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Finite Element Study of Acoustic Mode Force Transmission in a Loaded, Structural-Acoustical Tire Model

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Force transmission characteristics for a loaded structural-acoustic tire model

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Rui Cao and J. Stuart Bolton
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I. Introduction

- Traffic noise
  - Vehicle noise
  - Roadside residences
    - Power Unit noise
    - Aerodynamic noise
    - Tire/pavement noise
  - Transfer paths
  - Interior noise

- Passengers
I. Introduction

- High frequency interior noise is mostly airborne and usually is not associated with structural vibration from road excitation. However, low frequency noise, has a strong association with structural vibration and can be perceived by the passengers.
- A major component of structure-borne noise comes from the tire’s acoustic cavity mode near 200 Hz

**Why do two tires of same size and geometry, from different manufacturers, have very different responses, in terms of cavity noise perception?**

- Study force transmission from contact patch excitation to rim center
- How the cavity resonance may affect force transmission
- Ways of identifying bad tires/good tires, in terms of structure-borne noise
A Finite Element structural-acoustical tire model was created to investigate the tire cavity-induced structure-borne noise

- Create realistic tire-road contact patch
- Point excitation at the contact patch edge
- Calculate dispersion relation in tire tread to identify vibration modes, as from test results
- Calculate force transmission from excitation location to the rim center, to act as input for full vehicle analysis
- Comparison study to identify the influencing factors
II. Finite element tire model

All modeling was performed in Abaqus 6.13

Assembled model
Air cavity model
Meshed assembled model

A 245/40R20 tire was used for dimension
II. Finite element tire model

All parts are using homogeneous material

<table>
<thead>
<tr>
<th>Part</th>
<th>Density [kg/m³]</th>
<th>Modulus [Pa]</th>
<th>Thickness [mm]</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rim</td>
<td>2700</td>
<td>7×10¹²</td>
<td>10</td>
<td>0.3</td>
</tr>
<tr>
<td>Tread</td>
<td>1200</td>
<td>7.5×10⁸</td>
<td>10</td>
<td>0.45</td>
</tr>
<tr>
<td>Sidewall</td>
<td>800</td>
<td>5×10⁷</td>
<td>8</td>
<td>0.45</td>
</tr>
<tr>
<td>Air</td>
<td>1.204</td>
<td>149180</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

- Material properties were simplified and approximated
- Rim was set to be very stiff, so it’s resonances were above the frequency of interest in this study
- Air bulk modulus was given at 97 °F
III. Analysis process

Overview

- CAD model creation
- Model structure assignment
- Material property assignment

Create analysis steps and select solvers

- Boundary condition setting
- Loading application

Calculation

Data visualization and post processing
III. Analysis process

**Boundary conditions**

- **Continuity boundary**: Tread – Air Cavity, Sidewall – Air Cavity, Rim – Air Cavity. “TIE” function was applied to enforce the two surfaces stay in contact at all times.

- **Contact boundary**: Tread surface – rigid ground. Ground is considered rigid in the normal direction; a small friction coefficient is added to increase solution robustness (prevent tire sliding horizontally as the contact starts).
### III. Analysis process

**Excitations**

**Vertical static loads**
1300 lbs (approximately 6000 N) applied at the rim center – with 650 lbs on each side

**Static inflation pressure**
A $2.05 \times 10^5$ Pa inflation pressure was applied to all tire interior cavity surfaces

**Point harmonic excitation**
A 1 N point harmonic point excitation over the investigated frequency range was applied at the contact patch leading edge
III. Analysis process

**Analysis Steps**

- **Initial step – fix rim center**
- **Step 1 – Tire inflation** - rim center is still fixed
- **Step 2 – Apply vertical load** - rim center is released - require adaptive mesh of the air cavity
- **Step 3 – Modal analysis** - extract modes from 10 Hz to 320 Hz
- **Step 4 – Forced response calculation** - direct approach - 0.5 Hz increment
IV. Data visualization and comparison study

- What to expect from the results
  - Surface velocity of the tire tread – identify vibration modes
  - Dispersion relation of the tire tread – identify wave types
  - Rim center acceleration – force transmissibility study
  - Cavity and structural mode shapes

Contact patch area
IV. Data visualization and comparison study

Spatial Surface velocity - unloaded tire

Velocity was measured at points along the tire tread centerline

Dispersion relations - unloaded tire

Dispersion was based on the wavenumber decomposition of the surface mobility data
Vertical cavity mode (pressure distribution)

Deformation causes cavity resonance split
One occurs below undeformed cavity resonance (horizontal)
One occurs above undeformed cavity resonance (vertical)

Undeformed resonance: 200.1 Hz; vertical mode: 201.4 Hz; horizontal mode: 199.3 Hz
IV. Data visualization and comparison study

For GY245/40R20 tire, the material property of the tread was modified to be soft (low stiffness), medium (medium stiffness) and stiff (high stiffness) to align the \textit{vertical cavity resonance} to either the symmetric circumferential 8\textsuperscript{th} mode or the asymmetric circumferential 9\textsuperscript{th} mode of the treadband.

