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Sound Radiation Control Resulting from Tire Structural Vibration

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Sound Radiation Control Resulting from Tire Structural Vibration

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Introduction

Importance of Tire Noise

- Large contribution to pass-by noise regulation
- Bigger contribution expected on future cars
  (hybrid car and fuel-cell car)

Problem Definition

- Tire's structural vibration and its sound radiation
- Sound radiation control using tire's structural modification

Objectives

- To investigate how to control structural wave propagation with a view to reducing tire noise resulting from structural vibration
- To identify the most effective material parameters among various orthotropic material parameters that control tire structural vibration
- To optimize orthotropic material parameters of a tire to reduce sound radiation based on the structural vibration control strategy.

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Contents

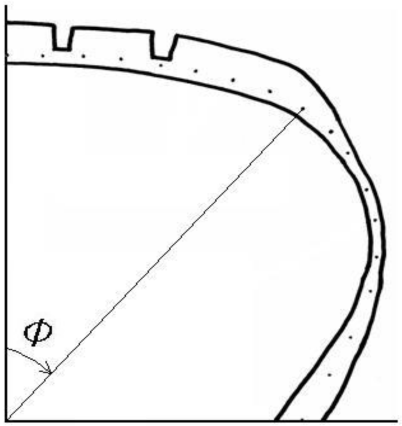
- **Structural Wave Propagation on Tire Surface**
  - Orthotropic tire FE model for structural harmonic analysis
  - Material parameter study
  - Effective material parameters to control structural wave propagation

- **Sound Radiation from a Tire**
  - Tire BE model for radiation calculation
  - Relationship between tire's structural vibration and its sound radiation

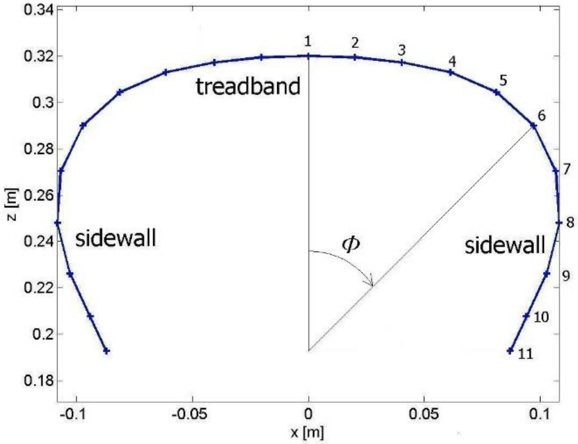
- **Sound Radiation Control Resulting from Tire's Structural Modification**
  - Strategy to control structural wave propagation
  - Orthotropic material parameter optimization

Structural FE model

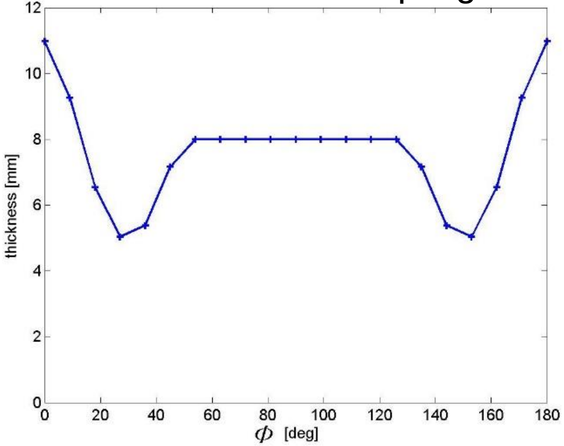
■ Tire Cross-section



cross-section re-sampling



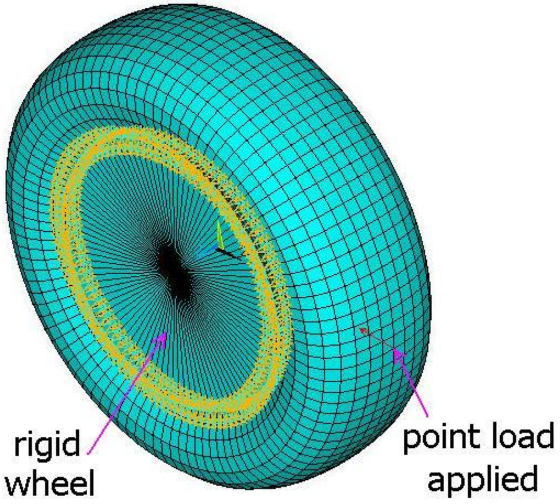
thickness re-sampling



- based on 205/70R14 tire
- 21 points re-sampled from the previous sampled tire data [Kim & Bolton (2001)]

Structural FE Analysis

■ Tire FE model



- Shell elements were used.
- To consider stiff belt and rubberized carcass,

  orthotropic material properties were applied on treadband and sidewall.
- Wheel and boundary between wheel and tire were modeled as rigid.
- inflation pressure: 30 psi

■ Structural Harmonic Analysis

- Full matrix method was performed using ANSYS ver. 7.1.
- Harmonic point source was applied at the point in contact with the ground.
- Frequency range: 12.5 Hz – 1600 Hz (constant bandwidth 12.5 Hz)

Orthotropic Material Properties

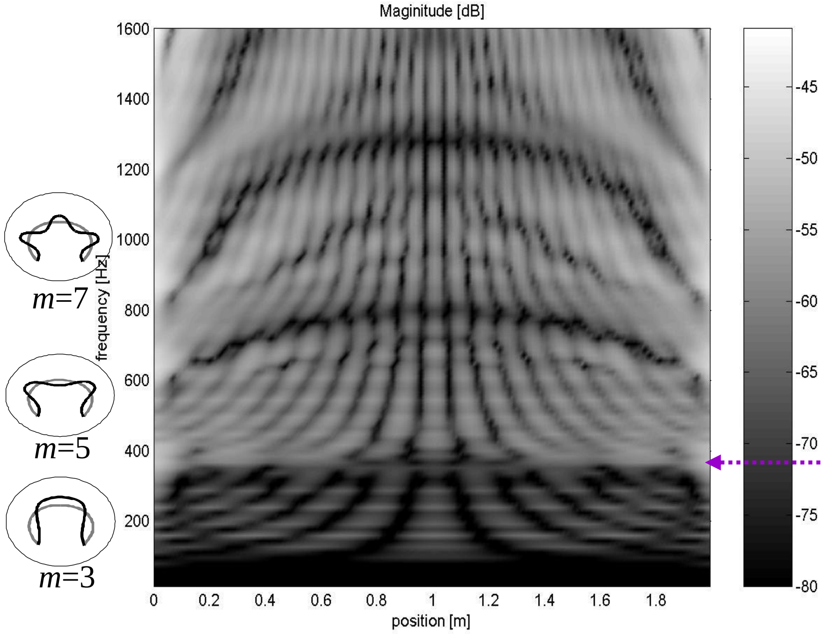
tread band	circumferential Young’s modulus	750 MPa	side wall	circumferential Young’s modulus	7.5 MPa
	cross-sectional Young’s modulus	320 MPa		cross-sectional Young’s modulus	50 MPa
	shear modulus	50 MPa		shear modulus	1.5 MPa
	Possion’s ratio	0.45		Possion’s ratio	0.45
	density	1200 kg/m^3		density	800 kg/m^3
inflation pressure		30 psi (207 kPa)			

- Adapted from the work of Kropp [1989] and Pinnington and Briscoe [2002] or based on physical reasoning, or obtained by direct measurement at Continental Tire.

