Acoustics'08
Paris
June 29-July 4, 2008
www.acoustics08-paris.org

Deploying successfully Laser Doppler Vibrometry techniques within the automotive NVH process

Mehdi Batel

Polytec, 32 rue Delizy, 93694 Pantin Cedex, France
l.korn@polytec.fr

Laser Doppler Vibrometry is becoming today an established technique and the gold-standard for non-contact measurements in the automotive industry. These methodologies are widely used to characterize the mechanical behavior of structures in vibration or strain, with always zero mass loading. They provide high precision results with very low operating costs as well as optimized set-up times. The applications of laser vibrometry in the automotive industry are extremely various, and are helping today automotive professionals to improve dramatically the NVH performance of components and full vehicles. This paper explains how these methodologies are fitting today in the everyday challenge of automotive NVH Test & CAE engineers: providing best in class noise and vibration quality with mass reductions constraints. A new laser scanning technique including the use of a 3D robot is also presented, providing an innovative way to characterize the dynamics of body structures with very high precision and rapidity. The paper will present a measurement performed on a full vehicle.

1. Introduction

In today’s competitive environment, automotive manufacturers and suppliers are asked to achieve product quality that matches customer demands to a higher extend. The acoustic and vibration comfort in cars becomes now more and more important, and is a direct value of the overall perception of the quality of the vehicle. This holistic perception of the vehicle includes different so-called attributes taken into account: sound quality, tactile impressions, whole body vibration, as well as the visual experience. The ability to cascade this overall perception into objective component or sub-system target is key for automakers. The need for evaluating the interior sound, and the contribution of different sound sources becomes therefore critical. Determining precisely the various contributions of these noise sources to the interior cabin is a complex task, and requires experience, but more importantly it requires a very precise characterization of the sources, structure borne and airborne type.

Fig.1 shows the classical NVH (Noise vibration and Harshness) sources generated in a vehicle, and identifies several classical NVH issues for different frequency ranges.

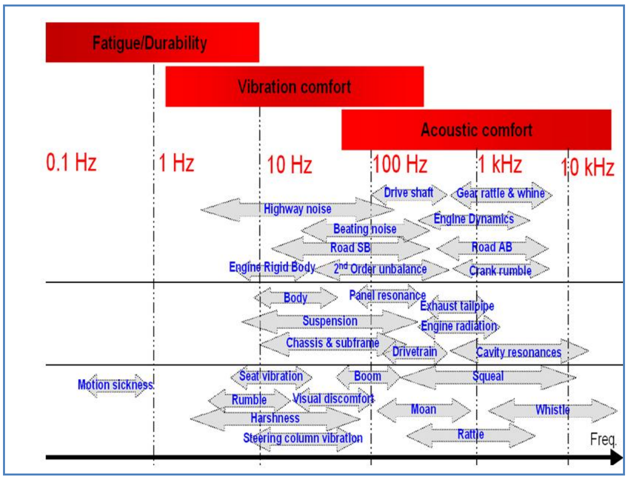

Fig.1 NVH issues in a vehicle

The automotive NVH process typically involves 3 distinctive types of procedures: Benchmarking (Repetitive testing for validation of design compliance to target), Troubleshooting (Investigation of cause of design non-compliance), and Target Setting (Developing realistic and economically achievable targets that reflect customer perception). Today’s automotive trend is to use analytical tools earlier in the process in order to reduce the amount of physical testing. It is also to avoid ”design-build-test-redesign” methodology, the objective being clearly to build right the first time, meet (or exceed) targets, and optimize the process. The main goal of the industry is clearly to shorten the development cycle and making sure that the physical tests are meeting customer targets. This difficult challenge has to take into consideration the fact that there are less and less prototypes available for testing, and also that engineeers need the right test to validate the analytical models, and troubleshoot the physical prototypes in order to meet higher customers expectations. All these requirements are today challenged by the fact that there are tighter demands on cost, weight, recycling, quietness, safety and fuel efficiency.

