Experimental Characterization of the Dynamic Behavior of Rolling Tires for Noise and Comfort Applications

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Introduction

- TIRE-DYN project
- Tire structural wave propagation
- Measurement of rolling tire vibrations
- Operational modal analysis of a rolling tire
- Effect of rolling on the tire dynamic behavior:
  - analytical example: rotating flexible ring
  - measured rolling tire dispersion curves
- Conclusions

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TIRE-DYN project

TIRE-DYN

Experimental and Numerical Analyses of the Dynamic Behavior of Rolling Tires in order to Improve the Tire Modeling Accuracy

- Industry-academia pathways and partnerships (IAPP) project
- Duration: **48 months**
- Start date: **Sept. 1st, 2010**
- Project website: http://www.tiredyn.org

KATHOLIEKE UNIVERSITEIT LEUVEN	Katholieke Universiteit Leuven	Belgium
GOODYEAR	Goodyear S.A.	Luxembourg
LMS	LMS International N.V.	Belgium

Project ID: 251211

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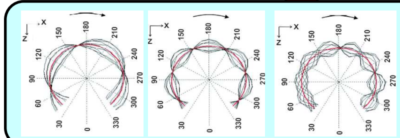
TIRE-DYN project – objective & approach

Obtain more accurate structural tire models through a <u>better understanding of the influence of rolling</u> on the tire dynamic behavior.

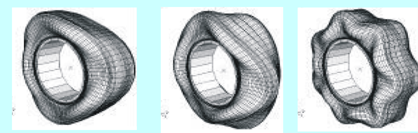
EXPERIMENTAL tire dynamics



measured rolling tire modes

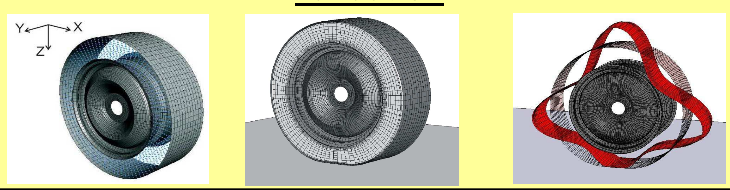
NUMERICAL tire dynamics

predicted rolling tire modes



Analyze effects of rolling on the tire dynamic behavior

<u>implementation</u> of the effects of rolling in simplified structural tire models
+ <u>validation</u>



Combine state-of-the-art in <u>experimental</u> and <u>numerical</u> tire structural dynamics.

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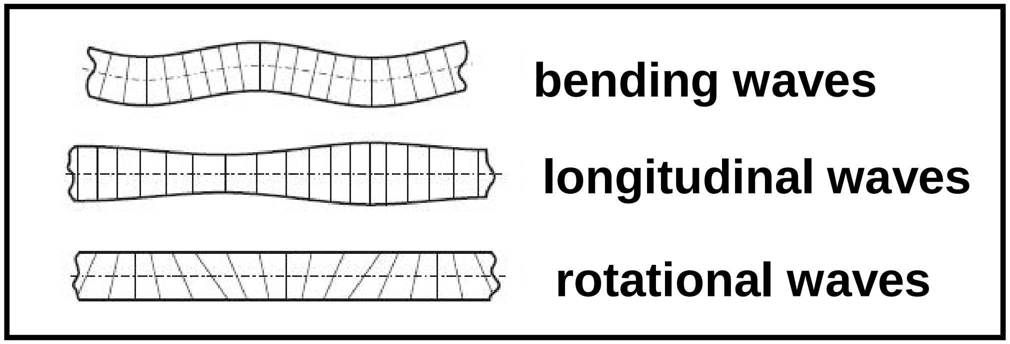
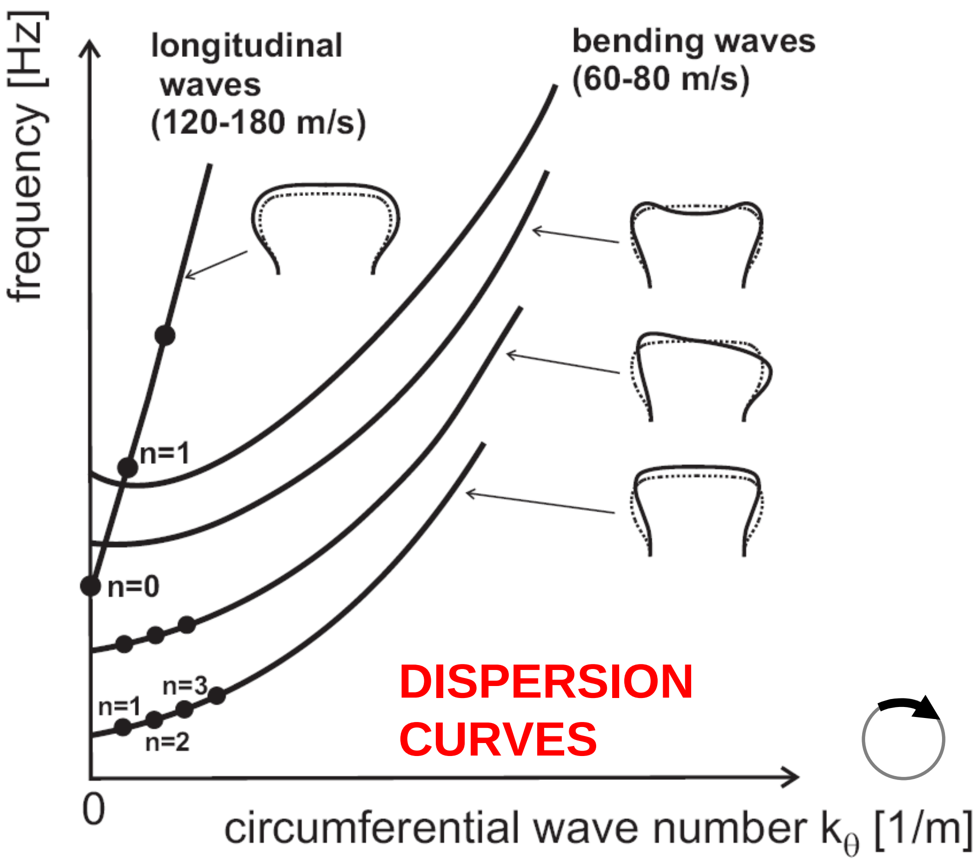
Tire structural wave propagation



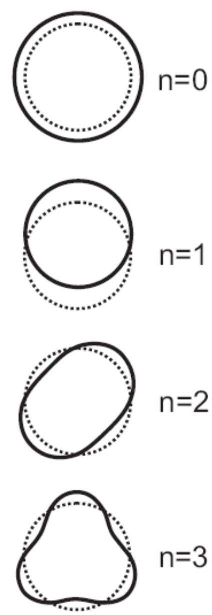
$$y = Ae^{-\alpha x} e^{j(\beta x - \omega t)}$$

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

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



circumferential mode number



Resonance condition:

