XIX CNIM 15-16/11 Castellón

Structural Dynamic Behaviour of Tyres

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Road traffic noise

- **Vehicle noise:**

➔ ***drive train noise***

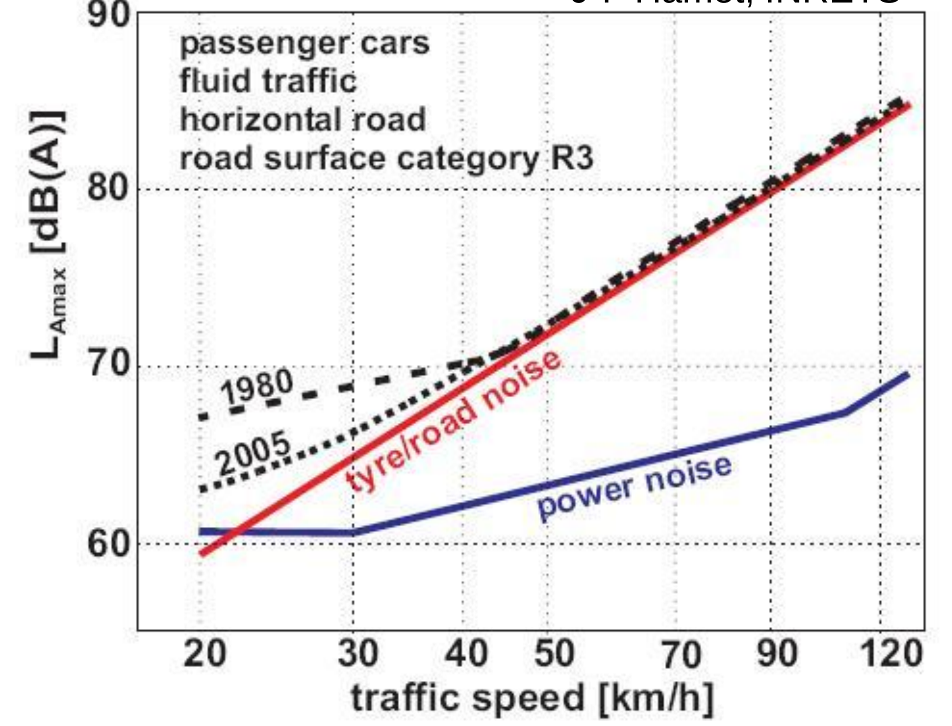
(engine, intake, exhaust, transmission)

➔ ***aerodynamic noise***

➔ ***tyre/road noise***

Tyre/road noise dominates at constant speeds above 15-25 km/h

J-F Hamet, INRETS



Tyre/road noise legislation

- **Directive 2001/43/EC**

  (80 km/h coast-by on ISO10844 road surface)

	CURRENT		PROPOSED		
tyre class	tyre section width [mm]	limit value [dB(A)]	tyre section width [mm]	proposed reduction [dB(A)]	
C1a	≤145	72	≤185	2.5-4.5	**70**
C1b	>145 ≤165	73	>185 ≤215	4.5	**71**
C1c	>165 ≤185	74	>215 ≤245	5.5	**71**
C1d	>185 ≤215	75	>245 ≤275	4.5	**72**
C1e	>215	76	>275	2.5	**74**

1) **expected to come into force in 2012**
2) **more realistic reference road surface**

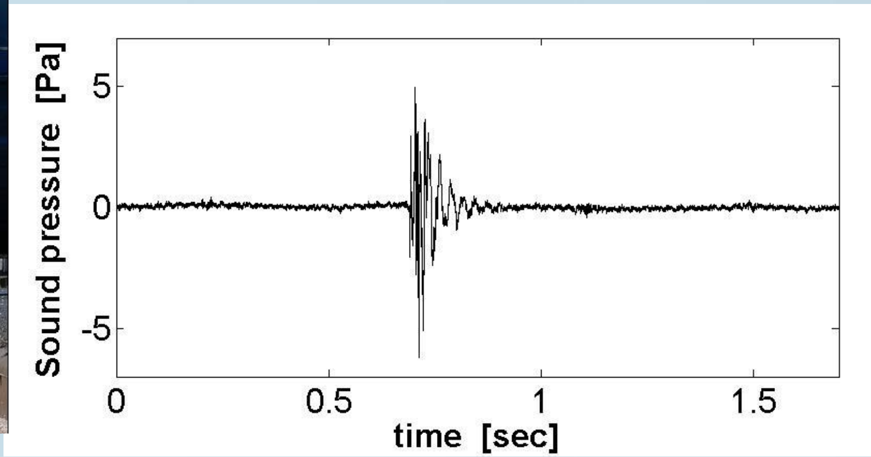
Crossing a road surface discontinuity

- <u>Tyre/road noise **EXTERIOR** to the vehicle:</u>

  - significant increase of <u>instantaneous</u> noise emission level

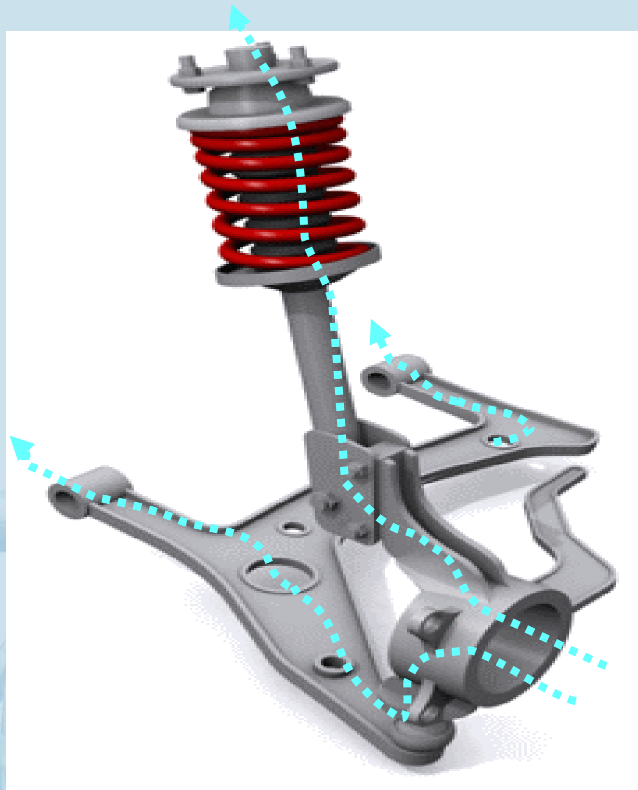
  - transient noise is perceived as <u>highly annoying</u>

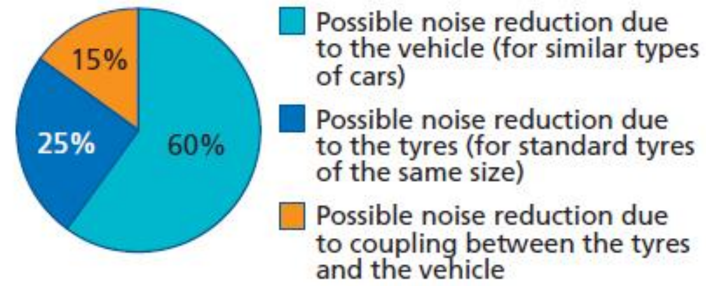
  - demand for more quiet tyres and road surfaces in urban areas



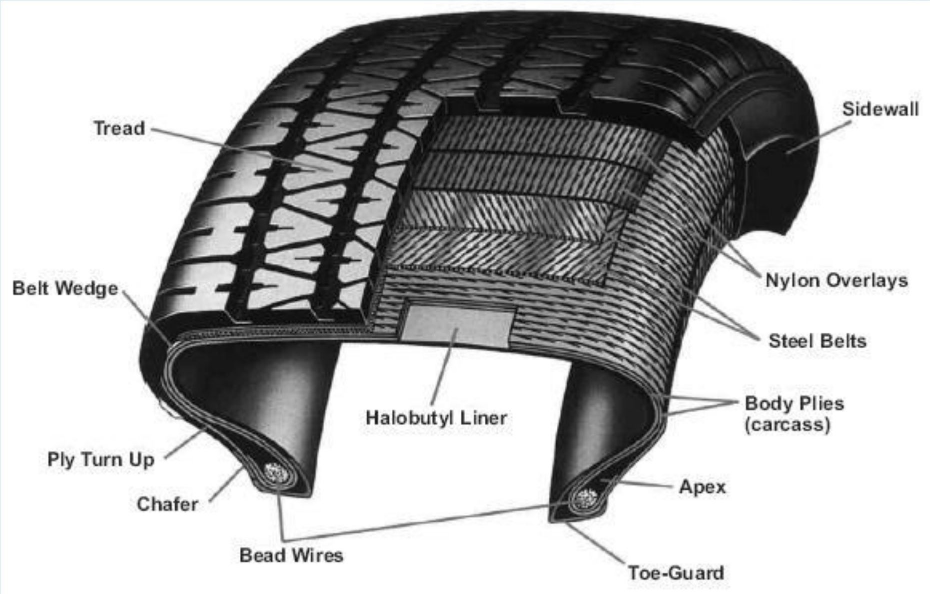
Relevance of tire dynamics

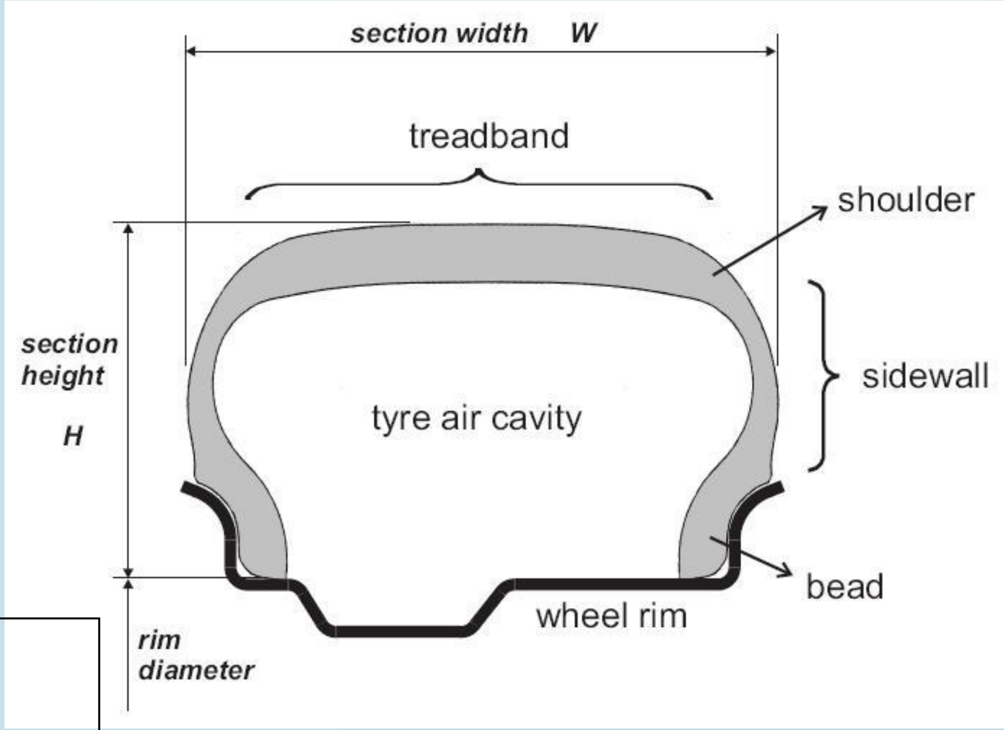
- **Interior vehicle noise (NVH):**





The pneumatic tyre



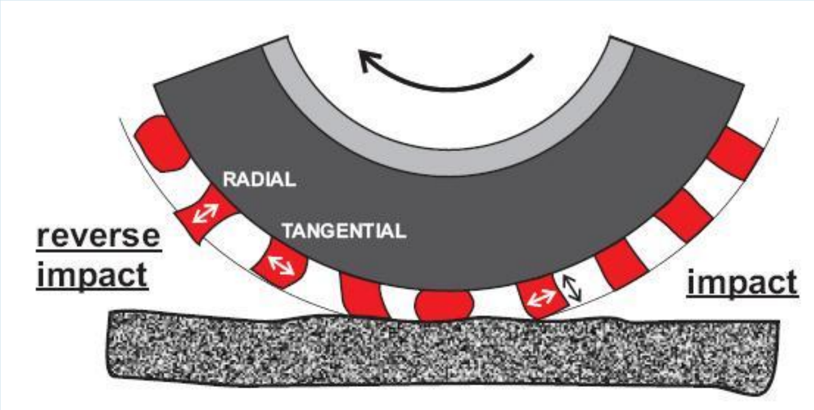


Typical passenger car tyre contains:

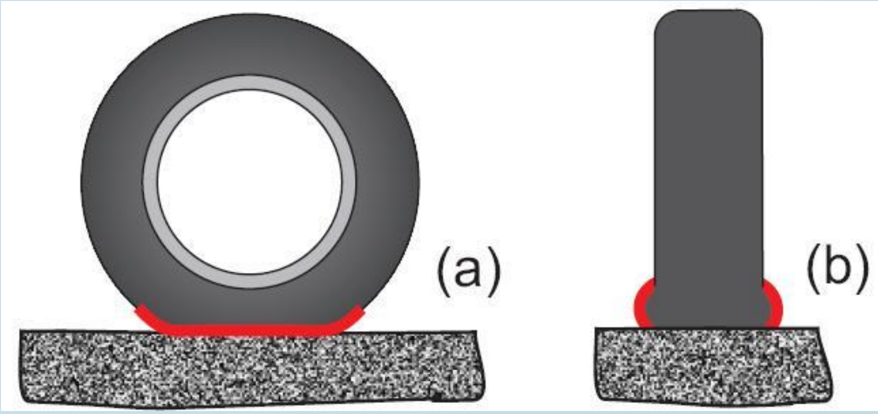
- 13 different types of rubber compounds
- 8 types of fillers (carbon black, silica)
- reinforcement: steel cords, polyester, nylon, rayon
- 40 different kinds of chemicals

approximately 500 different specifications

Tyre/road noise – VIBRATIONAL phenomena

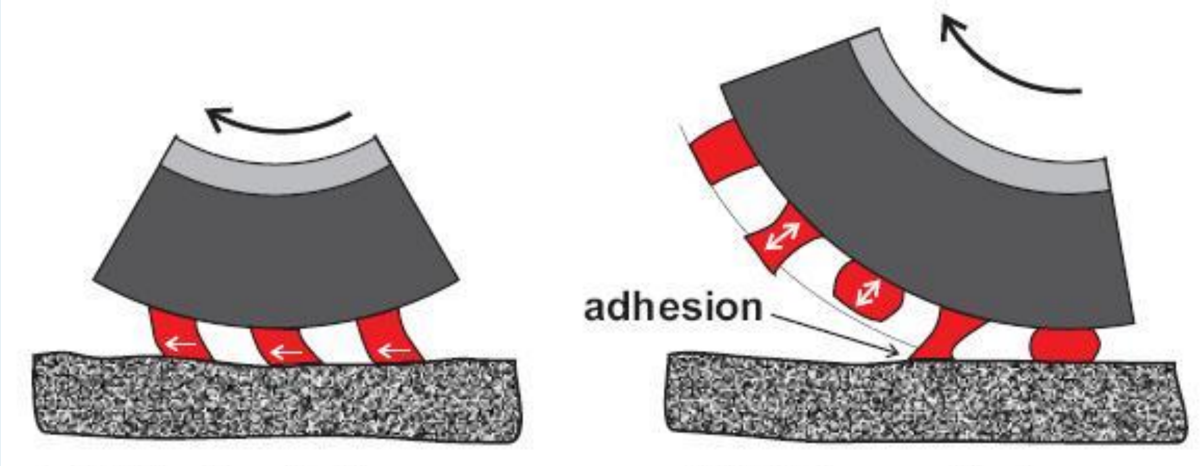


Tread element impact



Running deflections

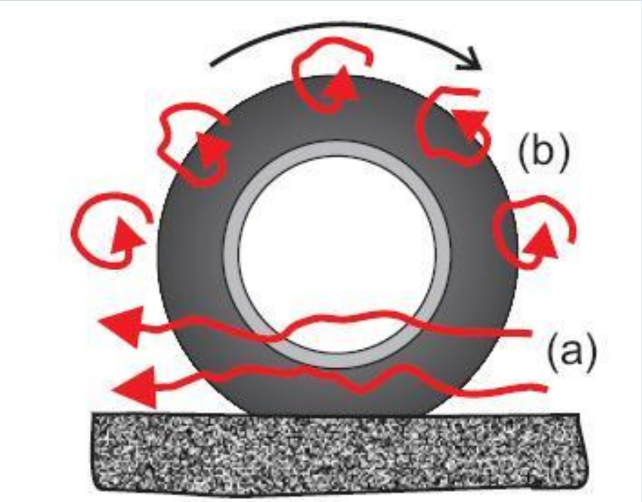
Road texture impact



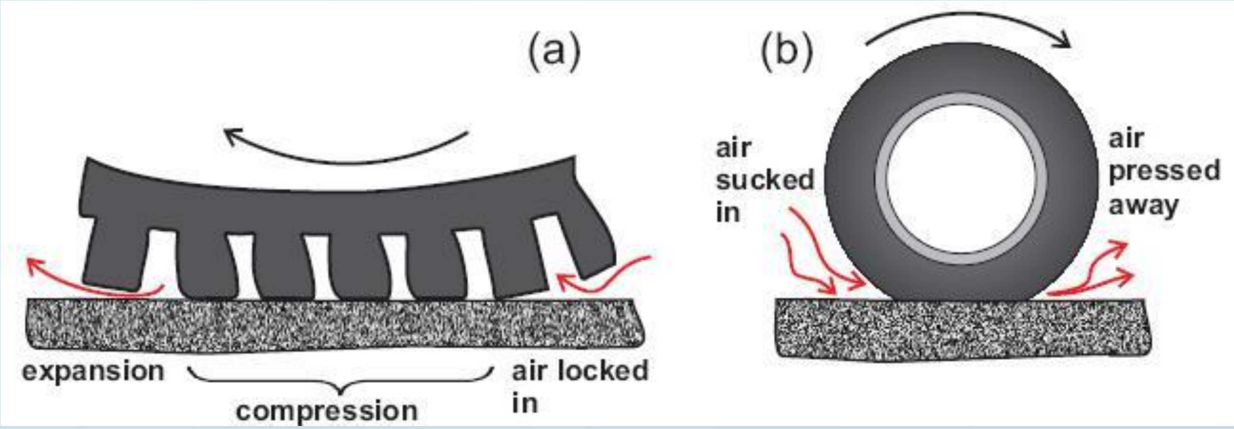
Stick-slip adhesion

Stick-snap adhesion

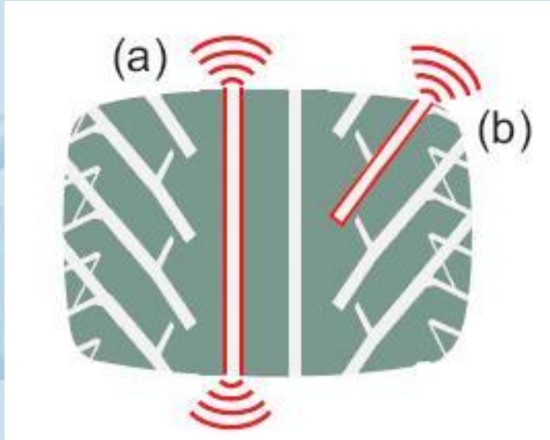
Tyre/road noise – AERODYNAMICAL phenomena



