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Characterising dynamics of MEMS devices at wafer level using optical measurement techniques

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The use of microelectromechanical systems (MEMS) has become increasingly prevalent in industries such as aeronautic, automotive, biomedical, consumer, medical and telecommunications. To ensure high yield and reliability at a low cost, early wafer-level MEMS testing is crucial. While electrical tests verify functionality, advanced optical measurement techniques are needed to characterise important physical properties of MEMS devices that are not accessible with electrical tests.

This article describes automated optical measurement capabilities for dynamic response measurements of MEMS devices at the wafer level using an automatic or semi-automatic probe station in combination with a laser Doppler vibrometer. This technology enables real-time dynamic response measurements with high accuracy and frequency bandwidths up to 25 MHz in standard instruments and up to 6 GHz in specialised setups. Users in fabs will benefit from the outlining of complete, customised solutions based on proven technology components for wafer handling, wafer probing, sample excitation, optical metrology, process control and data handling. Several characterisation studies are presented here to demonstrate the usefulness of this technology in typical application fields.

> **"While electrical tests verify functionality, advanced optical measurement techniques are needed to characterise important physical properties of MEMS devices that are not accessible with electrical tests."**

Optical measurement systems

For characterising MEMS devices optically, a wide range of measurement techniques and commercial solutions are available to measure a wide range of physical properties (dimension, film thickness, step height, cross section, roughness, stress, stiction, modulus elasticity, response time, thermal expansion, resonance frequency, etc.).

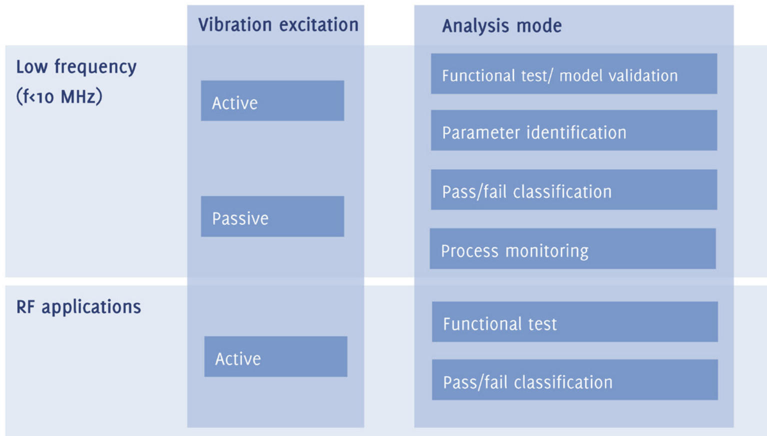
For example, basic optical microscopy with digital image processing can provide dimensional analysis and measure deformations. More advanced optical measurement systems are tailored towards specific capabilities (3D shape measurement, dynamic response, high lateral resolution and/or high vertical resolution). The non-contact principle of any optical measurement predestines these for wafer-level testing.

If real-time capability—or equivalently, a fast broadband measurement—is required to characterise the dynamical mechanical properties of a device, laser Doppler vibrometry (LDV) is an appropriate method to solve the measurement task, affording the highest displacement resolution, limited only by the shot noise of light.

Optical microsystem analysers incorporating a scanning laser Doppler vibrometer are the ideal instrumentation for dynamic response measurements of MEMS devices, which typically involve actively moving elements for sensing and actuation. Dynamic response measurements provide critical information that cannot be determined by electrical testing alone. Examples of dynamic response measurements include settling time dynamics of micromirrors, displacement amplitudes of resonators and resonance frequency of cantilevers. Here, non-invasive measurement techniques are needed that are precise, real-time and high resolution. Besides the scanning laser Doppler vibrometer for out-of-plane measurement, microsystem analysers optionally include a strobe video microscope to also measure in-plane motions and a white-light interferometer to add the capability of surface topography measurement for static shape.

