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Sound Radiation Modes of a Tire on a Reflecting Surface

J Stuart Bolton
Purdue University, bolton@purdue.edu

Kiho Yum
Hyundai Motor Company

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Kiho Yum and **J. Stuart Bolton**

Ray W. Herrick Laboratories

Mechanical Engineering

Purdue university

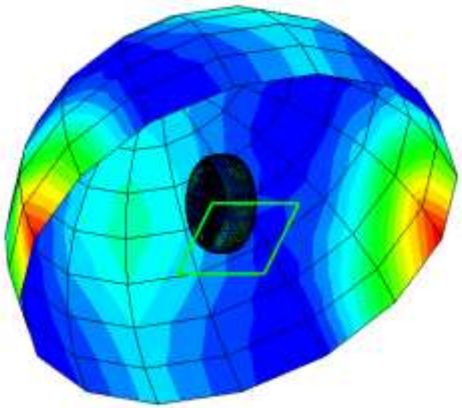
Sound Radiation from a Tire

■ **Significance of Tire Noise**

- one of main sources in automotive noise, especially pass-by noise

■ **Generation Mechanism of Tire Noise**

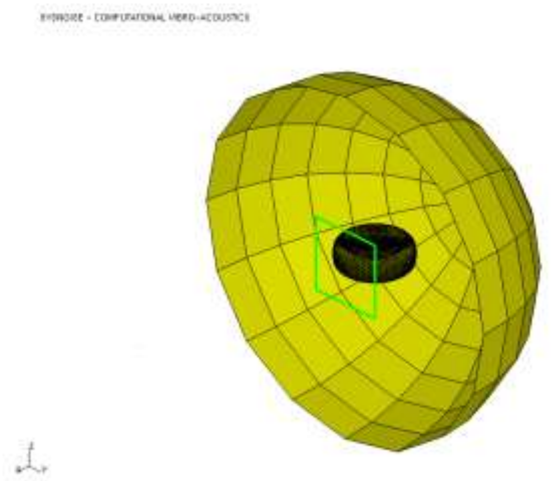
- **Radial vibration by tread impact**
- Tangential vibration by tread adhesion (slip/stick)
- Air pumped out and sucked in
- Amplification by **horn effect**
- Tire cavity resonance



■ **Objective: sound radiation from a tire**

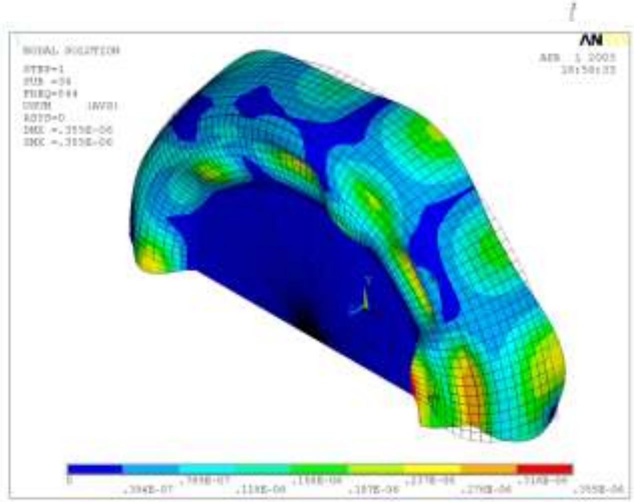
- To investigate 3-D radiation characteristics resulting from a tire and ground geometry using **Acoustic Radiation Modal Analysis**
- To identify the relationship between structural wave propagation and its radiation characteristics

Analysis Procedure

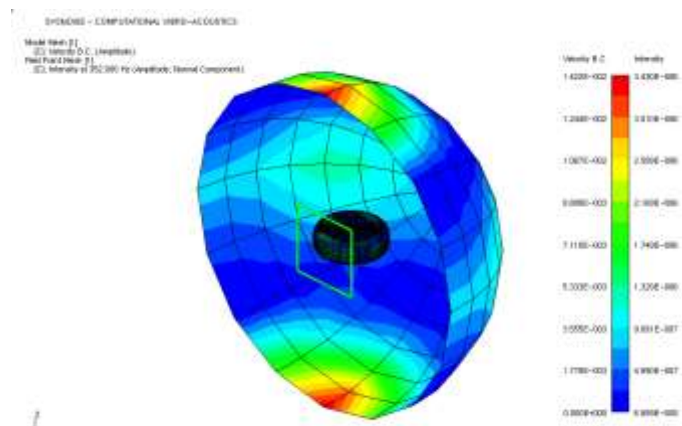


[Direct BEM]