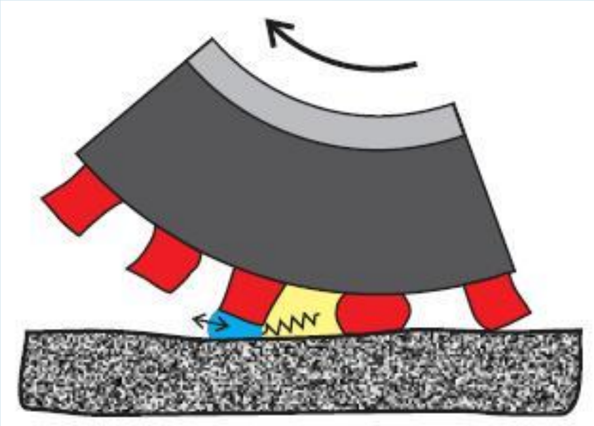
Air turbulence



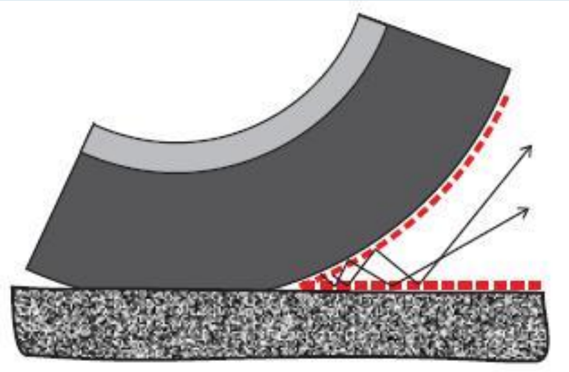
Air pumping



Pipe resonances



Helmholtz resonator



Horn amplification

Tyre/road noise

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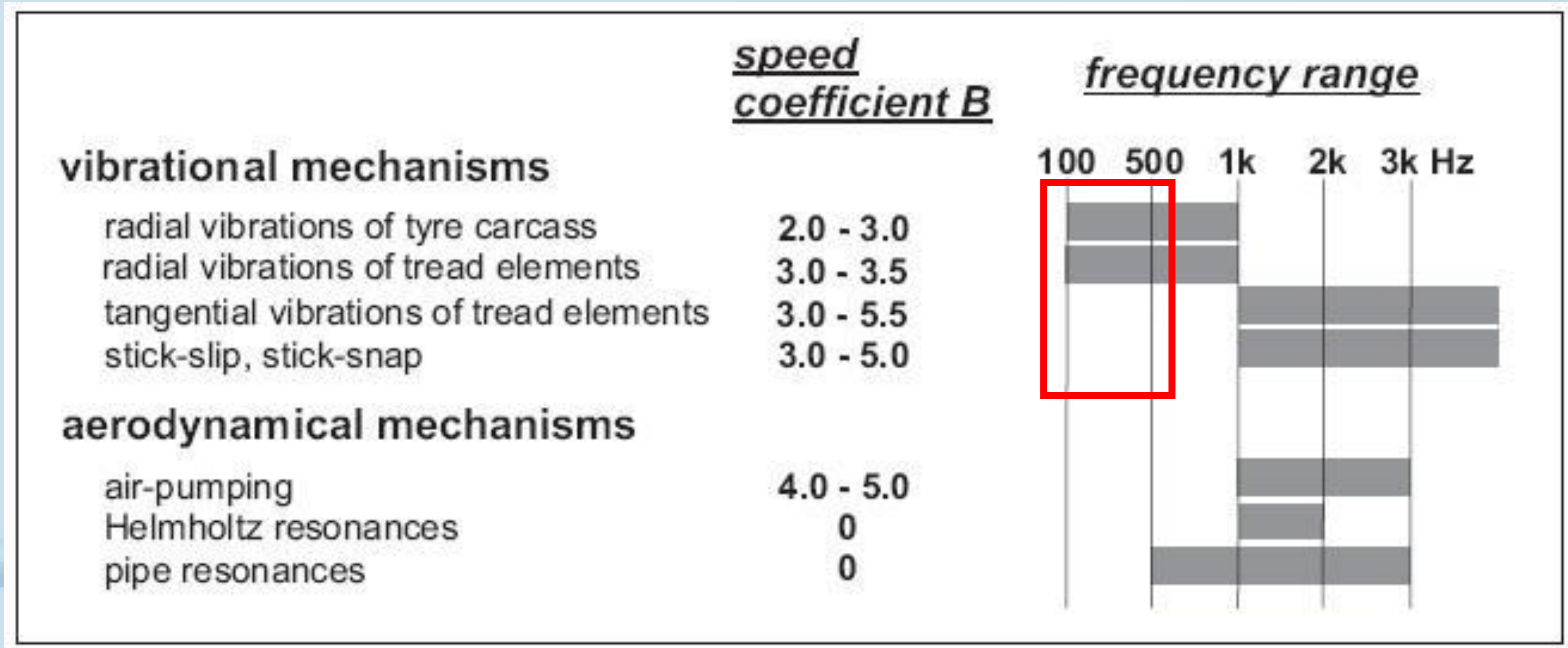
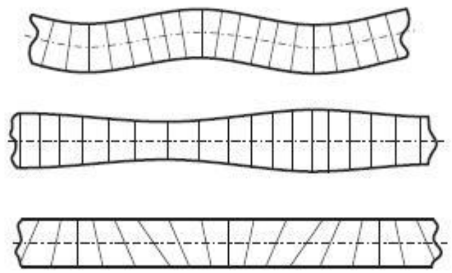


structure-borne tyre/road noise

Tyre dynamics



bending waves

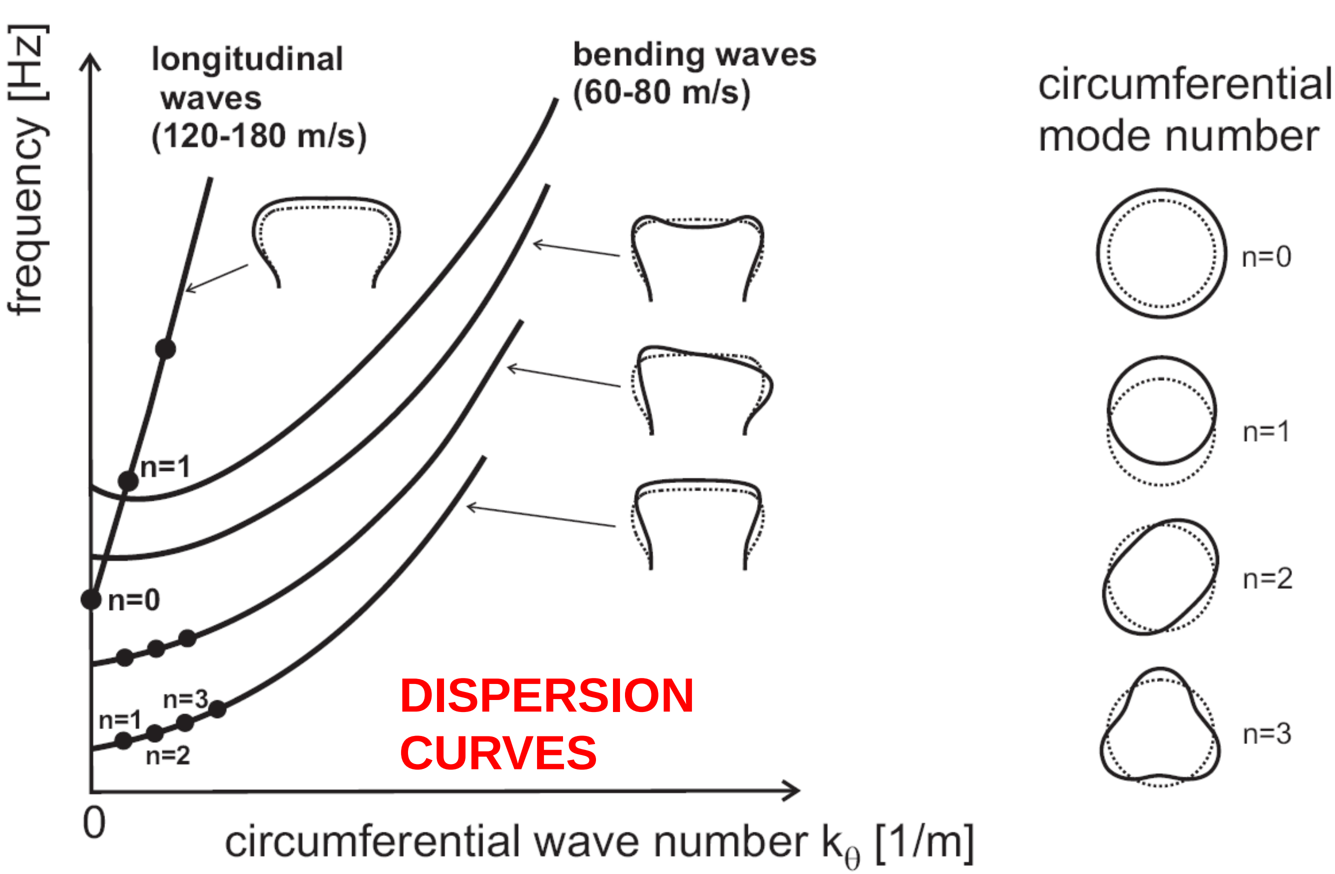
longitudinal waves

rotational waves

$$y = Ae^{-\alpha x} e^{j(\beta x - \omega t)}$$

wave number $k = \beta + j\alpha \quad [m^{-1}]$

wavelength $\lambda = \frac{2\pi}{k} \quad [m]$



Resonance condition:

$$2\pi R = n\lambda \quad [m]$$

or

$$k_\theta = n/R \quad [m^{-1}]$$

Experimental modal analysis

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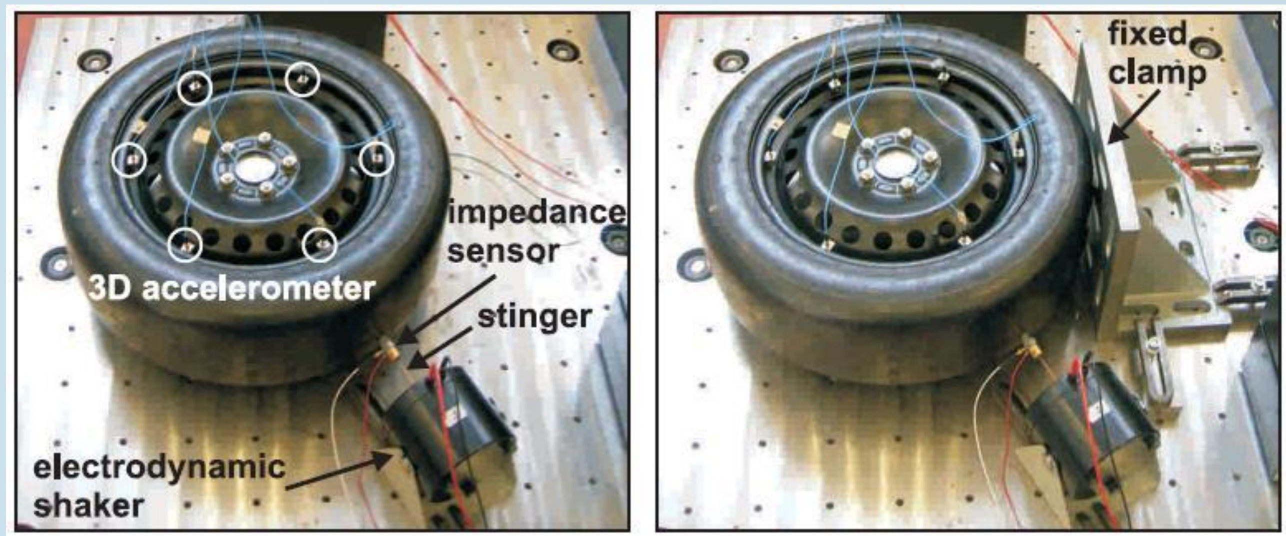
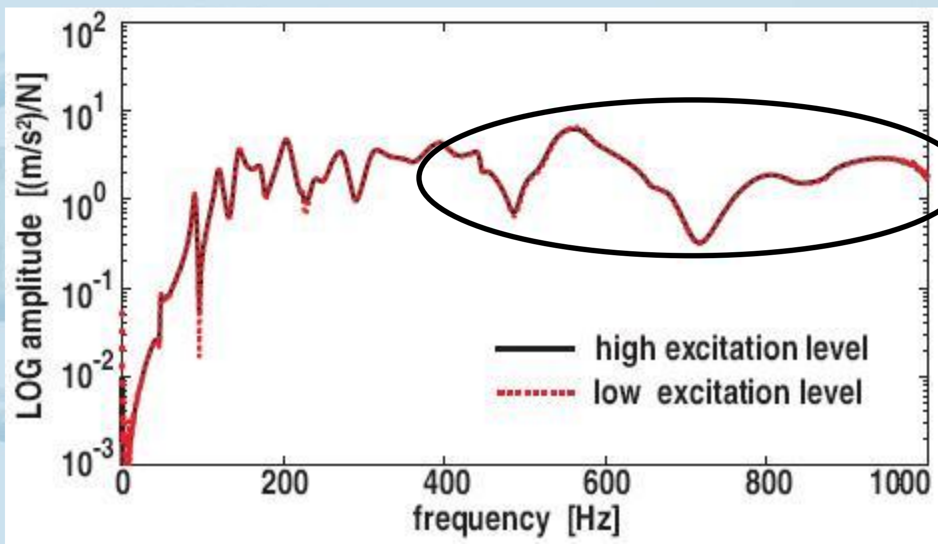
- Experimental analysis of the dynamic behaviour of a ***non-rolling*** tyre.

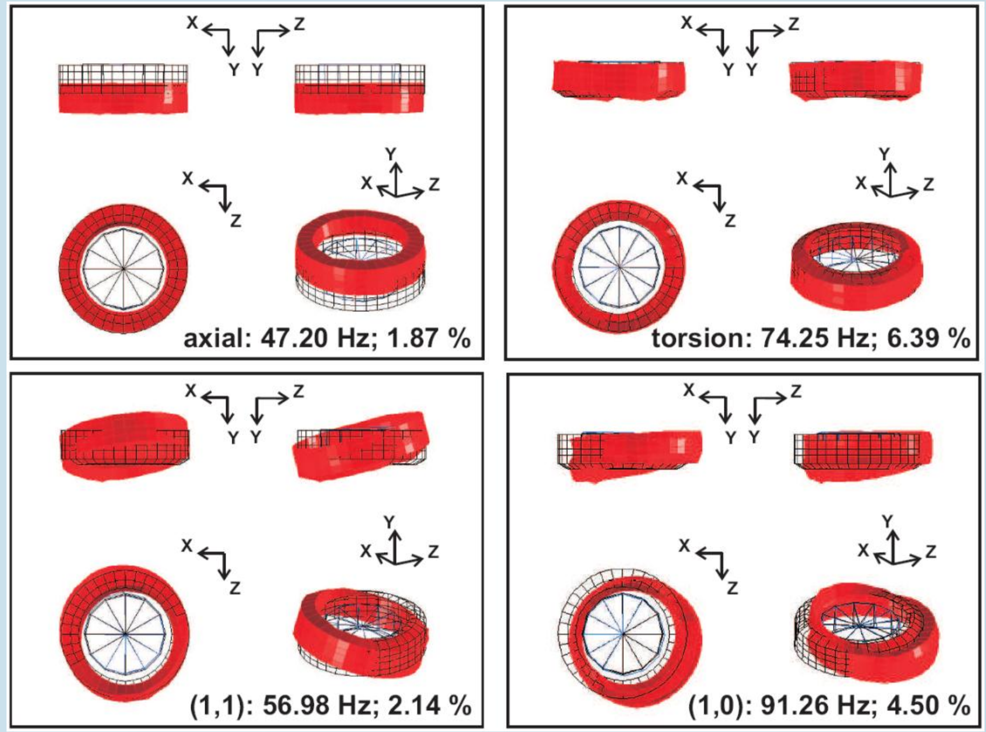


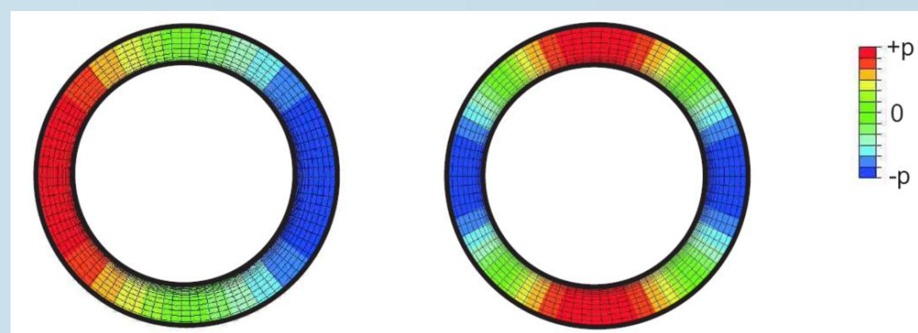


High modal density (2 modes/Hz)
High damping of structural waves.

Unloaded tyre

mode	*freq. [Hz]*	*ξ [%]*
axial	47.20	1.87
torsional	74.25	6.39
(1,1)	56.98	2.14
(1,0)	91.26	4.50
(2,0)	118.55	3.26
(2,1)	89.37	2.07
(3,0)	141.97	2.78
(3,1)	171.91	2.73
(4,0)	169.96	3.01
(4,1)	222.88	3.57
(5,0)	201.79	2.41
(5,1)	252.63	4.13
(6,0)	233.75	2.82
(6,1)	279.90	3.65
(7,0)	268.96	2.98
(7,1)	*	*
(8,0)	306.04	3.18
(8,1)	*	*
1st acoustic	225.75	0.25
2nd acoustic	445.08	0.64
1st rim bending	187.22	2.12
rim pitch	189.89	0.69
rim axial	325.82	0.52
2nd rim bending	345.60	0.98





225.75 Hz; 0.25%

445.08 Hz; 0.64%

Unloaded tyre

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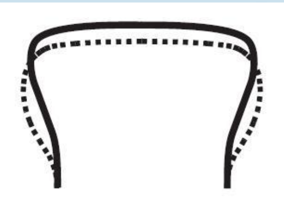
- **Tyre damping**

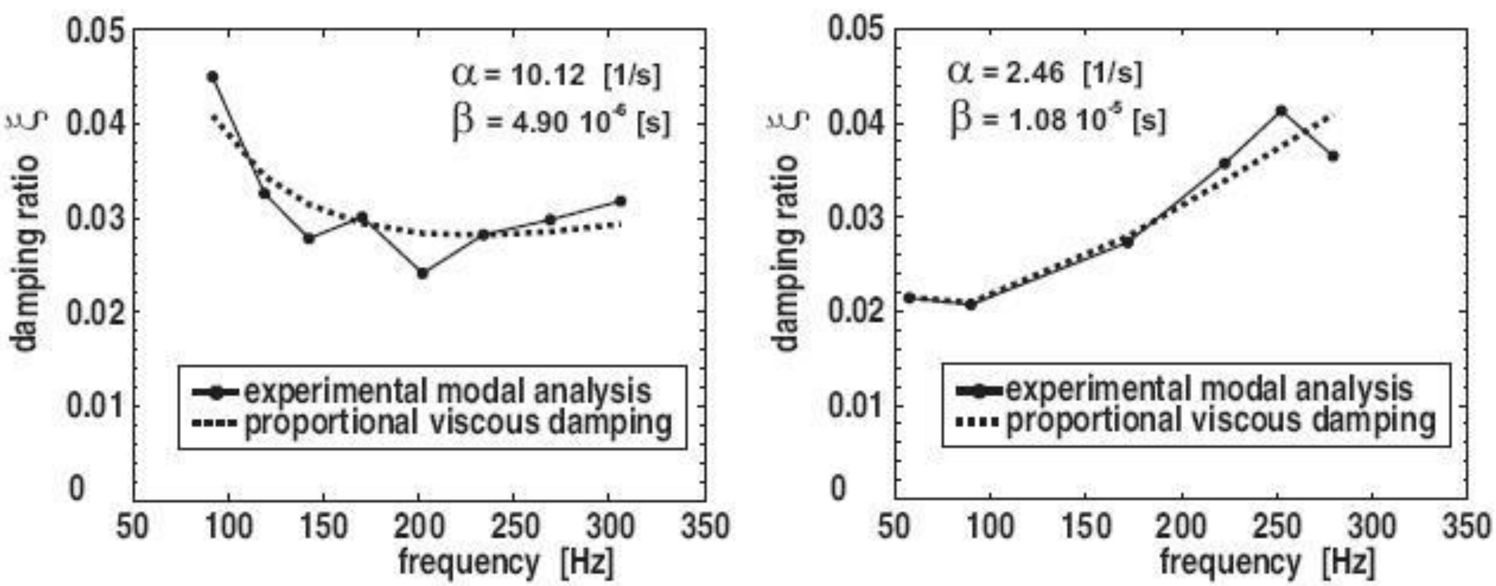
$$[C] = \alpha[M] + \beta[K]$$

proportional viscous damping

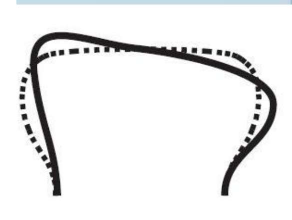
$$\xi_r = \frac{\alpha}{2\,\Omega_r} + \frac{\beta\,\Omega_r}{2} \quad with \quad \Omega_r = \frac{\omega_r}{\sqrt{1-\xi_r^2}}$$

A more complex damping model is required.



