.7 Hz	193.1 Hz	7.4 Hz	0.574 m	5986 N
5	20 inch	35	197 Hz	188.9 Hz	200.9 Hz	12 Hz	0.556 m	4812 N

FE Simulation

Description of Modeling

- ❑ A FE simulation for one tire (#3) has been implemented to attempt to reproduce both structural modes and the split in the cavity mode frequency due to loading and the resulting deformation of the tire
- ❑ An axisymmetric model was created based on the shape of a 2D cross-sectional area, including a detailed outline of the rim



(a) Exterior

235/50/R18

(b) Interior

(c) Iso-view

FE Simulation

Information about the candidate tire (235/50/R18)

- A coupled FE model was constructed consisting of treadband, sidewall, rim, air cavity and contact patch.
- For simplification, it was assumed the tire was a slick, since tread-pattern noise is not considered here
- The normal surface velocity at 106 measured points along the sidewall was extracted at the same radius as the measurement, to compare mobility and dispersion curves. The input force f_0, was applied near the leading edge of the contact patch in the loaded case.

Information about the model tire, #3

No.	Size	Width	Aspect ratio	Mass	Stiffness	Inflation	Load	Harmonic input
3	18 inch	235 mm	50	25 kg	306 N/mm	0.24 MPa	5496 N	5 N

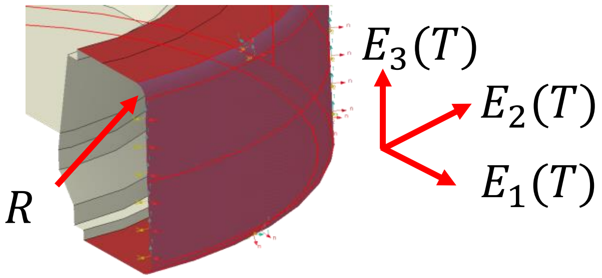
FE Simulation

Material properties fitted into the experimental result

- Based on the experimental observations, the material properties in the tire structure such as Young's modulus, Poisson's ratio, and shear modulus, were adjusted to coincide with the observed patterns of the structural resonance modes.
- The air density and bulk modulus corresponding to the inflation in the air cavity were also carefully chosen to evaluate the fundamental cavity mode both in frequency and wavenumber more accurately.

Material properties in tire structure

No.	Part	Thickness, *t*	Density, ρ	Young's modulus, E (Radial/Tangential/Axial)	Poisson's ratio, υ	Shear modulus, G
	Rim	5 mm	4387 kg/m^3	70,000 MPa	0.3	N/A
3	Treadband	12 mm	1520 kg/m^3	200/650/200 MPa	0.5	50 MPa
	Sidewall	6 mm	1013 kg/m3	250/10/250 MPa	0.5	3 MPa