Acoustic Transfer Vector
Acoustic Radiation Mode
calculation



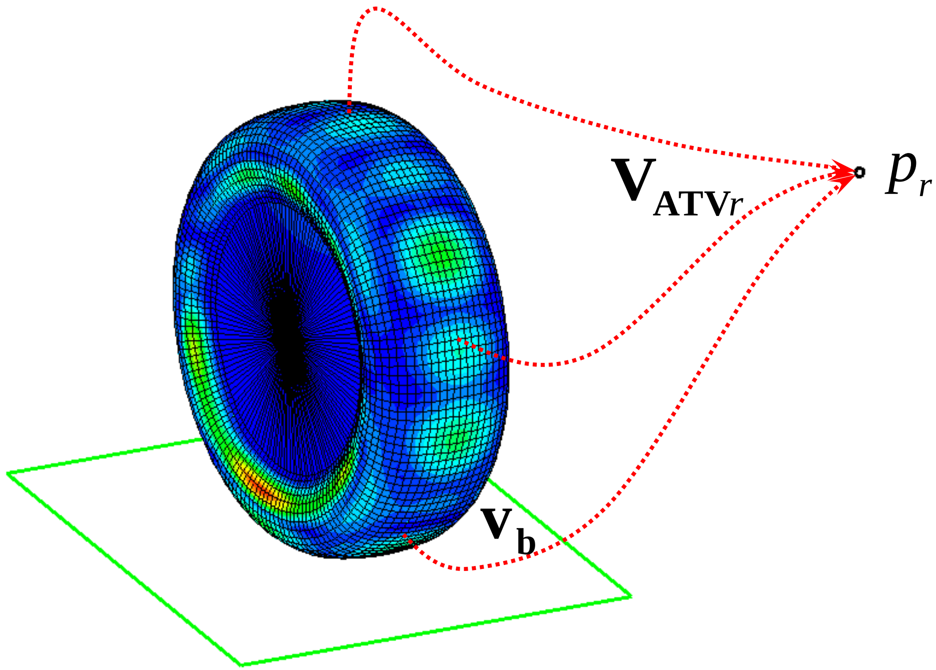
[Structural Harmonic FEM]
Surface normal velocity



SPL & Sound Intensity
on a hemisphere
surrounding a tire

Sound Power
Radiation Efficiency
Radiation Mode Contribution

Acoustic Transfer Vector (ATV)



$$p_r = \mathbf{V}_{\mathrm{ATV}r}^{\mathrm{T}} \mathbf{v}_{\mathrm{b}}$$

- 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: $p_r = \mathbf{d}^{\mathrm{T}}\mathbf{p}_b + \mathbf{m}^{\mathrm{T}}\mathbf{v}_b$

pressure at a field point

pressure & normal velocity on the boundary

$$p_r = \mathbf{V}_{\mathbf{ATV}r}^{\mathbf{T}} \mathbf{v}_{\mathbf{b}}$$

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

pressure matrix at all field points on the recovery surface

- ▶ $\mathbf{V}_{\mathbf{ATV}r}^{\mathbf{T}} = \mathbf{d}^{\mathrm{T}}\mathbf{A}^{-1}\mathbf{B} + \mathbf{m}^{\mathrm{T}}$: **Acoustic Transfer Vector (ATV)**
- ▶ $\mathbf{V}_{\mathbf{ATV}}^{\mathbf{T}}$: Acoustic Transfer Matrix

Sound Radiation Mode

■ Radiated sound power in far-field

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

apply **ATV** relationship

$$W = \sum_{r=1}^{R} \frac{\mathbf{v}_b^{\mathbf{H}} \mathbf{V}_{\mathrm{ATV}r}^{*} \mathbf{V}_{\mathrm{ATV}r}^{\mathbf{T}} \mathbf{v}_b}{2\rho c} S_r = \mathbf{v}_b^{\mathbf{H}} \mathbf{R} \mathbf{v}_b$$

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

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

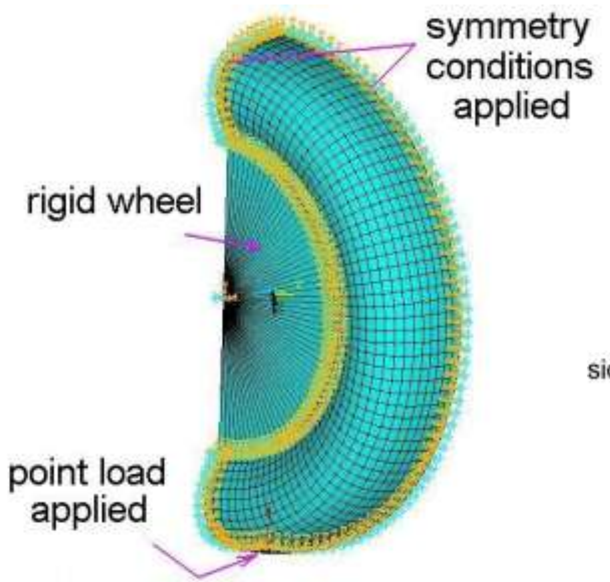
$$\mathbf{R} = \mathbf{Q}^{\mathbf{H}} \mathbf{\Lambda} \mathbf{Q}$$

