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FE Simulation of Split in Fundamental Air-Cavity Mode of Loaded Tires: Comparison with Empirical Results

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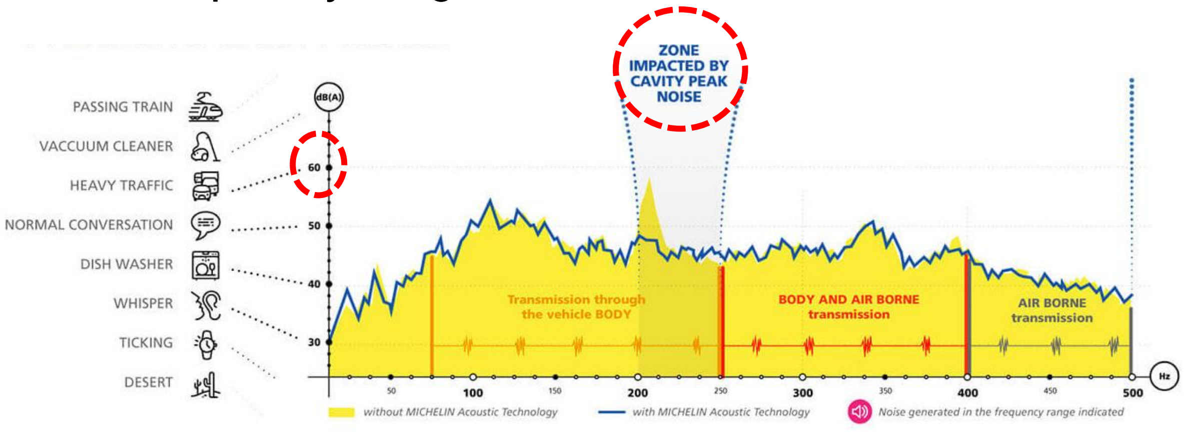
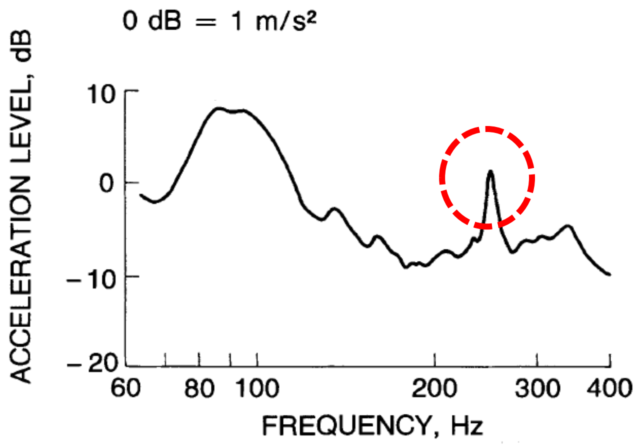
Introduction

- Tire/road noise may be a dominant source of cabin and pass-by noise for Electric Vehicles since powertrain noise is largely eliminated
- 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



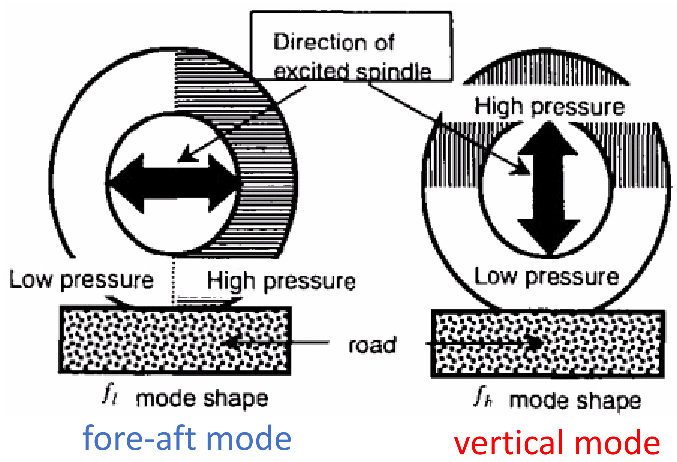
Introduction of cavity noise, courtesy of Michelin tire [1]



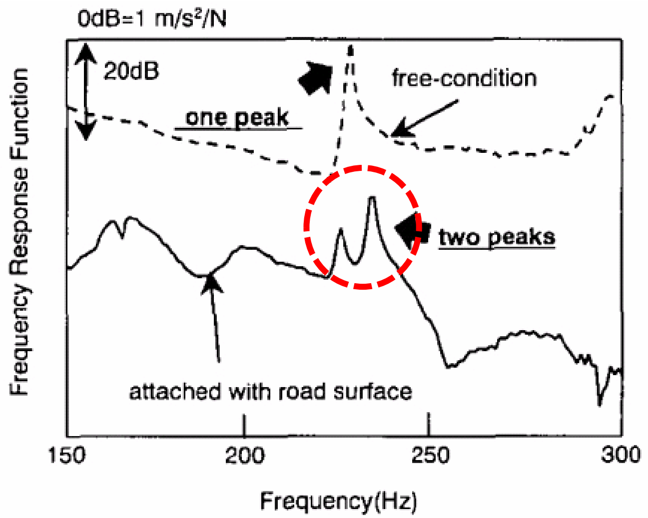
Air-cavity mode in acceleration, Sakata and et al [2]

Introduction

- Loading breaks tire's geometrical symmetry, which splits acoustic cavity mode
- Fore-aft mode shifts to lower frequency, contributing to horizontal force at the hub
- Vertical mode shifts to higher frequency, contributing to vertical force at the hub



Two acoustic modes, Yamauchi and Akiyoshi [3]

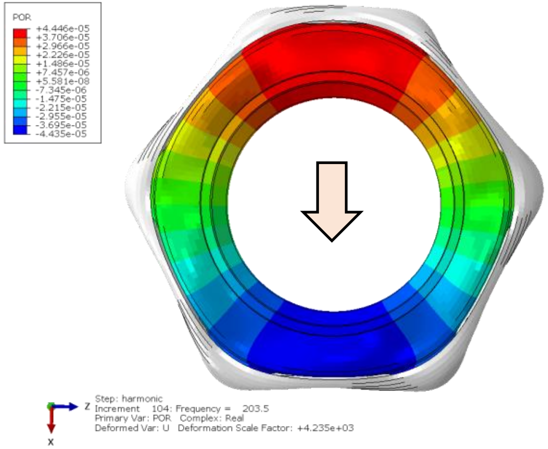


Split in a cavity mode, Yamauchi and Akiyoshi [3]

