VEGA MOTION PLATFORM DESIGN OVERVIEW

PM, a company well known for its precision linear bearings, has also gained experience in the development and production of custom motion systems. Recently, PM launched a stage that was completely developed and assembled in-house. The motion platform – designated as 'Vega' – was developed to set new standards for optical wafer inspection speed and accuracy. The central design concept was to position all driving dynamics in one plane, in order to prevent undesired reaction torques on the sensitive parts of the system.

MATHYS TE WIERIK AND JAN WILLEM RIDDERINKHOF

For more than 50 years, PM has been developing and producing very precise linear and rotating bearings. The Dutch family company focuses on bearings for the precision industry, where strict requirements are set for straightness, smoothness and stiffness. As well as these bearings, PM also develops high-end mechatronic motion solutions.

The development and production of these motion stages is often not the core competency of PM's customers and therefore it is something that they prefer to outsource. Typically, these customers are responsible for realising complex production process steps in the semiconductor, medical, optical or analytical industry. For PM, developing motion systems is a perfect addition to its bearing business, as the knowledge of making precision bearings can conveniently be used for developing stages, and vice versa.

PM normally builds motion platforms that are dedicated for customer projects. A year and a half ago, however, the company started to develop its own motion platform. PM engineers visited a number of customers to see what developments are taking place in their markets and what products they need to be competitive in five years' time. From all these discussions, PM derived a set of requirements that a next-generation motion system would need to meet.

The Vega motion platform had to be a fast, accurate stage, focused on back-end wafer inspection. This represents a particularly demanding market. Once having proven its competitiveness in that market, PM should be able to extend platform application to, for example, the medical market.

High throughput required

The bar was set high with the following critical performance requirements:

- Over a stroke of more than 300 mm, the mechanical accuracy in the X- and Y-direction must be better than 1 µm.
- Motion profiles include accelerations of 2 g and speeds of up to 2 m/s in the horizontal plane.
- Vibrations in the horizontal plane must remain below 25 nm, assuming the machine is operated on a cleanroom floor that vibrates at a VC-C specification.
- Vibrations in the vertical direction – the direction used to move the wafer into the optics' focal point – may not even exceed 10 nm.

Achieving high accelerations and short settling times are crucial in a wafer inspection application, where a high wafer throughput is key. Along with the technical demands, the timing of the project was also challenging: the complete design and production phase of the project needed to be performed within 12 months. Moreover, the stage had to be cost effective and robust, which was achieved by minimising the use of exotic materials and by manufacturing almost all components in-house at PM.

The starting point for the design was that all of the driving dynamics need to be in one plane. As a result, the motors do not cause any undesired reaction torques on the sensitive parts of the system. This was achieved by properly aligning the centres of mass for all moving bodies, the position of the motor forces and the position of the bearings. An additional advantage of keeping all the dynamics in one plane is that the out-of-plane loads on the bearings will also remain minimal – a lower bearing load adds to a longer lifespan with less wear and thus fewer bearing-induced inaccuracies.

Designing all of the dynamic components in one plane is relatively easy for a single-axis system. Normally, a second axis would be put on top of the first to realise the movement orthogonal to the first direction. Also, if needed, a third axis could be stacked on top. By stacking axes like this, however,

AUTHORS' NOTE

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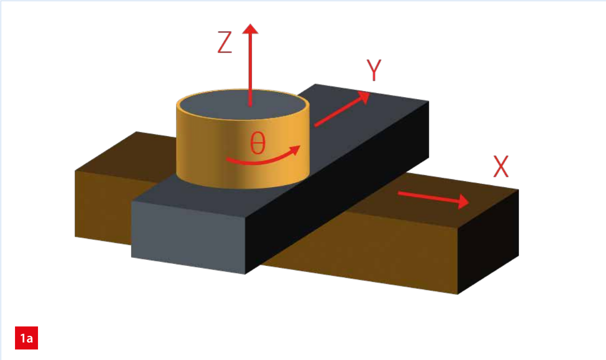
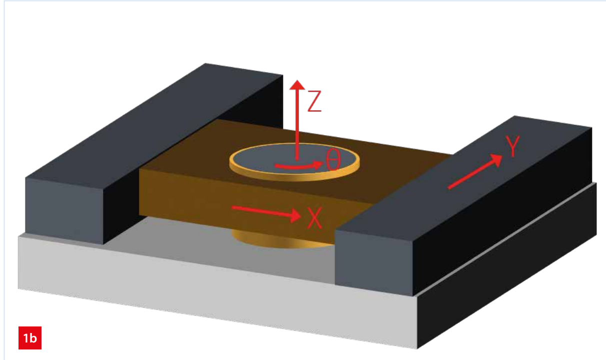




XYZθ-architecture alternatives
(a) Conventional low-speed.
(b) High-throughput-optimised, with all COGs in one single plane.

the centre of gravity (COG) of the moving mass is no longer ideal for each of the axes and, as a result, reaction torques occur when accelerating or decelerating the axes. These reaction torques create yaw, pitch and roll errors.