▶ normalized eigenvector $\mathbf{Q}$: **Sound Radiation Mode**

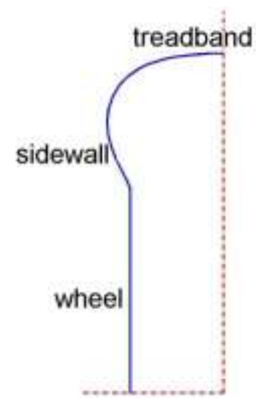
▶ eigenvalue $\mathbf{\Lambda}$: proportional to radiation efficiency

Structural FE Analysis

■ Tire Model



quarter tire model



tire cross-sectional shape

- ▶ 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

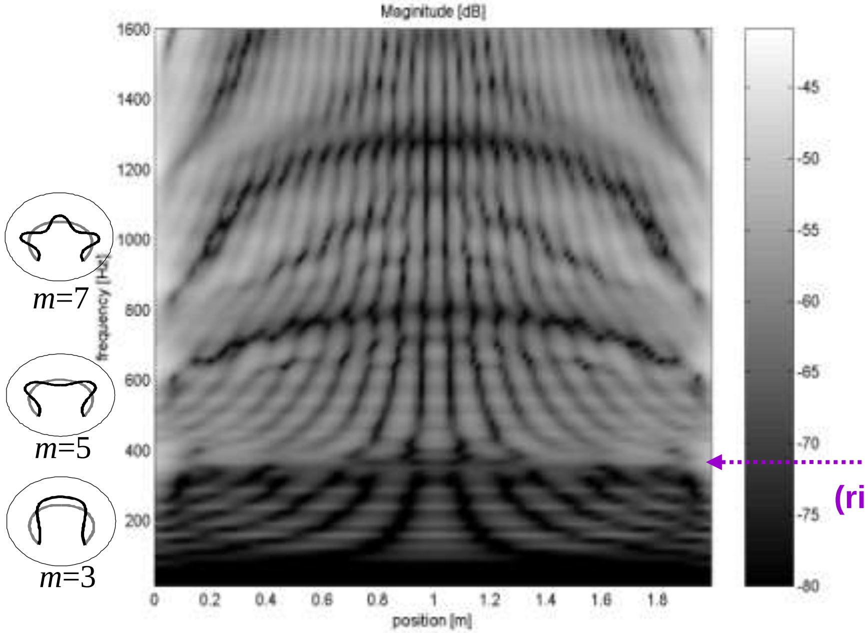
■ Structural Harmonic Analysis

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

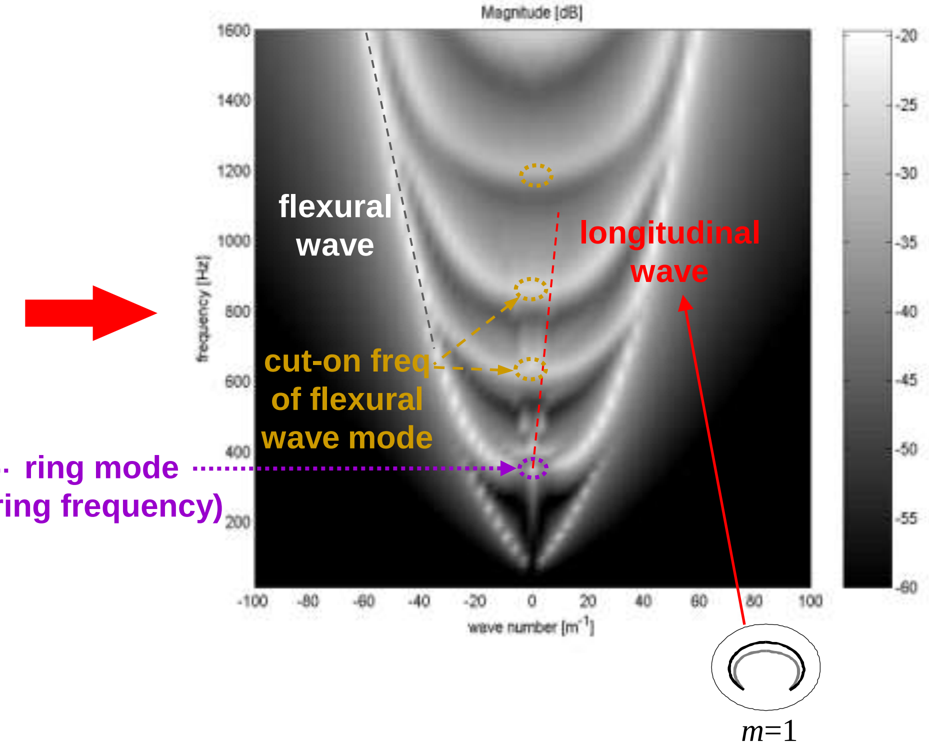
Structural Wave Propagation

■ **Circumferential Wave Number Decomposition**

structural velocity distribution in space domain



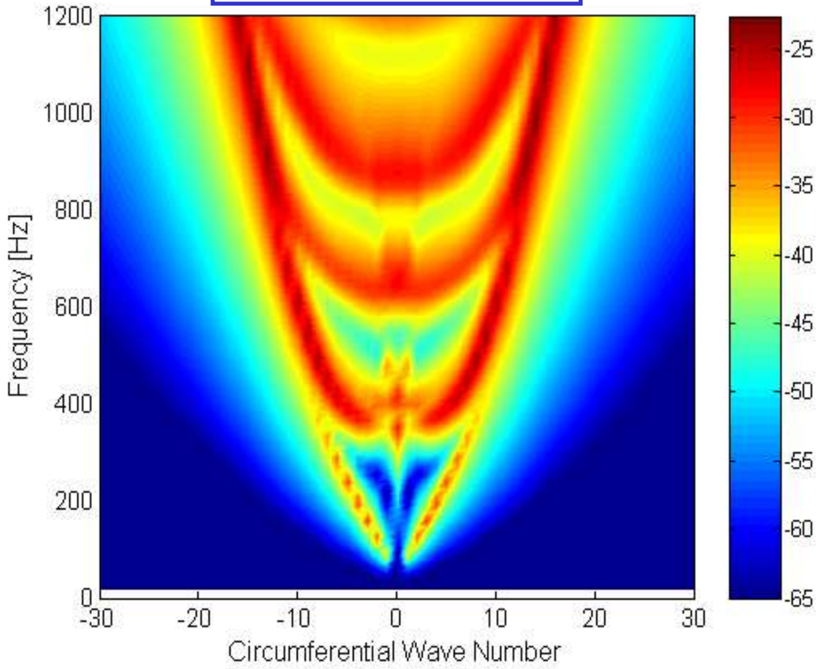