Introduction

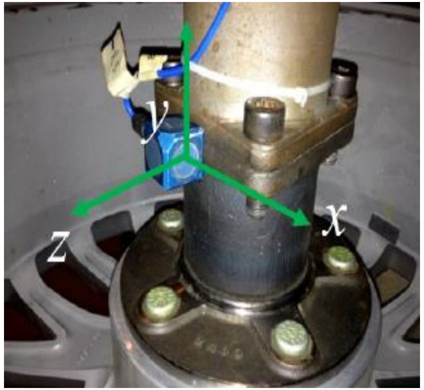
- Alignment between structural modes and cavity modes can result in amplified force at the hub (Rui Cao and J. Stuart Bolton [4])
- Identify mechanism of force generation and ultimately avoid any coupling between these two features

Air-cavity mode coupled with structural resonances



Prediction by the validated FE Model

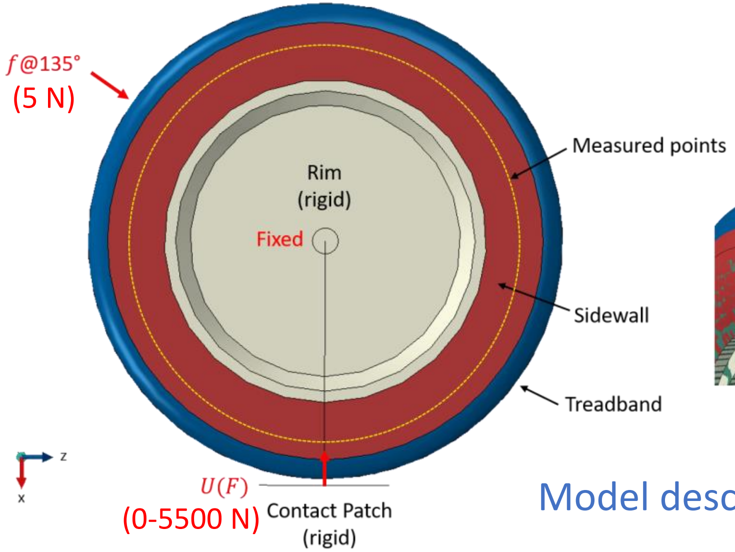
Forces at the hub

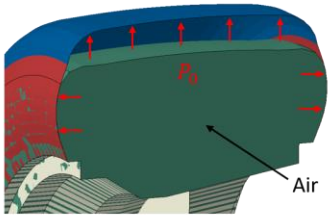


The influence of coupling on force level at the hub

FE Model Description

- An axisymmetric model was created based on the shape of a 2D cross-sectional area, consisting of treadband, sidewall, rim, air cavity and contact patch.
- A FE simulation has been implemented to attempt to reproduce both structural modes and the split in the cavity mode frequency for deformed tire



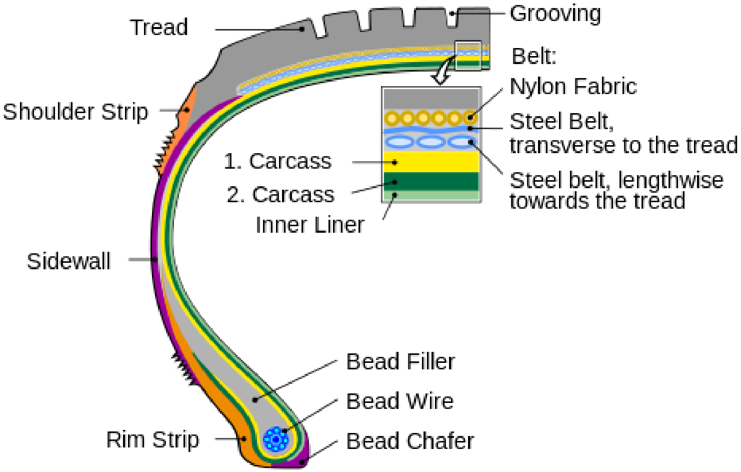


Model description

1. Inflation
↓
2. Deformation
↓
3. Modal analysis
↓
4. Harmonic analysis

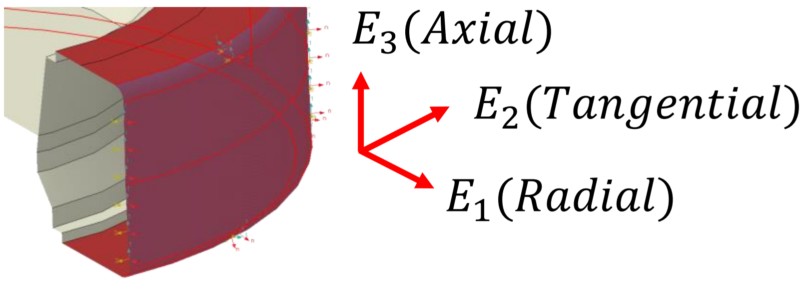
FE Model Description

- 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 bring model into agreement with the observed patterns of the structural resonance modes
- Macroscopic and orthotropic material properties to reflect complexity of tire structure



Tire composition,
courtesy of Wikipedia

Orthotropic material properties



FE Model Description

- As an example of material optimization, properties in structure and air cavity are given here for the modeled tire #1 (R18, 235/50/R18)

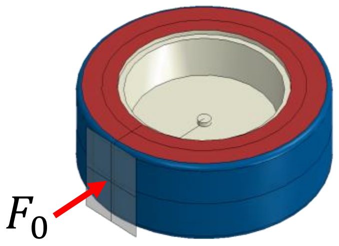
Property in tire structure

ID	Part	Thickness, t	Density, ρ	Young's modulus, E (Radial/Tangential/Axial)	Poisson's ratio, υ	Shear modulus, G
18-4	Rim	5 mm	4387 kg/m³	70,000 MPa	0.3	N/A
	Treadband	12 mm	1520 kg/m³	200/650/200 MPa	0.5	50 MPa
	Sidewall	6 mm	1013 kg/m³	250/10/250 MPa	0.5	3 MPa

Property in air cavity

$$c = \sqrt{\frac{\gamma \beta_T}{\rho_{air}}}$$

Part	Density, ρ_{air}	Bulk modulus, $\beta = \gamma \beta_T$
Air	2.15 kg/m³	0.26 MPa



