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- THEME: ACOUSTICS AND VIBRATIONS
- EXPERIMENTAL STRUCTURAL DYNAMICS
- DAMPING POSITION-DEPENDENT PARASITIC VIBRATIONS
- QUADRA: METROLOGY FOR THE ONGOING EVOLUTION OF MOORE'S LAW

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The cover image (semicon metrology and inspection solution QUADRA) is courtesy of Nearfield Instruments. Read the article on page 20 ff.

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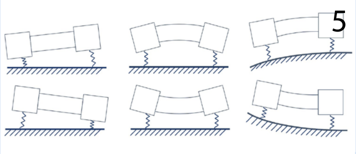
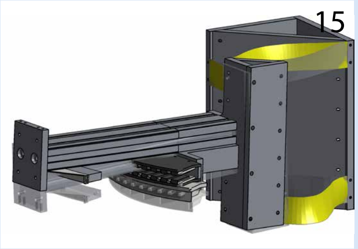
THEME: ACOUSTICS AND VIBRATIONS





FEATURES

NANOTECHNOLOGY: PRECISION SURGERY WITH TREMBLING HANDS?

The Dutch daily newspaper NRC featured an article on 6th August about the company Nearfield Instruments, a potentially very large player, perhaps of the calibre of ASML. The company develops machines that can measure chips accurately to the atom. How much more accurate do you want it to be? The company does this using the principles of an AFM (atomic force microscope), in which a needle is used to scan the surface of the object to be tested; please read the article in this *Mikroniek* issue, on page 20 ff. The technique for scanning the surface is somewhat comparable to that of a record player.

In addition, the company uses a second technique, called 'acoustic microscopy technique'; this is an ultrasonic measuring technique that allows the various layers within the wafer to be viewed – non-destructively. Both methods can be used to position chips accurately and then stick them together. Given the developments in the semiconductor world, this is a very important and essential step; an incorrectly stacked chip sandwich is unusable.

What I found remarkable to read was that the start-up is located on an industrial estate between Rotterdam and Schiedam, in very close proximity to the A13 motorway and to Rotterdam Airport. It is the last place where you would expect to find a manufacturer of hyper-sensitive equipment, given the ground vibrations caused by the (freight) traffic on the A13 as well as the high noise level of planes taking off. Inevitably, the ground vibrations cause the objects being measured to vibrate, as does the acoustic noise level.

In reference to this, the intellect behind the company, Hamed Sadeghian, commented, "Exactly right". He continued, "It's a kind of torture method, so that we know our equipment will continue to work under difficult conditions". Well, Sadeghian has a point there; it will require the utmost efforts from his technicians to set up the equipment so that it is sufficiently isolated from vibrations, as well as to create sufficient acoustic shielding to prevent the test objects from vibrating too much. The intended accuracy of one atom thick is a very big challenge! Especially in a technical room right next to the A13 and a busy airport.

The above example could be compared metaphorically to that of a surgeon, whose hands always shake a little, having to perform an exceptionally difficult operation. We, as technicians, are faced with the challenge of keeping the hands of this surgeon sufficiently still. Acoustically induced vibrations and floor vibrations are becoming a major issue in the semiconductor world today. Or they have already become so...

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MEASURING VS MODELLING MODES

Understanding dynamic behaviour is essential in the development of precision systems to achieve the required system performance. This article discusses the value of experimental structural dynamics, highlighting its role in mitigating risks by verifying system dynamics and bridging gaps between model predictions and real-world performance. Two key techniques, experimental modal analysis (EMA) and transmissibility measurements, are explored, showing how they identify dynamics in complex systems. A practical precision-engineering use case illustrates how experimental structural dynamics uncovered unexpected dynamics.

REINOUT VELDHUIZEN AND LAURENS KOOLS

Introduction

At the start of a new development, dynamic requirements are defined and compiled in a dynamic error budget. Next, the system's architectures are developed and compared with these requirements. Finally, a detailed design is created and the system is built and verified.

In this precision engineering process, the term 'first-time-right' is frequently used. However, for highly accurate and complex systems, achieving first-time-right, based on the idea that all phenomena can be modelled and simulated, is challenging or even impossible due to the model complexities and model (input) uncertainties. As a result, a mismatch between model-based predicted and real system performance is not uncommon. This is where experimental dynamics adds its value in precision engineering by providing methods to make dynamic verifications possible.