structural velocity distribution in wave number domain



Structural FE Results

■ Wave number decomposition

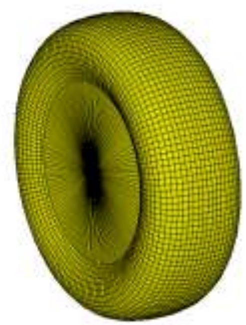
Dispersion Curve



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

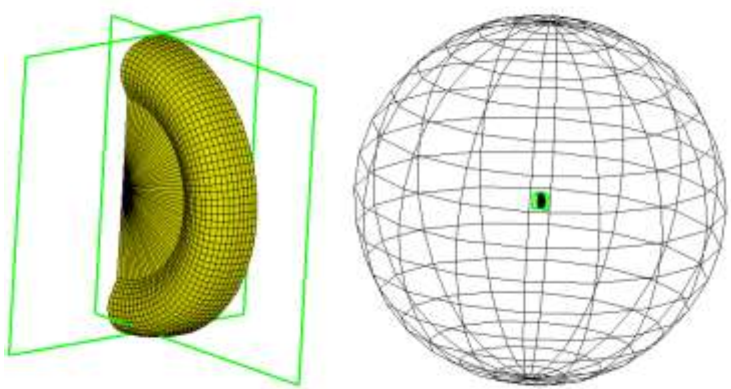
- Dispersion Relationship
  - **longitudinal wave**
    - high phase speed
    - first mode appears at the ring frequency
  - **flexural wave**
    - low phase and group speed
    - related to cross-sectional propagating wave

Radiation BE Model

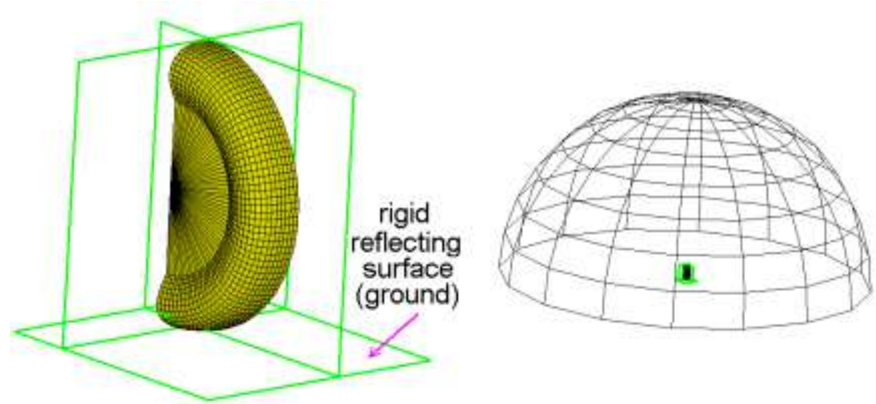


full tire model
(4560 elements)

- 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.