PM found a different solution, as can be seen in Figure 1. The construction consists of a horizontal box frame supported by a linear bearing on each side. In this square frame, the second axis is mounted, coplanar with the first axis. Then, the Zθ-module is integrated in this second axis, which is responsible for rotations and vertical movements. Only short-stroke vertical movements are made, so the centres of mass and actuation remain mostly in one plane. This means that the moving masses cannot exhibit lever arm behaviour, resulting in a much better positioning accuracy. Recirculating ball bearings were found to be accurate enough for optical wafer inspection when they are mounted correctly and the proper design principles have been applied.

Topology optimisation

After establishing the global layout, PM entered the detailed engineering phase. The dynamic requirements for such a wafer inspection stage meant that the box frame should be given a high structural stiffness at a minimum of moving mass. For accomplishing this, aluminium is an obvious material of choice. To shape the aluminium frame, PM developed its own topology optimisation program in Matlab.

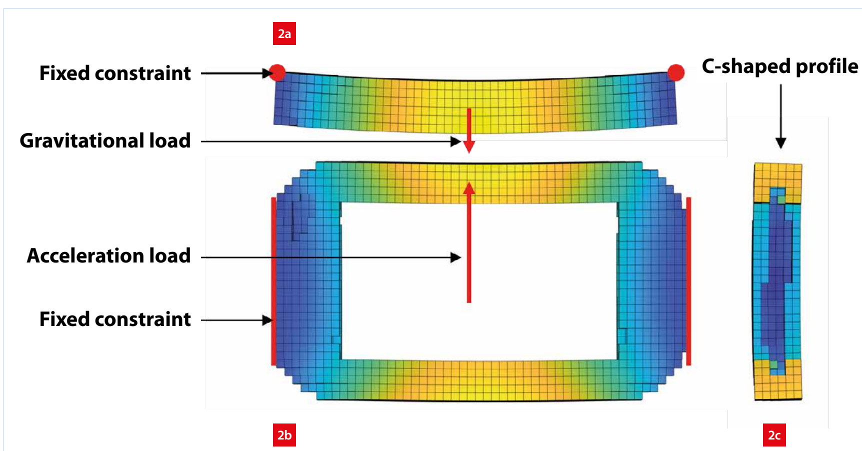
In the topology (shape) optimisation study, manufacturability was also considered. One of the constraints was having a constant material thickness for the cross members, allowing cost-effective and accurate manufacturing. The software eventually iterated to produce relatively large C-shaped profiles for the main cross members (see Figure 2). The C-shaped profile offers a good stiffness-to-weight value as well as a good base for installing bearings.

Actuators

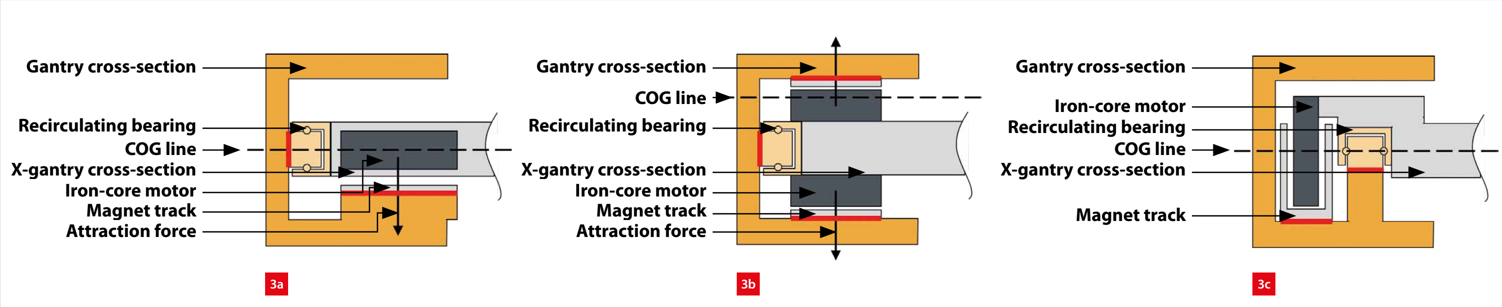
The next question was how the motion platform should be driven. Various concepts were discussed and evaluated (Figure 3). The concepts in Figure 3a and 3b do not make optimal use of the bearing stiffness and require expensive grinding tolerances on two separate components (indicated in red), whereas the concept in Figure 3c only requires tight grinding tolerances on a single component.
Eventually, PM selected this third concept (Figure 3c); a solution based on an ironless motor with moving coils. This choice resulted in a somewhat complex construction, but this way the motor, the bearing and the encoder can all be mounted on the lower part of the C-profile. This choice helped to minimise the number of surfaces that needed very tight grinding tolerances to reach the accuracy requirements. Therefore, this design is cost effective, as it minimises manufacturing cost.

