Automakers are developing new vehicles, they fabricate prototypes to check whether physical tests match the results predicted by their design models. They use experimental measurements, along with computer-aided engineering, to further optimize their products. This sort of iterative engineering frequently involves making tradeoffs to get an optimal balance of durability, cost, functionality, weight, and a measure called noise/vibration/harshness (NVH). Automakers want durability without adding excessive material, minimal NVH at a low cost, functionality that’s best in class, and optimal weight. Engineers use many test methodologies to achieve these objectives.

Computer-aided holographic interferometry (CAHI), electronic speckle pattern interferometry (ESPI), and scanning laser Doppler vibrometry (SLDV) have become essential in the development process due to their unique capability to make sensitive, non-contact, full-field measurements.

Interferometry converts phase differences between wavefronts into detectable irradiance variations (fringes). Although there are many variations of CAHI, ESPI, and SLDV, only the techniques used in the applications discussed below will be briefly described.

Real-time phase-stepped CAHI first records a reference wavefront and an object wavefront on a holographic plate. After development, the hologram is kinematically replaced in its original position. The reconstructed object wavefront interferes with the real-time object wavefront. When the object is deformed, interference fringes appear, which are digitized via a video camera. A series of images are recorded with the reference beam shifted in optical phase. These images $I_n$ can be described as

$$I_n = I_0 [1 + \gamma \cos(\phi + \delta_n)]; \quad n = 1, 2, 3, 4$$

for $\delta_n = (n - 1)\pi/2$ optical phase shifts. These are solved for three unknowns—the modulo $2\pi$ phase discontinuity $\phi_{\text{mod}}$, the intensity $I_0$, and the fringe modulation $\gamma$.

$$\phi_{\text{mod}} = \arctan((l_4 - l_2)/(l_1 - l_3)),$$

$$I_0 = (l_1 + l_2 + l_3 + l_4)/4,$$

$$\gamma = \left( \left( (l_4 - l_2)^2 + (l_1 - l_3)^2 \right) / 4I_0^2 \right)^{1/2}.$$  

Removing the modulo $2\pi$ phase discontinuity yields the unwrapped phase map $\phi$.
plane deformation is given by $L = \phi \lambda / 4\pi$.

The double-pulsed ESPI technique uses a pulsed ruby laser to illuminate a vibrating object.\(^3\) The first pulse is synchronized with a reference wavefront and the object on a single video frame (interline transfer video camera) that is digitized. The second pulse is synchronized with the vibration and is recorded in the next video frame. The correlation Moiré fringe system obtained by subtracting the two images is given by $I = I_0 [1 + \gamma \cos (\delta \phi)]$, where $\delta \phi = \phi_1 - \phi_2$, $\phi_1$ is the phase of the object wavefront in the first video frame, and $\phi_2$ is the phase in the next. A Fourier transform method is used to obtain the phase change $\delta \phi$. The peak-to-valley vibration amplitude is given by $A = \delta \phi \lambda / 4\pi$.

In heterodyne SLDV, a scanned laser beam incident on the vibrating test surface undergoes a Doppler radial frequency shift ($\omega_B$) proportional to the instantaneous velocity. A reference beam, shifted in radial frequency by $\omega_B$ with a Bragg cell, is combined with the object beam in a detector. The instantaneous intensity is $I = I_0 [1 + \gamma \cos (\omega_B \nu + \phi)]$ where $\nu = \omega_B - \omega_0$ is the RF radial frequency of the light interference, and $\phi = \phi_B - \phi_0$ is the phase difference between the object and reference waves. The surface velocity is given by $v = \lambda \omega_B / 4\pi$. To get the complex surface velocity, a vibration amplitude map $v_0$ is first obtained at the structural driving frequency and then a vibration amplitude map $v_2$ is obtained with the phase of the structural driving frequency shifted by $\pi/2$.\(^4\) The complex amplitude is $v = (v_0^2 + v_2^2)^{0.5}$ and the phase is $\theta = \arctan(v_2/v_0)$.

### cutting down on noise

A major factor in interior NVH is the vibrational and acoustic behavior of vehicle body panels. Energy from the primary noise sources—the powertrain, the contact between road and tire, and wind, etc.—propagates through structure-borne and airborne paths and induces vibration of the body panels. The vibrating panels, in turn, excite air inside the vehicle and produce interior noise. In positive contribution areas, interior sound pressure increases as vibration amplitude increases. Neutral areas make no significant contribution. The interior sound pressure is the vector sum of the contributions from all vehicle body panels.