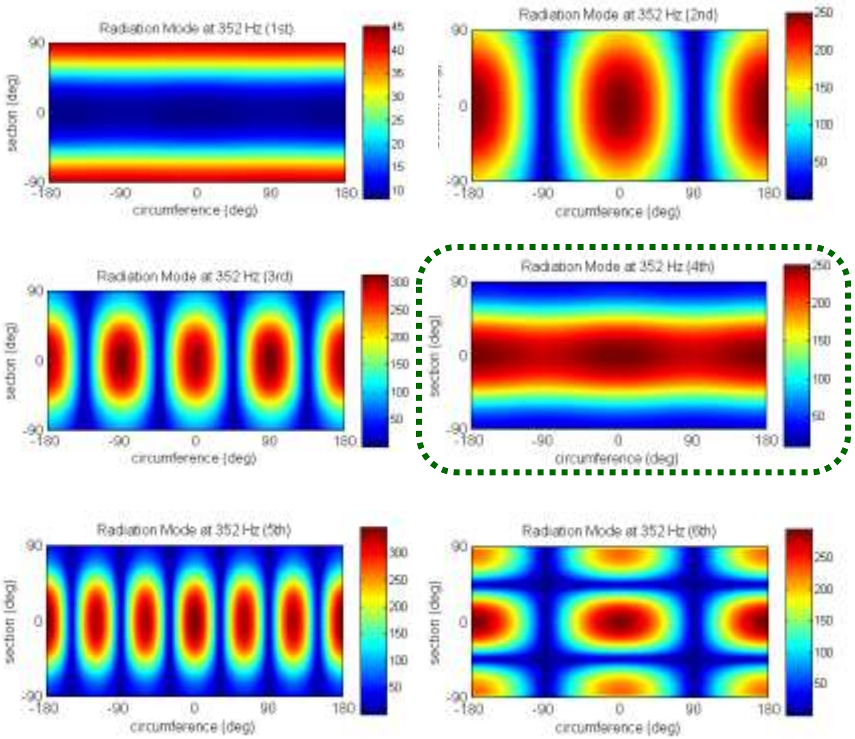
[free space radiation]



[reflecting surface radiation]

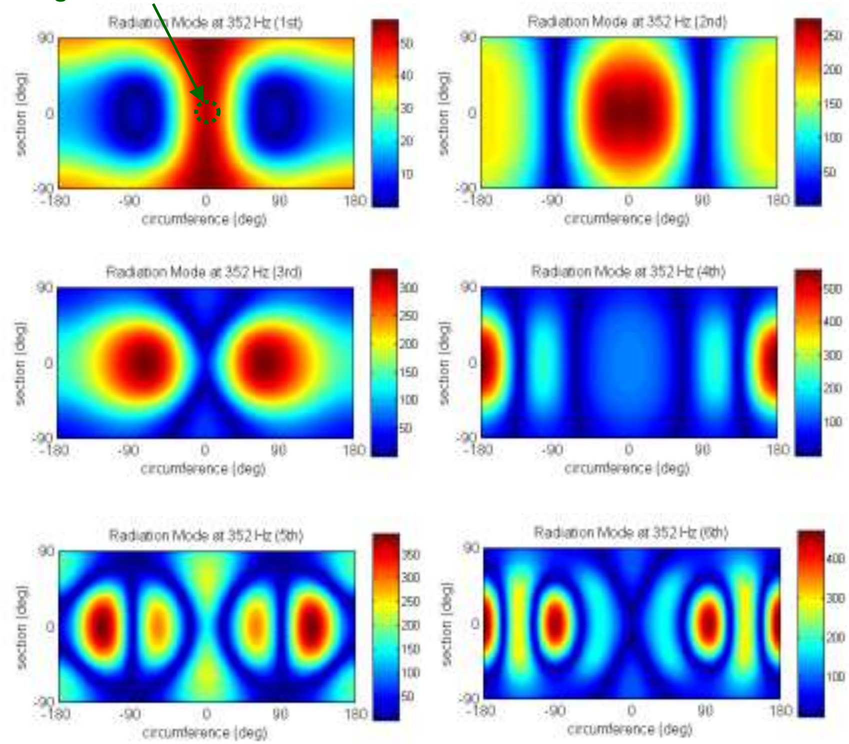
Sound Radiation Mode (352 Hz)

[free space radiation]



point contacting with reflecting surface

[reflecting surface radiation]

