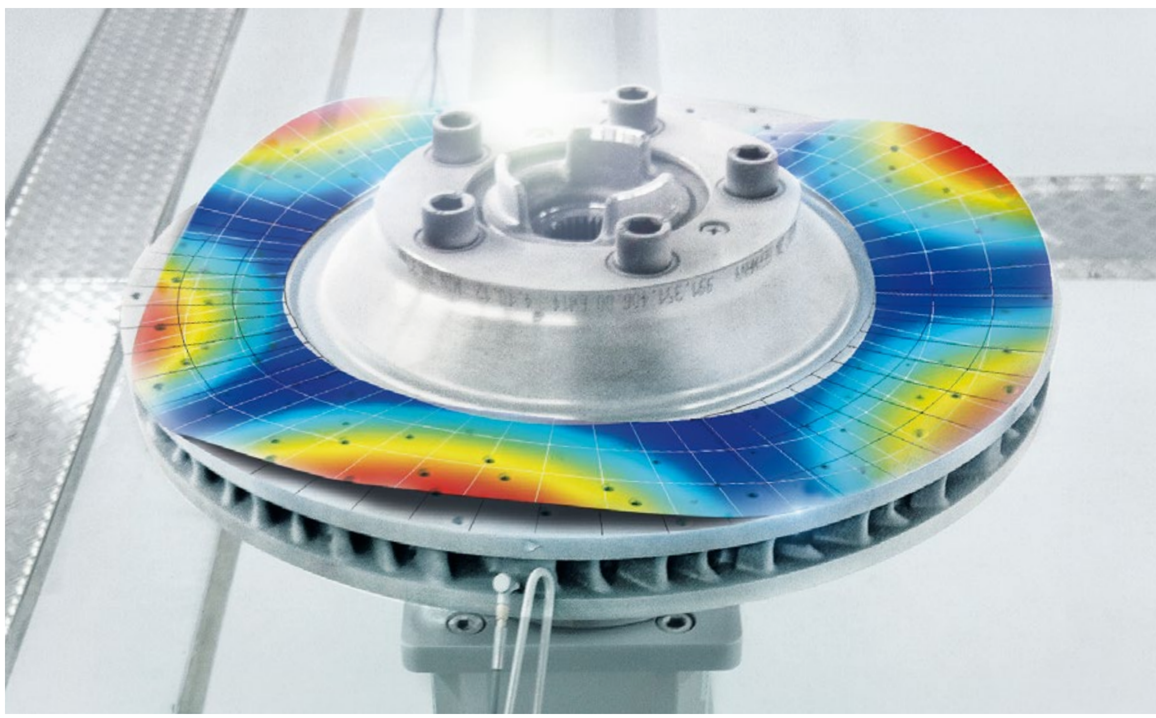
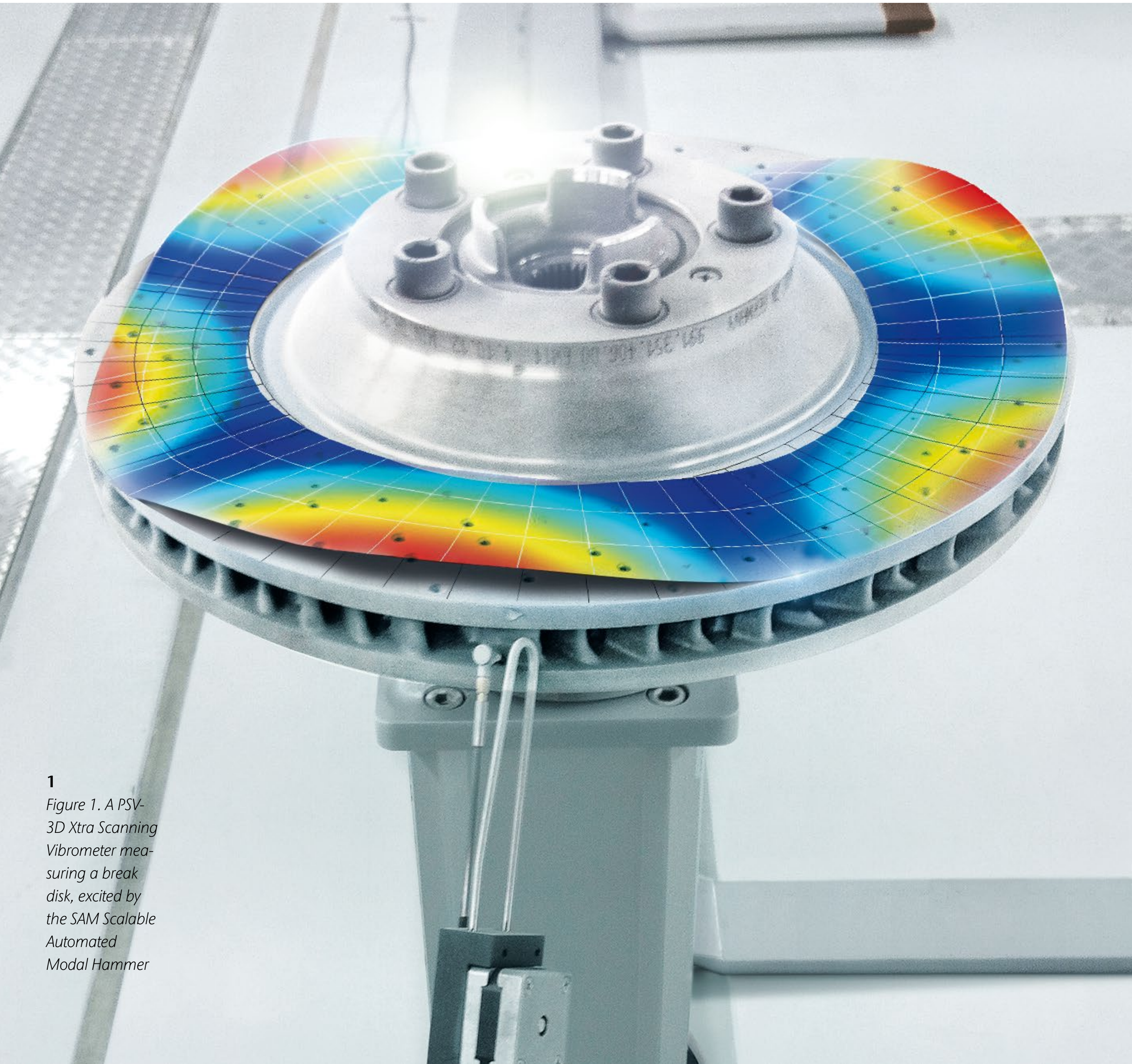


