# Design of an Inclining Probe Station for MEMS Accelerometer Testing

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ABSTRACT: Micro-electromechanical system (MEMS) accelerometers are small devices measuring acceleration. Current testing practices are not sufficient to completely test MEMS accelerometers. The acceleration measuring of the devices can be tested by inclining them. Requirements for a probe station to test MEMS accelerometers are defined, and a novel design of a probe station to test acceleration measuring, incorporating an inclining function, is designed. The feasibility of the design is validated by comparing it with alternative options and analyzing dynamic effects.

Key words: probe station, MEMS accelerometer, wafer testing, inclination system, precision positioning

## 1 INTRODUCTION

MEMS accelerometers are used in situations where high-precision acceleration measurements are required. The MEMS accelerometers are used, for example, in aerospace and automotive industries, scientific measurements, and safety monitoring applications [1]. The accelerometers are combined with electronics to be used in the desired applications. Especially in positioning and safety applications, high reliability is critical, necessitating thorough testing of the devices.

MEMS accelerometers are small microchip devices. To test the manufactured devices, a probe station is used to make electrical measurements. A wafer with the device under test (DUT) is attached to the probe station and a probe card with probe needles is positioned to contact the contact pads on the DUT. Currently, this testing is done while the DUT is stationary. If the testing shows unsatisfactory performance, the device is discarded. If the device passes the probe station testing, it is attached to electronics and other components. Then, the functionality and performance of the assembly can be tested. If unsatisfactory performance is noticed only after assembling, the whole assembly is discarded. Discarding the whole assembly, including the accelerometer, electronics, and other components, results in additional costs.

Innoseis is a company developing MEMS accelerometers. The devices can be used in satellite systems and geophysics measurements, among other applications to measure accelerations with high precision [1]. The current probe station at Innoseis is not specifically designed for testing MEMS accelerometers. In the current situation, only the electrical characteristics of the devices in a horizontal orientation can be tested. This creates a need for a new probe station.

To test the acceleration measurement performance of the devices, the device has to be inclined during the test. The current probe station does not allow for inclining the device. The performance under an inclination is not tested and thus the acceleration measurement capabilities of the device are unknown. Thus, the devices are not completely tested leading to a chance of defective products being used.

The small size of the accelerometers, especially of the contact pads, brings challenges to testing them. The precise alignment of the probe needles on the DUT is done with actuated stages. The design of the positioning system is critical to achieving the desired positioning precision of a probe station. Quick and reliable positioning can also lead to time savings in the testing process. The contact between the probe needles and the contact pads has to be maintained throughout testing, bringing an additional design challenge to the system design.

Probe stations not designed for accelerometer testing do not include inclining capabilities. Repeatable and smooth inclining of the device is necessary to get repeatable measurements with no undesired vibrations. Inclining during testing is a MEMS accelerometer testing specific functionality of the probe station.

### *1.1 General Working Principle*

The basic parts of a probe station with the respective main functions are shown in Table I. The parts with actuators in them are the three stages. Attention is paid to these parts to ensure high-precision positioning.

Table I
General probe station parts [2]

| Part | Function |
|---|---|
| Chuck | Holding the DUT |
| Probe card | Contact with DUT |
| XY Stage | Positioning the chuck |
| Rotary Stage | Rotating the chuck |
| Vertical Stage | Contacting the DUT with the probe card |
| Frame | Connecting the parts |
| Optics | Magnification for positioning |

In addition to these general parts, in this research an inclination mechanism for a probe station is developed.

### *1.2 Available Designs*

Existing design principles are used as a reference and a starting point in this research. An overview of general design principles and choices is described in [3]. The capstone project described is similar to this research. A generic probe station, i.e., without inclining, was designed with a budget of 3000 USD in 2006. The moving range of the chuck is 10 cm using a manual XY stage. The design uses gold as the surface material of the chuck due to its high electrical conductivity. The design of the probe station in this project has major differences with the probe station being designed in this research. The capstone project design uses micromanipulators to position individual probes on the device [3]. In this research, the probe needles are in a probe card and the whole probe card is positioned on the device, thus micromanipulators are not used. Instead, in this research the aim is to use the positioning stages to only move the chuck with the wafer while the probe card stays fixed.