This instrumentation is presently being used throughout the MEMS community to characterise devices such as micromirrors, cantilevers, accelerometers, gyros, actuators, RF switches, ultrasonic transducers, ink jets, microphones, pressure sensors, resonators and many more. Applications include:

- dynamic testing of device response to determine mechanical parameters such as resonant frequency, stiffness and damping after applying specific physical stimulus;
- model-based identification of material parameters on the basis of vibration measurement data, e.g., material stress determination of MEMS membranes;
- design validation of performance versus expected FE model predictions;
- measurement of settling time dynamics to determine precise movement versus time and show 3D visualisation of response;
- calibration of actuator and sensor displacements versus drive voltage over wide range of motion and frequencies; and
- topography measurement to determine surface characteristics after fabrication process (shape, geometry, curvature, roughness, step height, film stress, delamination).



▶ ***Figure 1:*** *Classification of different vibrometer applications for wafer-level testing of MEMS.* ▶

This article describes the technology components of a complete wafer-level test station, including probe station and laser Doppler vibrometer, sample excitation schemes and typical applications showing the versatility of the method. The principles of operation are important for understanding the possibilities and inherent advantages but also limitations of the technology used. A detailed summary of this technology is included, followed by examples showing how the above-mentioned techniques are used for key applications.

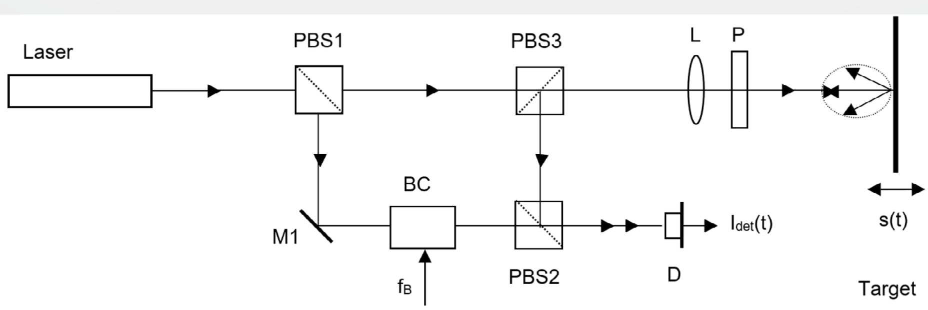
Laser Doppler vibrometer

The laser Doppler vibrometer is an optical instrument using laser technology to measure velocity and displacement at selected points on a vibrating structure. Laser vibrometers measure without contact and are not affected by surface properties or environmental conditions. The laser beam can be focused to a spot below 1 µm in diameter, allowing investigation of MEMS structures visible under an optical microscope. Diffraction limitations prevent measurements of devices smaller than the wavelength of light used (532 nm). LDV is a very sensitive optical technique with the overall capability of measuring displacements from centimetres to picometres at frequencies from near DC to GHz. In addition to their broad frequency range, laser Doppler vibrometers also have a high dynamic range (over 170 dB) for velocity amplitudes from below 0.01 µm/s up to 150 m/s. These features allow measurements not possible using holographic or other techniques.

The laser Doppler vibrometer uses the Doppler effect, where light backscattered from the moving target carries information about the motion quantities, velocity and displacement at the point of incidence. Displacement of the surface modulates the phase of the light wave while instantaneous velocity shifts the optical frequency. Using interferometric techniques, the received light wave is mixed with a reference beam so that the two beams recombine at the photo detector. The basic arrangement of a modified Mach-Zehnder interferometer is depicted in figure 2.

The signal measured at the photo detector carries direction sensitive frequency and phase modulation from the moving target. Target displacement s(t) results in a phase modulation where λ represents the laser wavelength:

$$\varphi_m(t) = \frac{4\pi s(t)}{\lambda}$$



▶ ***Figure 2:*** *An optics schematic of a modified Mach-Zehnder interferometer.* ▶

According to the basic relationships $d\Phi/dt = 2\pi f$ and $ds/dt = v$, that phase modulation corresponds to a frequency deviation known as the Doppler frequency:

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

The resulting frequency of the detector output signal correctly preserves the directional information (sign) of the velocity vector.