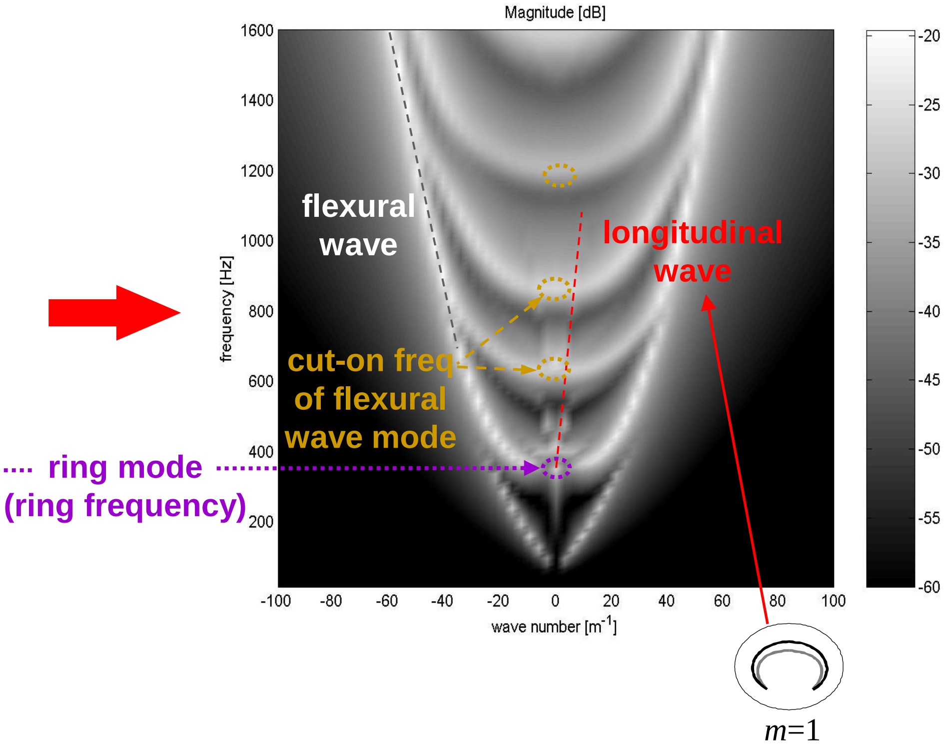
Structural Wave Propagation

■ Circumferential Wave Number Decomposition

structural velocity distribution
in space domain



structural velocity distribution
in wave number domain



Influence of Material Parameters

Objectives

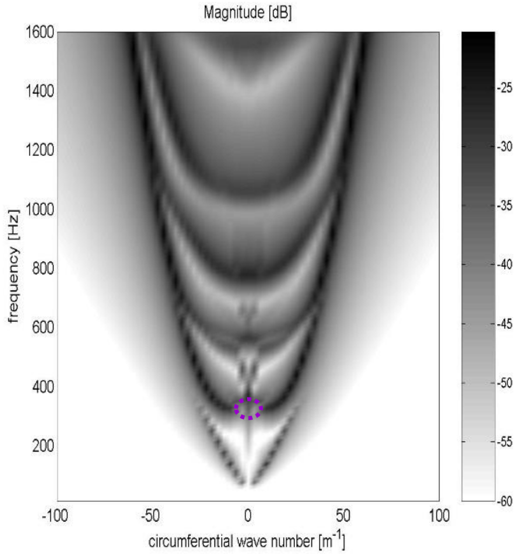
- Material parameter modification is a passive method to control the structural wave propagation on tire surface
- To know effective parameters among tire's orthotropic material properties

Procedure

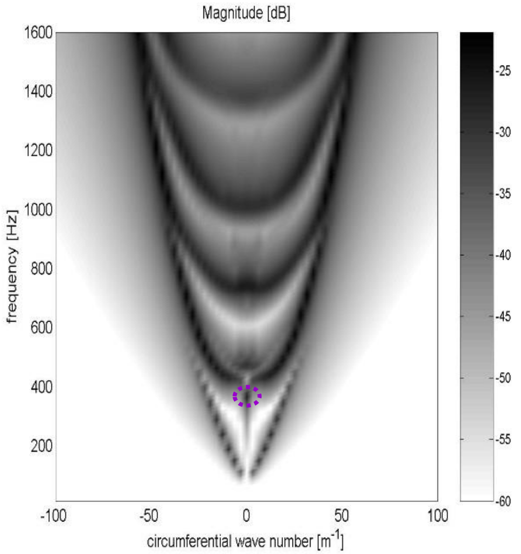
- Performing structural harmonic analysis by changing each material parameter
- Comparison of ring frequency and cut-on frequency of the 7th flexural wave mode

		base	half	twice
tread band	circumferential modulus [MPa]	750	350	1500
	cross-sectional modulus [MPa]	320	160	640
	shear modulus [MPa]	50	25	100
side wall	circumferential modulus [MPa]	7.5	3.75	15
	cross-sectional modulus [MPa]	50	25	100
	shear modulus [MPa]	1.5	0.75	3
inflation pressure [psi]		30	15	60

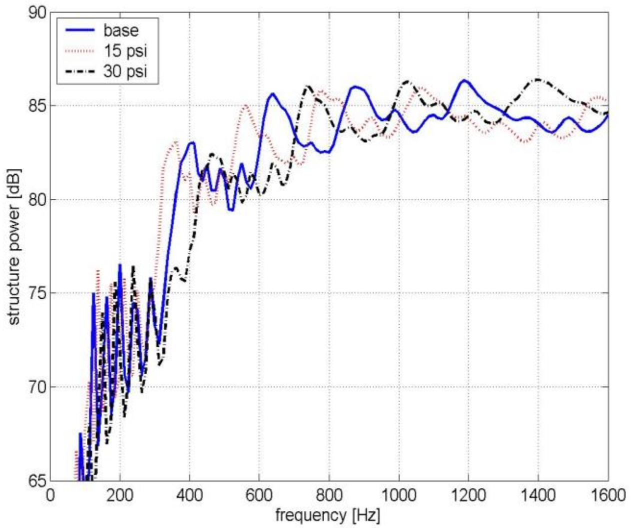
Influence of Inflation Pressure



(a) 15 psi



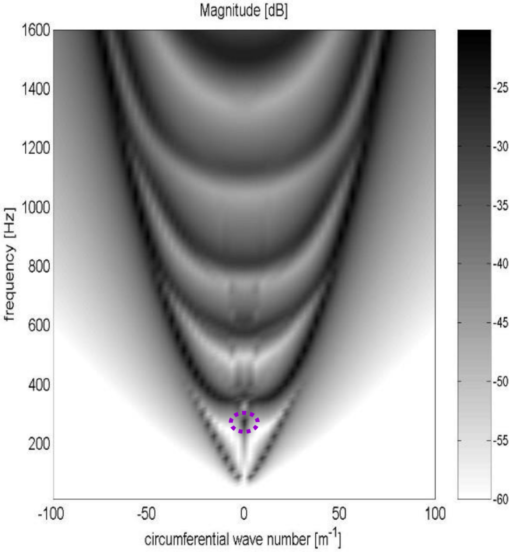
(b) 60 psi



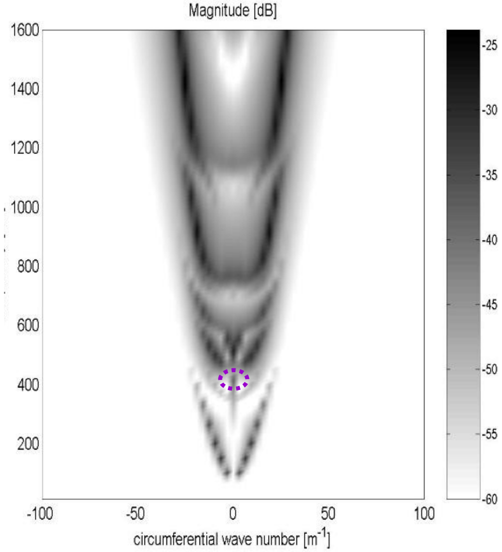
structural input power

- As inflation pressure increases, the cut-on frequencies of the flexural wave modes increase and the ring frequency increases slightly.
- Asymptotic flexural wave speed increases with inflation pressure.