Experimental dynamics is the identification of dynamic parameters by means of physical measurements. In every phase of the V-model, experimental dynamics can add value by verifying a requirement, a feasibility set-up and/or a realised (sub)system, which results in a feedback loop back to the design. This can reduce projects risks and time to market.

Experimental dynamics covers or has interfaces with many activities in the development process, such as acoustics, disturbance identification, motion control tuning, sensitivity analysis and system identification. This article focuses specifically on experimental structural dynamics, defined here as the estimation of dynamic properties of structures (via estimation methods often involving the determination of modal properties of the structures) from experimentally measured data in the time domain. The aim here is to explain fellow engineers the value of experimental structural dynamics during the development of high-precision systems.

Two key measurement techniques are further elaborated upon: experimental modal analysis (EMA) and transmissibility measurements. For both techniques it is important to know how to transform a time-domain signal to the frequency domain and how to go from signal analysis to system analysis. In both techniques, the frequency response function (FRF) is an important measurement, which establishes a linear time-invariant relation between input and output signal in the frequency domain. These topics have been further explained in three Mikroniek articles published in 2014 [1] [2] [3].

Experimental modal analysis

EMA is a method to determine the modal parameters of a structural system. The basis of EMA is the measurement of multiple FRFs. For measuring FRFs, a particular position and direction is excited and the response is measured simultaneously. If the point of excitation and measurement coincide, it is called a driving-point measurement, which is often the first measurement. The position of the driving point needs to be selected carefully to avoid that it is placed in a node of a certain mode shape; otherwise, the modal estimation of this mode will be of poor quality.

After the driving-point measurement, either the excitation point or the response position is moved or orientated in another direction, and another FRF is measured. This sequence continues until all measurements are done. The number of measurement points depends on which behaviour of the system needs to be identified; e.g., a higher-order mode shape has a higher spatial frequency and needs more measurement points to prevent spatial aliasing. Finite-element method (FEM) simulations, when available,

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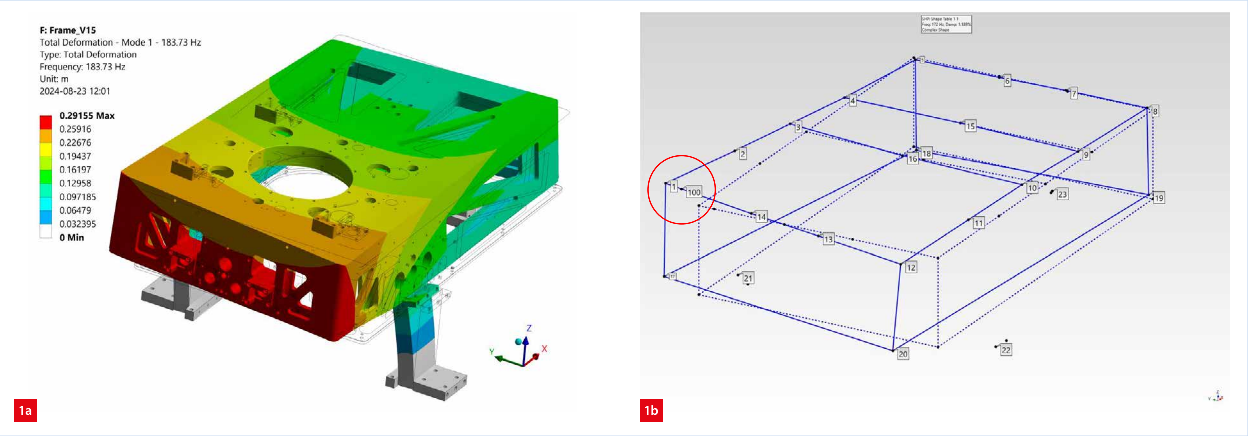


Visualisation of a flexible mode of a metro frame.
(a) Modal FEM analysis result predicting 184 Hz.
(b) Modal experimental analysis result identifying 172 Hz.

are useful to determine the position of the driving-point measurement and the number of required measurement points.

The most commonly used excitation equipment is a shaker or an excitation hammer. Alternatively, an existing actuator in the measured system can also be used as excitation source. However, it often turns out to be difficult to measure forces reliably with this kind of self-excitation. An accelerometer is often selected to measure the response. If the added mass of an accelerometer is relatively high with respect to the modal mass of the measured part or when accessibility is limited, the response can better be measured using laser-doppler vibrometry or photogrammetry.

After performing the measurement, the data can be used to quantify eigenfrequencies, damping and modal vectors using proper tooling based on modal parameter estimation techniques. The background of experimental modal analysis is explained in detail in [4].