Body NVH

Automotive body structures are very complex. There are about 100 major parts plus 30 reinforcements such as the hood hinge, steering rack assembly mounting, deck lid latch support and gearshift mounting as well as 20 brackets such as the battery tray and the spare tire mounting. A stiff body, including local suspension mounting brackets, makes it easier for the ride and handling engineer to tune the vehicle, using rubber mount stiffness and spring/damper properties. Changes in these attributes are more easily discerned when the body is not adding much to the total compliance. Examples of typical body targets are:

- Mass < 200 kg
- Static torsional rigidity > 13000 Nm/deg
- Static bending rigidity > 12000 Nm/deg
- First Body structure mode > 40Hz

A stiff body is typically preferred to a pliant one: it handles better and resists excitment produced by road vibrations. A body excited by outside forces (bumps, potholes, etc) will create vibration at a particular frequency, the natural frequency or resonance. Sound is also generated between closure panels and body, it therefore important to minimize deviations in the dimensions of openings under load conditions (hood, front doors, rear doors, deck lid). Components attached to the body also have their individual natural frequencies: suspension & powertrain. It is crucial to design structural components with vibration frequencies that do not excite each other: avoid coupling (dissonance and unpleasant vibrations). In the automotive NVH process, it is therefore key to characterize the dynamics of the car body by use of intensive CAE (Computer Aided Engineering) and intensive Physical Testing.

2. Laser Doppler Vibrometry

A Laser Doppler Vibrometer (LDV) is based on the frequency shift that a laser beam goes through when reflected off of a structure with a velocity in the direction of the beam [1]. An LDV has as its main component: a laser, typically Helium-Neon, which produces a laser beam with a stable wavelength, λ, (632.8 nanometers) and frequency, f, (4.74 x 10^{14} Hz). The wavelength and frequency are related by the equation:

$$c = \lambda . f \qquad (1)$$

Where C is the speed of light (2.9977 x 10^8 m.s^{-1}). This beam is typically optically split inside the LDV to produce two beams. One beam, the reference beam, remains inside the instrument and acts as a frequency reference. The second, measurement beam, leaves the instrument. The measurement beam reflects off of a point on the structure. In reflecting off the structure the measurements beam's frequency is shifted due to the Doppler effect. The frequency shift, Δf, is given by the formula:

$$\Delta f = \frac{2v}{\lambda} \qquad (2)$$

Where v is the velocity of the structure in the direction of the laser beam and λ is the wavelength of the laser beam. The reflected beam is back scattered to the LDV where it is recombined with the reference beam and the frequency shift, Δf, is measured by one of several methods. The frequency shift is typically converted by the LDV into an analog voltage for measurement by standard instrumentation like oscilloscopes, Fast Fourier Transform (FFT) Analyzers or Analog-to-Digital (A/D) converters. Fig.2 shows the principle of a Laser Doppler Vibrometer.

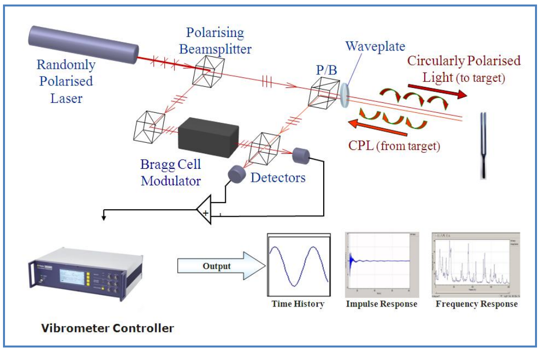

Fig.2 Laser Doppler Vibrometer principle

Advantages of Laser Doppler Vibrometry

Using a laser beam to measure velocity has many practical advantages. One of the chief advantages of the LDV is that it is non-contacting in reference to the structure under test. Only the laser beam encounters the structure and it has virtually no momentum and has no effect on all but the smallest, microscopic structures. The fact that a laser has virtually no mass loading effects gives it a significant advantage over contacting sensors like accelerometers and strain gauges whose own mass changes the systems they are measuring. Fig.3 shows the effect of mass on the dynamics equation of motion.