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

or

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

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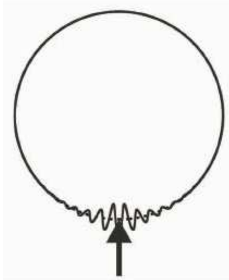
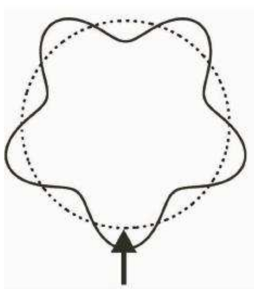
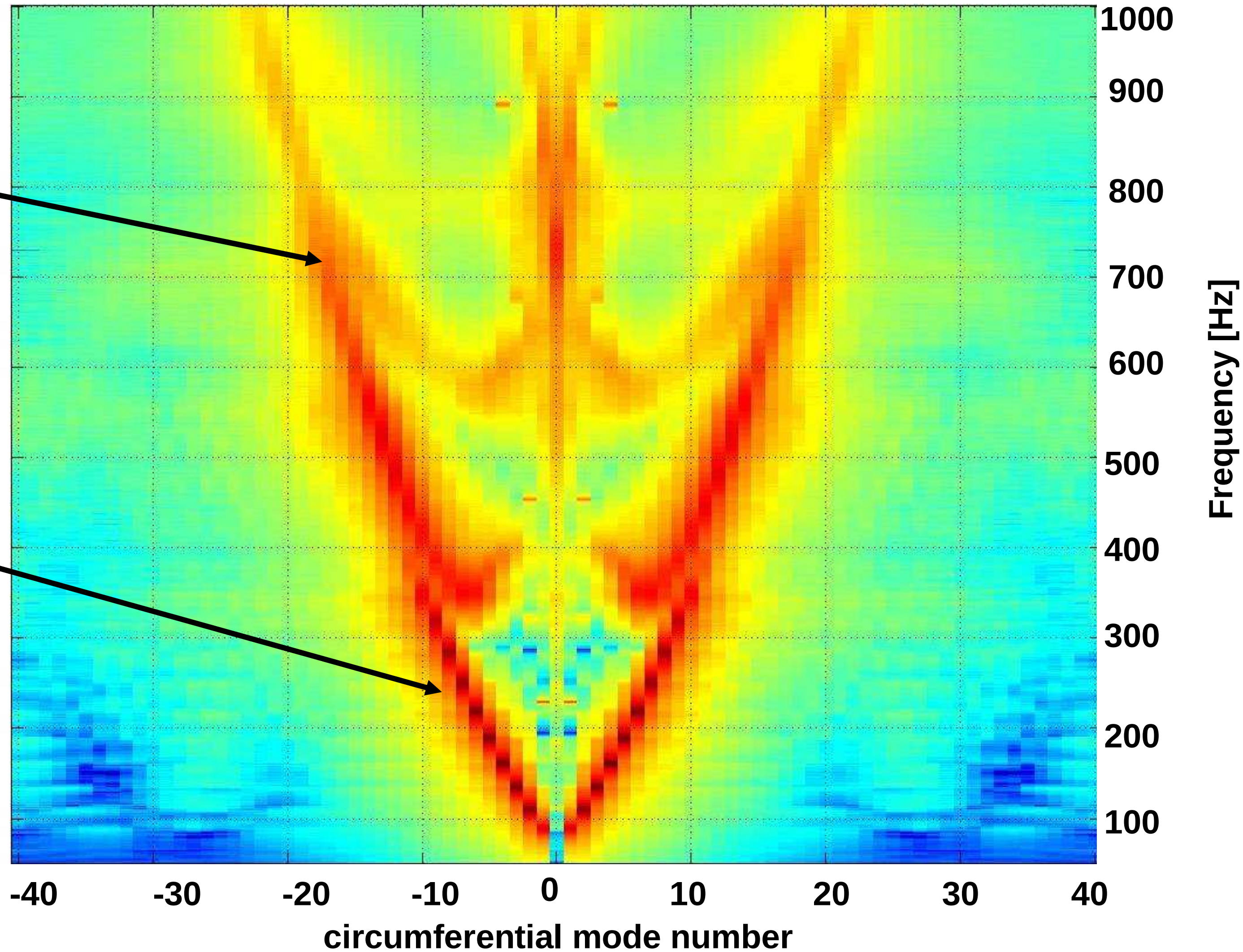
Tire dispersion curve – non rolling

non-modal behavior



modal behavior





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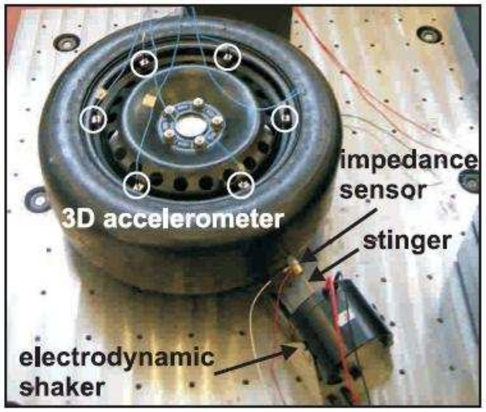
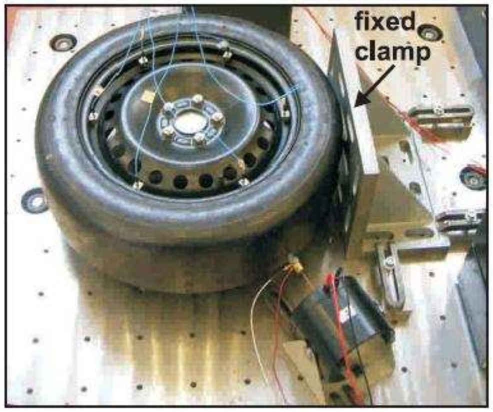
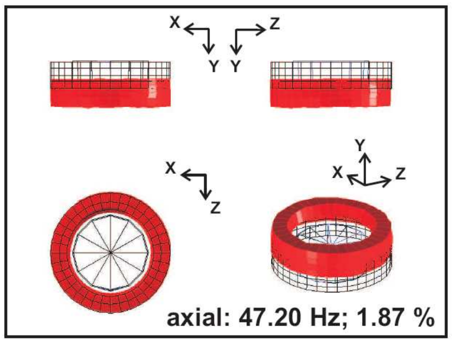
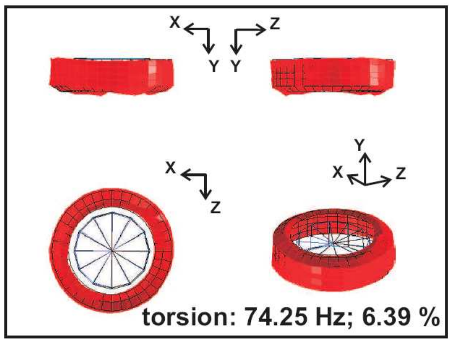
Experimental modal analysis