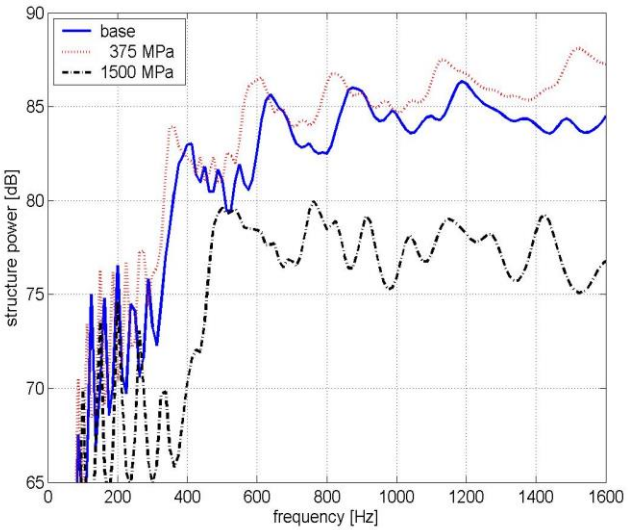
Influence of Treadband Circumferential Stiffness



(a) 375 MPa



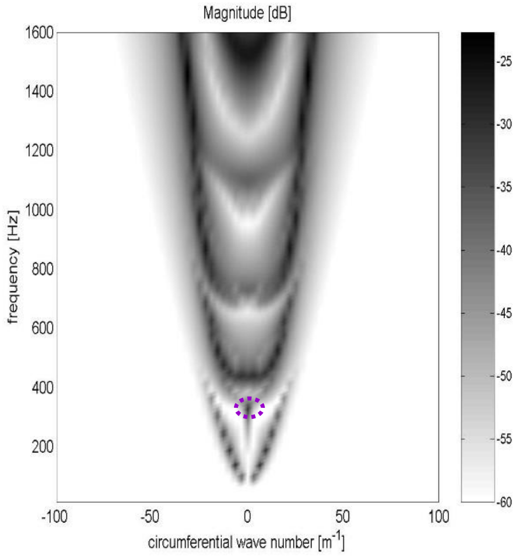
(b) 1500 MPa



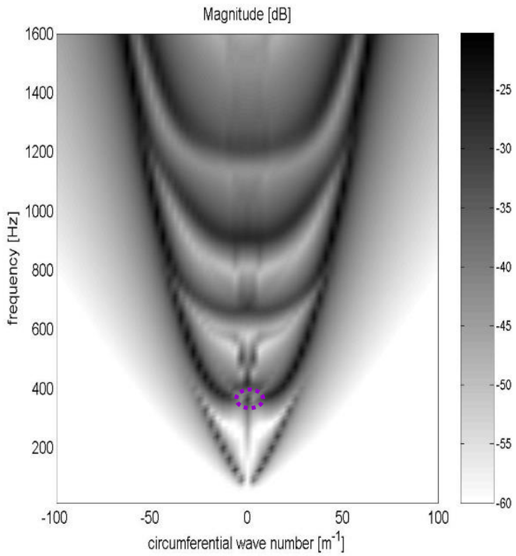
structural input power

- As treadband circumferential stiffness increases, the ring frequency and the cut-on frequencies of the flexural wave modes increases, as do wave speeds.
- Treadband circumferential stiffness is the effective controller of tire's structural vibration.

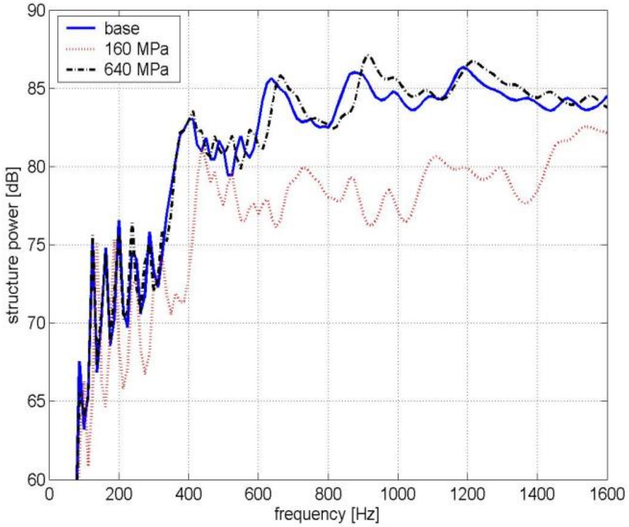
Influence of Treadband Cross-sectional Stiffness



(a) 160 MPa



(b) 640 MPa



structural input power

- As treadband cross-sectional stiffness increases, the structural wave propagation characteristics change.

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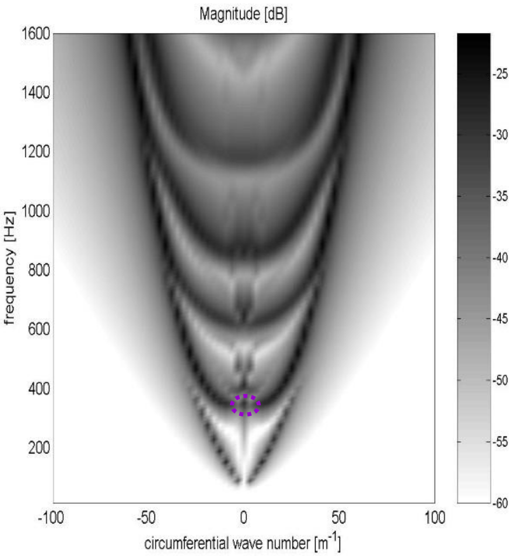
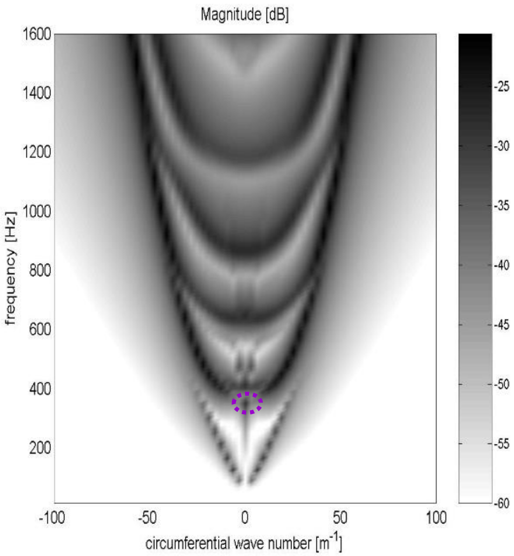
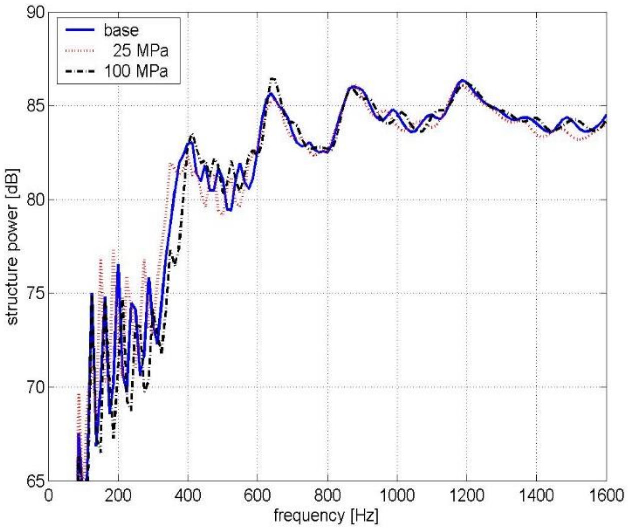
Influence of Treadband Shear Stiffness



(a) 25 MPa



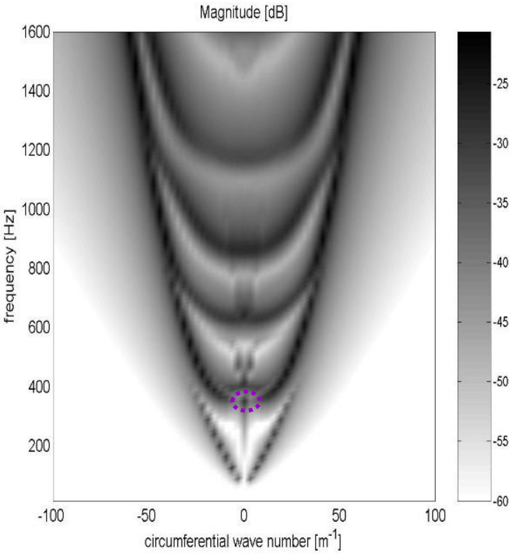
(b) 100 MPa



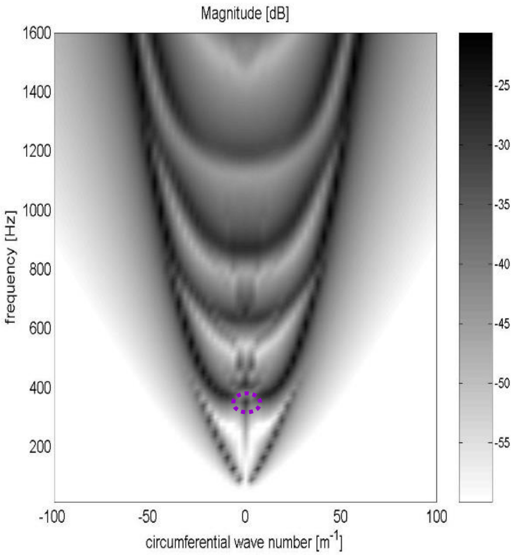
structural input power

- Treadband shear stiffness has little contribution on tire’s structural vibration.