# MIMO modal testing

## Mode separation at symmetrical objects for improved model correlation

Application Note

# Improved model correlation by modal testing using a PSV-3D Scanning Vibrometer and two SAM Scalable Automatic Modal Hammer at highly symmetrical test objects.



**1**
*Figure 1. A PSV-3D Xtra Scanning Vibrometer measuring a break disk, excited by the SAM Scalable Automated Modal Hammer*

**Modal testing of structures with closely coupled modes is a very frequent task. Structures often have modes that have almost the same resonant frequency. For example, a plate's specific bending mode might occur at almost the same frequency as its torsion mode. This "accidental" frequency degeneracy is common among more complex geometries and structures. On the other hand, when a structure is planned to be highly symmetric, the coupled modes are expected "by design." In finite element (FE) simulations, all of these modes appear separately. However, in real world testing, extracting the modes from measurement data can be challenging. This application note introduces a novel approach to separate closely spaced modes with MIMO testing (multiple input, multiple output) using two automated modal hammers.**

**The need for modal extraction using MIMO**

In the case of a brake disk, the frequency splitting of the peaks is normally small as the disk is typically highly symmetric. Therefore, when animating the measured deflection shape at the peak frequency of a slightly broadened resonance, the combined effect of both underlying mode shapes is visible and can't be separated. For FE correlation, the engineer would like to extract all mode shapes from the test data and correlate them with corresponding modes from the FE simulation. This extraction is done by curve fitting of the measured data using special modal analysis software such as PolyWave or FEMtools. If the asymmetry of the object is large enough and the excitation of the underlying modes is comparable, the modal extraction can separate the symmetric modes and allow for proper correlation of the complete data set using one excitation source at one fixed point. Frequently these conditions are not fulfilled and, for some or even all modes, only one out of the two symmetric modes can be extracted.