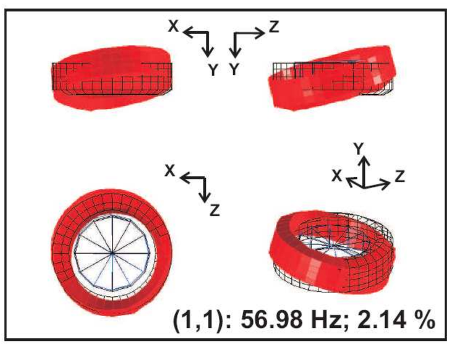




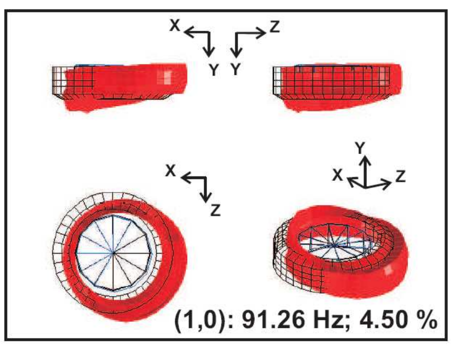
axial: 47.20 Hz; 1.87 %



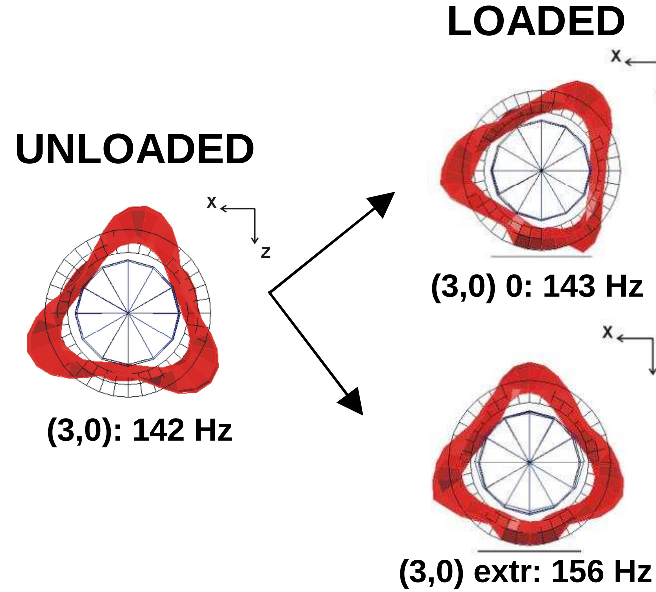
torsion: 74.25 Hz; 6.39 %

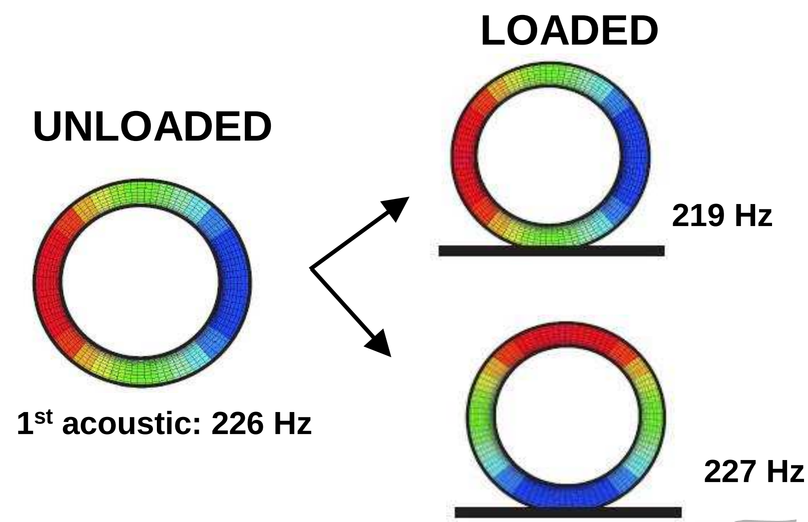


(1,1): 56.98 Hz; 2.14 %



(1,0): 91.26 Hz; 4.50 %





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Measurement of rolling tire vibrations

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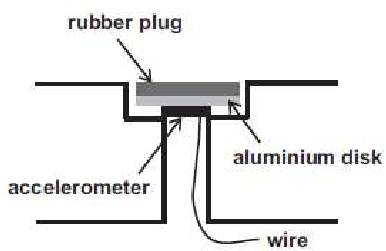
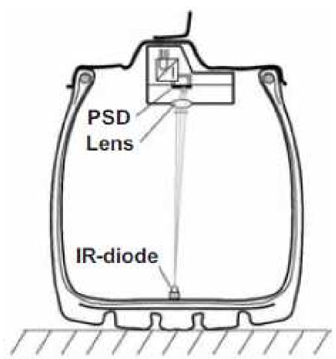
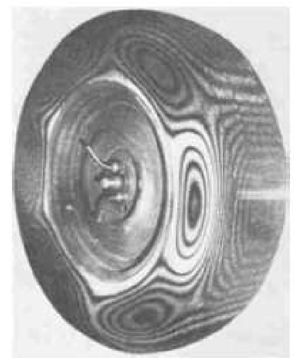
	ref. system	structural changes	data from contact area	treaded tires	remark
embedded accelerometer	co-rotating	yes	yes	yes	low durability of sensor fixation
optical deformation sensor	co-rotating	yes	yes	yes	vibrations of the belt inner surface
holographic interferometry	fixed	no	no	yes	no quantitative data
laser vibrometry	fixed/co-rotating	no	no	no	applicable to treaded tires with circumferential groove
indirect method	fixed/co-rotating	no	yes	yes	acoustic environment has to be characterized



(a)



(b)



(c)

(a) C.B. Burroughs and E.L. Dugan. Measurement and analysis of blank tire tread vibration and radiated noise. Technical report,The Institute for Safe, Quiet and Durable Highways, 2003.
(b) J. Holtschulze, H. Goertz, H. Wunderlich, G. Mackle, T. Varpula, F. Mancosu. Der Reifen -Informationsquelle zur Fahrassistenz.13th Aachener Kolloquium Fahrzeugund Motorentechnik, Aachen, Germany, pages 559–579, 2004.
(c) G.R. Potts. Application of holography to the study of tire vibration. Tire Science and Technology, TSTCA, 1(3):255–266, 1973.

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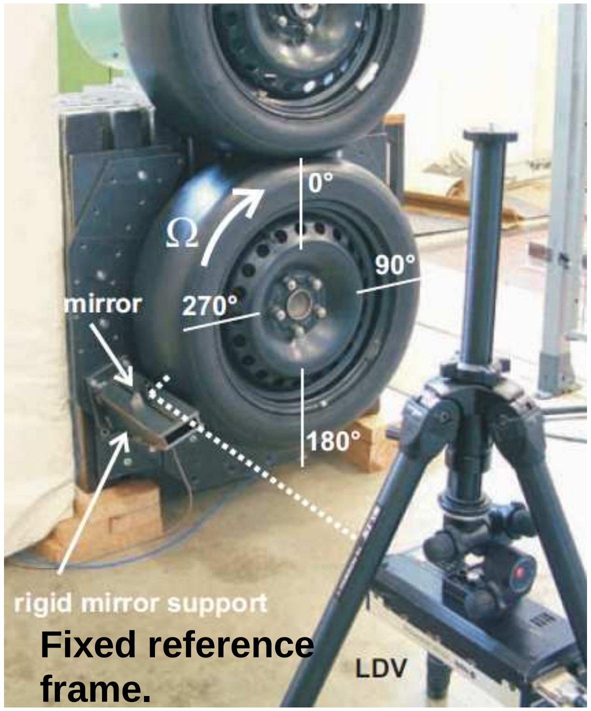
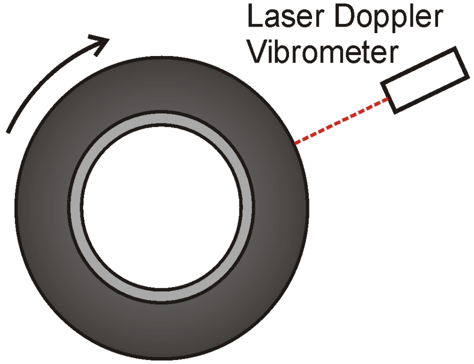
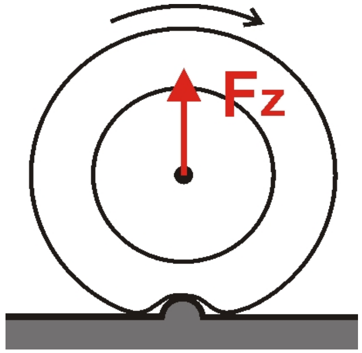
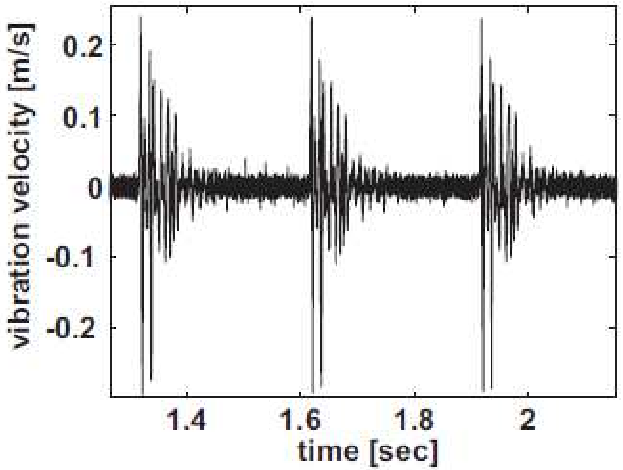
Measurement of rolling tire vibrations