Settling-time simulations

To get a good understanding of what kind of settling times can be achieved, the frequency response functions of the



The optimum topology for the X-axis cross members has C-shaped cross sections placed near the outside of the box. The colour coding indicates displacement under gravitational and acceleration loading, from small (blue) to large (yellow) displacements.
(a) Side view.
(b) Top view.
(c) Cross section (the middle part showing a box frame member in the background).



Three conceptual layouts (X-axis perpendicular to the drawing plane) that have been evaluated, each featuring the C-shaped profile that emerged from the topology optimisation. The surfaces that require expensive grinding tolerances are indicated in red.
(a) Iron-core motor force aligning with bearing and COG; attraction force loads the bearing.
(b) Dual-iron-core combined motor forces aligning with bearings and COG; attraction forces cancel each other out.
(c) Motor force aligning with bearing and COG; no attraction force.

stage needed to be accurately predicted. The stage structure consists of a rigid base plate and a number of machined metal cross members, while in between each axis the bearings are located. See Figure 4 for an impression of the resulting stage.

The difficulty in getting accurate transfer function predictions was mostly in the bearing dynamics. Conventional bearing stiffness models based on ideal Hertzian contact theory significantly overestimate the stiffness of bearings in practice. PM therefore used a combination of Hertzian contact theory and component-based testing, where experimental modal analysis was applied to a bearing with a rigid dummy load (see Figure 5). Extensive testing revealed that the enriched bearing models are much more realistic than conventional idealised Hertzian contact theory models.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The resulting design: a stage featuring a rigid granite base plate, linear motors and linear bearings for each axis, and a Zθ-module in the centre of the XY-axes. Wafers can be placed on the black circular plate on top of the Zθ-module.

Based on FEM (finite-element method) simulations of the stage assembly (including the aforementioned bearing stiffnesses), the open-loop transfer functions were determined, revealing that the first observable eigenmode was comfortably above the target bandwidth of the stage. A feedback control loop was modelled around these transfer functions, so that the settling times of the stage, including its control, can be predicted. As well as the settling-time prediction, the complete motion profile, based on a wafer inspection cycle, can be simulated to evaluate the maximum throughput of the machine.

Active vibration isolation

In view of the tight residual vibration requirements, a vibration isolation system is an absolute necessity. With high acceleration requirements in particular, the granite is loaded by high lateral forces and therefore the vibration isolation system needs to be active (see Figure 6); the alternative of eliminating vibrations by using a balance mass was discarded because of the tight footprint requirements. The requirements for the vibration isolation systems were conflicting. The settling times would benefit from a stiff set-up, whereas the low residual vibration requirement can be


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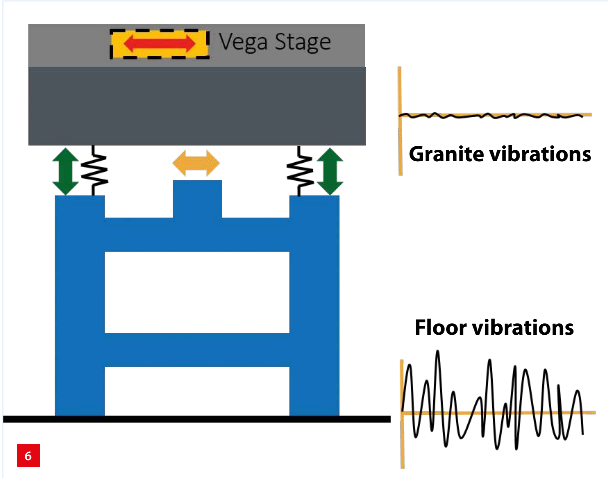
Hammer impact testing was applied to the bearings to identify their stiffness in the relevant degrees of freedom.



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Schematic representation of the Vega stage mounted on an active vibration isolation platform. Compliant springs prevent transfer of floor vibrations to the stage. In addition, skyhook damping is applied as well as an advanced floor feedforward algorithm (green arrows). The forces applied by the stage (red arrow) on the granite are counteracted by feedforward control (orange arrow).

reached by using a compliant vibration isolation system; the transmissibility of floor vibrations to the stage would quickly diminish above the first eigenfrequency of the isolation system.

As the vibration isolation system has a strong influence on the stage settling times, its dynamics were also incorporated into the aforementioned settling-time simulations.