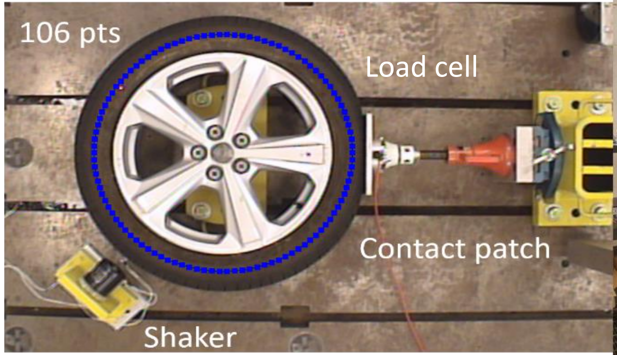
Empirical measurement

- The objective is to observe the split in tire's cavity mode in an experimental way for a set of loaded tires under static condition [5]
- Secondly, the relation between load level and amount of split needs to be verified
- A single tire from each rim size is chosen to visualize test results with a different range of operation

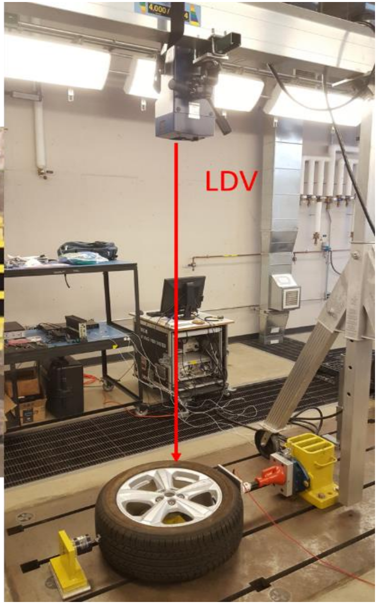
Model	R18	R20	R16	R17	R19
Rim [inch]	18	20	16	17	19
Width [mm]	235	265	205	215	255
Aspect ratio	50	35	65	55	40
Mass [kg]	12.7	13.2	10	10.3	13.4
Stiffness [N/mm]	306	349	245	274	295
Inflation [MPa]	0.24	0.24	0.23	0.23	0.22
Rated load [N]	5496	4812	4741	4913	4776

Empirical measurement

- Mobility data can be obtained by measuring surface velocity (V) and input force (f) for the deformed tire for 106 points along sidewall using Laser Doppler Vibrometer
- Static force (F) (Max. 1700 lbs.) was applied through a load cell
- Wavenumber (k_θ) can be identified by applying Discrete Fourier Transform to the mobility spatially distributed along sidewall

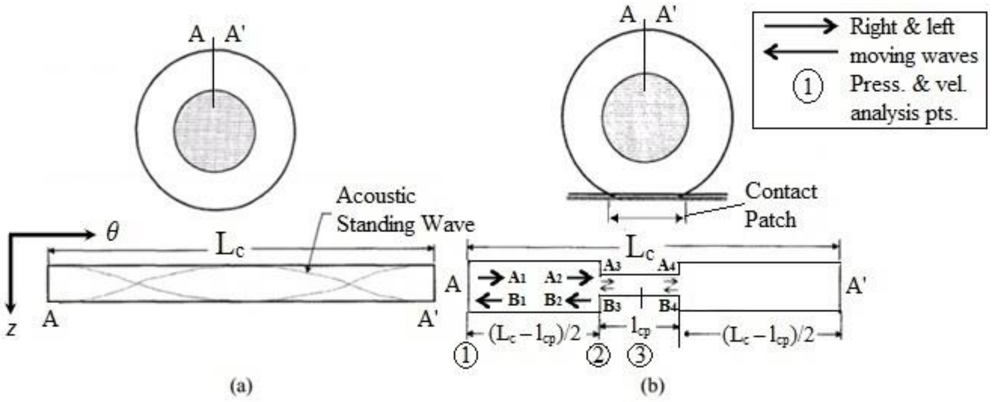


Shaker at 135° from contact patch



Simulation results : Analytical model for frequency split

- Analytical formula is adopted from Thompson's model
- Difficulty in obtaining m value experimentally; It was obtained from FE static simulation
- Investigate the variation of frequency split ($\Delta = f_V - f_H$) depending on applied load



Loaded tire model adopted from Thomson [6]

1. Horizontal mode

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

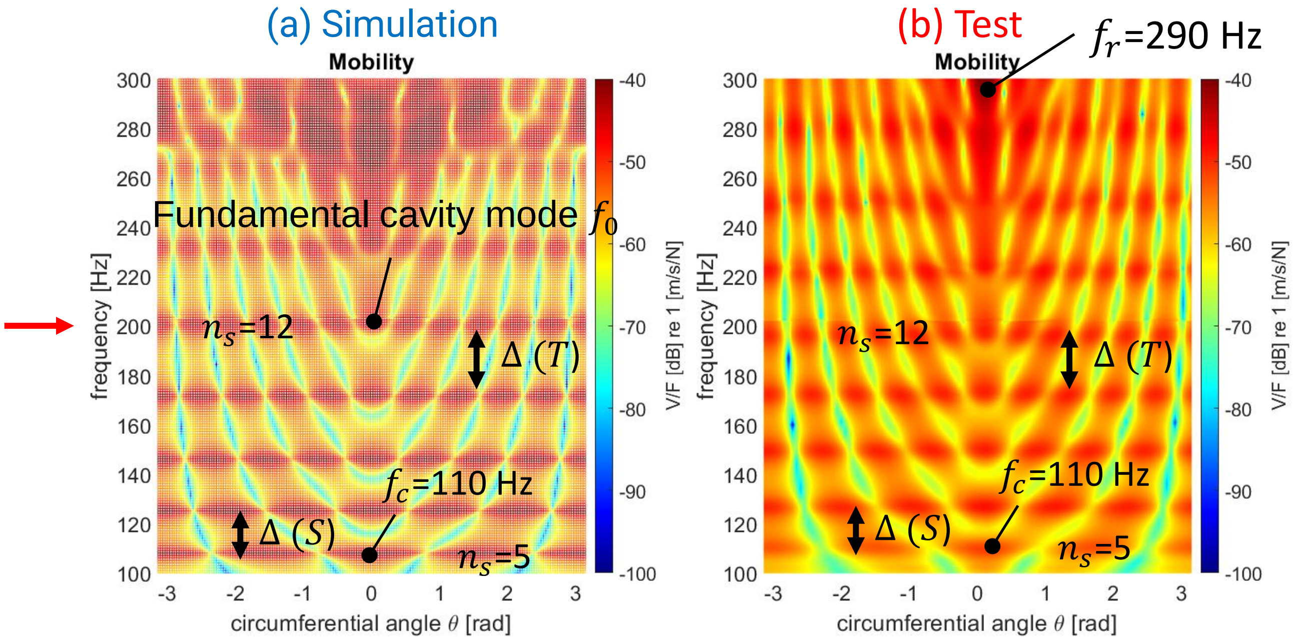
2. Vertical mode

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

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

Simulation results : Mobility , R18 (unloaded tire)

