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

Sound Power
Radiation Efficiency
Radiation Mode Contribution

[ Structural Harmonic FEM ]
Surface normal velocity

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Acoustic Transfer Vector (ATV)

\[ p_r = V^T_{ATVr} v_b \]

- 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

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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:
    \[ A p_b = B v_b \]
  - In far-field:
    \[ p_r = d^T p_b + m^T v_b \]

\[
p_r = V^T_{ATVr} v_b
\]
\[
p = V^T_{ATV} v_b
\]

- **Acoustic Transfer Vector (ATV)**
  - \( V^T_{ATVr} = d^T A^{-1} B m^T \)
  - \( V^T_{ATV} \) : Acoustic Transfer Matrix

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Sound Radiation Mode

Radiated sound power in far-field

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

apply

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

Radiation Resistance Matrix

\[ R = \sum_{r=1}^{R} \frac{V_{ATVr}^* V_{ATVr}^T}{2 \rho c} S_r \]

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

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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.
Structural FE Results

■ Wave number decomposition

▶ 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.

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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

[ Image: Diagram showing radiation modes at 352 Hz for free space and reflecting surface conditions. ]

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Sound Radiation Mode (960 Hz)

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

Radiation Mode at 960 Hz (1st)

Radiation Mode at 960 Hz (2nd)

Radiation Mode at 960 Hz (3rd)

Radiation Mode at 960 Hz (4th)

Radiation Mode at 960 Hz (5th)

[ free space radiation ]

[ reflecting surface radiation ]

sidewall

treadband

point contacting with reflecting surface

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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

  \[
  \sigma = \frac{W}{\rho c S_y \left< |v(\bar{y})|^2 \right>}
  \]

  where \(< >\) 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 2\textsuperscript{nd} 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

\[ W = v_b^H Q v_b = y^H \Lambda y = \sum_{n=1}^{N} W_n = \sum_{n=1}^{N} \lambda_n |y_n|^2 \]

- Free space radiation: mode number with high contribution increases as frequency increases.
- Reflecting surface radiation: 2nd 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 2\textsuperscript{nd} radiation mode above 700 Hz is principally responsible for the horn effect in the presence of reflecting surface.