Having a good look at vibrations

by Prof Stephan Heyns

The growing demand for reliable engineering products that can withstand very severe dynamic environments, as well as the human desire for more pleasant and healthy working conditions, is leading to rapid growth in the sophistication of vibration test techniques and instrumentation. Optical techniques to conduct such measurements are becoming increasingly important and offer some very significant advantages compared to traditional vibration measurement techniques.

These measurements are non-contact and do not influence the dynamics of the structure under consideration. This allows for detailed vibration measurements on structures ranging from very light, such as the vibration of loudspeaker diaphragms, to large engineering structures where physical access is difficult and measurements from large standoff distances might be required, and red-hot vibrating metal sheets and rotating machinery. Vibration measurements on bio-medical structures, such as *in vivo* tests on human skin during the interaction of operators with vibratory machines, are also very feasible.

The Department of Mechanical and Aeronautical Engineering at the University of Pretoria is now uniquely positioned to conduct specialist vibration measurements using very advanced optical equipment. Recent acquisitions include a PSV400 Polytec scanning laser vibrometer and a GOM Aramis and Pontos system for using stereophotogrammetry with digital image correlation to track the motion history of optical markers on structures dynamically in three-dimensional space, and to further process this information to get full-field dynamic images of strain in structures by looking at the structures. These instruments were purchased through a grant from the Department of Education, and allow undergraduate students to develop an excellent physical understanding of the way in which structures deform and vibrate under different dynamic loading conditions.

Of course the equipment also allows very exciting research to be conducted. The reliability of computational models of structural behaviour is becoming increasingly important in the design and optimisation process. However,

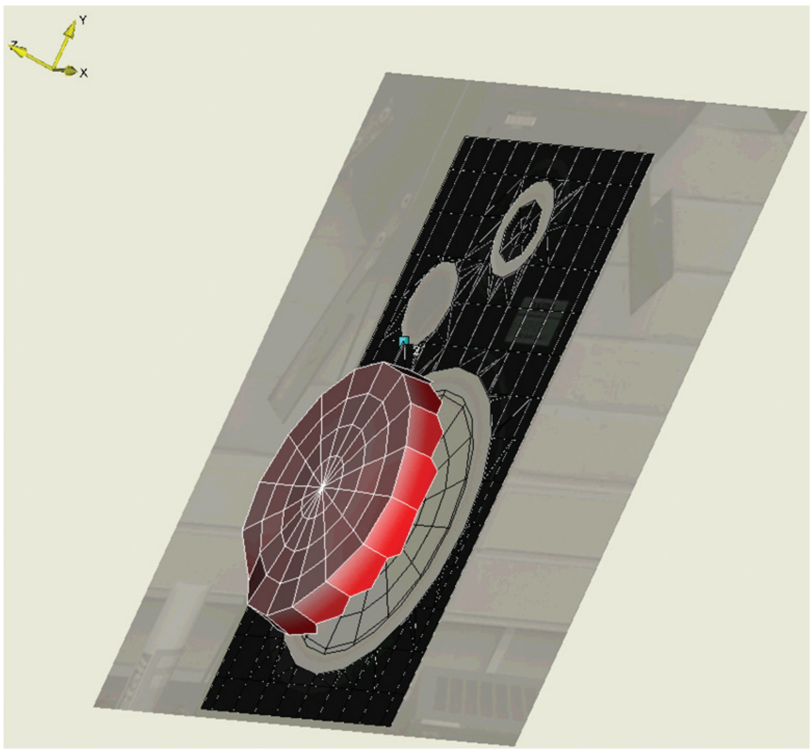


Figure 1. Measured rigid body mode of a loudspeaker membrane.

Figure 2. Scanning laser vibrometer measurements on a composite model aircraft wing.

very little is often known about the properties of advanced new materials, such as specialised composites or even human tissue and bone.

By updating the computational models with very accurate high-resolution experiments, much can be learnt about the effective dynamic characteristics of these materials and reliable modelling strategies.