- 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

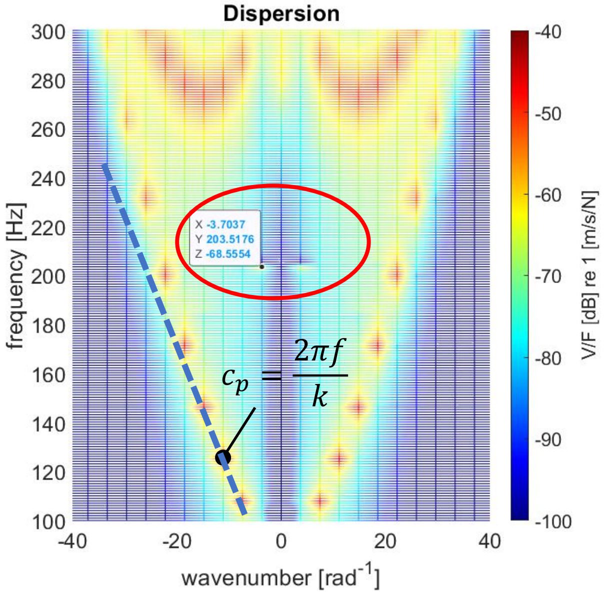


f_0 : fundamental cavity mode
f_r : ring frequency
f_c : cut-on frequency
n_s : mode number on sidewall
$\Delta(S)$: mode interval by sidewall
$\Delta(T)$: mode interval by tread

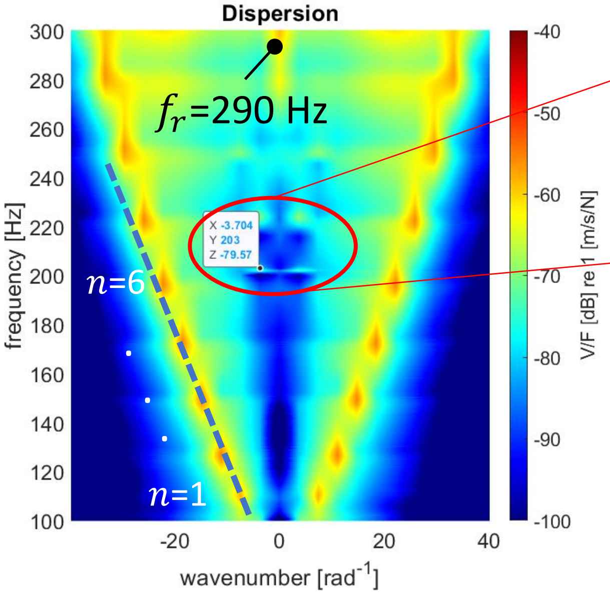
Simulation results : Dispersion, R18 (unloaded tire)

- 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
- Cross-sectional mode above 280 Hz is different due to the complexity of tire structure

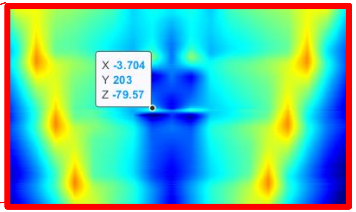
(a) Simulation



(b) Test



Fundamental cavity mode
f_0=203 Hz @ k=3.7 [rad/m]

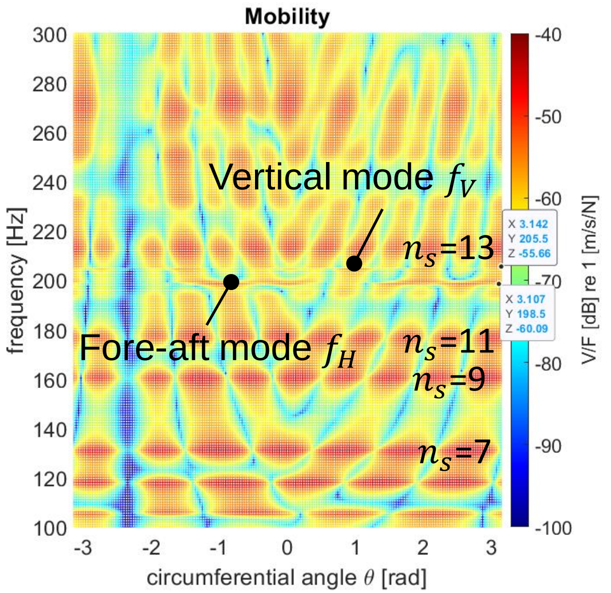


n : mode number on tread
c_p : phase speed of wave

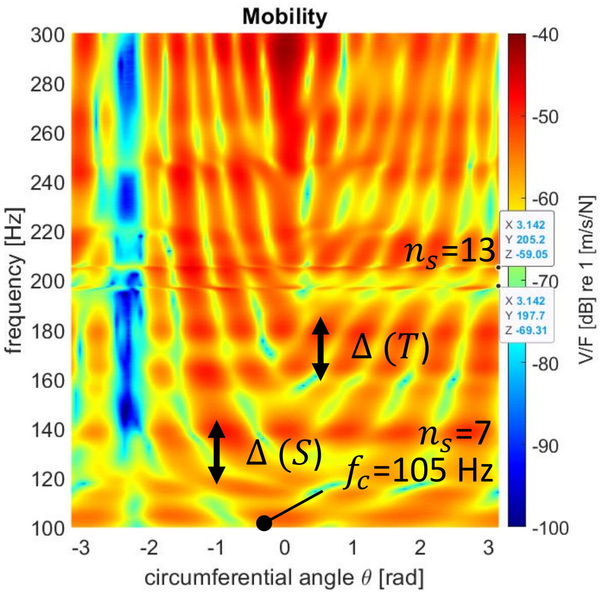
Simulation results : Mobility, R18 (loaded tire)

- Fore-aft acoustic mode at 198 Hz and the vertical acoustic mode at 205 Hz are well predicted even considering the difference in frequency resolution: 0.5 Hz (simulation) versus 0.15 Hz (test)
- The modal cut-on frequencies and the resonance frequencies of the structure are also in good agreement in the current simulation