Let's examine the case of a rotationally symmetric brake disk. Due to its symmetry, the FE model calculates two first bending modes, both at exactly the same frequency but with a 45° shift in the node line in-between the two mode shapes. In a real modal test, the situation is much less ideal:

- The disk is not perfectly symmetric, leading to a frequency splitting of the two resonances and separated peaks in the spectra. Depending on the amount of separation and damping (peak width), the peaks may be resolvable or simply appear as a slightly broadened single peak.

- The amplitudes of each resonance depend on the chosen excitation location. For example, if excitation is located close to one mode's deflection shape node, one resonance will dominate the spectra, the other will barely be detected.

Using test data obtained by exciting at two or more locations often resolves this problem. This approach of using more than one excitation location is called MIMO - (multiple-input, multiple-output).

Typically, MIMO tests are performed by attaching two or more shakers to a structure and performing a principal component analysis of the acquired data to separate the influences from each excitation source. Because these shakers contact the structure, they have a certain influence on the vibration behavior of the structure. This is especially true for lightweight objects, or structures with little damping, where the perturbing influence of the shaker can significantly affect the results.

**A better approach: Scanning laser Doppler vibrometry (SLDV) with automated modal hammers**

Scanning laser Doppler vibrometers (SLDV) are state-of-the-art instruments for measuring the vibration response without mass-loading or modifying the damping of the test object. Furthermore, compared to relatively large contact transducers, a high spatial resolution scan is easily performed with a focused laser beam, clearly showing the higher-order deflection shapes. Similarly, an automated modal hammer with its transient impact avoids altering the vibration behavior of the object under test and is a perfect match for a modal test using scanning vibrometers. To date, either MIMO tests using several shakers or a single hammer exciter have been reported; however, no MIMO tests using scanning vibrometers and two hammer exciters can be found in the literature. This highly beneficial setup is tested in the following experiment

# Better mode separation with MIMO excitation and non-contact vibration measurement

**Experimental setup**

A brake disk is suspended on soft foam and excited by a Polytec SAM – the Scalable Automated Modal Hammer. The 3D surface velocity is measured at 256 individual scan points by a Polytec PSV-3D Xtra Scanning Vibrometer.

Two measurement runs were performed, each one corresponding to a different hammer excitation position. In the following images, the results for the first bending mode are shown. The marked points correspond to the respective excitation locations.The first excitation point mainly excites the resonance shown on the left-hand side; the second point's response is shown on the right-hand side.

**Data handling for modal extraction**

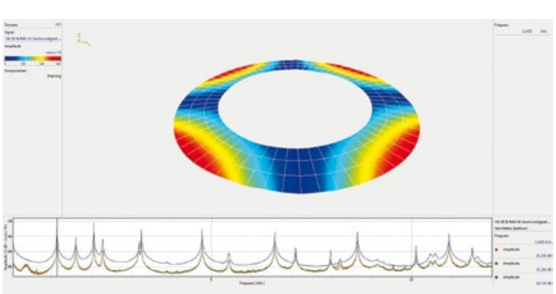
When using two excitation sources simultaneously (for example two shakers), the integrated PCA (Principle Component Analysis) option of the PSV software can be used to separate the influence of each excitation source in the subsequent post-processing. In this case, the measurements are performed separately, creating two independent data files. These two data files can be combined manually into one common universal file and are imported into the software PolyWave or FEMtools for modal extraction. The results are then compared to those obtained with only one excitation point.

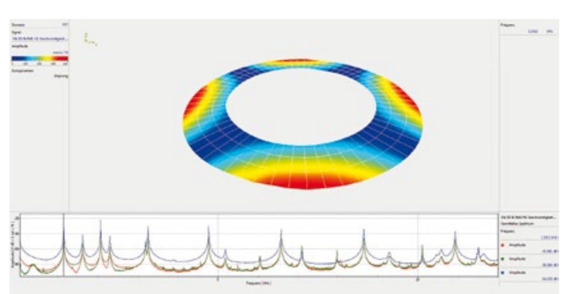
For modal extraction based on stability diagrams, a maximum modal order must be specified. The proper choice of this parameter is critical for the quality of the obtained results: if chosen too low, not all modes will be extracted obscuring the separation of close-by symmetric modes. If chosen too high, many extraneous computational modes can appear that do not correspond to "real" physical ones. This latter effect leads to large, off-diagonal values in the MAC (modal assurance criteria) matrix which quantifies the similarity of the obtained mode shape.