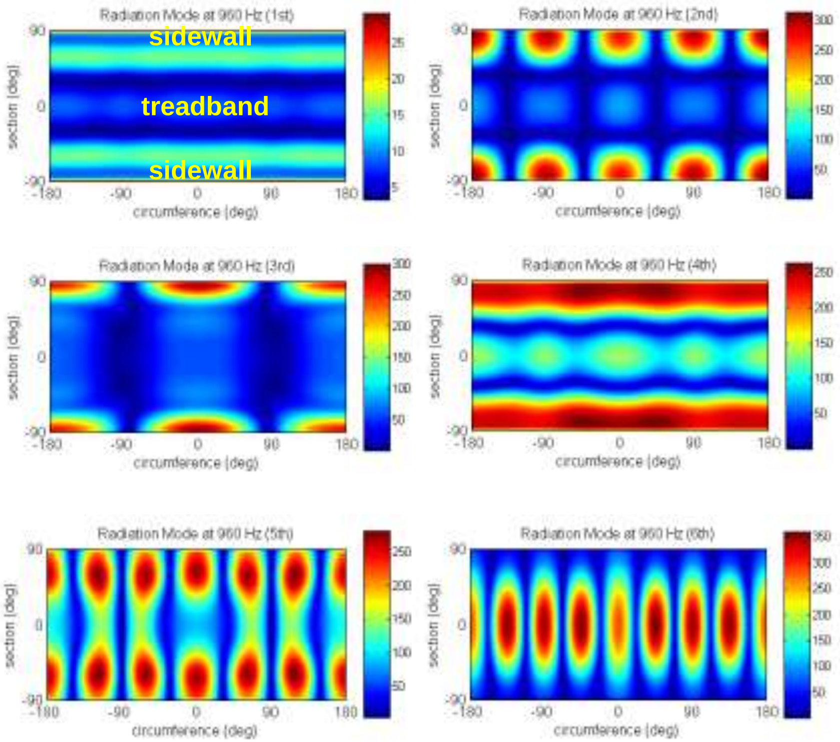


- 1st mode: sidewall dominant
- 4th mode: ring mode on treadband

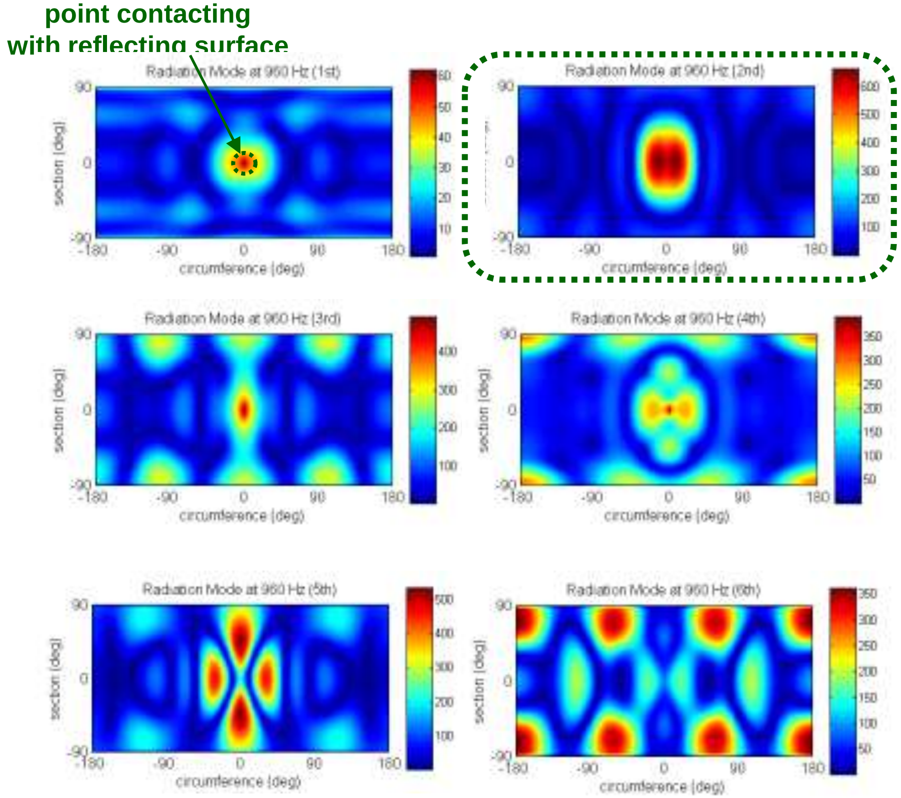
- 1st & 2nd mode:
  similar with free space radiation case
  but peak added on the contact patch area

Sound Radiation Mode (960 Hz)

[free space radiation]

