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Force Amplification at the Wheel Hub Due to the Split in the Air-Cavity Mode for a Rolling Tire

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PURDUE MECHANICAL ENGINEERING

Force amplification at the wheel hub due to the split in the air-cavity mode for a rolling tire

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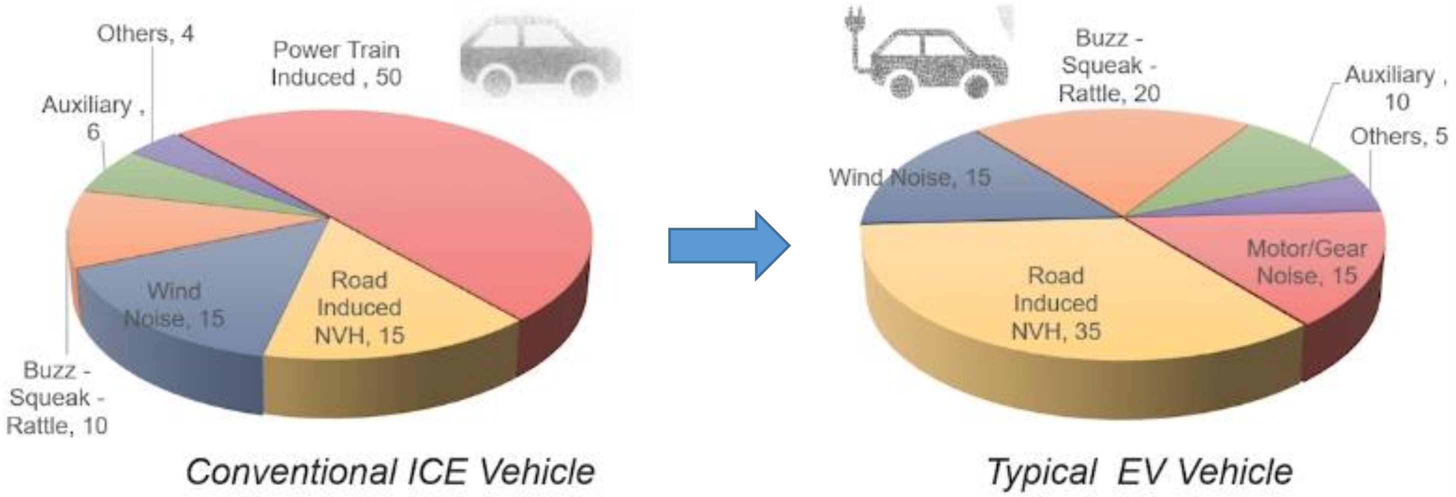
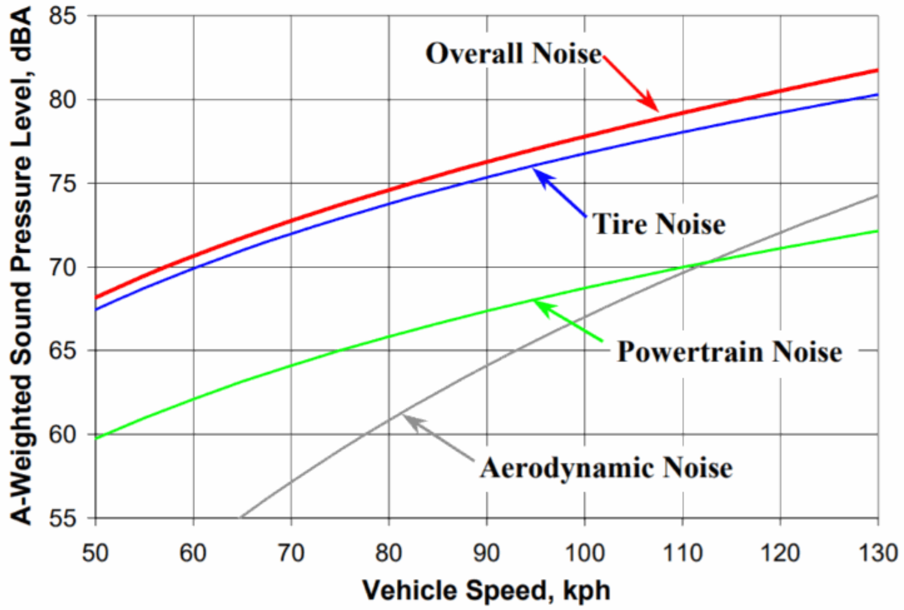
Contents

Introduction

1. Reduction of tire/road noise is an important issue for EV vehicles.
    - Powertrain noise is eliminated for EV vehicles
    - A driver becomes more sensitive to tire/road noise
2. Tire/road noise is also a key contributor in a pass-by noise.
    - Traffic noise level in regulation is lowered (e.g., EU, Asia)
    - Development of a low-noise tire and pavement enhancement are required



Tire noise in EV vehicle (Parmer [1]).



The dominance of tire noise in pass-by noise (Bernhard [2]).

Cavity Noise

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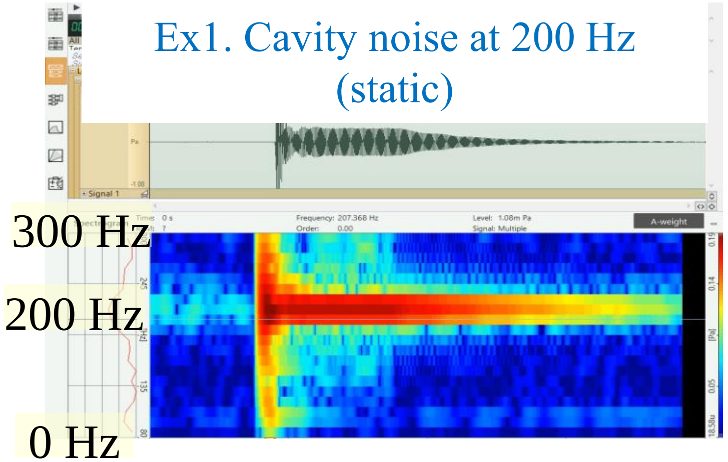
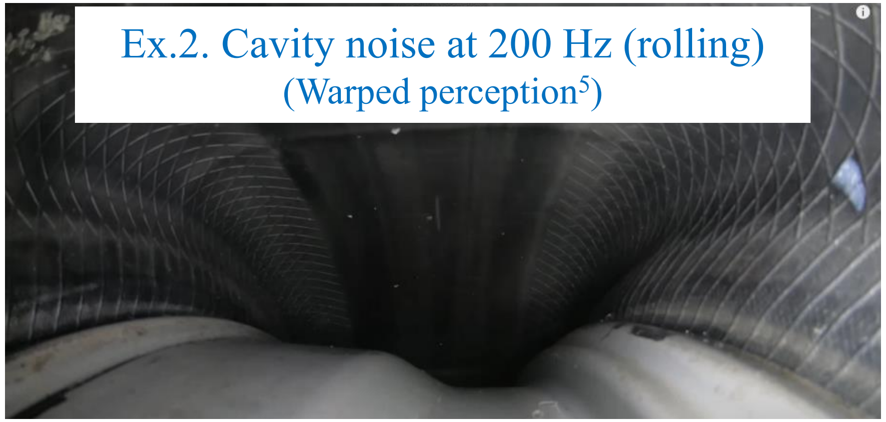
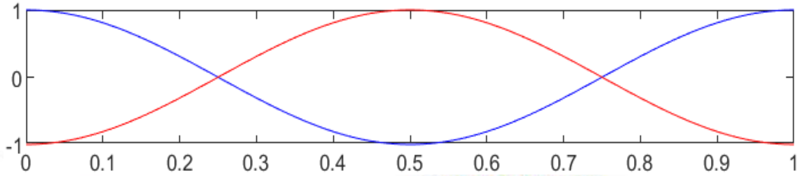
1. The fundamental air-cavity mode is an acoustic resonance mode between 180 Hz and 250 Hz, $f = \frac{c}{2\pi R}$.
2. It contributes to the increased force and cabin noise in the structure-borne transmission due to the large net displacement. (e.g., same noise level of 60 dB as heavy traffic)

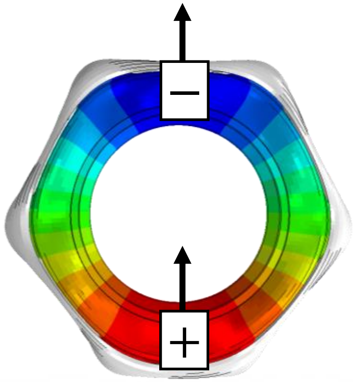


Ex1. Cavity noise at 200 Hz (static)

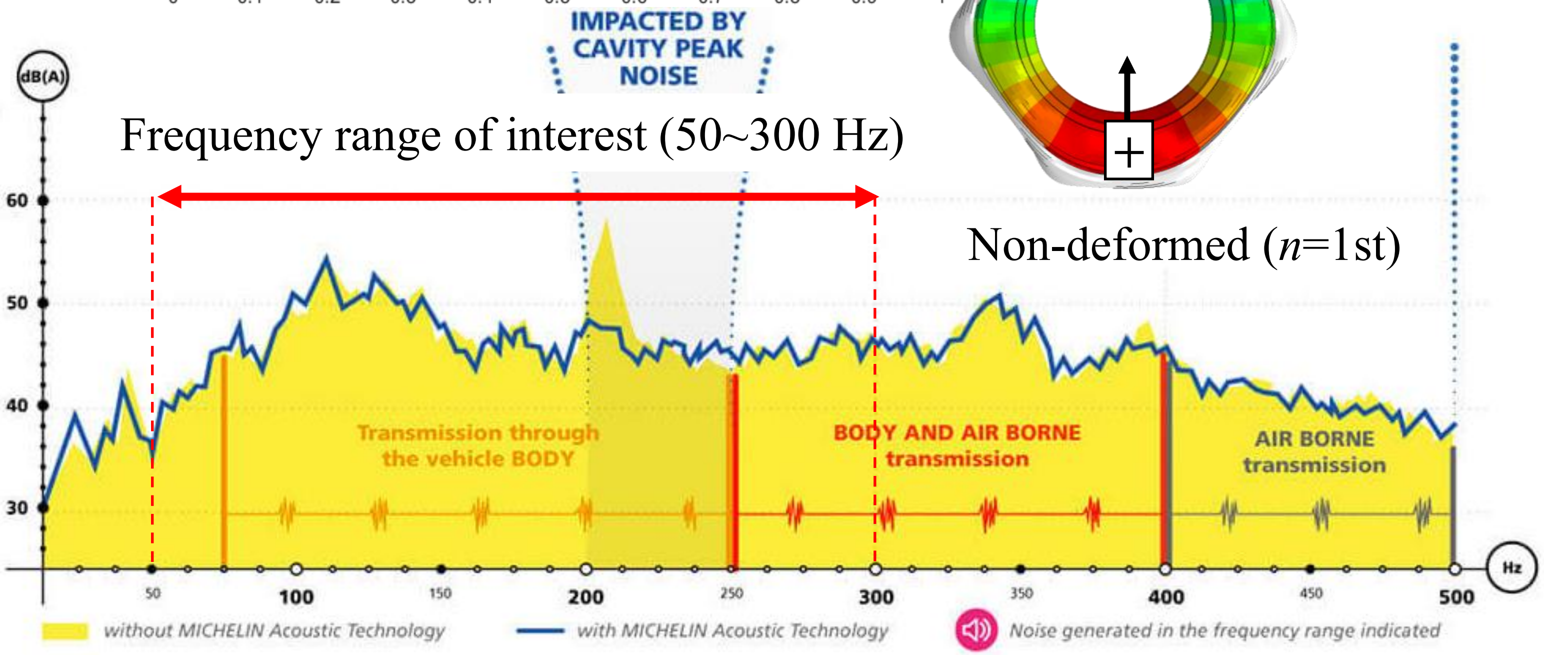


Ex.2. Cavity noise at 200 Hz (rolling) (Warped perception[5])





Non-deformed (n=1st)



A cavity noise with structure-borne transmission (Michelin North America[3]).