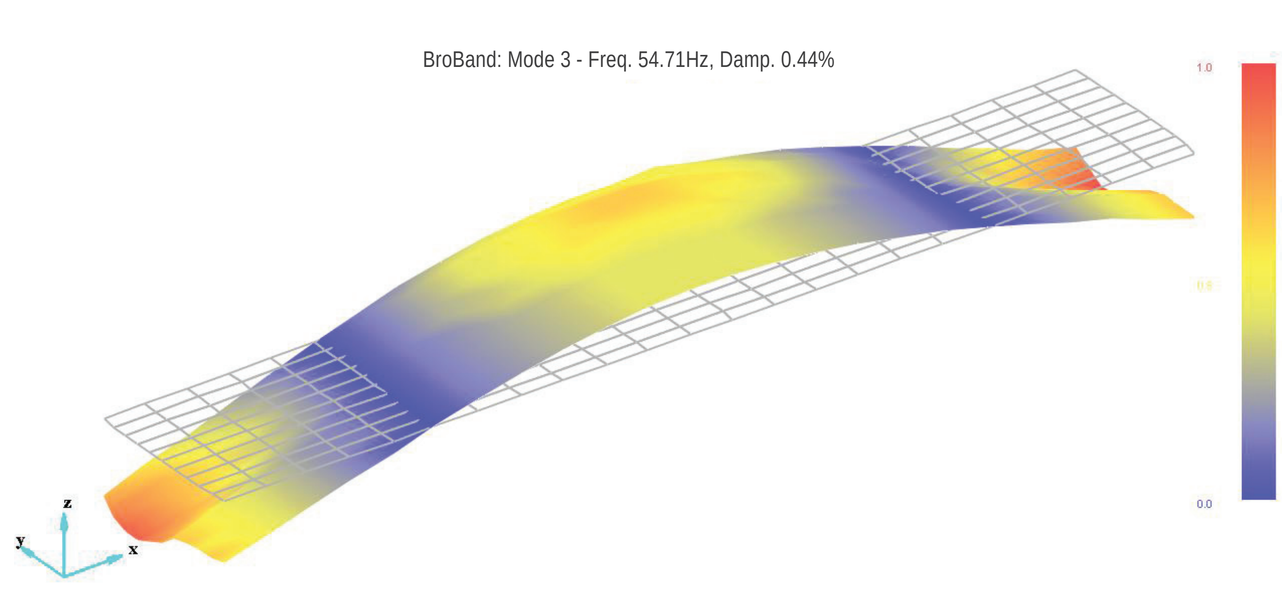
Laser Doppler vibrometry is an optical technique based on the Doppler effect when laser light is scattered from a vibrating surface and on the interference between the measuring and reference beams. This allows for determining the instantaneous velocity component of the moving surface, along the direction of the incident laser beam. Scanning from point to point on the structure allows a very fine resolution of the system dynamics, without disturbing the system dynamics by mass-loading, as is the case with conventional accelerometers. When the system is excited by real operational excitation, so-called operational vibration modes can be measured. Using artificial excitation, which is accurately measured (such as with a shaker or impact hammer with a load cell), one can also capture the inherent modal properties of the system, such as natural frequencies, mode shapes and damping.

One example of measurements on a light structure at the University is depicted in Figure 1. Here a scanning laser vibrometer was used to study the dynamic behaviour of a loudspeaker membrane, without mass-loading the membrane. It thus allows reliable understanding of the membrane motion in a way that can easily be visualised and understood.

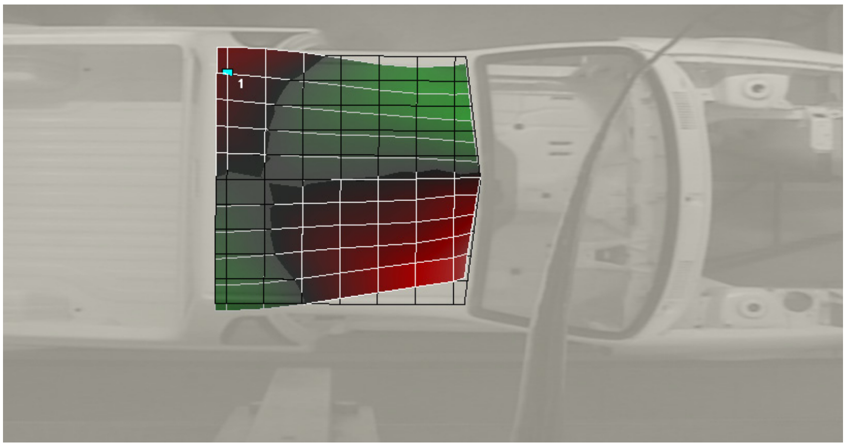
Current research in the department includes the modelling of very light composite materials typically used in aerostructures. The aim is to extract accurate structural dynamic models, which can be used to improve finite element models for detailed design and damage detection purposes. Since the laser scans the structure point by point, this requires steady excitation conditions if one wants to obtain a high-resolution image of the vibration modes of the system. Figure 2 depicts the laser vibrometer at the University while it is conducting experiments on a composite wing for a model aircraft. Because of the black light-absorbing composite material and the desire to do very accurate measurements in this case, small reflective stickers were attached to the wing to improve the quality of the reflected light and the signal-to-noise ratio. By exciting the wing with an electrodynamic shaker (not seen in the figure) and measuring the input force, one can construct frequency response functions, which capture the inherent dynamics of the structure, and allow one to extract the natural modes of the structure. A typical natural mode is shown in Figure 3, which clearly illustrates the effect of the spar on the wing response. Detailed information like this allows updates or improvements of the finite element models through optimisation studies, in which the material or modelling parameters that are considered to be most uncertain are systematically changed to best fit the model to the measured results.