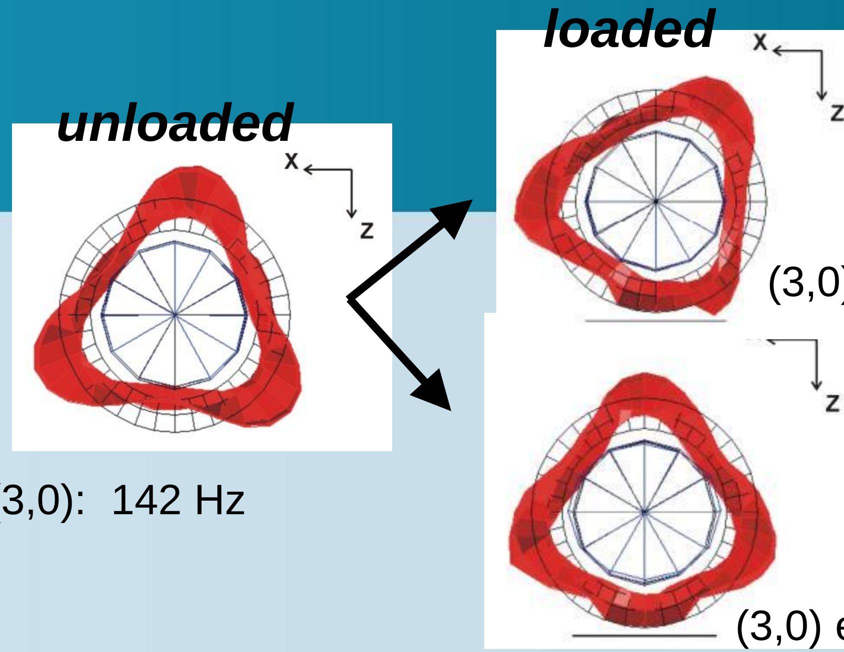


(a) (n,0) modes (b) (n,1) modes



Loaded tyre

	no spindle rotation	
mode	freq. [Hz]	ξ [%]
axial	/	/
torsional	/	/
(1,1) hor.	51.85	1.97
(1,1) vert.	64.75	2.48
(1,0) hor.	82.15	5.42
(1,0) vert.	98.22	4.09
(2,0) 0	117.94	3.43
(2,0) extr.	126.74	3.18
(2,1) 0	102.10	2.78
(2,1) extr.	86.99	2.46
(3,0) 0	142.56	2.87
(3,0) extr.	156.03	2.75
(3,1) 0	*	*
(3,1) extr.	162.36	2.78
(4,0) 0	172.66	2.89
(4,0) extr.	189.10	2.86
(4,1) 0	236.63	2.38
(4,1) extr.	225.23	1.44
(5,0) 0	205.11	3.10
(5,0) extr.	222.14	2.79
(5,1) 0	*	*
(5,1) extr.	258.03	3.47
(6,0) 0	242.34	2.75
(6,0) extr.	*	*
1st acoustic hor.	219.02	0.69
1st acoustic vert.	227.35	0.43
1st rim bending	183.13	2.53
rim pitch	189.62	1.15
rim axial	326.33	0.62

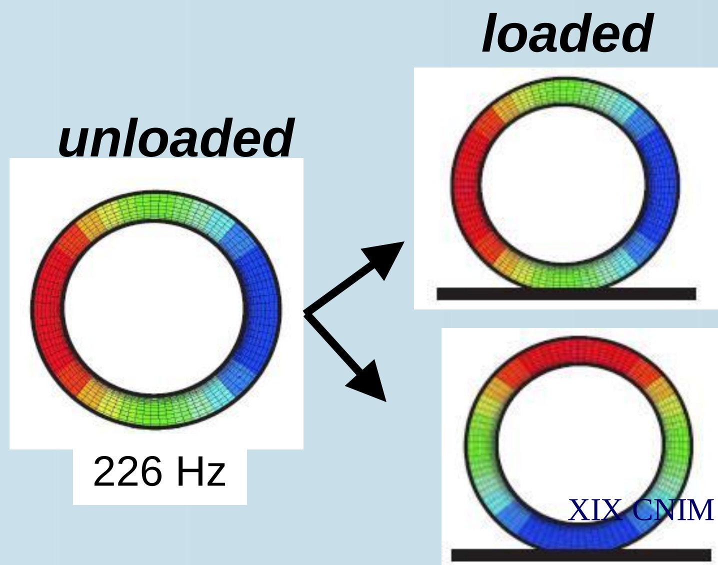


(3,0) 0: 143 Hz

(3,0): 142 Hz

(3,0) extr: 156 Hz

Double poles of unloaded tyre split up due to non-axisymmetry of loaded tyre.



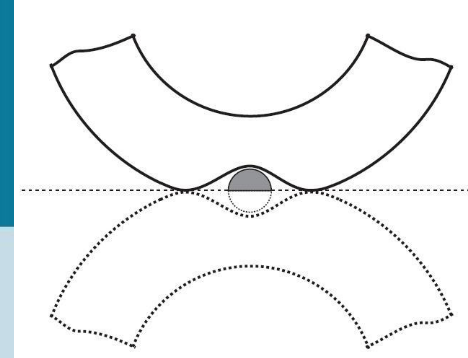
219 Hz

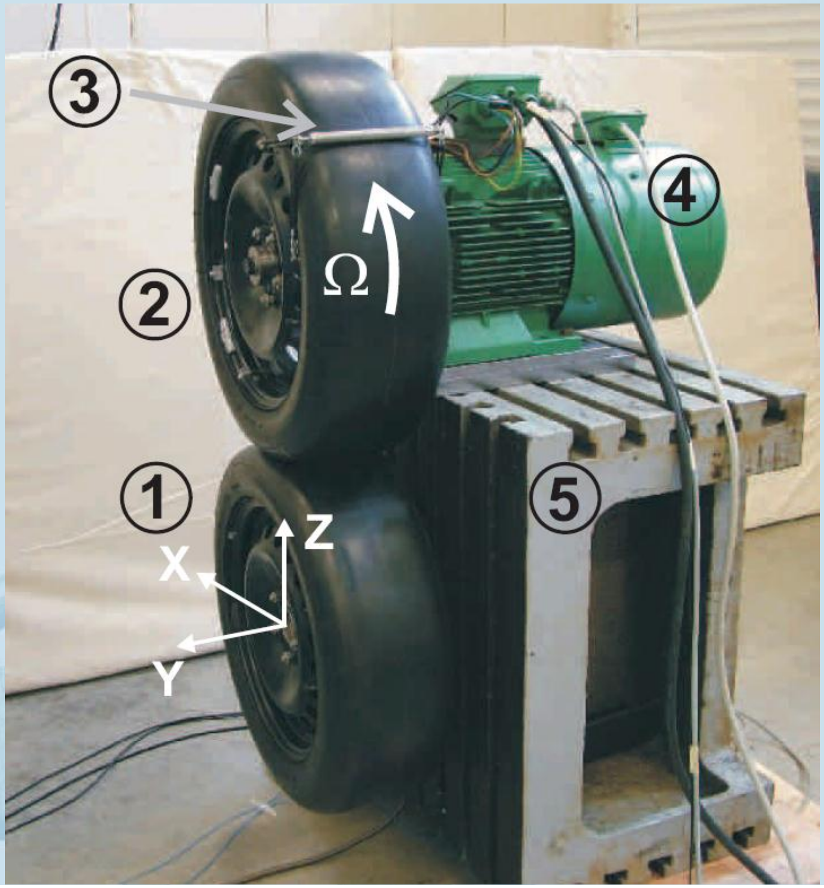
226 Hz

227 Hz

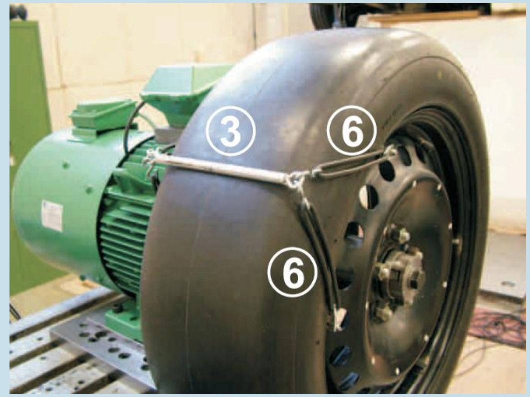
Tyre-on-tyre test setup

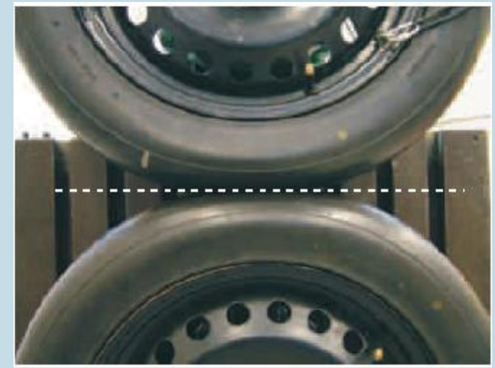
- 2 identical tyres

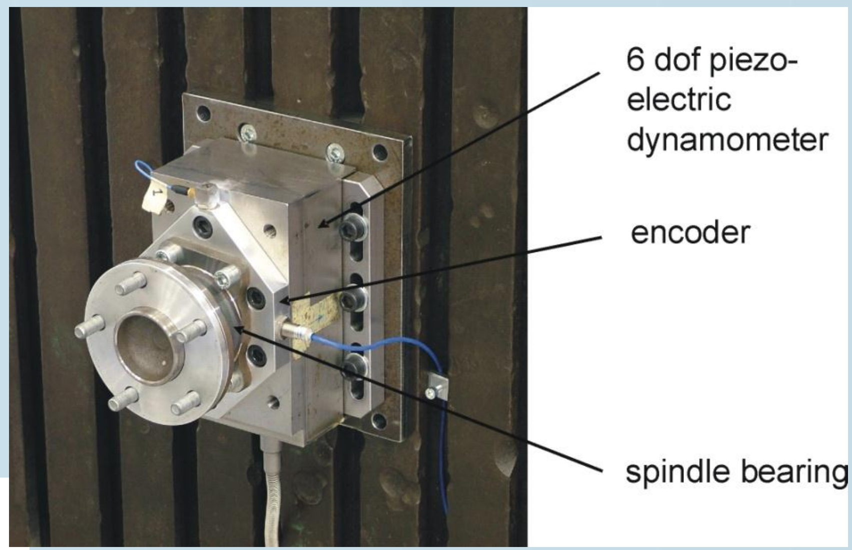




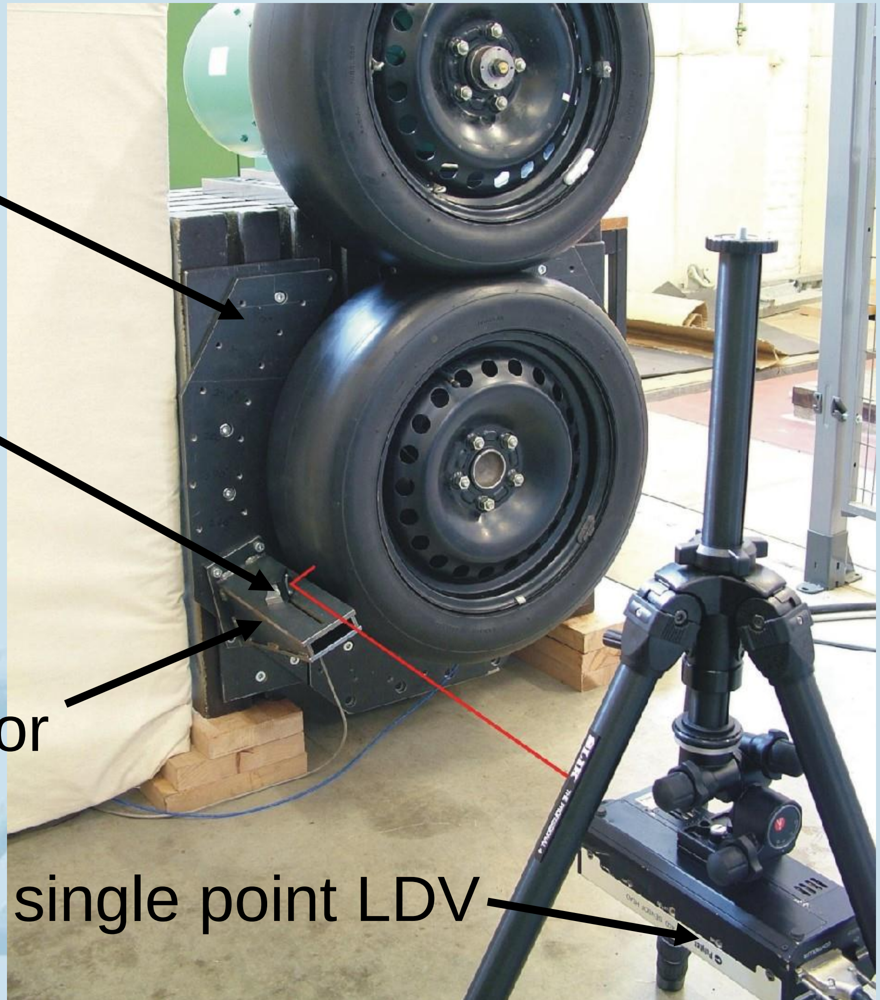
1: test tyre
2: driven tyre
3: cleat
4: electric motor
5: cast iron block
6: flexible cleat fixation

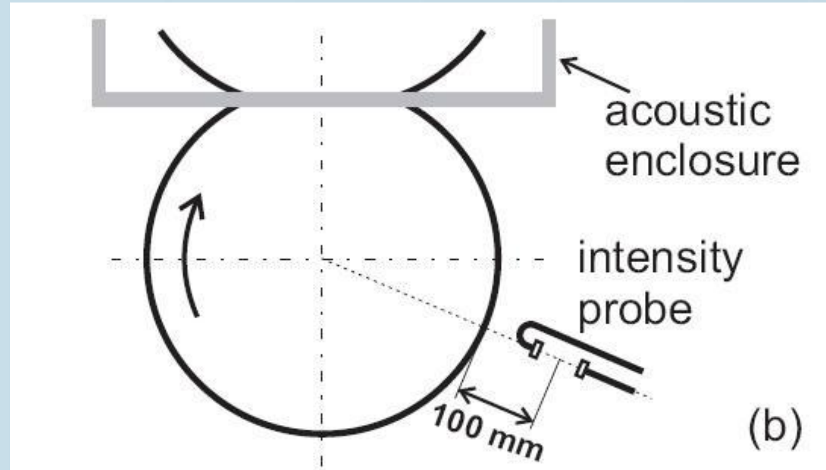


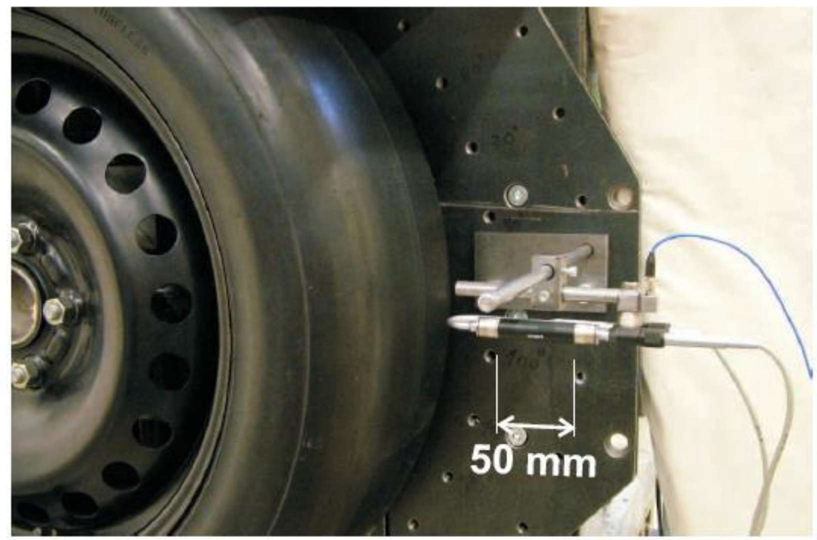




Tyre-on-tyre test setup

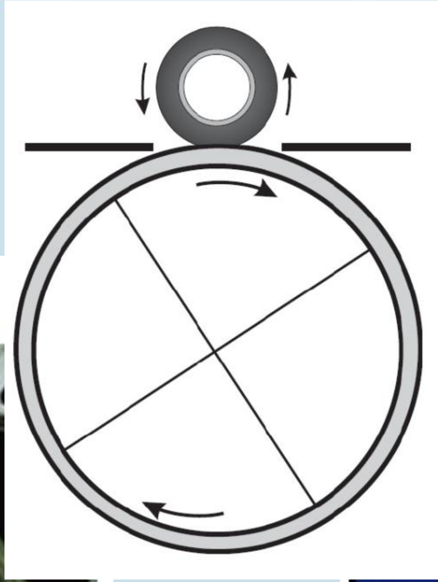


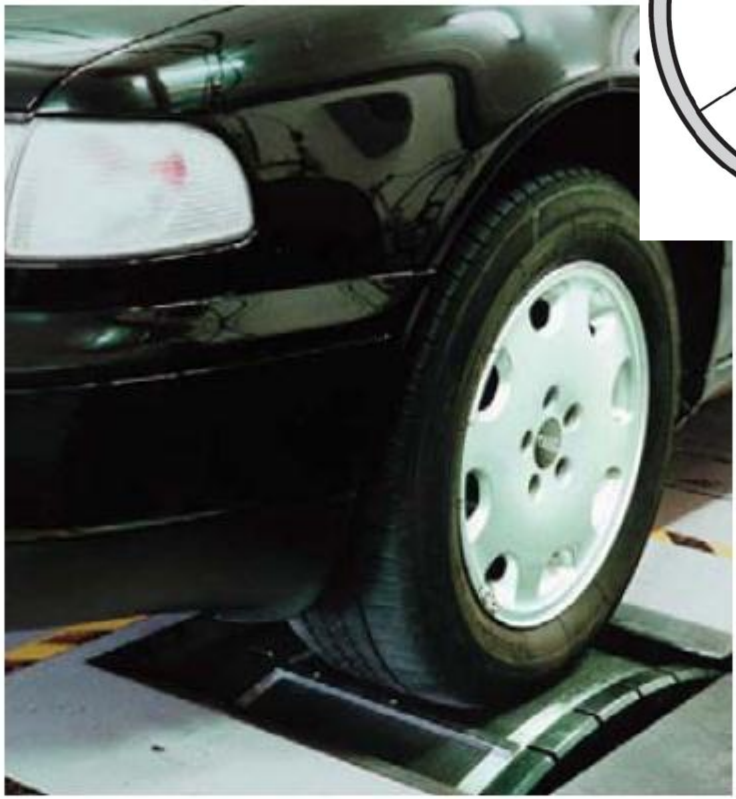




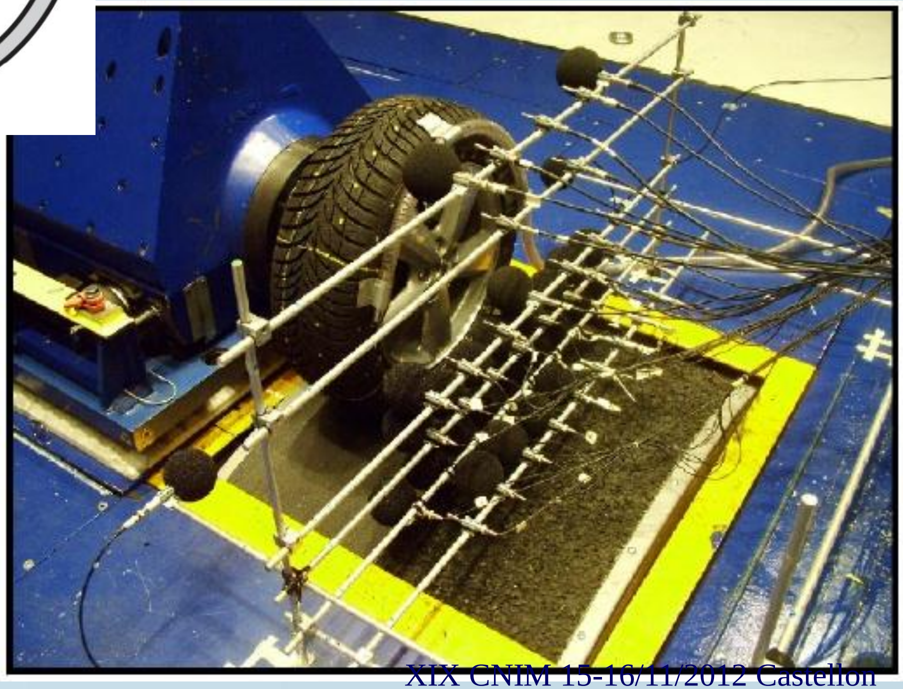
Measurements relative to FIXED REFERENCE FRAME

Test Methods: Drum Tests



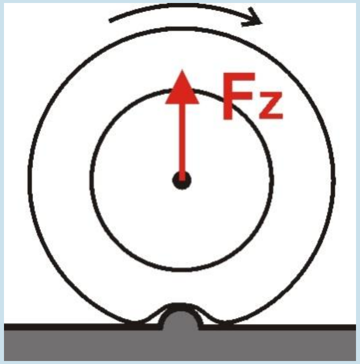


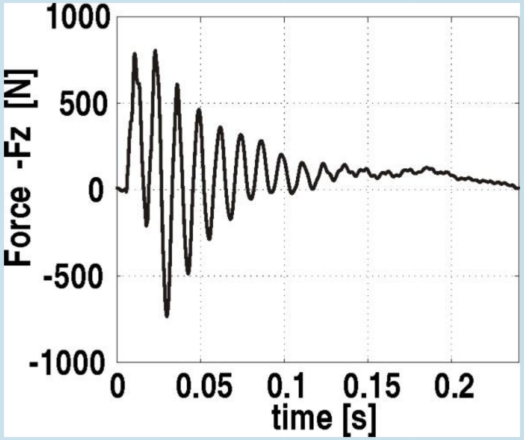
Rolling rig for mechanical and acoustic comfort tests

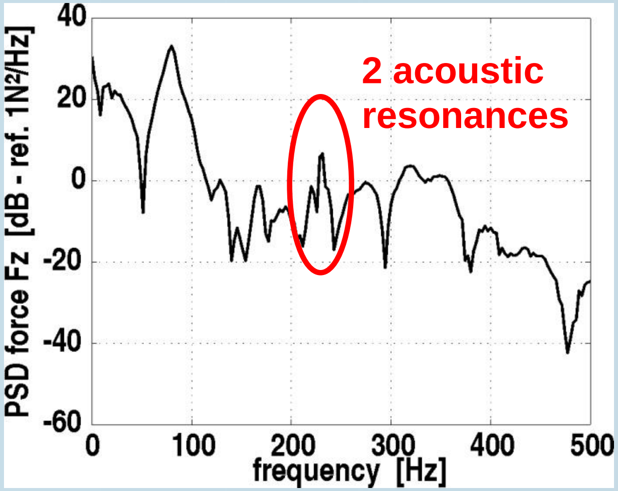


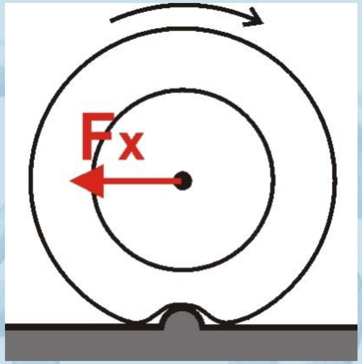
Dynamic spindle forces

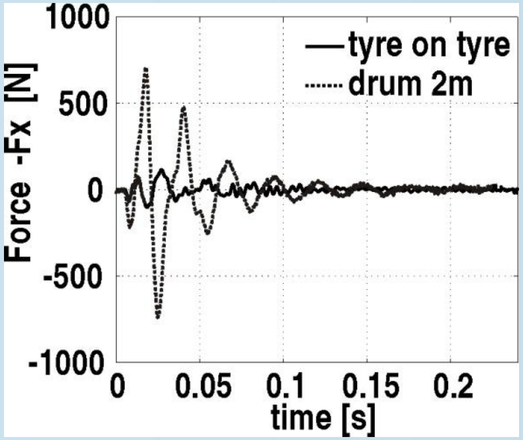
- 5 mm semi-circular cleat; 28 km/h; 2.2 bar

