ADVANCED SCANNING TECHNIQUES APPLIED TO VIBRATIONS AND OPERATIONAL DEFLECTION SHAPES IN REAL MEASUREMENT SCENARIOS

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The product development process often involves CAE modeling and testing for structures and materials optimization. Model updating techniques have been developed to link the experimental analysis with numerical models like FEM or BEM. Several well-known testing methods are available, like for example modal analysis, operational modal analysis and operational deflection shapes. An advanced scanning technique is presented in this paper using the combination of a video camera, a reference accelerometer and a moving PU probe. The ODS analysis can be obtained in few minutes, being able to validate the result of a mathematical model. The advantages and limitations of this method are discussed in this paper.

1. Introduction

During the different development stages of a product, several modal analysis techniques can be used to characterize the dynamic properties of a structure. In the early stage of development, before a physical product exists, numerical techniques such as FEM and BEM are used to create virtual mathematical models that simulate the dynamic behavior of the real product.

Once a physical product is available, experimental modal analysis (EMA) techniques can be applied\(^1\). During this stage the results of the numerical models are compared with experimental data. The model can now be updated by changing some key parameters like stiffness, modal damping or smaller geometry details. The next step in the product development is the simulation of structural modifications designed to achieve the desired dynamic behavior. Simulation techniques are able to define the sensitivity of the model to change in design parameters\(^2\). In this way the product can be optimized to achieve the best dynamic performance with the smaller impact on cost for development.

Operating Deflection Shapes (ODS) is typically used in the last stage of the refinement process, when the physical product is mounted in real operational condition. The ODS is used to describe the motion of a structure under some operating forces, for instance a running rotating machine, measuring only the response of the structure. Often the ODS shapes do not coincide with mode shapes from Modal Analysis. When a structure is subject to real-life excitations (during typical operation)
only a sub-set of modes will contribute to the motion. The deflected shapes are subjected to multiple excitations (even at one single frequency). In simple words, the forced and free vibration shapes for a 'complex' structure are not typically the same. For some particular scenarios it has been proven that direct measurements of ODS are faster, simpler and more accurate than analytical predictions or EMA.

Operational Deflection Shapes (ODSs) can be also used as integration of more complex CAE models, to investigate which optimal modifications should be applied in the final product. This approach involving both experimental analysis and virtualization can be defined as “Hybrid technique”; experimental data can be used as input for the virtual model. The most widespread technique for testing Operational Deflection Shapes is based on step by-step or simultaneous measurements with accelerometers. A drawback of this method consists in mounting restrictions and mass load effects. Those limitations have increased the popularity of non-contact solutions based on measurements with Laser Doppler Vibrometers (LDV). The high price and setup complexity of current commercial systems limit the use of LDV for some applications.

Scanning measurement techniques allow reducing significantly the number of sensors, time and cost of the experiments but they are constrained to assess time-stationary sound fields. Therefore, scanning ODSs measurements are suitable for characterizing structures excited with time-stationary forces. Acoustic particle velocity sensors or Microflows have been proven to be suitable for measuring non-contact vibrations. This is possible because of the so-called Very near Field (VNF) assumption. It states that in the region really close to a vibrating surface, the air particle velocity equals the velocity of the corresponding point on the surface.

2. Measurement method

The measurement chain consists in only one PU regular probe and a reference channel. This can be for example an accelerometer or a force sensor. The reference channel is used to keep the relative phase information between all the measurement points.

The Scan & Paint method comprises a simultaneous measurement of the acoustic signals and a video camera that captures the movement of the probe measurement as it is scanned over the surface. Here, the acoustic signals are acquired with the PU regular probe. The position of the probe at each particular time of the record is determined by tracking a color mark on the probe in the video. Thereafter, the measurement positions are overlaid on a static background image. The sound pressure and the particle velocity, and ultimately the ODS, are calculated from a short section of the time signals of the sensors that starts just before and ends right after the time each probe position detection. With this technique is possible to quickly visualize the overall dynamic properties of large surfaces, which allows identification of regions with high deformation and acoustic radiation.

