8-22-2022

Finite Element Modeling of Force Amplification at the Spindle due to a Tire's Cavity Mode: Experimental Verification

Won Hong Choi
Purdue University, choi124@purdue.edu

Kyosung Choo
Indiana University - Purdue University, Indianapolis, choo7@purdue.edu

J Stuart Bolton
Purdue University, bolton@purdue.edu

Finite element modeling of force amplification at the spindle due to a tire's cavity mode: experimental verification

Won Hong Choi and J. Stuart, Bolton

Ray W. Herrick Laboratories, Purdue University

inter.noise 21-24 AUGUST SCOTTISH EVENT CAMPUS GLASGOW 2022

PURDUE MECHANICAL ENGINEERING

Biography

Won Hong Choi

Ph.D Graduate Student,

Purdue University, West Lafayette, USA.

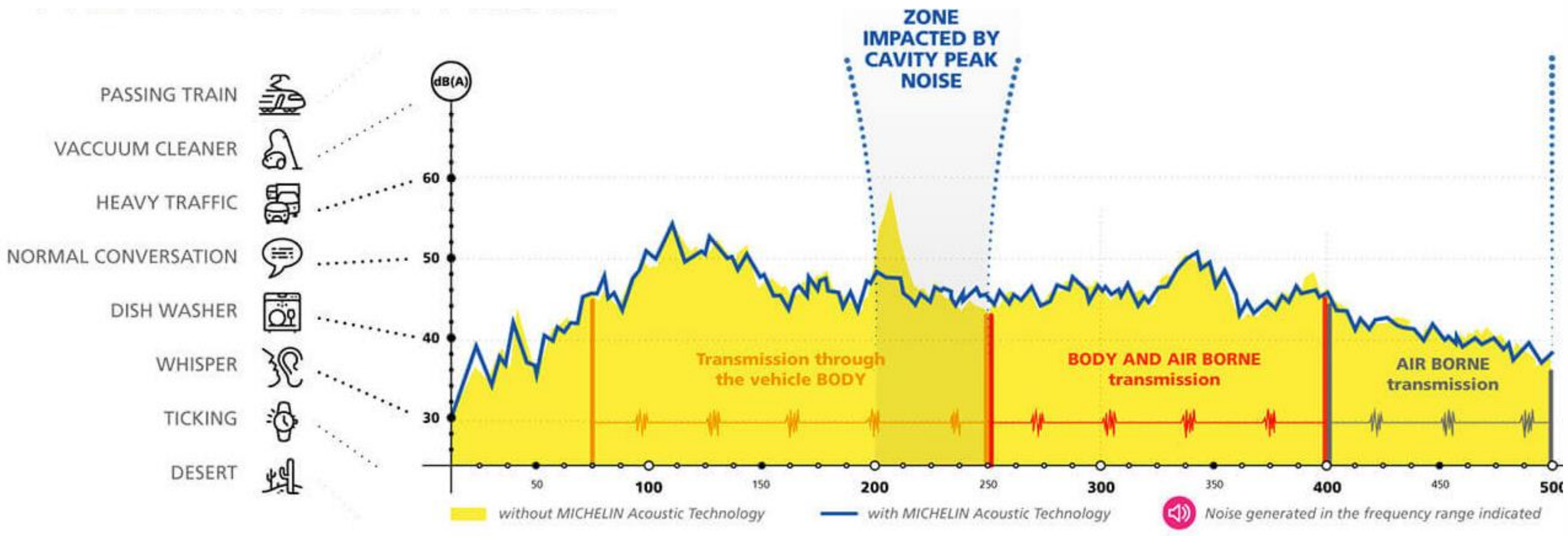
He is currently pursuing a Ph.D. degree in mechanical engineering at Purdue University. After completing his bachelor's degree at Kyushu University, Japan in 2009 and his master's degree at Purdue University in 2011, he worked for Samsung SDI and Agency for Defense Development in South Korea. His research interests are tire/road-noise, noise control, and CAE simulation. He is working with Prof. J. Stuart Bolton to investigate the influence of air-cavity mode on the transmitted force in a vehicle.

Content

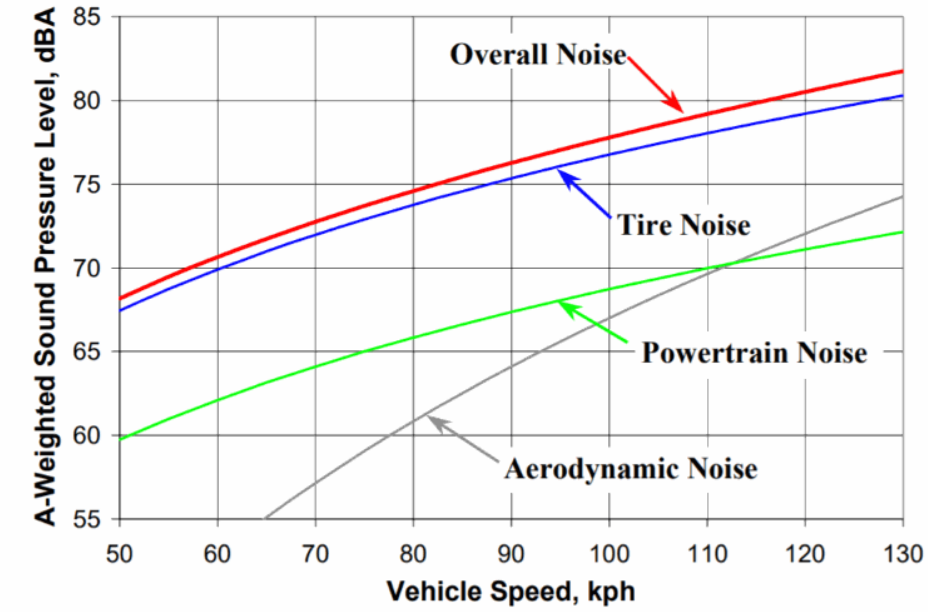
- Introduction
- Literature review
- Measurement in TPTA (Tire Pavement Test Apparatus)
- FE Simulation
- Conclusions

Introduction-tire's cavity noise

- Reduction of tire/road noise is an important issue for luxury sedans and EV vehicles[1].
- Tire/road noise can be categorized into air-borne and structure-borne noise[3].
- Structure-borne noise is dominant in the low-frequency range up to 400 Hz, transmitted through vehicle's body structure[3].
- The fundamental (first) air-cavity mode is the culprit of increased force and cabin noise between 200 Hz and 250 Hz in the structure-borne transmission due to the huge net displacement[4].



Cavity noise (Michelin tire[1]) .

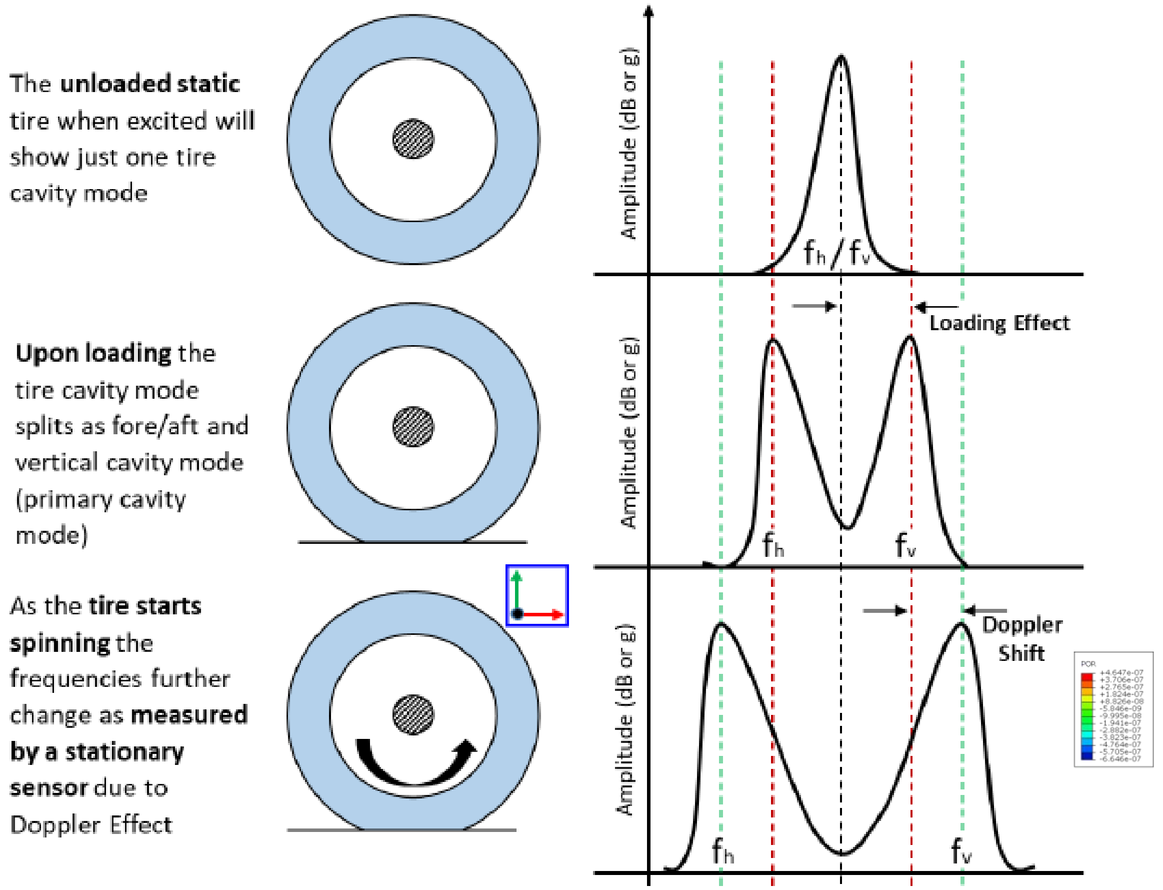


The dominance of tire noise (Bernhard [2]).

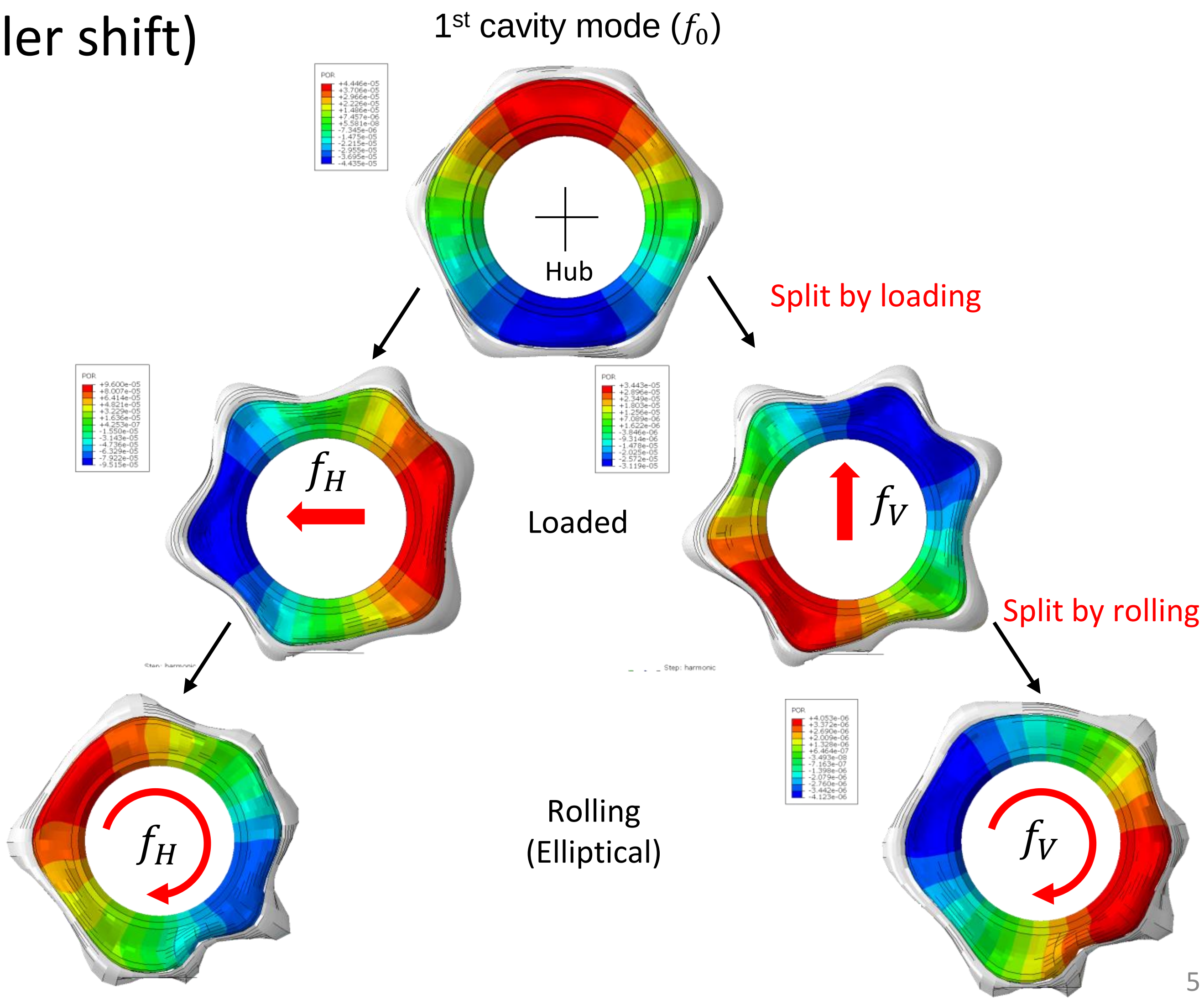
Introduction-frequency split

- The frequency split in the fundamental air-cavity mode is induced by two factors

  : Static loading (Asymmetry), Rolling (Doppler shift)



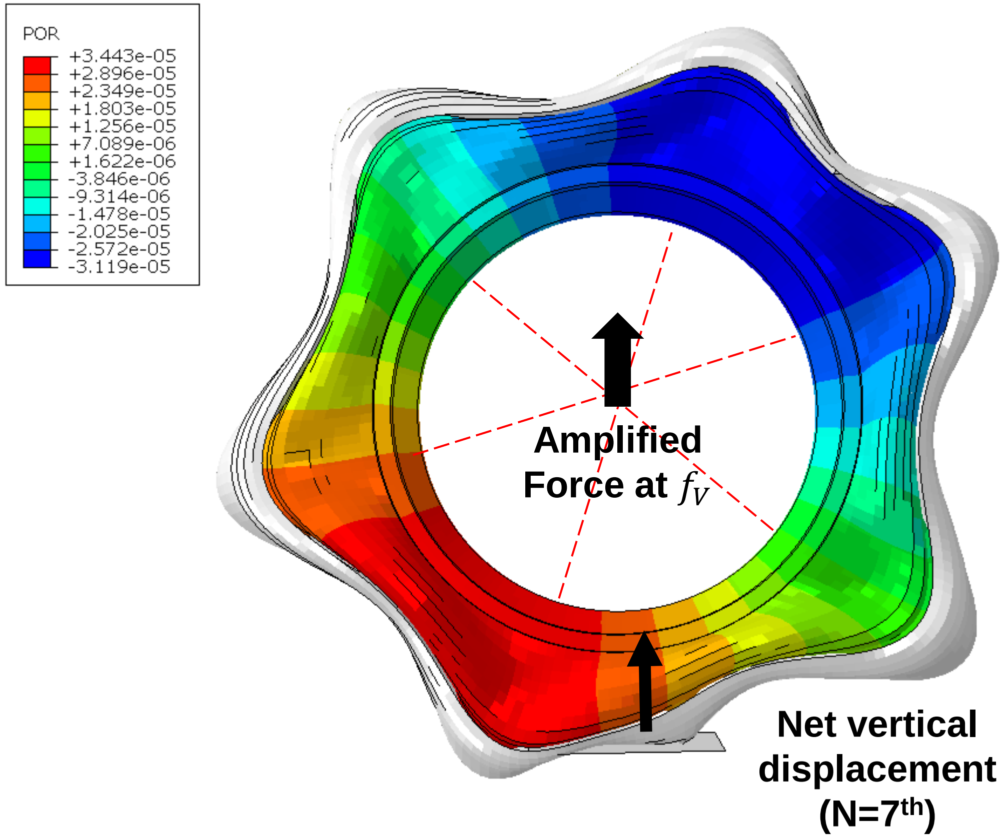
The frequency split by static load and rolling (Patil)[5].