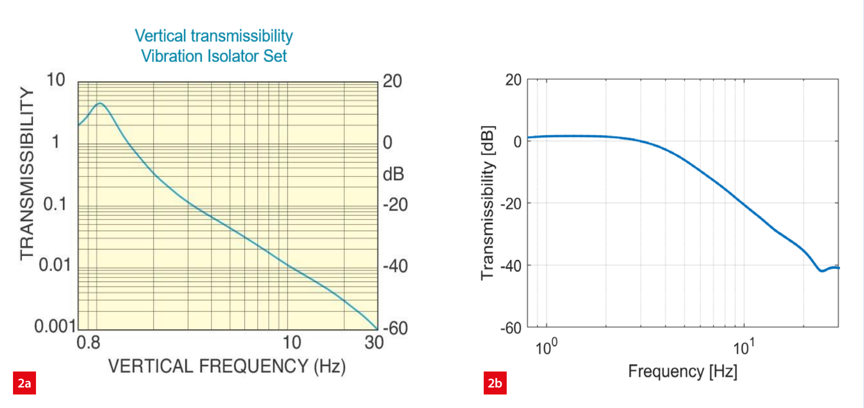
Figure 1 shows a practical example of a comparison between a FEM modal analysis and an experimental modal analysis. Figure 1b shows the wire-frame representation of the device under test indicating the measurement points. For the driving-point measurement, point 100 (encircled in red) was chosen. With roving hammer excitation, the FRFs between all indicated points and the reference point (100) were identified. The mode shape is comparable, but the eigenfrequency is 12 Hz lower in the measurement. This difference did not have a significant impact on the system performance.

Transmissibility

In addition to modal analysis, identifying the transmissibility of vibrations through the system is often required, i.e. the ratio of motion from one point to another point as a function of frequency. This method is a practical way to investigate how disturbances propagate through a particular transmission path. This is particularly useful for components with high damping, such as vibration isolation systems, bearings or dynamic links (cable slabs), as their dynamic behaviour is challenging to predict accurately.

The transmissibility function is a special case of the FRF by being dimensionless. Typically, the measured input and output signals are acceleration, velocity or displacement. While measuring these with two sensors, the system should be excited with, e.g., a shaker or excitation hammer to get a good signal-to-noise ratio (SNR). Additionally, care must be taken to ensure that the transmissibility is measured for the intended path, avoiding interference from unintended parallel paths.

Figure 2 provides an example of a transmissibility function of a vibration isolation table. This table was selected to attenuate floor vibrations for a precision system. In Figure 2a, the supplier's specified transmissibility of a general isolator is shown, while Figure 2b presents the transmissibility of the specific system version as measured using two seismic accelerometers. Comparing the two shows the resonance



Example of the transmissibility of a vibration isolation table.
(a) General definition by the supplier's datasheet.
(b) Experimental measurement of the specific system version.

QUADRA: METROLOGY FOR THE ONGOING EVOLUTION OF MOORE'S LAW

The semiconductor roadmap is currently fuelled by innovations along three trends – hybrid bonding for advanced packaging at system level, the transition from FinFET towards GAAFET 3D design technology for faster switching times, and the move towards EUV lithography and high-NA allowing 3 nm and lower nodes in high-volume manufacturing (HVM). Conventional metrology solutions in semiconductor fabs face the daunting task of enabling process control with these trends. Nearfield Instruments' QUADRA has been proven to provide the necessary metrology solution for these three developments in HVM. This article shows how QUADRA tackles these challenges head-on through a systems engineering approach including measurement mode, probe and image processing development.

EKATERINA CHERNYSHEVA, SAMANTHA MAZZAMUTO, ARNOLD ZONDERVAN, RUDI WILHELM AND NIRANJAN SAIKUMAR

Semiconductor roadmap trends

The semiconductor roadmap features three manufacturing trends for 3D device architecture:

1. Hybrid bonding or direct bond interconnects provide vertical connections on a die-to-wafer or wafer-to-wafer level through copper pads allowing for heterogeneous integration and 3D device stacking. Reliable interconnections between copper-to-copper/dielectric require a highly smooth and planar surface. Insufficient surface quality may lead to the formation of voids along bond lines followed by device failure. This requires wafer-level metrology of the planarised copper pads where height variations need to be captured at the sub-nm level.
2. The 3D design technology for transistor fabrication, which started with Fin Field-Effect Transistor (FinFET) technology, allowed for continued device scaling and has been cemented with Gate All Around Field-Effect Transistor (GAAFET) technology. GAAFET's use of nanosheets or nanowires allows for a gate-enclosing channel design overcoming the leakage current and short channel effect issues faced by FinFET, while further allowing channel width scaling. However, the strict full 3D critical dimension control necessary for such complex epitaxial structures is very challenging.
3. High-NA EUV lithography is essential for continued scaling beyond 3-nm nodes with single patterning methods for improved resolution and reduced edge placement error benefits. This requires thinner photoresist layers, which consequently makes roughness and stochastic errors worse during the lithography step and creates metrology problems due to the low-contrast nature of the materials used.