Thermal management

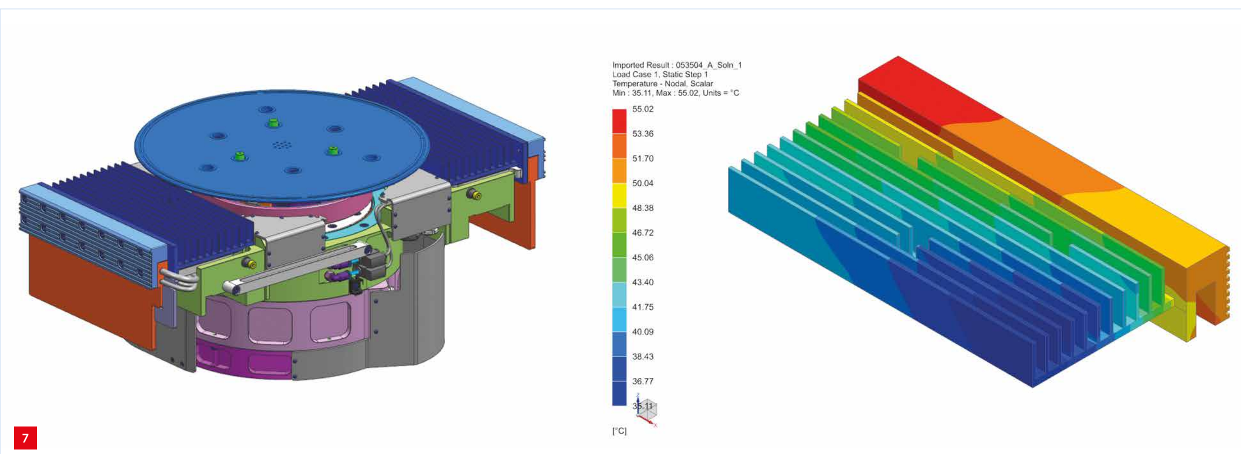
Also, thermal management was a topic that deserved special attention because of the stringent accuracy requirements. The location of the tool point – the point of interest on the wafer – must be known with an accuracy of a single micrometer, even when the system is operating at its maximum throughput cycle and the actuators are generating a considerable amount of heat.

During the concept phase, a comprehensive thermal network model was built to understand the implications of conceptual choices on thermal management. Based on the requirements of PM's customers, the use of any form of liquid cooling was strictly forbidden, as this would pose a major risk in terms of potential coolant leakages that could damage the expensive payload or could cause expensive stops in critical production steps. Also, the use of cooling fans was not preferred, as a forced airflow could induce vibrations on the stage or on the sensitive payload.

With active cooling not being allowed, the design was pushed towards passive cooling, which posed a significant design constraint. To get rid of the heat of the actuators, relatively large heatsinks were designed to keep the temperature, and therefore the thermal expansion, relatively low. The heat sinks are structurally connected but thermally isolated from the rest of the system by means of thermal barriers. This way, the heat sinks contribute to the stiffness of the stage without affecting its accuracy.

FEM analyses revealed that the thermal barriers functioned well, but further improvements were necessary to minimise the thermal deformation of the stage. One option was that some structural components would be made of invar, a nickel-iron alloy with a low coefficient of thermal expansion. This would not be very cost effective, however, given the high price of this material. In addition, the stiffness-to-weight ratio of invar is not as high as that of alternative materials.

Instead of making use of expensive materials throughout, PM decided to employ strategically placed aluminium flexures that allow the stage structure to expand freely. In addition, a small number of stiff invar components were attached to the centres of thermal expansion, keeping the centres of the components position-independent of



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Zθ-module with heat sinks (dark and light blue) on each side. A convective heat transfer study was performed on this assembly to get an impression of the temperatures of the heat sinks. In this analysis, the assembly was assumed to move at a uniform speed. On the right, the temperature ranges from 35 °C (blue) to 55 °C (red).

temperature variations. This way, the use of expensive materials could be limited to only a few components.

The last step in the thermal management study was to optimise the shape of the heatsink for maximum effectiveness. A conjugate heat transfer model was made in which air flows through the heatsink. In this way, the thickness, the height and the spacing of the cooling fins were determined. Figure 7 gives an impression of the convective heat transfer analysis.

Thermal (as well as dynamic) stability was also an issue in determining optimal encoder positions.

Outlook

One prototype stage has been built, which was demonstrated at the Precision Fair in November 2019. Construction of a second stage, including a vibration isolation system, is currently ongoing. This second prototype will be used to validate that all design requirements have been met and to further quantify specifications, using for example external interferometers, grid encoders and application-oriented equipment. Meanwhile, several potential customers have already shown their interest in the Vega stage, which could lead to a further evolution of the current design approach.

VIDEO

- www.youtube.com/watch?v=sO3hUWLTco8