Acoustics of Vehicle Noise: Tires

Lane Beale
Final Presentation

University of Washington
PHYS 536: Introduction to Acoustics And Digital Signal Processing

2023-02-28


How, why, and who cares?

Why it matters

- The growth of electric vehicles is eliminating engine noise, making tire noise the critical factor
- Rapid global urbanization takes up more space, leaving less pace between major ground transportation routes and residents’ living areas

Causes

- Water on pavement
- Grooved, composition, or coarseness of pavement
- Tread slap/impact (sidewall stiffness, inflation pressure)
- Internal resonance waves
- Transmission of vibration from road to wheel hub

Interior vs. Exterior

- Interior
  - Bothers passengers
  - Caused by resonate standing waves in air inside tire caused by road surface and transferring to the interior
  - Structural noise
- Exterior
  - Noise pollution
  - Neighborhood noise
  - Caused mostly by tire shape and tread
  - Air-borne noise

Models and Techniques

Models

- Analytical Tire Models
- Tire Cavity Models
- Coupled Tire Models
- Tire Noise Experimental Studies
- Numerical Tire Models

Analytical Tire Models

- Model tire as a thin rotating ring structure with flexural vibration
- Fast propagating wave in direction of rotation
- Slow wave in the opposite direction
- Analytical results using finite element method predicted first order rigid modes in tires
- Extensional ring model on elastic foundation confirmed results

Analytical Tire Models

- Two layer tire model can model high frequency waves, up to 3kHz (Larsson&Kropp)
  - Found slow bending wave, fast longitudinal wave, and an in-plane shearing wave
- Belt tire model (Pinnington)
  - Includes bending, tension, and shearing
  - Curved-belt-model includes internal air pressure, sidewall stiffness, rotational effects
  - Able to predict 3 new modes: tire-rigid-body mode, bending modes, circumferential modes

Tire Cavity Models

- Wave equation in in-plane rigid circular waveguide is theoretical foundation for tire-cavity mode (tire cavity resonance)
- Occurs between 230-300Hz
- Geometry of tire is primary factor
- Sound absorptive materials can eliminate this effect

Coupled Tire Models

- Describes coupling of cylindrical shell with a cylindrical air cavity
- Results in structural modes and cavity modes
- Predicts high frequency acoustical modes in radial direction
- Verified by wavenumber decomposition of tire surface mobilities (Cao and Bolton)

Tire Noise Experimental Studies

- Doan et al
  - Coast-by-tire noise peaks at 1kHz in spectrum
  - Tread vibration significant contributer
  - Tread shoulder gives higher contribution
- Iwao and Yamazaki
  - An eye-like vibrating spot (emphasized by horn effect) very effective noise radiator
- Zegelaar
  - Deformation of the tire breaks geometric symmetry and leads to resonance frequency splits

Tire Noise Experimental Studies

- Jessop and Bolton
  - Acoustical modes are different between empty-cavity and fiber-filled cavity tires
- Kamiyama
  - By attaching helmholtz resonators on the wheel, achieved 10 dB reduction!
- Dare and Bernhard
  - Flexural waves excited by gap were NOT primary contributor to slap noise

Numerical Tire Models

- Finite Element Method/Boundary Element Method
  - Used from 1980’s to 2000’s
  - Models tire surface vibration to derive radiated sound
  - Continues to evolve and improve today
- Arbitrary Lagrangian-Eulerian method
  - Used for large deformation and rolling analysis

Numerical Tire Models

- Waveguide FEM
  - Improves computational efficiency
  - Can obtain dispersion relation up to 1.4kHz
  - Including coupling effect can show high sensitivity to sidewall stiffness for low (100Hz) frequencies

Research, Results, and Engineering Solutions

Acoustic Foam!

- Porous material attached to the inner surface of a tire ensure a silent tire
- Different manufacturers are developing different types of foam
- Relatively new technology
- From 3-9dB reduction in noise!

