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The Reduction of Tire/Road Interaction Noise

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The Reduction of Tire/Road Interaction Noise

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Introduction

• Tire/Road noise is everywhere.

• In many locations establishes background noise levels.

• Numerous source mechanisms (controversy?)

• Here, concentrate on radiation from vibration of the tire and implications regarding potential for noise reduction.
Tire Vibration and Sound Radiation

- Three components of sound radiation from tire vibration
  - Input force distribution
  - Vibration response of tire
  - Sound radiation

- Wave number transform analysis make possible an integrated approach to these three topics

Future work

Addressed in the current work

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Contents

• Measurement of Stationary Tire Vibration
  – Dispersion Curves

• Modeling of Tire Vibration
  – Full tire model
  – Parametric Study

• Sound Radiation Calculations (SYSNOISE)
  – Frequency response: Sound Power and Radiation Efficiency
  – Relation between Dispersion Curves and Sound Radiation
  – Source of passby noise
PART 1: Wave Number Domain Analysis of Stationary Tire Vibration
Wave Number Decomposition

Phase speed: Since

\[ \lambda = c_p T \quad \Rightarrow \quad c_p = \frac{\omega}{k} \]

Group speed:

\[ c_g = \frac{d\omega}{dk} \]

- Wave number gives information about wave propagation speed and attenuation
EXPERIMENTAL DISPERSION RELATIONS

Circumferential Modes
- \( n = 0 \)
- \( n = 1 \)
- \( n = 2 \)

Cross-sectional Modes
- Fast extensional modes
  - \( m = 1 \)
  - \( m = 7 \)
  - \( m = 5 \)

Slow flexural modes
- \( m = 3 \)

\( \theta \): circumferential direction

Force
Radial Acceleration Level

40 psi inflation pressure

154 Hz: m=3
356 Hz: m=5
Circumferentially Averaged RMS Velocity

(a) Inflation Pressure: 20 psi

(b) Inflation Pressure: 40 psi

• Overall vibration dominated by flexural wave groups.
TIRE CARCASS DISPERSION CHARACTERISTICS - Static

- Tire carcass vibration is composed of superposition of “waveguide modes”
- Circumferential modes occur when $k_\theta \pi d = 2n\pi$
Stationary Tire Vibration - Conclusions

- Wave number/Frequency spectrum of stationary tire vibration is the tire’s “fingerprint”.
- Tire behaves like a waveguide: i.e., various propagating cross-sectional modes cut-on as the frequency increases.
- Tire vibration is controlled by a small number of propagating modes (six below 1000 Hz).
- High phase speed components are associated with longitudinal wave motion coupled to flexural motion by tire curvature and they can radiate effectively.
PART 2: Tire Modeling

- Full Tire Model
- Parametric Study
FULL FE MODEL

Sampling points

θ

Thickness

x

y

Sampled points

Curve fitting

x [m]
y [m]

Sampled points

Curve fitting

x [m]

Sampled points

Curve fitting

θ [deg]

Thickness [m]

0 20 40 60 80

4

5

6

7

8

9

10

11

10^{-3}

0 20 40 60 80

4

5

6

7

8
Full FE Tire Model (ANSYS)

- **Treadband**
  - $E_\theta = 7.5 \times 10^8$ Pa
  - $E_z = 3.2 \times 10^8$ Pa
  - $E_r = 7.5 \times 10^6$ Pa
  - $\nu_{\theta z} = 0.45$
  - $\nu_{zr} = 0.35$
  - $\nu_{\theta r} = 0.35$
  - $G_{\theta z} = 5.0 \times 10^7$ Pa
  - $\rho = 1200$ kg/m$^3$

- **Sidewall**
  - $E_\theta = 7.5 \times 10^6$ Pa
  - $E_r = 5.0 \times 10^7$ Pa
  - $\nu_{\theta r} = 0.45$
  - $G_{\theta z} = 1.5 \times 10^6$ Pa
  - $\rho = 800$ kg/m$^3$

[ ▶ Element Type: Shell63, ▶ Number of Elements: 1368 ]
Effect of Treadband Longitudinal Stiffness