Not only the measurement procedure but also the post processing stage is very intuitive. The use of a video camera makes sure that almost all areas are captured and the measurements are filmed; this is proved to be very helpful with trouble shooting. Colour maps overlaid on pictures give a direct feedback and are easy to understand.

The ability of resizing the measurement grid in a post-processing stage allows creating the high spatial and frequency resolution results that could only be compared with step-by-step measurements which are much more time consuming.
3. Validation of the method

In order to prove how accurate the S&P ODS method and results are, a simple test is set up. The idea is to investigate a metal plate vibration patterns from 3 different approaches: applying an analytical model, using the Chladni technique and measuring the ODSs with the Scan and Paint method. Having proof the feasibility of the method in this well-known case, we can move on to test other more complicated structures.

3.1 Chladni patterns approach

One of the first methods focused upon the visualization of sound and vibration phenomena were introduced by Ernst Chladni at the end of the 18th century. The method was based on using sand sprinkled on vibrating plates to show dynamic behaviour of a vibrating body. He generated the nowadays called Chladni patterns by strewing sand on a vibrating plate excited with a violin bow which causes the sand to collect along the nodal lines.

The structure used for the test is a flat horizontal plate. Using Chladni method makes it possible to visualize its deflection shapes. To be able to know the frequencies in which to excite the plate, the transfer function is measured between the acceleration near the center of the plate and the acceleration applied to the frame. It gives us the resonance frequencies: 82Hz, 201Hz, 360Hz.

Then, by exciting the plate with a shaker on each of its frequencies, it is possible to observe their deflection shape by sprinkling salt. Under the effect of vibration, salt grains accumulate in areas not distorted, revealing the nodal lines at each frequency:

![Figure 1. Mode at 82 Hz (left), mode at 201 Hz (center), mode at 360 Hz (right).](image)

This simple experiment allows an easy way to observe the vibration behavior of a plane and horizontal plate.

3.2 Analytical model approach

The analytical model of the clamped steel plate can permit also to find the modes observed with the Scan & Paint device.

The dimensions of the plate are: length : 0.5 m, width : 0.3 m, thickness : 0.001 m. Based on the theory of plates of AK Mitchell and CR Hazell, this model made with Mathcad shows a good correlation between measurement and calculation Figure 2.

![Figure 2. Analytical deflections at 82, 201, 360 Hz.](image)
3.3 Scan and Paint ODS approach

3.3.1 Reference sensor position

The measurement on the vibration plate is again performed, in this case using the Scan & Paint technique. At each resonant frequency a velocity colour map and ODS is extracted. The reference accelerometer is fixed to the frame of the structure, exciting the vibrating plate. This reference signal is only used to keep the phase relation between the measurement positions. Since no analytical models have to be applied and the displacement mapping is performed in a relative way, ODS are able to show the dynamic behaviour of a structure even when the coherence is fairly low.

By combining the signals acquired with the static reference and the moving P-U probe it is possible to produce colour maps of pressure, particle velocity, sound intensity, transfer functions and coherence, showing the local distribution of those quantities across the surface structure. The coherence colour map can give an indication about the degree of linear relationship between reference and scanning probe. Using at least two reference sensors in different positions is possible to choose one or the other one for the visualization of the ODS in the processing stage, depending on the best coherence achieved at a determined frequency. The probe should be measuring as close as possible to the radiating surface, to achieve the Very near Field (VNF) assumption. This condition is dependent on the frequency and effective size of the radiating surface; typically at lower frequencies a measurement distance of about 2 to 5 cm is enough to achieve the VNF condition.

3.3.2 Measurement results

The main resonant frequencies are identified by the average velocity spectra over the surface. As determined by the analytical model and the transfer functions measurements, the 3 main resonances at: 82 Hz, 199 Hz and 351 Hz. Those can be compared with the above mentioned analytical model to see the correspondence between the experimental data and the mathematical model.

The colour map of the ODS show clearly the phase relation of the different radiating areas, and suggest how the structure is deformed at each frequency when excited in a broad band by an electrodynamics shaker. The modal response at 199 Hz and 351 Hz “Fig.3” show respectively a vertical and horizontal pattern.