Since the symmetrical resonances are only slightly separated, the curve fitting was performed in small spectral segments; each one containing one or two visible peaks and corresponding to one to three underlying mode shapes. From the simulation results, 11 modes were expected in the chosen frequency range, five pairs and one rotationally symmetric mode.

**Single excitation point results**

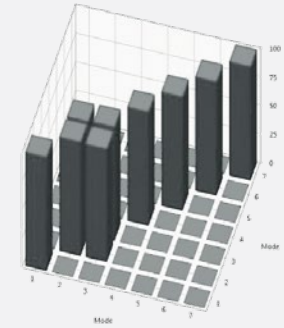
First, a modal extraction has been performed with the results from a single excitation point measurement. For this case, two variants of evaluation have been tried: one with a low maximum modal order of 12, and one with a considerably higher maximum order of 60. For the low maximum order of 12, not all modes can be identified finding only 6 out of 11 modes plus one





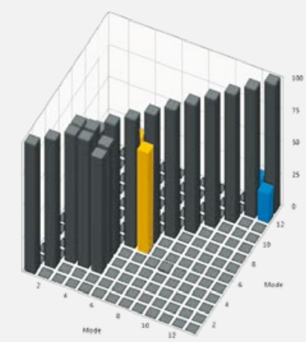
**2**
Points of excitation; ODS for first excitation point (left), ODS for second excitation point (right).

| Mode # | Frequency [Hz] | Damping [%] | MPC [%] | MPD [*] | MAC alias [%] |
|---|---|---|---|---|---|
| ☑ 1 | 1141.057 | 0.04 | 99.9 | 1.6 | 0.4 |
| ☑ 2 | 1613.210 | 0.23 | 100.0 | 1.1 | 99.3 |
| ☑ 3 | 1619.208 | 0.16 | 99.8 | 2.1 | 99.3 |
| ☑ 4 | 2065.746 | 0.03 | 99.5 | 3.9 | 0.0 |
| ☑ 5 | 2299.589 | 0.18 | 99.8 | 2.4 | 0.0 |
| ☑ 6 | 3186.371 | 0.09 | 97.7 | 10.4 | 0.4 |
| ☑ 7 | 3249.870 | 0.06 | 99.5 | 4.4 | 0.2 |



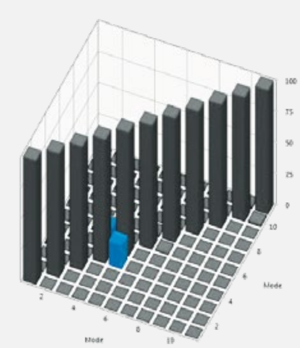
**3**
Mode table and AutoMAC for a single excitation point test with a low maximum order of 12.

| Mode # | Frequency [Hz] | Damping [%] | MPC [%] | MPD [*] | MAC alias [%] |
|---|---|---|---|---|---|
| ☑ 1 | 1141.088 | 0.03 | 100.0 | 1.0 | 0.4 |
| ☑ 2 | 1145.476 | 0.04 | 100.0 | 0.4 | 0.2 |
| ☑ 3 | 1612.595 | 0.21 | 100.0 | 0.7 | 0.1 |
| ☑ 4 | 2065.520 | 0.04 | 99.5 | 3.5 | 15.1 |
| ☑ 5 | 2065.668 | 0.04 | 93.8 | 15.2 | 15.1 |
| ☑ 6 | 2286.801 | 0.17 | 99.8 | 2.4 | 0.4 |
| ☑ 7 | 2299.565 | 0.19 | 99.9 | 1.8 | 0.4 |
| ☑ 8 | 3186.303 | 0.08 | 99.8 | 1.9 | 0.4 |
| ☑ 9 | 3195.274 | 0.11 | 99.8 | 2.3 | 0.2 |
| ☑ 10 | 3249.974 | 0.06 | 99.8 | 2.5 | 1.7 |
| ☑ 11 | 3251.203 | 0.05 | 96.8 | 10.5 | 1.7 |