- As stiffness goes up, ring frequency and cut-on frequencies of flexural modes increase.
Tire Modeling – CONCLUSIONS

- Models can be used to establish which design parameters control features in dispersion curves.
- Tire design parameters can control location and character of various features in the dispersion relations that are related to sound radiation.
- Full FE model will be used to generate input for sound radiation prediction.
PART 3: Sound Radiation

- resulting from tire carcass vibration (calculated using ANSYS)
- modeling the ground effect
- wave number/frequency sound power distributions
Modal Radiation Procedure

Reconstruction of surface velocity related only with a particular root on dispersion relation.

By frequency-wavenumber filtering or Prony Series Method

Sound intensity on a sphere surrounding tire

Input for BEM (Surface normal velocity)

Mapping on the dispersion relation with an acoustic weighting calculated from the radiation efficiency

Radiation Efficiency
Sound Radiation Procedure

Harmonic FE Results

Input for BEM (Surface normal velocity)

Input Power

Model in indirect BEM

Sound Intensity on a hemisphere surrounding tire

Sound Power & Radiation Efficiency
- Import FE (ANSYS) model and vibration data for a tire
- Use quarter model with 3 symmetry planes
  (one of the planes creates an image tire.)
Sound Power

Sound Radiation Comparison (Ground effect)

- Compared with single tire in free space, output power peak appears at 880 Hz when ground effect included.
- Peak at 880 Hz results from Horn effect (geometric effect).

Effect of Tire Width (Horn Effect)

As tire geometry changes, sound power peak at 928 Hz in base case translates. As tire width increases, horn effect frequency goes down.

[Graphs and diagrams showing sound power and input power variation with frequency for different tire widths.]

[Same material properties applied]
Effect of Treadband Longitudinal Stiffness

- As stiffness decreases, input power generally goes up, input power peaks occur at lower frequencies, and output power peaks below 400 Hz shift to lower frequencies.
- Output power peaks at 880 Hz, not specifically related to input power peaks and occur in all cases, which indicates horn effect.
Radiation Efficiency

Effect of Treadband Longitudinal Stiffness

- Radiation efficiency characteristics are similar to output power’s.
- As stiffness goes down, peaks below 500 Hz occur at progressively lower frequencies.
- Peaks inside the red circle relate to cut-on frequencies of fast longitudinal modes.

# Radiation Efficiency : \( \sigma = \frac{W}{\rho c S \langle v_n^2 \rangle} \)
Sideline Sound Levels

Effect of Treadband Longitudinal Stiffness

- SPL characteristics are similar to output power’s.

- As stiffness goes down, peaks below 500 Hz occur at lower frequencies, and SPL above 800 Hz go up.

[ Measuring Position: 7.5m from the tire side, 1.2m from the ground, same as in passby test ]
- Flexural modes relate to input power. Cut-on frequencies of flexural modes correspond to input power peaks.

- Fast longitudinal mode relates to output power. Low wave number components correspond to output power peaks below 800 Hz.
Tire Dispersion Relations

\[ E_\theta = 4.5 \times 10^8 \text{Pa} \]
Tire Dispersion Relations

▶ $E_\theta = 1.0 \times 10^8$ Pa
## Radiation Patterns

<table>
<thead>
<tr>
<th></th>
<th>High Stiffness ($E_\theta=7.5e8$)</th>
<th>Med Stiffness ($E_\theta=4.5e8$)</th>
<th>Low Stiffness ($E_\theta=1.0e8$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>176Hz</td>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
<td><img src="image3.png" alt="Diagram" /></td>
</tr>
<tr>
<td>S/Power</td>
<td>4.765e-10 W</td>
<td>5.211e-10 W</td>
<td>1.799e-7 W</td>
</tr>
<tr>
<td>288Hz</td>
<td><img src="image4.png" alt="Diagram" /></td>
<td><img src="image5.png" alt="Diagram" /></td>
<td><img src="image6.png" alt="Diagram" /></td>
</tr>
<tr>
<td>S/Power</td>
<td>1.706e-8 W</td>
<td>8.242e-7 W</td>
<td>7.311e-8 W</td>
</tr>
</tbody>
</table>