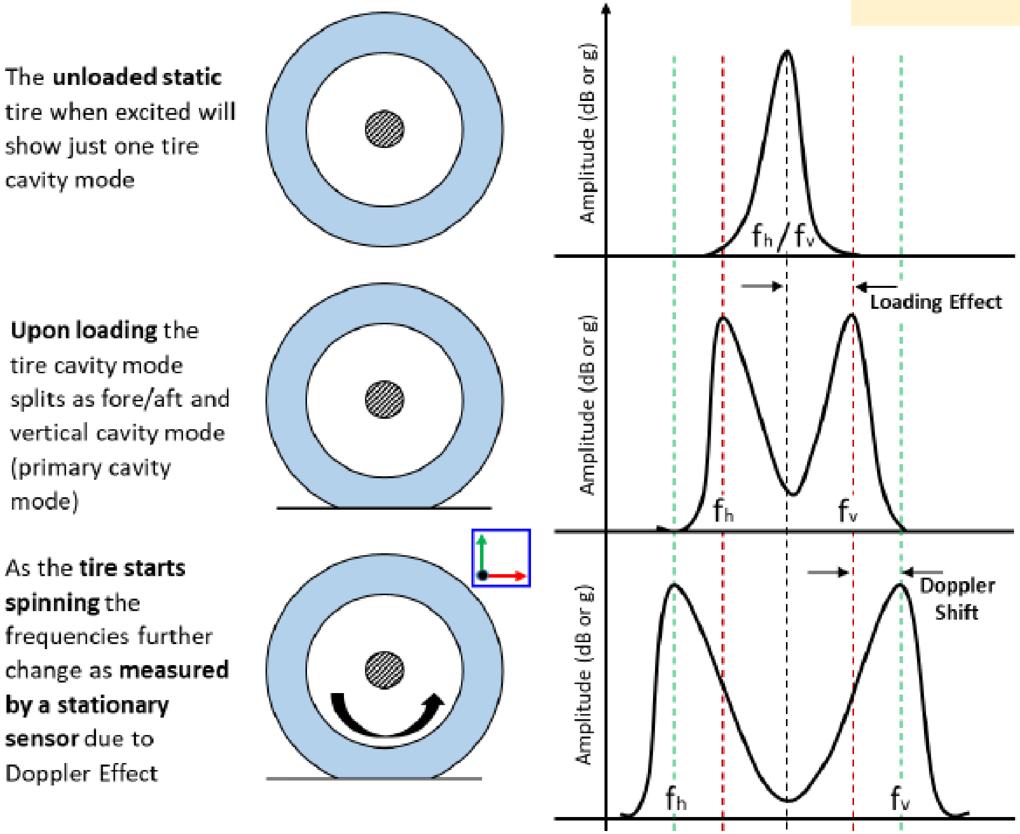
Frequency Split

1. The frequency split in the fundamental air-cavity mode is caused by two factors.

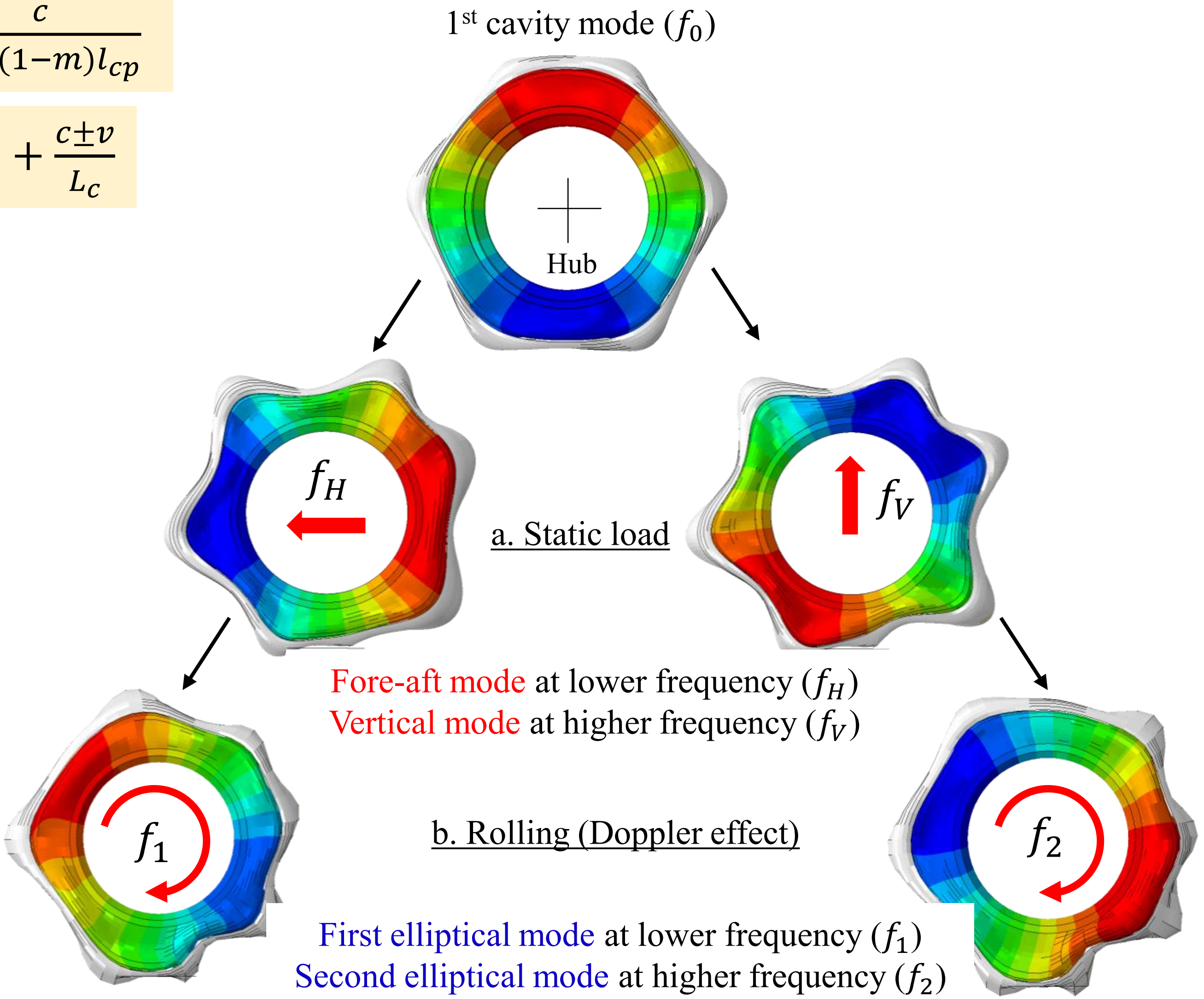
   a. Static load (Asymmetry in geometry)

   b. Rolling (Doppler shift)

- $f_{H,V} = \frac{c}{L_c \pm (1-m) l_{cp}}$
- $f_{1,2} = f_{H,V} + \frac{c \pm v}{L_c}$



The evolution of frequency split (Patil [4]).



Force Amplification at the Wheel Hub

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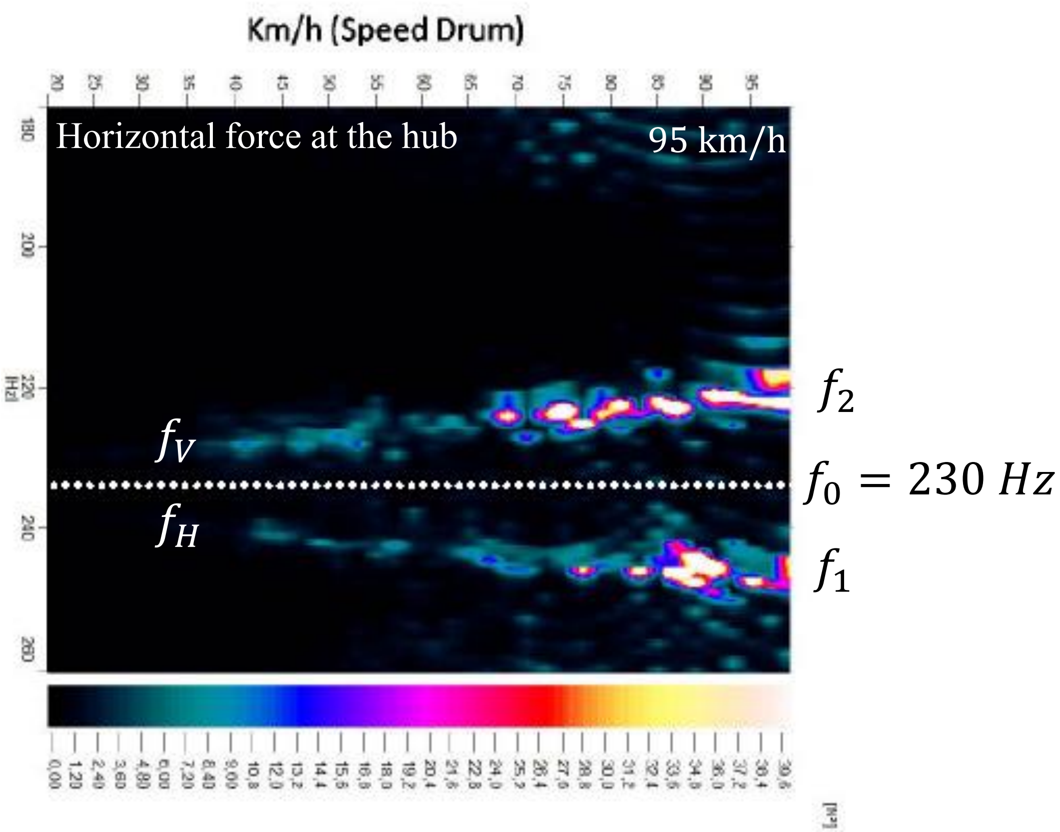
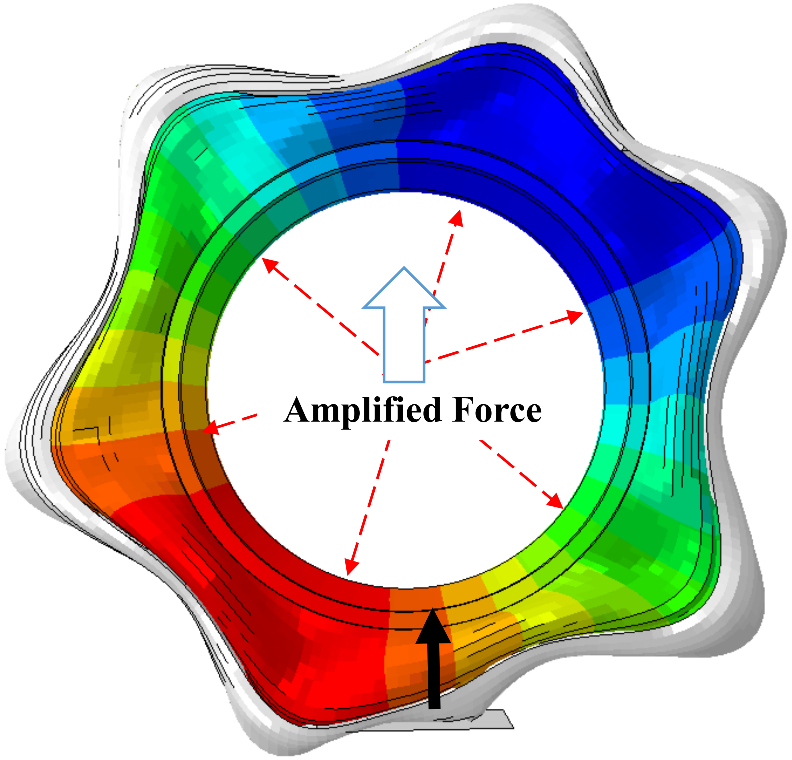
1. Previous studies discovered the possible contribution of cavity mode to increased force.
2. The coupling between two directional acoustical modes and structural resonance mode amplifies the force level at the wheel hub (thus, increased cabin noise).