Orthotropic material properties

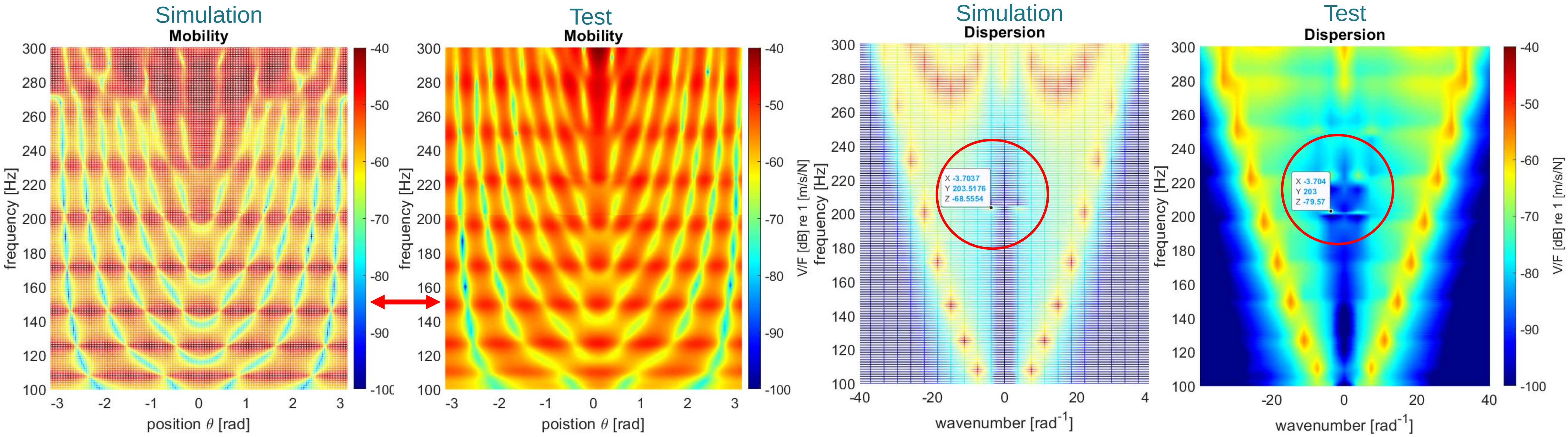
Material properties in air cavity

Part	Density, ρ	Bulk modulus, β
Air	2.15 kg/m^3	0.26 MPa

FE Simulation

Result and discussion (Non-deformed)

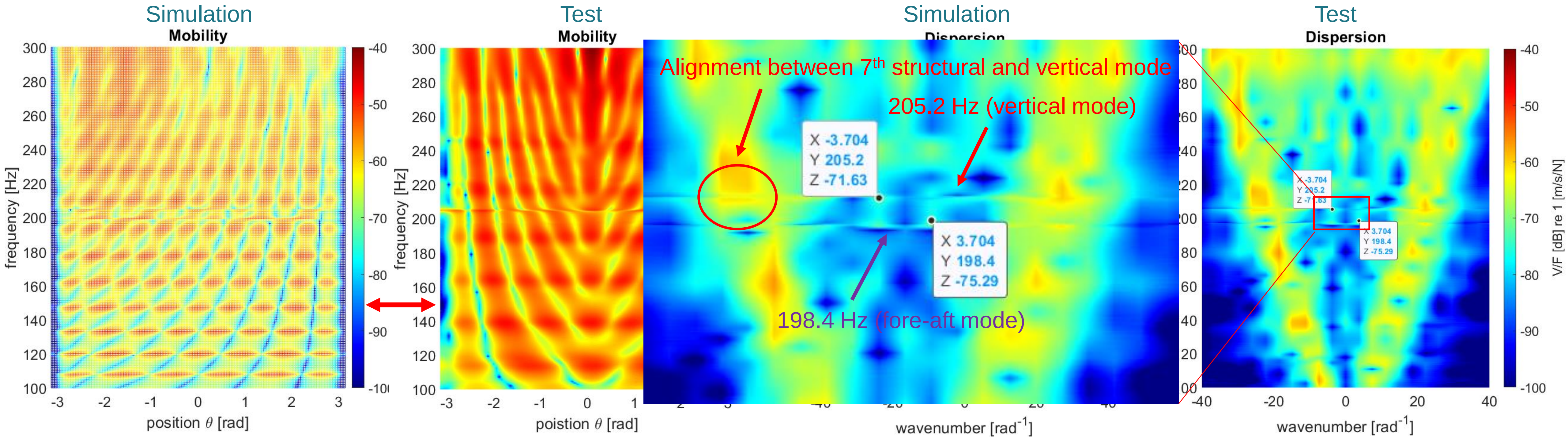
- The FE simulation and measured mobility plots for the unloaded tire (i.e., normal surface velocity divided by input force) are compared
- The results confirm that the two patterns are in a good agreement, especially near 200 Hz, close to the acoustic cavity mode
- All of the structural modes are placed at equivalent positions with the same phase speed, and also the acoustic cavity mode appears at the same frequency and wavenumber in both cases



FE Simulation

Result and discussion (Deformed)

- ❑ Horizontal acoustic mode at 198.4 Hz and the vertical acoustic mode at 205.2 Hz are well predicted even considering the difference in frequency resolution: 1 Hz (simulation) versus 0.15 Hz (test)
- ❑ In simulation, additional features appear between the major structural resonance modes in the circumferential direction for the deformed tire, which differs from the test results, and this feature is more evident in the dispersion curve where blue region indicates contact patch