![Figure 3. Absolute velocity map (top) and ODS (bottom), at 82 Hz, 199 Hz and 351Hz (from left to right).](image-url)
A good correspondence between the three methods is found, proving that the S&P ODS is a good way to extract and test the results of an analytical model, taking only some minutes to perform the test.

4. Measurement results in real application scenarios

4.1 Measurement on car door

A measurement on a car door, a coffee machine and a paper cutting machine are performed. The measurement and test set-up does are very fast, and can be applied in a non-anechoic condition like normal office environments, with a good degree of accuracy.

A car door is suspended with elastic ropes. The reference force sensor is attached to the door structure. The excitation is given by a small actuator attached to the force sensor. The test is repeated moving the reference in 2 different positions. The resonant frequency at 60Hz is clearly visible from the average velocity spectra.

The velocity colour map displays the dominant radiating sources at the frequency of interest. The ODS map shows the phase pattern of the mode.

Figure 4. Velocity colour map (left) and ODS map (right) – reference position 1.

Figure 5. Velocity colour map (left) and ODS map (right) – reference position 2.

Depending on the excitation point the velocity pattern shows slightly different areas of radiation. This is expected as the light structure can be affected by the mass of the force sensor and actuator attached in different positions, affecting the local dynamic behaviour of the door panel.
4.2 Measurement on a coffee machine

On the coffee machine several dominant frequencies are excited by the electric compressor, as harmonics of the main rotation order, which is 50Hz.

The machine runs in stationary condition for about one minute, during this time the probe is moved along the side surface. The frame rate of the video camera is about 15fps, meaning that 1016 measurement points are processed in about one minute. Such high spatial resolution cannot be achieved with a step by step technique.

For some tonal frequencies the velocity (absolute) colour map and the relative ODS is extracted “Fig.6-7”.

![Figure 6. 50Hz - velocity map (left) and ODS (right).](image)

![Figure 7. 200Hz - velocity map (left) and ODS (right).](image)

The ODS colour map shows the phase relation between the different radiating areas on the structure. At 200 Hz “Fig.8” there is a clear dominant source at the right side of the surface of the coffee machine. The ODS contour shows how this dominant sources are radiating in phase with the surrounding areas, so that is clearly visible the line where higher deformation occur. This line indicates an area where the gradient of the velocity is much higher, in other words where the structure is more subjected to deformation. This information is very important to understand what treatment would be more efficient.

Adding a mass where the velocity is higher could be the more intuitive solution, but not the most convenient. To reduce the vibration at the structure is also possible to apply layers of damping material. The position of this material is very important to ensure best efficiency of the treatment. Damping materials typically must be applied where the gradient of the velocity is higher, where the structure is more deformed. A wrong position of the damping layer could not work.
4.3 Measurement on a paper shredding machine

In the following test a shredding paper machine is working under stationary conditions. The accelerometer is fixed on the front of the machinery.

The experiment is performed scanning the front surface with the PU probe and using the accelerometer as a reference in 2 different positions.

The reference position of the accelerometer is chosen by evaluation of the velocity distribution over the surface of the machinery “Fig.8 left”.

![Figure 8. Velocity colour map at 50Hz vel/Ref (left) and coherence function (right).](image)

The accelerometer in the first measurement is positioned where there is the maximum of the surface radiation. In a second measurement the accelerometer is moved where the velocity signal is very poor, at the top part of the front plate of the machinery. The average coherence at 50 Hz strongly decreases in the second measurement as expected “blue curve, Fig.8 right”.

Even though the variation in the coherence function the ODS map displays a comparable phase pattern in both measurements “Fig.9”.

This test shows the low sensitivity of the presented technique to the positioning of the reference sensor, and therefore the robustness of the method.

![Figure 9. 50Hz – ODS of the first measurement (left) and second measurement (right).](image)

5. Conclusions

A novel scanning technique has been investigated on a real application case and compared with an analytical model. Results show the potential and the advantages of the method in term of applicability, measurement time and costs.
The robustness of the method has been proven; being not sensitive to the measurement set up and applicable even in non-anechoic conditions.

REFERENCES


