Automated Robot-Based 3D Vibration Measurement System

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The expectations of automobile customers for lower noise, reduced vibration levels and improved ride comfort have become ever more demanding on the engineering community. These demands together with the needs of automobile manufacturers to improve their product development efficiencies and costs are the main driving force behind the design of a revolutionary, fully automated, robot-based system for acquiring three-dimensional structure-borne vibration data with far higher measurement point density than is typically obtained using the conventional accelerometer approach. This article describes the system and presents results obtained from a production car body and chassis of an eco-vehicle. It also hints at potential future applications for structural health monitoring in the aerospace industry.

Experimental modal analysis is traditionally a labor-intensive process that requires attaching accelerometers and cables to the surface of the structure under test. In the automotive industry, the surfaces are so large and complex that finite-element models used to simulate vibrational behavior generate a mesh comprising hundreds of thousands of elements. Limited availability of accelerometer channels and high-count sensor cost typically limit the number of simultaneous measurement points to around 100. To characterize structural behavior, many more locations must be measured and the accelerometers are therefore moved to a new set of locations and the test repeated.

In the case of a body in white, dummy masses are added to the structure so that when the accelerometers are moved, overall structural behavior is unchanged. The effect of the mass of the large number of accelerometers, dummy masses and cables is of course significant and needs to be taken into account in the model when attempting to validate the simulation with measured data. For some structures, it may be impossible to completely model the effects of added mass in the simulation. For acoustics analysis at higher frequencies, measuring the required higher measurement point density is often impossible using a contact sensor approach.

In addition to the resulting time and cost constraints, the entire process is complex and subject to human error. Each triaxial accelerometer needs to be positioned and axially aligned very precisely. Their locations on the structure also need to be known very accurately relative to the nodal points in the FE model if the data are going to be used to update the CAE model. Every one of the large number of sensors must be calibrated on a regular basis, and transducers cannot be allowed to fail, come unglued or suffer from a broken cable during the test.

To reduce costs and improve time to market, noise, vibration and harshness (NVH) studies are today relying more and more on the simulation process. Fewer prototypes are being built, resulting in the need for significantly more thorough testing than in the past. This requires improved test productivity, data reliability, density and accuracy.

All of this leads to the need for a fully integrated prototype testing approach to providing feedback for updating and refining the CAE models.

A common approach for noncontact experimental modal analysis is scanning-laser Doppler vibrometry. Scanning laser Doppler vibrometers (SLDVs), introduced in the 1980s,[1] are systems for noncontact measurement of vibration utilizing the optical Doppler effect, which causes a shift in the frequency of light backscattered from a moving surface.

The frequency shift is given by:

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$$\Delta f = 2v / \lambda \tag{1}$$

Where λ is the wavelength of the laser, typically a visible HeNe laser operating at 632.8 nanometers, and v is the velocity of the surface.

Sophisticated frequency decoding electronics produce a real-time output signal proportional to instantaneous velocity of the surface relative to the SLDV in the direction of the laser. Computer-controlled, galvanometer-driven mirrors scan the laser over the test surface to obtain vibration data at hundreds or even thousands of locations. Because the vibrometer output is directional and can be acquired, stored and processed in the same way as signals from an accelerometer, it's possible using FFT signal processing together with multichannel data acquisition to acquire all of the information necessary for a modal analysis. The additional channels are used to simultaneously gather data from other sources such as load cells, accelerometers, and microphones.

A complete experimental modal analysis for model updating requires the vibration amplitude and phase spectra in all three orthogonal axes of the test object's coordinate system. It also needs to know the geometric shape of the object under test and the exact coordinate location of each measurement.

3D Laser Doppler Vibrometry

As already noted, a laser vibrometer measures the vibration component in the direction of the laser beam. With three laser vibrometers, it's possible to determine the three-dimensional motion of a surface by focusing three laser beams from three different, known directions onto the measurement point and, through a coordinate transformation matrix, transform the measured data into any right-angled coordinate system. It's not necessary to align the lasers at right angles to each other.