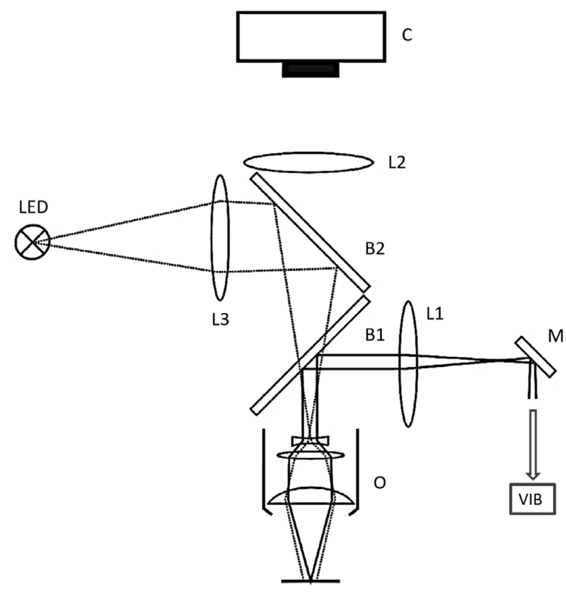
The measurements taken by LDV are dynamic by nature and do not carry information about static shape (as is possible using other techniques like digital holography or white-light interferometry (WLI)). Displacement and velocity are encoded in phase and frequency modulation of the detector output signal. To recover the displacement and velocity time histories from the modulated detector signal, phase and/or frequency demodulation techniques are used in the signal decoder blocks of a laser vibrometer. The high-quality digital demodulation electronics used provide critical accuracy, linearity, sensitivity and signal-to-noise ratio.

The LDV measurement instruments can be extended to a 3D vibrometer setup, enabling pm-resolution for both out-of-plane and in-plane motion.

One specific property of using LDV is that the measurements are at a single point, rather than captured on a full field as done using video interferometry techniques. For inline inspection at wafer level, a single point measurement is by far the fastest method for extracting characteristic mechanical parameters.

However, if needed, deflecting the laser measurement beam in X and Y directions using scanning mirrors extends the LDV technique to full area scanning. The schematic for this is shown in figure 3 with 2D scanning mirror M. The laser measurement beam can be positioned at any point visible on the live microscope video. This technique is used to scan an area point by point to measure the velocity field of the structure. The phase of each point is determined by simultaneous measurement of an additional reference channel (typically the drive signal produced by the internal signal generator). From this data, 3D deflection shapes are calculated. The result comprises the mapping of the velocity and/or displacement field over the structure that allows 3D animations of the response either in the frequency or time domain.

Recent developments extend the method to optical vibration measurements in silicon-capped MEMS by implementing an infrared short-coherence light source in combination with an infrared camera. A sophisticated depth scan allows positioning of the measurement plane exactly at the moving component of the device and supression of all disturbing contributions from all other non-moving functional layers of the device.



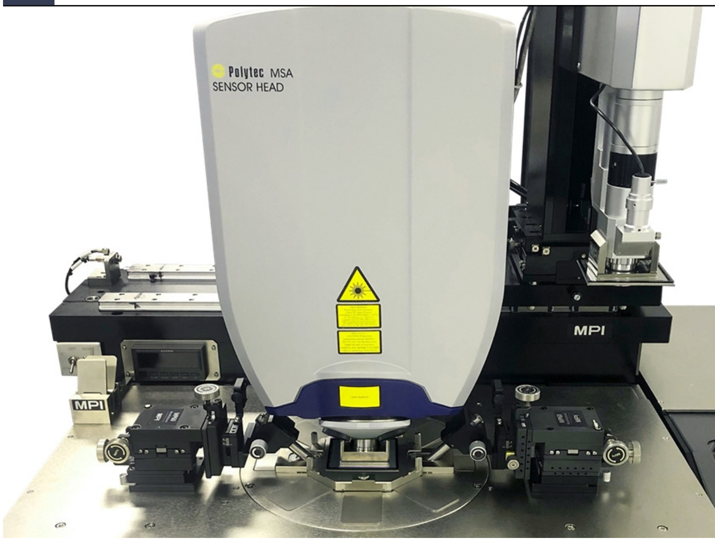
▸ ***Figure 3:*** *The optical layout of a microscope scanning laser vibrometer.* ▸

The method thus enables measurements to be taken at all relevant points in the development and manufacturing process of MEMS, right through to final post-packaging checks.

Probe station solutions for wafer-level testing of MEMS

For wafer-level tests, one can choose between manual or automated probe stations. While the wafer is placed on the chuck, the optical alignment microscope on wafer probe stations is essential to have an unrestricted view of the device under test (DUT) and align the probe needles to the test pads. Electrical probing can be done in various ways, from DC to high-frequency RF signals. Also, the number of contacts can differ from just two manual probe positioners placed on the probe platen above the wafer up to many probe needles requiring a needle probe card.