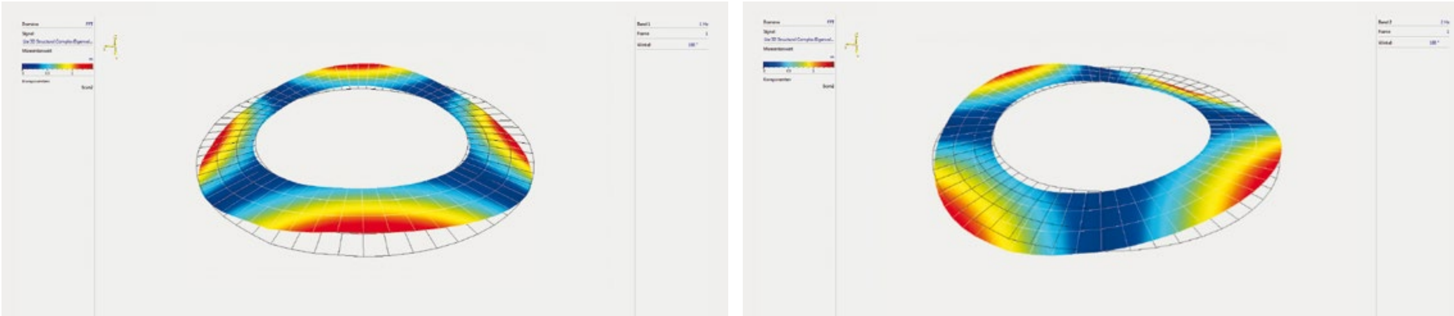


**4**
Mode table and AutoMAC for a single excitation point test with a high maximum order of 60.

| Mode # | Frequency [Hz] | Damping [%] | MPC [%] | MPD [*] | MAC alias [%] |
|---|---|---|---|---|---|
| ☑ 1 | 1141.073 | 0.03 | 100.0 | 1.0 | 0.5 |
| ☑ 2 | 1145.486 | 0.05 | 99.8 | 2.1 | 0.4 |
| ☑ 3 | 1613.324 | 0.25 | 100.0 | 1.1 | 99.5 |
| ☑ 4 | 1618.715 | 0.22 | 99.8 | 1.9 | 99.5 |
| ☑ 5 | 1631.379 | 0.07 | 96.8 | 9.5 | 91.1 |
| ☑ 6 | 2065.015 | 0.07 | 98.4 | 7.0 | 78.6 |
| ☑ 7 | 2065.995 | 0.03 | 97.0 | 10.3 | 78.6 |
| ☑ 8 | 2287.820 | 0.16 | 99.8 | 2.8 | 0.7 |
| ☑ 9 | 2299.319 | 0.20 | 99.6 | 3.7 | 1.3 |
| ☑ 10 | 3186.388 | 0.09 | 99.8 | 2.1 | 0.4 |
| ☑ 11 | 3195.319 | 0.10 | 99.1 | 4.0 | 0.3 |
| ☑ 12 | 3249.786 | 0.07 | 99.9 | 1.8 | 23.0 |
| ☑ 13 | 3251.546 | 0.05 | 88.6 | 20.1 | 23.0 |