### *1.3 Air Bearings*

There are different bearing options to use in a probe station with distinct advantages and disadvantages. In a rolling element bearing, such as a ball bearing, there are rollers between the two moving surfaces carrying the load and allowing movement. A rolling element bearing is one of the most common bearing types.

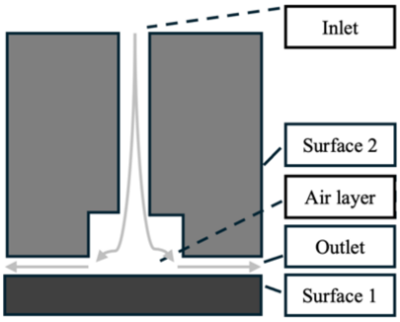

Fig. 1. Layout of an aerostatic air bearing. Air is supplied through the inlet and forms an air layer between two surfaces.

Another potential bearing option for a probe station is an air bearing shown in Fig. 1. Air bearings offer lower friction compared to rolling element, not to mention plain, bearings [4]. Air bearing is a type of a gas bearing, in which air is used as a lubricant in hydrodynamic lubrication. Manufacturing of air bearings is complicated compared to other bearings due to manufacturing tolerance and surface roughness requirements [4].

In air bearings, a thin film of air is created between two surfaces. This thin film carries the loads and all but eliminates friction. There are two types of air bearings, aerostatic and aerodynamic bearings. In aerostatic bearings, there is an external supply of pressurized air creating the thin film between the two surfaces [5]. In aerodynamic bearings, no external supply of air is needed. Rather, as the relative speed between the surfaces increases, a pressure gradient naturally forms causing the thin film [5]. The need for an external supply of air in aerostatic bearings adds complexity to the system. Aerodynamic bearings require high relative speeds for a pressure gradient to form between the two surfaces. Such high speeds are not expected in a probe station. Furthermore, the stability of air bearings is an ongoing topic of research. Air vortices inside an air bearing can lead to small vibrations reducing stability [6]. A phenomenon called “pneumatic hammer” occurs when the outflow of air is constrained more than necessary for equilibrium [7]. This leads to oscillations and thus instability. Air bearings are a viable option in many applications, nevertheless, their implementation and manufacturing is challenging compared to rolling element bearings.

## 2 METHODOLOGY

The design process consists of requirements and functions definition, subsystem division, component selection, and evaluation. A modular design approach is used by dividing the functions of the probe station into distinct subsystems. This yields a simpler design over an integrated approach. The interfaces between the subsystems are analyzed and taken into account in the design.

### *2.1 Requirements*

The requirements for the probe station consist of requirements for general probe station functionality, requirements for MEMS accelerometer testing, and safety and reliability requirements. The requirements are formulated based on existing probe station designs, company needs, and design constraints. The requirements are divided into system-level and subsystem-specific requirements. In addition to functional and technical requirements ("shall" statements), goals for the design are defined ("should" statements). Goals are used when no specific requirement can be made but there is a preference that the solution should achieve.

Function statement: The probe station shall test MEMS accelerometers, including under an angle to the horizontal.

As system-level functional requirements, the probe station shall:

- Work with the current probe card.
- Work with foreseen future probe cards.
- Securely attach the probe card.
- Accommodate the range of wafers the company needs to test.
- Move a chuck with the wafer for positioning.
- Not damage the wafer.
- Not damage the probe card.
- Not harm the user.
- Be manufacturable with available commonplace workshop tools and machines.
- Have distinct functions be performed by distinct components.

