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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

SYSNOISE - COMPUTATIONAL VIBRO-ACOUSTICS

[Direct BEM]

Acoustic Transfer Vector
Acoustic Radiation Mode
calculation

[Structural Harmonic FEM]
Surface normal velocity

SYSNOISE - COMPUTATIONAL VIBRO-ACOUSTICS

Model Mesh [1]
[C] Velocity B.C. (Amplitude)
Field Point Mesh [1]
[C] Intensity at 352.000 Hz (Amplitude, Normal Component)

SPL & Sound Intensity
on a hemisphere
surrounding a tire

Sound Power
Radiation Efficiency
Radiation Mode Contribution

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Acoustic Transfer Vector (ATV)

- ▶ 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:

$$\underline{p_r} = \mathbf{d}^T \mathbf{p}_b + \mathbf{m}^T \mathbf{v}_b$$

pressure at a field point
pressure & normal velocity on the boundary

$$p_r = \mathbf{V}_{\text{ATVr}}^T \mathbf{v}_b$$

$$\mathbf{p} = \mathbf{V}_{\text{ATV}}^T \mathbf{v}_b$$

pressure matrix at all field points
on the recovery surface

► $\mathbf{V}_{\text{ATVr}}^T = \mathbf{d}^T \mathbf{A}^{-1} \mathbf{B}$ **Acoustic Transfer Vector (ATV)**

► $\mathbf{V}_{\text{ATV}}^T$: Acoustic Transfer Matrix

Sound Radiation Mode

■ Radiated sound power in far-field

$$W = \sum_{r=1}^R \frac{|p_r|^2}{2\rho c} S_r = \sum_{r=1}^R \frac{p_r^* p_r}{2\rho c} S_r \quad \xrightarrow{\text{apply ATV relationship}} \quad W = \sum_{r=1}^R \frac{\mathbf{v}_b^H \mathbf{V}_{ATVr}^* \mathbf{V}_{ATVr}^T \mathbf{v}_b}{2\rho c} S_r = \mathbf{v}_b^H \mathbf{R} \mathbf{v}_b$$

$$\triangleright \quad \mathbf{R} = \sum_{r=1}^R \frac{\mathbf{V}_{ATVr}^* \mathbf{V}_{ATVr}^T}{2\rho c} S_r \quad : \text{ Radiation Resistance Matrix}$$

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

$$\mathbf{R} = \mathbf{Q}^H \mathbf{\Lambda} \mathbf{Q}$$

- ▶ normalized eigenvector $\mathbf{Q}$: **Sound Radiation Mode**
- ▶ eigenvalue $\mathbf{\Lambda}$: 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.

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

SYSNOISE - COMPUTATIONAL VIBRO-ACOUSTICS

SYSNOISE Default Model

full tire model
(4560 elements)

[free space radiation]

[reflecting surface radiation]

- ▶ 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.

Sound Radiation Mode (352 Hz)

[free space radiation]

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

point contacting
with reflecting surface

[reflecting surface radiation]

- 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]

point contacting
with reflecting surface

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

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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

$$\sigma = \frac{W}{\rho c S_y \langle |\vec{v}(\vec{y})|^2 \rangle}$$

where $\langle \rangle$ 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

$$\sigma_n = \frac{\lambda_n}{\rho c S_y} \quad \text{proportional to eigenvalue of radiation resistance matrix}$$

- 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

$$W = \mathbf{v}_b^H \mathbf{Q}^H \mathbf{\Lambda} \mathbf{Q} \mathbf{v}_b = \mathbf{y}^H \mathbf{\Lambda} \mathbf{y} = \sum_{n=1}^N W_n = \sum_{n=1}^N \lambda_n |y_n|^2$$

[free space radiation]

[reflecting surface radiation]

- ▶ Free space radiation: mode number with high contribution increases as frequency increases.
- ▶ Reflecting surface radiation: **2nd mode is dominant above 700 Hz.**

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.