(a) Simulation



(b) Test

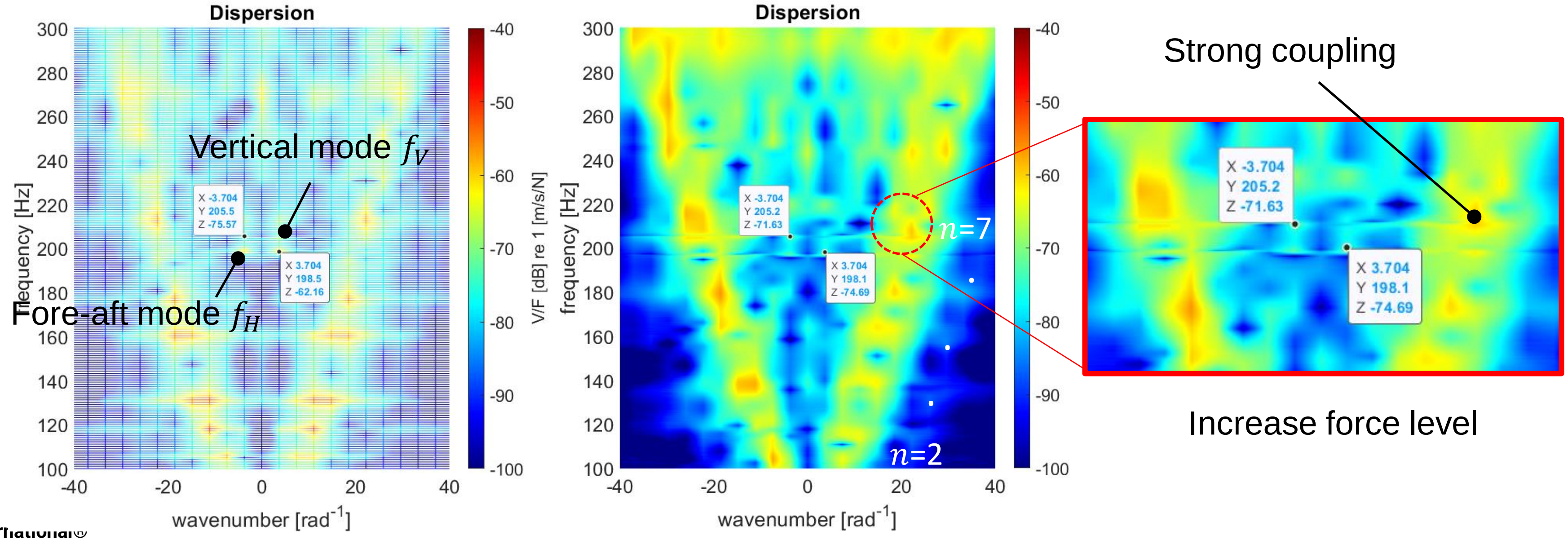


Simulation results : Dispersion, R18 (loaded tire)

- Strong coupling between the 7th structural mode and the cavity resonance at vertical mode can be observed, indicating an amplified force response in the vertical direction at the hub
- Deformation plays the role of a spatial low-pass filter that suppresses high wavenumber components, thus making the plot "blurrier"

(a) Simulation

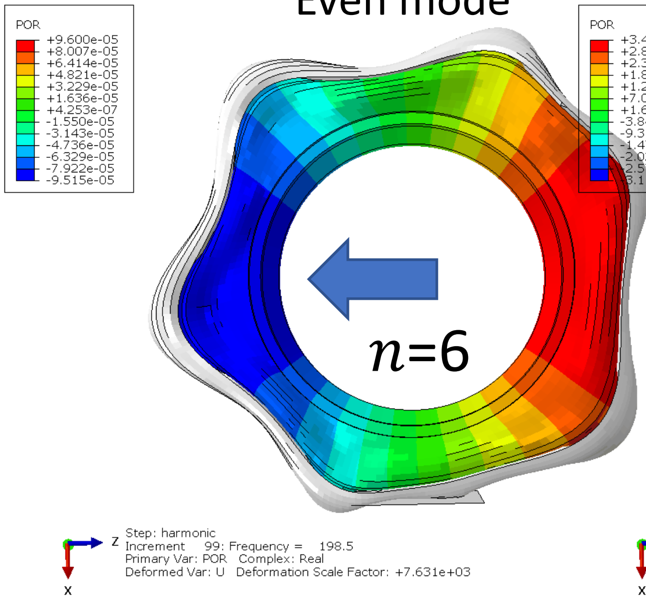
(b) Test



Simulation results : Acoustic Pressure, R18 (loaded tire)

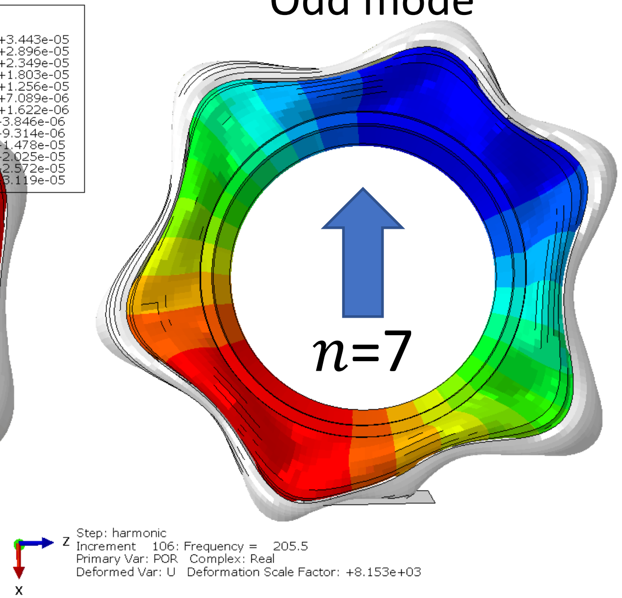
- Mode number of the structural vibration is an odd number (n = 7) at the vertical mode frequency, so the net structural vibration is directed vertically
- Even mode couples with fore-aft mode to create net horizontal vibration