Introduction-force amplification at the wheel hub

- The coupling between two directional acoustical modes and structural resonance mode increases the force level at the wheel hub (thus, increased cabin noise) [7].
- Previous studies discovered the possible contribution of cavity mode to increased force.

Ex.) Alignment between vertical mode and structural resonance mode



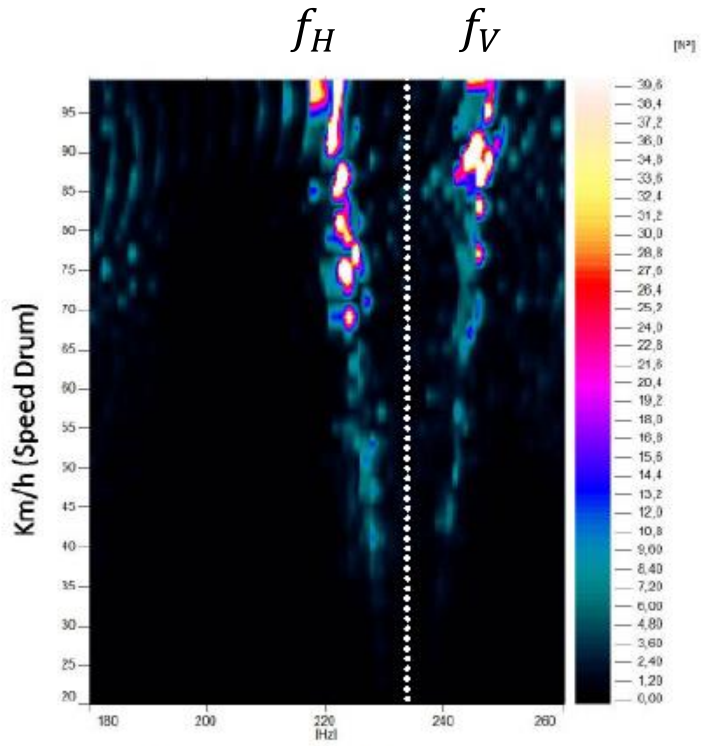
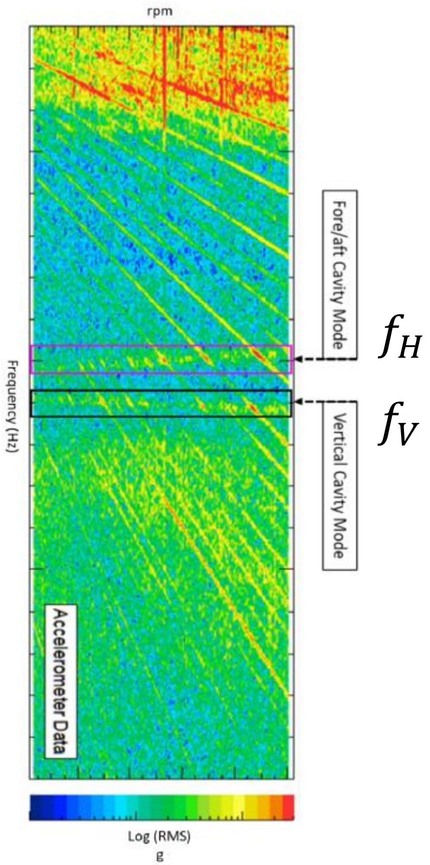


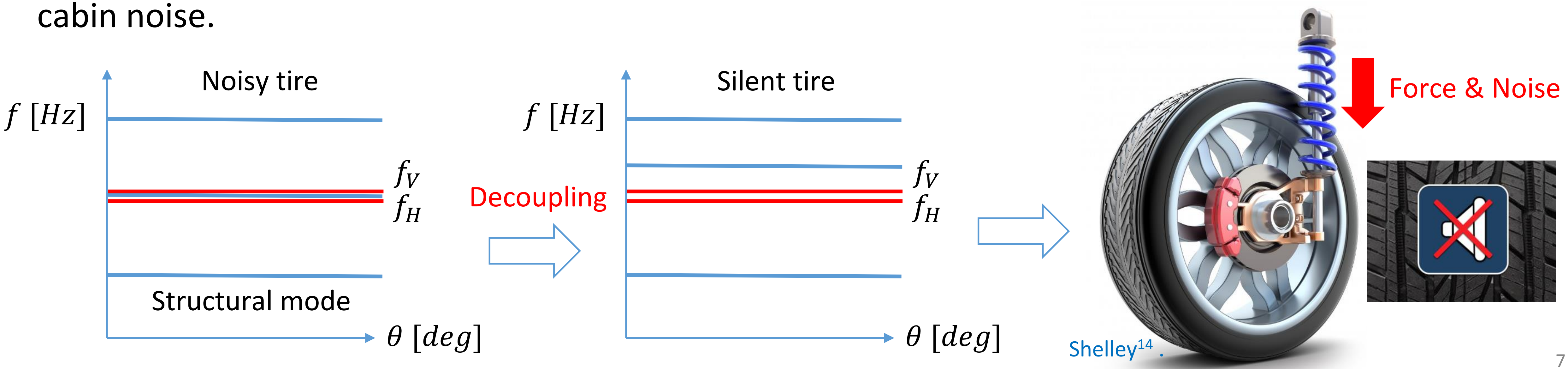
Figure 9: Measurement of the horizontal forces at the hub during a run-down from 100 km/h to 20 km/h



The influence of cavity mode on the force [5,6] .

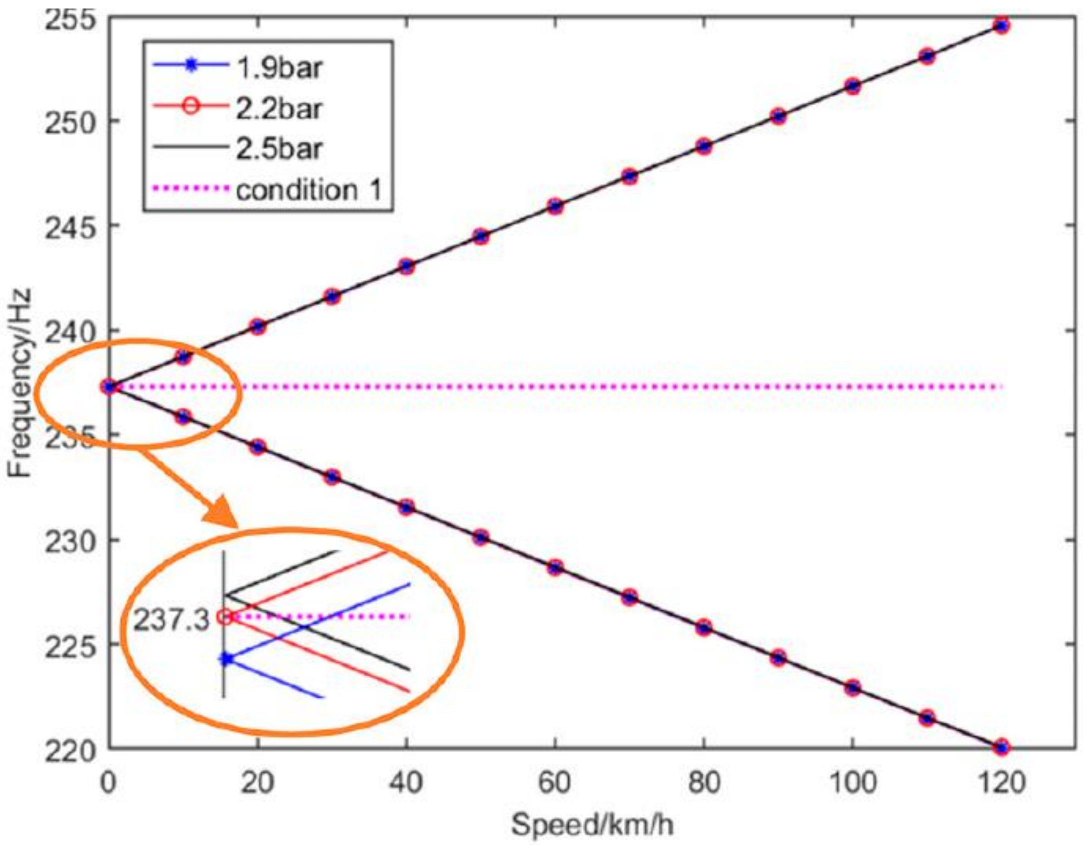
Introduction-Objective

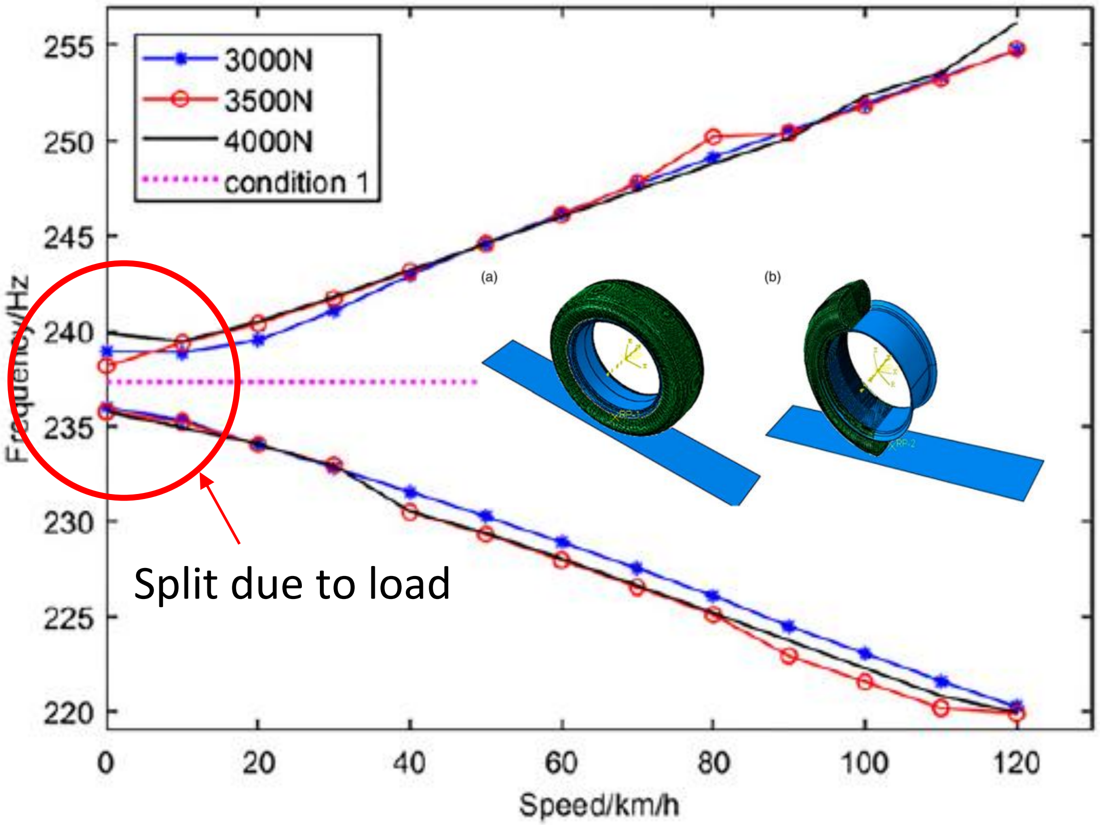
- Decoupling between 1st cavity mode and the adjacent structural mode is suggested to accomplish a low-noise tire as well as reduced force transmission from a tire to the vehicle.
- To this end, the prediction of the frequency split caused by a static deformation and rolling effect needs to be implemented both in numerical (CAE) and empirical ways.
- Actual acceleration and force response at the hub were measured for rolling tires in TPTA (Tire Pavement Test Apparatus) at different rotation speeds up to 48 km/h (30 mi/h).
- Further, the spindle force (X, Z) response between 50 Hz and 300 Hz is reproduced in simulation, which will be used as a input source of tire/road interaction in the transfer path analysis for a cabin noise.