As system-level technical requirements, the probe station shall:

- Position the probes anywhere within a 150 mm diameter wafer.
- Position the probes to the defined location ±5 µm.
- Adjust a rotational alignment offset of the wafer within 5 degrees.
- Keep the probes stationary on the pads when inclined.
- Contact the probes with the pads on the device with any specified override ±0.5 µm.
- Offer clearance between the probes and the wafer of 10 mm.
- Incline the wafer from the horizontal orientation at the minimum by 90 degrees in one and 20 degrees in the opposite direction towards a vertical orientation.
- Incline the wafer to a defined angle ±0.2 degrees.
- Use motorized actuators compatible with computer control.

As system-level goals, the probe station should:

- Consist of commercially available components when available.
- Reduce the time to test a wafer.
- Avoid custom-designed parts when unnecessary.
- Have a lower cost than other satisfactory options.
- Have a maintenance interval of 6 months or more, except for routine upkeep.
- Have high performance in terms of precision, speed, simplicity, and reliability.

And the test results should:

- Be within the allowed error in repeat tests.
- Be representative of the wafer.

### *2.2 Subsystem Division*

The probe station is divided into eight subsystems. The subsystems are shown in Fig. 2 and their respective main functions in Table II. For each subsystem the respective requirements are defined. Since some of the requirements depend on other subsystems, expected characteristics are used without favor on the design of the subsystems.

Table II
Subsystems and their main functions

| Subsystem | Main function |
|---|---|
| A | XY positioning |
| B | Rotational positioning |
| C | Vertical positioning |
| D | Holding the wafer |
| E | Load carrying structure |
| F | Inclining the wafer |
| G | Holding the probe card |
| H | Optics and other alignment |

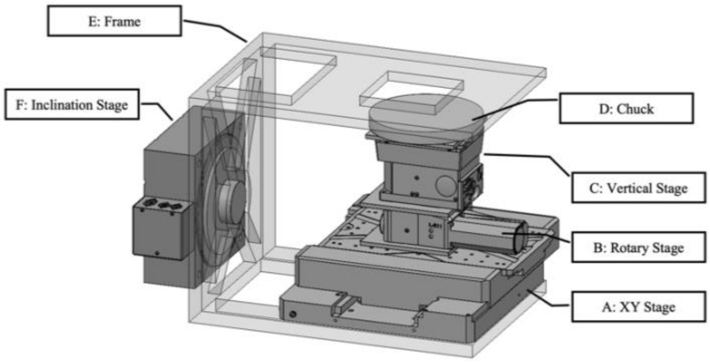

Fig. 2. Layout and subsystems of the designed probe station.

### *2.3 Interfaces Between Subsystems*

As the probe station is an interconnected system, there exist interfaces between all the subsystems. The focus is on the interfaces expected to cause design requirements and constraints. The most notable ones are the ones caused due to the load caused by carrying other subsystems. In other words, the mass of a subsystem creates a minimum load requirement for other subsystems.

The interfaces between the subsystems have a significant influence on the subsystem-level requirements. Thus, many of the subsystem-level requirements formulated next are in terms of the characteristics of other subsystems. This means that if the design of a single subsystem is changed, it will most likely change the requirements and, consequently, the designs of other subsystems.

### *2.4 Subsystems*

#### 2.4.a Subsystem A: XY Stage

This subsystem is responsible for the in-plane positioning of the DUT. Its main functions are translating the wafer in the XY plane and ensuring rigidity during measurements and inclining.

<u>Function statement</u>: Subsystem A shall position a wafer in the horizontal plane.

Subsystem A:

- Shall position the probes to the center of the pads ±5 µm.
- Shall position the probes with a range of ±75 mm from the center of a disc.
- Shall move and hold subsystems B, C, and D.
- Shall maintain position when inclined.
- Should consist of commercially available components.

#### 2.4.b Subsystem B: Rotary Stage

This subsystem is responsible for the rotational positioning. Its main function is rotating the wafer around the Z-axis.

<u>Function statement</u>: Subsystem B shall rotate the wafer around the vertical axis.

Subsystem B:

- Shall position the probes parallel to the centerline of the pads ±0.2 degrees.
- Shall have a rotational range of 10 degrees.
- Shall rotate and hold subsystems C and D.
- Should consist of commercially available components.