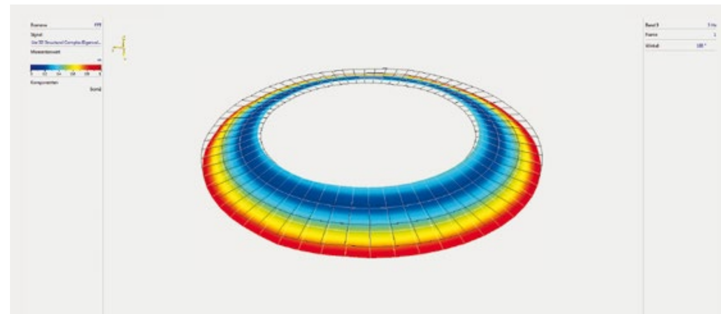


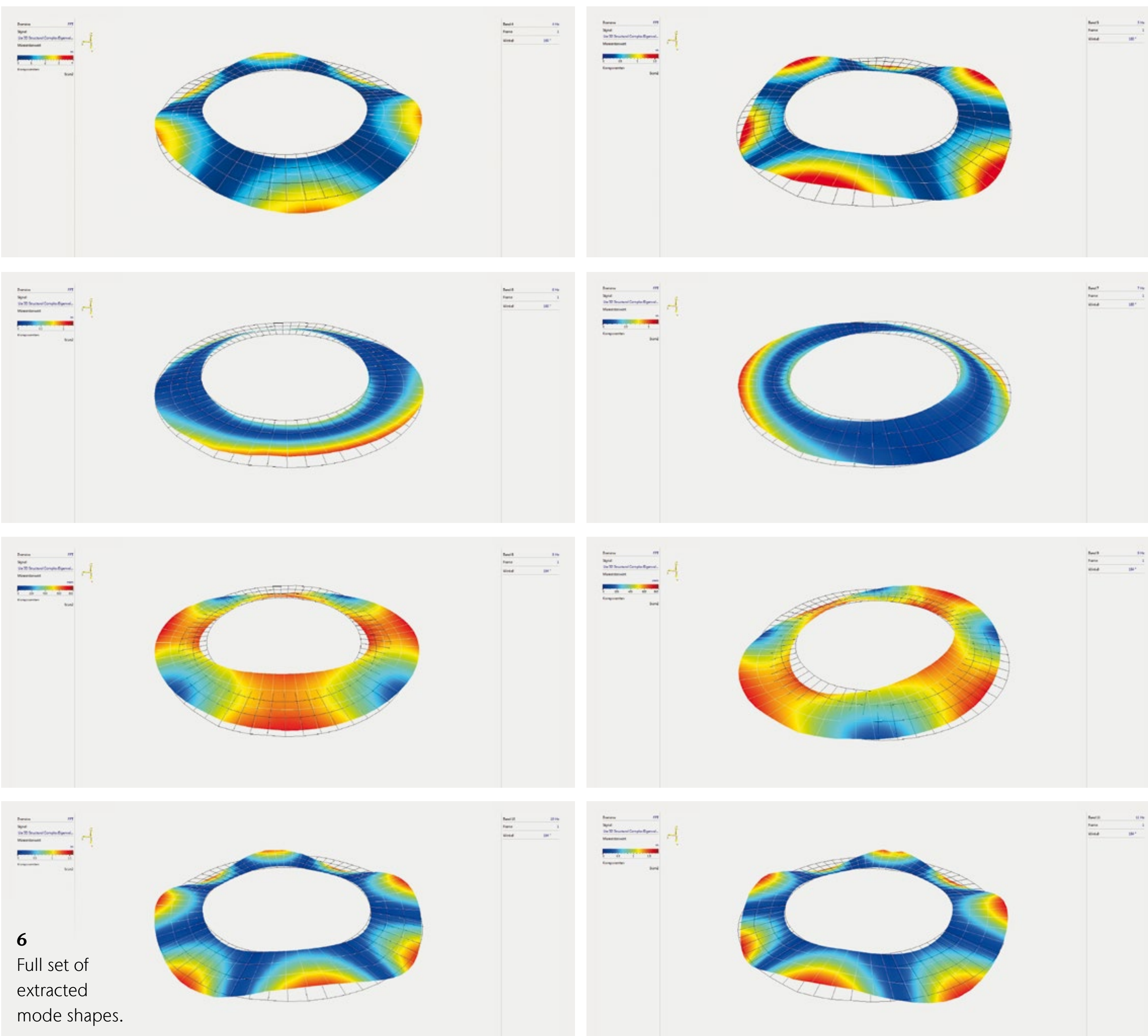
**5**
Mode table and AutoMAC for a dual excitation point test with maximum order of 12. All modes were identified and well separated with no computational modes introduced.



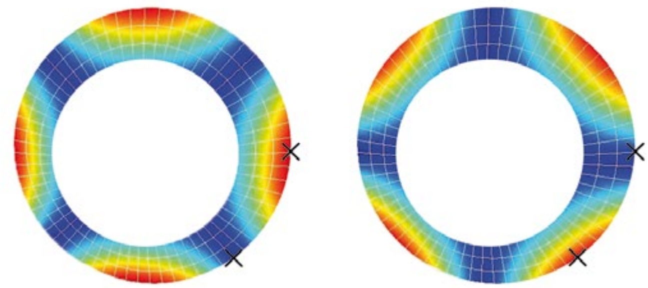
# Unambigious representation of mode shape pairs for comparison with FE

Mode 3 is rotationally symmetric and appears only once. ▸





**6**
Full set of extracted mode shapes.



**8**
Figure 8. Points of excitation are shown with respect to the maxima of the first mode pair.

computational mode (Figure 3). For a maximum order of 60, non-physical computational modes appear: 13 modes are found instead of 11 physical modes. Significant off-diagonal values in the AutoMAC indicate computational modes. Furthermore, two mode pairs - 6 and 7 around 2.065 Hz and 12 and 13 around 3.250 Hz - are not well separated (Figure 4).