Literature review

- Liu et al.[11] performed the FE simulation to investigate the frequency split depending on the speed.
- The influence of inflation and static load is smaller than the rolling effect (i.e., Doppler shift)

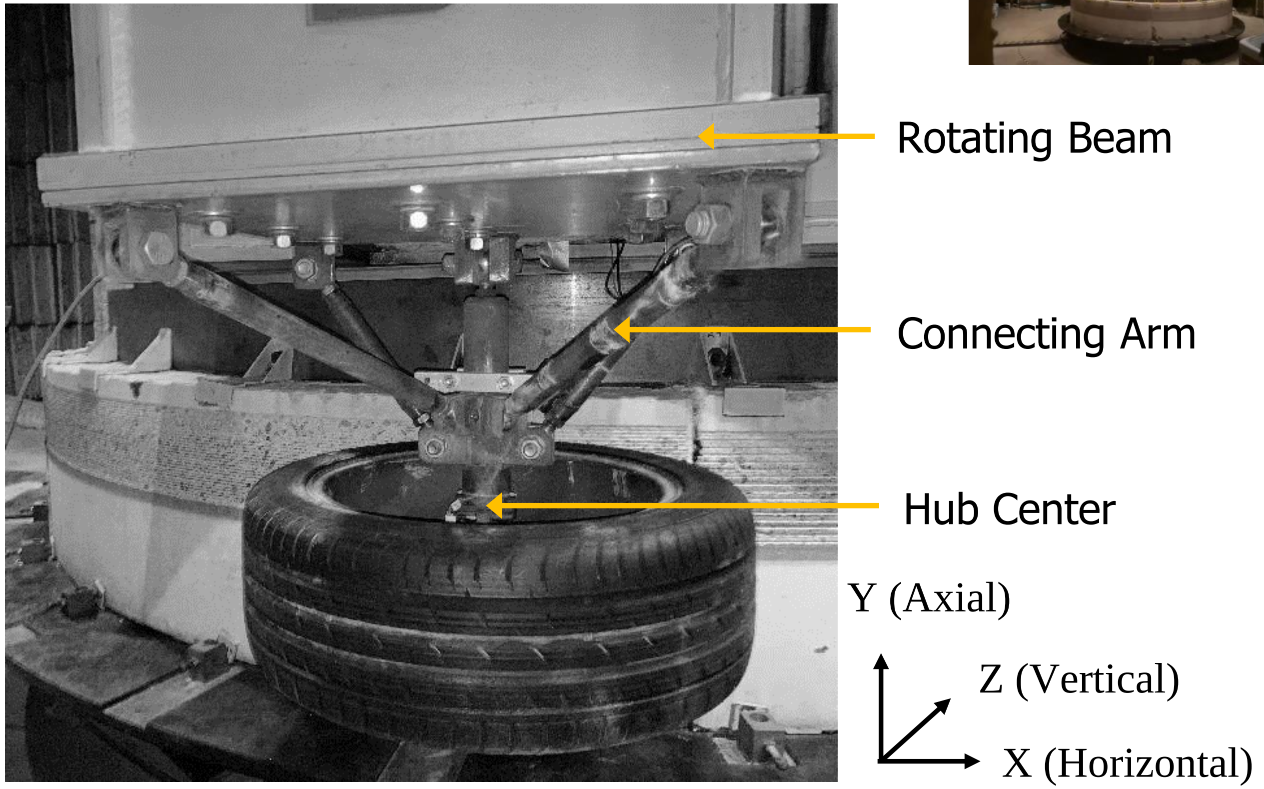




Measurement-TPTA (Tire Pavement Test Apparatus)

- TPTA (Tire Pavement Test Apparatus) for tire noise measurement (Max. Speed 48 km/h (30 mi/h), Load 6,000 N)
- Previously used for tire-pavement interaction noise (above 400 Hz)
- Recently utilized for tire-cavity noise measurement (below 250 Hz)
- It consists of six different concrete blocks, the diameter is 4.4 m

TPTA in hemi-anechoic chamber

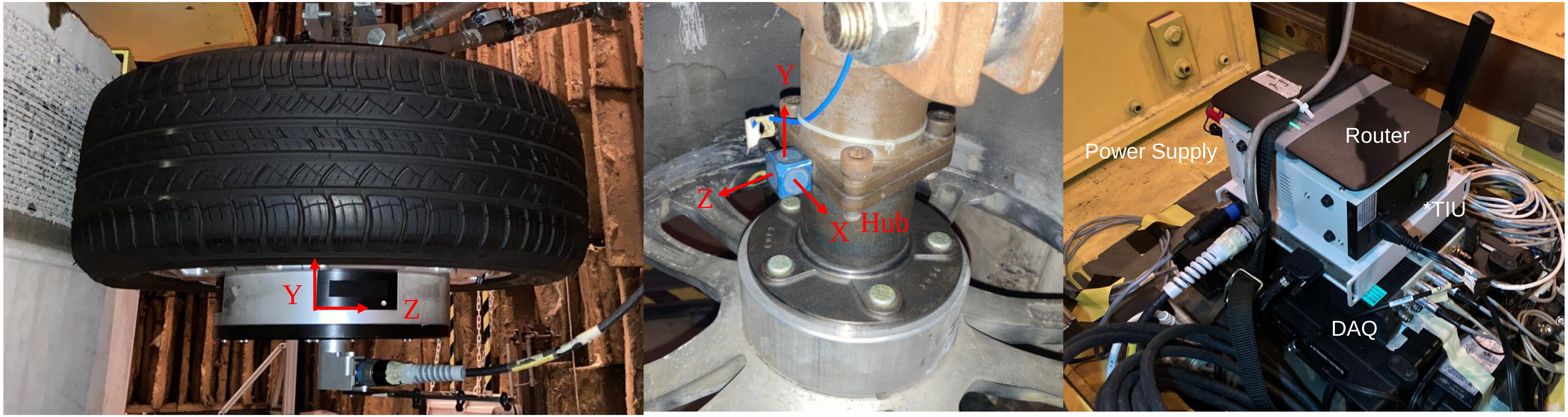


Test rig[12]

Measurement-Setup

- WFT (Wheel Force Transducer)
- A single tri-axial accelerometer
- Wireless connection via a router

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) Data Acquisition Devices

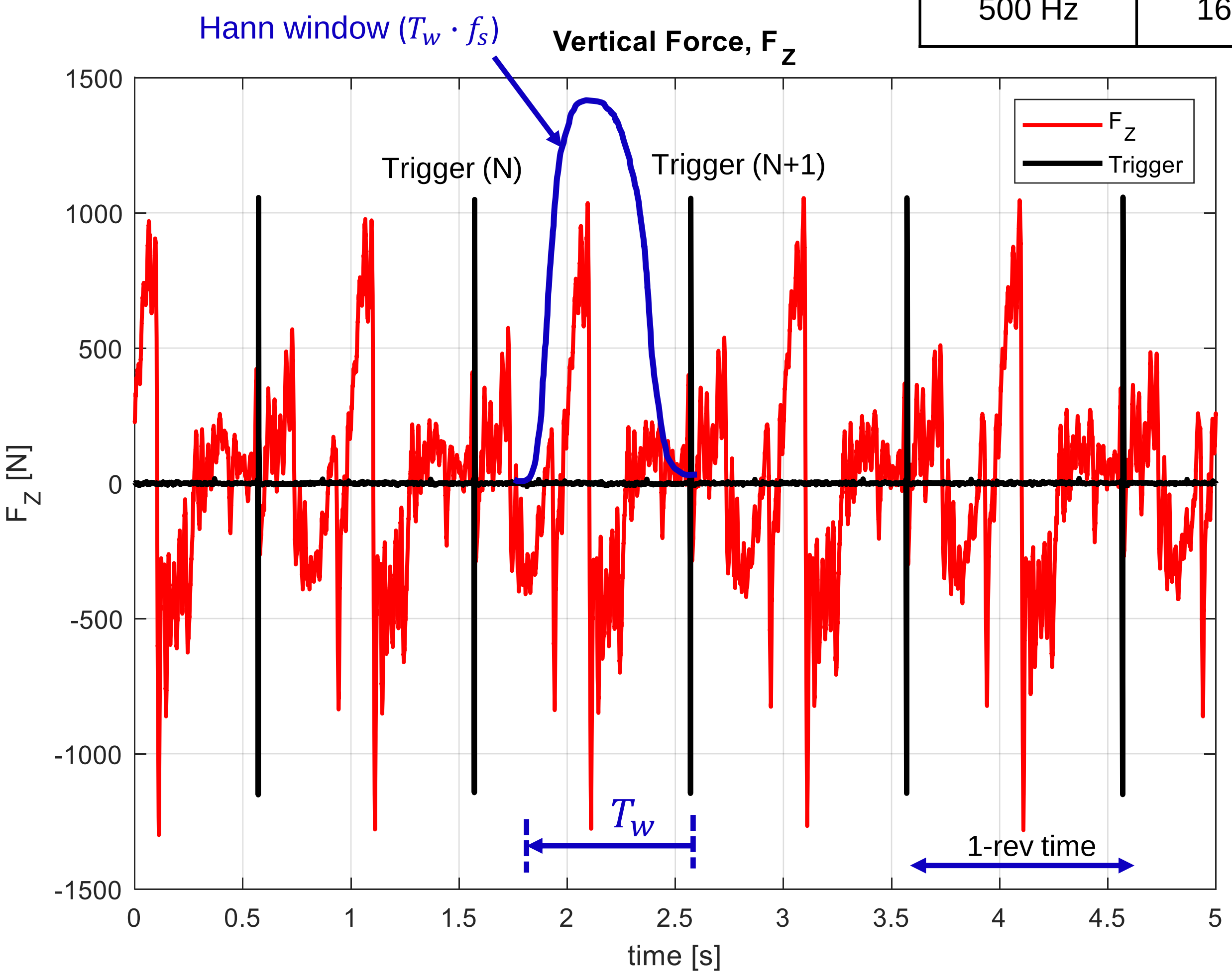
The layout of measurement devices

*TIU : Transfer Interface Unit (WFT control module)

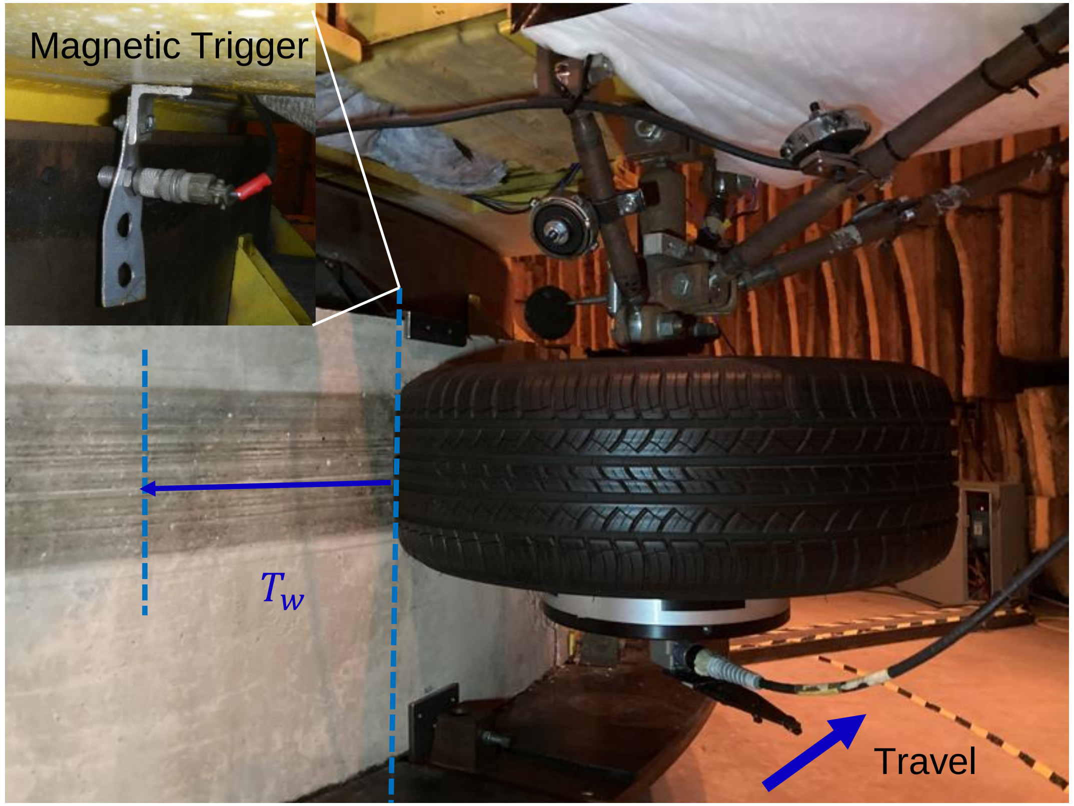
Measurement-Signal processing

- Test was performed between 6.4 km/h to 48 km/h. (4 mi/h to 30 mi/h)
- A trigger signal was also captured.