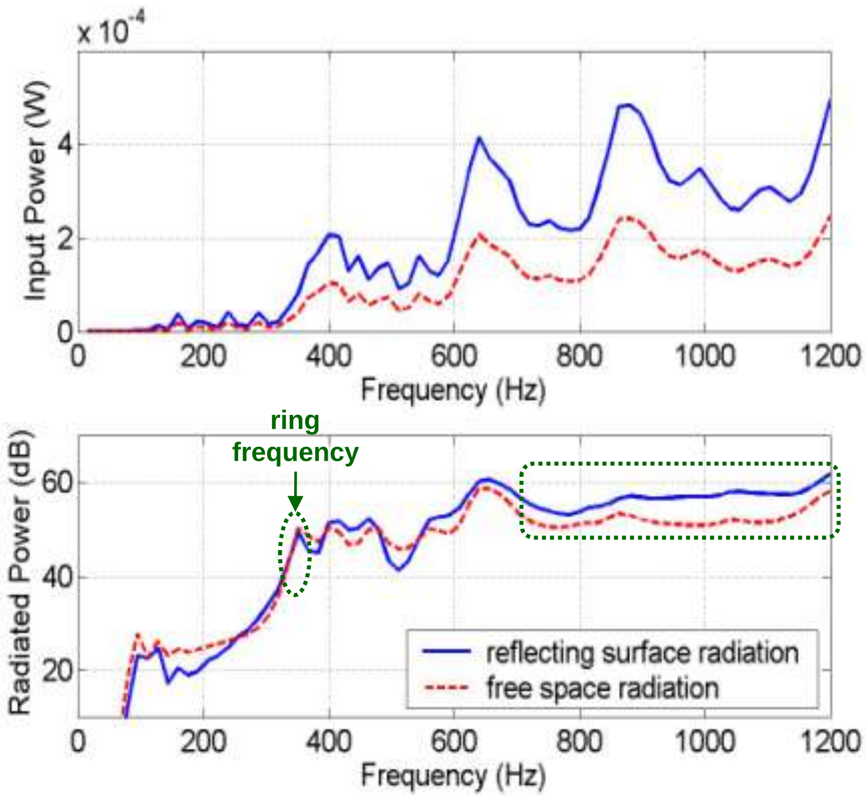


[reflecting surface radiation]



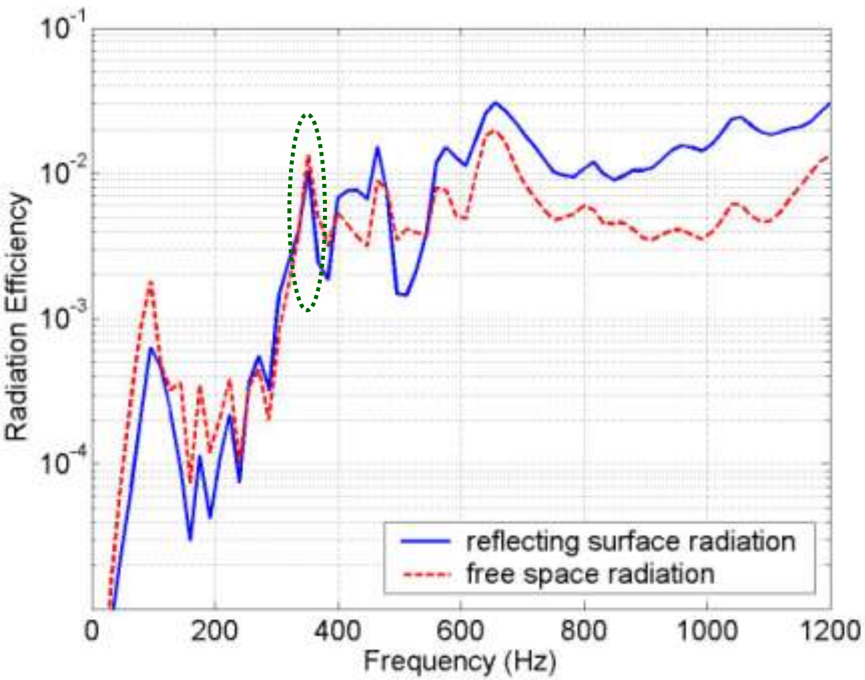
- 1st - 5th mode:
  peaks located in the contact patch area

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

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

where < > denotes space average

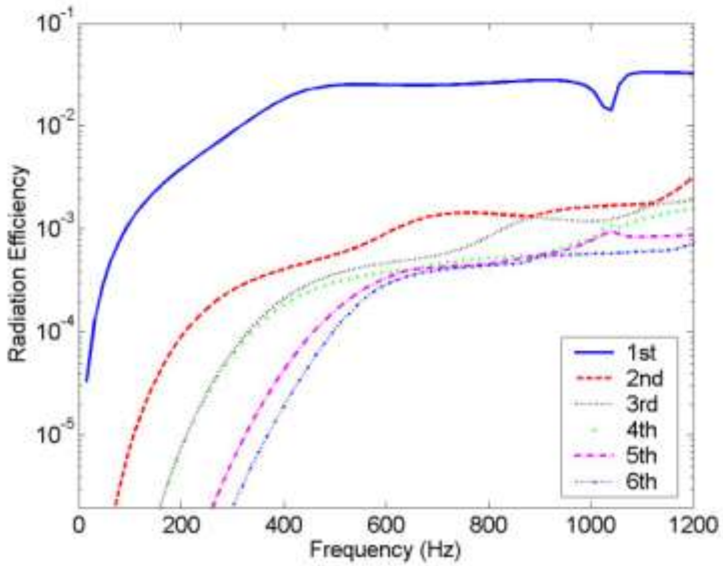
- Radiation characteristics
  - High radiation efficiency characteristics appears at '**ring frequency**', 352 Hz, for both radiation cases.
  - Radiated power for reflecting surface radiation case is amplified above 700 Hz due to '**horn effect**'.