#### 2.4.c Subsystem C: Vertical Stage

This subsystem is responsible for the vertical positioning. Its main function is lifting and lowering the wafer.

<u>Function statement</u>: Subsystem C shall position the wafer in the Z axis.

Subsystem C:

- Shall contact the probes on the pads with a precision of ±0.5 µm.
- Shall have a range of 10 mm.
- Shall move and hold subsystem D.
- Should consist of commercially available components.

#### 2.4.d Subsystem D: Chuck

This subsystem consists of the chuck and related components responsible for holding the wafer. The design of the chuck is outside the scope of this research. Assumptions for representative characteristics of this subsystem are used in this research. When necessary, the wafer is considered a part of this subsystem.

<u>Function statement</u>: Subsystem D shall hold the wafer during measurements.

#### 2.4.e Subsystem E: Frame

The frame of the probe station carries the load of all subsystems excluding F and connects these subsystems with the inclining subsystem F. Thus, this subsystem has significant interfaces with all the subsystems in the probe station.

Function statement: Subsystem E shall connect subsystems A, B, C, and D with subsystems G and H and subsystem F.

Subsystem E:

- Shall have a mass less than the load capacity of subsystem F, taking into account the load due to other subsystems.
- Shall keep subsystems D and G in place relative to each other.
- Shall carry the loads of subsystems A, B, C, D, G, and H.
- Shall carry all loads and stay rigid in angles from -20 to 90 degrees.
- Shall be manufacturable with available commonplace workshop tools and machines.

### 2.4.f Subsystem F: Inclining

This subsystem is responsible for the inclining of the wafer and the probe card from the horizontal to an angle between -20 and 90 degrees. The subsystem will turn the frame (Subsystem E) and, consequently, the subsystems connected to the frame.

Function statement: Subsystem F shall rotate the wafer between horizontal and vertical orientations.

Subsystem F:

- Shall tilt the wafer with the probe card to a specified angle ±0.2 degrees.
- Shall have an inclining range ranging from -20 to 90 degrees.
- Shall rotate and hold the frame subsystem E and subsequent subsystems.
- Should consist of commercially available components.

As one of the system-level goals – as well as a subsystem-specific goal – is the use of commercially available components, the design of the inclining subsystem favors the use of an existing design of a rotation stage. This approach is expected to avoid custom-designed parts while achieving high simplicity and reliability and satisfying the set requirements. The options to consider include different stage types as well as different ways to support the frame. In stage types, goniometers, air bearing rotary stages, and rolling element bearing rotary stages are evaluated. As to supports, the number of stages and the use of additional bearings is considered. The results of these considerations are used as preferred designs in component selection, described in section 3.7.

### 2.4.g Subsystem G: Probe Card Holding

The probe card holder attaches the probe card with the probe needles to the probe station.

The detailed design of this subsystem is outside the scope of this research. Thus, no subsystem requirements are defined.

Function statement: Subsystem G shall hold the probe card fixed.

### 2.4.h Subsystem H: Alignment Guidance

This subsystem consists of cameras, optics, and other devices necessary to accurately align the DUT with the probe needles.

As for Subsystem G, no requirements are defined for this subsystem since its design is outside the scope of this research.

Function statement: Subsystem H shall provide information on the relative position between the probe needles and the wafer.

## *2.5 Component Selection*

For subsystems A, B, C, and F, component manufacturers are chosen based on prominence and reliability. The aim is to use well-known suppliers to ensure the reliability and precision of the selected components. From each supplier, a list of relevant products is made. These lists are compared to the subsystem requirements. Three different concept component combinations of subsystems A, B, and C are made. The concepts are compared on mass, precision, compatibility, and load capacity as evaluation criteria, each equally weighted.