The following equation represents the unit vector, which expresses the laser beam direction of the first scan head:

$$L_1 = \left(l_{1x} \quad l_{1y} \quad l_{1z} \right) \tag{2}$$

The matrix below contains the directional information of all three laser beams. It is used to transform the three measured vibrometer signals (v_1, v_2, v_3) into the orthogonal object coordinate system (v_x, v_y, v_z):

$$\begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} \begin{pmatrix} l_{1x} & l_{1y} & l_{1z} \\ l_{2x} & l_{2y} & l_{2z} \\ l_{3x} & l_{3y} & l_{3z} \end{pmatrix}^{-1} \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix} \tag{3}$$

If the lasers are to be scanned over the surface, all three lasers must strike the same location for each scan point. To do this, the system must be taught the relative position of the three scan heads in a global (or test object) coordinate system. This procedure, known as 3D alignment (first described in Reference 2), is performed through software by manually orienting the three laser beams so that they merge onto a single point, defining or entering the coordinates of this point and repeating this procedure for a number of locations on the structure. Mirror angles are recorded by the software and the coordinates of each point must be known. The coordinates can be measured or predetermined from the design model. For example, it is typical to define the location of the origin, a point on the x,y plane, a point on the x axis and a number of additional alignment points. To minimize any errors, these points should be widely spaced in x, y and z within the field of view of all three SLDVs. There must be at least four points visible for each vibrometer.

Figure 1. 3D-SLDV scan heads measuring a car body.

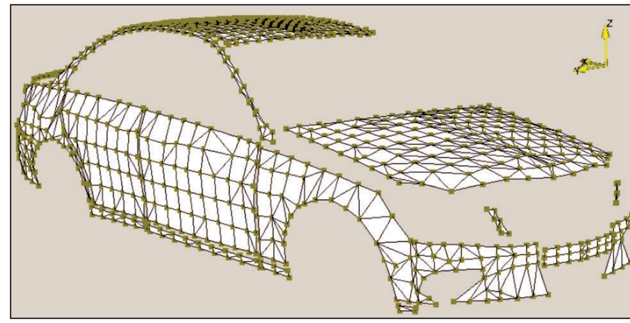

Figure 2. Interactively defined and measured 3D geometry comprising 1094 points.

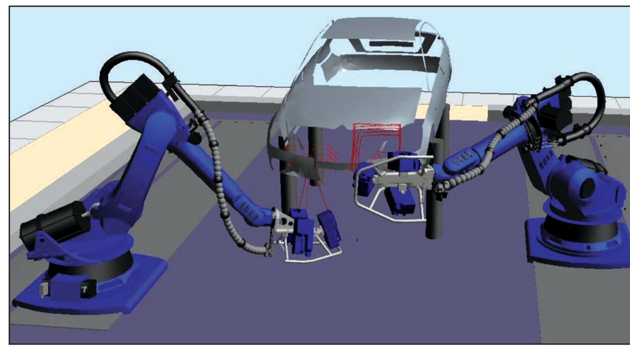

Figure 3. Floor-pan measurement preparation in robot simulation software.

By providing the system with the exact geometry of all points to be measured during the scan (not just the points used for the 3D alignment), the lasers will always merge to a single location for every scan point via software. If there is no numerical model available for importing the locations, a fast and convenient geometric measurement method is needed, especially if thousands of points are to be measured over the surface.

The 3D-SLDV developed by Polytec uses a time-of-flight laser operating through the scan mirrors, coaxial with the laser vibrometer, to experimentally determine the geometry of the structure. Alternatively, geometry files in universal file format (UFF) can be imported into the system. This geometry information can be displayed as a 3D plot and the vibration data superimposed over it. A file comprising the measured geometry can also be exported into the simulation program together with the 3D vibration data. The ability to measure geometry as well as vibration can be very useful, for example, when benchmarking a competitor's product.

The data can be presented as a color-coded 3D animation of the operating deflection shape (ODS) at any selected frequency of interest. 3D vibration components can either be visualized simultaneously or separately in any combination of v_x, v_y and v_z. Software together with an eight-channel data acquisition system is capable of performing multiple-input/multiple-output (MIMO) modal testing.

Combining 3D Scanning-Laser Vibrometry and Robotics

To measure the complete surface of a complex three-dimensional object such as the car body in Figure 1, the three scan heads need to be moved to a number of locations, and the relative position of the scan heads to the object need to be re-taught for each location. The data from each scan head array position can be stitched together into a single file using reference points with known coordinates on the test surface. Prior reference points must be visible from each subsequent scan head array location. Although potentially resulting in a huge amount of data, manual repositioning of the scan heads can be subject to human error and while, much faster than conventional techniques using accelerometers, requires a significant amount of set-up time.

Since it could take as many as 20 different positions of the scan head array to measure the entire surface of an automobile body, an automated approach that avoids 20 3D alignment steps would save a considerable amount of time and effort.

An industrial robot is designed to have all of the flexibility of a human arm and hand and can have the weight-carrying capacity and stability needed to accurately position three SLDV scan heads plus fixtures and cabling. It can also be controlled via computer so that the relative *x*, *y* and *z* position of the object it is holding can be controlled and continuously monitored. The robot used in this article has three rotation axes in its arm and an additional three rotational axes in the hand. A seventh linear axis can be used to extend the reach of the robot arm. Potentially, whole aircraft fuselages could be measured using this approach.