Highest freq.	Sampling	Total time	Time window	Time span	Overlap	Averaging
500 Hz	16,384	240 s	Hann	1 s (1 Hz)	50%	32 ~ 240 times



Vertical force with a trigger signal (48 km/h)



Smooth pavement at a trigger signal position

Measurement-Specification of test tire

- Test tire, 235/50/R18

No	#1
Size	235/50/R18
Pressure	0.24 MPa (35 psi)
Load	5496 N (1245 lbs.)
Stiffness (N/mm)	306
Mass (tire)	12.7 kg
Mass (custom rim)	11.8 kg
Mass (adapter)	2.7 kg
Mass (WFT, force transducer)	8.6 kg

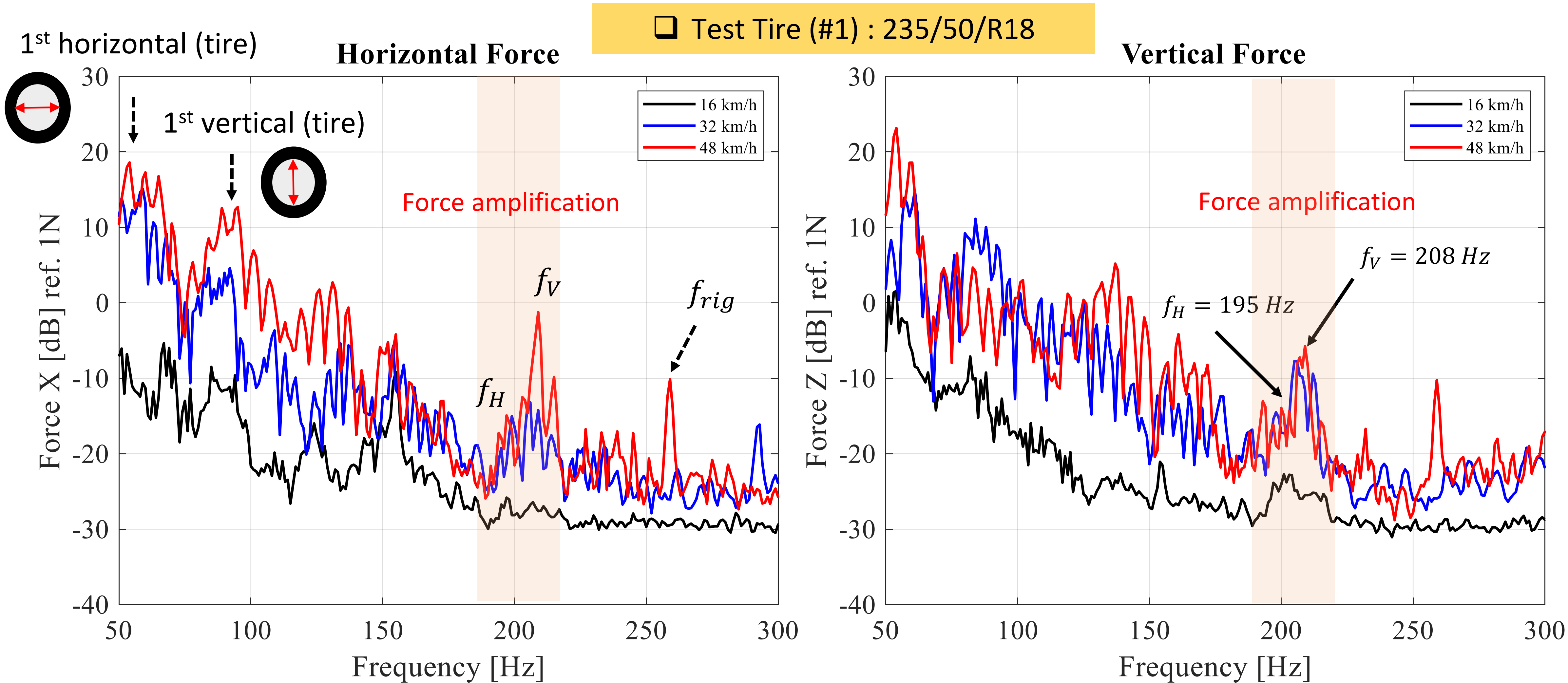
Custom rim

Wheel force transducer

Tuned mass damper for 160 Hz rig resonance[12]

Measurement-Dynamic Force at the hub

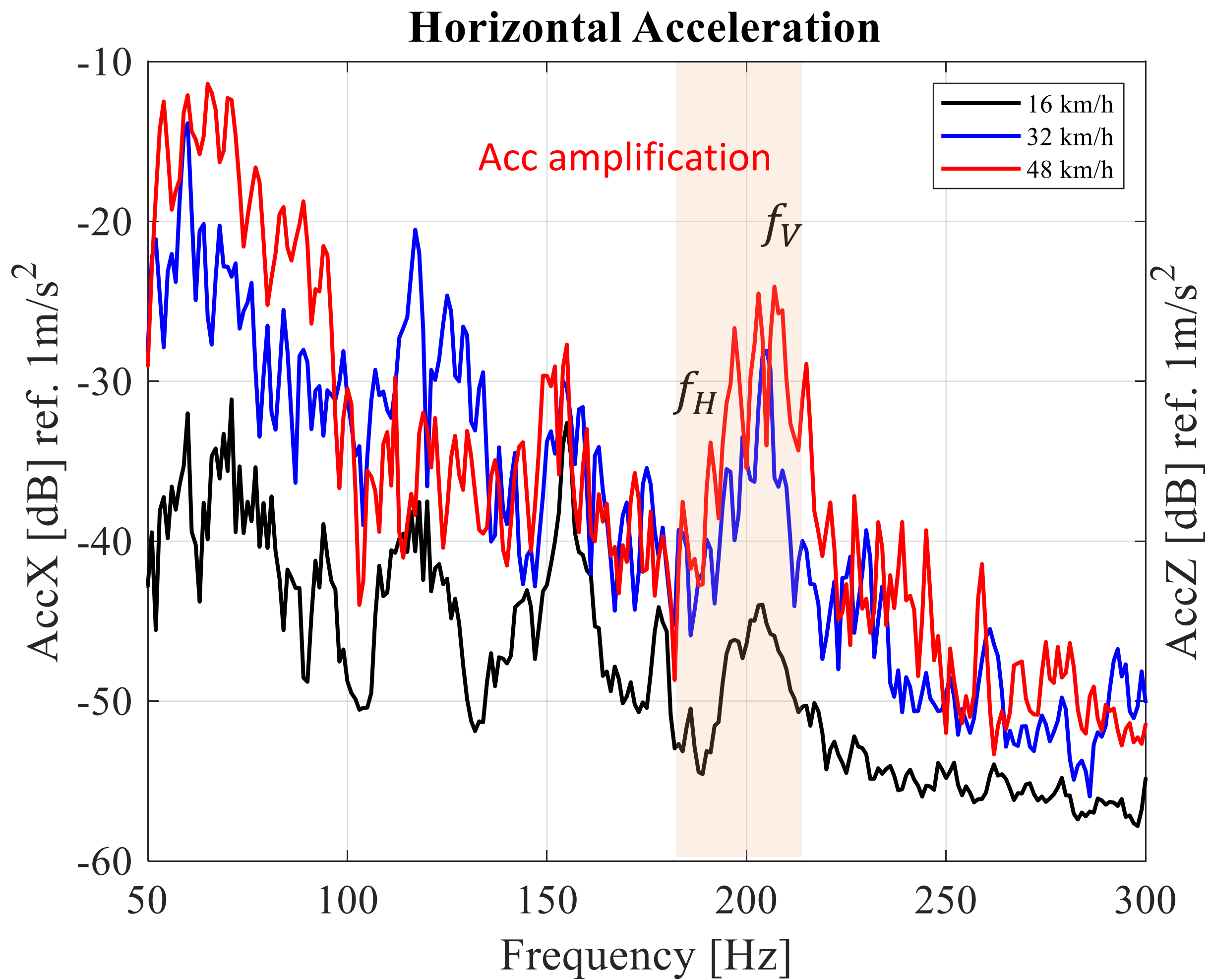
- Force amplification was identified near 200 Hz due to the cavity mode.
- The frequency split is observed at 195 Hz and 208 Hz at 48 km/h.

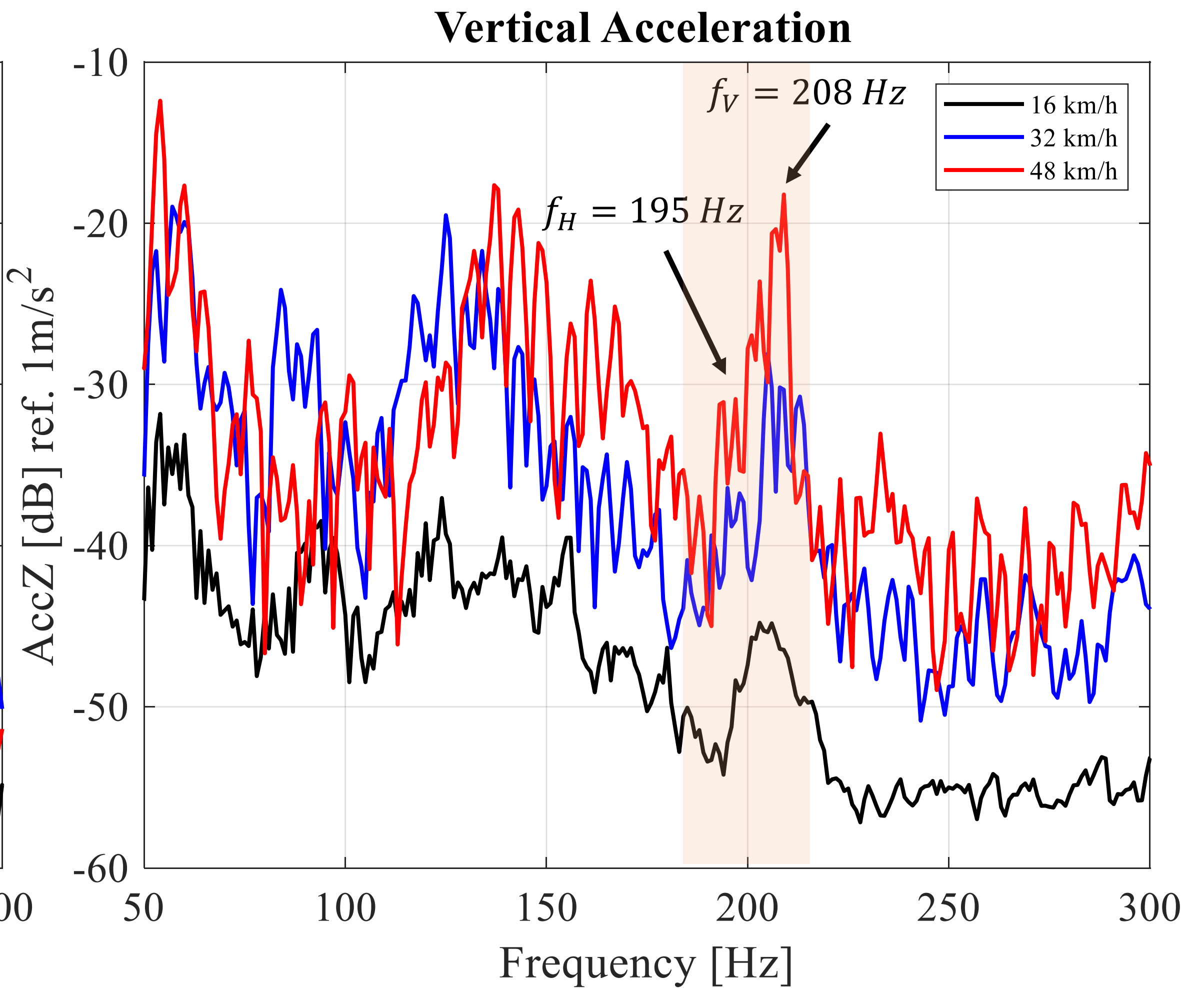


Measurement-Acceleration

- Acc. amplification was identified near 200 Hz due to the cavity mode, mixed with other vibrational modes.
- The frequency split is observed at 195 Hz and 208 Hz at 48 km/h.