For subsystem F, a more streamlined selection procedure is used. A search of available components is made, and the available components are evaluated against the preferred designs. The overall suitability of the requirement-satisfying components is evaluated, and the most suitable one is chosen. In this suitability analysis, attention is given to the technology used in components, load capacity, compatibility with other subsystems, as well as precision, speed, simplicity, and reliability.

### 2.6 *Positioning Segment*

The subsystems having similar general functions are grouped into a segment. Subsystems A, B, and C, all responsible for positioning the wafer, form a segment. The subsystems within this segment have stronger interfaces with each other. Thus, these subsystems can be analyzed together as an integrated segment. Factors such as resolution and precision are compounding among the three positioning subsystems.

### 2.7 *Frequency Analysis*

As the probe station is a dynamic system, parasitic vibrations must be avoided. This also follows from the requirements. Otherwise, the probes would not necessarily be stationary on the pads. The frequencies to avoid are, for instance, the resonance frequencies of the probe needles in the probe card. These resonance frequencies need to be determined to avoid them.

A finite element analysis (FEA) Matlab script is made to calculate the eigenfrequencies of the probe needles. The script calculates the resonance frequencies of a single needle. In the probe card, there are 40 probe needles. The probe needles are made from tungsten, have a total length of 38 mm, and a diameter of 0.25 mm. All the needles have approximately the same dimensions, thus their respective resonance frequencies are similar. The Matlab script is evaluated by comparing the results to a 3D FEA simulation done with Ansys Mechanical, a commercial FEA software.

A flowchart of the structure of the FEA Matlab script for determining the resonance frequencies of the probe needles is shown in Fig. 3. The probe needle is divided into 12 elements and parameters such as area and second moment of inertia for these elements are calculated. Next, element-level matrices are defined, and assembled into global stiffness and mass matrices. The boundary conditions are applied to find the eigenfrequencies and respective eigenmodes. The force due to overdrive is applied to solve for the static deformation.

In addition to the probe needles, the resonance frequencies of the positioning segment are estimated and the resonance frequencies of the frame are considered. A finite element approach is used to estimate the resonance frequencies of the positioning segment using an FEA Matlab script. Assumptions are made for the stiffness values of the parts for which none is available.

## 3 RESULTS

### 3.1 *Selected Components*

The components for subsystems A, B, and C are chosen from the product line of PI (Physik Instrumente), a positioning stage manufacturer. PI offers positioning stages for these subsystems satisfying the requirements. For subsystem F, a rotary stage from Dover Motion is used to satisfy the requirements. Detailed requirements for subsystem F are updated in section 3.7. The chosen components are shown in Table III below and the specifications of the designed probe station in Table IV.

Table III
Selected probe station components

| Subsystem | Main Function | Supplier | Product Name |
|---|---|---|---|
| A | Linear positioning in XY plane | PI | L-731 |
| B | Rotational positioning around the vertical axis | PI | L-611 |
| C | Vertical positioning | PI | L-310 |
| F | Inclining the wafer | Dover Motion | DRT-200 |

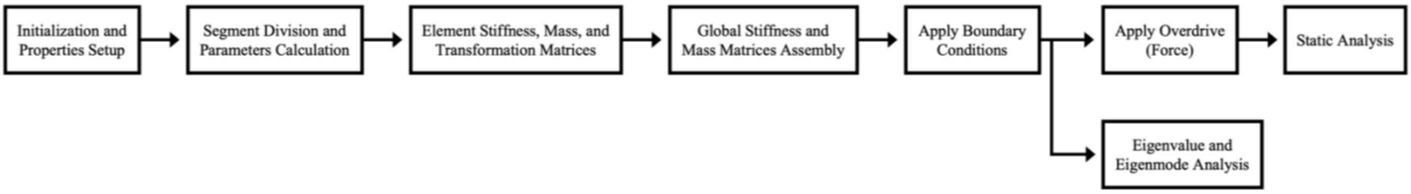

Fig. 3. Flowchart of the developed FEA Matlab script for finding the resonance frequencies and static deflection of a probe needle.