Measurements like these have also been used at the University of Pretoria to study the effects of damping materials on the noise, vibration and harshness behaviour of automotive structures. Figure 4 shows the measured vibration of a roof panel on a pickup to explore the effects of different damping configurations. While vibrations can often be reduced by adding more damping material to the inside of the vehicle panels, this should be done very carefully because of the detrimental effect of the additional mass on the responsiveness of the vehicle and the effect on fuel consumption.

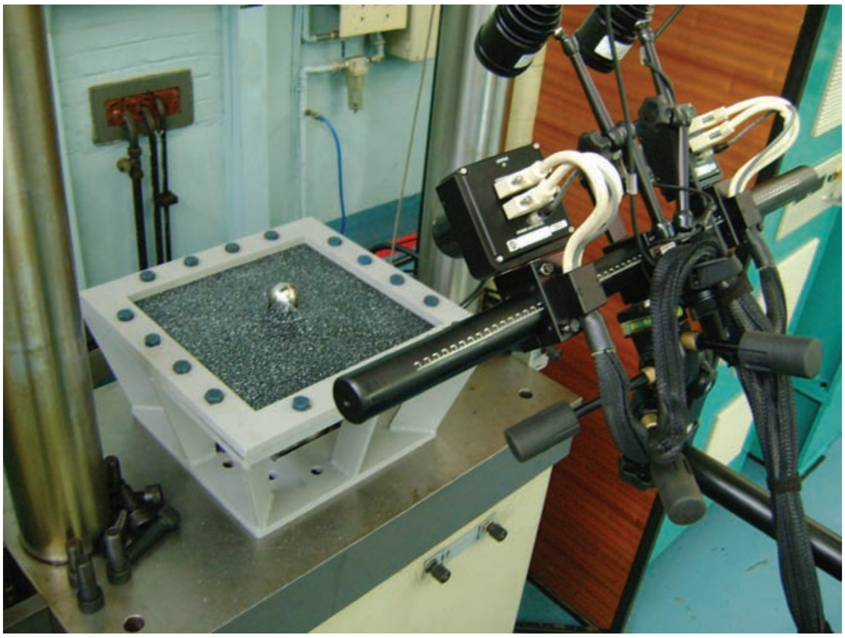
An alternative approach to looking at vibrational phenomena is through the use of full-field stereophotogrammetry. In this approach, two high-resolution cameras are used to take sequential photographs. By employing digital image correlation techniques that follow the relative deformation of a speckled surface (prepared by using



→ *Figure 3. Typical elastic mode of the composite wing.*



→ *Figure 4. Vehicle roof vibration mode.*

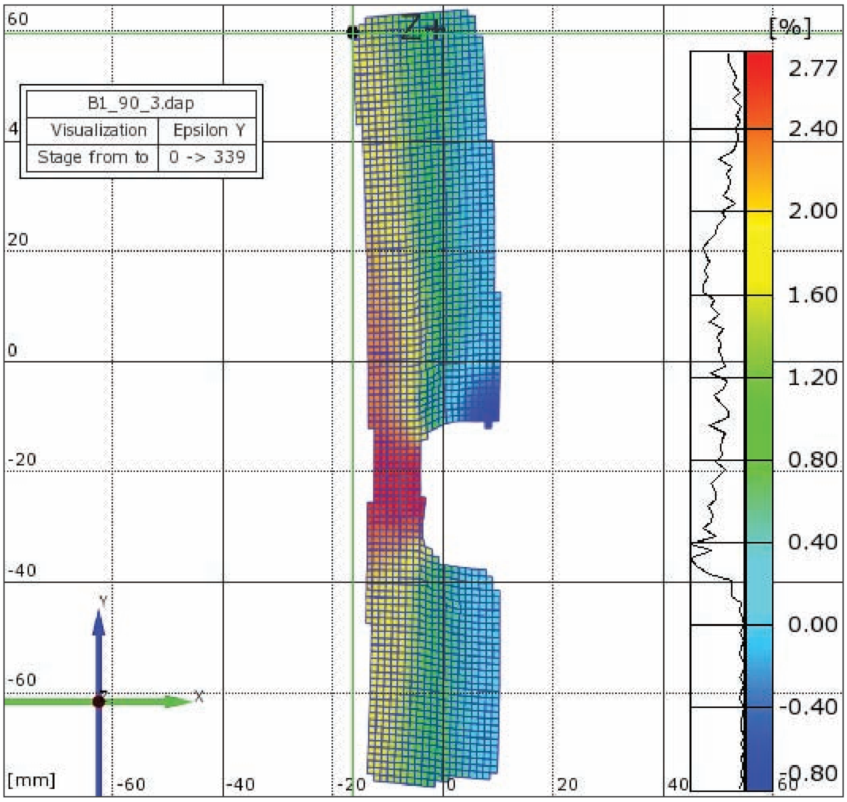


→ *Figure 5. Experimental setup for measuring full-field dynamic strain in a plate being perforated by a steel ball.*