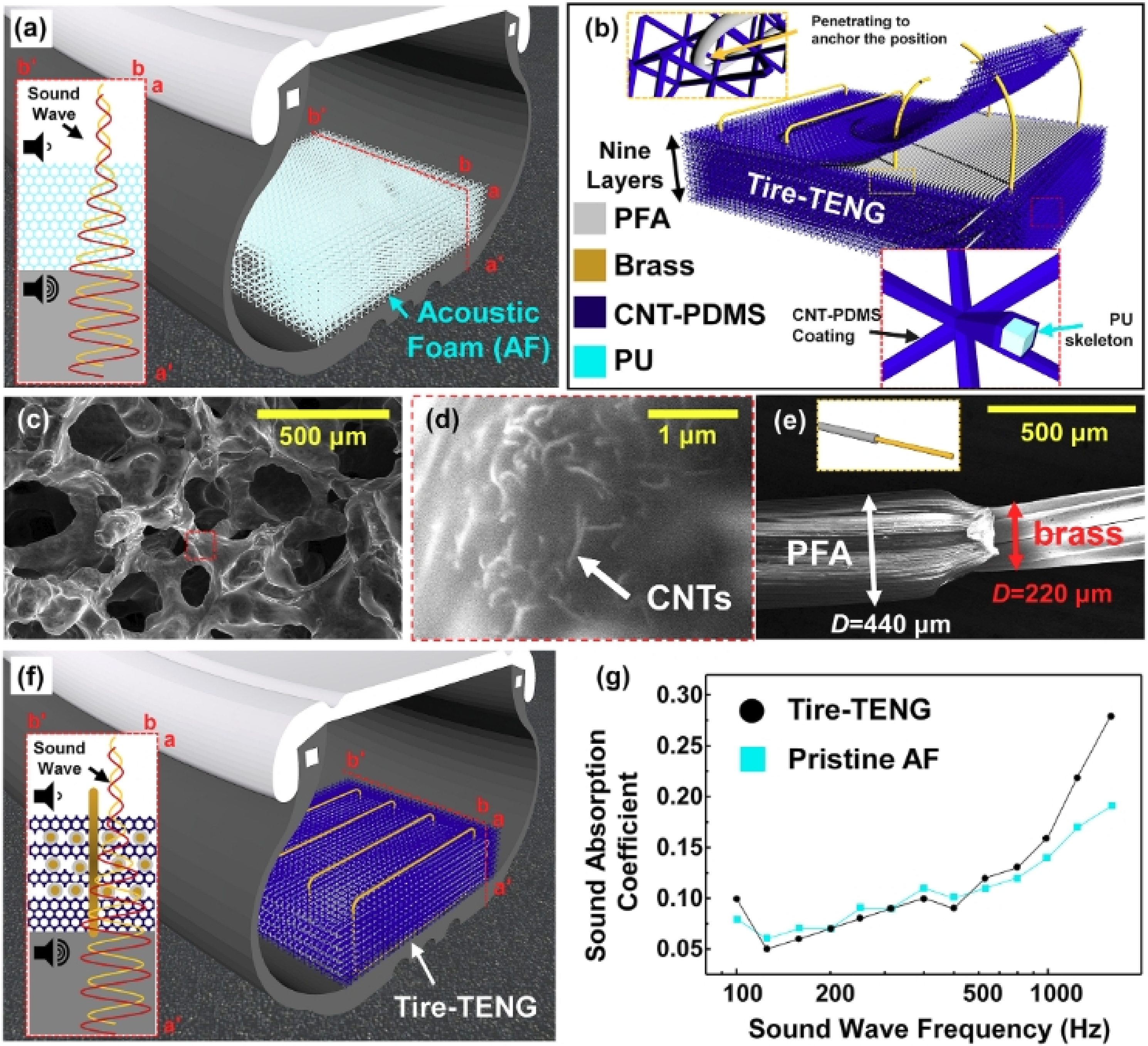
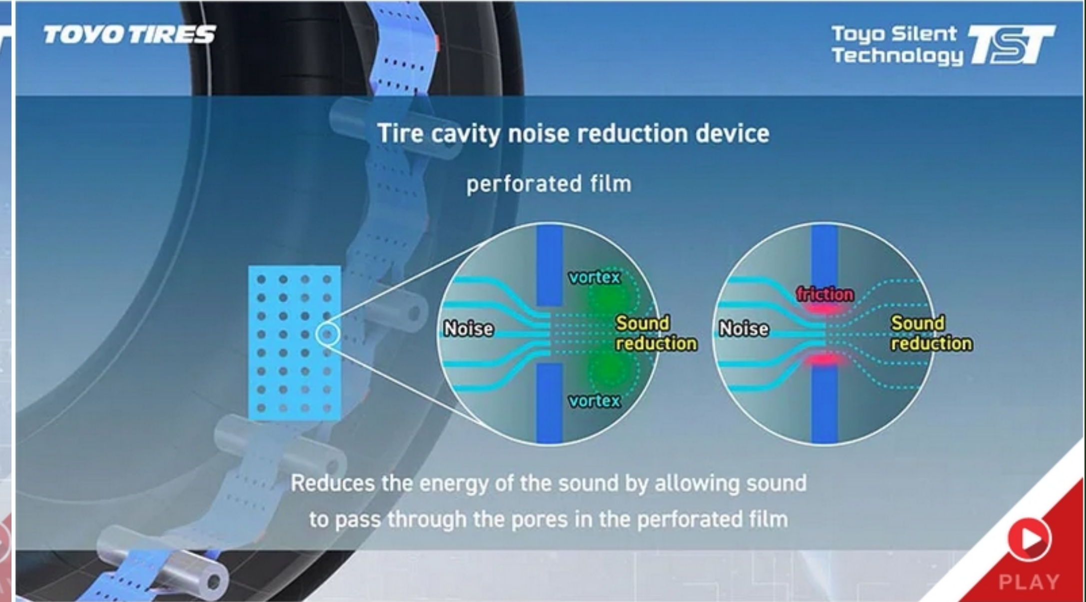