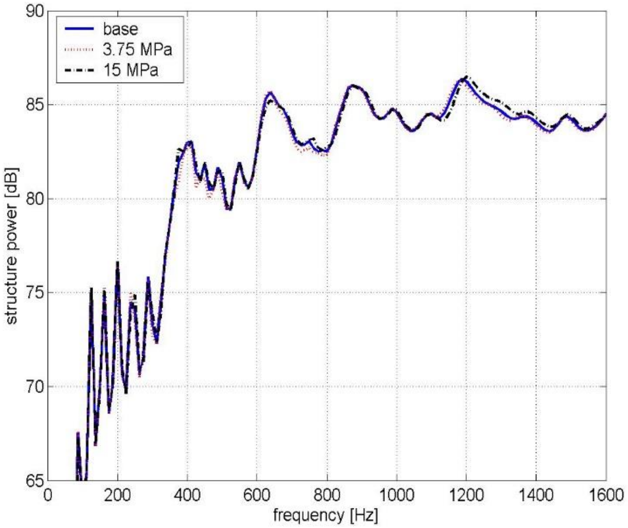
Influence of Sidewall Circumferential Stiffness



(a) 3.75 MPa



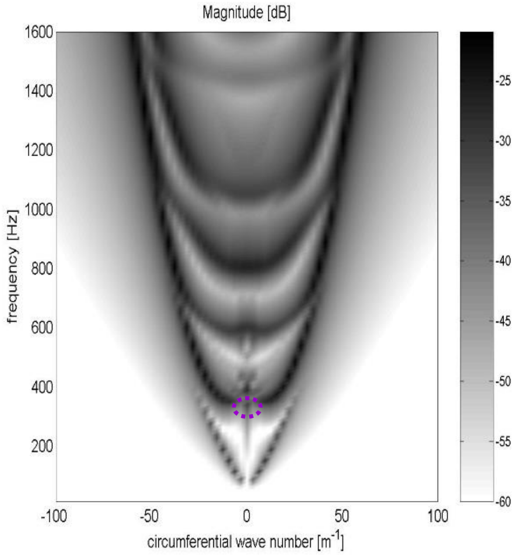
(b) 15 MPa



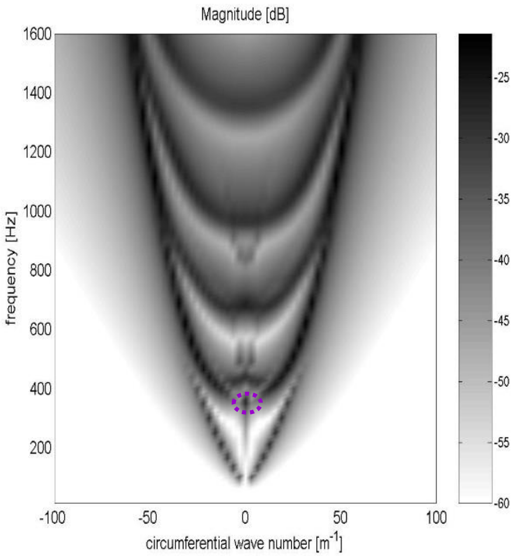
structural input power

- Sidewall circumferential stiffness has little contribution on tire's structural wave propagation.

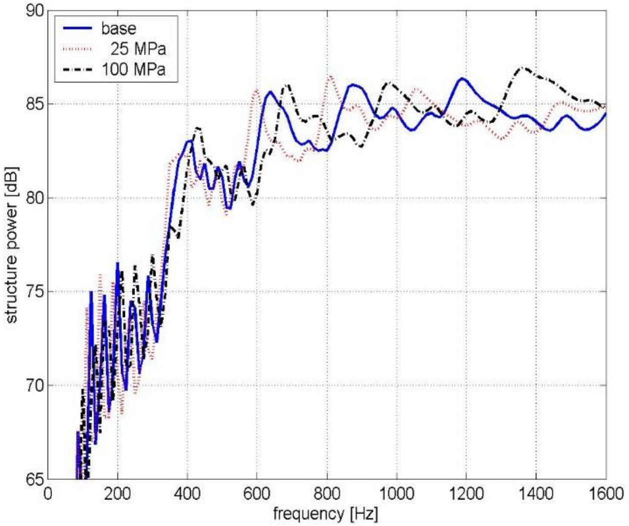
Influence of Sidewall Cross-sectional Stiffness



(a) 25 MPa



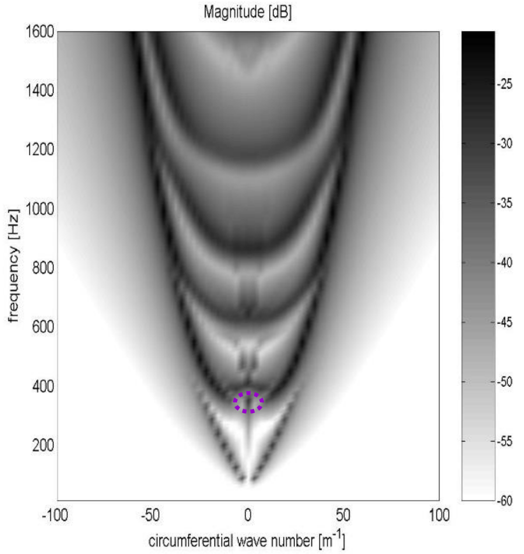
(b) 100 MPa



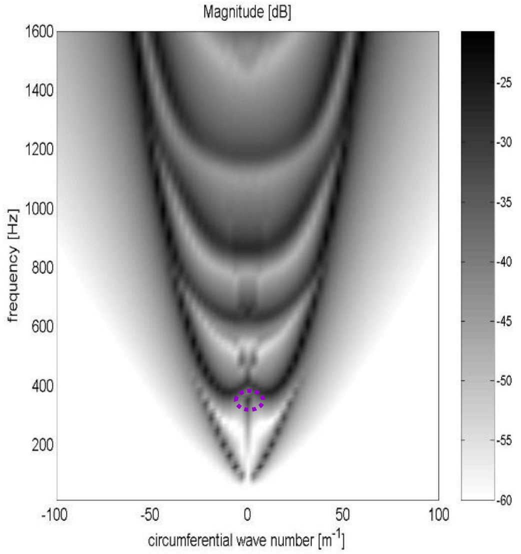
structural input power

- Sidewall cross-sectional stiffness has an influence on the flexural wave motion but little contribution on the longitudinal wave motion.

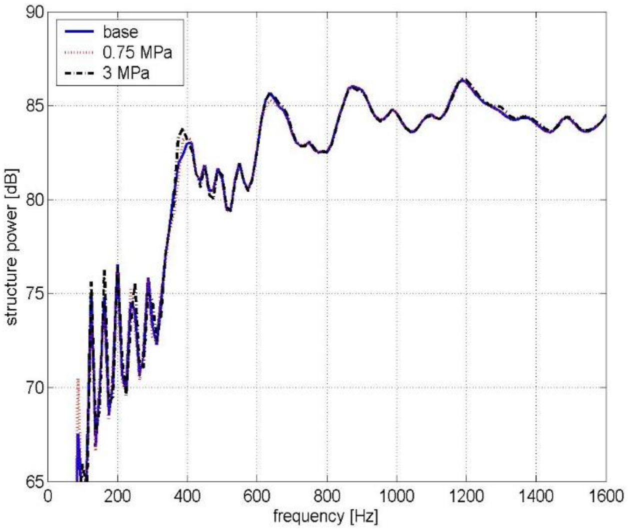
Influence of Sidewall Shear Stiffness



(a) 0.75 MPa



(b) 3 MPa



structural input power

- Sidewall shear stiffness has little contribution on tire’s structural vibration.

