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Sound Radiation Modes of a Tire on a Reflecting Surface

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Sound Radiation Modes of a Tire on a Reflecting Surface

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Sound Radiation from a Tire

- **Significance of Tire Noise**
  - one of main sources in automotive noise, especially pass-by noise

- **Generation Mechanism of Tire Noise**
  - Radial vibration by tread impact
  - Tangential vibration by tread adhesion (slip/stick)
  - Air pumped out and sucked in
  - Amplification by horn effect
  - Tire cavity resonance

- **Objective:** sound radiation from a tire
  - To investigate 3-D radiation characteristics resulting from a tire and ground geometry using Acoustic Radiation Modal Analysis
  - To identify the relationship between structural wave propagation and its radiation characteristics
Analysis Procedure

[ Direct BEM ]
Acoustic Transfer Vector
Acoustic Radiation Mode calculation

SPL & Sound Intensity on a hemisphere surrounding a tire

[ Structural Harmonic FEM ]
Surface normal velocity

Sound Power Radiation Efficiency Radiation Mode Contribution

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Acoustic Transfer Vector (ATV)

\[ p_r = V_{ATVr}^T v_b \]

- relationship between surface normal velocities and radiated sound pressure in frequency domain
- dependent on geometry of vibrating surface, field point location and physical properties of acoustic medium
Acoustic Transfer Vector (ATV)

- **Helmholtz integral equation**

\[
p(\vec{x})\alpha(\vec{x}) = \int_S p(\vec{y}) \frac{\partial G(\vec{x}|\vec{y})}{\partial n_y} dS_y + j\rho \omega \int_S v(\vec{y}) G(\vec{x}|\vec{y}) dS_y
\]

- **Discretization**

- On the surface:
  \[\mathbf{A} \mathbf{p}_b = \mathbf{B} \mathbf{v}_b\]

- In far-field:
  \[p_r = \mathbf{d}^T \mathbf{p}_b + \mathbf{m}^T \mathbf{v}_b\]

\[\mathbf{p} = \mathbf{V}_{ATV}^T \mathbf{v}_b\]

\[\mathbf{p}_r = \mathbf{V}_{ATVr}^T \mathbf{v}_b\]

- **Acoustic Transfer Vector (ATV)**

\[\mathbf{V}_{ATV}^T = \mathbf{d}^T \mathbf{A}^{-1} \mathbf{B} \mathbf{m}^T\]

\[\mathbf{V}_{ATV}^T : \text{Acoustic Transfer Matrix}\]
Sound Radiation Mode

- Radiated sound power in far-field

\[ W = \sum_{r=1}^{R} \frac{|p_r|^2}{2\rho c} S_r = \sum_{r=1}^{R} \frac{p_r^* p_r}{2\rho c} S_r \rightarrow \]

\[ W = \sum_{r=1}^{R} \frac{v_b^H V_{ATV_r} V_{ATV_r}^T v_b}{2\rho c} S_r = v_b^H R v_b \]

apply \( ATV \) relationship

\[ R = \sum_{r=1}^{R} \frac{V_{ATV_r}^* V_{ATV_r}^T S_r}{2\rho c} : \text{Radiation Resistance Matrix} \]

- Sound Radiation Mode: resulting from eigenvector decomposition of radiation resistance matrix

\[ R = Q^H \Lambda Q \]

- normalized eigenvector \( Q \) : Sound Radiation Mode
- eigenvalue \( \Lambda \) : proportional to radiation efficiency
Structural FE Analysis

■ Tire Model
  ▶ based on 205/70R14.
  ▶ quarter tire model used to reduce calculation cost.
  ▶ orthotropic material properties applied on the tread band and sidewall. (provided by Continental Tire Co.)
  ▶ inflation pressure: 20 psi

■ Structural Harmonic Analysis
  ▶ Full Matrix Method performed using ANSYS.
  ▶ Harmonic point source was applied at the point of contact with the ground.

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Structural FE Results

- Wave number decomposition

\[ \text{Dispersion Curve} \]

- Circumferential wave number decomposition of structural velocities resulting from the harmonic FE analysis in the space-frequency domain was performed.

- Dispersion Relationship
  - **longitudinal wave**
    - high phase speed
    - first mode appears at the ring frequency
  - **flexural wave**
    - low phase and group speed
    - related to cross-sectional propagating wave
Radiation BE Model

- using Direct BEM in SYSNOISE.
- quarter tire model used in FE analysis (ANSYS) was imported.
- R7.5 sphere space (hemisphere) field points used for Pass-By Noise test.
- For reflecting surface radiation case, reflecting surface was modeled as rigid.

[ free space radiation ]
[ reflecting surface radiation ]

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Sound Radiation Mode (352 Hz)

- 1st mode: sidewall dominant
- 4th mode: ring mode on treadband

- 1st & 2nd mode: similar with free space radiation case but peak added on the contact patch area
Sound Radiation Mode (960 Hz)

[ free space radiation ]

[ reflecting surface radiation ]

- 1st - 5th mode:
  peaks located in the contact patch area
Radiated Sound Power

- Input power
  - Input power of reflecting surface radiation case is twice than that of free radiation case.
  - Peaks match cut-on frequencies of flexural waves.

- Radiated sound power
  - Radiated power peaks don’t match those of input power.
  - The peak at 352 Hz relates to ‘ring frequency’.
  - Radiated power for reflecting surface radiation case is amplified above 700 Hz due to ‘horn effect’.
Radiation Efficiency

- **Definition**: ratio of radiated power to input power

\[
\sigma = \frac{W}{\rho c S_y \langle |\vec{v}|^2 \rangle}
\]

where \( \langle > \) denotes space average

- **Radiation characteristics**
  - High radiation efficiency characteristics appears at ‘ring frequency’, 352 Hz, for both radiation cases.
  - Radiated power for reflecting surface radiation case is amplified above 700 Hz due to ‘horn effect’.
Radiation Efficiency of Radiation Mode

- Radiation efficiency of each radiation mode for a unit surface normal velocity

\[ \sigma_n = \frac{\lambda_n}{\rho c S_y} \]

proportional to eigenvalue of radiation resistance matrix

- Radiation efficiency of the 2nd mode of the reflecting surface case is higher above 700 Hz.

  strong radiation region from the contact patch area
Sound Power Contribution of Radiation Mode

- Sound power contribution of each radiation mode when combined with structural velocities
  
  \[ W = v^H_b Q^H \Lambda Q v_b = y^H \Lambda y = \sum_{n=1}^{N} W_n = \sum_{n=1}^{N} \lambda_n |y_n|^2 \]

  
  - Free space radiation
  - Reflecting surface radiation

- Free space radiation: mode number with high contribution increases as frequency increases.
- Reflecting surface radiation: 2\textsuperscript{nd} mode is dominant above 700 Hz.

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Summary and Conclusion

• Radiation characteristics of a 3-D tire model in contact with a reflecting surface and enclosed by a hemispherical recovery surface were studied by using acoustic radiation modes.

• The sound radiation resulting from the structural wave propagation was investigated.

• Sound radiation mode is good guide in tire structural noise control.

• Most tire vibration does not contribute to sound radiation.

• The fast longitudinal wave propagating through the treadband contributes on sound radiation at the tire’s ring frequency.

• The 2nd radiation mode above 700 Hz is principally responsible for the horn effect in the presence of reflecting surface.