Radiation Efficiency of Radiation Mode

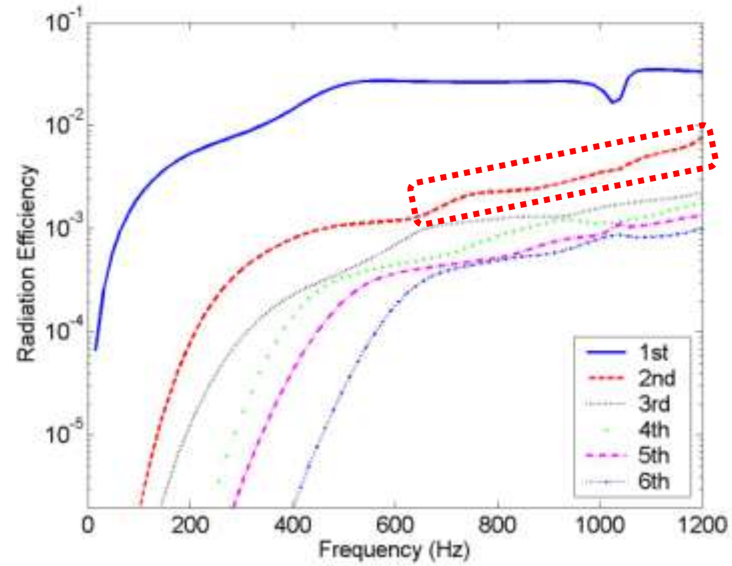
▶ Radiation efficiency of each radiation mode for a unit surface normal velocity

: $\sigma_n = \dfrac{\lambda_n}{\rho c S_y}$ proportional to eigenvalue of radiation resistance matrix

[free space radiation]



[reflecting surface radiation]



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

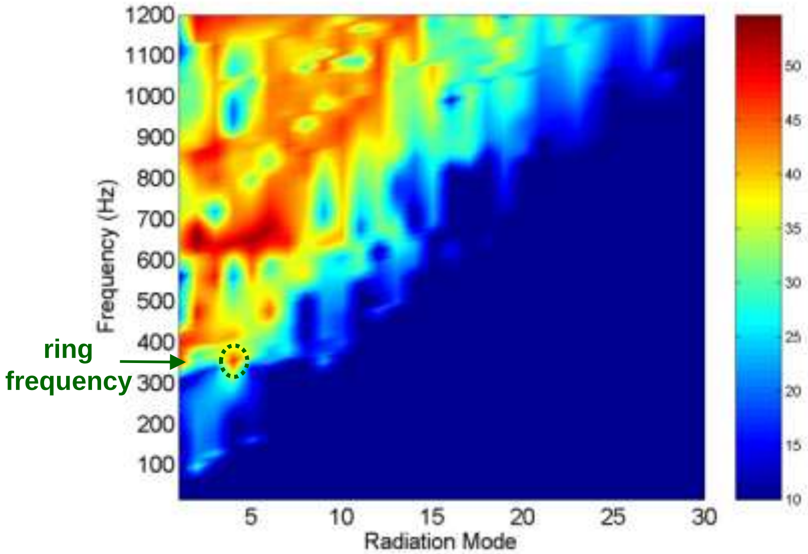
➡ **strong radiation region from the contact patch area**

Sound Power Contribution of Radiation Mode

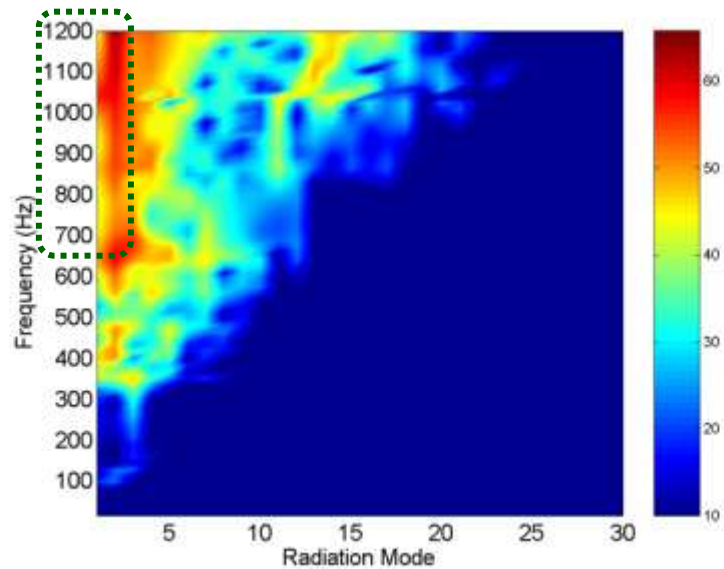
- Sound power contribution of each radiation mode when combined with structural velocities

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

[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.