A Laboratory Procedure for Measuring the Dispersion Characteristics of Loaded Tires

Won Hong Choi  
*Purdue University*, choi123@purdue.edu

J Stuart Bolton  
*Purdue University*, bolton@purdue.edu

Dan Haakenson  
*Ford Motor Company*

Matthew Black  
*Ford Motor Company*

Follow this and additional works at: [https://docs.lib.purdue.edu/herrick](https://docs.lib.purdue.edu/herrick)
A LABORATORY PROCEDURE FOR MEASURING THE DISPERSION CHARACTERISTICS OF LOADED TIRES

Won Hong Choi, J. Stuart Bolton, Dan Haakenson†, Matthew Black†
Ray W. Herrick Laboratories, Purdue University
†Ford Motor Company
1. Background and Objective

2. Design of Test Rig

3. Modal Analysis

4. Impact Hammer Test

5. Experiment with Laser Doppler Vibrometer

6. Conclusion
Background and Objective

Research background (1/2)

- Tire/road noise is becoming more significant with the advent of Electric Vehicles (EVs)
- Acoustic cavity mode usually happens around at 200 Hz depending on the size of tire and inflation
- It has been identified as a key contributor to cabin noise and transmitted force in a suspension system

Source: Sakata and et al. (1990) [1]

Source: Bruel and Kjaer website
Background and Objective

Research background (2/2)

- Deformed tire can break geometrical symmetry, which produce two acoustic modes [2]
- Need to identify ‘Frequency-split’ of the cavity mode for deformed tires experimentally

Source: Yamauchi and Akiyoshi (2002) [3]

Background and Objective

Research objective

- Test rig should be designed to observe the **dispersion behavior** of **deformed tires** when measured with laser doppler vibrometer (LDV): i.e., type and speeds of waves in the coupled, stationary tires

Design requirements

1. Avoid structural resonance between **200 and 300 Hz**
2. Capability of deforming on tires with a specific load
3. Economical, compact and robust structure
Conceptual design

- Horizontally positioned tire is beneficial since higher natural frequency comes from short vertical support that can be achieved with a light-weight structure.

(a) Vertically positioned tire

(b) Horizontally positioned tire
Physical overview

- Test rig consists of testbed, loading device, and shaker support
Design of Test Rig

Testbed

- Mounted on commercial steel floor with T slot
- Adapter is compatible with two different bolt radii

36.8 kg (carbon steel), Unit [mm]
Design of Test Rig

Loading device

- Equipped with a slide table to adjust height
- Impose deformation on the tire using screw jack and patch

61.2 kg (carbon steel & Al), Unit [mm]
Design of Test Rig

**Shaker support**

- Compatible with mini shaker (B&K 4810)
- Adjustable height by incorporating a long slot

4.5 kg (Al), Unit [mm]

![Diagram of the design of the test rig with details on the shaker support and dimensions.]
Modal Analysis

Verification for cantilever beam

- Preliminary study on reliability of simulation software, Abaqus 2018
- Simulation results conform to the analytical calculation [5]

1(L)×0.1(W)×0.1(H), steel

\[ f_1 = \frac{1.875^2}{2\pi L^2} \sqrt{\frac{E}{\rho A}} = 80 \text{ Hz} \]

(refer to Appendix)

(a) 1-D mesh
(b) 3-D mesh
Boundary and load

- Tie condition is applied for welding and assembly with fixed mounting
- Tire is modeled as a combination of point mass, spring, and static force to simulate deflection

- Point mass for tire (33 kg)
- Spring (515 N/mm)
- Force (7505 N)
- Fix (four mounted)

- Tie (welded and assembled)
- Point mass for patch (2.5 kg)
- Spring (515 N/mm)
- Force (7505 N)
- Simply supported
Modal Analysis

Simulation results

- Testbed

(a) without tire
900 Hz

(b) with tire
312 Hz
Simulation results

- Loading device & Shaker support

(c) Loading device 433 Hz
(d) Shaker support 1670 Hz
Impact Hammer Test

Test setup

- To confirm the results of numerical modal analysis
- Three-axis accelerometer is attached to a point where coherence factor is above 0.8

(a) without tire

(b) with tire under loaded

(refer to Appendix to see lists of measurement devices)
Impact Hammer Test

Test setup

- To confirm the results of numerical modal analysis
- Three-axis accelerometer is attached to a point where coherence factor is above 0.8

(c) shaker in support

(refer to Appendix to see lists of measurement devices)
Impact Hammer Test

Results for testbed

- First natural frequency beyond 300 Hz for both cases, which conforms to numerical results

(a) without tire

Frequency Response H1, Magnitude

806 Hz (c.f. 900 Hz)

(b) with tire

Frequency Response H1, Magnitude

352 Hz (c.f. 312 Hz)
Impact Hammer Test

Results for loading device and shaker

- First natural frequency beyond 300 Hz for both cases, not perfectly matching prediction

(c) Loading device

569 Hz (c.f. 433 Hz)

(d) Shaker support

2094 Hz (c.f. 1670 Hz)
Impact Hammer Test

Summary

- Testbed has good agreement between numerical and experimental first natural frequency
- Loading device has a small discrepancy due to difficulty in fine modeling of moving slide and screw jack
- Shaker support matches reasonably well even though shaker modeling is challenging