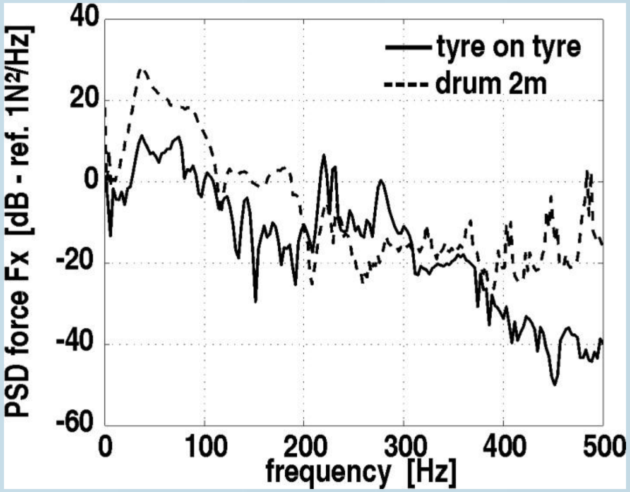




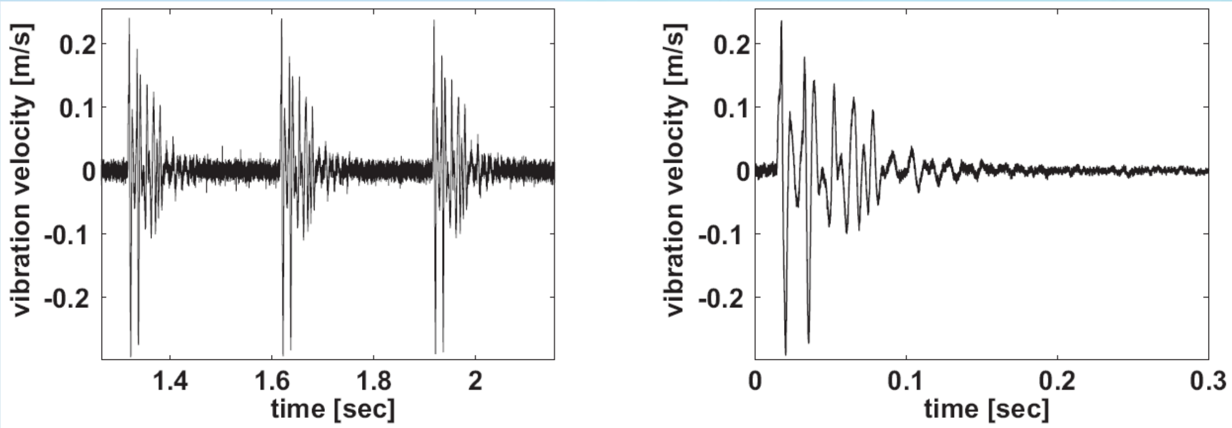




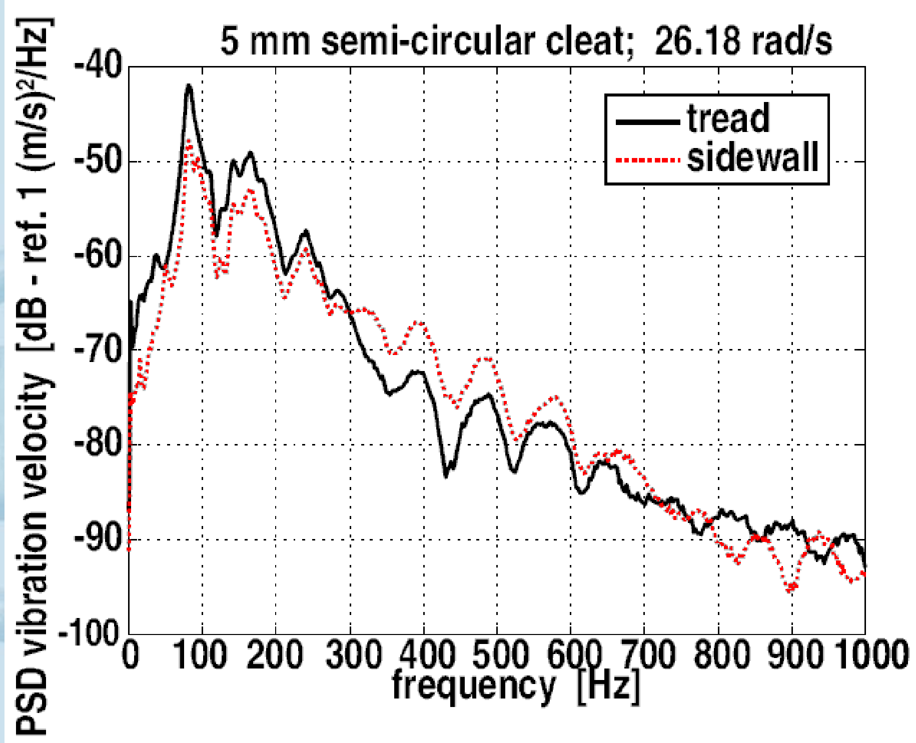


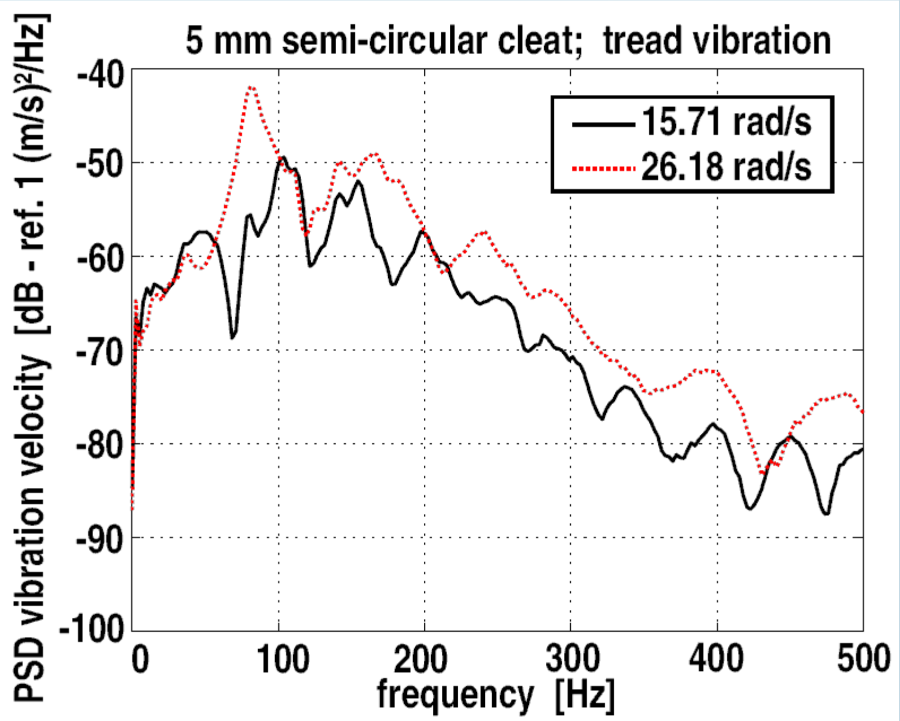


Rolling tyre vibrations



time-averaged vibration signal

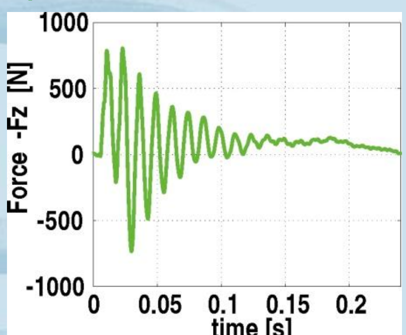


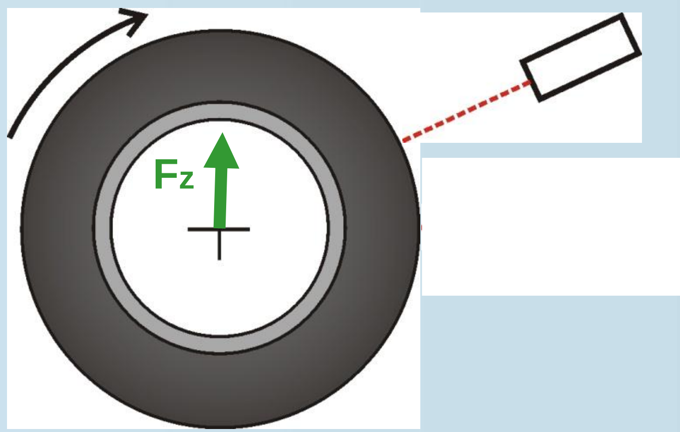


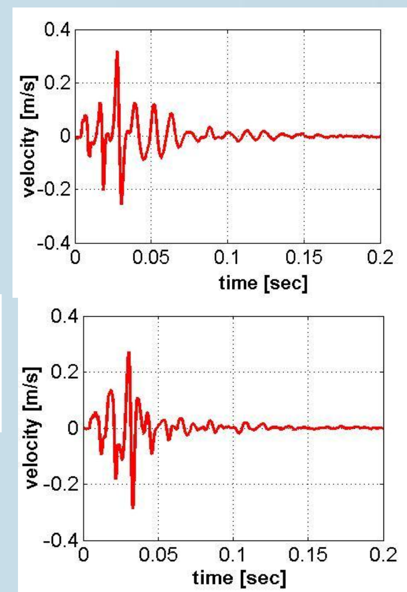
Operational Modal Analysis

- Excitation force of rolling tyre is difficult to measure.
- **Output-only method ➔** Polymax method applied to auto- and cross-power spectral density functions
- ***maintain phase relation*** between different response measurements:

time reference
(synchronization relative to excitation)

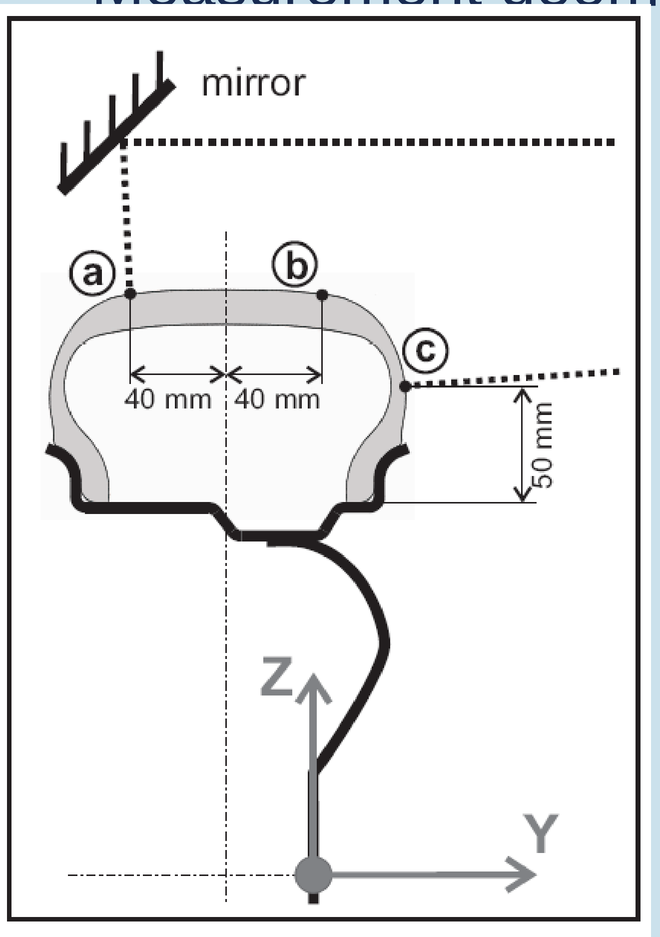


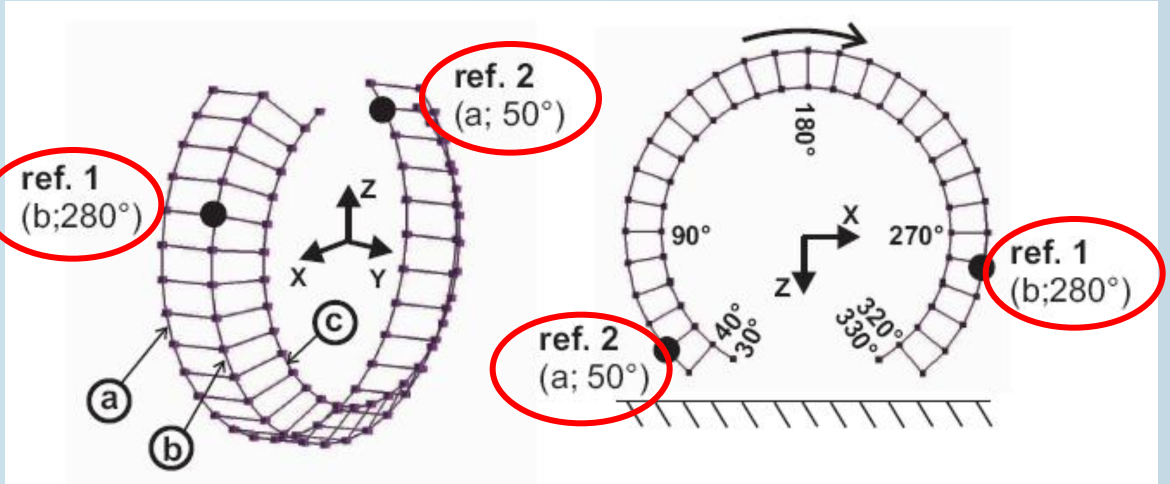




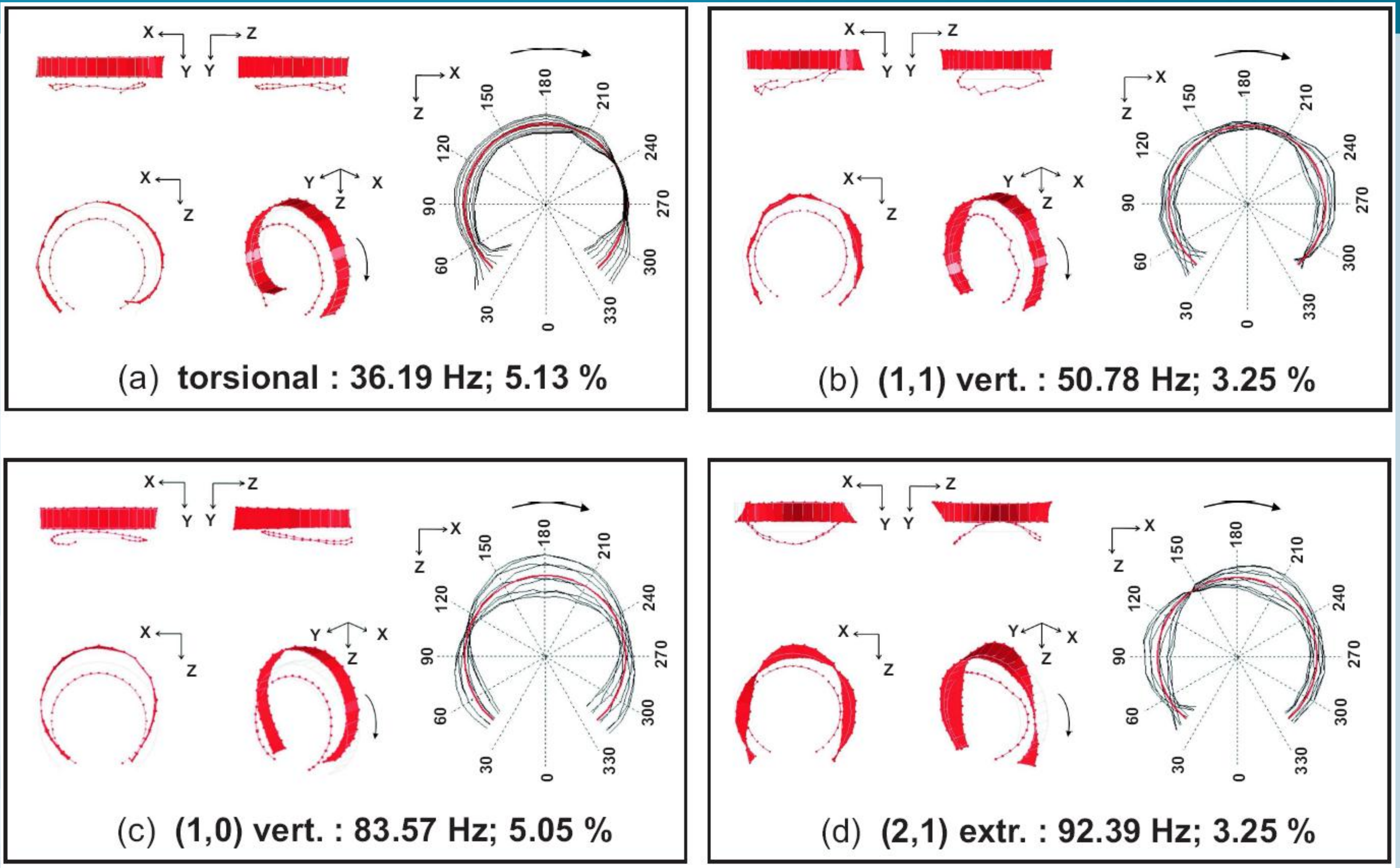
Operational Modal Analysis

- Measurement geometry



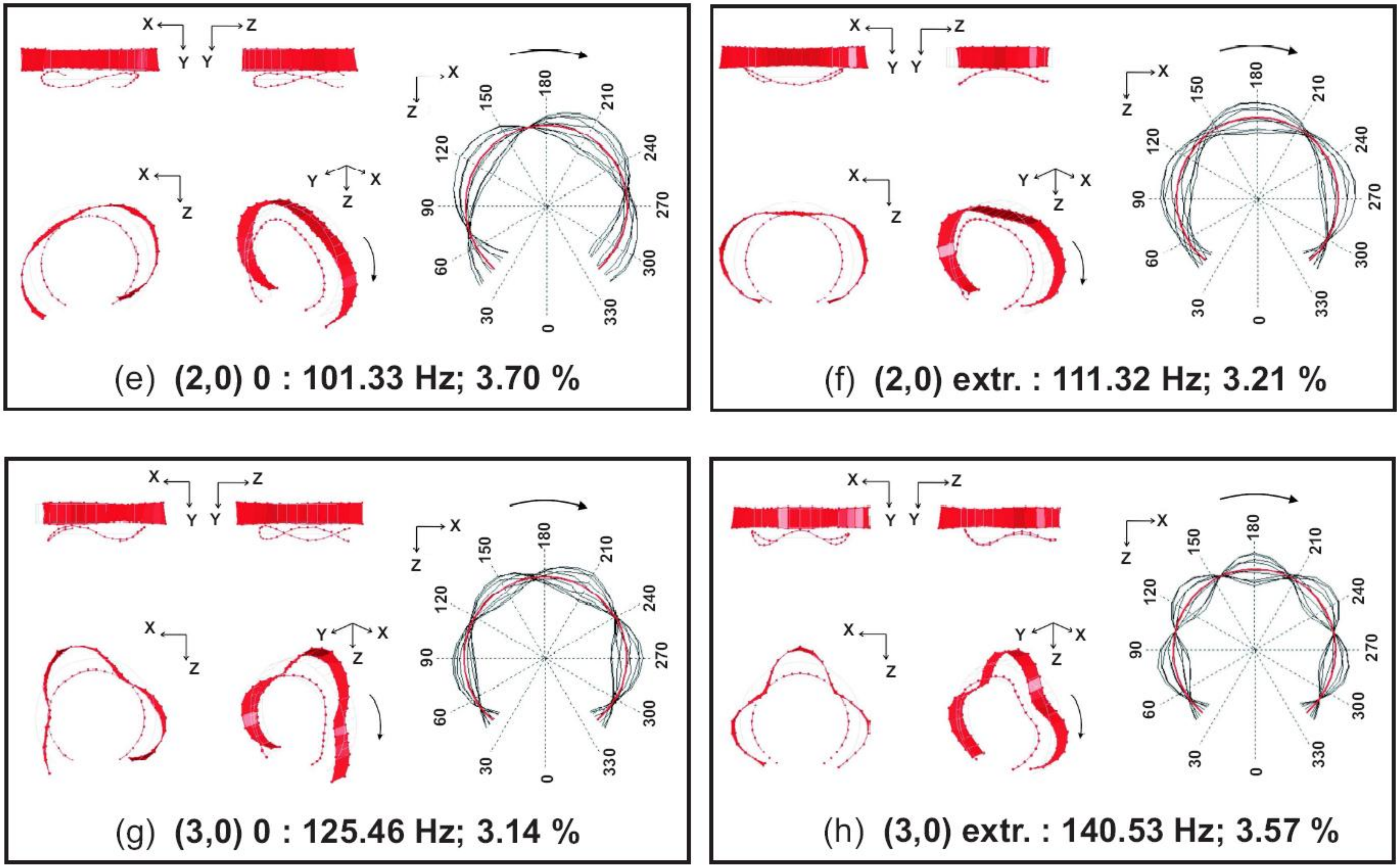


Rolling tyre modal parameters (26.2rad/s)



modes relative to FIXED ref. system

Rolling tyre modal parameters (26.2rad/s)