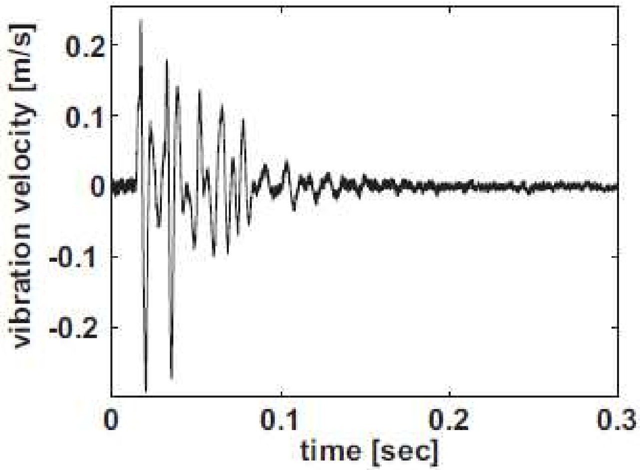




Tire surface vibration velocity due to rolling over a cleat



time-averaged vibration signal



Time averaging requires deterministic, highly repetitive time signals.

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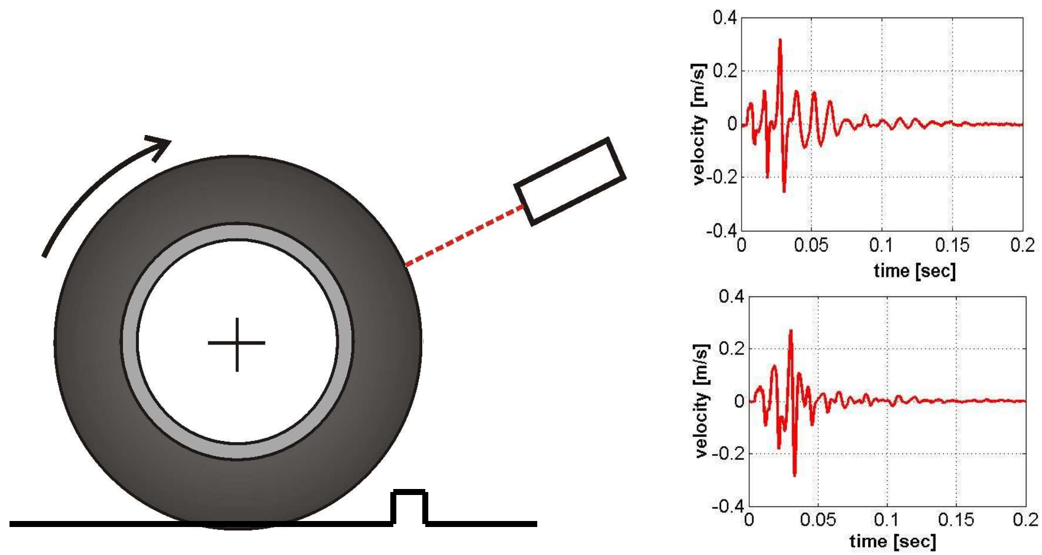
Synchronization

- Response in different points due to cleat excitation is not measured simultaneously (sequential measurement)
- Sequential measurements can only yield information about the complete vibration pattern if the **phase relation** between the different responses is maintained.



<u>2 approaches</u>:

1) measure **simultaneously** the response point and a reference point (use of two Laser Doppler Vibrometers)

2) Use of a **time reference** (if excitation is perfectly repetitive).
The acquisition of the individual responses has to start at a the same time instant relative to the excitation.

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Operational Modal Analysis (OMA)

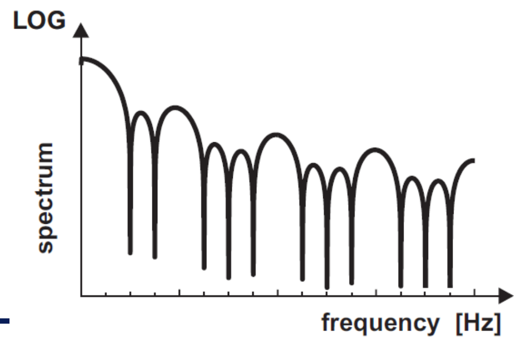
- Excitation force of tire rolling over cleat is difficult to measure.

- **Output-only method ➔** Polymax method applied to auto- and cross-power spectral density functions

  Assumption: excitation forces are the result of a stochastic process (white noise)

  =>The correlation functions between the response signals can be expressed as the sum of decaying sinusoids. Each decaying sinusoid has a damped natural frequency and damping ratio that is identical to that of a corresponding structural mode.

- **Cleat excitation**: relatively flat spectrum, except at certain frequencies where the excitation is low => some modes will not be excited by rolling over 1 cleat at 1 speed.