Table IV
Specifications of the designed probe station

| Subsystem | Specification | Value |
|---|---|---|
| A [8] | XY range | 205 x 205 mm |
| | XY precision | 0.1 µm |
| | Mass | 16 kg |
| | Load capacity | 20 kg |
| B [8] | Rotational range | 360° |
| | Rotational precision | 0.002° |
| | Mass | 2.6 kg |
| | Load capacity | 5 kg |
| C [8] | Vertical range | 26 mm |
| | Vertical precision | 0.2 µm |
| | Mass | 2.7 kg |
| | Load capacity | 10 kg |
| F [9] | Rotational range | 360° |
| | Rotational precision | 0.00057° |
| | Mass | 7.9 kg |
| | Load capacity | 49 kg |

Comparing the list of system-level technical requirements in section 2.1 and specifications in Table IV, all specifications exceed the requirements.

### *3.2 Alternative Suppliers*

Other suppliers considered are NSK and Suruga Seiki, among others.

PI was chosen as the supplier of the components for subsystems A, B, and C due to its prominence and availability of specifications, drawings, and 3D computer design models of its products [10], [11].

PI does not offer suitable components for subsystem F, thus Dover Motion is used as the supplier for this subsystem.

Compared to alternative suppliers, a combination of PI and Dover Motion components achieved the highest load capacity with a low mass.

### *3.3 Alternative Components*

Most of the other components considered for the rotary stages (subsystems B and F) differed only slightly in precision, mass, and load capacity. Notable exceptions were products from NSK and Suruga Seiki having more limited rotation ranges, 10 and 11 degrees respectively [12], [13]. For subsystem F, the required radial load capacity, that is load capacity perpendicular to the axis of rotation, reduced the number of available stages. The design decisions for subsystem F are described in section 3.7.

For the XY stage for subsystem A, some considered alternatives were one-dimensional linear stages. Two, linear stages would have been combined to achieve the two-dimensional positioning required in subsystem A. The variations in mass, load capacity, and range were significant between the different options. The masses ranged from 2.8 to 38 kg. Some of the considered XY stages did not achieve the required range of 150x150 mm but were nevertheless taken into consideration. It was found that the stages not fulfilling the requirements did not have any significant advantages over the chosen component.

The number of vertical stages considered for subsystem C is less than the number of products considered for other subsystems. Nevertheless, five different products were compared. The chosen stage has the highest range and second highest precision.

### *3.4 Alternative Subsystem Positions*

Subsystem C is placed on top of subsystem B. When the rotary stage is rotated, the connections to the vertical stage are also rotated, which is undesired. An alternative subsystem positioning would be subsystem B on top of subsystem C. This would result in the rotary stage being lifted by the vertical stage.

The selected vertical stage for subsystem C has the highest uncertainties and lowest stiffness out of all the components selected. It is preferred to reduce loads on it for higher precision. Thus, the chosen orientation is subsystem C attached to B, B attached to A, and A attached to E (the frame), with subsystem C carrying subsystem D.

### *3.5 Design of Subsystems A to D*

Assuming the mass of subsystem D, the chuck and the wafer, as 4 kg [3]. The total mass of subsystems A to D is 25.3 kg. Adapter plates are used to attach the subsystems together. The designs of adapter plates in the PI product line are used as a basis for the assumptions for the characteristics of the adapter plates. The thickness of these adapter plates is assumed as 6 mm with anodized aluminum as the material [8].

The load capacity of the rotary stage in subsystem B does not completely satisfy the set requirements. The cited load capacity is in the horizontal direction –

perpendicular to the axis of rotation – during rotation, when the stage is active [8]. In this probe station design, the stage is active only when the probe station is in the uninclined horizontal position. In this orientation, the load capacity of the stage is 10 kg [8], thus satisfying the requirements in practice.

### *3.6 Design of the Frame Subsystem E*

The frame consists of two surfaces, a bottom and a top one connected by beams on one side. There is an attachment point in the beams for the inclining subsystem F. The frame is designed to carry a load of 30 kg from the positioning segment and the chuck as well as 7 kg from probe card holding and optics subsystems G and H. Thus, the highest loads are carried by the bottom surface as well as the connecting beams between the bottom surface and subsystem F.