In some cases, it is necessary to place different instrumentation above the probing area. For optical testing, this can include an integrating sphere, available in different sizes, for the collection of device-emitted light. If the device is light sensitive, stimulation can be achieved via a specific light source. Or non-optical components can be excited using a magnet.



▶ ***Figure 4a:*** *An automated test solution with HF probes for sample excitation and optical measurement head.* ▶

Optical analysis tools can measure the mechanical properties and the behaviour of the DUT, such as 3D motion or topography. MEMS is an excellent example of such devices where an electrical stimulus causes an automatic movement. On manual probe stations, the standard alignment microscope can easily be replaced by the measurement-related microscope if the probe tips and pads can also be seen.

For automated probe systems, the microscope is used in combination with a camera for automatic wafer alignment, which is essential for automatic wafer testing. What all these scenarios have in common is that at first, a microscope is needed to align the wafer correctly and match the probe needles to the pads. After that, when the probe station automatically steps over the wafer, the microscope needs to be swapped with different instrumentation for the measurement.

MPI provides two solutions for automated wafer testing, namely a swappable microscope bridge and an off-axis alignment camera.

The swappable microscope bridge has a modular design and can be swapped between two positions to support the wafer alignment or measurement with the required instrumentation. Changing positions can be done either manually or in an automated fashion. The latter is required for fully automated test capability when testing several wafers from a cassette. The exceptional stability of the microscope bridge enables it to carry the two X, Y, Z linear drive units and additional instrumentation. Different standard microscope drive units—from a simple X, Y, Z stage to a heavy-duty, motorised scope support—can be placed on the bridge depending on requirements.

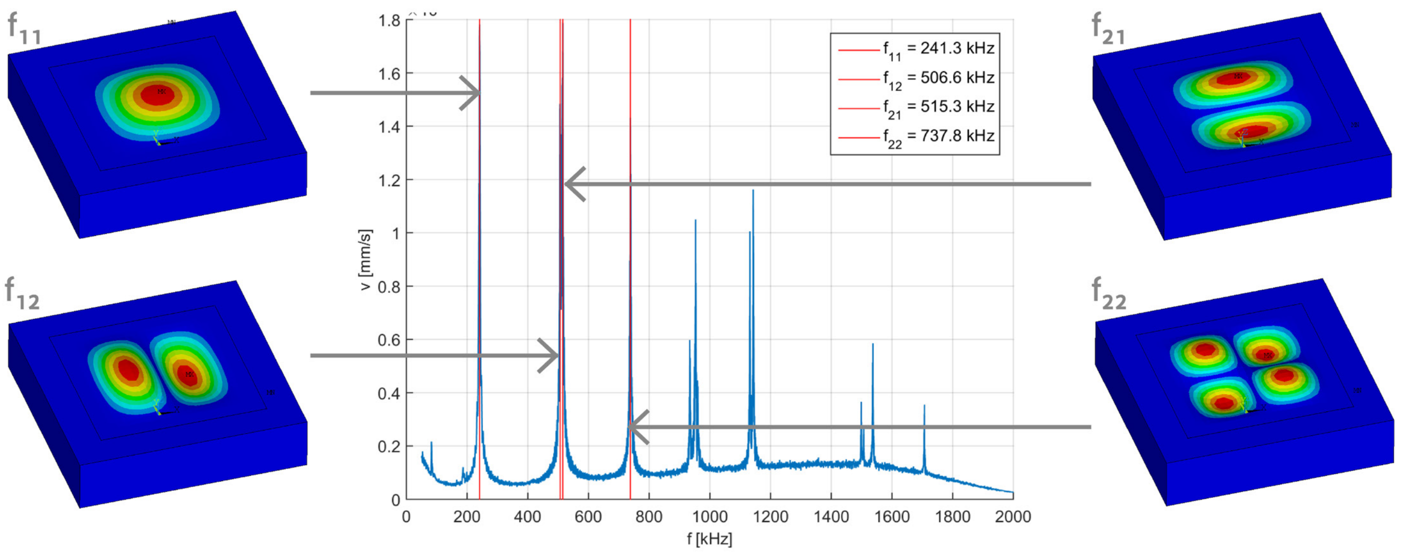
Furthermore, the swappable microscope bridge has an integrated safety switch that only allows instruments to be moved if they are in their upper position. This is highly important when using single positioners to avoid possible collisions.