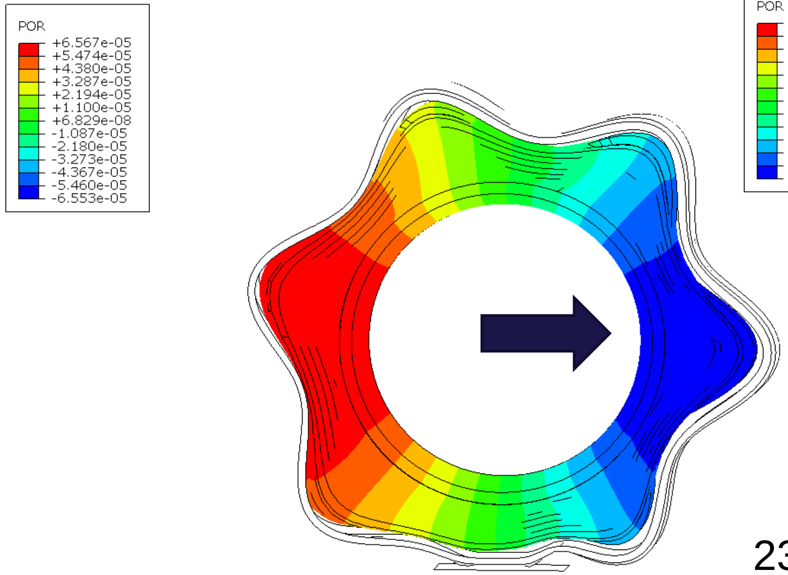


FE Simulation

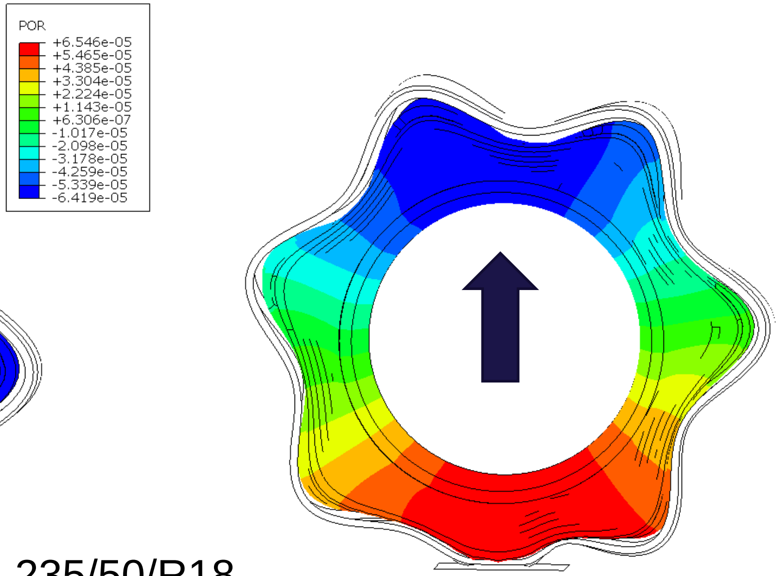
Result and discussion (Deformed)

- The horizontal acoustic mode appears at the lower frequency, and the vertical acoustic mode appears at the higher frequency
- Since the net structural vibration is directed vertically at odd mode, the vertical force at the hub can be amplified by coupling of the vertical acoustic mode and the spatially matched structural mode

Horizontal acoustic mode at 198.5 Hz (N=7)



Vertical acoustic mode at 205.5 Hz (N=7)