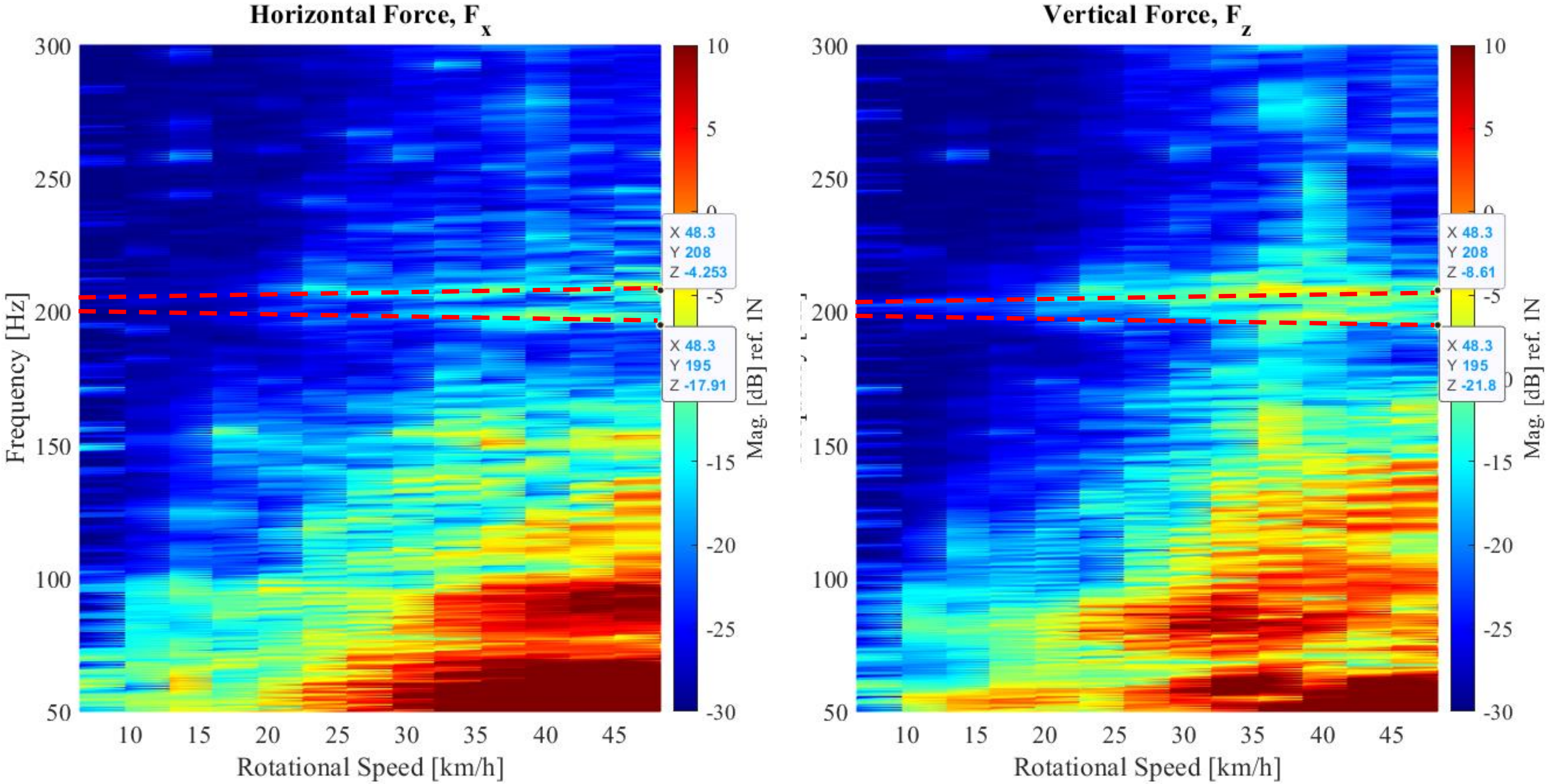
❑ Test Tire (#1) : 235/50/R18





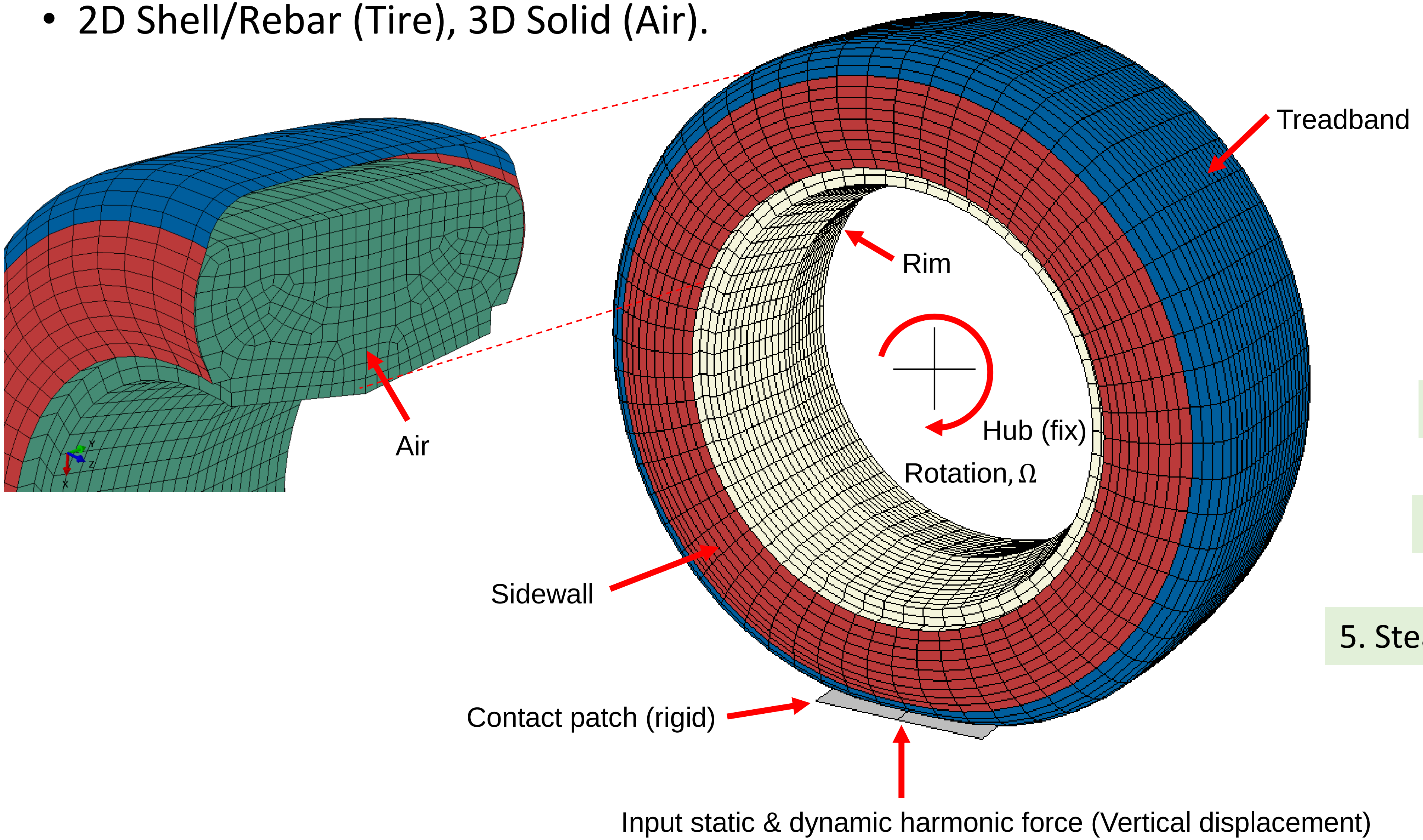
Measurement-Campbell diagram

- The two diverged lines, originating from 200 Hz, indicate the force amplification by the split in the cavity mode.
- The tire's low-order structural modes are prominent below 100 Hz.



FE Simulation-FE Model

- Abaqus 2020 was used for simulating rolling tire.
- 2D Shell/Rebar (Tire), 3D Solid (Air).



1. Inflation

⇩

2. Deformation

⇩

3. Modal analysis

⇩

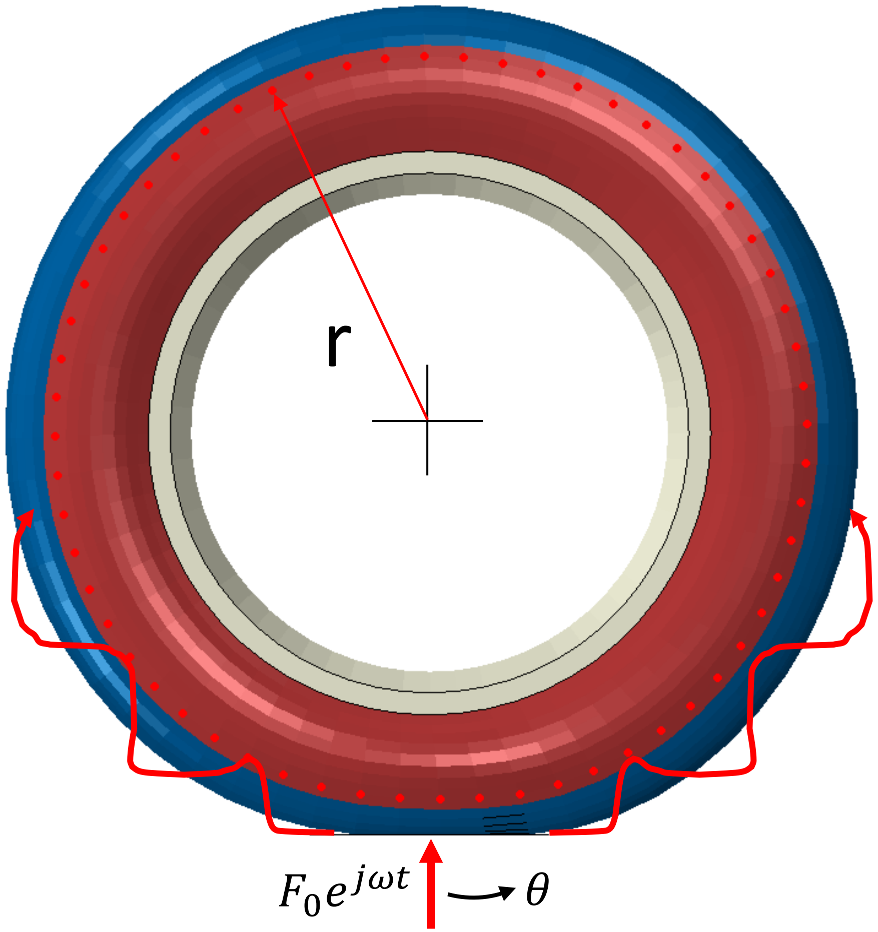
4. Harmonic analysis

⇩

5. Steady-state transport analysis

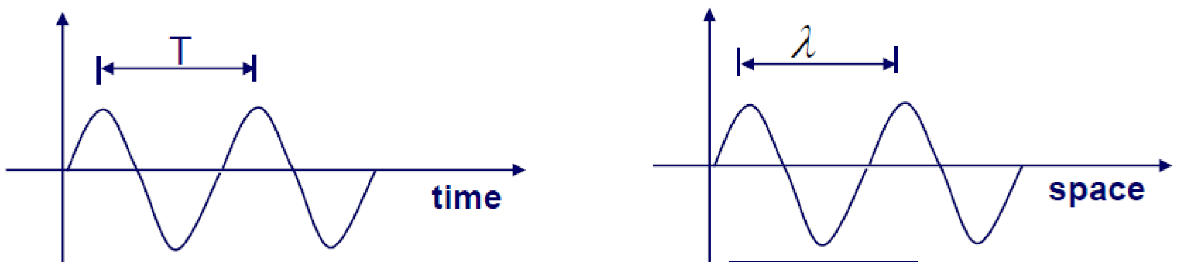
FE Simulation-Dispersion relation

- The surface velocity was extracted at mean radius in air-cavity in simulation.
- The mobility (surface velocity/input force) and dispersion curve were obtained.
- The resonance frequencies and characteristics in wave propagation were identified.



- $k_{max} = \frac{2\pi}{\lambda_{min}} = \frac{2\pi}{2\pi r/N} = \frac{N}{r} = 222\ [m^{-1}]$ > 100 (requirement)
- N=60 (the number of circumferential points on sidewall)
- r=0.27 [m]

Wave number Decomposition[13]



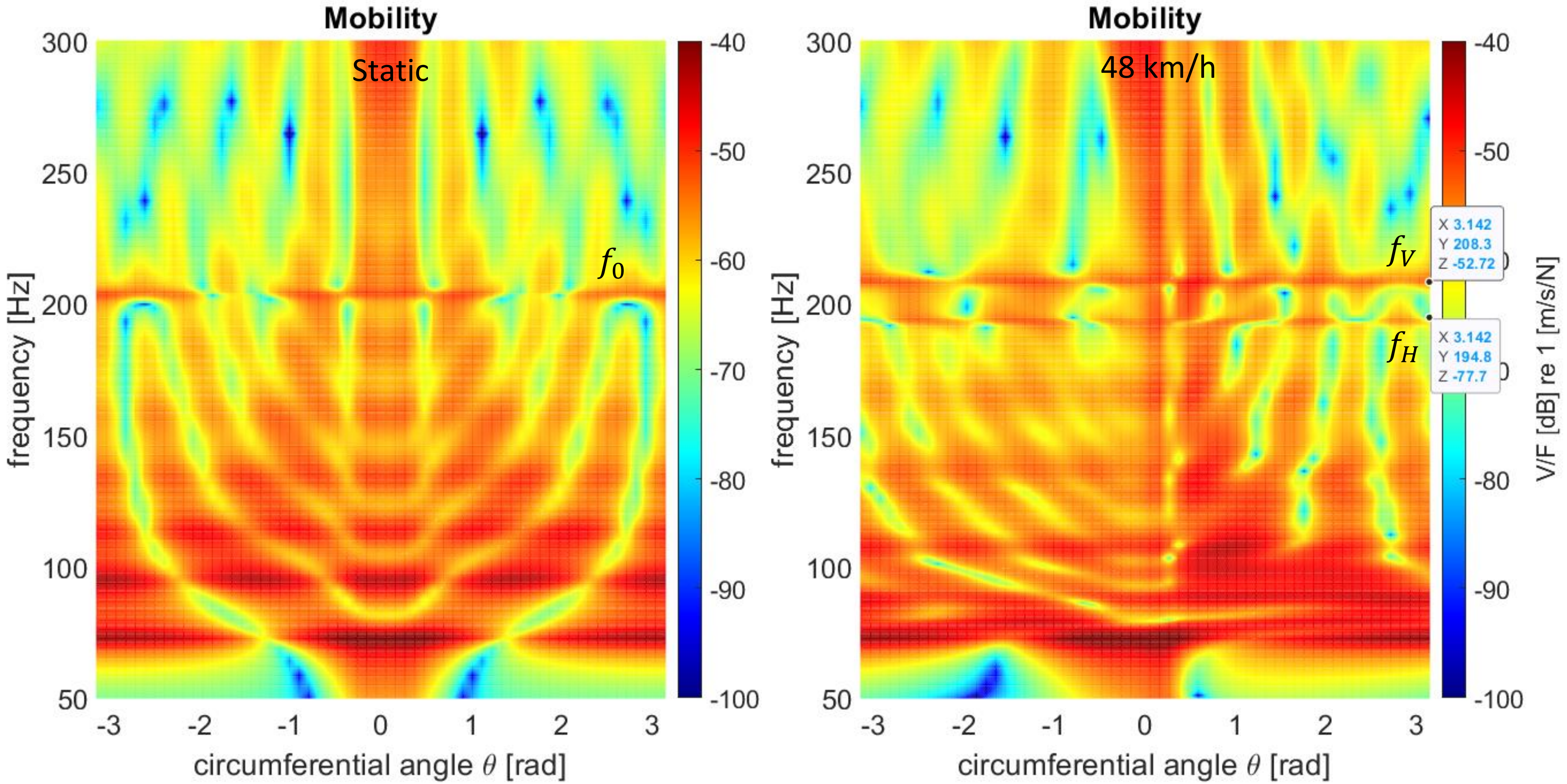
$\omega = \frac{2\pi}{T}$ — Phase change / Unit time