### *3.7 Design of the Inclining Subsystem F*

As Subsystem F is responsible for the inclining of the probe station, it is the most major customization compared to a conventional probe station design. Goniometers, air bearing rotary stages, and rolling element rotary stages were considered for the stage type.

In general, a goniometer stage is preferable for a subsystem responsible for tilting a load. In this application, however, the required inclining angle range is from -20 to 90 degrees. A typical goniometer stage is expected to achieve a range of -20 to 20 degrees [8]. This would only partially fulfill the set requirements. Using a goniometer stage would be an improvement compared to the current probe station. However, the wafer has to be inclined to angles of up to 90 degrees, in addition to an inclination of 20 degrees. Thus, goniometers are unsuitable to satisfy the requirements.

The goal guiding the selection between air bearing rotary stages and rolling element rotary stages is the preference for higher simplicity. Thus, if a rolling element bearing satisfies the requirements, it should be used instead of an air bearing. A major requirement for the subsystem is the load capacity, in a rotary stage responsible for inclining the load will be in the perpendicular direction to the axis of rotation. As already stated earlier, this reduces the number of available stages. Most rotary stages from the considered suppliers have radial load capacities of less than 20 kg.

The required load capacity for the rotary stage depends on the way the frame is supported. Using two actuated stages along the same axis is undesirable since it would lead to overconstraints, lowering reliability and simplicity, as well as causing manufacturing challenges. Thus, the choice to be made is between the use of only a single rotary stage carrying the full load of the frame or using a bearing mounted on the same axis to distribute the radial load. Using an additional bearing would reduce the required radial load capacity of the rotary stage by a factor of 2. However, it would overconstrain the mechanism leading to similar problems as with two actuated stages. Thus, the preferred design is a single rolling element bearing rotary stage carrying the full load of the frame. Updating the requirements and goals, subsystem F:

- Shall tilt the wafer with the probe card to a specified angle ±0.2 degrees.
- Shall have an inclining range ranging from -20 to 90 degrees.
- Should have a radial load capacity of 42 kg.
- Should use rolling element bearings.
- Should have a single load-carrying bearing.
- Shall not excite vibrations in the resonance frequencies of the positioning segment and the probe needles.
- Should consist of commercially available components.

The selected component, Dover Motion’s DRT-200, satisfies the requirements and goals for the subsystem. The inclination of the probe station by the inclining subsystem F can be seen by comparing Fig. 4 below with Fig. 2 in section 2.2.

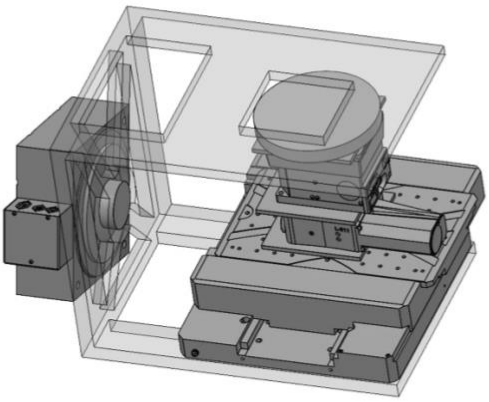

Fig. 4. Designed probe station under a 20-degree inclination by subsystem F.

### *3.8 Resonance Frequencies*

A custom-made Matlab script was used to calculate the resonance frequencies of the probe needles. The deformation of the needle due to overdrive is negligible and thus the force on the tip can be ignored when determining the eigenfrequencies. The first three resonance frequencies calculated by the script are 131.4, 660.9, and 1232.6 Hz.

The results of the software simulations show eigenfrequencies of 108.34, 108.61, 679.84, 684.54, 1910.6, and 1926.8 Hz. The frequencies appear in pairs of vertical and lateral resonance modes. Since the frequencies of these pairs are close to each other, only the frequencies representing the vertical modes can be considered. Hence, the frequencies considered are 108.34, 689.54, and 1926.8 Hz. The most important frequencies for the design of the probe station are the first two eigenfrequencies. The respective resonance modes of the first two frequencies are shown in Fig. 5.