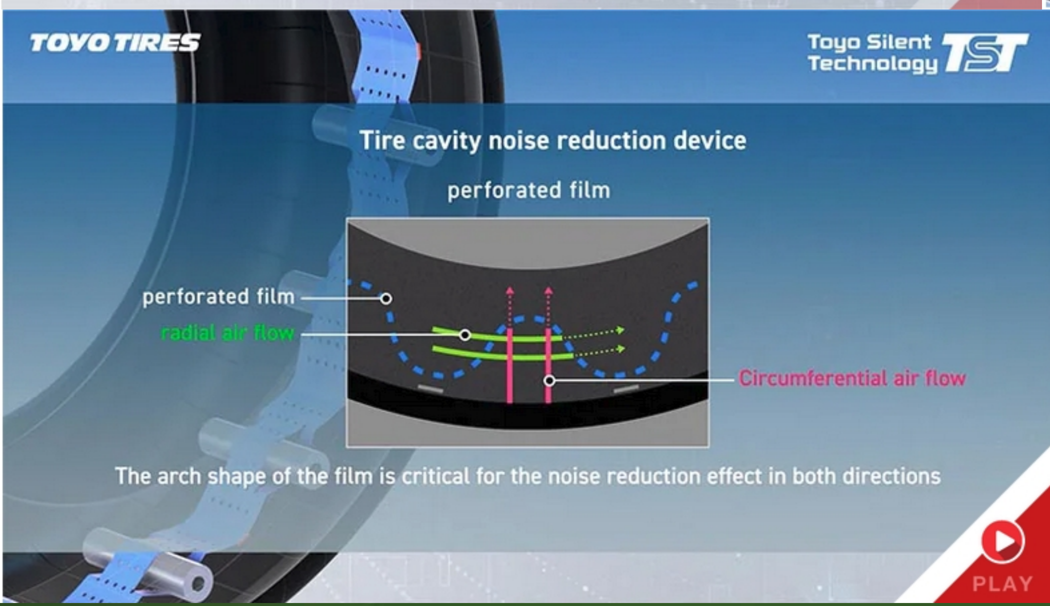
Fig. 1. (a) Shematic illustration of a tire with a pristine AF. The inset shows the noise reduction principle of the AF. (b) Schematic illustration of the Tire-TENG. (c) SEM image of the CNT-PDMS composite coated onto a PU skeleton. The yellow bar represents 500 μm. (d) Enlarged SEM image of the CNT-PDMS composite coated onto a PU skeleton. The yellow bar represents 1 μm. (e) SEM image of the PFA wire. The yellow bar represents 500 μm. (f) Shematic illustration of a tire with the embedded Tire-TENG. The inset shows the noise reduction principle of the Tire-TENG. (g) Sound absorption coefficient of the Tire-TENG and a pristine AF depending on the frequency of the sound wave.