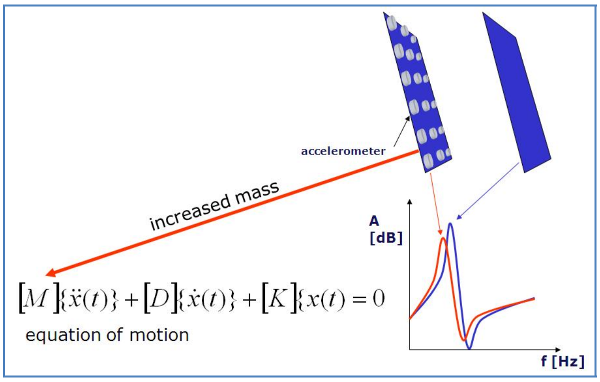

Fig.3 Mass loading effect

Scanning Laser Doppler Vibrometer (SLDV)

Even on structures where it is relatively easy to access and mount contacting sensors, the Laser Doppler Vibrometer (LDV), and particularity the Scanning Laser Doppler Vibrometer (SLDV) offer reduction in test setup time and sometimes even data acquisition time on test involving many physical points or Degrees of Freedom (DOF). The SLDV is the same as the LDV with the addition of two mirrors which allow the laser spot location to be moved horizontally and vertically on a test object [2, 3]. Using mirrors to move the laser is faster and usually more repeatable then manually or mechanically repositioning a LDV on a tripod or other mount. A SLDV can be used to position the laser spot at one point, take a measurement at that point, and then quickly reposition the beam (typically less then 10 milliseconds) for the next measurement. Even with this fast scan speed, the SLDV is still, fundamentally a single point measurement device. A line scan technique has been applied to SLDV but even with these techniques the SLDV requires stationarity in the system under measurement. The SLDV will reduce the test time on multiple DOF tests by not requiring the mounting of a transducer at every measurement point which can be a significant savings in setup time and test management. Compared to a test setup with one or more shakers, accelerometers at each measurement DOF and the accompanying large channel count data acquisition systems, a SLDV test takes longer to acquire the data with the related assumption that the system is stationary throughout the laser scan. But compared to a roving test setup with a hammer, one or more reference accelerometers and less expensive, low channel count data acquisition system, a SLDV test is faster in acquiring the data with same assumption that the system is stationary during the test for both the roving hammer and scanning laser techniques.

3. 3D Laser Doppler Vibrometry

Laser Doppler Vibrometers are designed in such a way that emitted and received light follow the same optical path, called the optical axis. Light that is scattered back in other directions can and should not be received. An LDV only measures the components of the object velocity, which run in parallel to its optical axis. By simultaneously using three Laser Doppler Vibrometers that are aligned from different spatial directions on the same measurement point, 3D velocity signals can be acquired. These three LDVs do not necessarily have to be at right angles to each other. If set up at an oblique angle to each other, the results are given in an oblique angled coordinate system. With the aid of coordinate transformations, the data can be transferred into any right-angled coordinate system. Three combined LDVs that are focused on the same point are also called 3D LDV. By combining every sensor head with scanning mirrors, 3D velocity acquisition can also be carried out across the surface at many points on an object; this configuration is called 3D SLDV. Operating deflection shapes (ODS) of the vibrating object can be presented as an animation with several viewing options. Each component of the vibration vectors can be simply represented as a two-dimensional color map or a set of isolines. A particularly powerful feature is the 3-D representation where the vibration data along the X, Y, and Z axes are presented either simultaneously or separately. When using a 3D SLDV, the coordinates of the measured object points have to be known to be able to position all the laser beams on particular object points. The positions and orientations of the scanning heads in the object coordinate system also have to be known. Polytec's software has implemented so-called 3D alignment for this purpose. Here, the laser beams have to be pointed at a couple of known object points. From the corresponding object coordinates and the angles of the scanning mirrors, the software calculates the positions and orientations of the scanning heads in space. With the aid of the positions of the scanning heads and the coordinates of the measurement points, the direction of the laser beams can be expressed as a vector. Equation (3) is an example of a unit vector which expresses the direction of the laser beam of the first scanning head:

$$L_1 = \begin{pmatrix} l_{1x} & l_{1y} & l_{1z} \end{pmatrix} \qquad (3)$$

The directional vectors of all three laser beams can be summarized in a matrix. This matrix is used to transform the vibrometer signals into the orthogonal object coordinate system:

$$\begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix} = \begin{pmatrix} l_{1x} & l_{1y} & l_{1z} \\ l_{2x} & l_{2y} & l_{2z} \\ l_{3x} & l_{3y} & l_{3z} \end{pmatrix}^{-1} \cdot \begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix} \qquad (4)$$