$k = \frac{2\pi}{\lambda}$ — Phase change / Unit length

Phase speed: Since $\lambda = c_p T \Rightarrow c_p = \frac{\omega}{k}$

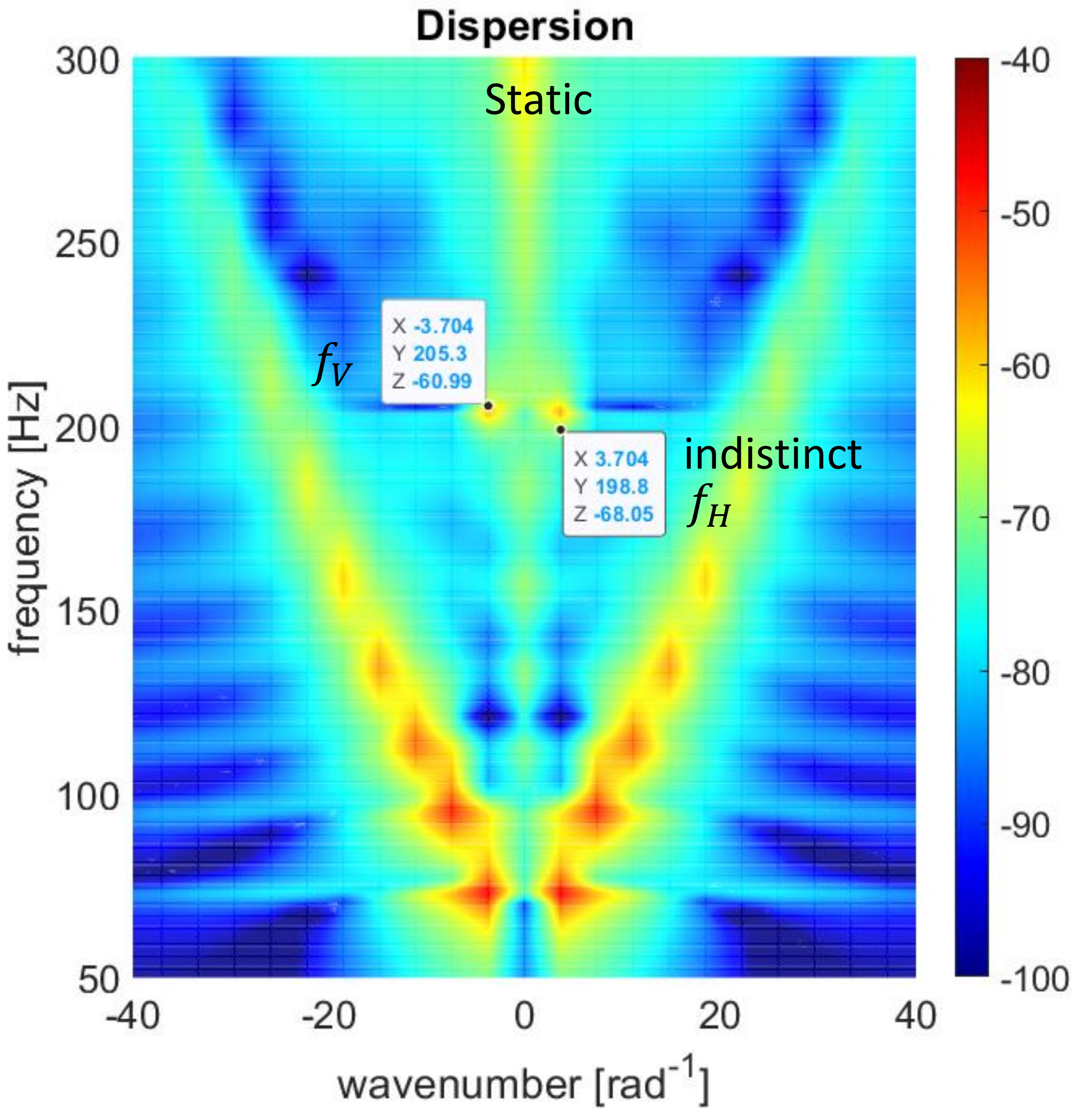
FE Simulation-Mobility

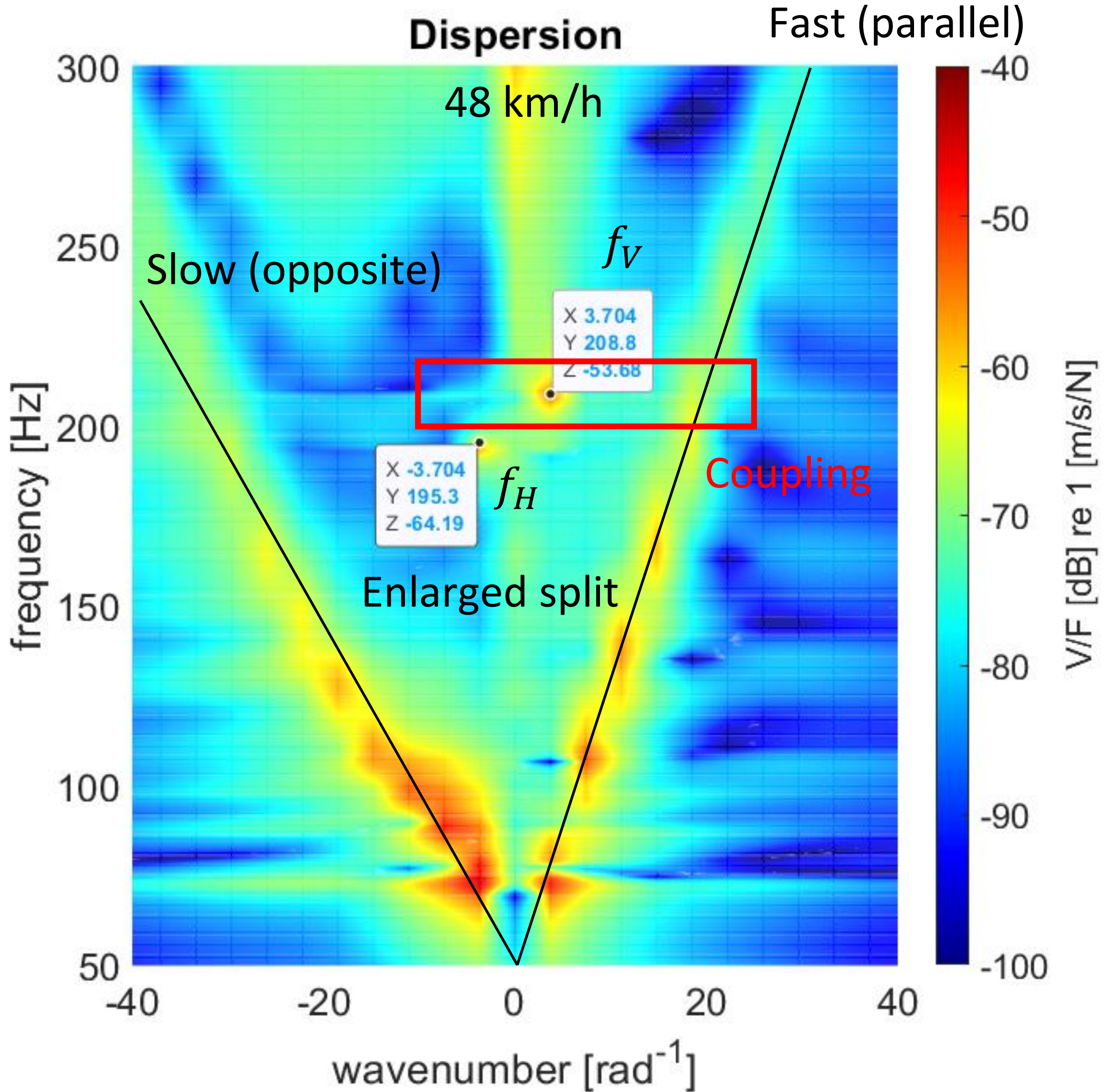
- The surface velocity was extracted at mean radius in air-cavity in simulation.
- The similar trend in the frequency split was observed.



FE Simulation-Dispersion relation

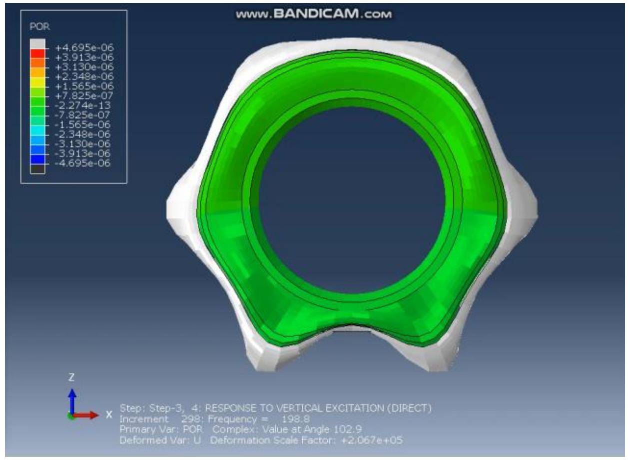
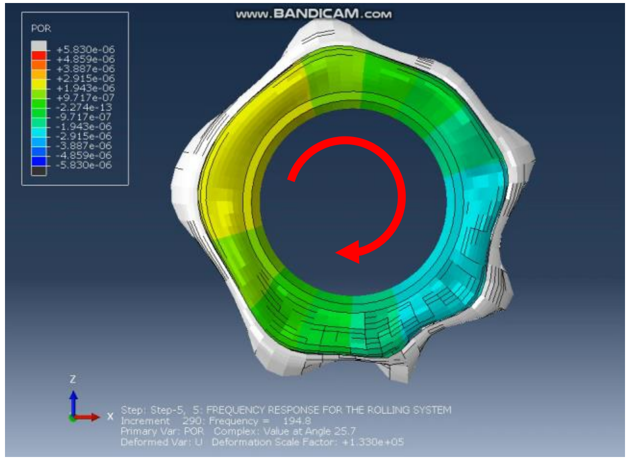
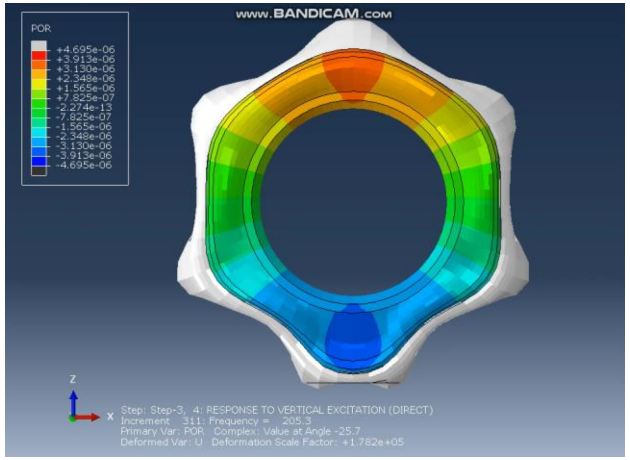
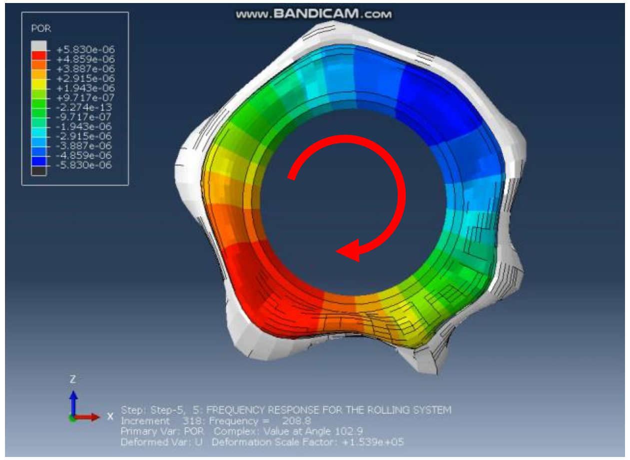
- The asymmetric curve (kinematic tilting) appears under rolling condition, phase speed difference.
- The frequency split can be expanded in the presence of rolling.





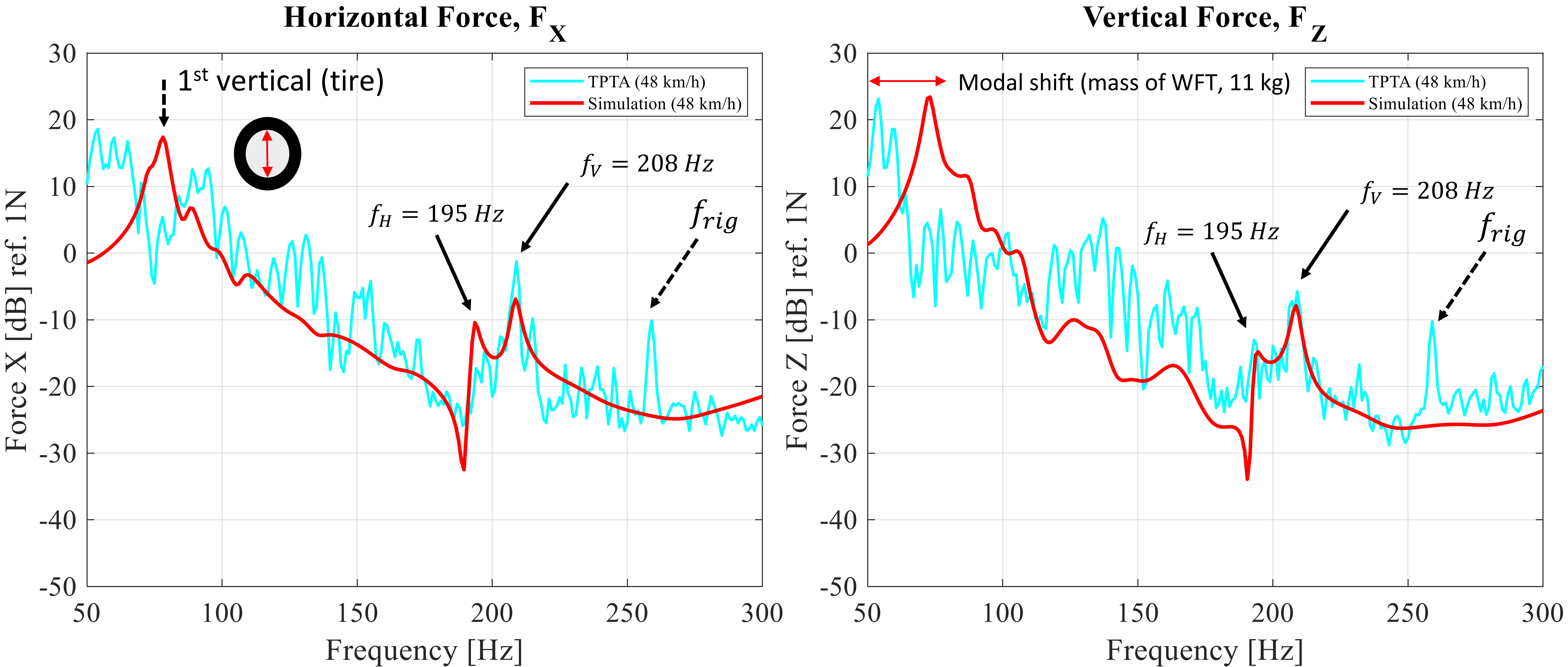
FE Simulation-Animation

- The clockwise air-flow made the split broader, interacting with structural vibration.