Force amplification with the frequency split (Patil [4]).

Ex.) Alignment between vertical mode f_V and structural resonance mode (Static)



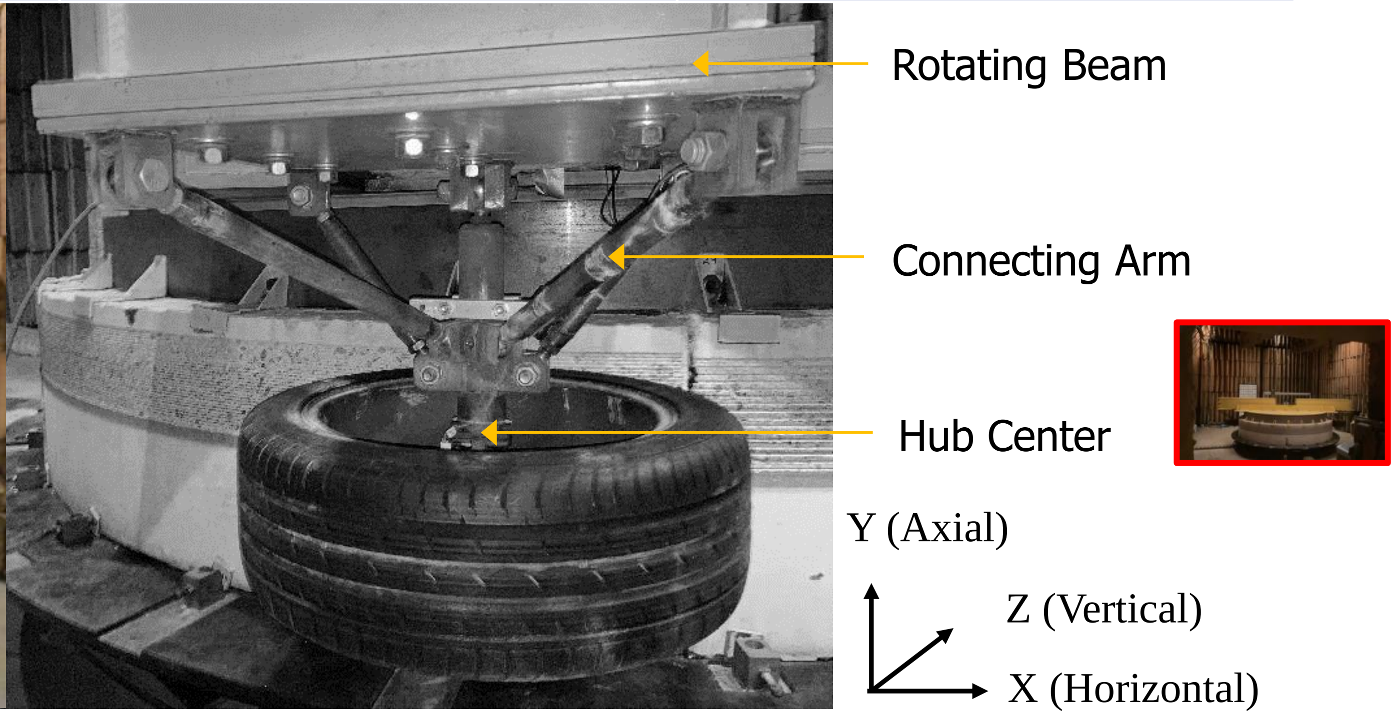
Net vertical displacement (n=7th)

TPTA (Tire Pavement Test Apparatus)

1. TPTA (Tire Pavement Test Apparatus) for tire noise measurement (Max. Speed 30 mph, Load 1,200 lbs.)
2. Previously used for tire-pavement interaction noise (above 400 Hz).
3. Recently utilized for tire-cavity force measurement (below 300 Hz).

Max. Speed	Max. Load	Mean diameter	Pavements
30 mph	1200 lbs. (5,297 N)	4.4 m (center to pavement)	Six concretes (rough, fine)

(a) TPTA in semi-anechoic chamber.



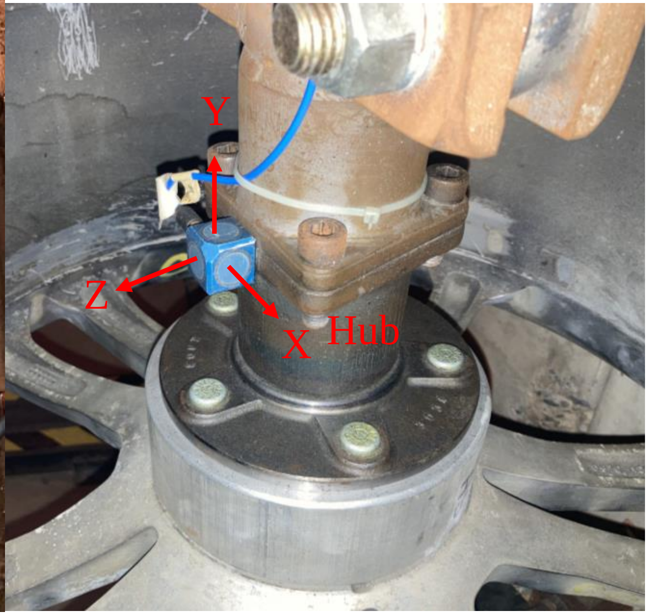
(b) Test rig.

WFT (Wheel Force Transducer)

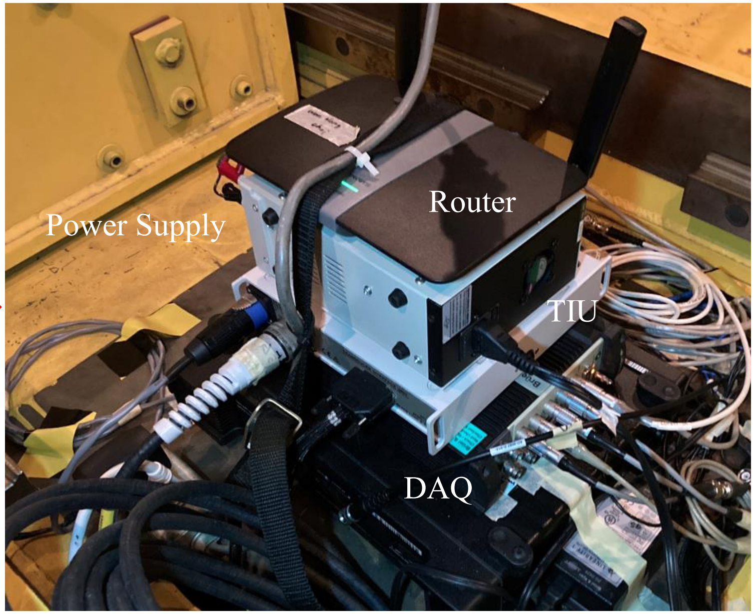
1. WFT (Wheel Force Transducer) was used to obtain dynamic force results at the hub.
2. Tri-axial accelerometer was also attached to capture supplementary vibrational response.
3. Wireless signal transmission was introduced to enable data recording for a rolling tire.

Type	Brand	Model	Remark
DAQ	B&K	3560-B/C-130	Eleven Ch.
Accelerometer	PCB	356B18	Tri-axial
WFT	Michigan Scientific	LW12.8-50	Passenger car

(a) Wheel Force Transducer.



(b) Accelerometer.



(c) Wireless signal transmission.

Frequency spectra

Introduction	Test (TPTA)	FE Simulation	Optimization	Conclusion

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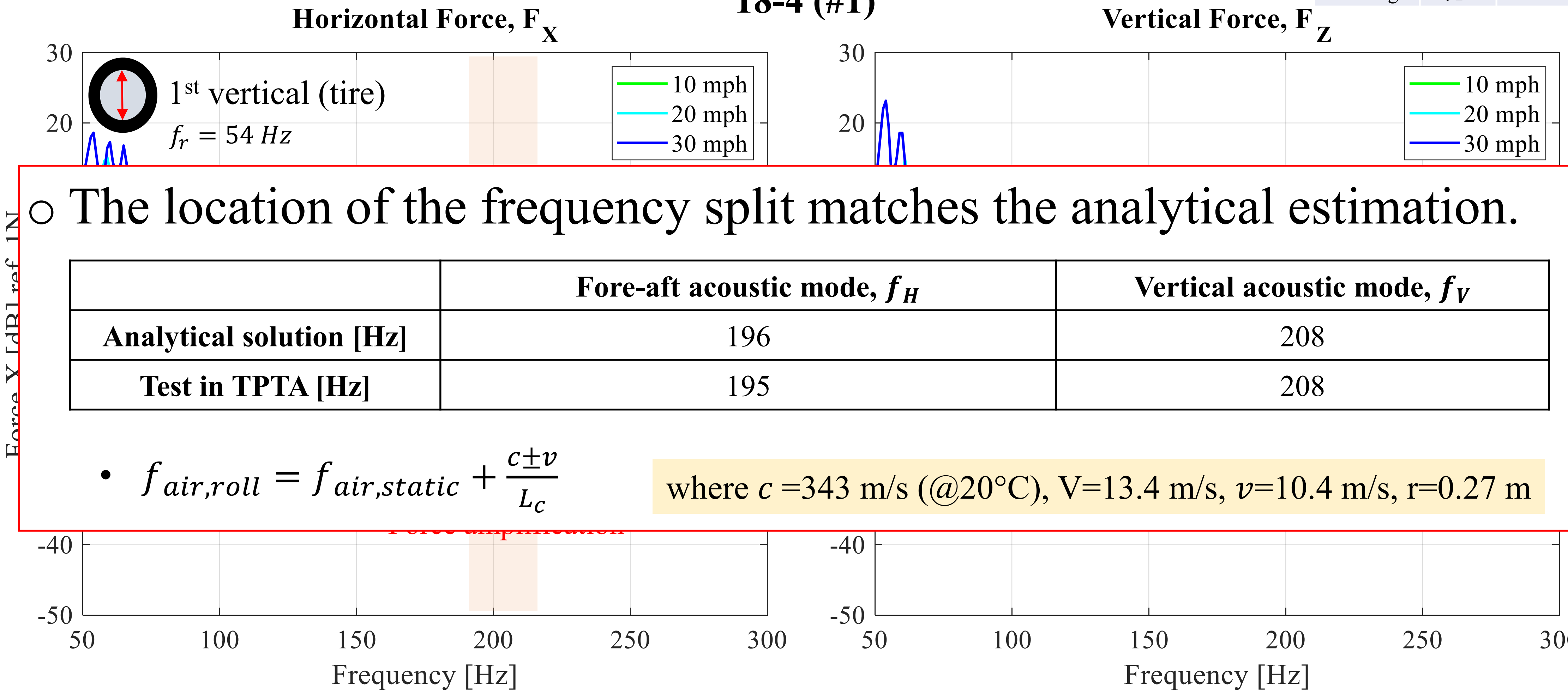
18-4	Peak	Frequency
Static	f_H	198 Hz
Rolling	f_1	195 Hz (-3 Hz)
Static	f_V	205 Hz
Rolling	f_2	208 Hz (+3 Hz)

1. As speed becomes faster, the frequency split and force level are increasing.
2. Force amplification due to air-cavity mode was observed at 208 Hz (second is bigger)

18-4 (#1)



○ The location of the frequency split matches the analytical estimation.