Influence of Material Parameters

material properties					ring frequency			**cut-on freq of 7th flexural wave**		
		base	half	twice	base	half	twice	base	Half	twice
tread band	circumferential modulus [MPa]	750	350	1500	350	**275**	**412.5**	637.5	**575**	**762.5**
	cross-sectional modulus [MPa]	320	160	640		325	362.5		**737.5**	**675**
	shear modulus [MPa]	50	25	100		350	350		650	637.5
side Wall	circumferential modulus [MPa]	7.5	3.75	15		350	350		637.5	637.5
	cross-sectional modulus [MPa]	50	25	100		337.5	350		600	687.5
	shear modulus [MPa]	1.5	0.75	3		350	350		637.5	637.5
inflation pressure [psi]		30	15	60		337.5	362.5		**562.5**	**737.5**

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Effective Material Parameters

- **Structural wave propagation in terms of orthotropic material parameters**
  - **Longitudinal wave motion** is primarily affected by treadband circumferential stiffness. Cross-sectional stiffness and inflation pressure have smaller effect.
  - **Flexural wave motion** can be controlled by several material properties such as treadband circumferential stiffness, cross-sectional stiffness and inflation pressure.

- **Effective material parameters**
  - treadband circumferential stiffness
  - treadband cross-sectional stiffness
  - inflation pressure

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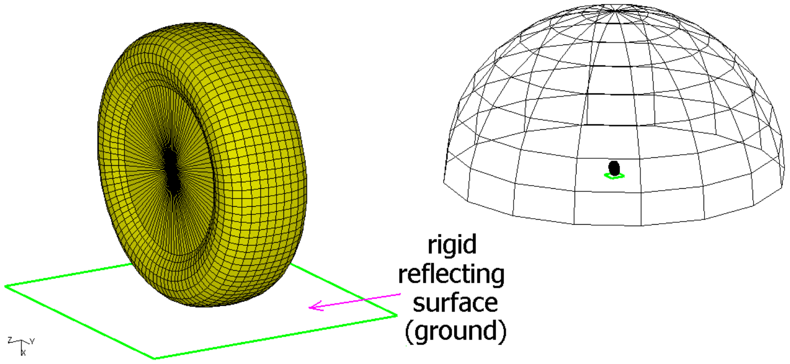
Radiation Model

Boundary Element Model

- Full tire model used in structural harmonic analysis was imported.
- Recovery surface: R7.5 hemisphere – related to pass-by noise test
- The reflecting surface was modeled as rigid.

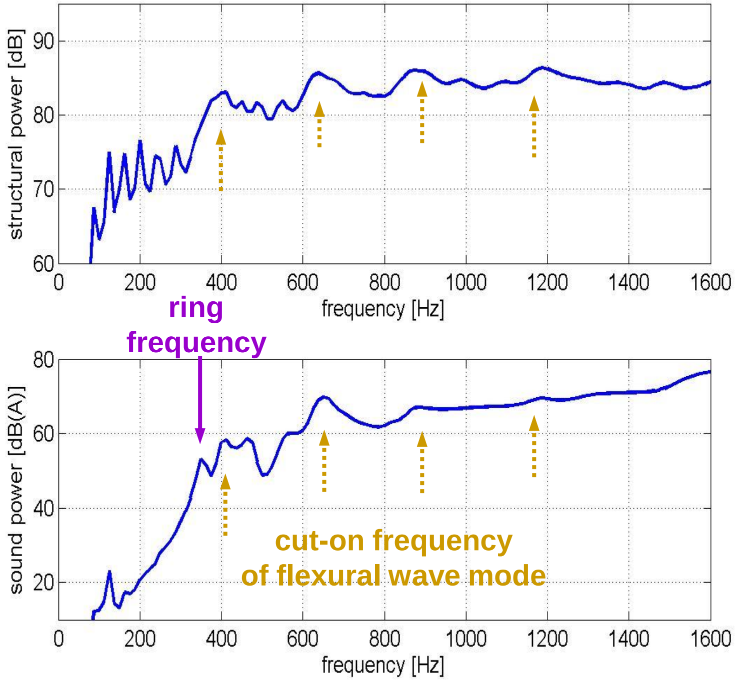


D-BEM Analysis

- Using Direct Collocation Boundary Element Method (D-BEM) in SYSNOISE ver. 5.6.
- Reason to use D-BEM: D-BEM takes less calculation time and allows model simplification for the interior singularity problem
- Frequency range: 12.5 Hz – 1600 Hz (constant bandwidth 12.5 Hz)

Structural Vibration/Radiation Relationship

- **Relationship between structural wave propagation and its radiation**
  - Radiated power peaks don't match with those of structural power.
  - **Radiated power peaks appear when structural wave has low wave number.**
  - The peak at 350 Hz relates to '**ring frequency**'. The structural vibration below the ring frequency does not contribute to sound radiation effectively.
  - The cut-on frequencies of the flexural wave modes appear as peaks in the radiated sound power plot.



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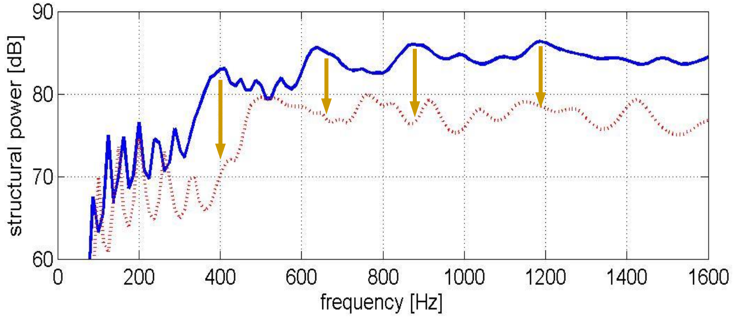
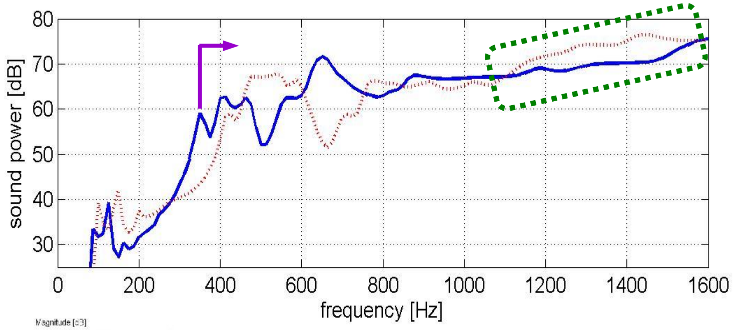
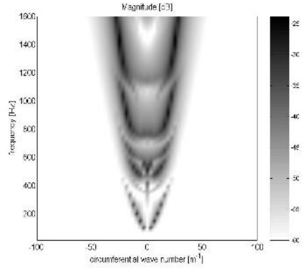
Structural Wave Control Strategy

- **The ring frequency should be increased.**
  - Since there is very little sound radiation below the ring frequency. Thus increasing the ring frequency decreases low frequency radiation.
- **Tire's structural power should be low**
  - To minimize the transfer of the tire's structural vibration to the vehicle structure.
- **All flexural waves should have as low phase speeds as possible to minimize the sound radiation.**
  - When a flexural wave propagates quickly, it results in higher sound radiation in high frequency region.