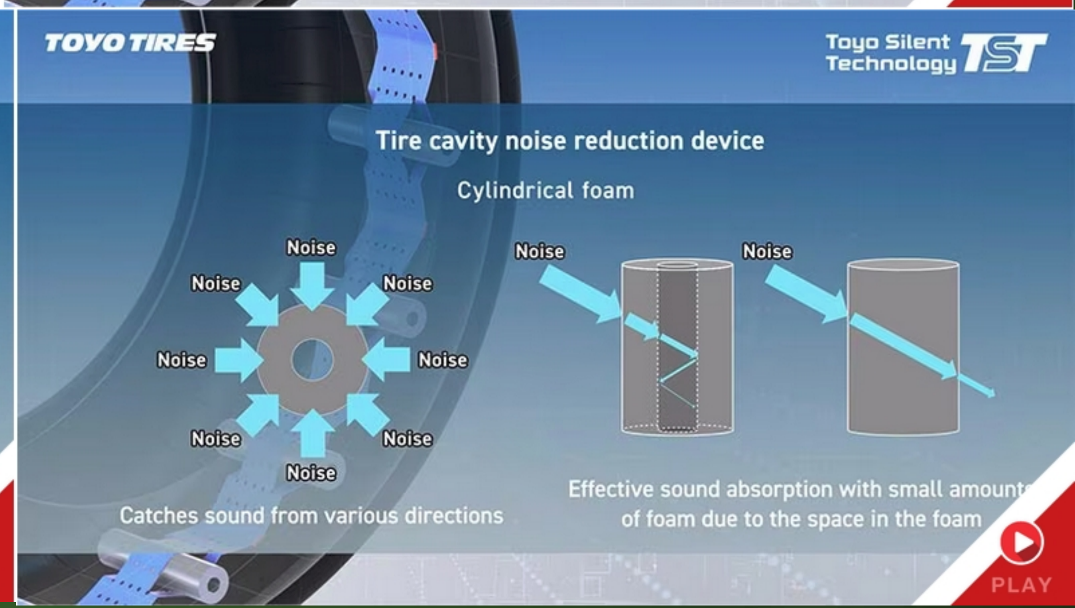
Tire Cavity Noise Reduction Device

- Made by Toyota
- Combines arch-shaped perforated film and cylindrical foam
- Causes friction and vortices to dissipate energy and disrupt standing waves
- Arch design disrupts both radial and circumferential airflow directions
- Hollow cylinders cause sound waves to experience internal reflection, further dissipating energy


TOYO TIRES
Toyo Silent Technology TST
Toyo Tires developed a device that effectively reduces tire cavity noise using its unique technology


TOYO TIRES
Toyo Silent Technology TST
Tire cavity noise reduction device
perforated film
Noise
vortex
Sound reduction
vortex
Noise
friction
Sound reduction
Reduces the energy of the sound by allowing sound to pass through the pores in the perforated film
PLAY


TOYO TIRES
Toyo Silent Technology TST
Tire cavity noise reduction device
perforated film
perforated film
radial air flow
Circumferential air flow
The arch shape of the film is critical for the noise reduction effect in both directions
PLAY


TOYO TIRES
Toyo Silent Technology TST
Tire cavity noise reduction device
Cylindrical foam
Noise
Noise
Noise
Noise
Noise
Noise
Noise
Noise
Catches sound from various directions
Noise
Noise
Effective sound absorption with small amount of foam due to the space in the foam
PLAY

Airless Tires

- Are actually noisier than air-filled tires!
- Air-filled tire industry has had more time to perfect noise reduction technology
- The more rigid structure transfers vibration more effectively to the interior
- Some composite airless tires have reduced noise by 5-10dB, but they are still not competitive in this regard

Backup Slides

References

- Investigation of Noise and Vibration in Tires Through AnalyticalInvestigation of Noise and Vibration in Tires Through Analytical Modeling, Tests and SimulationsModeling, Tests and Simulations
  Rui Cao, Purdue University, 12-2017
- A triboelectric nanogenerator implemented with an acoustic foam for a self-driven silent tire
  Weon-Guk Kim et al., Nano Energy, Volume 96, June 01, 2022
- Experimental Investigation of Tire Slap Noise
  Rui Cao, J. Stuart Bolton, Tire Science and Technology, Volume 46, Issue 1, January-March 2018
- Automobile Tire Noise: Results of a pilot study and review of the open literature
  W.A. Leasure, Jr., D.E. Mathews, M.A. Cadoff, Department of Transportation USA, August 1975
- Analysis of coast-by noise of heavy truck tires
  Yintao Wei et al., Journal of Traffic and Transportation Engineering, Volume 3, issue 2, April 2016, pg 172-179