	Fore-aft acoustic mode, f_H	Vertical acoustic mode, f_V
Analytical solution [Hz]	196	208
Test in TPTA [Hz]	195	208

- $f_{air,roll} = f_{air,static} + \frac{c \pm v}{L_c}$

where c =343 m/s (@20°C), V=13.4 m/s, v=10.4 m/s, r=0.27 m

Campbell diagram

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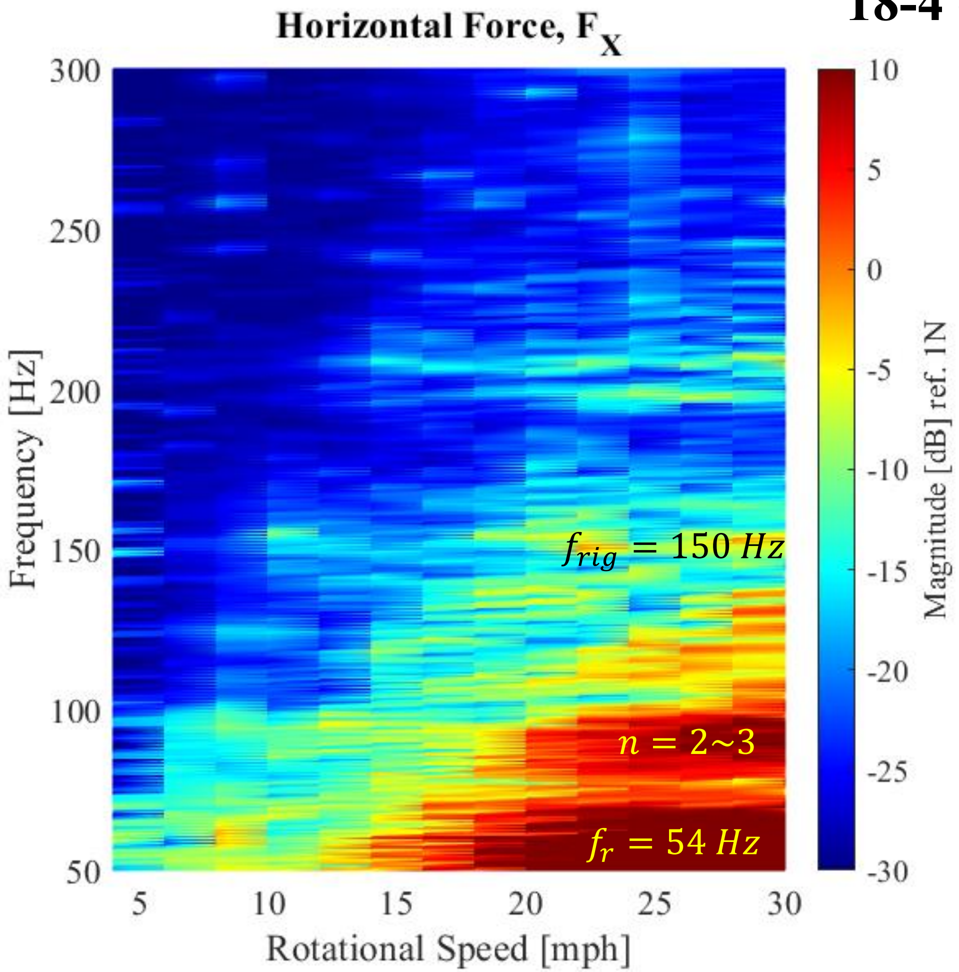
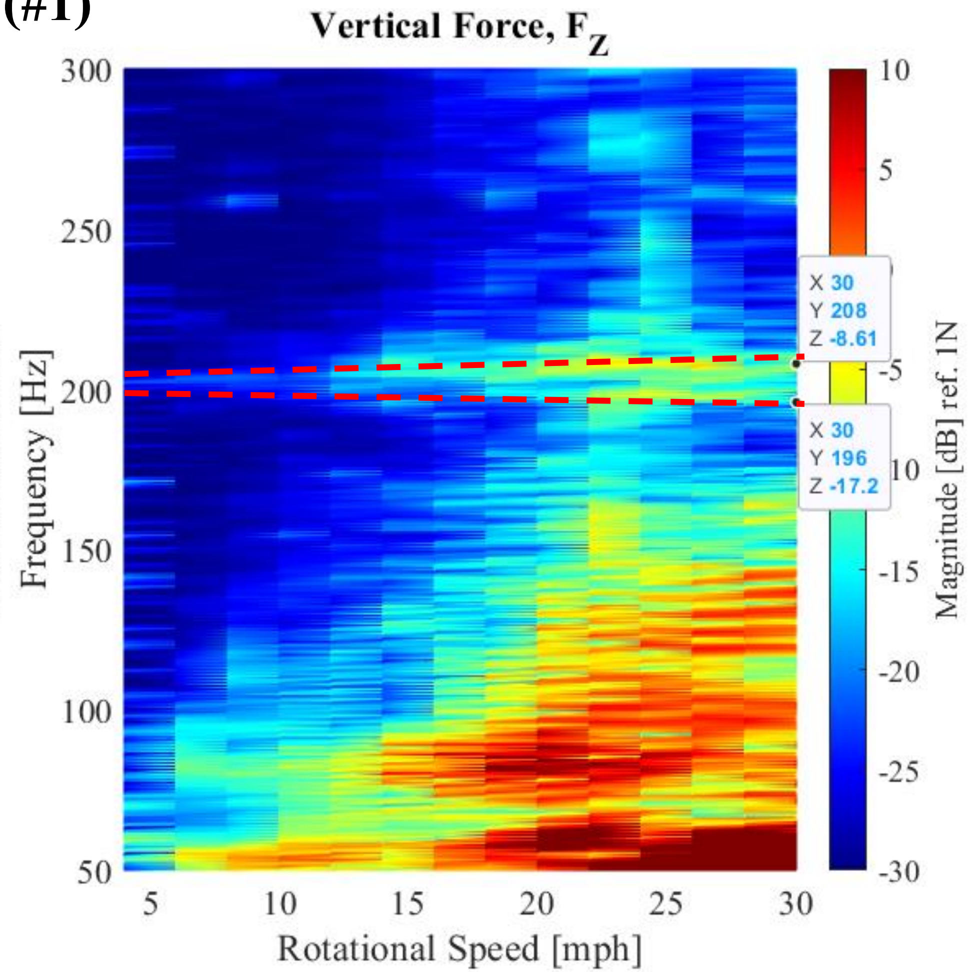
1. The two diverged lines, originating from 200 Hz, indicate the force amplification by the split in the cavity mode.
2. The tire's low-order circumferential structural modes (n=1, 2, and 3) are prominent below 100 Hz.

18-4 (#1)





Steady-state transport analysis in Abaqus 2020

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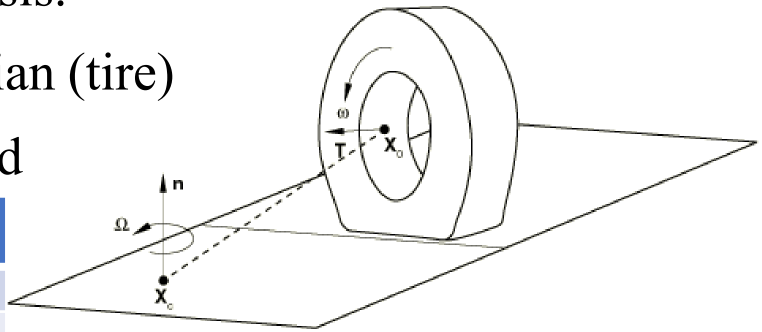
1. It is possible to simulate rolling tires by using frequency-based harmonic analysis.
2. Solution converged faster for coupled tires (air-filled) : Eulerian (air), Lagrangian (tire)
3. Symmetric model generation (SMG) and input-deck base modeling are required

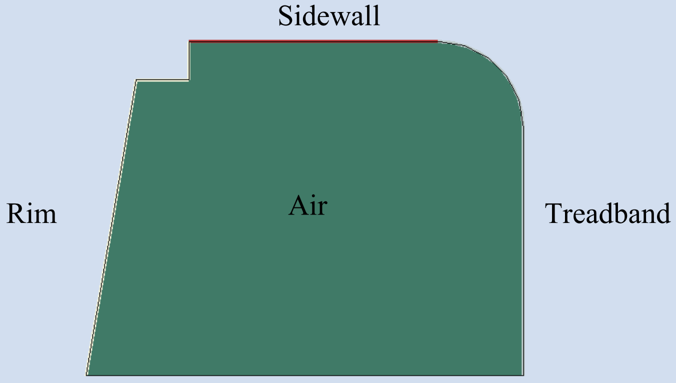
Angular velocity(ω) in a rotating coordinate.



#	ID	Spec	Inflation [psi]	Load [lbs]	Mass [Kg]
1	18-4	235/50/R18	35	1245	12.7
2	19-3	255/40/R19	32	1073	13.3

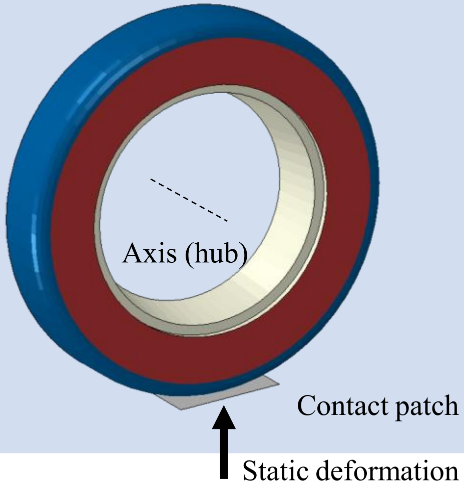
1. Symmetric Model Generation (SMG)

- Treadband (2D shell and rebar)
- Sidewall (2D shell and rebar)
- Air (3D solid)
- Rim (rigid body)



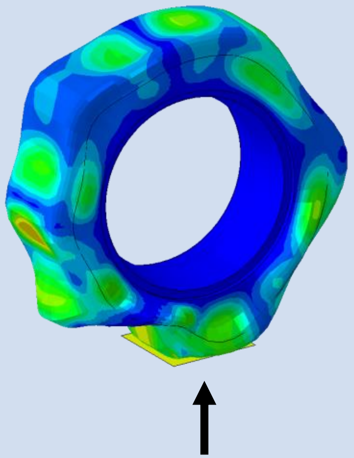
2. Static Analysis

- Inflation, P_0
- Static Deformation, δ_0
- Contact patch (rigid body)