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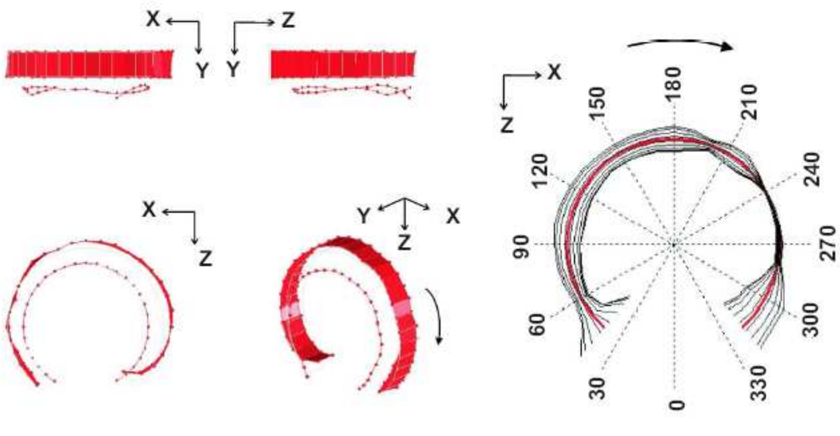
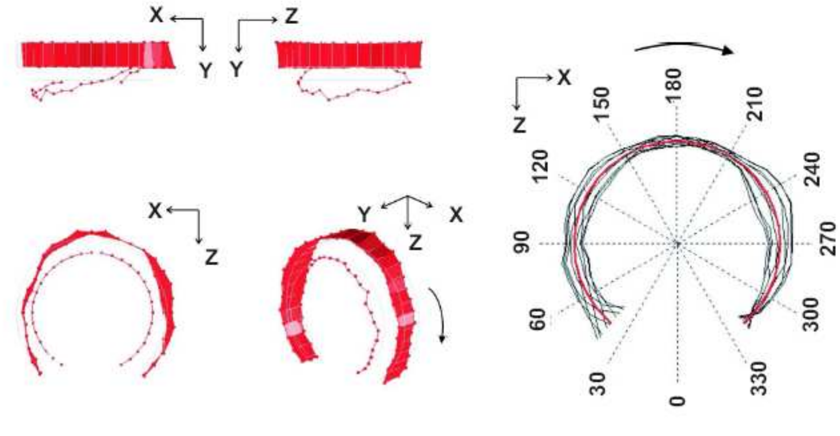
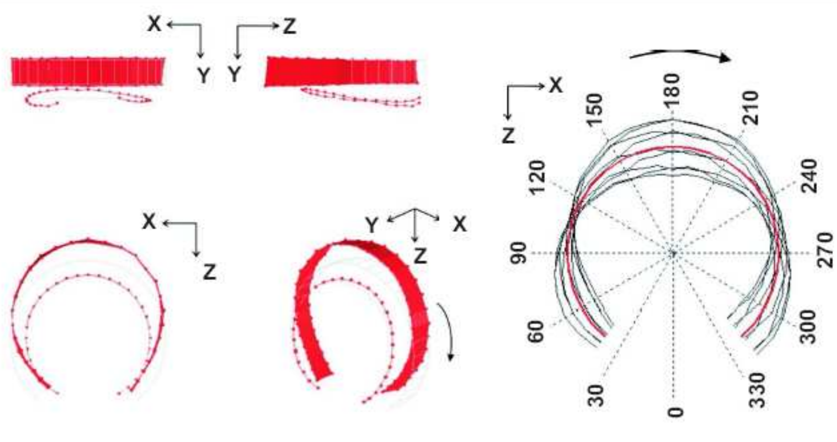
Rolling tire modal parameters (26.2rad/s)



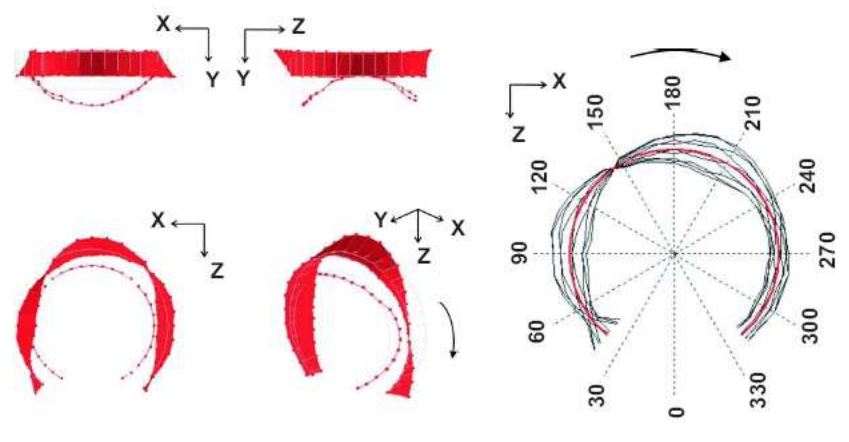
(a) **torsional : 36.19 Hz; 5.13 %**



(b) **(1,1) vert. : 50.78 Hz; 3.25 %**



(c) **(1,0) vert. : 83.57 Hz; 5.05 %**



(d) **(2,1) extr. : 92.39 Hz; 3.25 %**

modes relative to FIXED ref. system

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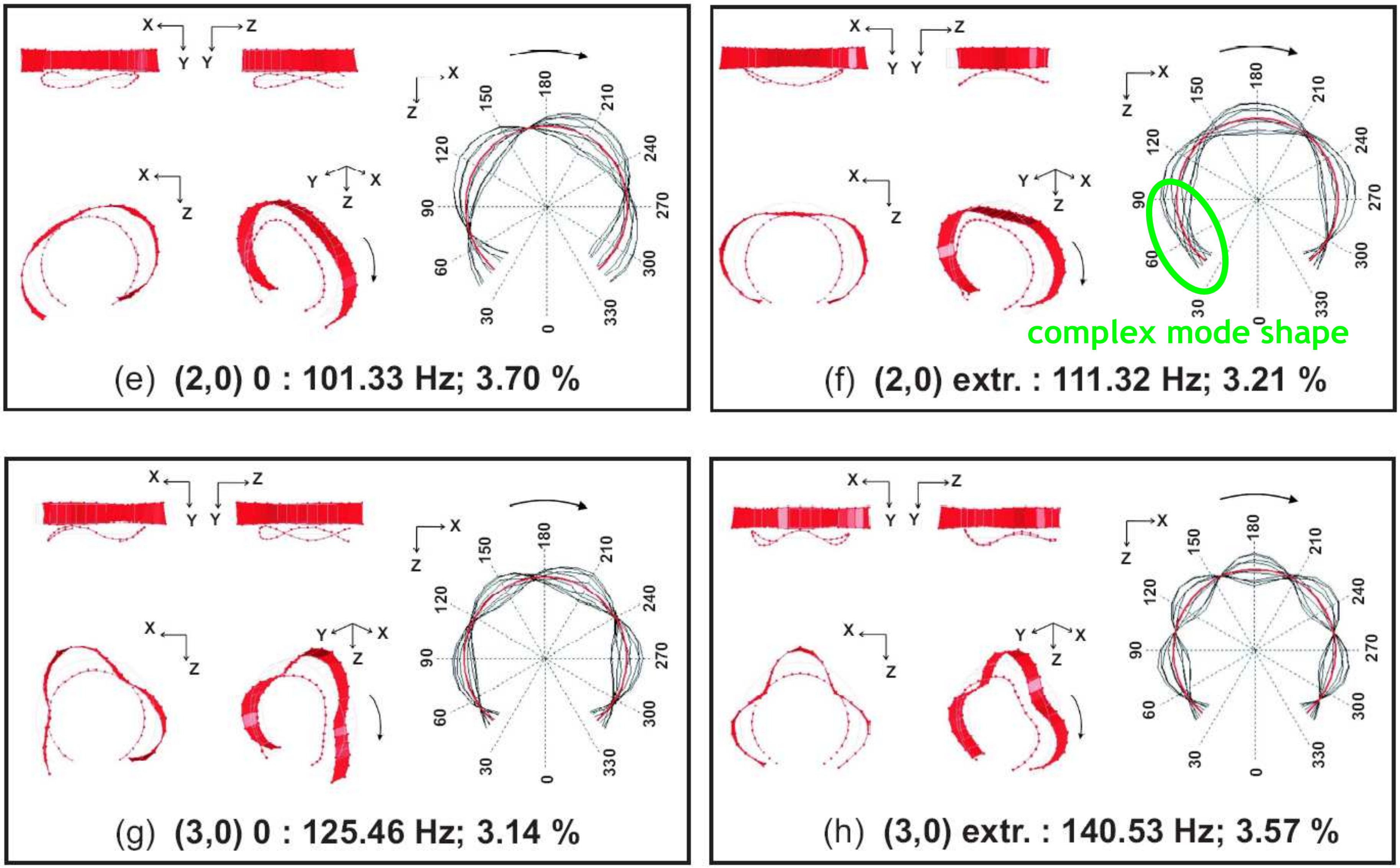
Rolling tire modal parameters (26.2rad/s)