Fig.4 Typical 3D vibrometer setup

4. Automated Modal Testing with Robot 3D SLDV

To be able to measure the exterior parts of complete vehicles or car bodies using a 3D SLDV, the scanning heads have to be repositioned several times. From every position, a part of the object can be measured. All these parts are then stitched together afterwards to make a complete picture of the car. Compared to tactile measurement techniques, the non-contact laser-vibrometer saves a lot of time, even with manual repositioning of the scanning heads. The second benefit of using laser vibrometers is the possibility to augment the density of the measurement points. If repositioning the scanning heads is left to an industrial robot, then the degree of automation can be significantly increased again. This leads to greater time and cost savings. An industrial robot is designed to be like a human arm. Using six rotation axes, all degrees of freedom in space can be settled. A seventh - linear - axis which can be used to move the entire robot arm increases the reach. The three rotation axes at the end of the robot arm are referred to as the robot hand. The tool to be moved is affixed to the flange on the sixth axis. In the application described here, the robot's tool is the arrangement of the three scanning heads. A fixed arrangement of the scanning heads has been selected for mounting on the industrial robot. By means of the used fixture the scanning heads take a well defined position relative to the robot's flange. In order to obtain the positions and orientations of the scanning heads, the 3D alignment procedure is only needed once during installation of the system. After moving the robot, the software calculates the position and orientation of the scanning heads automatically from the robot's coordinates. This transformation of the 3D-alignment, uses the coordinate systems, which are standardized in robotics. During installation, the 3D-alignment is performed on coordinates in the so called TOOL coordinate system. The TOOL coordinate system is defined relatively to the Robot's flange. When moving the robot, the TOOL coordinate system moves together with the robot. The actual position and orientation of the TOOL coordinate system can be retrieved from the robot controller. The robot's BASE coordinate system (also referred to as "user" coordinate system) is calibrated to coincide with the car's coordinate system. This calibration uses the three lasers, being directed to an arbitrarily chosen point with known coordinates in the TOOL coordinate system. With help of the robot, the lasers can be moved to intersect on calibration points on the car. Out of the coordinates of those calibration points and the corresponding robot positions, the BASE coordinate system can be calculated. With the 3D-alignment in the TOOL coordinate system and the BASE coordinate system calibrated on the car, the positions of the scanning heads in the car's coordinate system can be calculated for any robot position. Measurement points can either be imported from FEM programs or can be ascertained interactively. During interactive measurement point definition, the 3D coordinates are ascertained by the integrated geometry measurement. The result of the geometry measurements from different robot positions is shown in Fig.5.

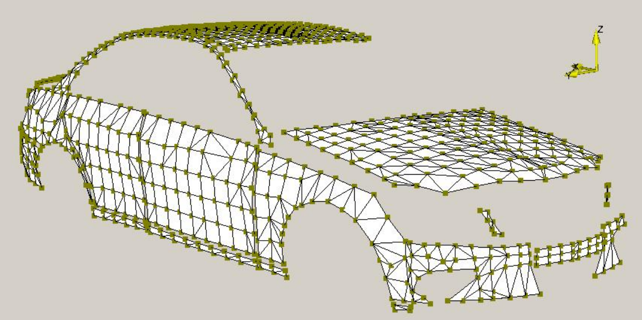

Fig. 5 Interactively defined and measured 3D geometry, 1094 measurement points

Before starting the measurement, the robot positions are defined, from which the measurement is made. This can either be done directly on the robot using "teach-in" or through robot simulation software. The robot positions and their sequence are saved in a robot program. A calculation is carried out to ascertain which measurement point can be reached optimally from which robot position. For this purpose, special software has been developed which takes into consideration the angle of incidence of the laser beams on the surface as well as possible shadowing. Fig.6 shows an installation with two robots and two measurement systems. An installation of this kind can be used to measure all the external surfaces of a vehicle.