3. Steady-State Transport Analysis (SSTA)

- Modal analysis
- Harmonic analysis for rolling tire



Dynamic force, $F = F_0 e^{j\omega t}$

Correlation of force response at the hub

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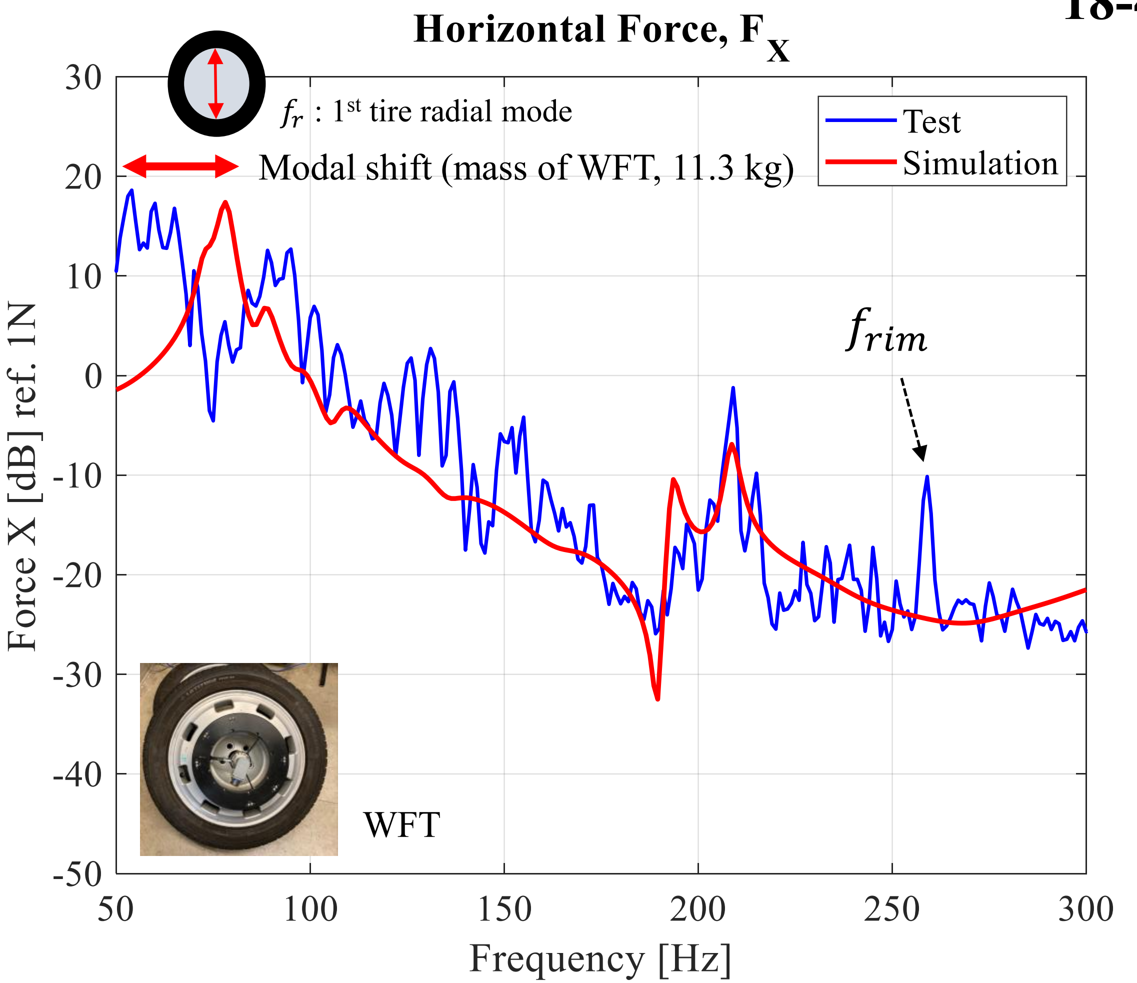
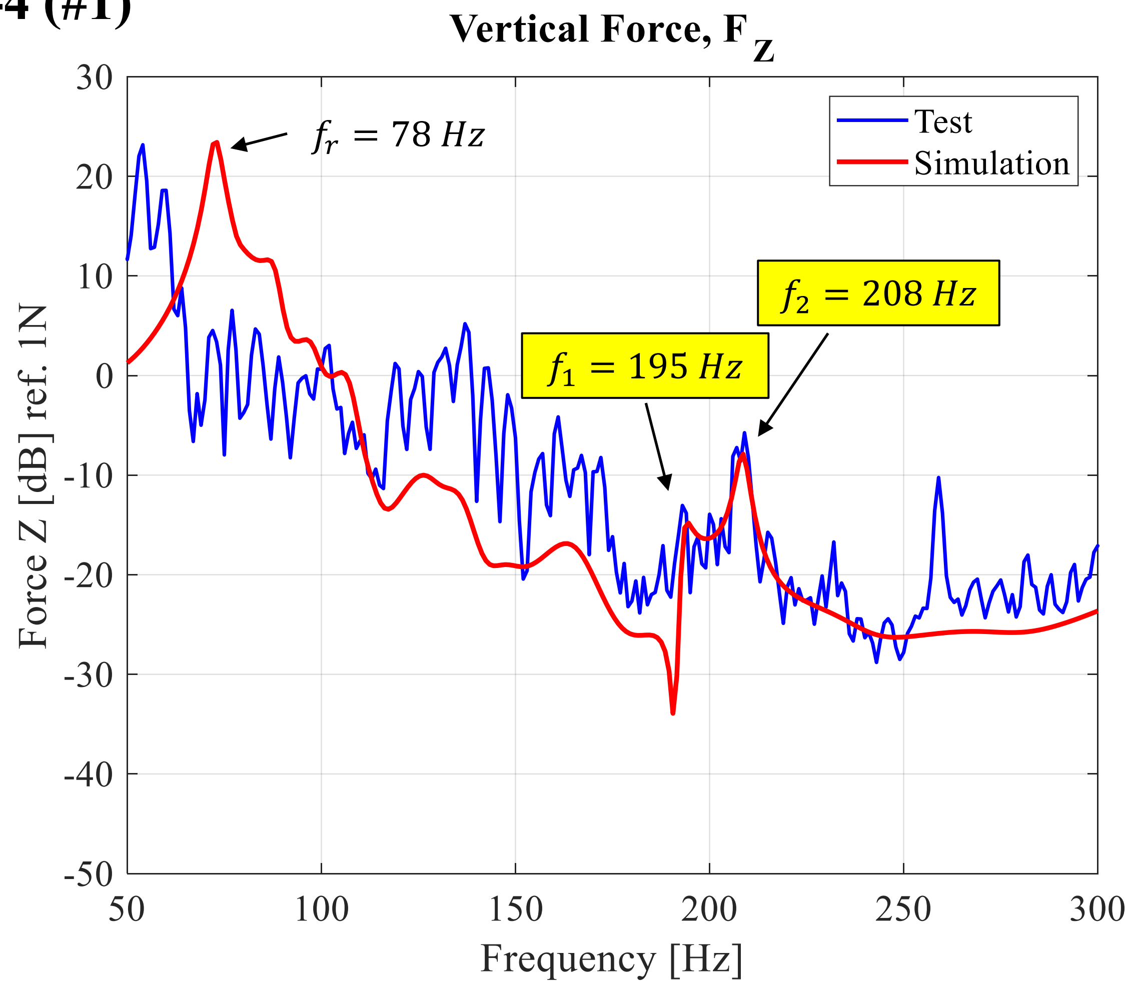
1. The two force responses in simulation are similar as the test measurement at 30 mph.
2. Modal shift is observed in test due to the mass of wheel force transducer (WFT) at the hub.

18-4 (#1)





Reproduction of Campbell diagram

Introduction	Test (TPTA)	FE Simulation	Optimization	Conclusion

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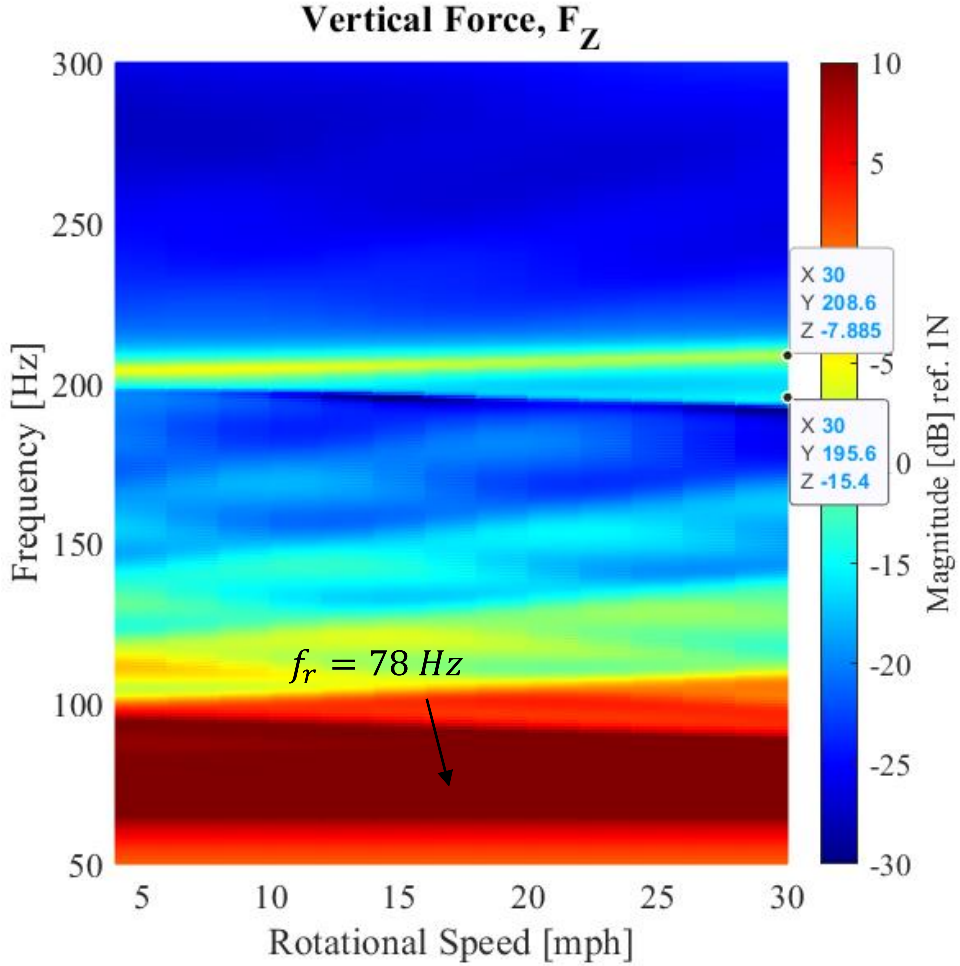
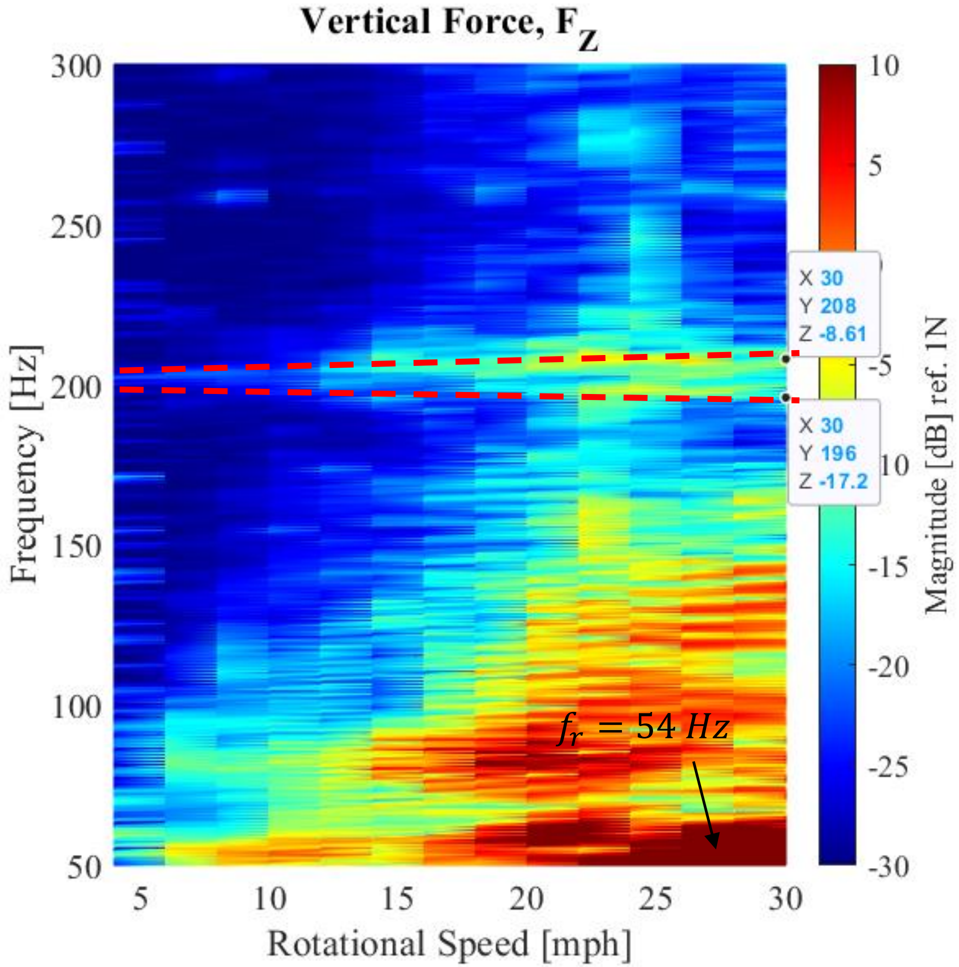
1. The force amplification due to air-cavity mode is well reproduced.
2. Test result has some blurry effect due to the tire's structural damping and external noise signals (gearbox, rig).