(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

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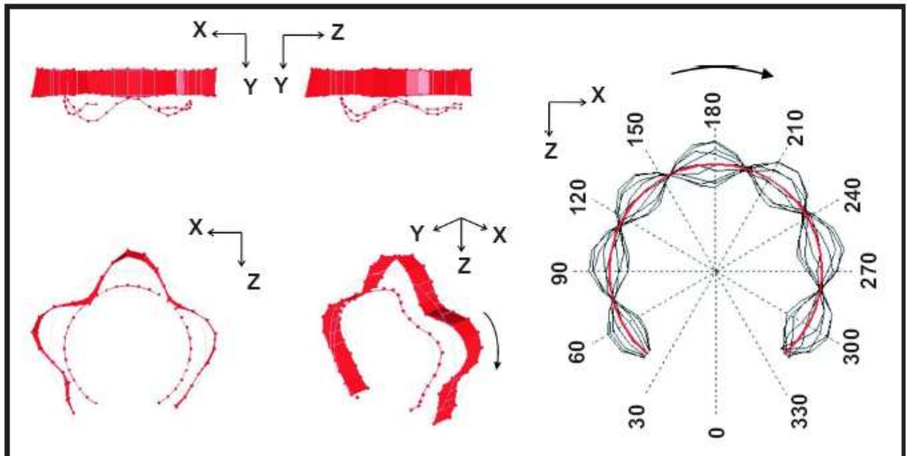
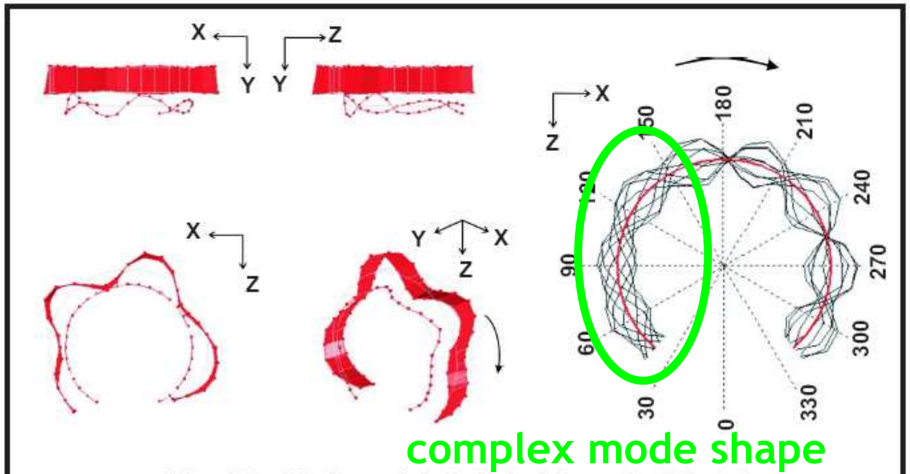
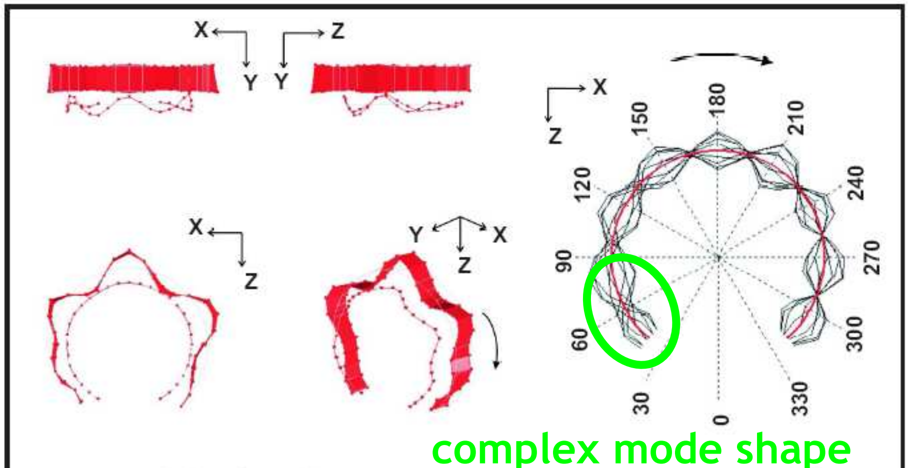
Rolling tire modal parameters (26.2rad/s)



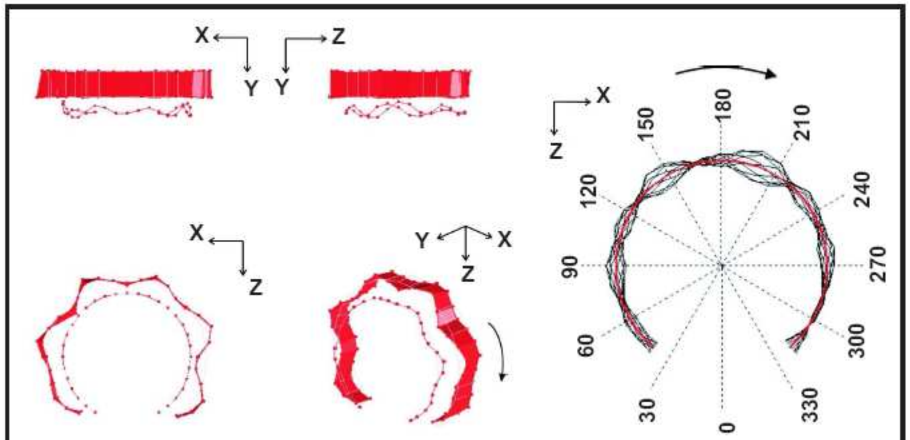
(i) **(4,0) extr. : 167.07 Hz; 3.47 %**



(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

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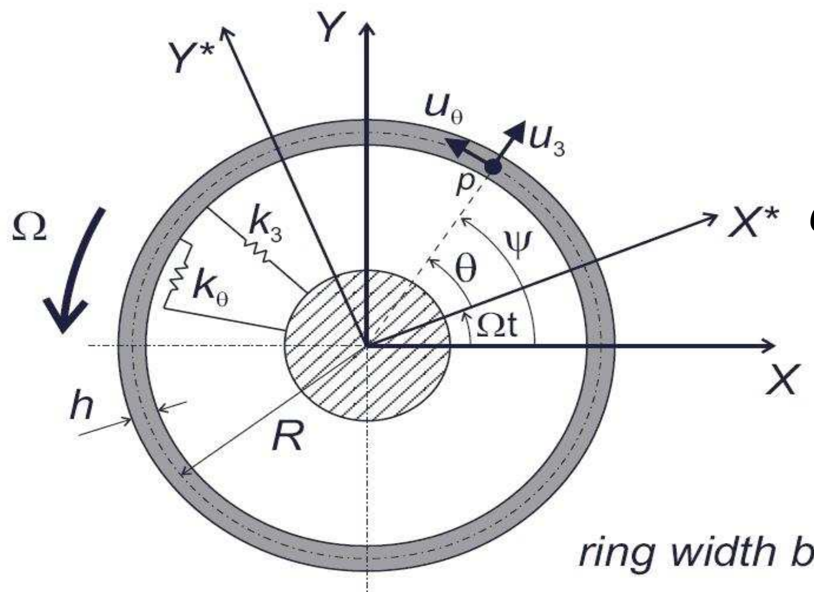
Rotating flexible ring – analytical example