The scan heads are fixed relative to the robot flange. The 3D alignment procedure only needs to be performed one time during installation to obtain the scan head positions and orientations relative to the robot flange. The robot control software can then automatically calculate from the robot's coordinates the positions and orientations of the scan heads relative to the test object at any time.

During installation, the 3D alignment is performed on coordinates in the so-called TOOL coordinate system. The TOOL coordinate system is defined relative to the robot's flange and moves together with the robot. The TOOL position and orientation can be retrieved from the robot controller.

A second robot coordinate system called the BASE system is calibrated to coincide with the test object's coordinate system. This calibration uses all three lasers which, by moving the robot, are made to intersect at each of several calibration points on the test object with known coordinates. The BASE coordinate system is calculated from the robot positions needed to intersect the lasers at these known calibration points.

With 3D alignment having been performed in the TOOL coordinate system and the BASE coordinate system calibrated on the test object, the scan head positions in the test object's coordinate system can be calculated for any robot position.

As with the 3D-SLDV, the geometry information can either be imported or measured using the integrated geometry laser. Figure 2 shows the result of geometry measurements of a car body from several robot positions stitched into a single geometry file.

Before a measurement can start, the robot positions and their sequence need to be defined. There are two methods available for doing this. The robot itself can be moved and those positions saved using the "teach-in" process. Alternatively, the robot's simulation software can be used in conjunction with special software developed to determine optimal laser scan angles and distances to eliminate the need for surface preparation and avoid points hidden from any laser view.

The simulation in Figure 3 shows two 3D-SLDVs mounted to a pair of robots and linear stages for even faster testing of a car body.

Measurement Procedure

The measurement procedure is completely automated. Communication between the robot control and measurement software are performed over a network via OPC client/server architecture. The robot sends a signal when it has moved to a new location

Figure 4. Vehicle measurement set-up

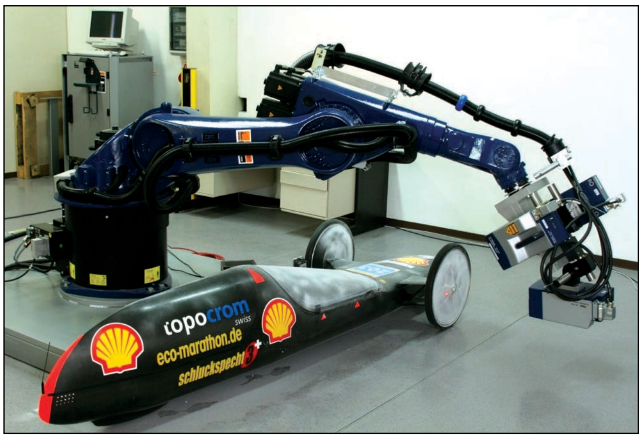

Figure 5. Eco-vehicle during measurement

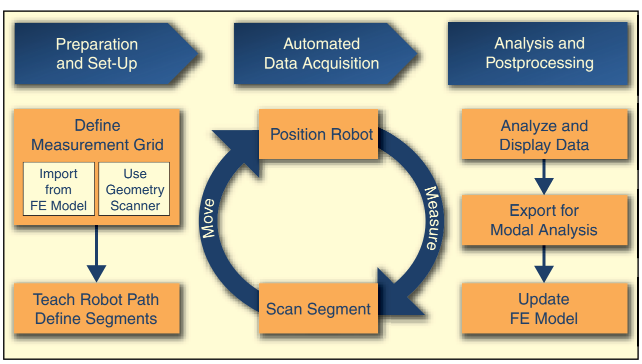

Figure 6. Robot-based SLDV workflow diagram.

and is ready for the lasers to begin scanning again. There is also a signal from the measurement system to the robot when the laser scan has finished and the system is ready for the robot to move to the next position.

For the measurements of the car body presented here, the vehicle was excited at one point with a single electrodynamic shaker using pseudo-random noise[3,4] periodically in the selected time window. A force gauge was used as a reference signal. Figure 4 shows the complete installation.

Some 1100 points were measured using 43 robot positions. The total measurement time was approximately 1.5 hours, averaging just 5 seconds per measurement point. Positioning the sensor heads for all 43 positions took less than 5 minutes.