- Model: Double Tires w/o Ground
- Field Points: Rectangular Plane 0.05m to the side of the Tire
Wave Number Radiation Procedure

Dispersion Relations

Wave Number-Frequency Filtering

Sound Power Distribution

BEM

Sound Power & R/Efficiency Calculation

Inverse Wave Number Transform

Reconstruction of Surface Normal Velocity: Input for BEM

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Wave Number Filtering

- Purpose: To identify the influence of wave number on sound power
- Pass velocities corresponding to only one wave number in wave number domain
Sound Power Distribution

Sound power distribution in wave number domain

- Sound power below 800 Hz is dominated by low wave numbers.
- Especially wave numbers for fast longitudinal mode contribute strongly to sound power below 800 Hz.
- Sound power at the frequency where horn effect appears is affected by broad range of wave numbers.
Radiation Efficiency Distribution

- R/Efficiency distribution characteristics is similar to sound power distribution’s.
- Fast longitudinal mode contributes strongly to R/Efficiency below 800 Hz.
- Flexural mode effect cannot be seen in R/Efficiency plot.
- R/Efficiency at horn effect frequency is affected by broad range of wave numbers.
Cumulative Sound Power Curve

- Sound power below 800 Hz is dominated by low wave numbers relating to fast longitudinal wave. Especially over 95% sound power at 400 Hz corresponding to ring frequency results from zero wave number.

- Sound power above 800 Hz is mainly affected by flexural waves. Sound power at 928 Hz where horn effect appears is also mainly affected by flexural waves.
**Low Wave Number Effect**

- Sound power below 800 Hz is dominated by low wave numbers.
- Especially 0 & 1 wave number components contribute strongly to sound power below 800 Hz.
- As wave number increases, sound power above 800 Hz increases.

▶ total: Total sound power  
▶ sum1: Sound power sum up to wave number 1  
▶ sum5: Sound power sum up to wave number 5
Sound Power Distribution

Effect of Treadband Longitudinal Stiffness

- $E_\theta=1.0\times10^8\text{Pa}$
- $E_\theta=7.5\times10^8\text{Pa}$ (Base)
- $E_\theta=1.2\times10^9\text{Pa}$
Effect of Treadband Longitudinal Stiffness

$E_\theta = 1.0 \times 10^8$ Pa

$E_\theta = 7.5 \times 10^8$ Pa (Base)

$E_\theta = 1.2 \times 10^9$ Pa
Sound Power Distribution

- As stiffness increases, frequencies relating to fast longitudinal waves go up, and frequency upper limit in sound power dominated by low wave numbers goes up.

- When the frequency where horn effect appears coincides with cut-on frequencies of flexural waves, \((E_\theta=7.5E+8Pa)\) sound power at the horn effect frequency is affected by flexural waves.

- Sound power at frequencies above the horn effect frequency is mainly affected by flexural waves. But as stiffness increases, low wave number contribution to sound power in this region increases.
Strategy for Passby Noise Reduction

- Eliminate low wave number components by controlling stiffness parameters of tire.
- Design tread to suppress forcing in flexural wave region.
- Structural modifications to tire to prevent wave propagation in horn effect region.

Sound Power Distribution

- Narrowband wave number filter: tread design to suppress contribution from this region
- Adjust stiffness parameters to reduce contribution from this region
Summary (Sound Radiation)

- BEM can be used to predict radiation from tires – directivity, total sound power and radiation efficiency.
- Procedures for calculation of sound power based on wave number have been developed.
- Relation between dispersion curves and sound radiation has been established.
- Sound radiation below 800 Hz is controlled by low wave number components of tire vibration.
- Flexural wave motion mainly contributes to horn effect.
Conclusions

• Wave number analysis has made it possible to highlight the tire vibration components that contribute significantly to sound radiation.

• Results suggest that passby noise can be reduced by a combination of structural modification and tread design.
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