Even mode



(a) Fore-aft mode, f_H, 198.5 Hz

Odd mode

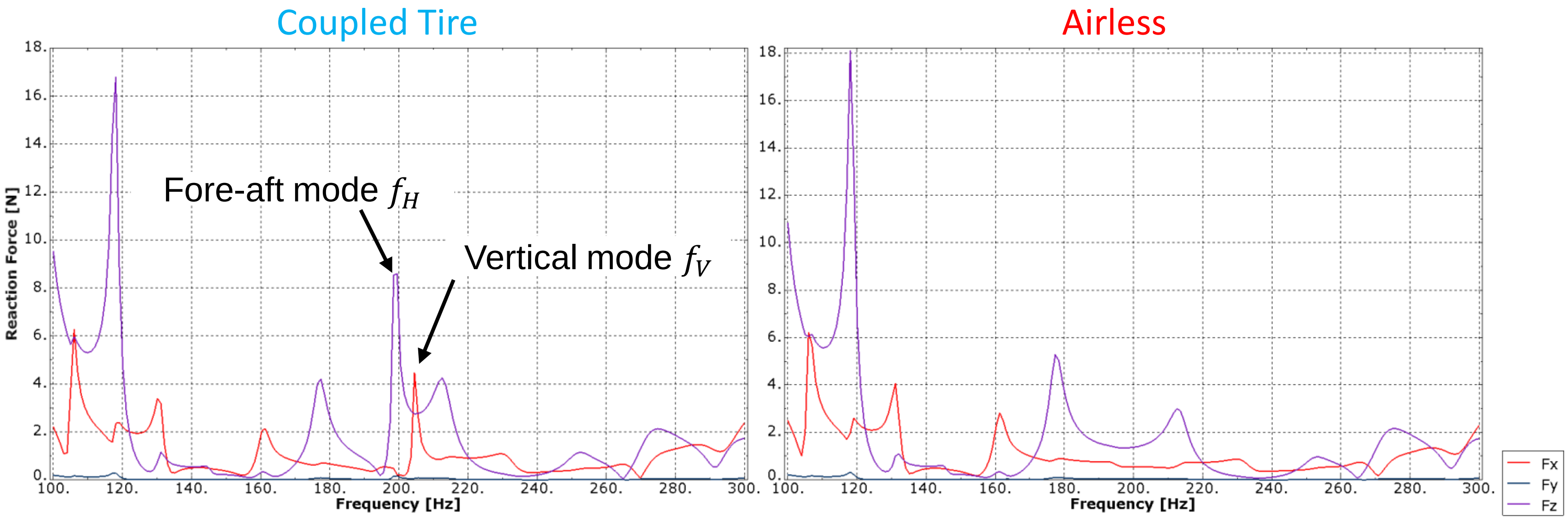


(b) Vertical mode, f_V, 205.5 Hz

Increase force level when coupled together

Simulation results : Reaction force, R18 (loaded tire)

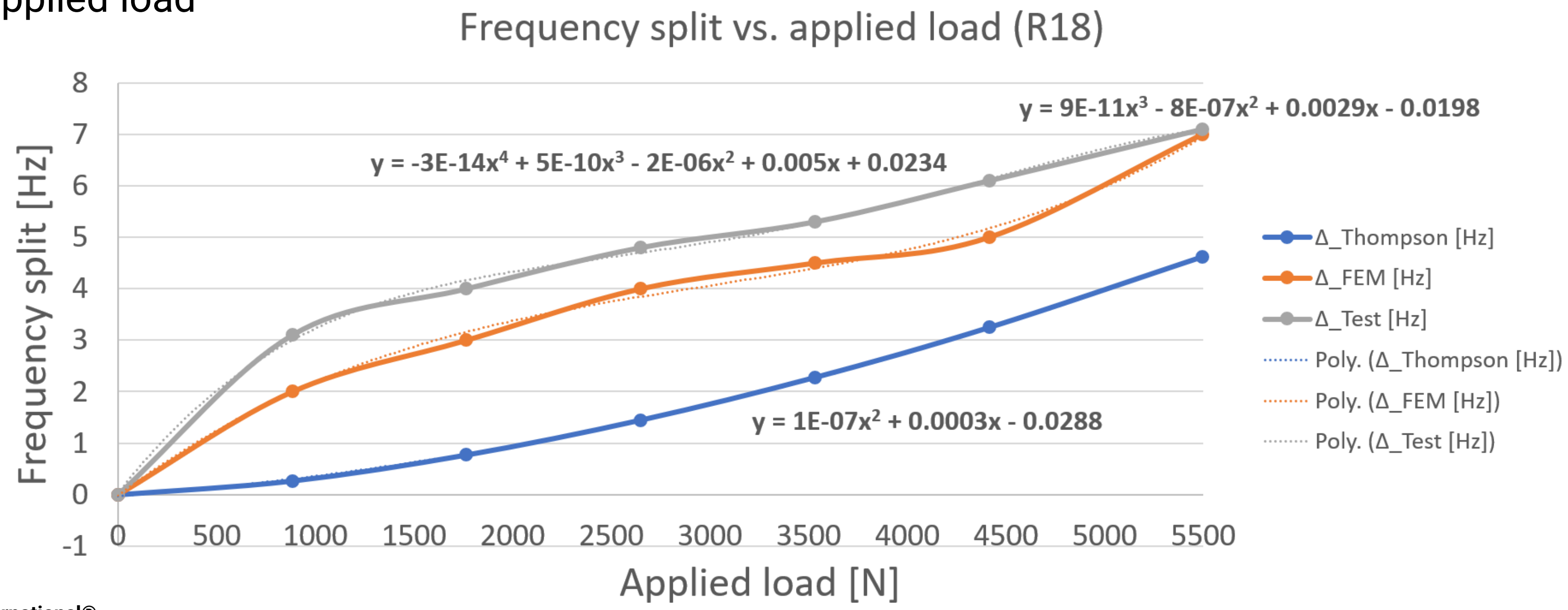
- Two distinct force peaks appear that are associated with the two acoustic modes
- Force level is determined by the interaction between the structural vibration and the acoustic mode