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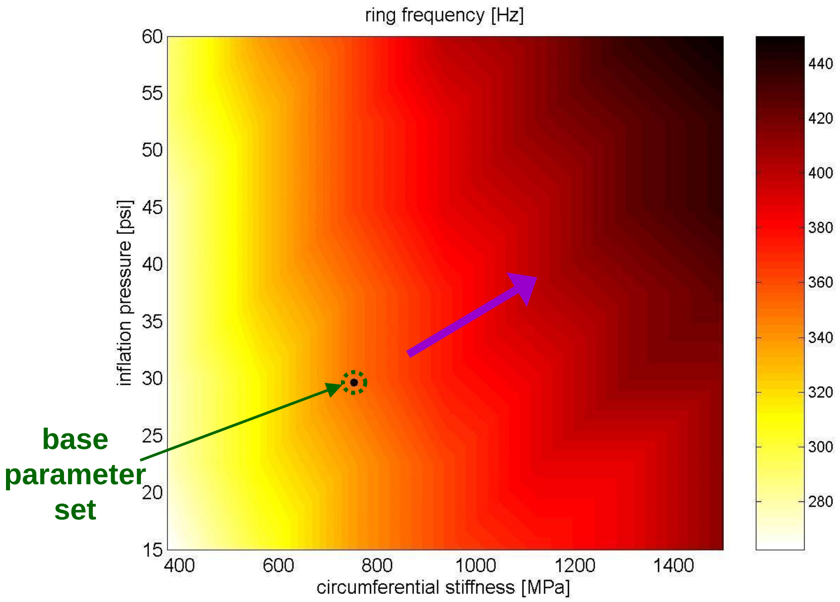
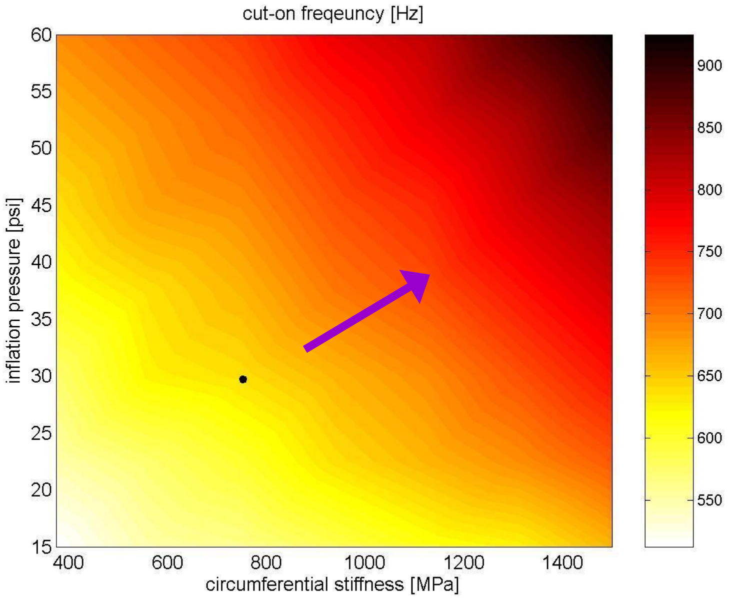
Structural Wave Propagation Control

■ Influence of treadband circumferential stiffness and inflation pressure



[ring frequency]

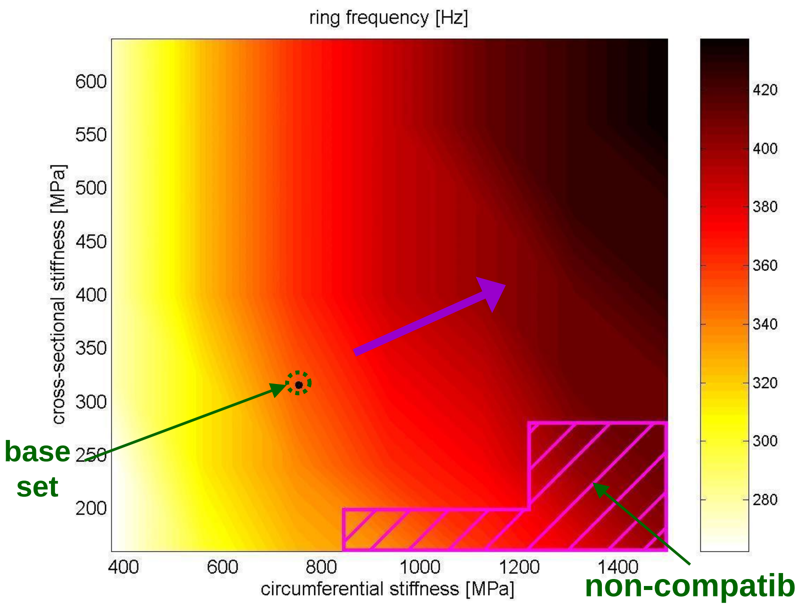


[cut-on frequency of 7th flexural wave mode]

- The ring frequency is mainly controlled by treadband circumferential stiffness.
- The flexural wave motion is controlled by the two parameters acting together.
- It is desirable to increase treadband circumferential stiffness and inflation pressure.

Structural Wave Propagation Control

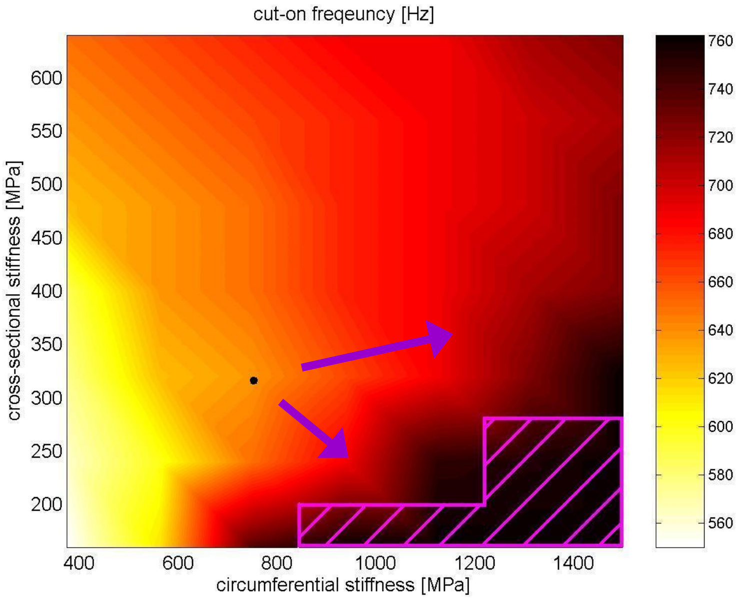
Influence of treadband circumferential and cross-sectional stiffnesses



base set

non-compatibility region (using extrapolation)

[ring frequency]



[cut-on frequency of 7th flexural wave mode]

- The ring frequency is primarily controlled by treadband circumferential stiffness.
- The cut-on frequency of the flexural wave mode increases as the circumferential stiffness increases.
- The cut-on frequencies are also high in the region close to the incompatible region.

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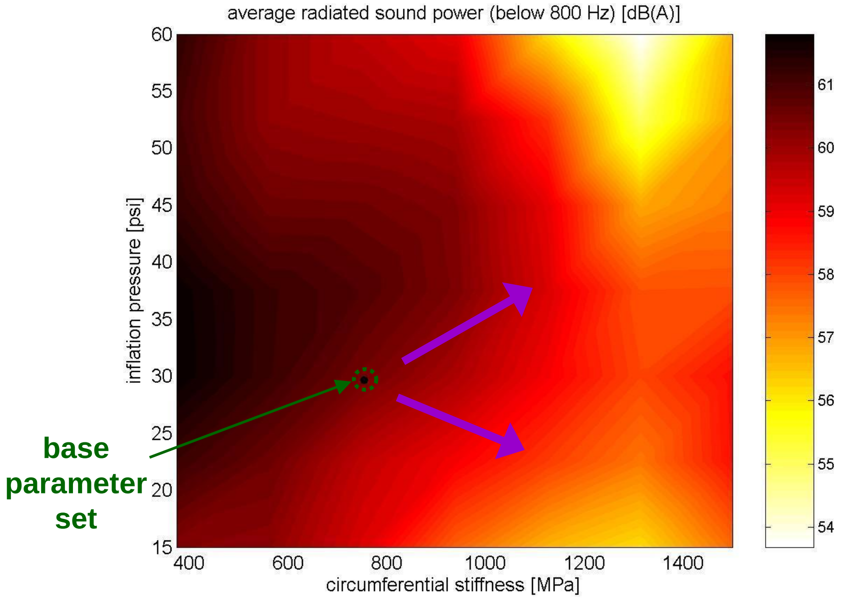
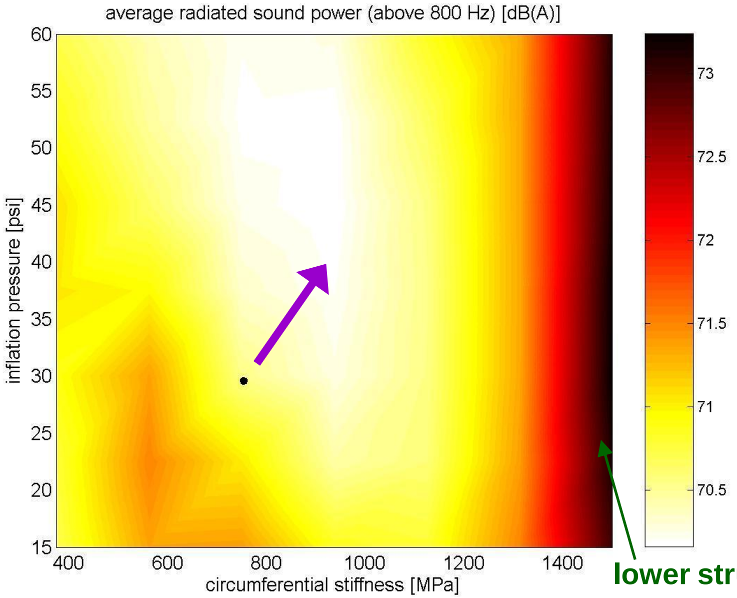
Radiated Sound Power Control

■ Influence of treadband circumferential stiffness and inflation pressure on averaged radiated sound power



base parameter set

[12.5 Hz – 800 Hz]



lower structural power region but higher phase speed

[800 Hz – 1600 Hz]

- An increase of treadband circumferential stiffness causes decrease of sound radiation.
- Extremely high treadband circumferential stiffness results in high sound radiation in the higher frequency region.