(e) (2,0) 0 : 101.33 Hz; 3.70 %

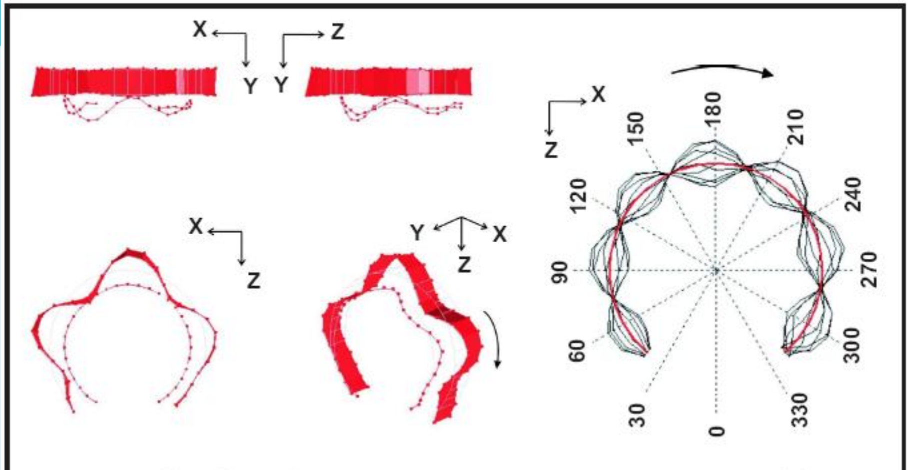
(f) (2,0) extr. : 111.32 Hz; 3.21 %

(g) (3,0) 0 : 125.46 Hz; 3.14 %

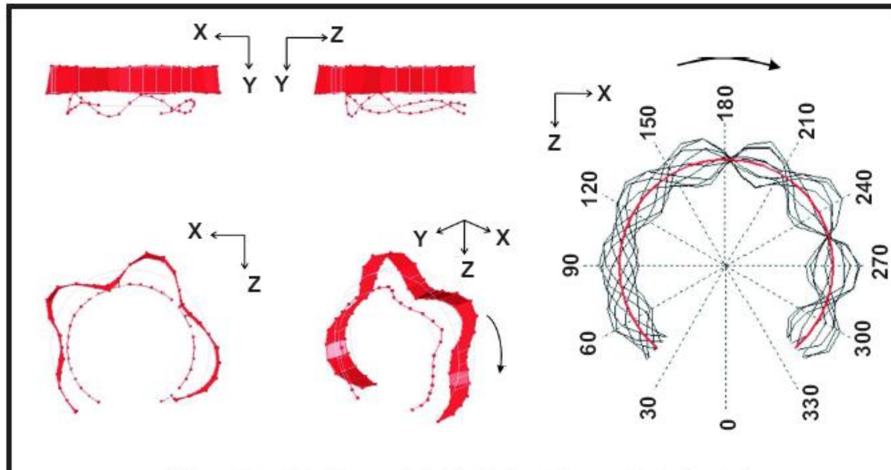
(h) (3,0) extr. : 140.53 Hz; 3.57 %

modes relative to FIXED ref. system

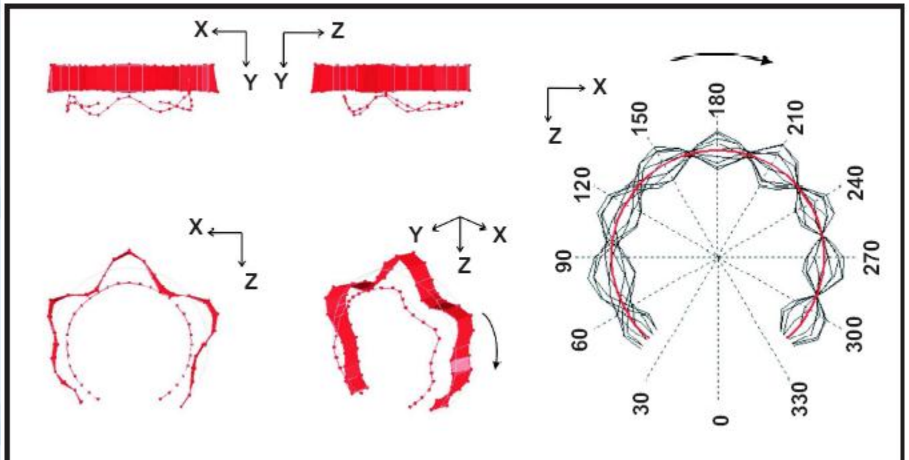
Rolling tyre modal parameters (26.2rad/s)



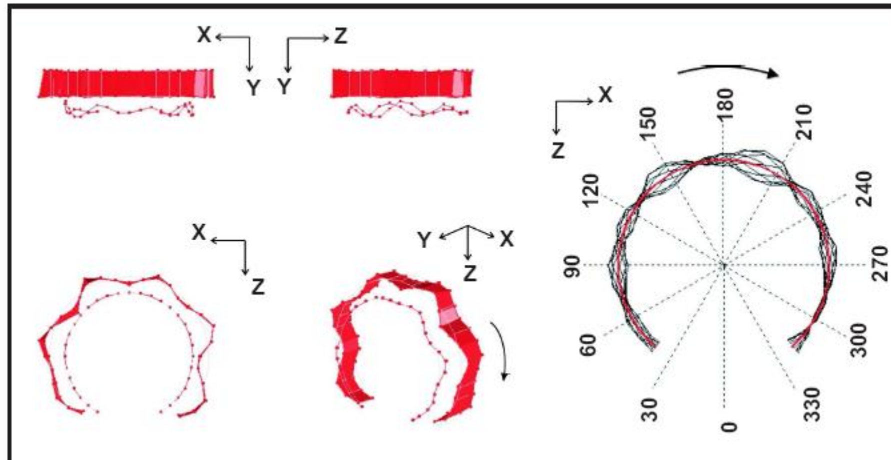
(i) **(4,0) extr. : 167.07 Hz; 3.47 %**



(j) **(5,0) 0 : 181.96 Hz; 2.51 %**



(k) **(5,0) extr. : 196.29 Hz; 2.63 %**

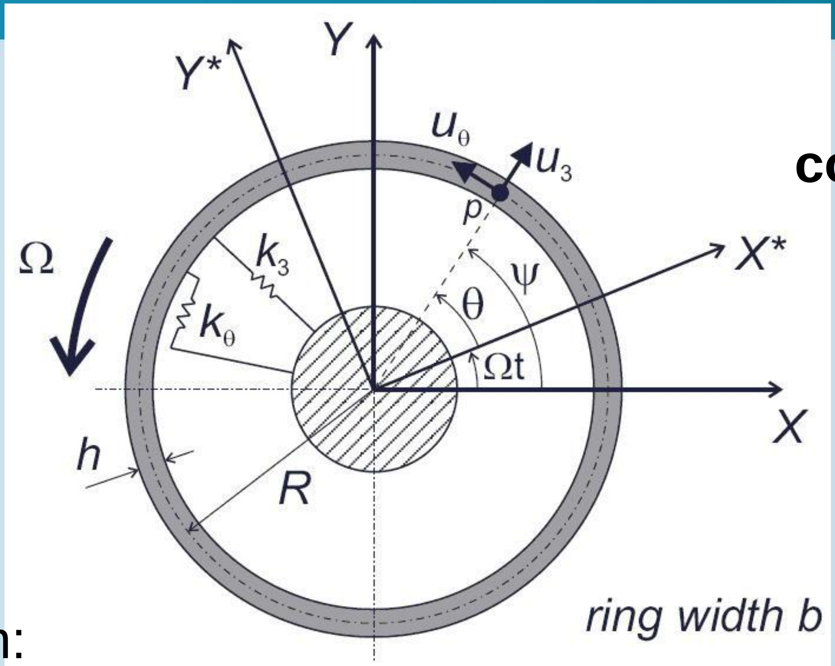


(l) **1st ac. hor. : 220.94 Hz; 1.21 %**

modes relative to FIXED ref. system

Rotating flexible ring

$$\psi = \theta + \Omega t$$



co-rotating ref. system

fixed ref. system

Coriolis acceleration terms

Equations of motion:

$$\frac{D}{R^4}\left(\frac{\partial^3 u_3}{\partial\theta^3} - \frac{\partial^2 u_\theta}{\partial\theta^2}\right) - \frac{K}{R^2}\left(\frac{\partial u_3}{\partial\theta} + \frac{\partial^2 u_\theta}{\partial\theta^2}\right) + \frac{\sigma^r_{\theta\theta}h}{R^2}\left(u_\theta - 2\frac{\partial u_3}{\partial\theta} - \frac{\partial^2 u_\theta}{\partial\theta^2}\right)$$

$$+k_\theta u_\theta + \rho h\left(\frac{\partial^2 u_\theta}{\partial t^2} + 2\Omega\frac{\partial u_3}{\partial t} - \Omega^2 u_\theta\right) = q_\theta$$

$$\frac{D}{R^4}\left(\frac{\partial^4 u_3}{\partial\theta^4} - \frac{\partial^3 u_\theta}{\partial\theta^3}\right) + \frac{K}{R^2}\left(\frac{\partial u_\theta}{\partial\theta} + u_3\right) + \frac{\sigma^r_{\theta\theta}h}{R^2}\left(R + u_3 + 2\frac{\partial u_\theta}{\partial\theta} - \frac{\partial^2 u_3}{\partial\theta^2}\right)$$

$$+k_3 u_3 + \rho h\left(\frac{\partial^2 u_3}{\partial t^2} - 2\Omega\frac{\partial u_\theta}{\partial t} - \Omega^2 u_3 - R\Omega^2\right) = q_3$$

Rotating ring in co-rotating ref. system

$$\omega_{n1} = \frac{2n}{n^2+1}\Omega + \sqrt{\omega_{fn}^2 + \frac{n^2(n^2-1)^2}{(n^2+1)^2}\Omega^2} \qquad > 0$$

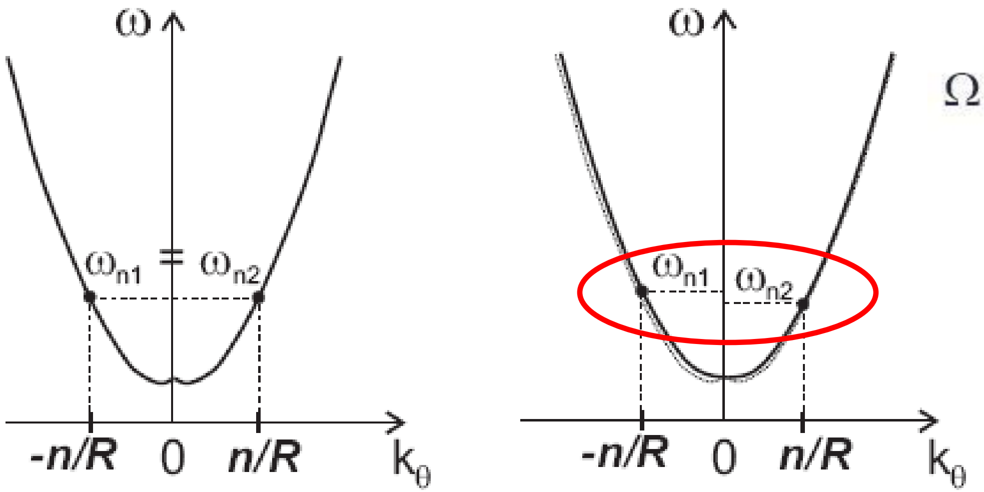
$$\omega_{n2} = \frac{2n}{n^2+1}\Omega - \sqrt{\omega_{fn}^2 + \frac{n^2(n^2-1)^2}{(n^2+1)^2}\Omega^2} \qquad < 0$$

natural frequencies
(n = circumferential mode number)

$$u_3(\theta, t) = A_n \; e^{j(n\theta + \omega_n t)}$$

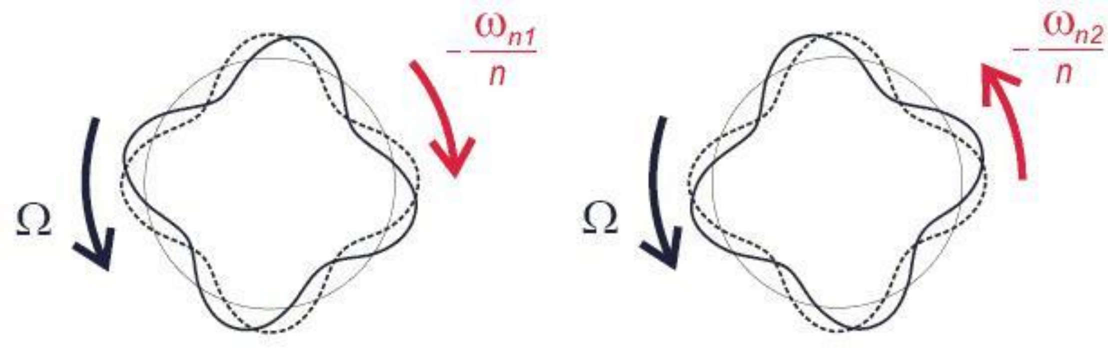
$$u_\theta(\theta, t) = B_n \; e^{j(n\theta + \omega_n t)}$$

mode shapes



(a) 0 rad/s

(b) Ω rad/s; co-rotating



(a) mode at ω_{n1}

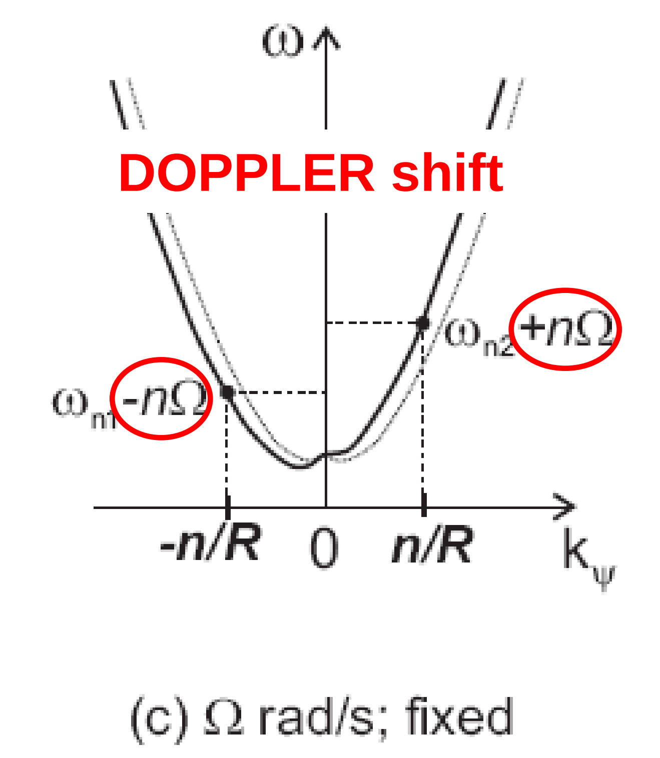
(b) mode at ω_{n2}

backward travelling wave

forward travelling wave

BIFURCATION effect

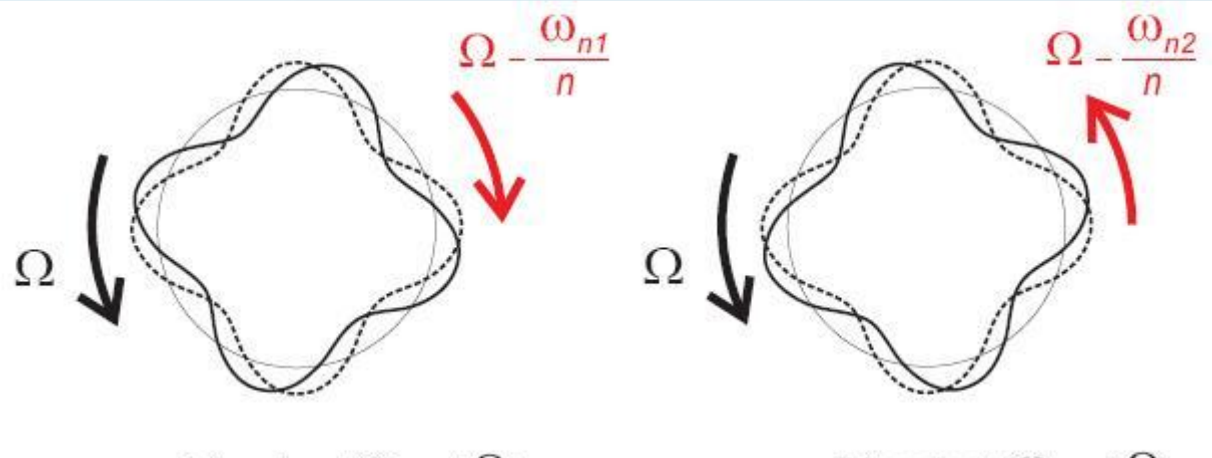
Rotating ring in fixed ref. system



(c) Ω rad/s; fixed

mode shapes

$$u_3(\psi,t) = \sin(n\psi + (\omega_{nk} - n\Omega)t)$$
$$u_\theta(\psi,t) = -C_{nk}\cos(n\psi + (\omega_{nk} - n\Omega)t)$$



(a) mode at $(\omega_{n1} - n\Omega)$ (b) mode at $(\omega_{n2} - n\Omega)$

backward travelling wave

forward travelling wave

Rolling tyre modal parameters

- **ANALYTICAL ROTATING RING**: a forward and backward travelling wave cannot interfere at a single natural frequency to form a standing wave pattern

  - at resonance: travelling wave deformation pattern

- **EXPERIMENT**: **standing** wave patterns with respect to the fixed reference frame

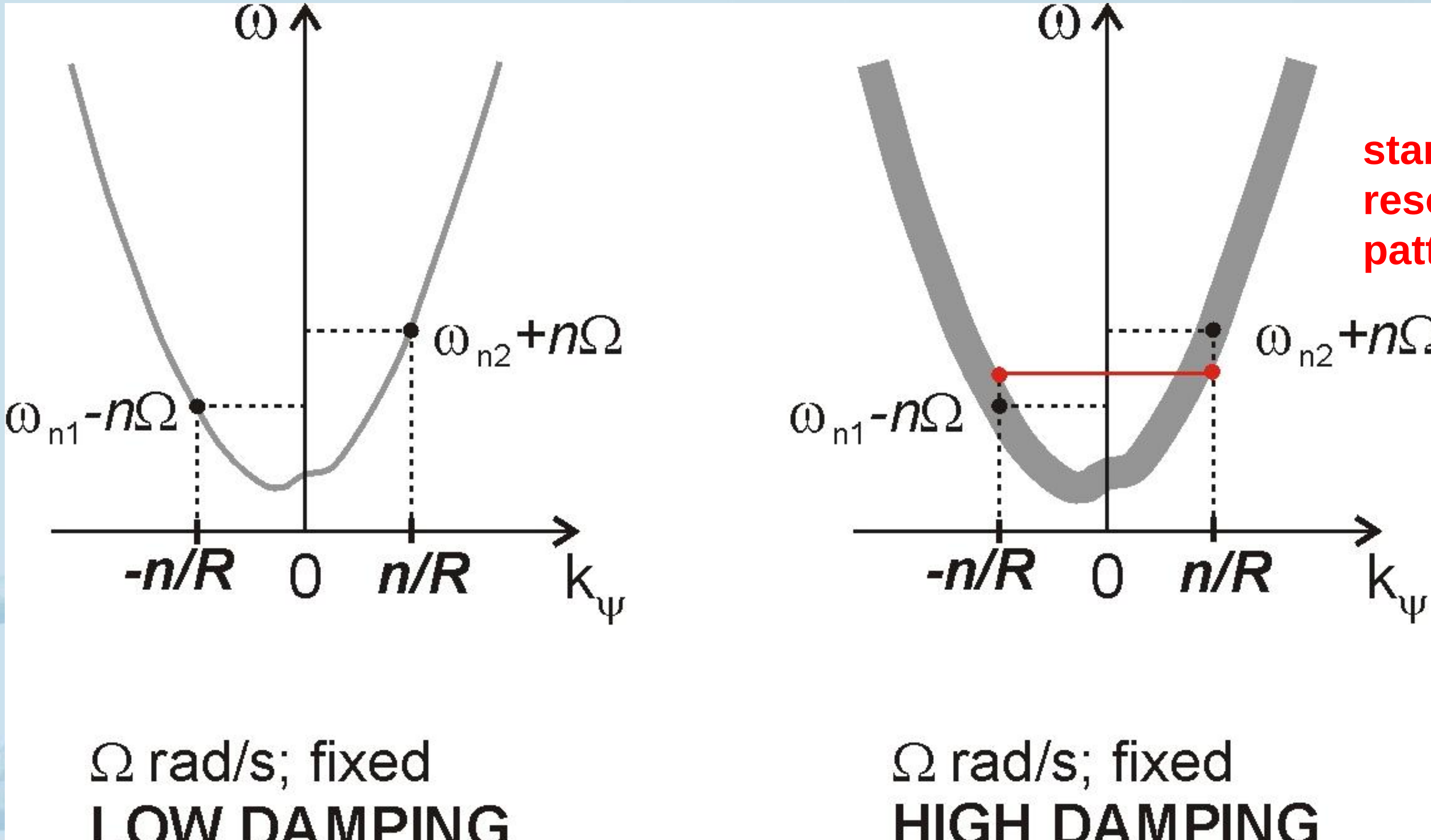
  - Influence of:

    ➔ **damping**

    ➔ **disturbed geometrical symmetry**

  on rolling tyre dynamic behaviour is not yet fully understood.