Metrology challenges

With the development of the semiconductor roadmap towards advanced nodes (Figure 1) and the new innovations introduced in HVM production, a higher and a more precise control over the manufacturing process is required. Moreover, the increased complexity of designs and the typical dimensions used need a re-evaluation of the traditional parameters of interest and the wafer-level sparse sampling of metrology measurements used for process control.

An HVM metrology system needs to satisfy several requirements. First of all, it must be a high-throughput, highly adaptive and robust in-line metrology system with fast time-to-solution. Moreover, measurements must be non-destructive, show high resolution and precision to successfully measure at the sub-nm level, and minimise tool and environment-induced measurement errors. This latter point is critical because of the small dimensions of the measured features. The characterisation techniques and metrology systems available on the market reach physical limits and, thus, cannot be fully adopted as metrology tools in an HVM environment for advanced nodes.

It is no longer sufficient to use high-speed 2D inspection techniques, such as Optical Critical Dimension (OCD) or Critical Dimension-Secondary Electron Microscopy (CD-SEM). The most used optical techniques lack resolution, are material dependent and, thus, are not able to measure the critical dimensions of complex structures such as FinFETs or GAAFETs. OCD provides global values and has low sensitivity to local variation of dimensions. With CD-SEM, due to the higher resolution needed with the ever-decreasing

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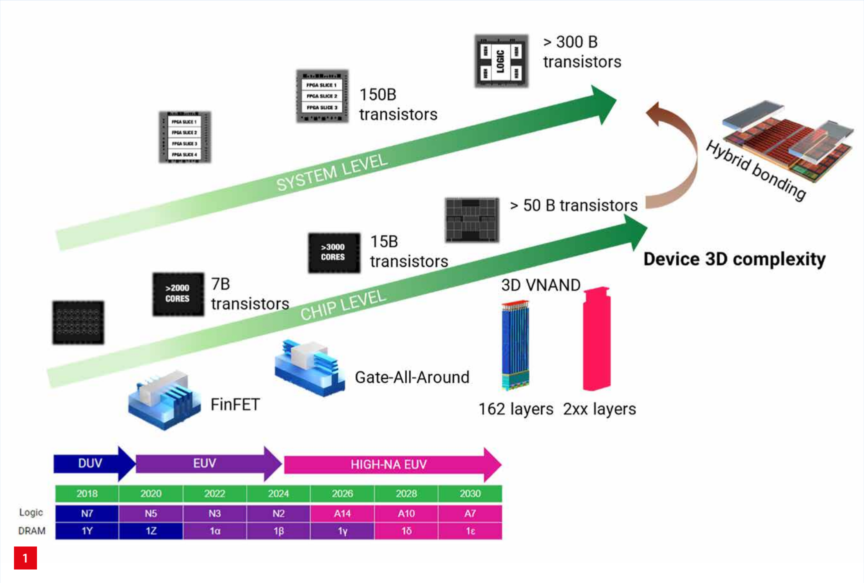


Semiconductor manufacturing trend for 3D device architecture ("Unleash the future of innovation", ISSCC, Feb 15, 2021).

sizes of semiconductor structures, higher-energy-density electrons are needed for good contrast and this leads to damage, especially with photoresists, referred to as resist loss.

Transmission Electron Microscopy (TEM) can achieve, on one side, the desired precision and resolution, but, on the other side, it is a destructive measurement and the throughput (TPT) is generally very low for being considered an ideal characterisation technique for metrology and inspection not only in an HVM environment but also in the ramp-up stage of R&D. Finally, the currently available Atomic Force Microscopy (AFM) tools are non-destructive and can achieve the required level of precision, but generally have a low TPT.