Fig. 5. Resonance modes of the probe needle. (Top) First-order resonance mode with a frequency of 108.34 Hz. (Bottom) Second-order resonance mode of the probe needle with a frequency of 684.54 Hz.

The calculated eigenfrequencies of the positioning segment are 153.2, 318.4, and 605.9 Hz. However, these are only approximate estimates due to uncertainties in the stiffness values used.

## 4 DISCUSSION

### *4.1 Feasibility of the Design*

The designed probe station satisfies the requirements and goals. Whether an inclining probe station works for MEMS accelerometer testing in practice, can be found out only by building and testing it. One major question is whether the probe needles and pads maintain contact during and after inclining. As long as the resonance frequencies are avoided, contact can be expected. Furthermore, the needles are pressed against the pads by moving the vertical stage by as much as 50 µm after first contact. This overdrive not only ensures that all 40 needles are in contact with the pads but will also help maintain contact during and after inclining.

As already discussed in section 3.7, the major loads on the inclining subsystem F are in the radial direction. This is inconvenient, especially when the load is carried by only a single stage. If the component chosen for subsystem F is changed, the option to include an additional bearing to distribute the load should be further considered. With the chosen component, the design is feasible and satisfies all the requirements.

### *4.2 Alternative Design Approach*

The probe station was divided into eight subsystems. This was done to simplify the design process. However, this approach also leads to a modular design, functions are performed by distinct subsystems. A viable alternative approach would be to use a more integrated approach. For example, by considering the positioning segment as a single subsystem. The alternative approach would likely lead to a more iterative design process since the interfaces between different functions cannot be explicitly addressed by the requirements. At the same time, the result of the integrated approach could achieve better performance.

Instead of giving preference to existing components, preference can be given to custom-designed parts. This would lead to more design work and likely add manufacturing challenges. On the upside, increased use of custom-designed parts can increase the overall performance of the probe station.

### *4.3 Dynamic Effects*

The results for the resonance frequencies of the probe needles differ based on the method used. The frequencies were calculated using a custom-made FEA Matlab script and a commercial FEA software, Ansys. The custom-made script does only a two-dimensional finite element analysis, whereas the software determines the frequencies in three dimensions. Thus, the results from the software simulation are better indicative of the resonance frequencies of the probe needles.

It is worth to note that the first two frequencies calculated by the custom-made script are within 30 Hz of the results of the simulation software. The software simulations show that the eigenmodes corresponding to frequencies 1910.6 and 1926.8 Hz the movement cannot be easily characterized as lateral or vertical but rather as diagonal. On its own, the custom-made script can be used for analysis of dynamic effects if a suitable safety margin is applied.

Eigenfrequency analysis of the frame is left outside the scope of this research. A detailed design of the frame is required for the analysis. The results of the frequency analysis of probe needles and the positioning segment should be taken into account in the design of the frame to ensure there is no relative motion between the probe needles and the DUT.

## 5 CONCLUSION

A prototype of the designed inclining probe station should be built to test its performance. The range of the designed probe station allows for wafer testing up to diameters of 200 mm, thus the company will have the option to increase the size of their wafers. The chosen stages allow for computer control, thus an automatic positioning system can be used to speed up positioning and as a consequence lower the total testing time.

Subsystems D, E, G, and H were left outside the scope of this research. Probe card holding and optics subsystems G and H are ancillary in the positioning of the probe needles on the DUT. These subsystems should be designed taking into account the interfaces with the subsystems designed in this research.

The designed probe station allows for better quality control in MEMS accelerometers, thus ensuring reliability in critical applications. Better testing will also help in the research and development of the accelerometers, thus improving industry practices and contributing towards technological advancements in MEMS accelerometers and in the semiconductor industry at large.

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