Influence of damping on dispersion curve



standing wave resonance pattern

Influence of rolling speed

	Frequency [Hz] / ξ [%]		
mode	*0 rad/s*	*15.71 rad/s*	*26.18 rad/s*
torsional	**46.98** / 3.95	**36.76** / 3.29	**36.19** / 5.13
(1,1) hor.	**49.06** / 1.38	**45.05** / 2.46	*
(1,1) vert.	**58.58** / 2.26	**51.23** / 1.99	**50.78** / 3.25
(1,0) hor.	**111.96** / 3.97	*	*
(1,0) vert.	**95.94** / 3.78	**79.42** / 2.40	**83.57** / 5.05
(2,0) 0	**117.34** / 3.24	**101.94** / 4.05	**101.33** / 3.70
(2,0) extr.	**124.03** /2.94	**113.13** / 3.37	**111.32** /3.21
(2,1) 0	**100.15** / 2.72	*	*
(2,1) extr.	**85.22** / 2.36	**88.51** /2.41	**92.39** / 3.25
(3,0) 0	**141.22** / 3.19	**127.61** / 2.49	**125.46** / 3.14
(3,0) extr.	**155.90** / 2.71	**141.27** / 3.11	**140.53** / 3.57
(3,1) 0	*	*	*
(3,1) extr.	**167.41** / 2.59	*	*
(4,0) 0	**171.18** / 2.68	**155.98** / 3.33	*
(4,0) extr.	**187.14** / 2.49	**169.58** / 1.95	**167.07** / 3.47
(4,1) 0	*	*	*
(4,1) extr.	**227.09** / 2.16	*	*
(5,0) 0	**203.39** / 2.89	**184.10** / 1.77	**181.96** / 2.51
(5,0) extr.	**219.63** / 2.32	**199.46** / 2.84	**196.29** / 2.63
1st acoustic hor.	**218.99** / 0.39	**222.56** / 0.34	**220.94** / 1.21
1st acoustic vert.	**226.23** / 0.31	**228.65** / 1.02	**228.38** / 0.28

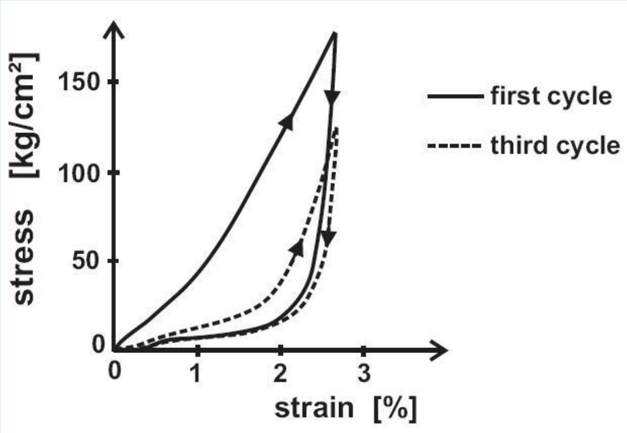
drop in resonance frequency as the tyre starts to roll

(n,0) modes: **-10.8 %**

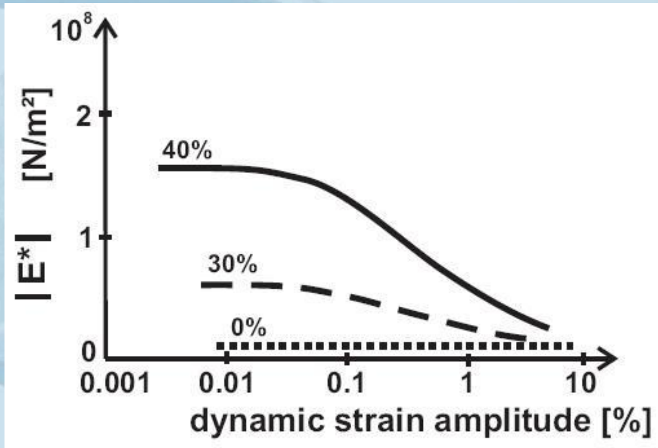
Initial drop in resonance frequencies

- Drop in resonance frequencies as the tyre starts to roll:

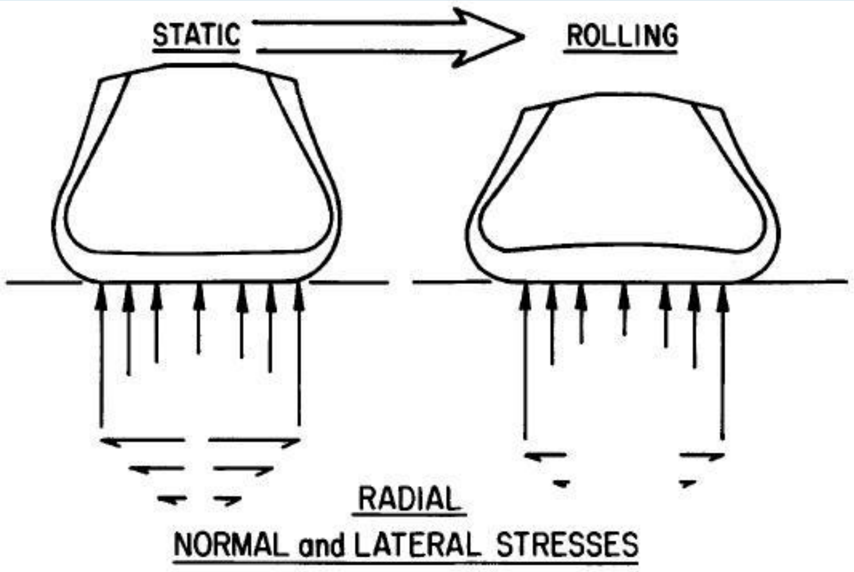
1) **Mullins effect**



2) **Payne effect**

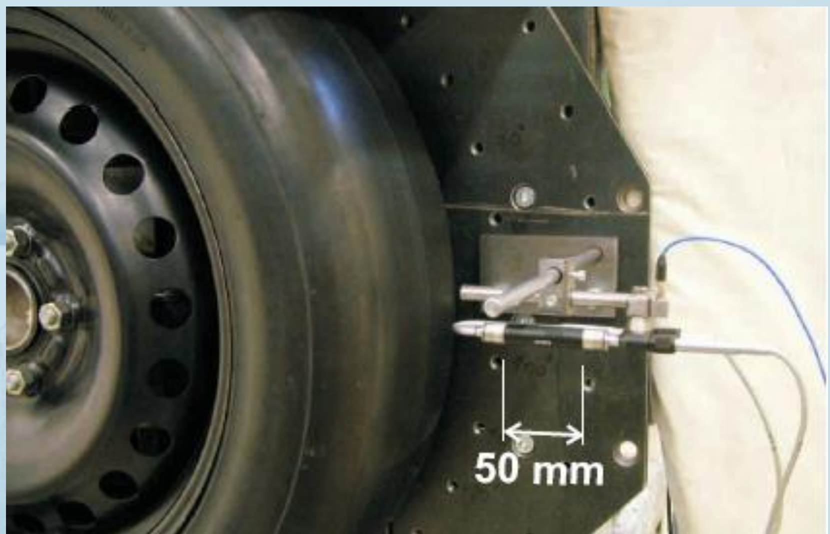


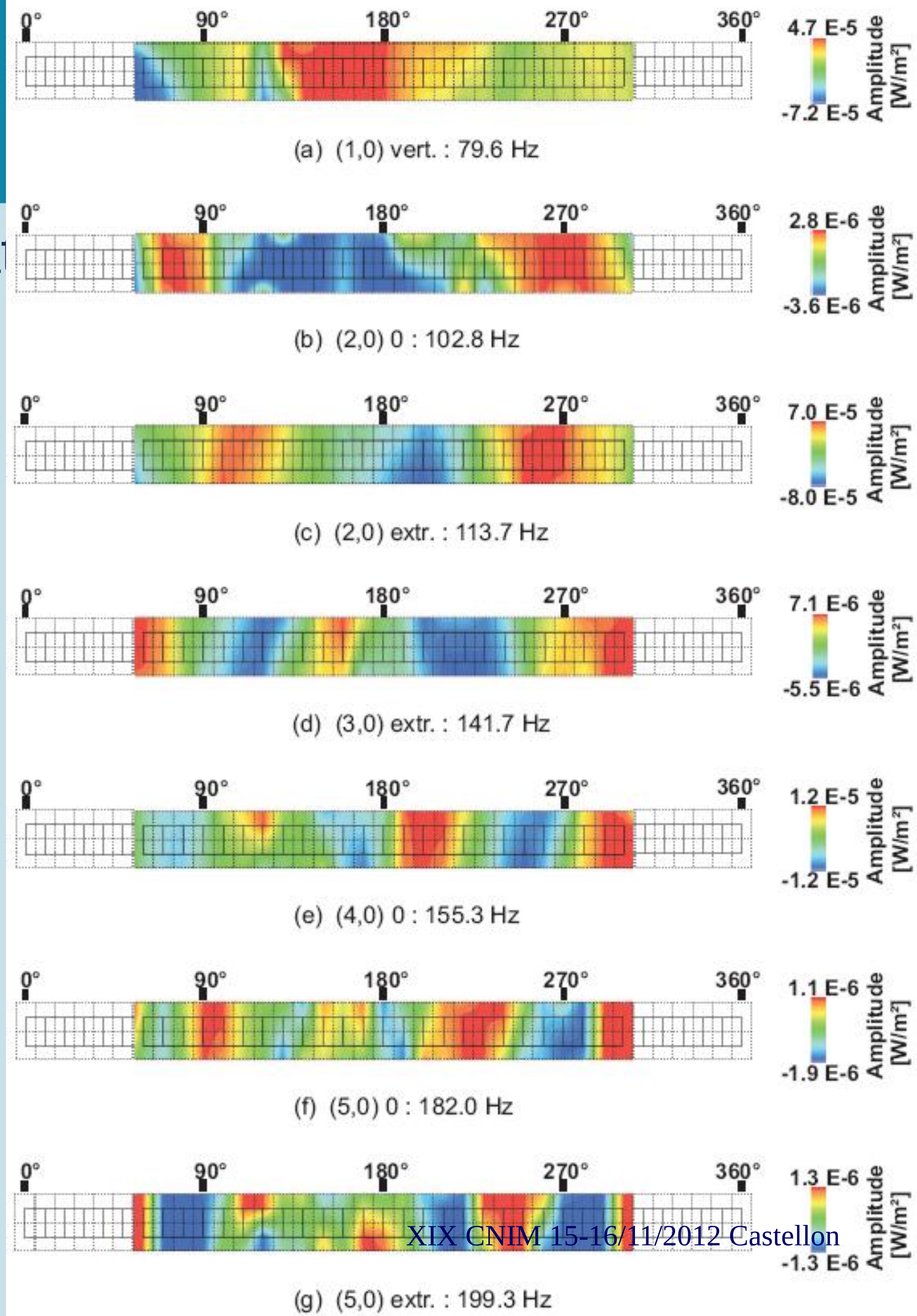
3) **Change in contact pressure distribution**



Acoustic response

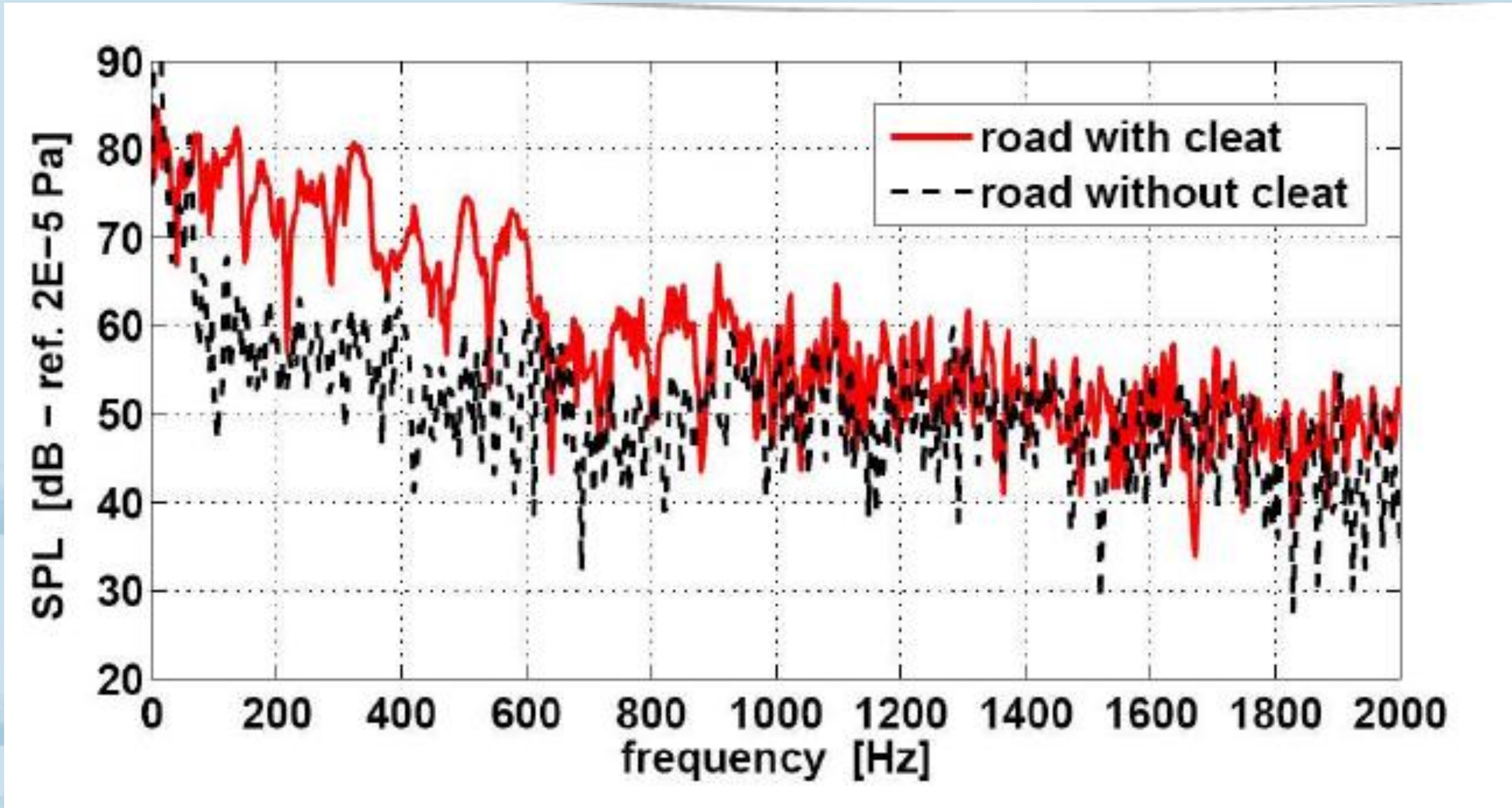
- Sound intensity distribution at the structural resonances
- Treadband causes main structure-borne noise radiation below 300 Hz