- Fx, Vertical force
- Fz, Horizontal force

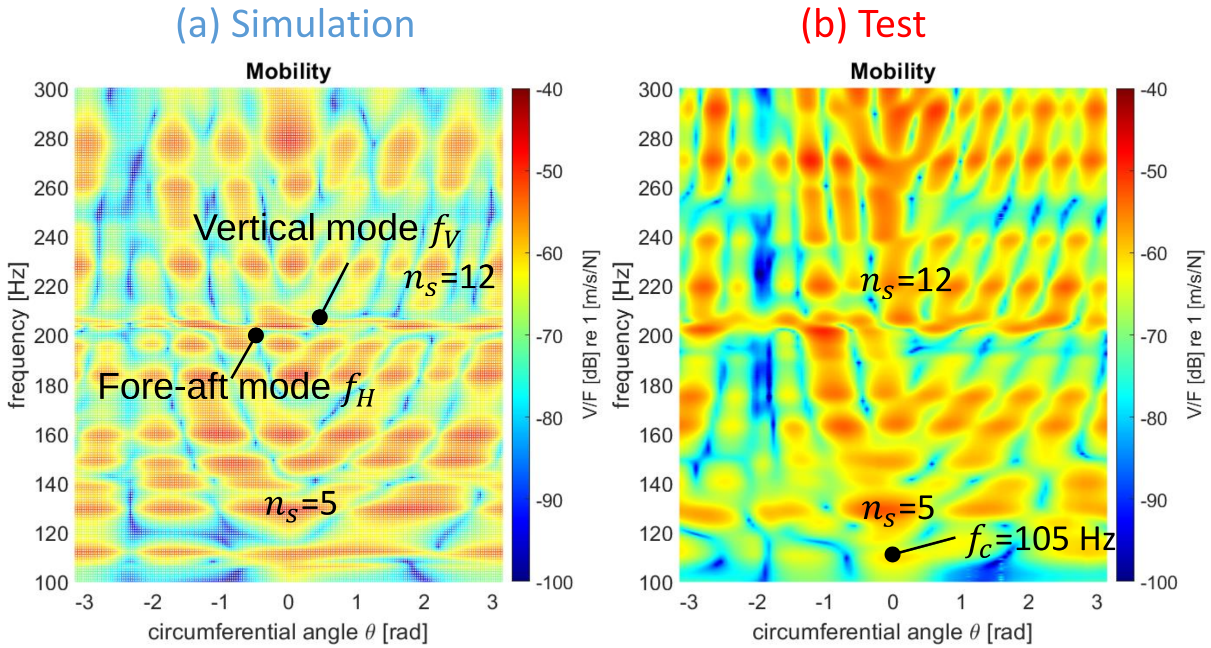
Simulation results : Frequency split vs. Applied load, R18 (loaded tire)

- The split in the cavity mode was examined when changing the applied load from 0 N to 5496 N (the rated load for this tire)
- FE simulation is much closer to the trend in test than Thompson theory as a function of applied load



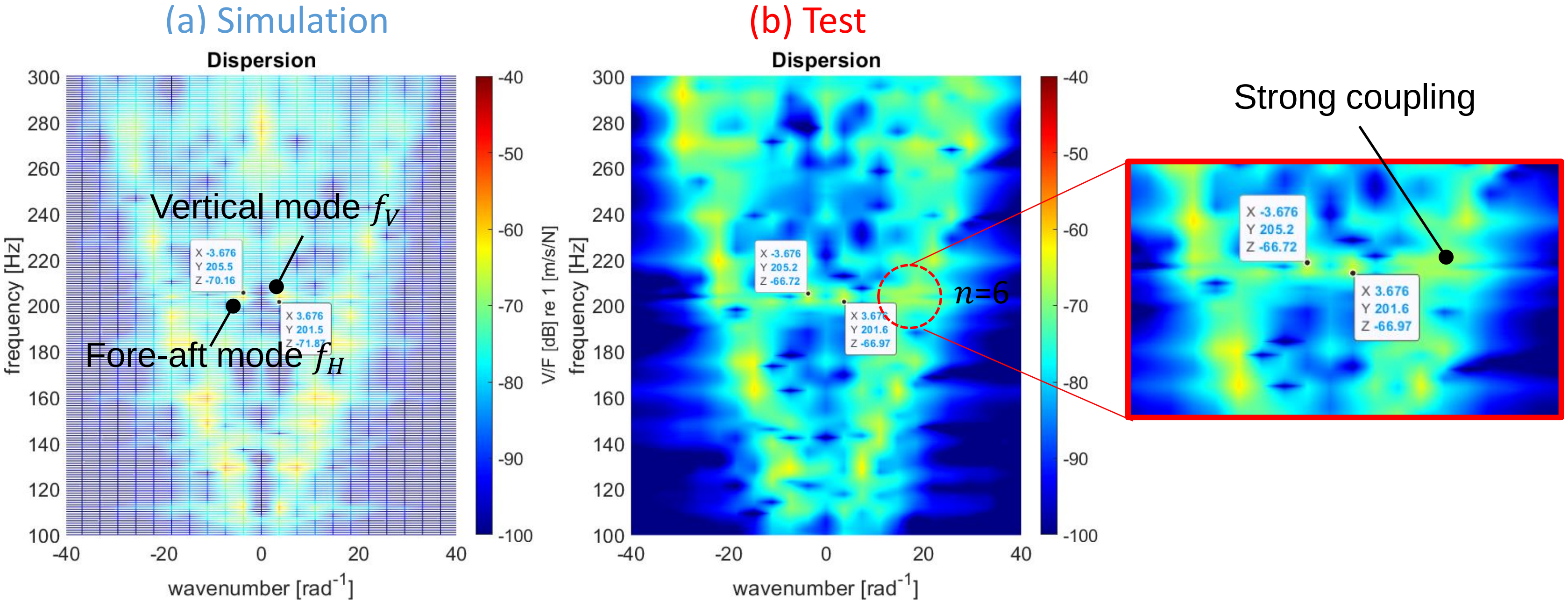
Simulation results : Mobility, R20 (loaded tire)

- The frequency split agrees closely with the experimental result
- Two mobility plots showed good consistency in the structural pattern, including the modal cut-on frequency at 105 Hz, and the natural frequency of the 5th structural mode, for instance



Simulation results : Dispersion, R20 (loaded tire)

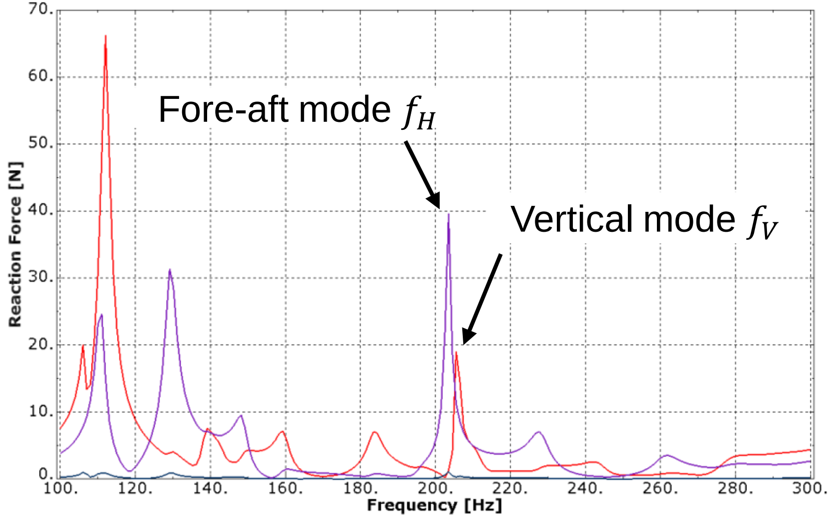
- The frequency split agrees closely with the experimental result
- The two acoustic modes interact with the 6th structural mode strongly near 200 Hz, contributing to an increased force response at the hub in both horizontal and vertical directions