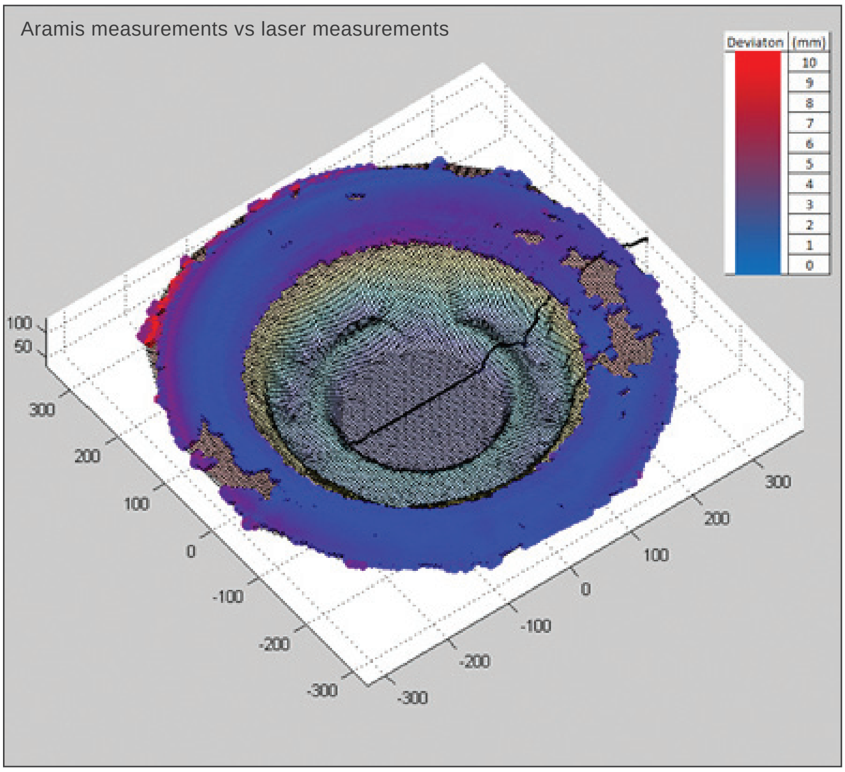
ordinary black and white spray paint), it becomes possible to produce very detailed 3D images of the dynamic deformation. Deformations of between 0.01% and several at 100% can be measured. These measurements could be used to study transient phenomena, such as buckling, door slamming or crash analysis, or even the deformation of human skin during exercise, by looking at full-field dynamic views of the deforming structure under transient conditions.

Figure 5 shows the two cameras with lights in a study of the plastic deformation of a suitably painted plate for the experimental verification of finite element models of rocks falling through the protective roofs on mining conveyances in mining shafts. Understanding such phenomena is important to reduce the risk of serious accidents.

Using the same approach to study the failure of composite material coupons to determine the characteristics of these materials (Figure 6), one can see what the strain field looks like the instant before the coupon breaks, while being tensioned on a universal testing machine. With the facilities available at the University, tests of this nature can be done with sampling frequencies of up to 460 Hz. Combining the system with ultra high-speed cameras that are available at the CSIR, however, 3D strain



→ *Figure 6. Three-dimensional strain field in composite coupon.*



→ *Figure 7. Using photogrammetry to determine tyre coordinates.*

images can be generated at very high frequencies that would even allow for measurement of strain fields under explosion conditions.

The department has a very active programme on the modelling and verification of off-road tyre behaviour. This is an important issue because of the pronounced influence that tyre behaviour has on vehicle response. It is also a complex problem because of the anisotropic properties of the materials and the very large non-linear deformations that tyres experience during off-road operation. The department has successfully studied the behaviour of large off-road tyres excited by large servo-hydraulic actuators, simulating impacts on tyres while driving off-road. A useful added advantage of the photogrammetry is that it can also be used to measure the three-dimensional coordinates of the tyre as an input to the finite element model. Results from such a three-dimensional model are shown in Figure 7, compared to other geometrical measurements.

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