

Full Field Measurement of Transient Tire Vibrations Using Digital Image Correlation and Dynamic Mode Decomposition

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A non-contact full-field framework was developed to characterize structural dynamics using modal hammer excitation, high-speed 2D-DIC, and frequency-weighted sparse DMD. The approach is designed to avoid the mass-loading effects of contact sensors while improving recovery of transient ring-down behavior. The method specifically addresses optical noise in high-speed measurements, including illumination variation, motion blur, and registration error. By reducing amplitude bias, it improves retention of higher-order resonances that are often difficult to capture reliably. Robustness was demonstrated across multiple test cases with distinct dynamic behavior, including an Aluminum 6061 plate, a PVC plate, and a pneumatic tire.

The experimental study examined two fixed-free structures: a dual-material cantilever beam rig and a pneumatic tire rig. Both systems were excited by modal hammer testing and measured using high-speed 2D-DIC. Image acquisition used a Chronos 1.4 CMOS camera with 300 W LED illumination to reduce motion blur. The beam experiments on Aluminum 6061 and PVC were recorded at 3000 fps for 6000 frames with 0.124 mm/pixel resolution and 3-pixel subset spacing. The tire experiments were recorded at 500 fps for 3000 frames with 0.611 mm/pixel resolution and 11-pixel grid spacing. Efficiency with measurement of localized carcass and tread deformation.

Dynamic Mode Decomposition (DMD) represents complex spatiotemporal dynamics as a linear combination of coupled spatial modes, oscillation frequencies, and growth or decay rates, as shown in Equation (1). To address the amplitude bias introduced by uniform L_1 penalization, Frequency-Weighted Sparse DMD applies an inverse-frequency penalty weighting scheme to preserve higher-order flexural content, as formulated in Equation (2):

$$\mathbf{x}(t) \approx \sum_{j=1}^J \phi_j b_j e^{w_j t} = \Phi \mathbf{D}_b \exp(\Omega t) \quad (1)$$

$$\min_b \|\mathbf{X}_1 - \Phi \mathbf{D}_b \mathbf{V}_{\text{dmd}}\|_F^2 + \gamma \sum_{j=1}^J w_j |b_j| \quad (2)$$

The non-contact framework accurately captured transient structural responses across varied damping regimes and showed strong agreement with accelerometer benchmarks in Aluminum 6061 and PVC cantilever plates. Full-field 2D-DIC displacement tracking produced correlation coefficients of 0.831 for aluminum and 0.818 for PVC, with NRMSE values of 7.9% and 5.5%, respectively. The Frequency-Weighted Sparse DMD method reduced amplitude bias, resolved higher-order resonances, and preserved mode-shape fidelity, with MAC values exceeding 0.9996 for aluminum and 0.9948 for PVC.

Comparative error analysis confirms the superiority of the proposed Frequency-Weighted Sparse DMD over conventional quantitative DIC-FFT and standard DMD. While DIC-FFT is constrained by temporal observation window limits resulting in spectral leakage with frequency errors up to 4.5% and damping estimation errors exceeding 25% standard DMD suffers from amplitude bias and noise-corrupted decay rates.

In contrast, the proposed framework resolves amplitude bias, reducing frequency identification errors to < 1.2% across the entire 0–150 Hz bandwidth and damping identification errors to < 5.0%. In pneumatic tire testing, standard DIC-FFT was heavily restricted by viscoelastic noise smearing; it isolated only the fundamental mode at 8.64 Hz and completely missed higher modes above 10 Hz.

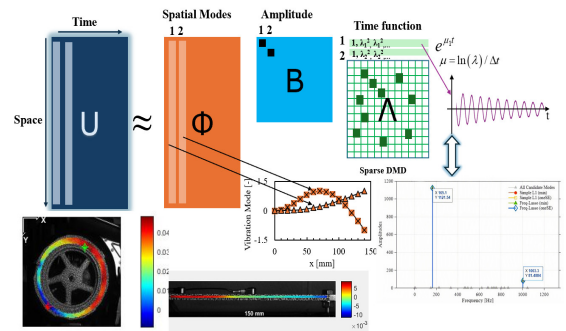


Figure 2. Mathematical architecture and spatio-temporal workflow of Sparse DMD

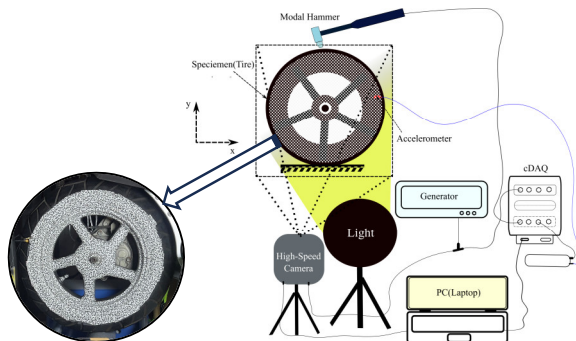


Figure 1. Overview of vehicle tire vibration test setup

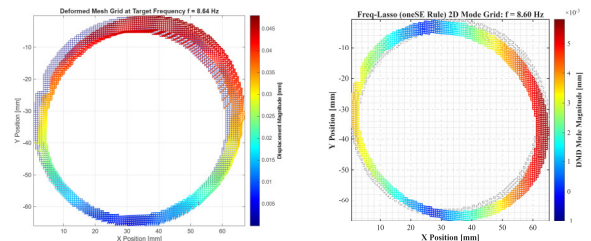


Figure 3. Deformed 2D-DIC mesh grid of the tire via DIC-FFT and DIC-sparse DMD at M1 ($f = 8.64$ Hz).