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



co-rotating ref. system

fixed ref. system

Equations of motion:

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

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

Coriolis acceleration terms

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

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

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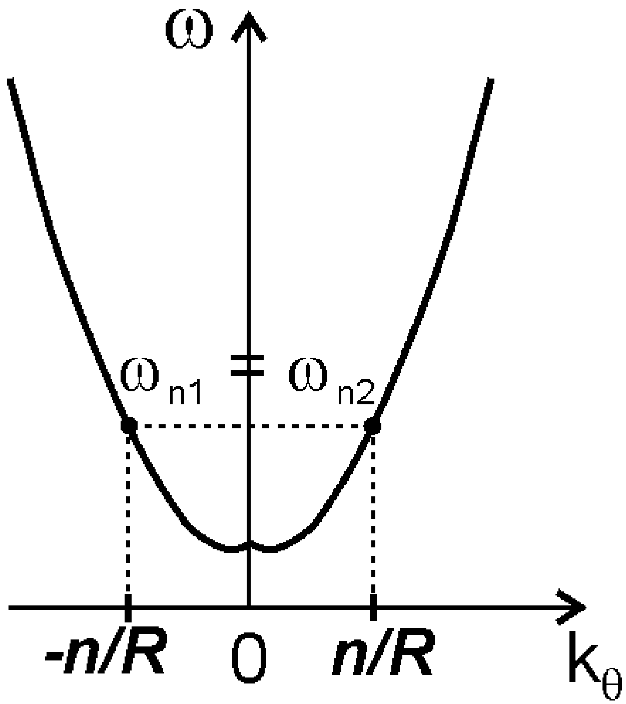
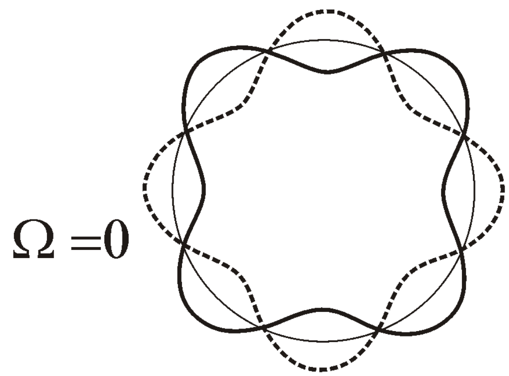
Rotating ring in co-rotating ref. system

dispersion curve:



0 rad/s

mode shape:



Mode at $\omega_{n1} = \omega_{n2}$

standing wave

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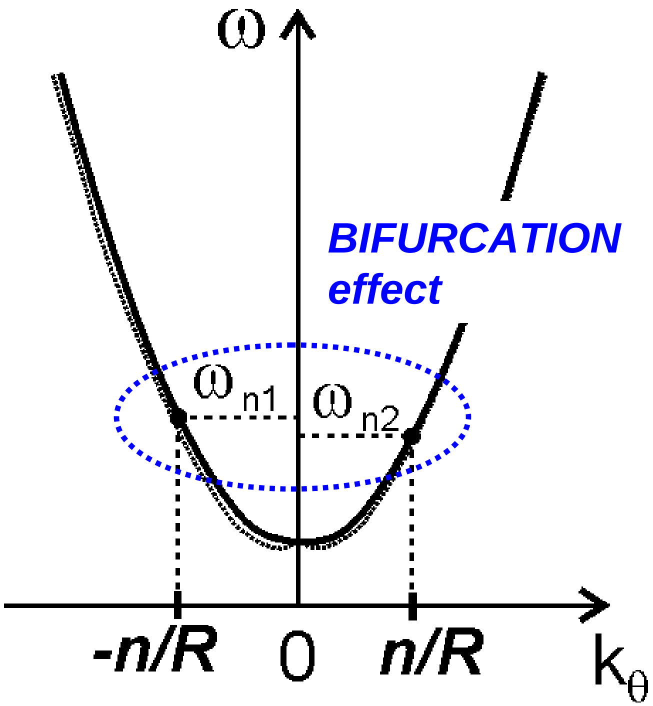
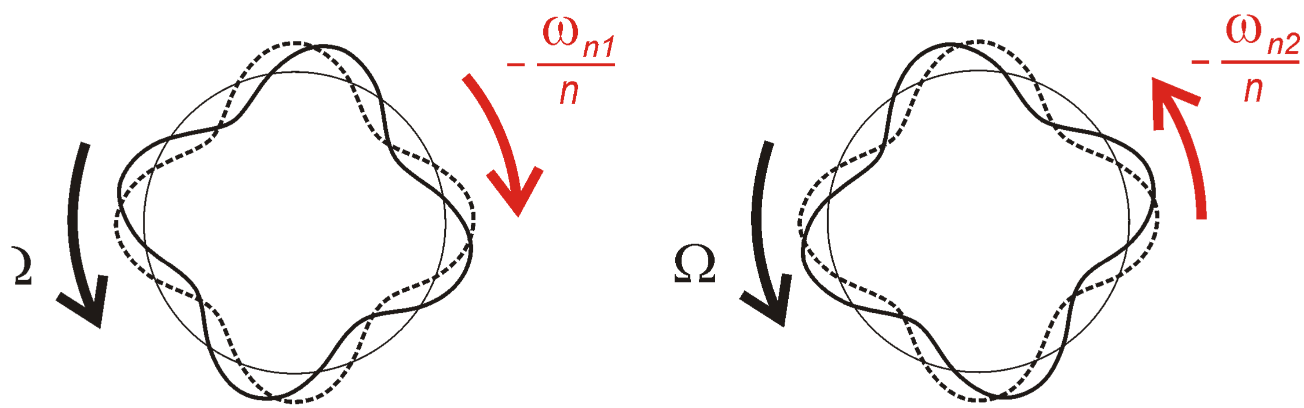
Rotating ring in co-rotating ref. system

dispersion curve:



Ω rad/s

mode shape:



Mode at ω_{n1}

Mode at ω_{n2}

backward travelling wave

forward travelling wave

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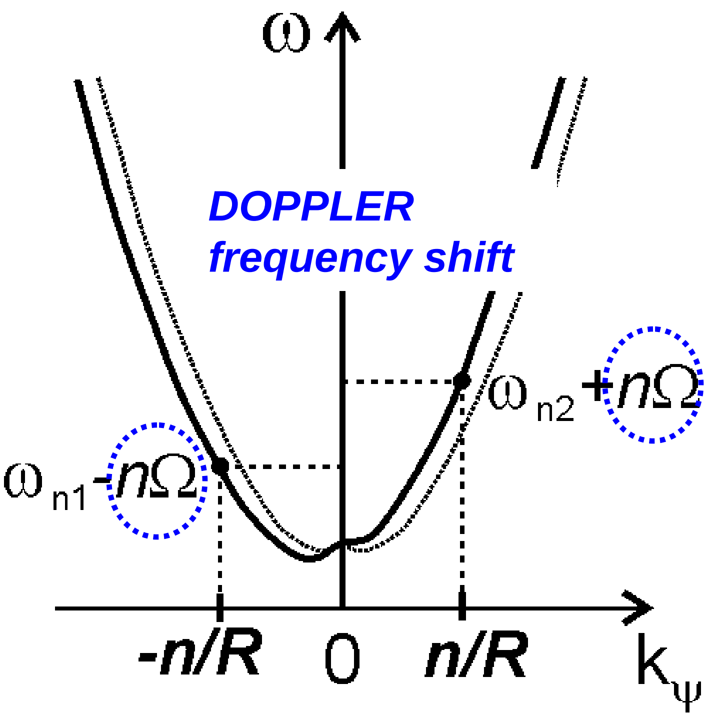
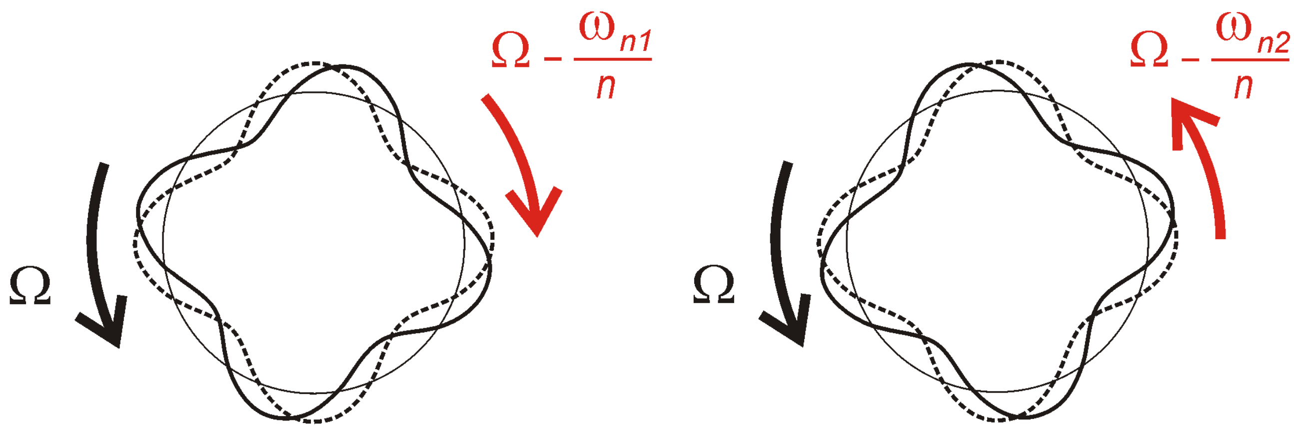
Rotating ring in fixed ref. system

dispersion curve:

mode shape:





Mode at (ω_{n1}-$n\Omega$)

Mode at (ω_{n2}-$n\Omega$)

backward travelling wave

forward travelling wave

Ω rad/s

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Summary: flexible rotating ring

- **Flexible 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

- **Tire operational modal analysis** :

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

  - Influence of:

    ➔ damping

    ➔ disturbed geometrical symmetry due to rolling

  on rolling tire dynamic behaviour is not yet fully understood.

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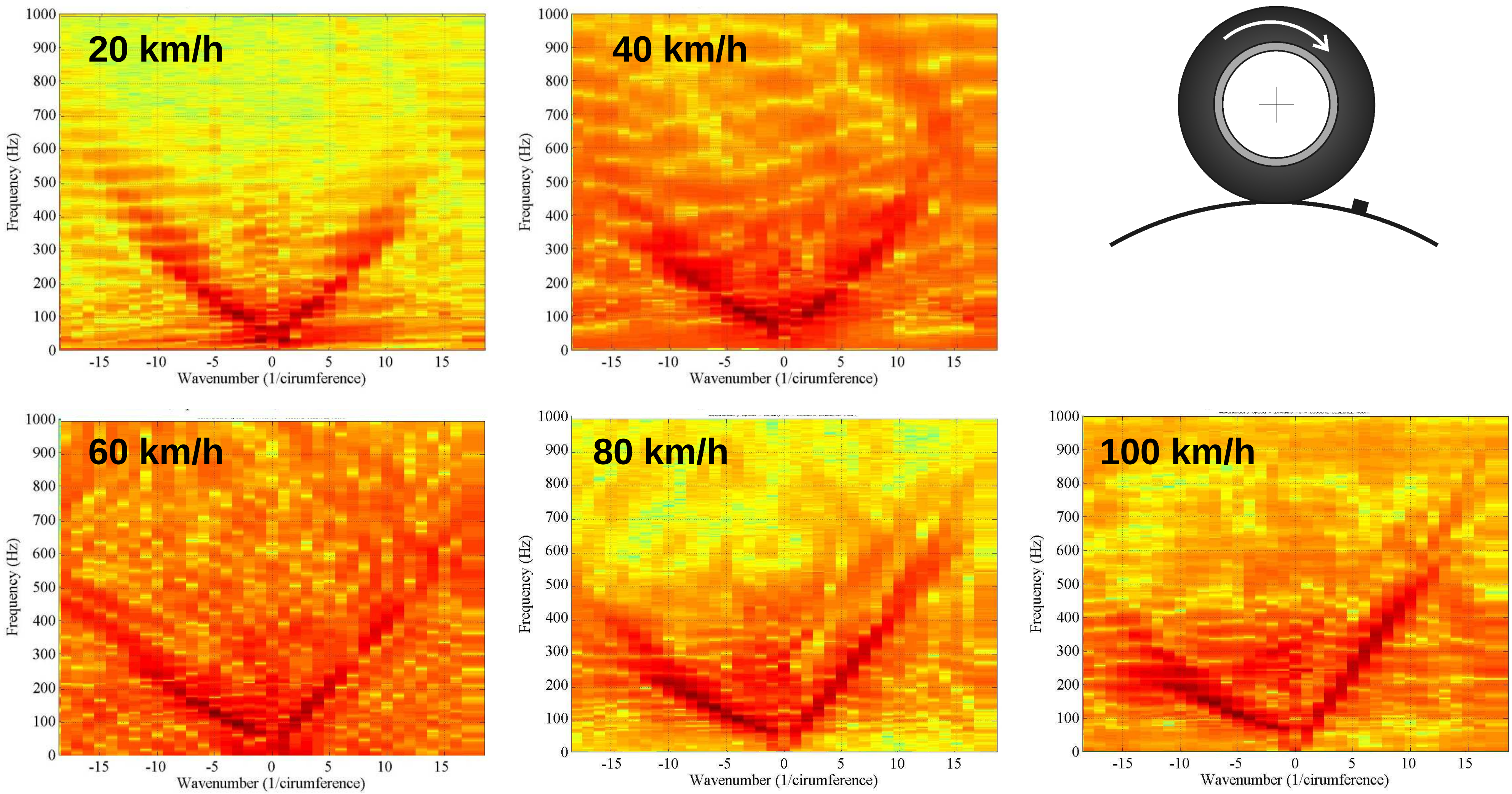
Measured rolling tire dispersion curves

- Tire excited by a cleat at the footprint.



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Conclusions

- An Operational Modal Analysis, based on rolling tire vibrations measured with a Laser Doppler Vibrometer, has proven to be a valid method to characterize the complex dynamic behaviour of a rolling tire in full detail.
- The main disadvantage of the method is the limited control of the excitation spectrum due to the cleat**.** The excitation spectral content is mainly determined by the cleat shape and the rolling speed.
- In case of a sequential measurement of the different response points, an accurate synchronization of the vibration measurements with respect to the cleat excitation is required in order to obtain the vibration pattern of the complete tire.
- Similarly as for the analytical model of a flexible (free) rotating ring, the dispersion curves of the rolling tire are asymmetric due to rotation. The Doppler frequency shift causes the asymmetry of the dispersion curves to increase with increasing rolling speed.

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