The off-axis alignment camera can be used when only a fixed magnification is needed, which applies for many test cases. It is located north of the probing area inside the probe platen. The chuck movement includes an extra travel to move below the microscope and perform a complete wafer alignment, such as with the standard on-axis microscope. Now the space on the microscope bridge is accessible for just one inspection microscope. Depending on requirements, a fixed, manual or motorised X, Y movement can be used together with a Z movement for focusing on the device.

▶ ***Figure 4b:*** *Auto focusing and refocusing guarantees excellent signal and data quality.* ▶

Excitation of the natural frequencies

A prerequisite for the vibrometric measurement of natural frequencies is their excitation. While vibration excitation is an inherent feature of sensors such as resonators or inertial sensors due to functional elements such as piezoelectric layers or capacitive comb structures, a large number of, e.g., membrane-based sensors, have no functional elements for generating mechanical forces. With such passive sensors, the vibration excitation must be external. There are two different methods for this. On



▸ ***Figure 5:*** *A frequency response function (FRF) with split frequency peaks.* ▸

the one hand, vibrations of sensor structures can be thermally excited by means of a laser, on the other hand, electrostatic excitation is possible in a frequency range of up to 10 MHz. To achieve the latter, an electrode connected to a high-voltage amplifier is positioned at a distance of a few micrometres above the sensor surface. The electrode is made of the transparent material indium tin oxide (ITO) and is mounted on a glass carrier to achieve the greatest possible electrostatic force without interfering with the beam path of the vibrometer. In addition, due to the extremely high measurement sensitivity of vibrometry, it is possible to measure resonance frequencies for structures that are excited by ambient thermal noise alone, e.g. for the calibration of atomic force microscopy (AFM) tips.

Application possibilities of vibrometry

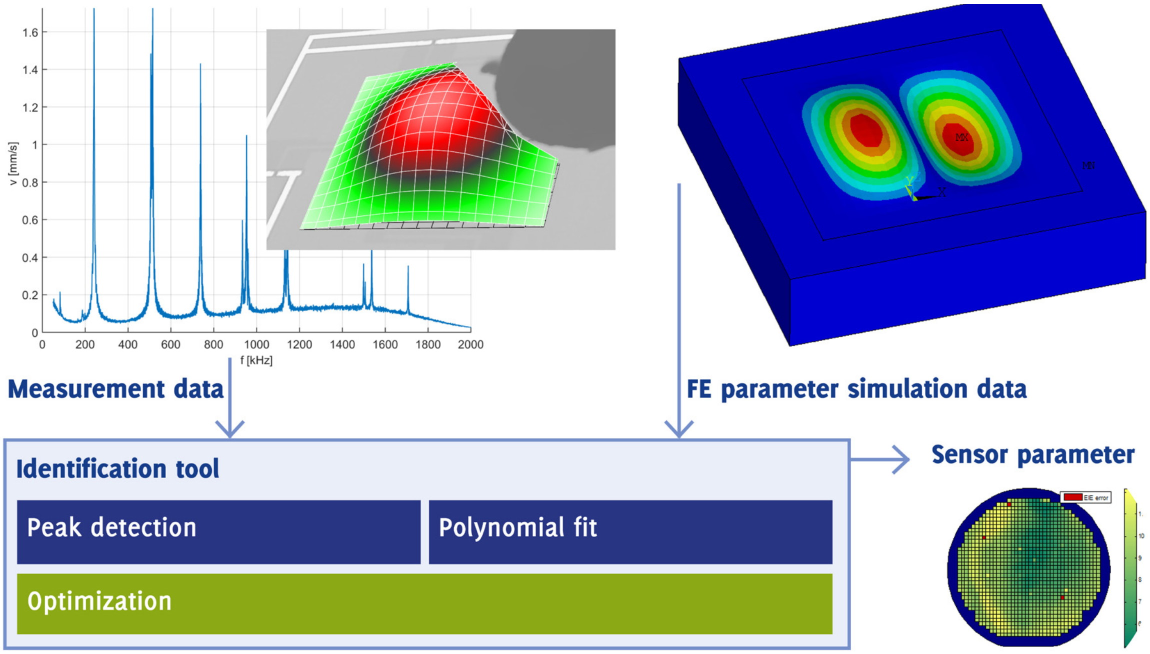
Vibrometry offers a wide range of applications beyond the obvious ones such as functional tests of sensors where frequencies are part of their functionality (e.g., resonators). In addition to the detection of manufacturing defects such as membrane cracks, vibrometry allows for the indirect identification of geometry and material parameters by means of measurement and simulation data. IMMS has developed a software solution that determines sensor parameters automatically from both measured values and simulation data by an optimisation algorithm. This software allows significantly decreased setup effort as well as enables non-expert users to easily achieve a wide range of sensor parameters.