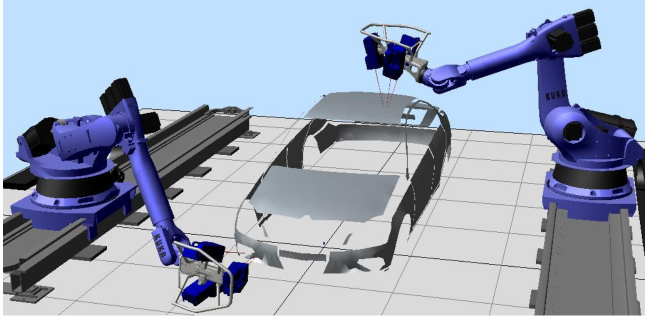

Fig.6 Preparation of the measurement in the robot simulation software

Measurement

The measurement process is fully automated. Thus the robot controller triggers the next measurement respectively as soon as a position is reached. The measurement software triggers the robot control to move on as soon as a measurement has been completed. The communication between the measurement system and the robot controller has been realized via Network, using an OPC client/server architecture. For the test, the vehicle was excited by an electromagnetic shaker at one point. The pseudo random excitation signal was selected which is a periodic noise-like signal that is adjusted to suit the settings of acquisition mode [4, 5]. The force applied was measured using a force transducer and was used as the reference signal for all measurements. The total installation is shown in Fig.7.

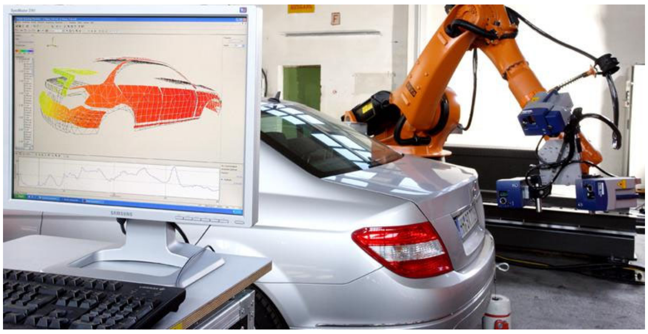

Fig.7 Measurement setup with scanning heads on robots, vehicle measured, shaker excitation and workstation for data acquisition/evaluation

The measurement was made at approx. 1100 measurement points. For this test, 43 robot positions were used. The required time was approx. 5 s per measurement point. The total measurement duration was approximately $1^{1/2}$ hours, positioning the sensor heads for all 43 positions took a total of less than 5 minutes.

Measurement Results

Once the measurements from all positions have been completed, the individual results are stitched together to an overall result and can be analyzed together. In Fig.8, one of the deflection shapes measured is shown. In the picture both the undeformed object (black lines) and also the deformed object (white lines with surfaces) are shown.

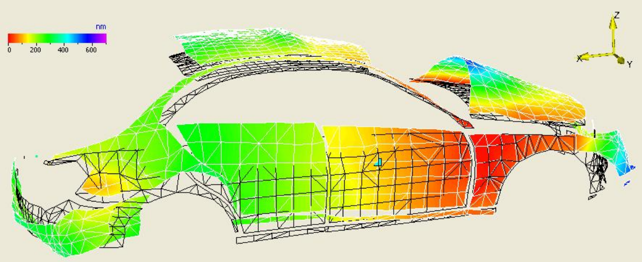

Fig.8 Measured deflection shape at 41 Hz

More clearly illustrated than through an individual image, the deflection shapes measured can be analyzed as 3D-animation in the software. An important application of the measurement results is the comparison of FEM simulation models with the measurement data derived from the experimental modal model. For this purpose, the measurement data is made available to the commercially available software packages for experimental modal analysis (EMA). A corresponding example was published in [5]. The EMA extracts the modal parameters from the measured transmission functions - the natural vibration shapes (modes) with the corresponding eigenfrequencies and modal damping. These results can be compared to the natural deflection shapes and the eigenfrequencies calculated from the simulation. Furthermore, the computation engineers get the values for modal damping. The simulation models can now be adapted in such a way that they generate the same natural vibration shapes and eigenfrequencies as the measurement. The comparison with the simulation models is often still carried out today through interactive evaluation and visual comparisons. Measurement grids and FEM grids are usually generated separately from each other. By using the robot-supported 3D Scanning Vibrometry, it is now possible to use automated FEM grids to prepare the measurement. The measurement results are then at the same coordinates as the simulation results. This then allows better computer support to be achieved when updating the simulation models, which permits the model updating to be faster, more precise and more efficient. An important criteria for evaluating the quality of the data is the coherence between excitation and answer signals. Fig.9 shows an example of a measurement point and a measurement direction of the frequency response function and the corresponding coherence function. The coherence function for almost all frequencies is virtually 1. This supports the conclusion that there is excellent correlation between the excitation signal and the answer signal. Through robot supported positioning of the scanning heads, it was possible to measure every measurement point from an optimal distance and at an optimal angle. This meant that the intensity of the light scattered back was so high that it was no longer necessary to prepare the surface at measurement points with a reflective coating.