**MIMO results, using two excitation points**

Next, the MIMO results using two excitation locations were processed. Because the results are obtained from two separate measurements runs, which are combined into one file only after the test, no principal component analysis (PCA) is necessary, since there is no influence from the second excitation source onto the transfer function from the first source to the output measurement points. During the curve fitting, it was quickly confirmed that the use of the combined file with the two excitation locations had significant advantages. Starting from a low model order, the fitting process works reliably, saving evaluation time and leading to a complete set of modes without adding non-physical modes. Such a result was achieved with only a maximum model order of 12. In Figure 5, the resulting mode tables and the corresponding AutoMAC matrices are shown.

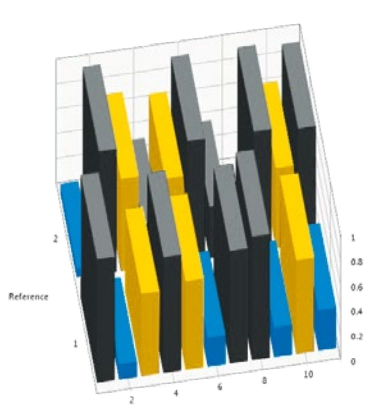
From the mode table and the AutoMAC diagram in Figure 6, it can be clearly seen that the extracted modes are nicely decoupled. Looking at the mode shapes, it is evident that all relevant modes were found. All symmetric modes were identified. Mode 3 is rotationally symmetric and appears only once.

In Figure 7, the modal participation factor documents that for many modes, one of the excitation sources (reference 1 or 2) dominates. This confirms that separating modes is much easier using two excitation points. For modes 5 and 10, the participation of the two excitation points is more balanced. This means that the excitation points were not optimally chosen for the complete separation of these two specific pairs of symmetric modes, but are still well enough suited, as can be seen in the mode shape table and the AutoMAC. To illustrate this last point, the two excitation locations are superposed on the first pair of symmetric mode shapes in Figure 8.

It is clear that the first excitation point is on a maximum of the first mode shape which is a minimum of the second mode shape and vice versa. This confirms that separating this mode pair is much easier when using two excitation points.

**Conclusion**

In conclusion, by combining a PSV-3D Scanning Vibrometer with two SAM Scalable Automated Modal Hammers, a state-of-the-art MIMO modal test was conducted that was very useful for mode separation, symmetric structures and FE model correlation. Especially for lightweight and low-damped, symmetric structures where the mass loading effect of two or more shakers prevents quality results, this method is a valid alternative.