One of the significant advantages afforded by vibrometry over other non-contact, non-destructive measurement methods is the determination of material parameters such as Young's modulus and material stress. Another is that it can be used for quality control during the entire process, from wafer production to packaging.

Good/bad classification

A simple application is the good/bad classification of sensors based on a 'learning phase' with good and bad reference sensors. If the natural frequencies of functioning and defective sensors differ, the standard deviation can be determined from the measurement of a significant number of good reference sensors as a criterion for good/bad classification in sensor production.

Due to this symmetry, nominally symmetrical sensor structures such as circular or square membranes have a large number of natural frequency pairs that are out of phase with each other at the same value. In the case of asymmetries, these frequency pairs split. Such split frequency pairs can be used to detect defects such as membrane cracks or the occurrence of asymmetrical material stresses, as can occur, e.g., as a result of packaging processes. IMMS has developed a frequency response postprocessing tool that detects split frequencies.



▸ ***Figure 6:*** *The parameter identification approach.* ▸

Parameter identification

The method of indirect parameter identification is based, on the one hand, on the vibrometric measurement of the natural frequencies, and on the other hand, on the simulation data of a modal analysis to determine the dependence of the natural frequencies on the geometry and material parameters of interest. By means of optimisation, the sensor parameters are then determined from the measured data within the postprocessing tool.

Depending on the structure to be investigated, the procedure allows the identification of one to, as a rule, a maximum of three parameters. The minimum number of natural frequencies to be measured is then derived from the number of parameters' to be identified. If more natural frequencies are measured than necessary, an estimated identification error (EIE) can be determined from these.

From the measured frequency response, values for the parameters' natural frequency, amplitude and quality factor can be extracted, and in the case of several measuring points, also the natural form. The natural frequency value is always used for parameter identification. If the determination of the internal pressure of a cavity is of interest, the quality factor also flows into the parameter identification. The mode shapes are considered particularly at frequencies that are close to each other, as the influence of material stresses can lead to a changed sequence from the nominal one. All parameters of interest can be determined from the frequency value, quality and shape. Therefore, there is no need for additional consideration of the frequency amplitudes; moreover, a complex calculation of the vibration amplitudes depending on the excitation (especially if this is done externally) is avoided.

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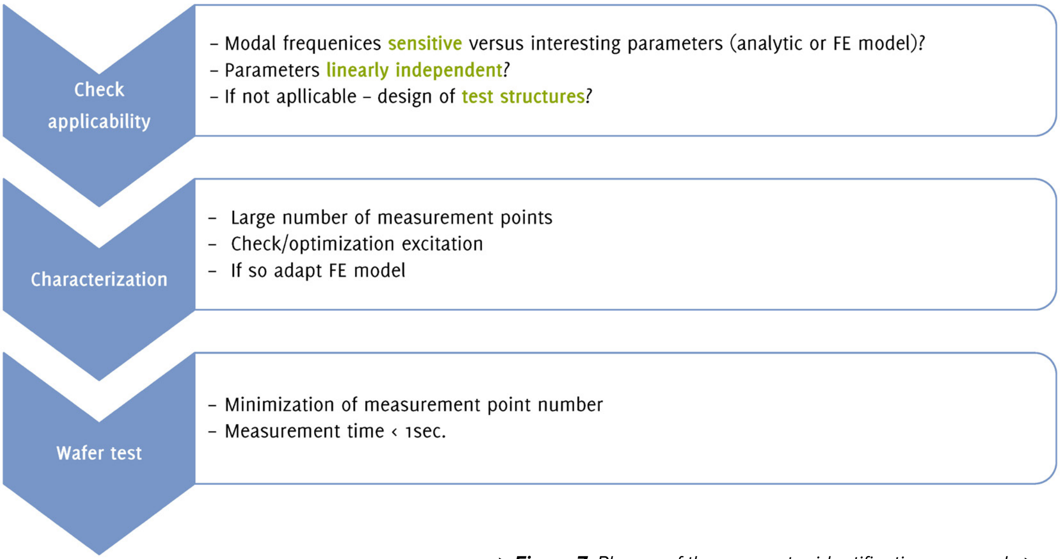
Phases of identification