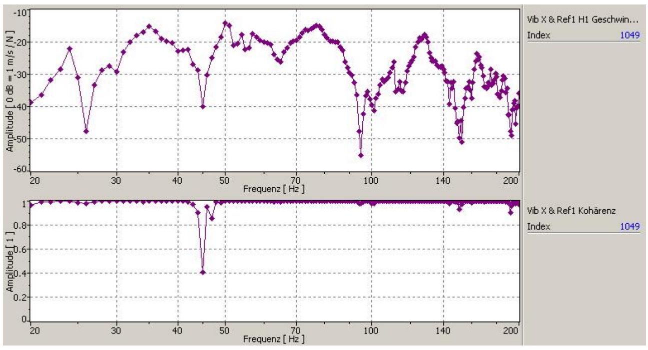

Fig.9 Frequency response function (H1) between excitation and response & coherence function at a measurement point

5. Conclusion

Structure-borne noise measurements made using Laser Doppler Vibrometry are the perfect way to optimize the noise and vibration characteristics in vehicle development. Earlier studies confirm the significant potential of this technology to increase the density of measurement points without influencing the vibration characteristics of the structure, while at the same time saving on measurement time. The increased measurement point density on the one hand improves the meaningfulness of the results of experimental modal analysis; on the other hand higher frequency ranges can be acquired for acoustic simulations (e.g. sound radiation). In this publication it has been shown how by combining Laser Doppler Vibrometers with an industrial robot, additional significant efficiency increases are possible. In particular, preparation with aid of simulation tools, more efficient scanning head positioning and improvement of the signals through more favorable angles of incidence should be mentioned here. Combining Laser Doppler Vibrometry with robots reduces the total measurement time – depending on the application – from what used to take weeks to days or even hours. In addition, the measurement process can be shifted to previously non-productive night hours. This means that the throughput of a modal analysis laboratory also increases, the prototypes are required for shorter lengths of time, measures that need to be taken can be defined and then implemented more quickly. Once they are generated, measurement programs can be used again and again as required. This means that every optimization step can be documented and analyzed at a level of resolution unattainable until now. Once again, with the aid of Laser Doppler Vibrometry, it has been possible to raise the bar in car development. This non-contact measurement technique will in future also be conducive to the trend towards quieter and more comfortable cars being maintained.

References

[1] Andrew C. Lewin, Non-contact surface vibration analysis using a monomode fiber optic interferometer, SCI. Instrum., 18, 1985

[2] B. Stoffregen, A. Felske, Scanning Laser Doppler Analysis System, SAE Paper No. 850327, 1985

[3] Xu, Y., Miles, R. N.: An Identification Algorithm for Directing the Measurement Point of Scanning Laser Vibrometers, Optics and Lasers in Engineering 22 (1995) 105-120

[4] Brown, D., Carbon, G., Ramsey, K.: Survey of excitation techniques applicable to the testing of automotive structures, International Automotive Engineering Congress and Exposition, Society of Automotive Engineers, 770029, 1977

[5] Schüssler, M., Wörtge, M.: Survey of excitation signals, with respect to scanning vibrometer measurements, Third International Conference on Vibration Measurements by Laser Techniques: Advances and Applications, SPIE Vol. 3411, pp. 386-393, 1998

[6] Bouteille, F., Schüssler, M.: MIMO-testing on a car body using a three-dimensional scanning vibrometer, Proceedings of the ISMA2006 International Conference on Noise and Vibration Engineering, Leuven, Belgium, pp. 3157 – 3163