<table>
<thead>
<tr>
<th>Description</th>
<th>FEM Mode</th>
<th>Test Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Testbed</td>
<td>900 Hz</td>
<td>806 Hz</td>
</tr>
<tr>
<td>Testbed with assembly</td>
<td>312 Hz</td>
<td>352 Hz</td>
</tr>
<tr>
<td>Loading device</td>
<td>433 Hz</td>
<td>569 Hz</td>
</tr>
<tr>
<td>Shaker support</td>
<td>1670 Hz</td>
<td>2094 Hz</td>
</tr>
</tbody>
</table>
Experiment with laser doppler vibrometer (LDV)

Schematic diagram
- Surface vibration on the sidewall under load can be detected from the top side

Measurement points on sidewall
106 EA

D=0.54 m
Experiment with laser doppler vibrometer (LDV)

Test Apparatus

- Mobility data can be obtained by measuring surface velocity and force for the deformed tire
- Static force (7505 N) is maintained through monitoring a load cell
Experiment with laser doppler vibrometer (LDV)

Test Apparatus

- Mobility data can be obtained by measuring surface velocity and force for the deformed tire
- Static force (7505 N) is maintained through monitoring a load cell
Example of measurement (20” tire)

- Dispersion curve is achieved by applying Fourier transform to spatial mobility

Unloaded

Dispersion

- Acoustic (346 m/s)
- Longitudinal (~320 m/s)
- Flexural (~53 m/s)

Loaded

Dispersion

\[ f_1 = \frac{c}{\lambda} = \frac{346 \text{ [m/s]}}{2\pi r} = 204 \text{ Hz} \]
\[ k = \frac{1}{r} = 3.7 \text{ rad}^{-1} \text{ (n=1)} \]
Conclusion

- Compact and cost efficient test rig was designed to measure dispersion characteristics of loaded tires
  - Allows height adjustment with force loading device
- Dynamically rigid behavior was achieved beyond 300 Hz, which was validated by both modal analysis and impact hammer test
  - More reliable to investigate frequency split in the first acoustic mode between 200 and 300 Hz
- Laser Doppler Vibrometer was used to observe dispersion characteristics of loaded tires combined with the test rig
  - Validated usefulness of the new test rig, generating meaningful results for the deformed tire
- Next steps are to quantify frequency split as function of load and deformation
Acknowledgement

- Ford Motor Company – Financial support / Tire & wheel sample provider
- Matthew Black – Main coordinator of this project
- Dan Haakenson – Technical advice and industrial feedback
THANK YOU

Won Hong Choi
choi124@purdue.edu
Ray W. Herrick Laboratories

J. Stuart Bolton
bolton@purdue.edu
Ray W. Herrick Laboratories


Natural frequency of cantilever beam

- $1(L) \times 0.1(W) \times 0.1(H)$, steel

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus, $E$</td>
<td>210 GPa</td>
<td></td>
</tr>
<tr>
<td>Moment of inertia, $I$</td>
<td>$8.33 \cdot 10^{-6} \text{ m}^4$</td>
<td>$bh^3/12$</td>
</tr>
<tr>
<td>Density, $\rho$</td>
<td>8000 $\text{ kg/m}^3$</td>
<td></td>
</tr>
</tbody>
</table>

$$f_1 = \frac{1.875^2}{2\pi l^2} \sqrt{\frac{EI}{\rho A}} = \frac{1.875^2}{2\pi (1 \text{ m})^2} \sqrt{\frac{2 \cdot 10^{11} \text{ N/m}^2 \cdot 8.33 \cdot 10^{-6} \text{ m}^4}{8000 \text{ kg/m}^3 \cdot 0.01 \text{ m}^2}} = 80 \text{ Hz}$$
# Lists of equipment for tests

## Impact Hammer Test

<table>
<thead>
<tr>
<th>Type</th>
<th>Brand</th>
<th>Model</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAQ</td>
<td>B&amp;K</td>
<td>3560-B-130</td>
<td>Frequency resolution, 1 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Five exponential averaging</td>
</tr>
<tr>
<td>Impact Hammer</td>
<td>PCB</td>
<td>086C03</td>
<td>Uniform window</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>B&amp;K</td>
<td>4506</td>
<td>Hanning window</td>
</tr>
</tbody>
</table>

## LDV Test

<table>
<thead>
<tr>
<th>Type</th>
<th>Brand</th>
<th>Model</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDV</td>
<td>Polytec</td>
<td>PSV-400</td>
<td>Frequency resolution, 0.156 Hz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Five exponential averaging</td>
</tr>
<tr>
<td>Shaker</td>
<td>B&amp;K</td>
<td>4810</td>
<td>White noise</td>
</tr>
<tr>
<td>Force transducer</td>
<td>PCB</td>
<td>208A3</td>
<td>Hanning window</td>
</tr>
<tr>
<td>Amplifier</td>
<td>QSC</td>
<td>1080</td>
<td>Max. force, 5 N</td>
</tr>
<tr>
<td>Analog filter</td>
<td>Wavetek</td>
<td>852</td>
<td>40 Hz ~ 1 kHz</td>
</tr>
<tr>
<td>Load Cell</td>
<td>Futek</td>
<td>LCF450</td>
<td>Max. force 8,829 N</td>
</tr>
</tbody>
</table>
Configuration of T slot

3/4" bolt, 100 lb-ft