Figure 5 shows another set-up, in this case for the measurement of an energy-saving eco-vehicle designed to be powered by a single fuel cell. Again, the body was excited by an electrodynamic shaker and a force gage used as a reference. The diagram in Figure 6 shows the complete CAE-integrated measurement workflow from test structure preparation and set-up through FE model updating.

Measurement Results

Results from all 43 robot positions are stitched together into a single seamless file. Data can be presented, for example, as a deflection shape corresponding to one of the peaks in the FRF. One such deflection shape is shown in Figure 7 as a color-coded 3D

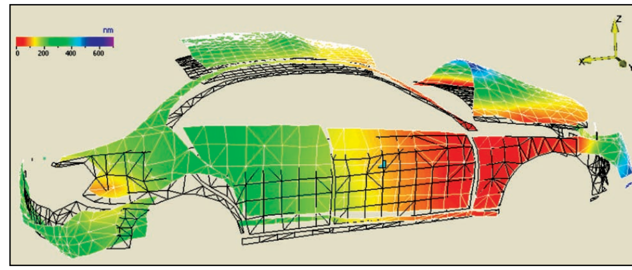

Figure 7. Measured deflection shape at 41 Hz.

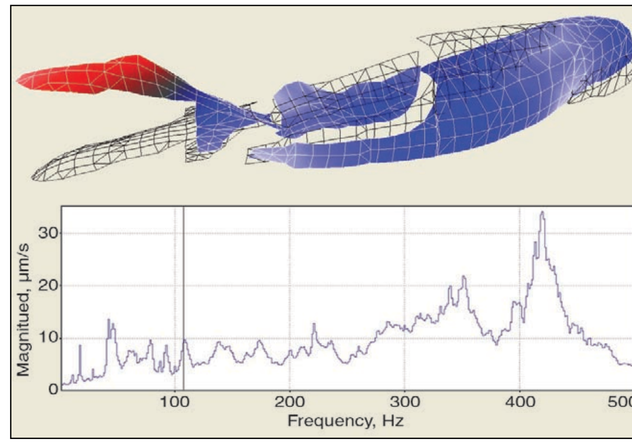

Figure 8. Deflection shape of eco-vehicle at 108 Hz.

representation. The static shape of the vehicle is represented by the black grid, with the measurement points located where the lines intersect. The deflection shape at 41 Hz is illustrated by the white grid with color shading. The highest amplitudes in this case are in the blue-shaded areas. The deflection shapes can also be animated in 3D by the software and saved as AVI files.

One major application of the system is to be able to compare and update FEMs. For this purpose, the complete spectral data files for all measurement points can be exported to an experimental modal analysis program via universal file format data transfer, where modal parameters (natural mode shapes, eigenfrequencies and modal damping) can be calculated from the measured transfer functions.[5,6] The mode shapes and eigenfrequencies can be compared to the values calculated from the simulation, and the modal damping can be added to the FEM. The FEM can now be tuned to the real structure, and an improved model can be derived.

As noted previously, measurements with the robot-based system presented here ensure that the measurement grids correspond precisely with the FEM grids and conveniently allow automatically generated FEM coordinates to prepare the measurement points. This method eliminates a degree of complication and improves productivity. The model updating can be more precise, faster and more efficient.

In the case of the eco-vehicle, no FEM grid was available. Therefore, the geometry was measured with the geometry scan unit integrated into the measurement system. One of the eco-vehicle measurement results corresponding to a peak in the average measured spectrum is illustrated in Figure 8.

Summary and Conclusions

Earlier studies demonstrated that 3D scanning laser Doppler vibrometry can greatly improve the productivity and scope of experimental modal analysis. Increased measurement density without influencing damping or stiffness can lead to a more powerful analysis as well as data at higher frequencies than were practical using accelerometers. This can lead to improved sound radiation simulations.

This article goes on to illustrate that dramatic further improvements in productivity can be made by adding an industrial robot. In particular, simulation tools can be used to help prepare the tests, scan heads are positioned more efficiently and optimal scan angles and distances are calculated and used. The total measurement time and especially the set-up time are dramatically reduced from what used to take weeks down to a day or even just a few hours. Testing can be performed during previously nonproductive night hours, improving the productivity of the modal analysis lab. Also, prototypes are required for shorter times. Once they are generated, control and measurement programs can be used again and again as required. In principle, automobiles could be tested on a production-line basis looking for flaws that show up in the dynamic structural characteristics. This will inevitably result in laser Doppler vibrometry contributing even further to making structures such as automobiles, quieter, more comfortable, higher performing and more reliable.

Along the same lines, several researchers are developing laser-Doppler-based, ultrasonic, nondestructive testing methods for structural health monitoring of aircraft during maintenance.

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