18-4 (#1)

(a) Simulation (1 Hz by 2 mph)



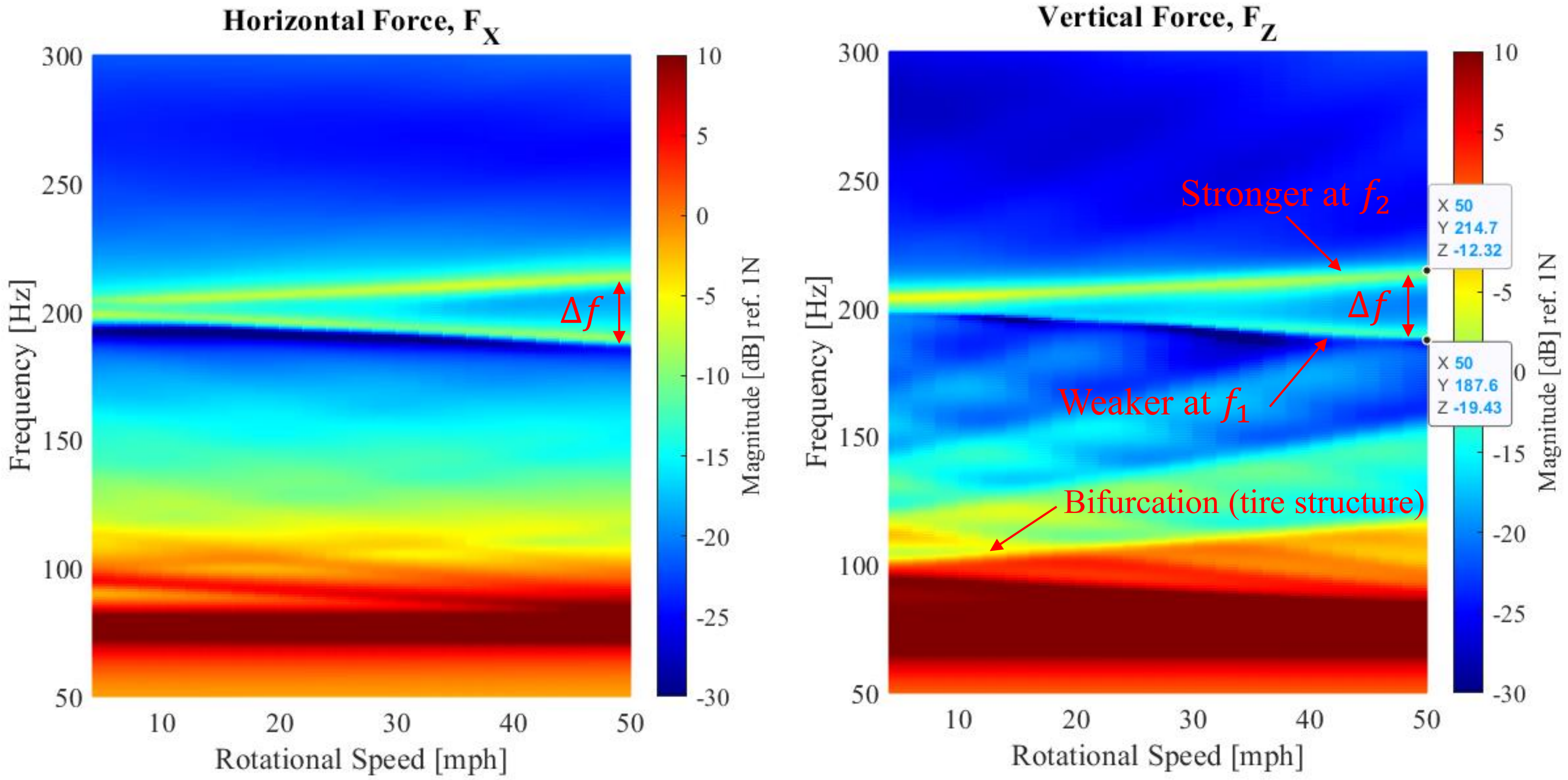
(b) Test (1 Hz by 2 mph)



Campbell diagram extended to 50 mph (80 kph)

1. The evolution of the split was observed at increased speeds (Δf=27 Hz).
2. Bifurcation in structural modes also appears near 100 Hz, owing to the Doppler effect and Coriolis force.

(a) Simulation (1 Hz by 2 mph) **18-4 (#1)** (b) Simulation (1 Hz by 2 mph)



Frequency split for rolling tire

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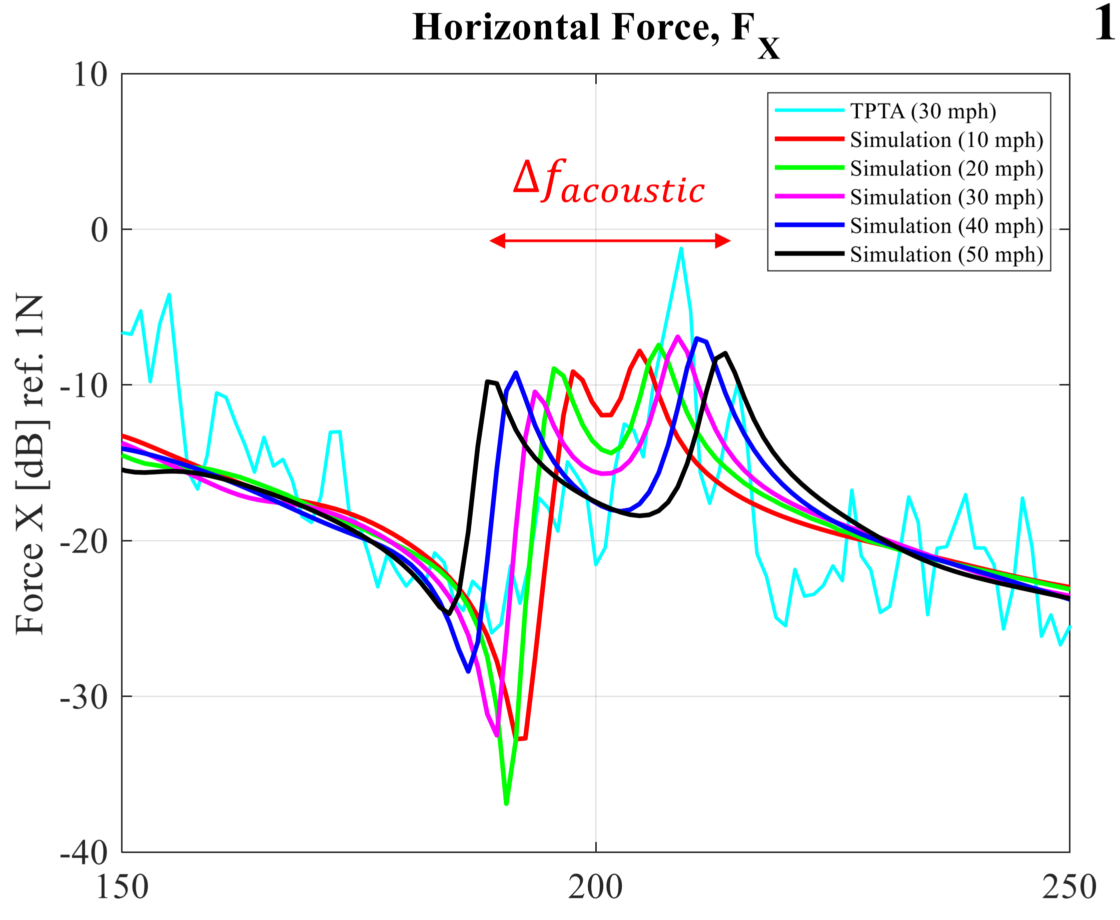
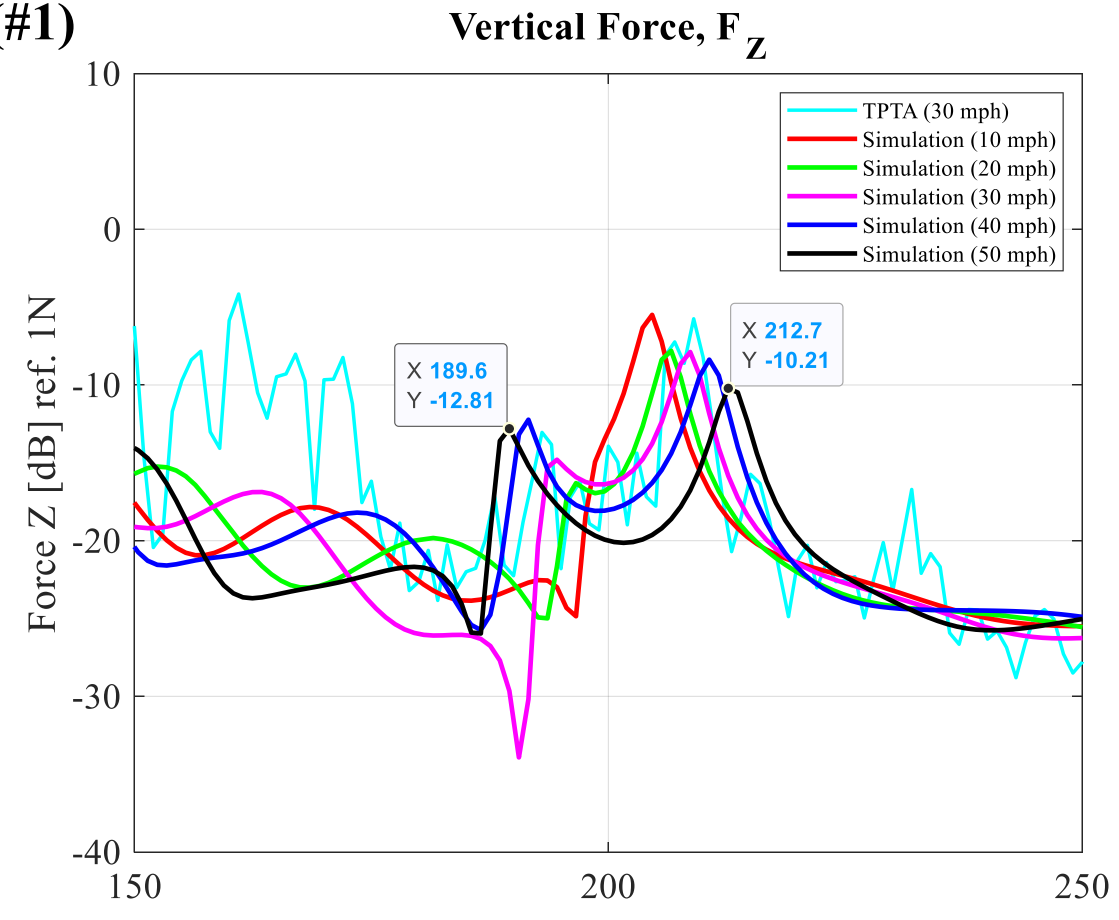
1. The evolution of the split was observed at increased speeds (Δf=27 Hz).
2. The Doppler shift makes the frequency split wider as rotation speed increases.