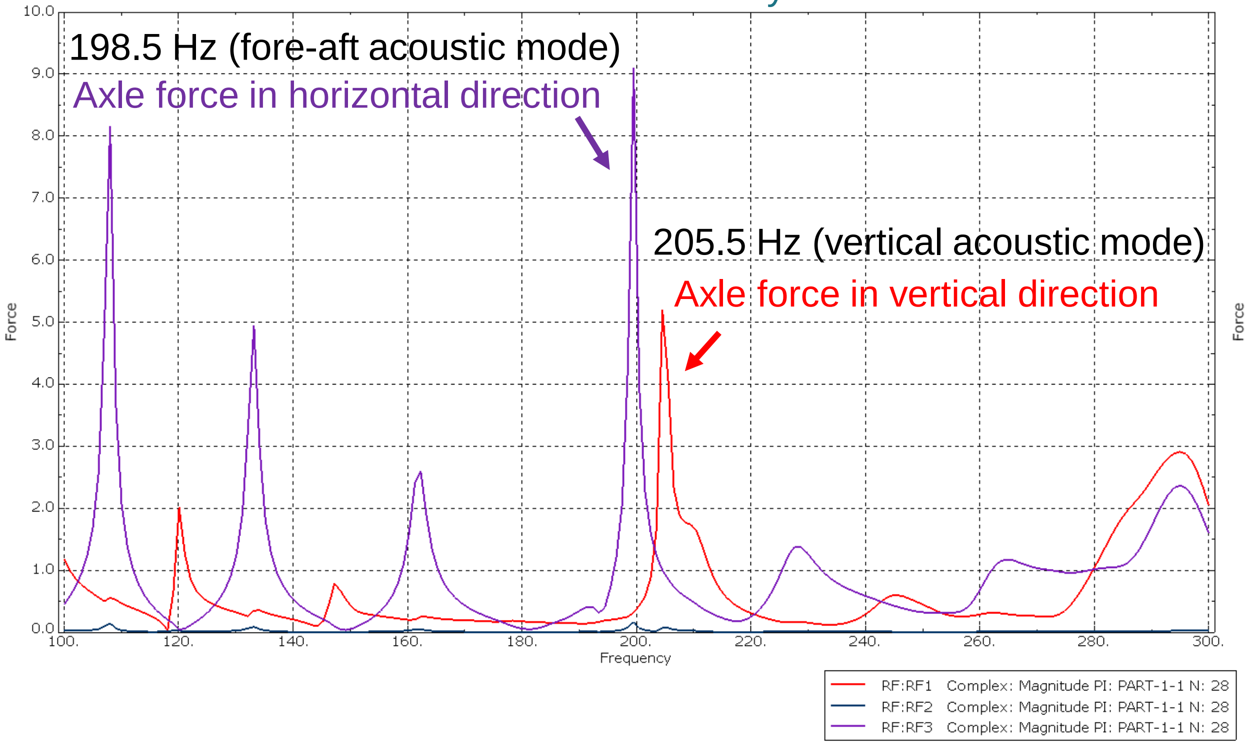
235/50/R18

FE Simulation

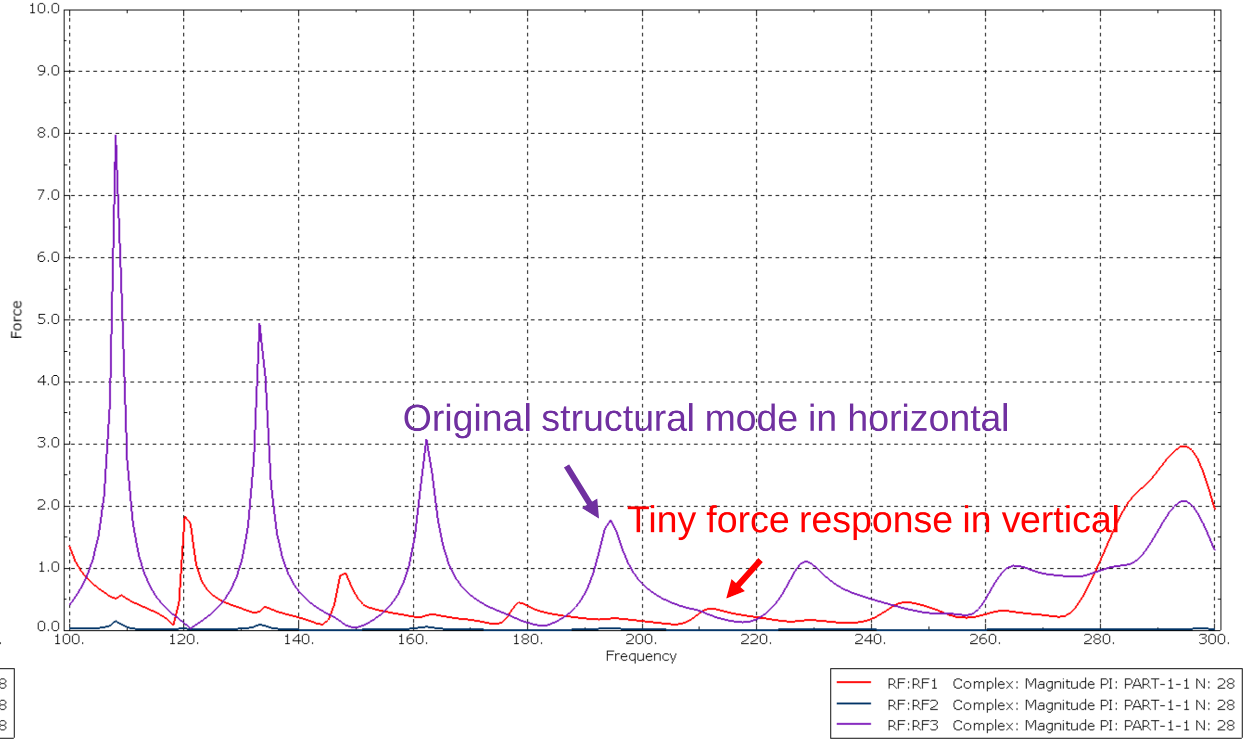
Result and discussion (Deformed)