	Static (loaded)	Rolling (loaded)	
198 Hz			195 Hz (3 Hz ↓)
205 Hz			208 Hz (3 Hz ↑)

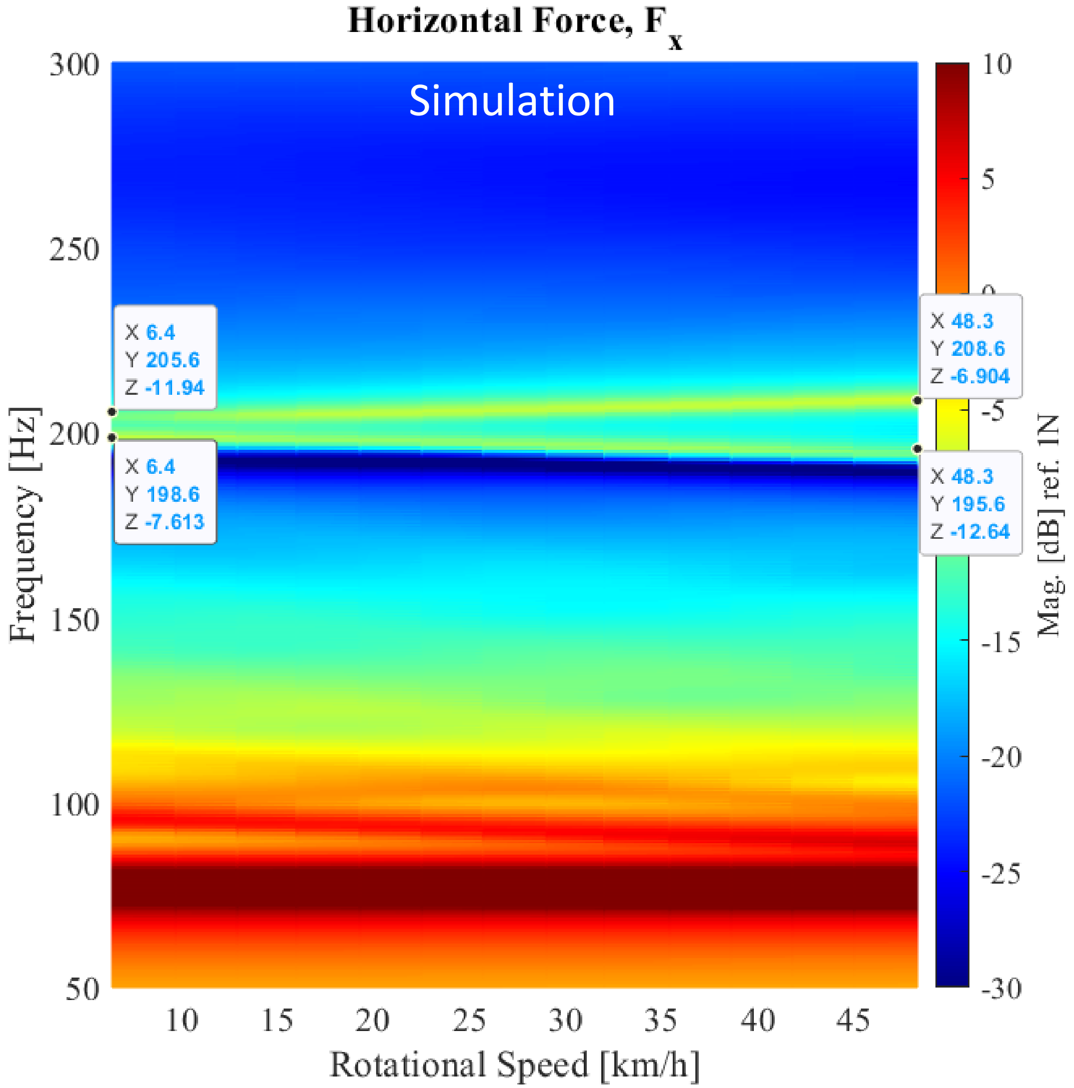
FE Simulation-Force response

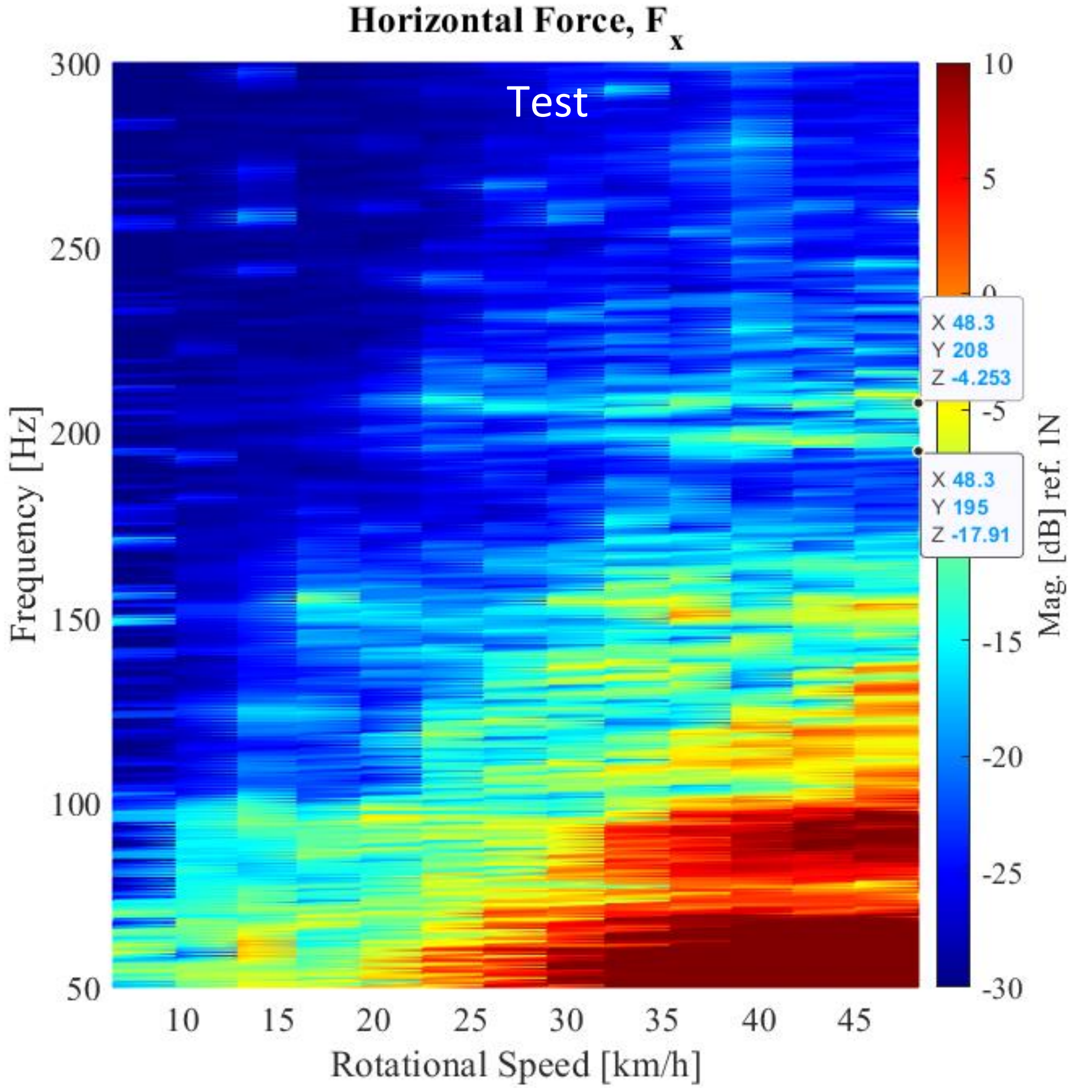
- The two force responses in simulation are similar as the test measurement.
- The frequency split is well reproduced at the similar location.
- Modal shift is observed in test due to the mass of wheel force transducer (WFT) at the hub.



FE Simulation-Campbell diagram

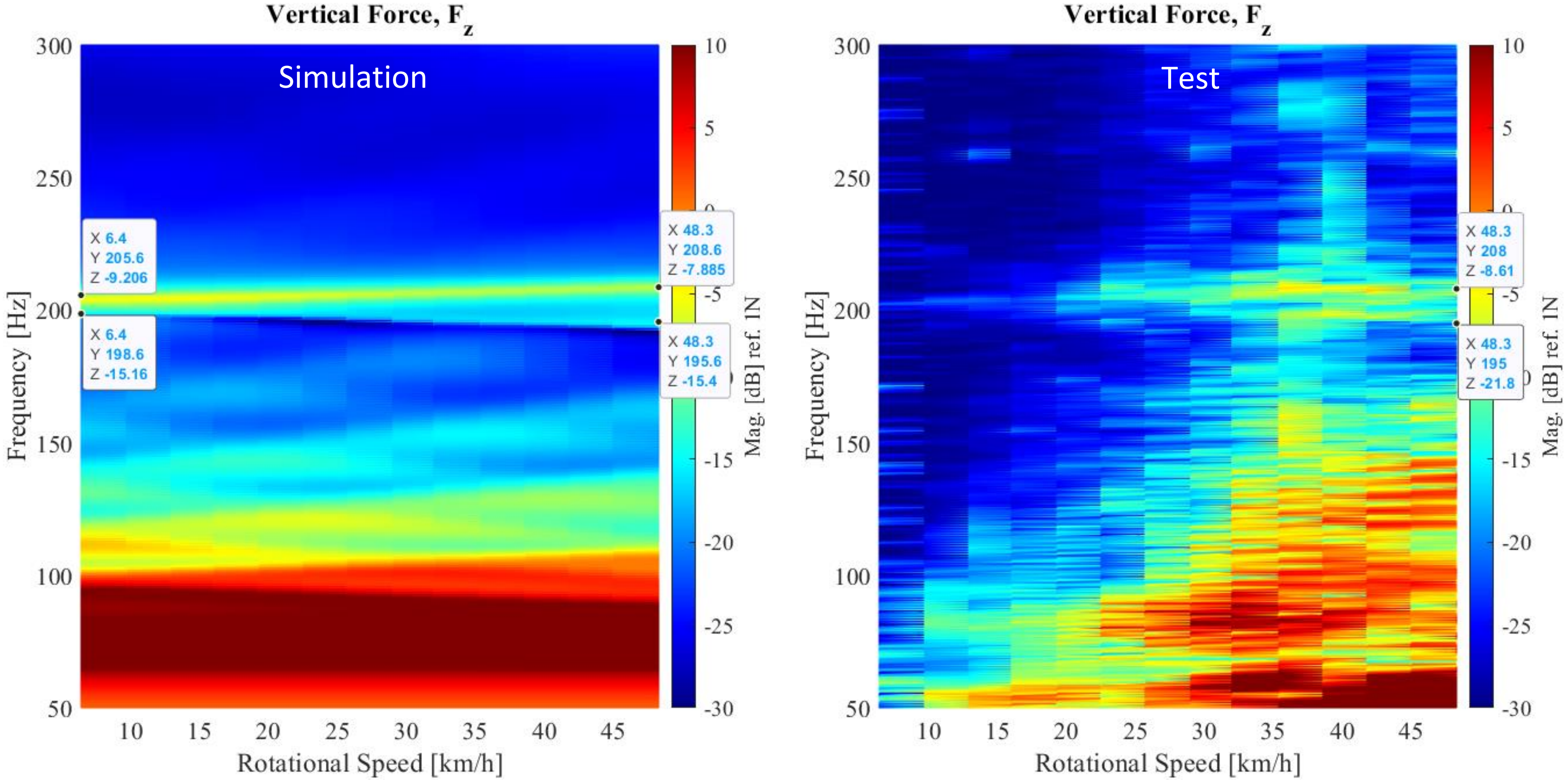
- The force amplification due to air-cavity mode is well reproduced.
- Test result has some blurry effect due to the structural damping and external noise signals.