Panel acoustic contribution analysis can determine the contributions of body panels to the vehicle interior sound pressure and pinpoint the local areas of panels that need treatment.\(^5\) The process is a combination of computer-aided engineering and experimental methods. Using CAHI, ESPI, or SLDV, engineers measure surface-normal complex velocities over the entire car body at specific body resonances that generate noise: sheet-metal coatings, panels, headliners, seats, floor mats, etc. These velocities and acoustic impedances form the boundary conditions for a boundary element model of the 3-D car body acoustic cavities.

Typically, boundary elements are spaced about 10 cm apart, yielding thousands of element locations. Designers then use multidomain boundary-element analysis to compute the vehicle interior sound pressure level, the acoustic contributions of panels, and the acoustic sensitivities of panels. Specific positive-contribution areas of the body structure are identified for damping treatment or structural modification to reduce noise. Neutral areas are identified and excluded from treatment. In one application using heterodyne SLDV, tests on chassis rolls (in which front and rear tires of a vehicle ride on large rotating cylinders to simulate on-the-road conditions) identified one panel as a major positive contribution area. Adding mass and damping to the small area identified as the most significant positive contributor reduced the noise without adding much weight (see figure 1).

In another application, engineers removed 5 kg of damping material in neutral areas under and in front of the rear seats and in the spare tire tub in the trunk on all production vehicles, which significantly reduced costs without changing the acoustic behavior. Close study revealed that velocity amplitude and phase were insufficiently large to permit identification of panels that actually contributed to a noise concern, let alone the parts of the structure that were acoustically sensitive to modification. No significant change in the noise spectra occurred as a result of removal of the damping material.

### manifold destiny

Assembly of the intake manifold and the engine cylinder head brings together contact surfaces that control the integrity of
the seal. Unexpected deformation in this area can impact engine performance. Bolts that pass through the intake manifold and thread into the cylinder head control the attachment. The bolts are torqued in a special sequence to draw the intake manifold and its molded rubber gasket on to the cylinder head. A holographic study quantified the deformation of the intake manifold relative to the mating surface on the cylinder head, providing insight into the sealing of the two surfaces.

Engineers imaged the intake manifold with real-time phase-stepped double-exposure continuous-wave CAHI. For the test piece, the intake manifold was bolted to the cylinder head of a complete engine assembly, which was rigidly attached to the top of a vibration-isolated optical table. The bolts fastening the intake manifold to the cylinder-head were torqued to a base value, and a holographic plate was exposed, developed, and reinserted into the CAHI system. Then, an additional delta torque was applied, and four fringed images with π/2 phase steps introduced in the reference beam were digitized.

The computed deformation shows the intake manifold to be bowing up in the center and tilting down along the edges (see figure 2). Color-coding depicts the direction and magnitude of the deformation, with red indicating deformation along the outward normal of the structure and blue along the inward normal. The deformation would give non-uniform load distribution on the contact surfaces, and there is room to improve the quality of the contact surface. With these images of deformation as a guide, the engineers made structural modifications to improve the manifold’s overall structural integrity for assembly and surface sealing.

Figure 3 A brake assembly (a), imaged with electronic speckle pattern interferometry, shows that the deformation pattern of the squeal noise (b) is due to the close vibration mode coupling between the brake disk and pad/backing plate (c).

Putting the Brakes on Squeal

We used the double-pulsed ESPI technique to investigate a brake that had a noise squeal at 5.92 kHz. An accelerometer placed at the tip of the brake pad was used for double-pulse triggering while the brake rotated at 30 rpm; adjustments in brake pressure and temperature reproduced the intermittent squeal. We triggered a 20-ns, double-pulsed ruby laser from the accelerometer signal using a 179-μs pulse interval to get one pulse in each of two sequential frames of a high-speed interline camera. The deformation pattern related only to the squeal noise vibration peak-to-valley (see figure 3). The results showed that the brake disk and pad/backing plate vibration modes are closely coupled. Design modifications eliminated the noise.

Interferometry identifies component deformation and excitation trends, allowing modifications of base components to address the cause of noise. These techniques are able to measure vibration characteristics and deformation distributions even in small, confined areas with convoluted geometries. Although the applications described here were done at the Laser Imaging Lab of Ford Motor Co. (Dearborn, M1), these and other interferometer methods are used throughout the automotive industry. Interferometry is clearly capable of high-resolution problem-solving. The test methodologies are very mature and steadily being improved, with faster data acquisition in both hardware and software. Interferometry has made and will continue to make a significant impact on the development of automotive structures.

References