- There exist two distinct force peaks that are associated with the two acoustic modes, and the force level is determined by the interaction between the structural vibration and the acoustic mode

Tire with Air Cavity



Airless Tire

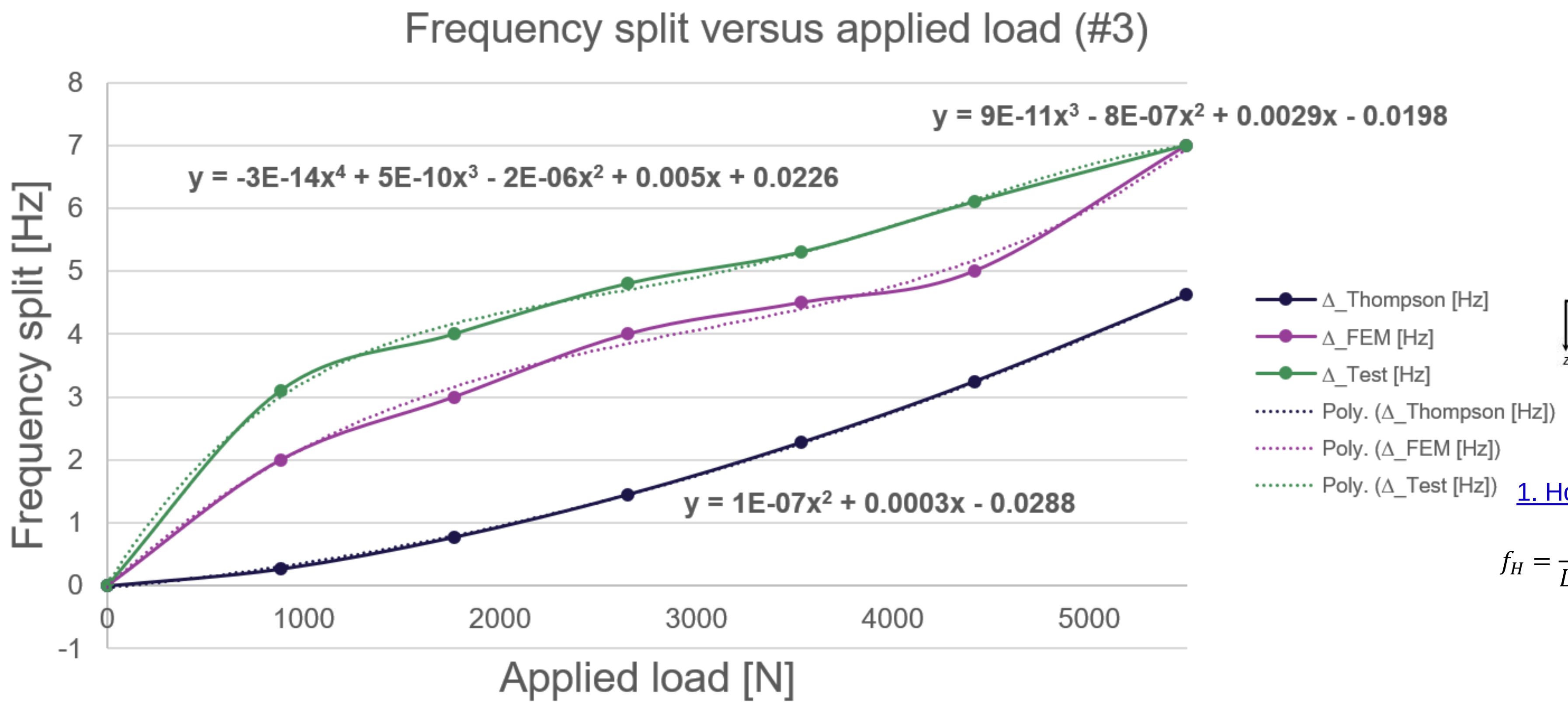


Dynamic force at the hub for tire #3

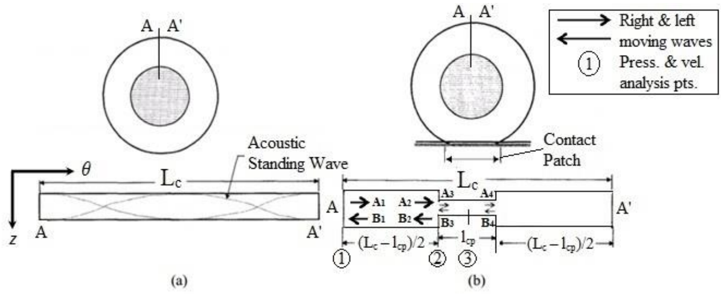
FE Simulation

Result and discussion (Deformed)

- ❑ The split in the cavity mode was examined by changing the applied load from 0 N to 5496 N
- ❑ FE simulation is much closer to the trend in test than an existing theory as a function of applied load



Thompson's model [5]



1. Horizontal mode

$$f_H = \frac{c}{L_c + (1-m)l_{cp}} \quad (1)$$

2. Vertical mode

$$f_V = \frac{c}{L_c - (1-m)l_{cp}} \quad (2)$$

$$m = \frac{A_{Loaded}}{A_{Unloaded}}$$

Conclusions

1. Experimental observations of the split of the fundamental air-cavity mode of loaded tires in a static condition were first reported

2. FE simulation was used to model the present experimental results: Both the structural and cavity resonance modes were well predicted in the non-deformed tire case between 100 Hz and 300 Hz, as was the frequency split when a load was imposed

3. Finally, it was verified that an amplified response in the vertical force at the hub could appear if an odd-numbered structural mode interacts with the vertical acoustic mode

4. The relation between the degree of the split and contact load showed a nearly fourth-order variation, which was more closer to FE simulation than Thompson's model

5. In the future, the frequency split for spinning tire will be investigated

Acknowledgement

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

References

[1] Bernhard, R. and et al. (2012) “An Introduction to Tire/Pavement Noise of Asphalt Pavement, ” *Virginia Asphalt Association.*

[2] 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.

[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] Cao R. and Bolton J.S. (2018) “Tire Cavity Induced Structure-Borne Noise Study with Experimental Verification, ” *Proceedings of InterNoise-2018*, No. 1482.

[5] Thompson, J.K. (1995) “ Plane Wave Resonance in the Tire Air Cavity as a Vehicle Interior Noise Source, ” *Tire Science and Technology,* Vol. **23**, pp.2-10.

[6] Choi W., Bolton J.S., and et al. (2019) “A Laboratory Procedure for Measuring the Dispersion Characteristics of Loaded Tires ,” *Proceedings of NoiseCon-2019,* **10**, pp.851-860.

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Thank You

Q&A Session

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