18-4 (#1)



(a)



(b)

Material optimization for force reduction

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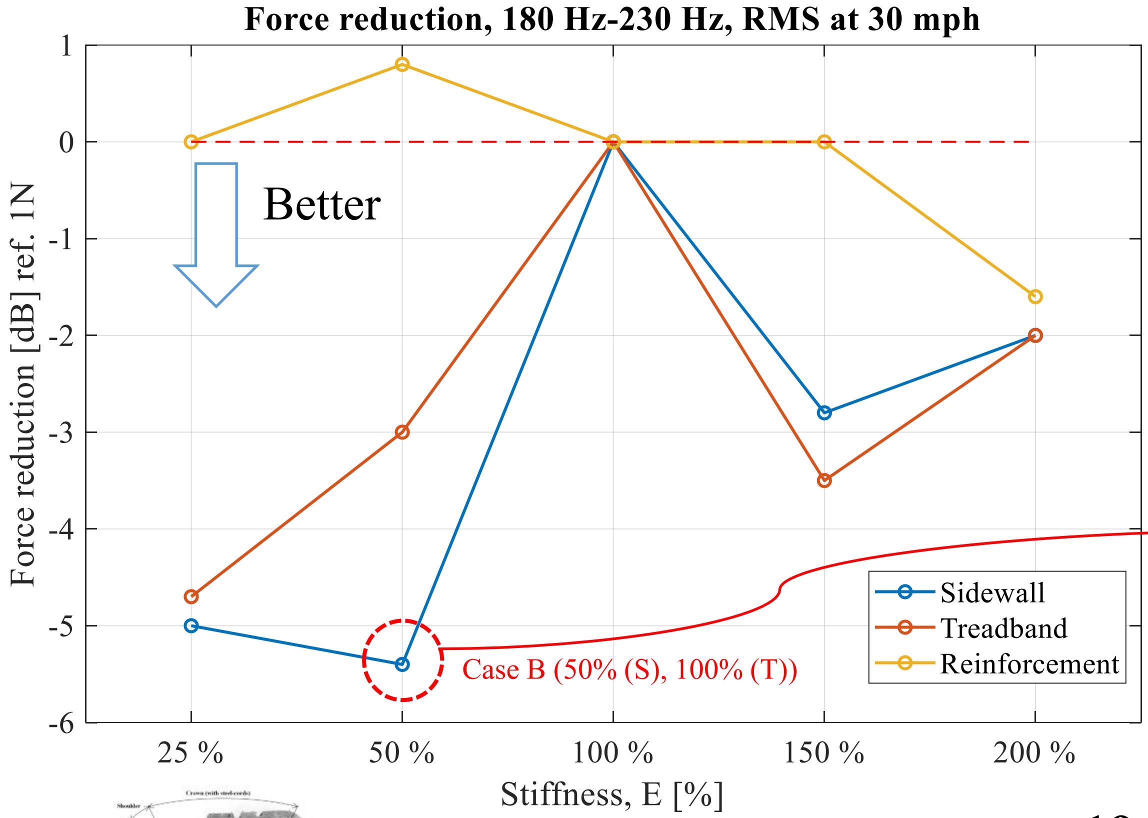
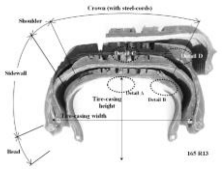
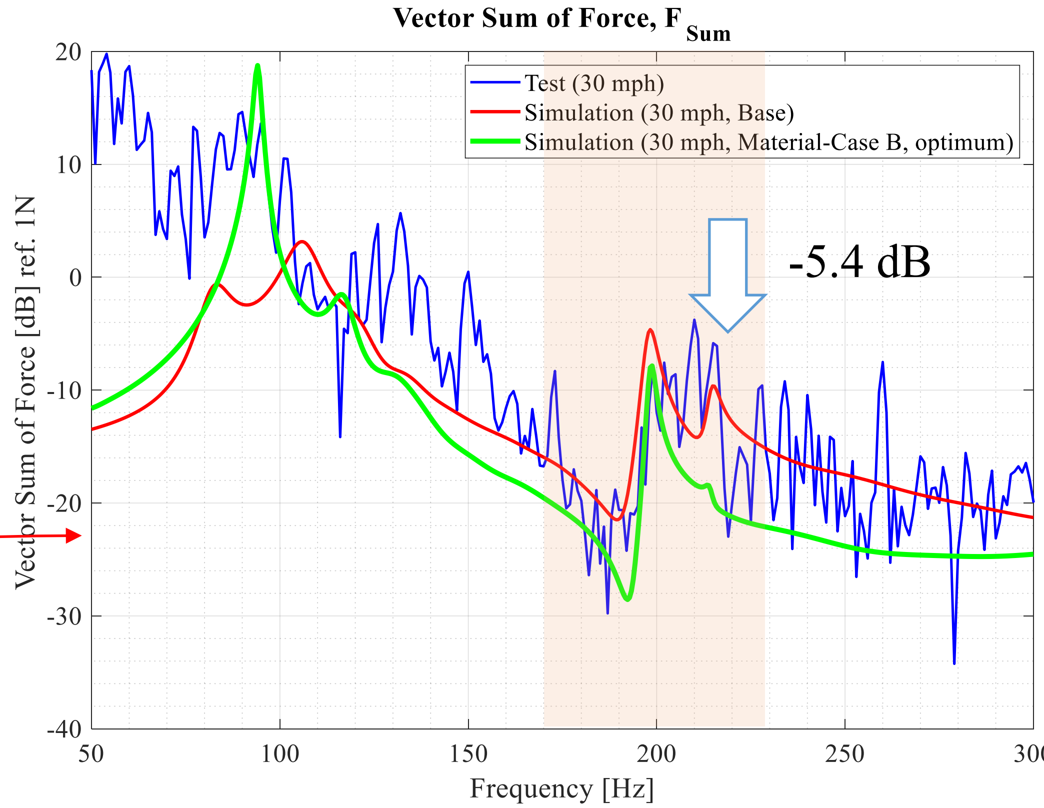
1. Modification of the rubber is more effective than the one in the reinforcement.
2. Sidewall is more sensitive to force reduction when reducing stiffness.





Reinforcement in tire rubber (composite)

(a)



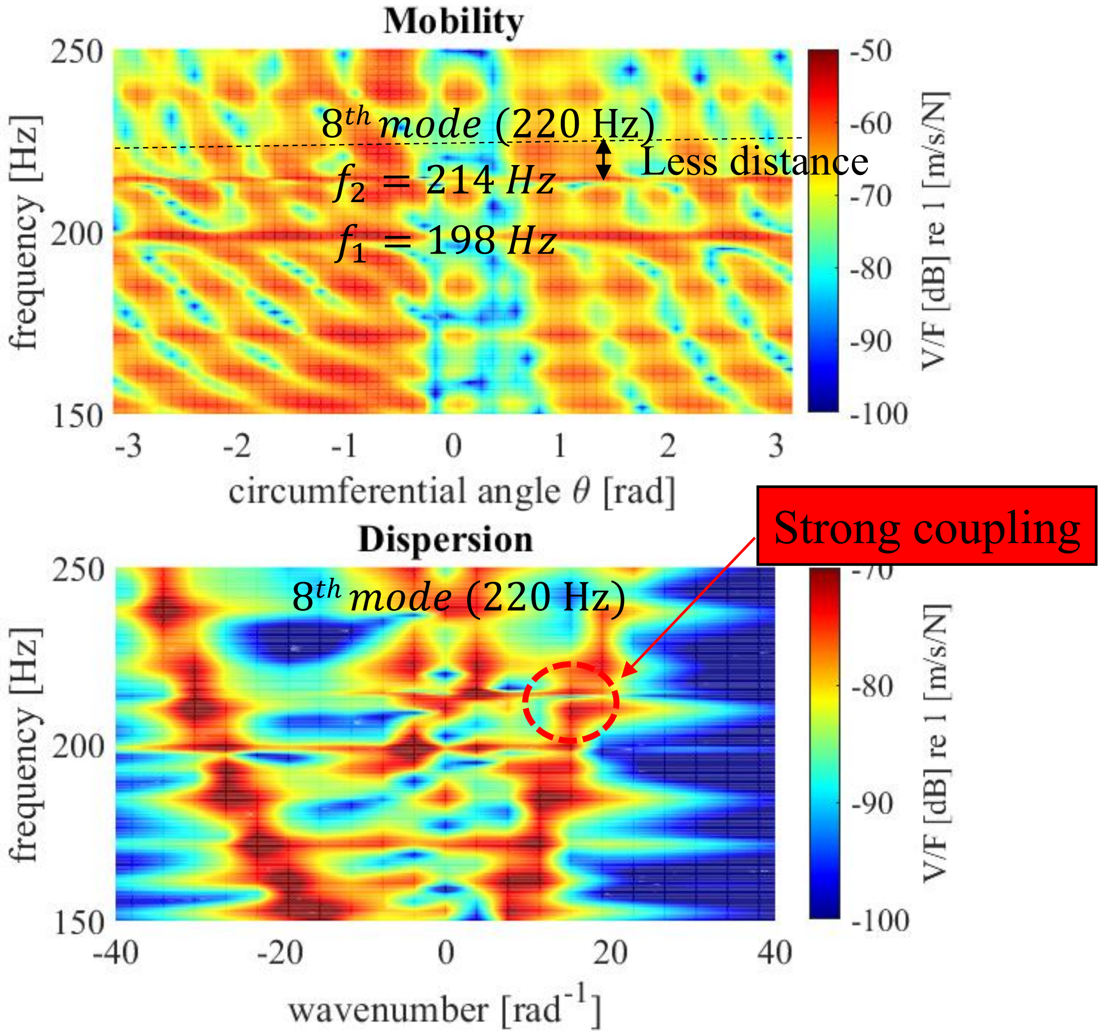
RMS averaged value (criteria)

(b)

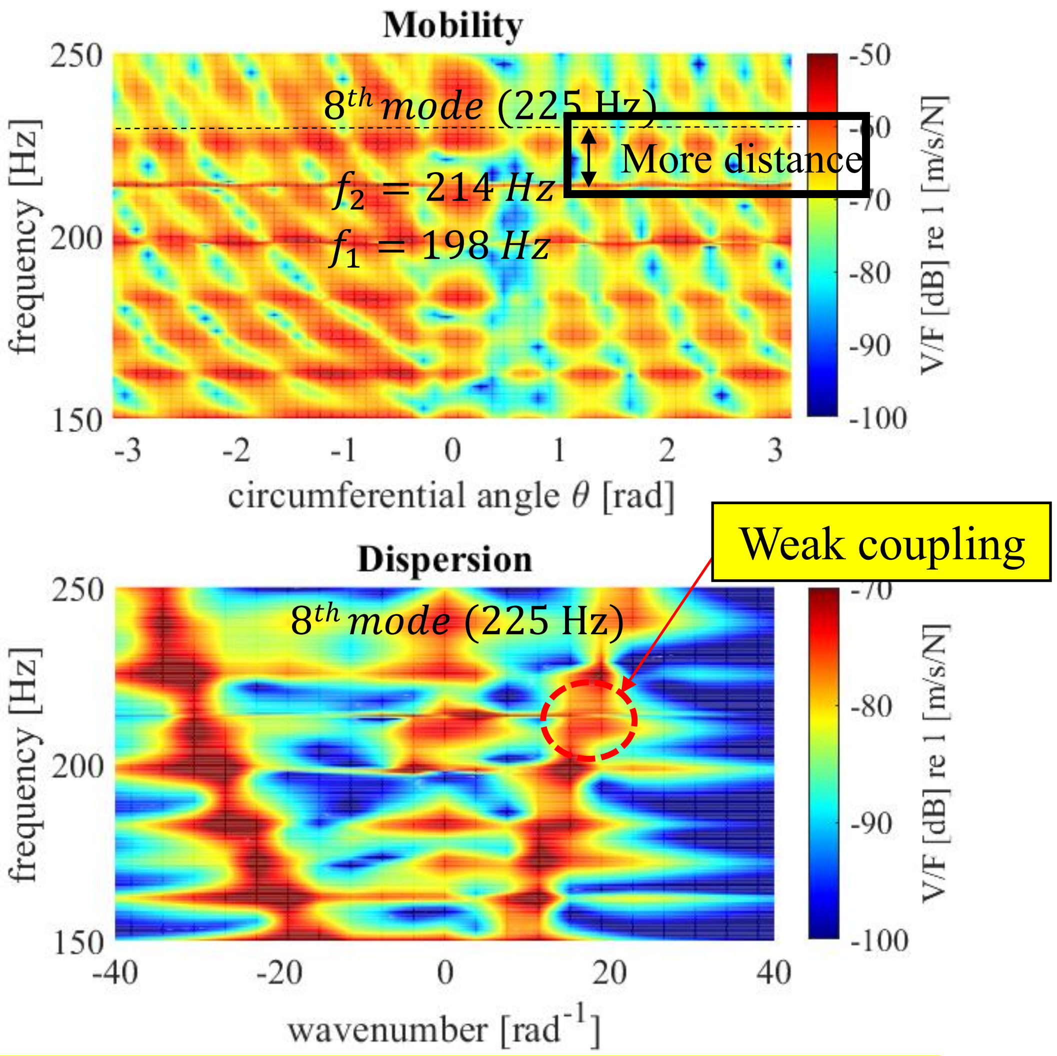
19-3 (#2)