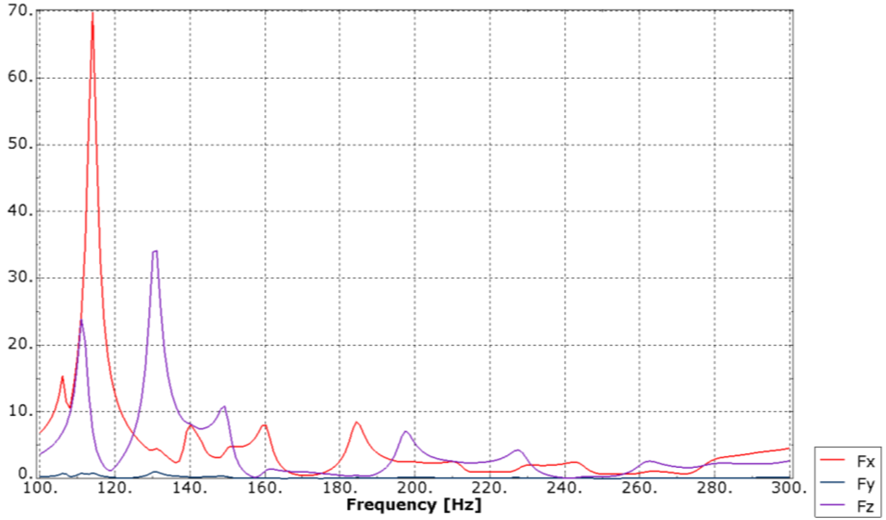
Simulation results : Reaction force, R20 (loaded tire)

- Two distinct force peaks appear that are associated with the two acoustic modes
- Frequency split is reduced compared to the previously presented R18 tire

Coupled Tire

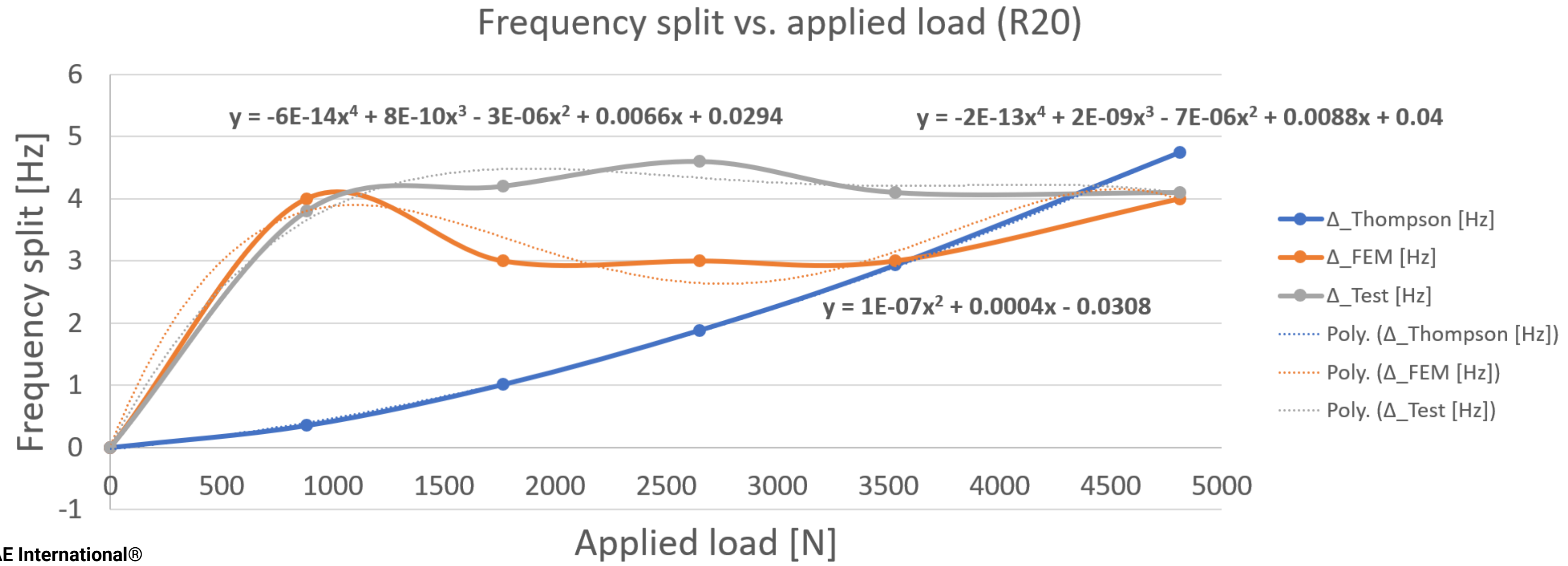


Airless



Simulation results : Frequency split vs. Applied load, R20 (loaded tire)

- The split in the cavity mode was examined when changing the applied load from 0 N to 4812 N (the rated load for this tire)
- The estimation from the FE simulation matches the trend of the experimental results quite well, and follows a fourth order polynomial fit



Summary

- The frequency split of the fundamental acoustic mode changes from 4 to 7 Hz depending on tire's specifications, such as rim size, stiffness, and applied load

Model	R18	R20	R16	R17	R19
f_0 $[Hz]$ 1st cavity mode	203.5	200.9	215.6	212.6	207.5
f_H $[Hz]$ Fore-aft mode	198.5	201.5	211.6	206.5	204.5
f_V $[Hz]$ Vertical mode	205.5	205.5	217.6	213.5	208.5
Δf $[Hz]$ Frequency split	7	4	6	7	4

Conclusions

- **A FE model** was developed to make it possible to predict **the split of the fundamental air-cavity mode** of loaded tires in a static condition for **five commercial tires**
- **The observed split** varied from a minimum of **4 Hz to a maximum of 7 Hz** at rated load in the five cases described here
- **A large dynamic force** at the hub resulting from the acoustic mode might be anticipated when the **air-cavity modes** are **close in frequency** to spatially-matched **structural modes**
- The relation between the degree of the split and contact load showed a nearly **fourth-order variation** in the test and the **FE simulation reproduced that trend**
- In the next stage of this work, **hub force data** measured in the laboratory **for rolling tires** will be quantitatively compared with the simulation results to demonstrate their reliability

Acknowledgement

- Ford Motor Company – Financial support / Tire & wheel sample provider
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Contact Info

- Thank you

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