Autofocus and motion error compensation methods for gantry machine in ultra-precise laser machining applications

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Abstract: Error compensation by applying motion control methods makes auto-focus easy and reliable in micro-machining applications. We present a method for dynamic roll and yaw compensation in gantry machines.

Micromachining applications for the semiconductor industry require ultra-precise motion control. The common method for solving these uncertainties in positioning errors is to use state-of-the-art mechanical components and controllers, however, this approach is not always applicable, moreover, it increases the complexity of the machine reducing its scalability [1].

In gantry-type machines, there are several sources of motion errors. First of all, to ensure high gantry stiffness the ball bearings are pre-loaded, however, even the small misalignment in the X-axis stages (X_1 and X_2) changes the bearing pre-load which leads to a resonance frequency in a lower part of the frequency response spectrum, thus reducing the bandwidth of the system and resulting in a tracking error (motion ripples). Second, since the gantry stage has two motors on each X-axis stage, the misaligned control signal may result in a yaw of the system, making the machine coordinate system rotate in accordance with the coordinate system of the sample, which is fixed to the table. Such motion also adds extra load on the bearings making the control of the system problematic. Third, the elastic deformation of the Y stage happens due to a moving load on the Y axis, which means that there is a convex shape along the Y-axis direction of motion resulting in a Y-axis roll and an out-of-focused laser beam. The latter can result in surface quality defects [2]. Overall, even very complex and sophisticated mechanical systems when used in uncontrolled environments have mechanical imperfections resulting from manufacturing tolerances or thermal effects, so even in those cases there is a need to compensate above-mentioned motion error sources.

A special one-degree-of-freedom decoupling unit (working in a Y-axis direction) was developed and integrated into a gantry-type system dedicated to ultraprecise micromachining application.

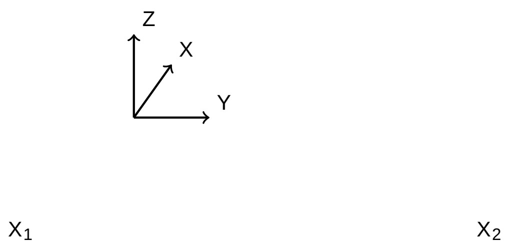

Fig. 1 Decoupling units shown for developed gantry-type machine

Decoupling unit, together with a true-gantry control algorithm, allowed to compensate yaw motion of the Y-axis when moving along the X-axis direction. This allowed us to align the grid of the gantry system with the sample. Also, the frequency response characteristics were improved with no resonance frequencies observed in the Bode plot, which allowed tuning the system with the required stiffness. Furthermore, the laser displacement sensor is integrated on the Z axis, and the analog signal of the sensor is fed to the motion controller. The signal is interpreted in real-time and the Z-axis position is adjusted accordingly on the controller side.

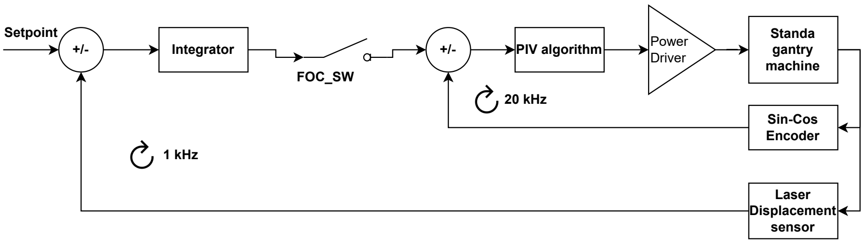

Fig. 2 Working principle of system feedback with a displacement sensor.

The main problem here is that the Z-axis shall be very fast to be able to respond quickly to changes in the Z-direction and the displacement sensor shall be stable in order not to introduce high-frequency noise into the system. The absolute accuracy of the system is ±1.5 μm, bi-directional repeatability RMS ≤0.5 μm, angular deviation ±20 μrad and ±25 μrad orthogonality.

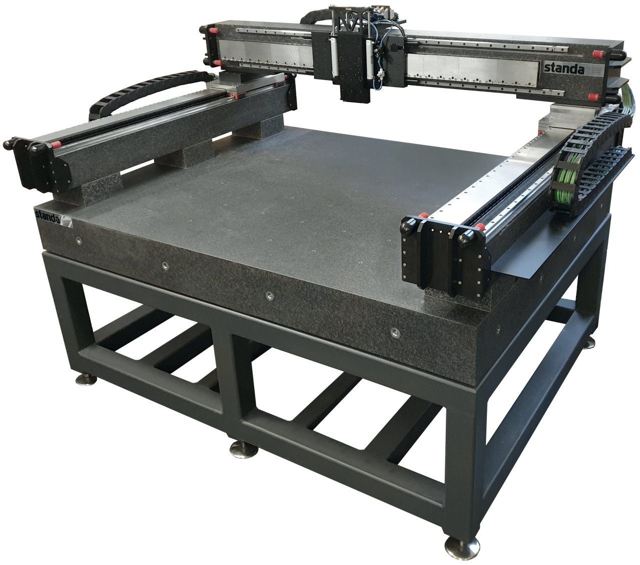

Fig. 3 Ultra-precise gantry-type system for laser-based micromachining applications.

References

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