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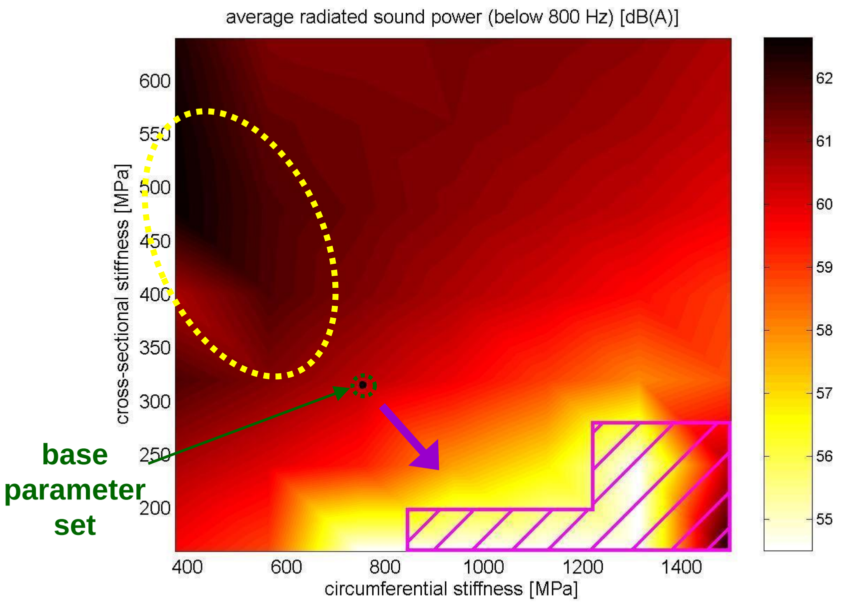
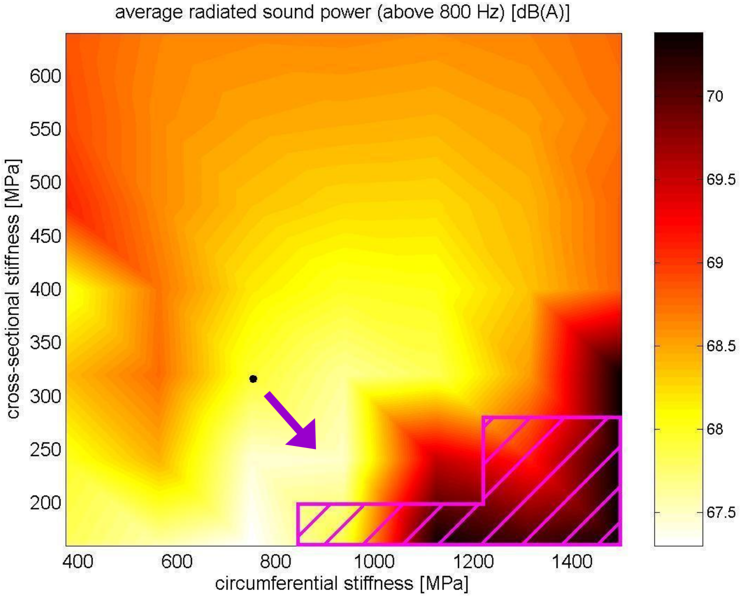
Radiated Sound Power Control

- **Influence of treadband circumferential and cross-sectional stiffnesses on averaged radiated sound power**



[12.5 Hz – 800 Hz]

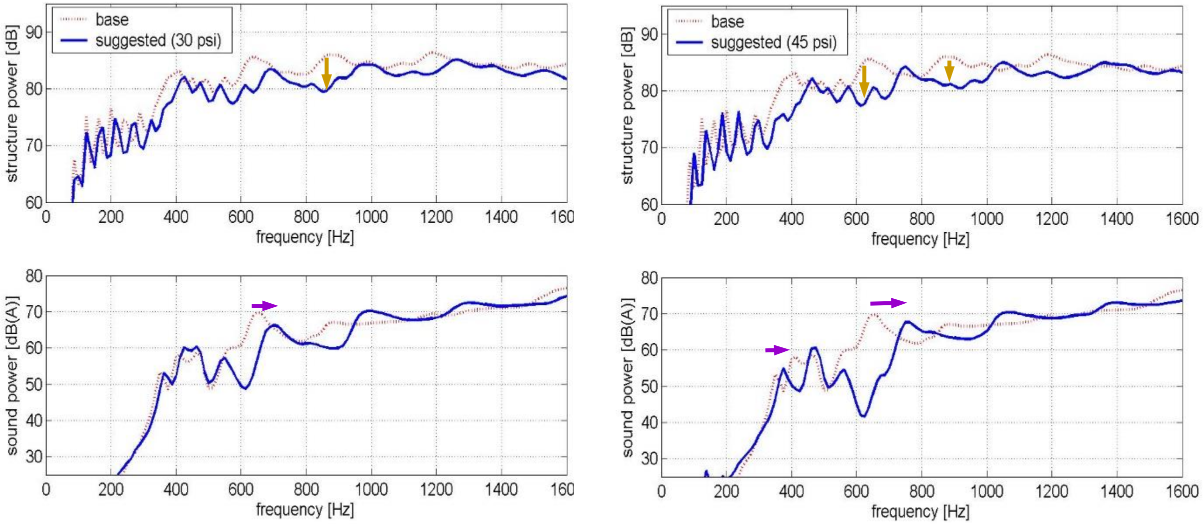


[800 Hz – 1600 Hz]

- Lower cross-sectional stiffness and higher circumferential stiffness is desirable.
- Radiated sound power control in the lower frequency region is related to the plot of cut-on frequency of 7th flexural wave mode.
- Higher power appears in the region whose cut-on frequency is around 625 Hz.

Tire Noise Optimization

■ Structural power and radiated sound power results



The higher pressure case causes less radiated power in the lower frequency region. But it cannot be used for practical reasons.

■ Optimized material parameter set

	treadband circumferential stiffness [MPa]	treadband cross-sectional stiffness [MPa]	Inflation pressure [psi]
base	750	320	30
suggested	938	240	30 (45)

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Summary and Conclusions

- **Effective material parameters** were determined by considering their impact on the tire's ring frequency and the cut-on frequency of the flexural wave modes.
- **Structural wave control strategy** for reducing sound radiation from a tire was suggested.
- Optimized set of tire parameters that reduced noise emission compared to the base tire model was suggested.

- An increase of treadband circumferential stiffness moves the onset of longitudinal wave motion within the treadband into a higher frequency region.
- The cut-on of the flexural wave mode was controlled by inflation pressure and treadband cross-sectional stiffness as well as treadband circumferential stiffness.