Material optimization for force reduction

1. The weak coupling contributes to the force mitigation as the 8th structural mode shifts to upper frequency.



(a) Simulation, Base, 30 mph



(b) Simulation, Case B (optimal), 30 mph

The influence of speed on the decoupling and thus force mitigation

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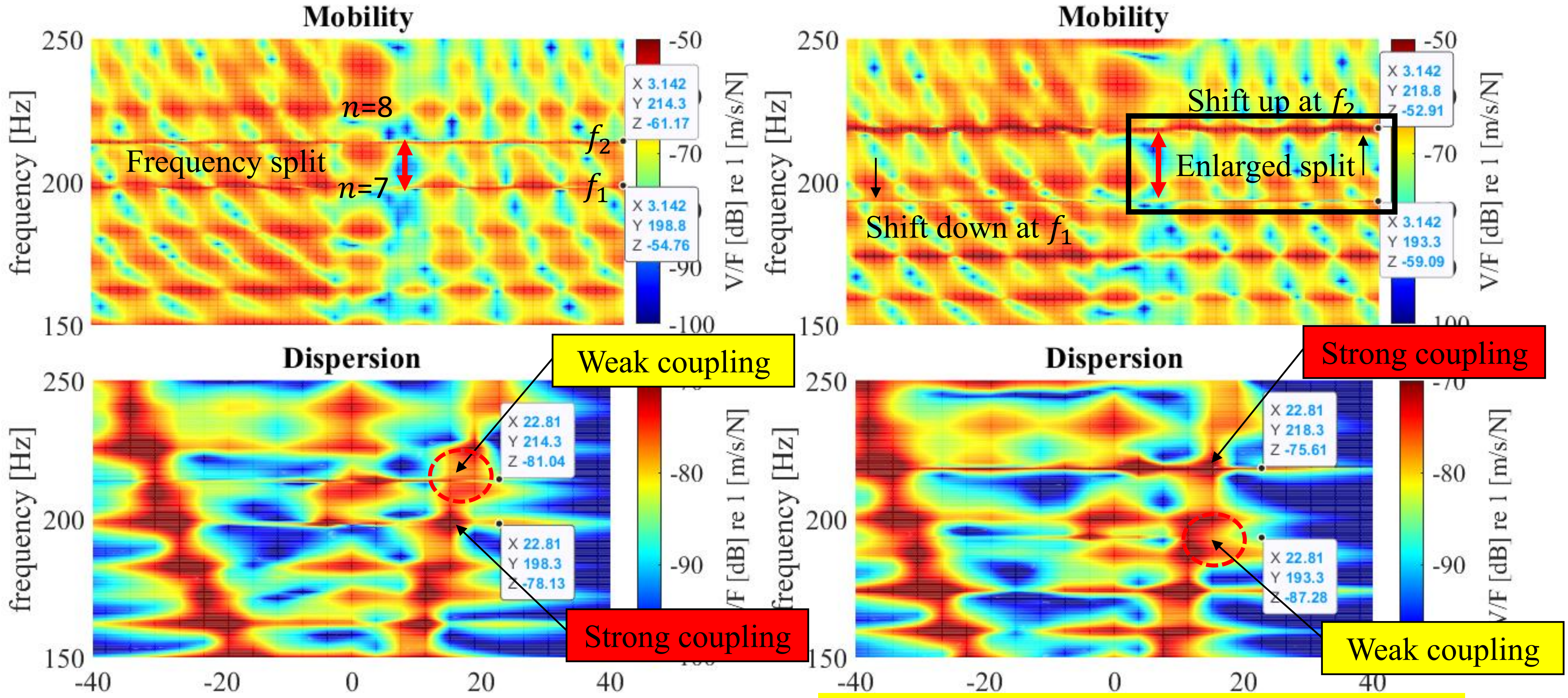
1. Increased speed causes the frequency split to be wider, the aspect of coupling was revered.



(a) Simulation, Case B (optimal), 30 mph

(b) Simulation, Case B (optimal), 50 mph

The implication of decoupling in waveform onto the force mitigation

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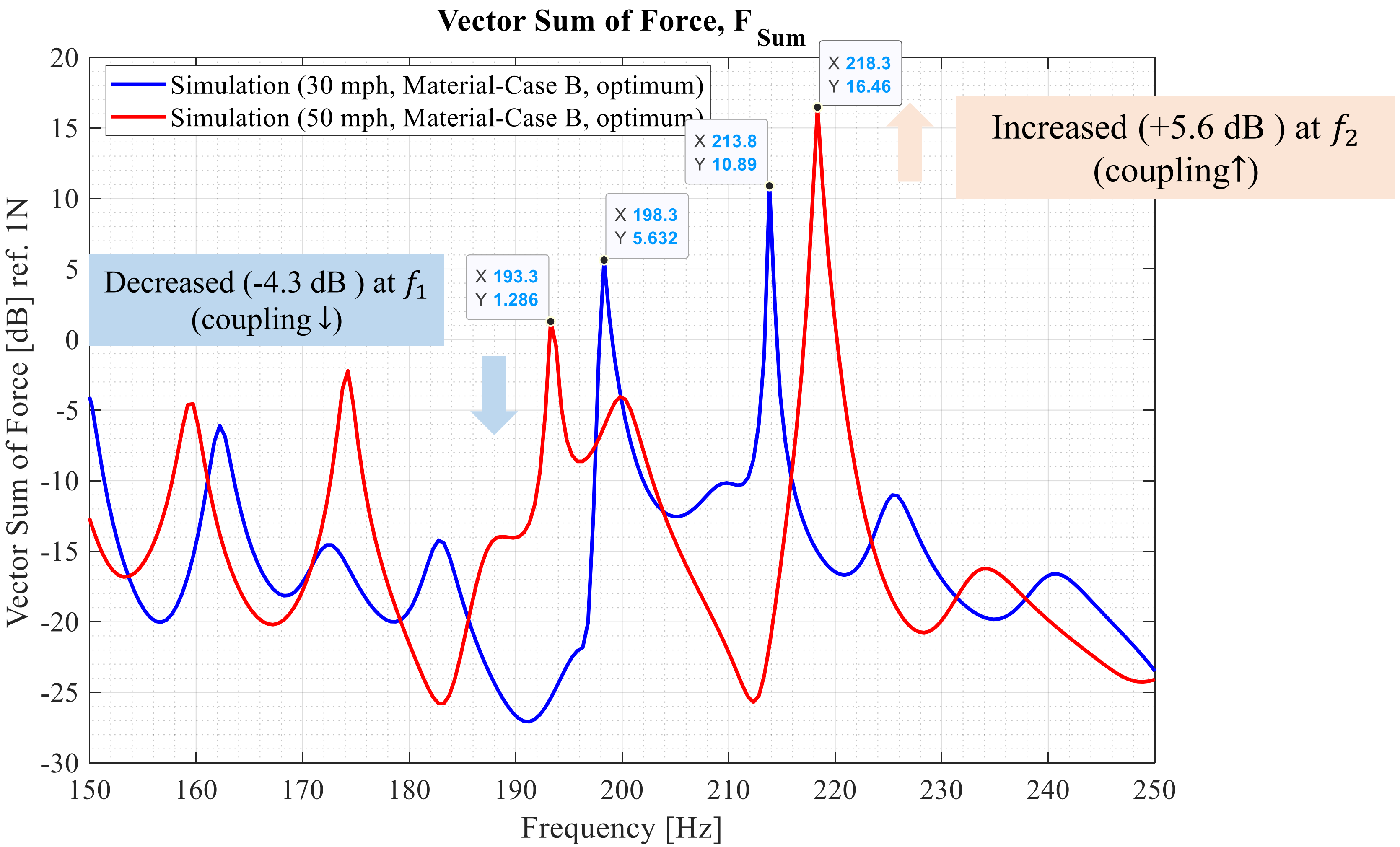
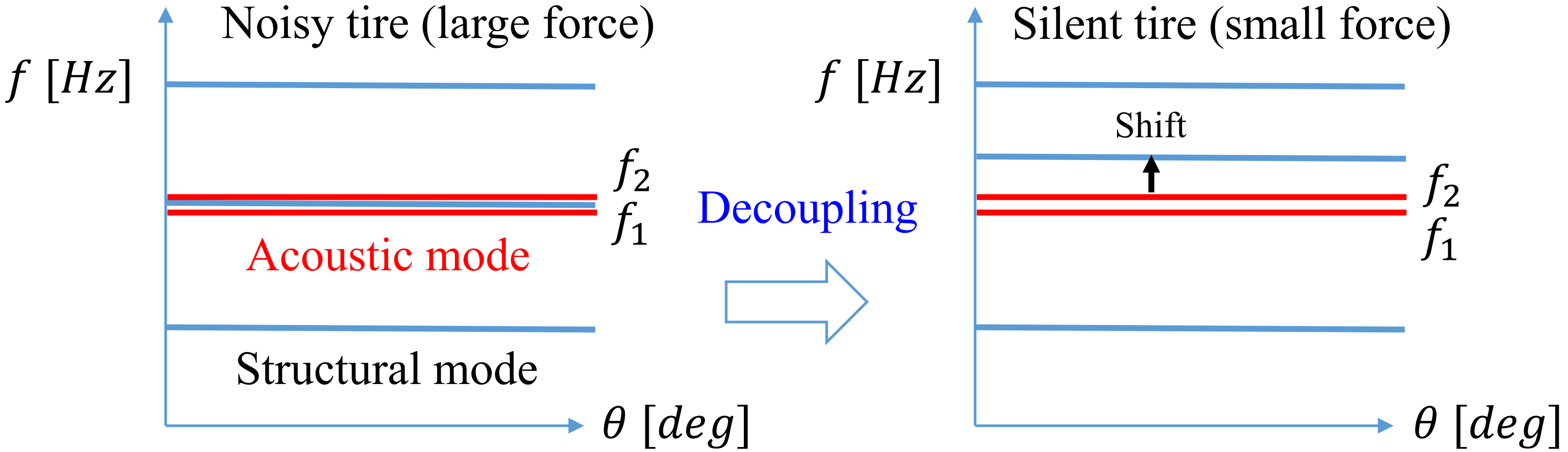
1. Speed that affects the acoustic frequency split needs to be considered together for force mitigation, as material properties only influence on the adjacent structural resonance modes.

2. It is practical to determine a target speed or averaging force levels at a certain range of speeds for noise evaluation.



Conclusions

1. The laboratory test environment was established for measuring spindle force when tire is rolling.
2. In the current work, the amplification in the transmitted at the wheel hub was well identified near 200 Hz due to the split in the air-cavity mode.
3. Campbell diagram is useful for identifying the evolution of the frequency split.
4. The frequency split due to the rolling effect was well estimated in simulation, comparable to the test result and analytical solution.
5. Force response and Campbell diagram were reproduced at various speeds in simulation, correlated to the test results.
6. The adjustment in tire's stiffness and rotation speed can attenuate the force level by decoupling acoustic mode with structural vibration.



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Thank you!

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