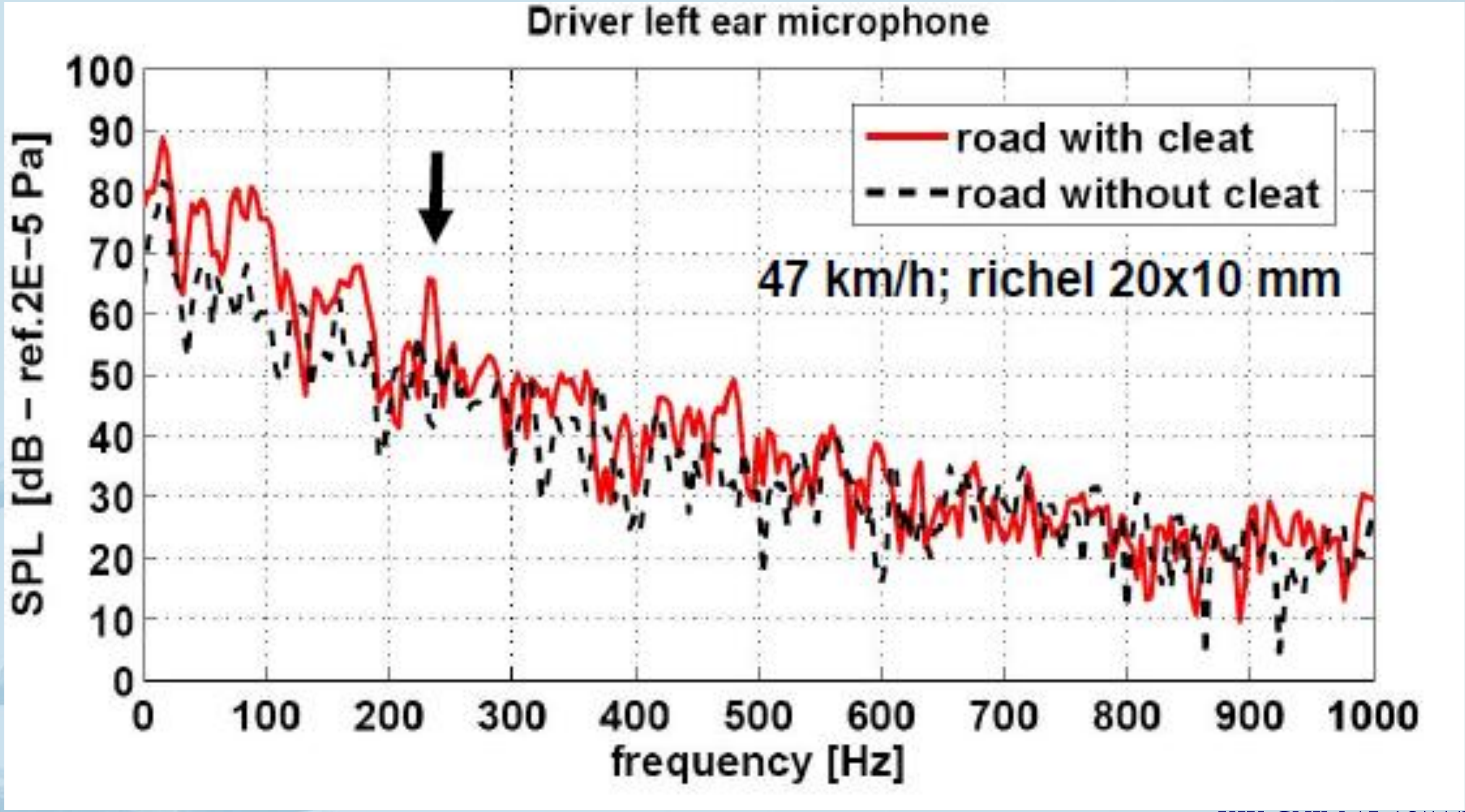
Acoustic response

- Exterior noise (47km/h), cleat 20x10mm



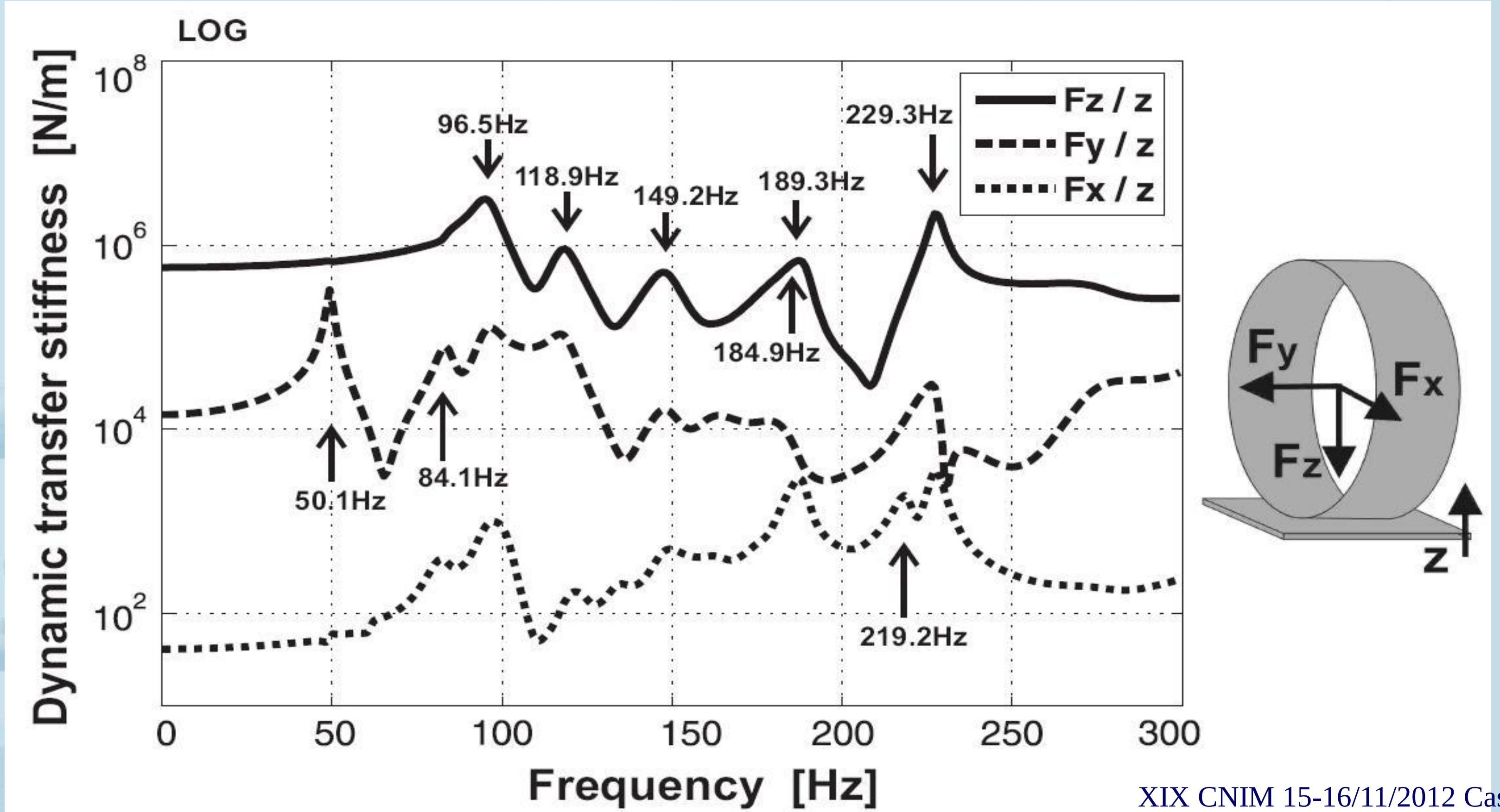
Acoustic response

- Interior noise (47km/h), cleat 20x10mm



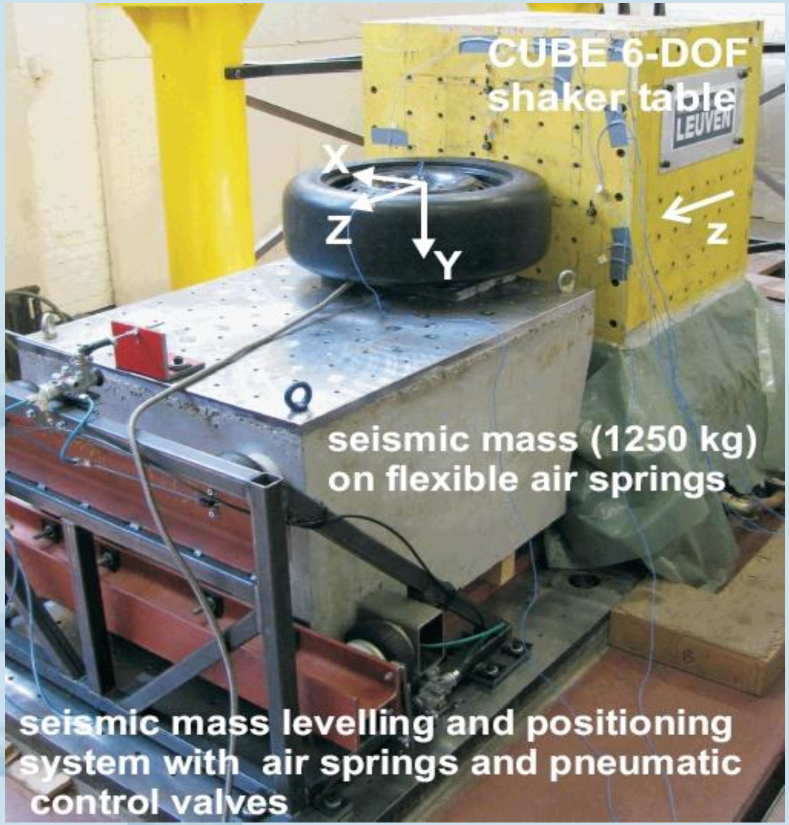
Tyre dynamic transfer stiffness

- Important characteristic for structure-borne interior tyre/road noise.

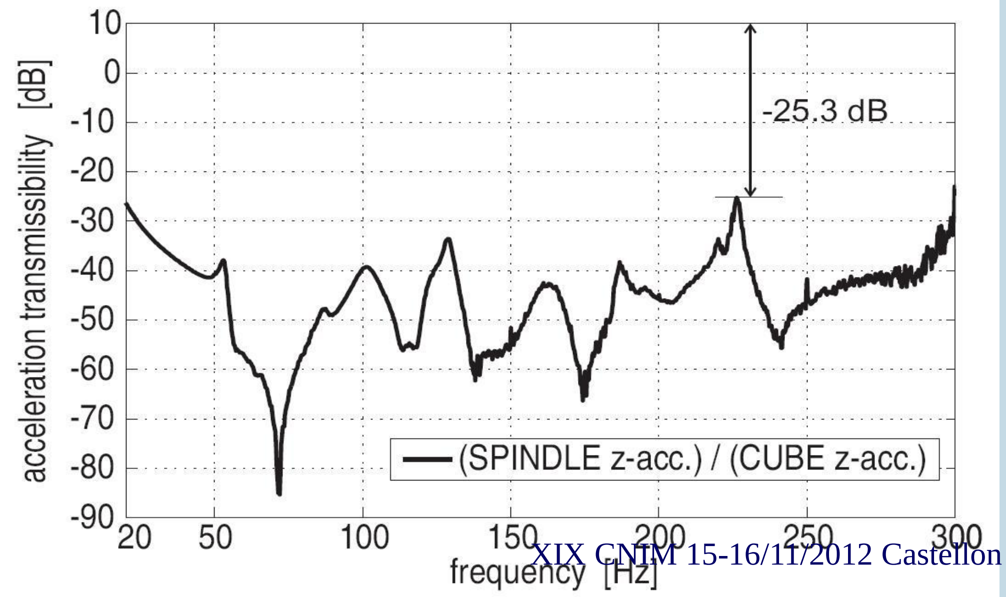


Tyre dynamic transfer stifness

- 205/55R16 tire without tread pattern; steel wheel
- dynamic stiffness of a tire that is **rigidly clamped at the spindle**
- ground vibration isolation: seismic mass (1250 kg) supported by four soft air springs (4 x100 kN/m)

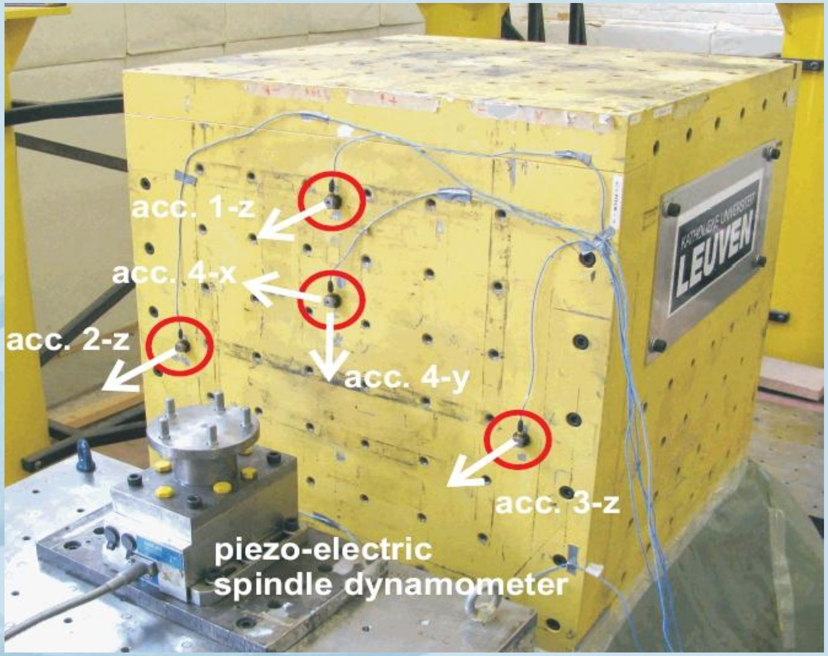


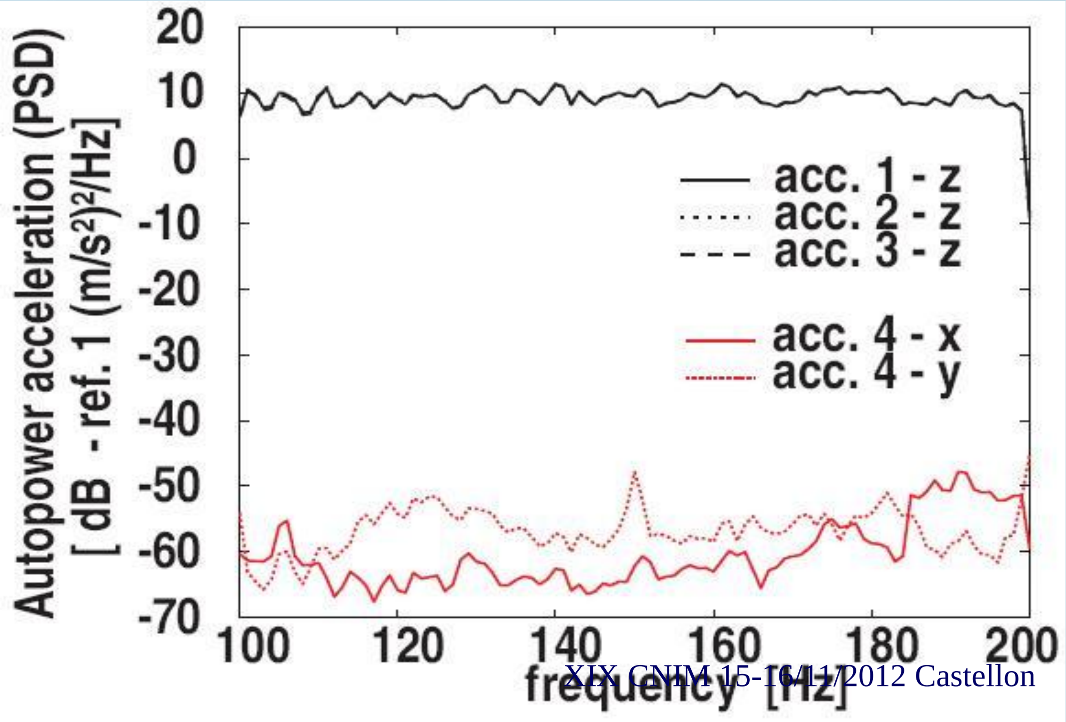
spindle can be considered as rigidly clamped in the frequency range of interest



Test setup layout

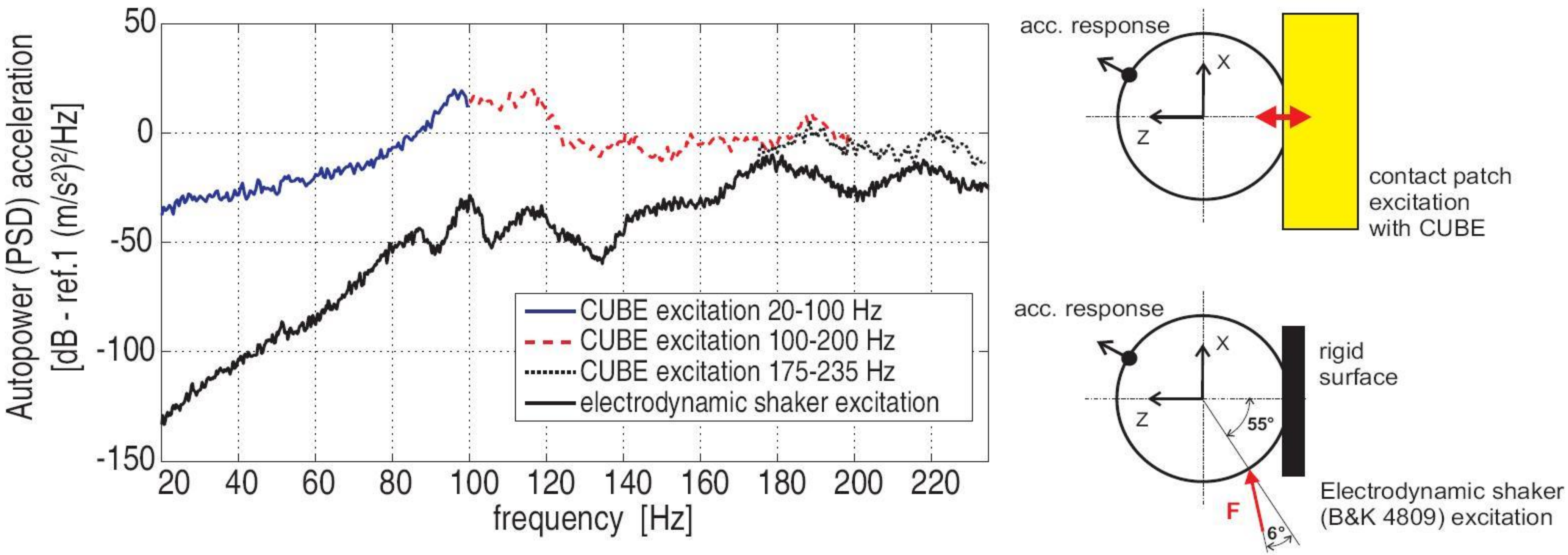
- CUBE 6-DOF hydraulic shaker table provides:
  ➔ static preload (285 kg)
  ➔ purely **uniaxial** dynamic **random** excitation at the tire contact patch
- motion of the hydraulic shaker table is monitored and controlled through a **Time Waveform Replication** (TWR) algorithm



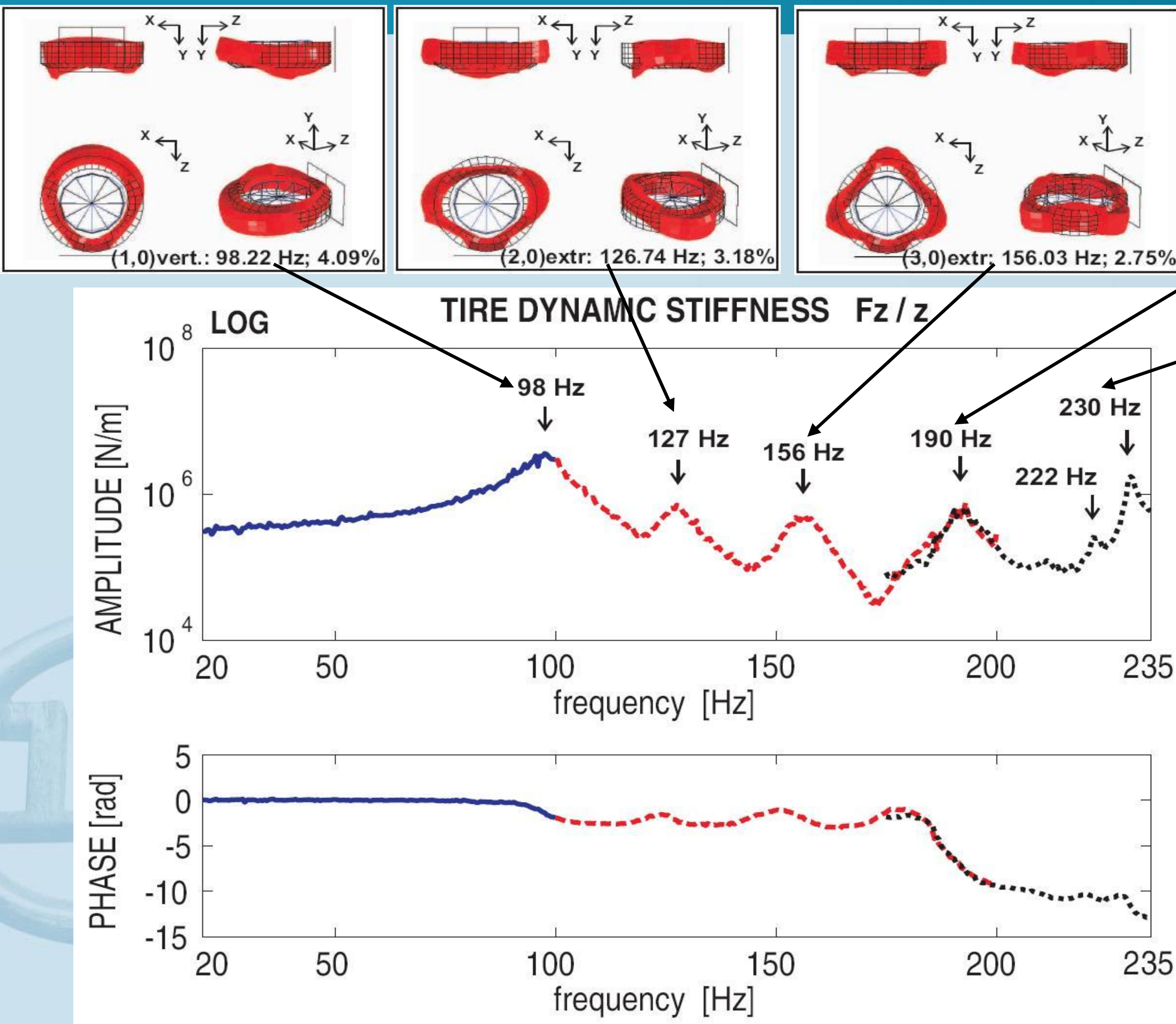


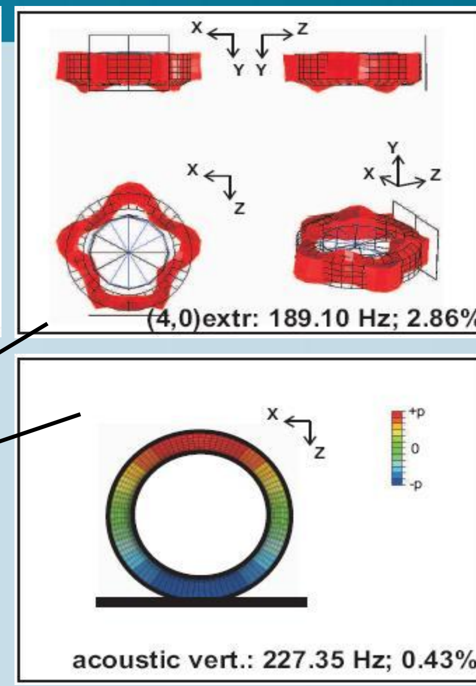
Operational excitation levels

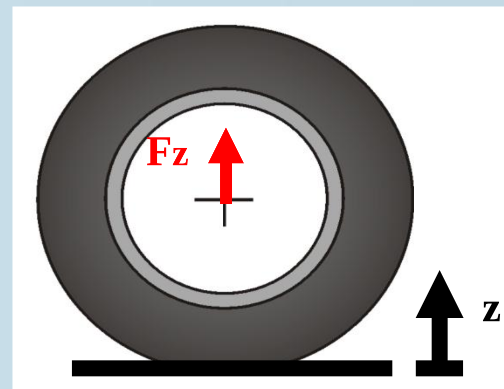
- measurement of the dynamic transfer stiffness is performed in 3 frequency bands
- higher excitation levels can be obtained in the individual frequency bands