The parameter identification procedure can be divided into three phases. First, it must be investigated whether the parameters sought can be determined with the required resolution using the procedure. Accordingly, prior to parameter identification, a sensitivity analysis is performed to determine the sensitivity of the natural frequencies versus the parameters of interest. For simple structures or for basic investigations, analytical formulas can be used;



▶ ***Figure 7:*** *Phases of the parameter identification approach.* ▶

for more complex structures, finite element (FE) programs provide suitable sensitivity analysis. If the structure to be investigated does not have the desired sensitivity, the desired parameters can be determined using specially designed test structures.

To get to know the sensor, the characterisation phase is followed by frequency measurement using a dense network of measuring points. This is accompanied by the selection of suitable frequency modes for identification as well as validation and, if necessary, adaptation of the FE model. In the third and final phase, the process is optimised for use in wafer production by, among other things, minimising the number of measurement points with regard to a short measurement time, which is usually significantly less than one second.

Examples

Examples for parameter identification can be well illustrated by the formula for the calculation of natural frequencies of simple supported quadratic membranes with material stress (the other clamping conditions compared with real sensors do not change the basic statement on parameter dependencies) depending on the values for Young's modulus E, density ρ, Poisson's ratio ν, the membrane height h and size a as well as the intrinsic stress σ:

$$f_{m,n} = \frac{1}{2a\sqrt{\rho}} \sqrt{(m^2+n^2)\sigma + \frac{Eh^2\,(m^2+n^2)^2\pi^2}{12a^2(1-\upsilon^2)}}$$

Relevant for the possibilities of parameter identification is the ratio of the geometry term to the stress term under the root. If the ratio of the geometry term to the stress term is very large, as in the case of pressure sensors, it is possible, e.g., to determine the membrane thickness for a given membrane size. With very thin membrane-based sensors such as microphones or thermopiles, the ratio is reversed. Due to the very large stress term compared to the geometry term, the method is predestined for an exact identification of the material stress.

Development of test structures

For the use of measured natural frequencies for the determination of material or geometry parameters, the prerequisite must be fulfilled that the natural frequencies have a functional dependence on the sensor parameters of interest. If several parameters are to be identified, they must also be linearly independent of each other. If these prerequisites are not fulfilled with the given sensor structures, however, there is the possibility of parameter identification by means of test structures specially designed for vibrometric measurement or the combined evaluation of two different structures.

An example of linearly dependent parameters are the thickness and size of stress-free square membrane structures; by means of the natural frequency values, only the ratio of thickness to size can be determined, but not the values themselves. The nominal identification of a parameter (e.g., membrane thickness) is also a de facto identification of several other

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parameters if the process-related tolerances of the model input variables (e.g., membrane size in potassium hydroxide (KOH) etching) mean that a sufficiently precise determination of the parameter of interest is no longer possible. A solution approach to identify the membrane thickness here is the combined evaluation of two rectangular test structures of different dimensions. By measuring the first three natural frequencies of two rectangular membranes of different sizes, membrane thickness and sizes can thus be determined.

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Conclusion

Sophisticated wafer-level test systems are available for industrial quality assurance in the production of MEMS devices, allowing for the verification of correct behaviour of mechanical functional components. Laser Doppler vibrometry is a tool used for real-time, broadband measurements of dynamic response, with resolution down to the picometre level. This article provides examples of how LDV is used for fast, automated production test measurements at the wafer level to increase yield and ultimately reduce product cost. ■

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