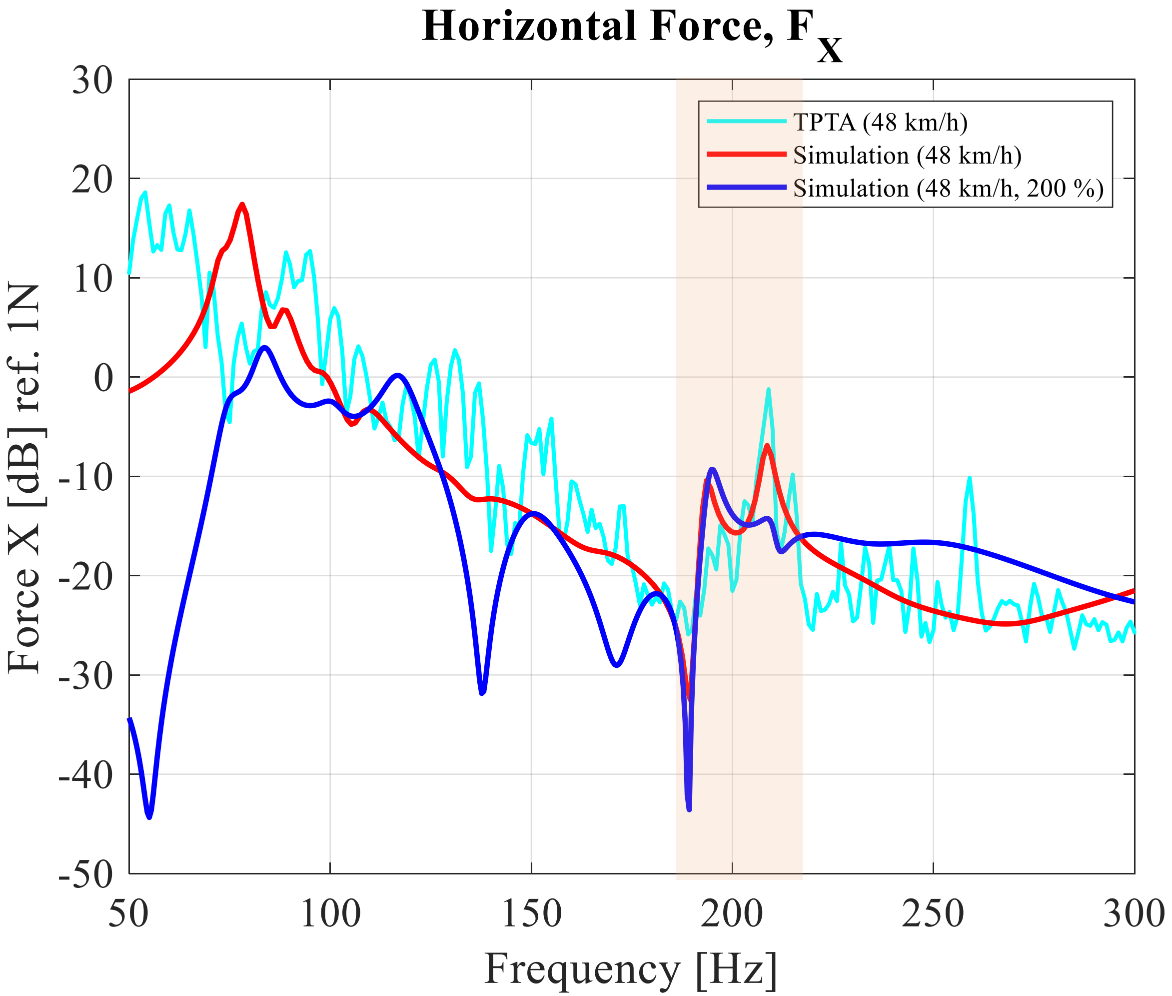
FE Simulation-Campbell diagram

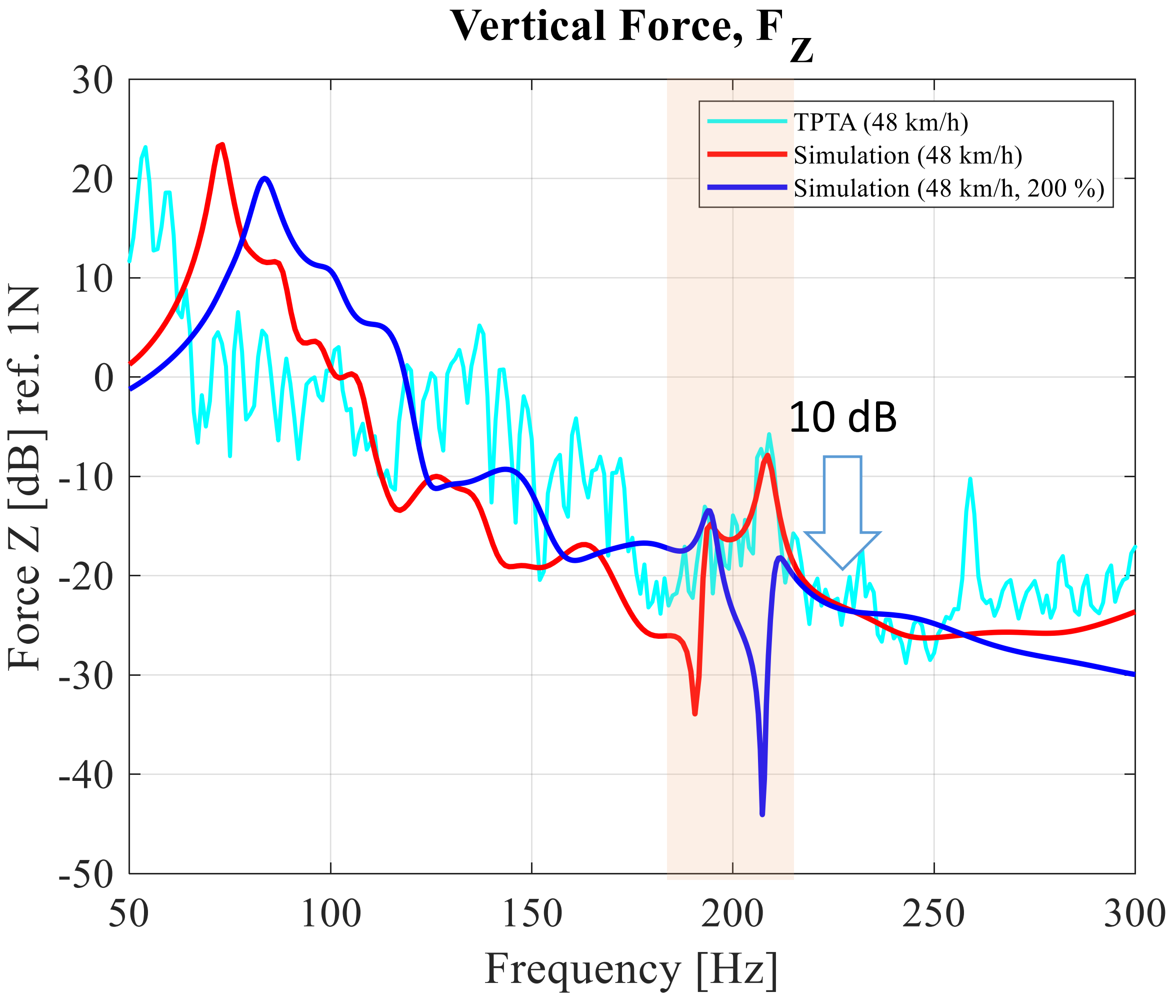
- The force amplification due to air-cavity mode is well reproduced.
- The 1st tire's vertical (radial) mode is shifted down by 20 Hz due to mass effect.



FE Simulation-Stiffness optimization for force mitigation

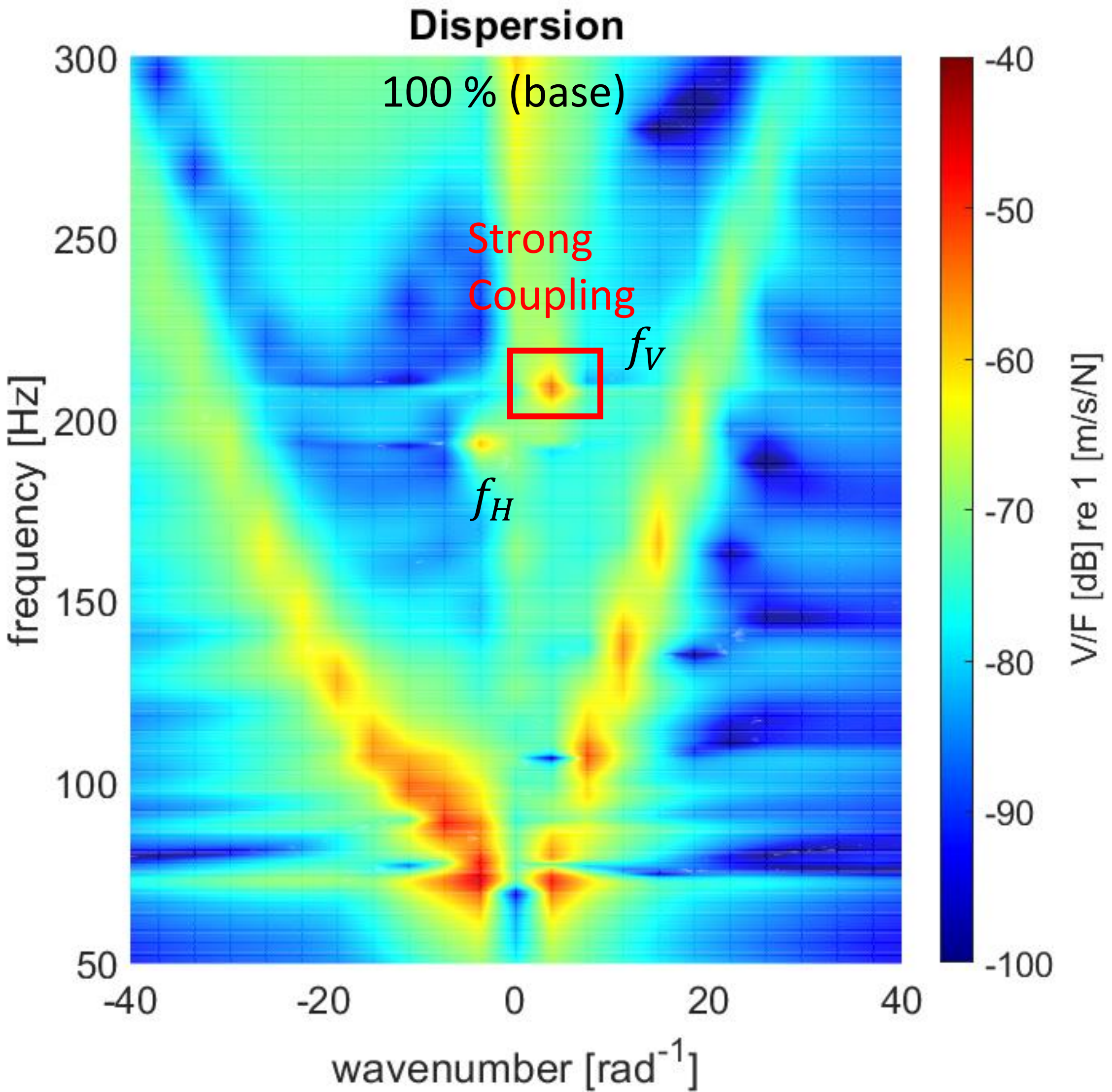
- Stiffness (Young's modulus) on sidewall and treadband was adjusted to 200 % from the reference value.
- The force level is reduced to 10 dB at maximum.

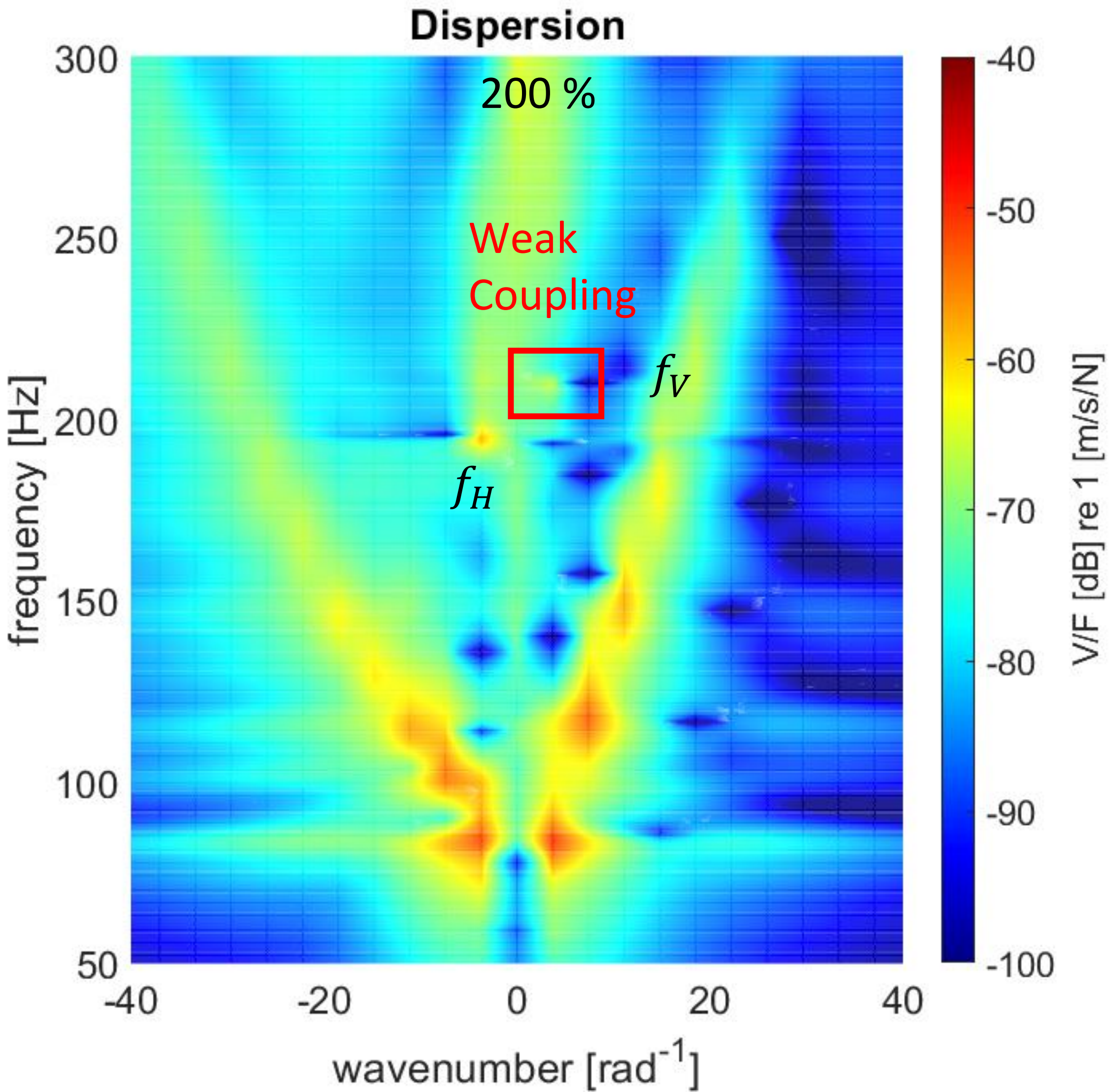




FE Simulation-Stiffness optimization for force mitigation

- The coupling at the vertical acoustic mode becomes less significant.
- Thus, it contributes to the force mitigation near the air-cavity mode.





Conclusions

- The laboratory test environment was established for measuring force and acceleration when tire is rolling.
- In the current work, the amplification in both force and vibration at the wheel hub was well identified near 200 Hz due to the air-cavity mode.
- The frequency split due to the rolling effect was well estimated in simulation, comparable to the test result and analytical solution.
- Force response and Campbell diagram were reproduced at various speeds in simulation, correlated to the test results.
- The adjustment in tire's stiffness can attenuate the force level by decoupling acoustic mode with structural vibration.
- In future work, on-board sound intensity measurement will be applied to see the relation between acoustic mode and near-field sound radiation.
- Also, Laser-scanning measurement under rotation can produce reliable dispersion relation, which will be introduced with further improvement in FE simulation .

References

[1] Michelin North America, *An introduction to tire cavity noise*, Michelin acoustic technology (https://www.michelinman.com/acoustic-technology.html), 2020.

[2] R. Bernhard et al., *An introduction to tire/pavement noise of asphalt pavement*, Virginia Asphalt Association, 2012.

[3] Michelin tire, *mechanical and acoustic comfort*, 2002.

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

[5] Patil et al., *Experimental Observations in Tire Cavity Resonance and Interactions with Periodic Noise Components*, InterNoise21, 2021.

[6] Ch. Bederna and E.-U. Saemann, *Contributions to better understanding of tire cavity noise,* NAG/DAGA09, 2009.

[7] Rui Cao and J. Stuart Bolton, and Matthew Black, *Force transmission characteristics for a loaded structural-acoustic tire model," SAE Int. J. Passenger. Cars*, Vol. 11(4), pp.1–15, 2018.

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

[9] Y.-J. Kim and J.S. Bolton., *Effects of rotation on the dynamics of a circular cylindrical shell with application to tire vibration*, Journal of Sound and Vibration, Vol. 275, pp.605-621, 2004.

[10] Stefan Uhlar, Florian Heyder, and Thomas König, *Assessment of two physical tyre models in relation to their NVH performance up to 300 Hz*, Vehicle System Dynamics, Vol. 59, pp.331-351, 2019.

[11] Yuting Liu et al., *Research on mechanism and evolution features of frequency split phenomenon of tire acoustic cavity resonance*, Journal of Vibration and Control, Vol. 0(0), pp.1-13, 2020.

[12] Kyosung Choo et al., *The application of tuned mass dampers to the Tire Pavement Test Apparatus to minimize the impact of rig resonance*, NOISE-CON22, Vol. 11, pp.509-519, 2022.

[13] J. Stuart Bolton et al., *The Wave Number Decomposition Approach to the Analysis of Tire Vibration*, Publications of the Ray W. Herrick Laboratories, Paper 12, 1998, http://docs.lib.purdue.edu/herrick/12.

[14] http://www.shelleysprecisionauto.com/services/complete-suspension-tire-service.

[15] https://studiousguy.com/doppler-effect-examples.

Acknowledgement

- Ford Motor Company – Financial support / Tire & wheel sample provider
- Matthew Black – Program manager and logistical support

Contact Info

Won Hong Choi
Ray W. Herrick Laboratories, Purdue University
177 S. Russell Street, West Lafayette IN 47907-2099
(765) 250-0354
choi124@purdue.edu