<table>
<thead>
<tr>
<th>Status</th>
<th>Modulus</th>
<th>Alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft</td>
<td>$4.5\times10^8$</td>
<td>9\textsuperscript{th} mode</td>
</tr>
<tr>
<td>Medium</td>
<td>$6.0\times10^8$</td>
<td>In between</td>
</tr>
<tr>
<td>Stiff</td>
<td>$10.0\times10^8$</td>
<td>8\textsuperscript{th} mode</td>
</tr>
</tbody>
</table>

Point excitation located at the contact patch on the tread centerline, toward the rim center. Most forcing component is in the vertical direction (+Z)
IV. Data visualization and comparison study

Rim center acceleration comparison

Peak at frequency corresponding to horizontal acoustic cavity mode
IV. Data visualization and comparison study

Rim center acceleration comparison

Peak at frequency corresponding to horizontal acoustic cavity mode
Levels are 100 times smaller 
Compared to x and z direction

Very low levels in the y-direction – some axial component due to the rim profile
IV. Data visualization and comparison study

Rim center acceleration comparison

Peak at frequency corresponding to vertical acoustic cavity mode
IV. Data visualization and comparison study

Rim center acceleration comparison

Peak at frequency corresponding to vertical acoustic cavity mode
IV. Data visualization and comparison study

**Spatial mobility comparison**

Low stiffness material

Medium stiffness material

High stiffness material

As stiffness increase, the spatial patterns move toward high frequency region

- Low stiffness – cavity mode matches 9th structural mode
- High stiffness – cavity mode matches 8th structural mode
IV. Data visualization and comparison study

As stiffness increase, the dispersion curve becomes narrower, indicating faster waves
IV. Data visualization and comparison study

Resultant mobility in X direction

Resultant mobility – vector sum of mobility around tire in horizontal direction

199.3 Hz
IV. Data visualization and comparison study

Resultant mobility in X direction

Resultant mobility – vector sum of mobility around tire in horizontal direction
IV. Data visualization and comparison study

Resultant mobility in Z direction

Resultant mobility – vector sum of mobility around tire in vertical direction

204.8 Hz
IV. Data visualization and comparison study

Resultant mobility in Z direction

Resultant mobility – vector sum of mobility around tire in vertical direction

204.8 Hz
V. Modal analysis

1st cavity mode - horizontal

Side views

Radial displacement
V. Modal analysis

1\textsuperscript{st} cavity mode - horizontal

Top view

Vertical motion components were canceled, leaving only horizontal motions.
V. Modal analysis

1st cavity mode - vertical

Side views

-X

+X
V. Modal analysis

1st cavity mode - vertical

Horizontal motion components were canceled, leaving only vertical motion.
V. Modal analysis

8th structural mode

Side views
V. Modal analysis

8\textsuperscript{th} structural mode

Top view

Motion on two sides cancel each other
V. Modal analysis

9th structural mode

Side views
V. Modal analysis

When 9th circumferential structural mode has same frequency as the vertical cavity mode, large response is observed
VI. Compare with airless case

*Compare with a model without air cavity*
VI. Compare with airless case

Compare with a model without air cavity

with air cavity

8th mode

9th mode

10th mode

without air cavity

8th mode

9th mode

10th mode

Zoom view of the cavity resonance frequency region
VI. Compare with airless case

**Compare with a model without air cavity**

Without air – fore-aft motion is substantially reduced near 200 Hz
VI. Compare with airless case

**Compare with a model without air cavity**

Without air vertical motion is substantially reduced near 200 Hz
A finite element tire model was created, which simulated tire inflation, static loading toward a rigid surface and modal analysis.

Reaction forces/acceleration at rim center were obtained, along with tread surface mobility and dispersion relations.

The coupling relation between cavity resonances and structural resonances were studied and odd-number structural modes were found to couple well with the vertical cavity mode due to similar mode shapes.

Force transmission was related to whether a net motion of the tire tread was created at a particular frequency.

A case without internal air cavity was simulated as an additional verification.
Appendix

Reference
Rui Cao, J. Stuart Bolton, Tire cavity induced structure-borne noise study with experimental verification, INTER-NOISE and NOISE-CON Congress and Conference Proceedings, 2018 (Conference submission)

Acknowledgement
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