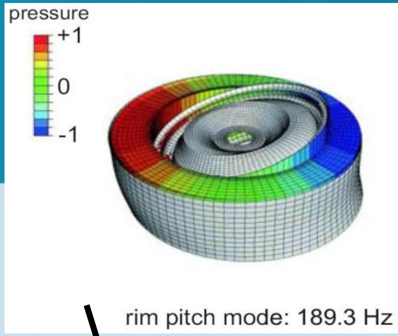
Measured dynamic transfer stiffness

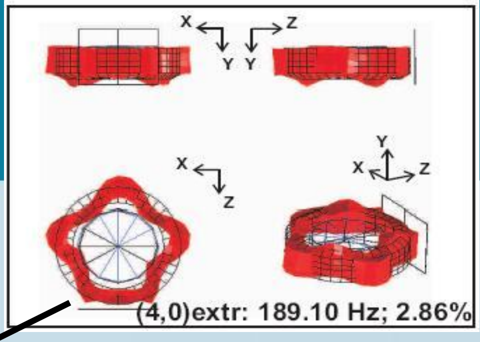


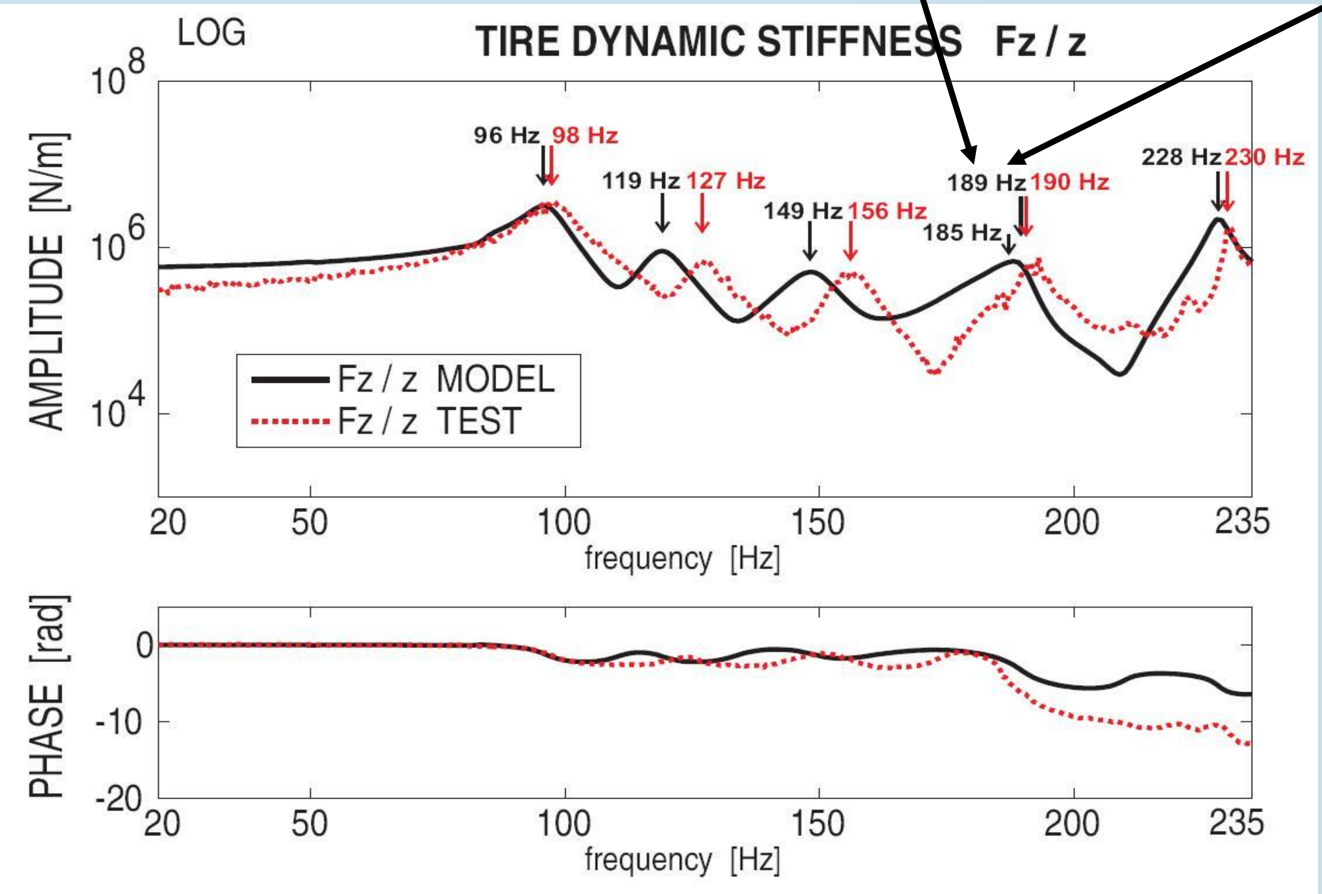


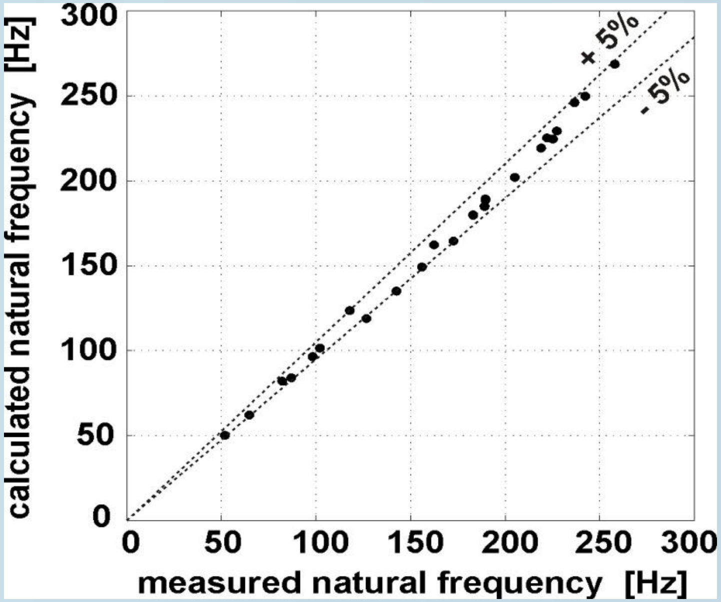


Validation


pressure
+1
0
-1
rim pitch mode: 189.3 Hz

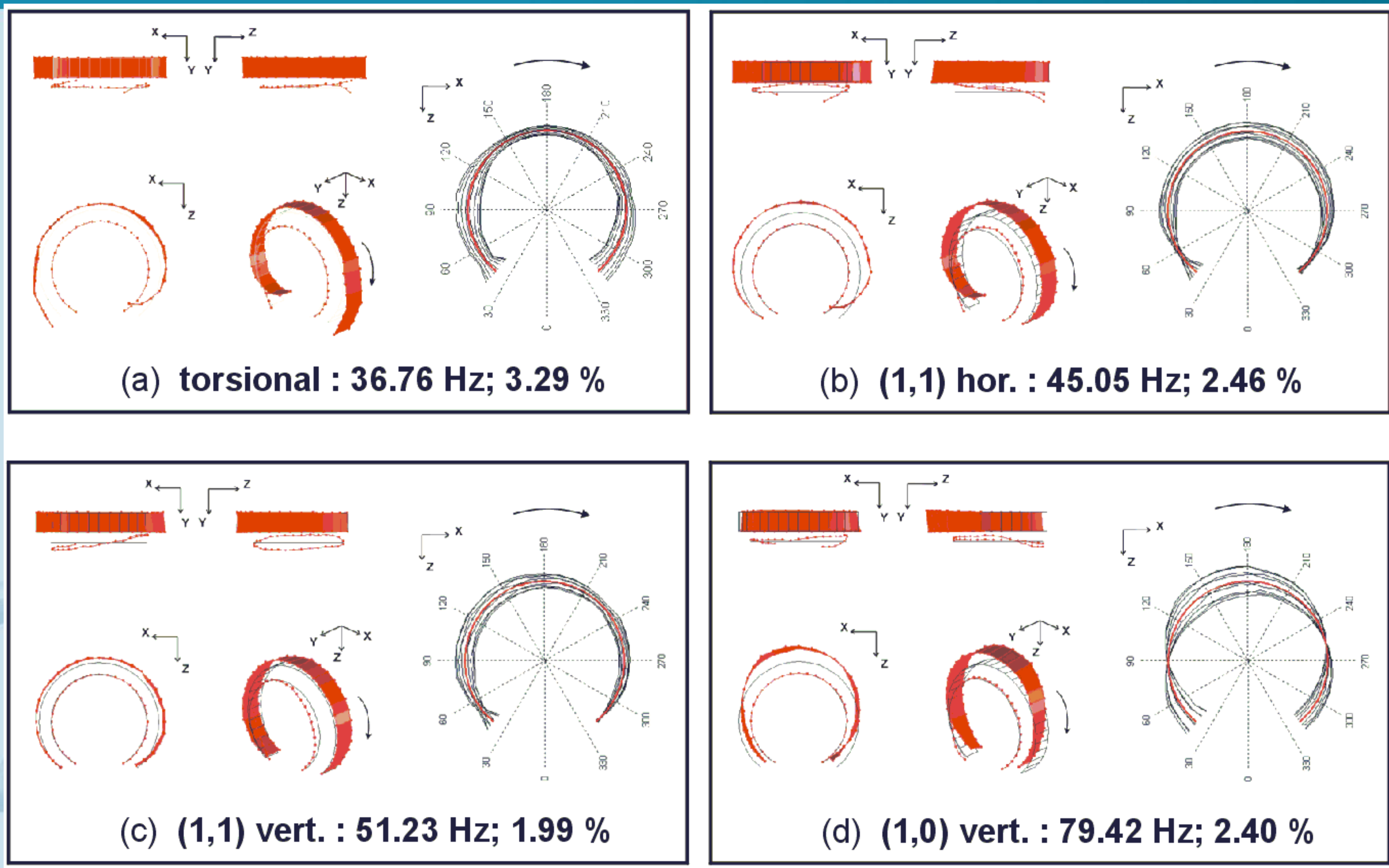

(4,0)extr: 189.10 Hz; 2.86%


LOG
TIRE DYNAMIC STIFFNESS Fz / z
AMPLITUDE [N/m]
96 Hz 98 Hz
119 Hz 127 Hz
149 Hz 156 Hz
185 Hz
189 Hz 190 Hz
228 Hz 230 Hz
Fz / z MODEL
Fz / z TEST
frequency [Hz]
PHASE [rad]
frequency [Hz]


calculated natural frequency [Hz]
+ 5%
- 5%
measured natural frequency [Hz]

Questions ?

Rolling tyre Modal Parameters (15.7 rad/s)



(a) **torsional : 36.76 Hz; 3.29 %**

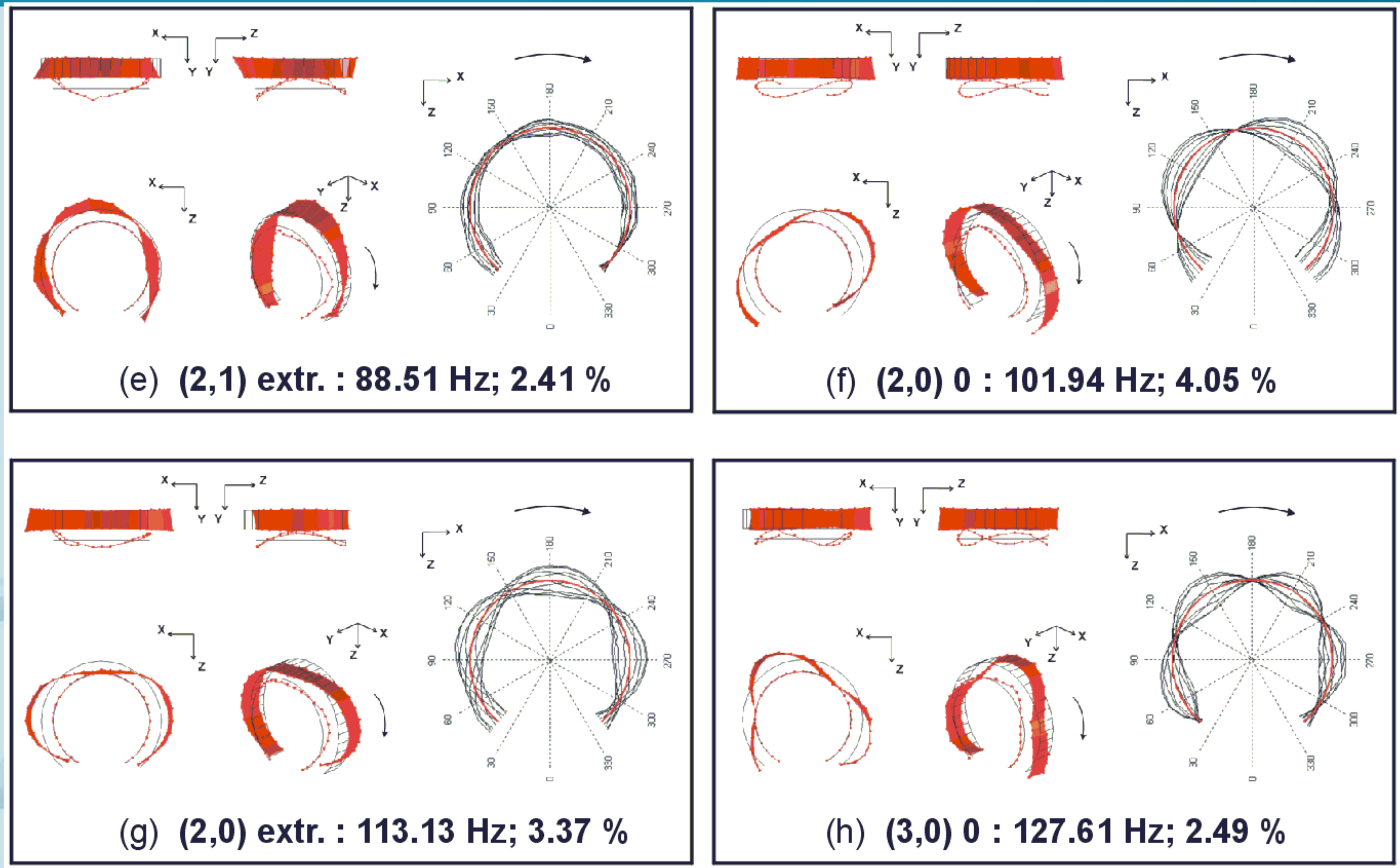
(b) **(1,1) hor. : 45.05 Hz; 2.46 %**

(c) **(1,1) vert. : 51.23 Hz; 1.99 %**

(d) **(1,0) vert. : 79.42 Hz; 2.40 %**

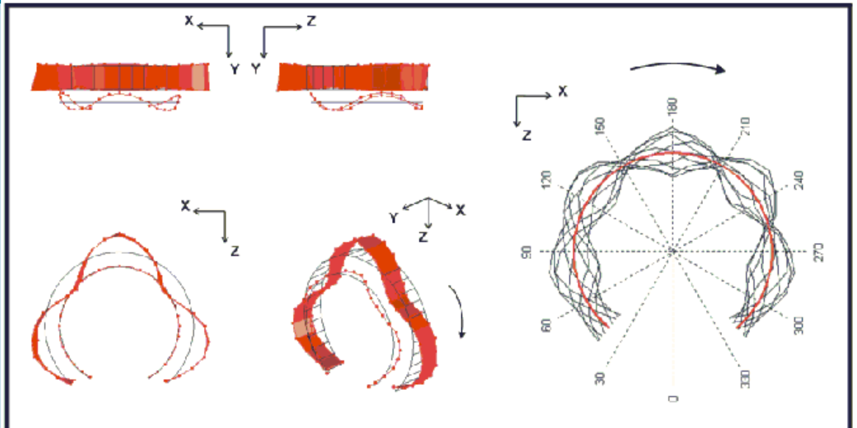
FIXED reference system

Rolling tyre Modal Parameters (15.7 rad/s)

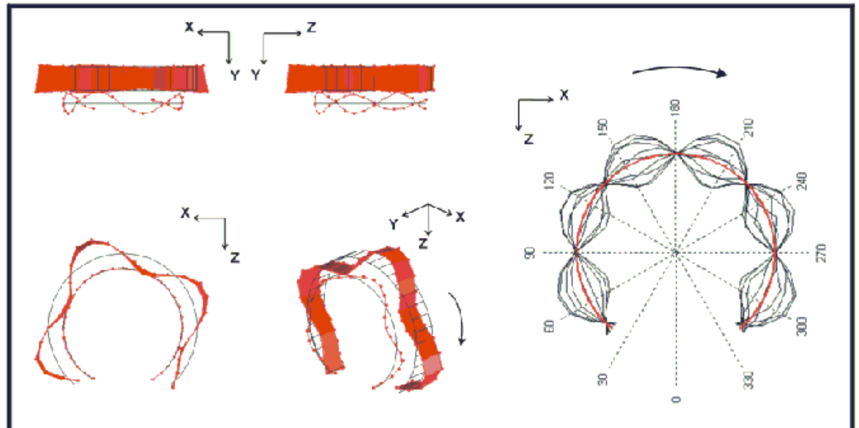


FIXED reference system

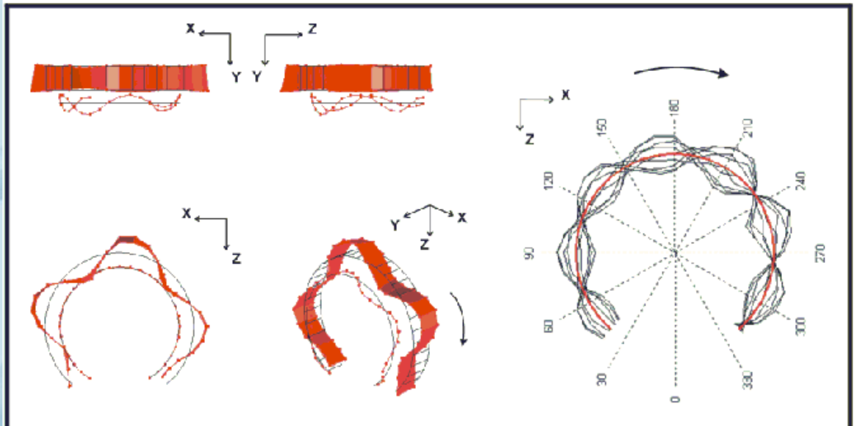
Rolling tyre Modal Parameters (15.7 rad/s)



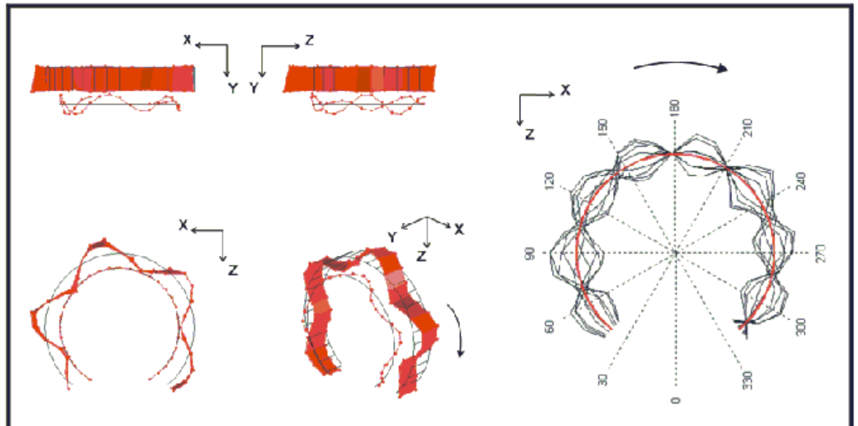
(i) **(3,0) extr. : 141.27 Hz; 3.11 %**



(j) **(4,0) 0 : 155.98 Hz; 3.33 %**



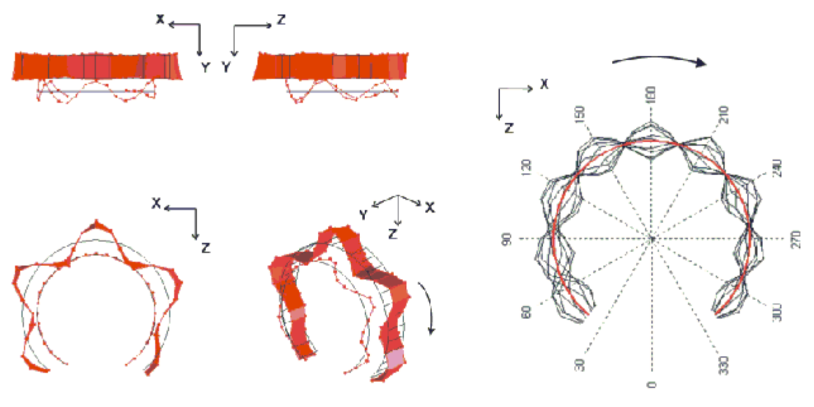
(k) **(4,0) extr. : 169.58 Hz; 2.80 %**



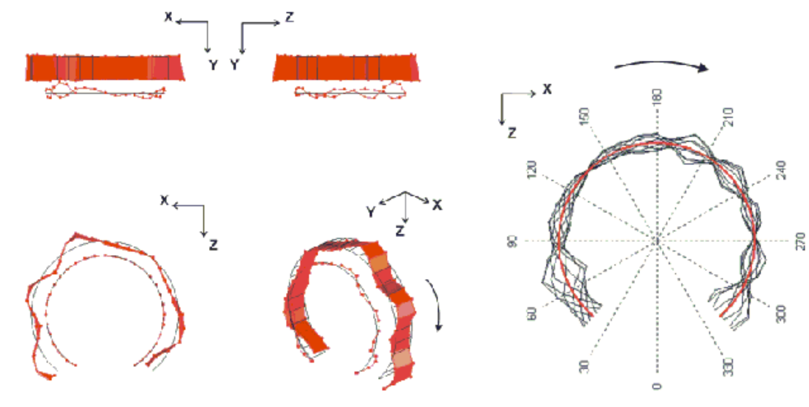
(l) **(5,0) 0 : 184.10 Hz; 1.77 %**

FIXED reference system

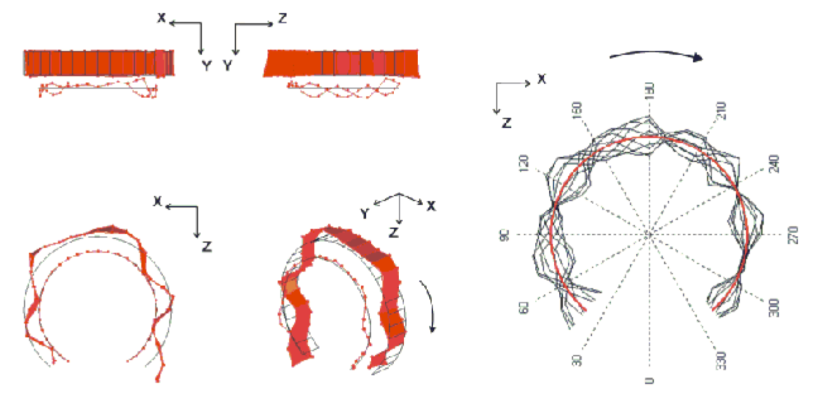
Rolling tyre Modal Parameters (15.7 rad/s)



(m) **(5,0) extr. : 199.46 Hz; 2.84 %**



(n) **1st ac. hor. : 222.56 Hz; 0.34 %**



(o) **1st ac. vert : 228.65 Hz; 1.02 %**

FIXED reference system