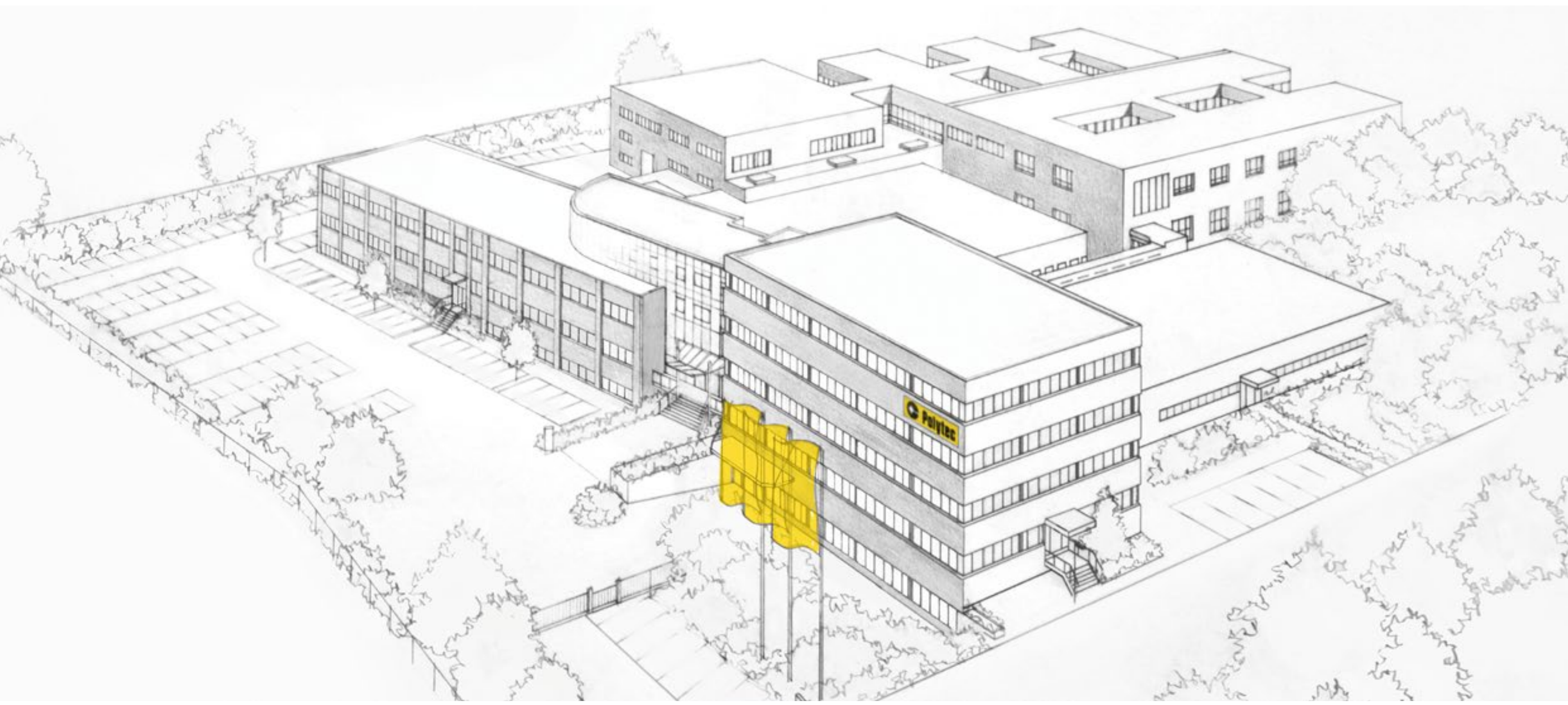



**7**
Modal participation factor for the dual reference test.

**Authors**

Jochen Schell, Polytec GmbH

Polytec



**Polytec GmbH (Germany)**
Polytec-Platz 1-7
76337 Waldbronn
Tel. +49 7243 604-0
info@polytec.de

**Polytec GmbH (Germany)**
**Vertriebs- und Beratungsbüro**
Schwarzschildstraße 1
12489 Berlin
Tel. +49 30 6392-5140

**Polytec, Inc. (USA)**
North American Headquarters
16400 Bake Parkway
Suites 150 & 200
Irvine, CA 92618
Tel. +1 949 943-3033
info@polytec.com

**Central Office**
1046 Baker Road
Dexter, MI 48130
Tel. +1 734 253-9428

**East Coast Office**
1 Cabot Road
Suites 101 & 102
Hudson, MA 01749
Tel. +1 508 417-1040

**Polytec Ltd. (Great Britain)**
Lambda House
Batford Mill
Harpenden, Herts AL5 5BZ
Tel. +44 1582 711670
info@polytec-ltd.co.uk

**Polytec France S.A.S.**
Technosud II
Bâtiment A
99, Rue Pierre Semard
92320 Châtillon
Tel. +33 1 496569-00
info@polytec.fr

**Polytec Japan**
Arena Tower, 13th floor
3-1-9, Shinyokohama
Kohoku-ku, Yokohama-shi
Kanagawa 222-0033
Tel. +81 45 478-6980
info@polytec.co.jp

**Polytec South-East Asia Pte. Ltd.**
Blk 4010 Ang Mo Kio Ave 10
#06-06 TechPlace I
Singapore 569626
Tel. +65 64510886
info@polytec-sea.com

**Polytec China Ltd.**
Room 402, Tower B
Minmetals Plaza
No. 5 Chaoyang North Ave
Dongcheng District
100010 Beijing
Tel. +86 10 65682591
info-cn@polytec.co

**www.polytec.com**