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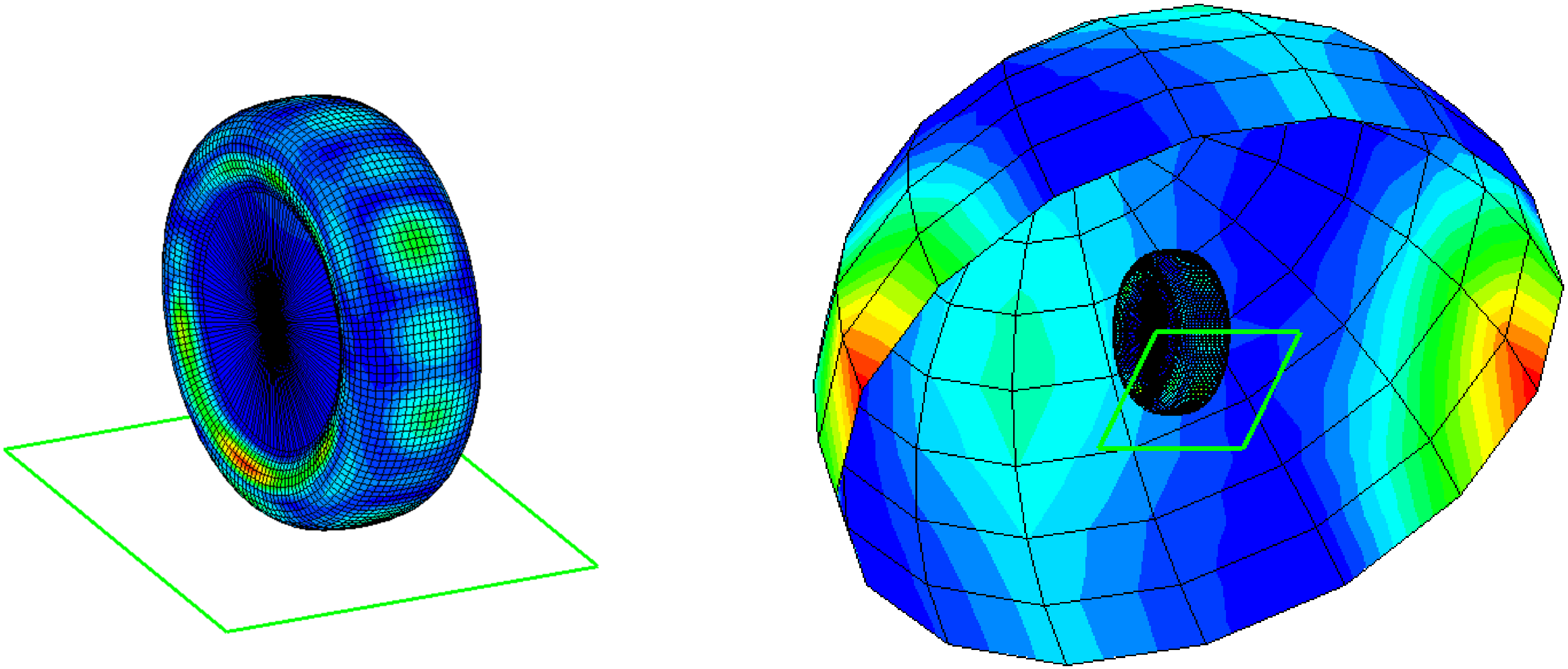
Questions

Thank you for attention.



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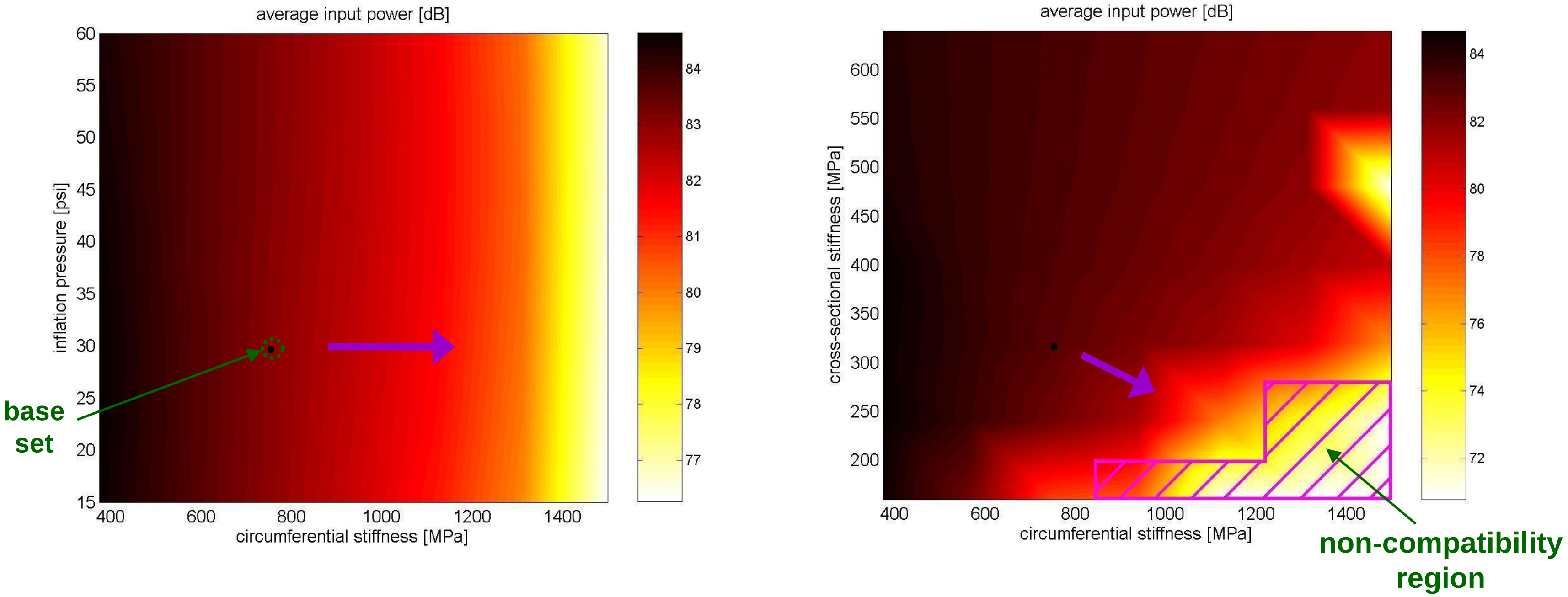
Structural Power Control

■ Averaged structural power (12.5 Hz – 1600 Hz) distribution



- An increase of the **treadband circumferential stiffness** causes structural power to decrease.
- Treadband cross-sectional stiffness and inflation pressure can affect characteristic frequencies of the flexural waves, but do not have a major effect on their amplitude.

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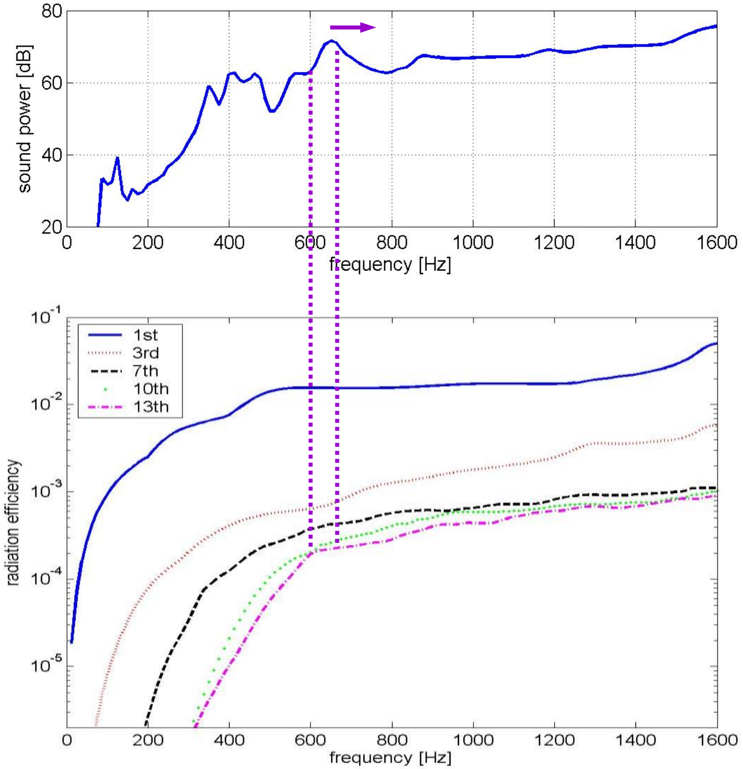
Structural Wave Control Strategy (2)

- **None of the flexural wave modes should cut on in the frequency region between 600 Hz and 650 Hz.**
  - The radiation efficiencies of sound radiation modes, which match with the velocity distribution at the cut-on frequency of the flexural wave mode, converge between 600 Hz and 650 Hz.

    [Yum & Bolton (2004)]



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