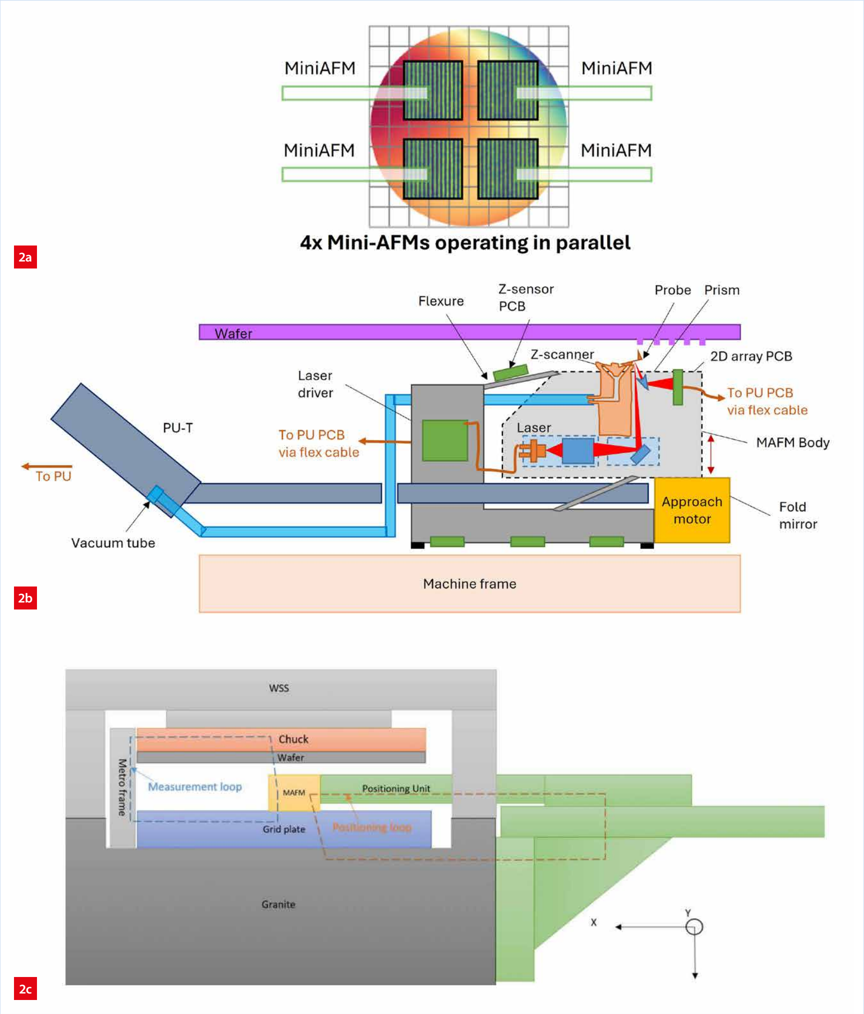
Nearfield Instruments has overcome the throughput limitations of the traditional AFM systems and offers an effective solution for current and future metrology challenges in the semiconductor industry. QUADRA is a high-TPT AFM-based metrology tool providing non-destructive characterisation in all three dimensions with sub-Ångström resolution and very high precision, long-term stability, a long probe lifetime and a versatile data processing toolkit to extract all necessary parameters of interest and relevant statistics.

System architecture and mechatronics design

The exceptionally high throughput, compared to existing AFM systems, is achieved by a revolutionary mechatronic design. Its innovative architecture based on four high-speed miniaturised AFM heads (MAFMs) allows to measure four areas of the wafer in parallel (Figure 2a). Each MAFM has its own positioning unit (PU) arm to be able to reach the required location of the wafer.

Compared to the conventional AFM systems, QUADRA has adapted an inverted architecture: the wafer is vacuum clamped on a chuck upside down and the tip approaches its surface from underneath (Figures 2b and 2c). This architecture combined with the unique design of the MAFM allows for shortening of the mechanical loop and reduces the noise contribution from mechanical resonances by removing excitation points. The shortening is achieved by releasing the kinematic coupling of the MAFMs with respect to the positioning units after moving to the desired location, where instead they make a local kinematic connection to the 'grid plate' in a process called 'landing' (Figure 2c). This grid plate is the local reference in the larger measurement loop between wafer and cantilever.

The MAFM scan head consists of:
- the Z-stage, which is the principal actuation mechanism in Z for measurements, also referred to as Z-scanner;
- the optical beam deflection system to sense the cantilever deflection;



QUADRA core overview.
(a) Top view, showing a configuration of four scan heads.
(b) Miniaturised AFM (MAFM) decoupled from the positioning unit (PU), which allows low noise even at high speeds.
(c) Global schematics.