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A HIGH PERFORMANCE X-Y STAGE WITH A NOVEL TOPOLOGY

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This paper describes a 350 mm travel X-Y positioning system with a novel topology, high dynamic performance, and an advanced real- time controller. While the initial implementation positions a 300 mm semiconductor wafer under a stationary laser system, the design can be scaled upwards or downwards in travel to suit a wide range of potential applications. The Delta Stage described below provides substantially higher performance than traditional X-Y stages, and its advantages become even more compelling as the travel is increased.

Existing solutions

While traditional single axis stage designs can, with moderate effort, provide high dynamic performance, the design challenges and tradeoffs grow substantially as the number of axes is increased. In particular, the requirement to position a payload in two axes with high dynamic performance encounters a number of design conflicts. The simplest expedient, that of stacking two similar axes, one above the other, suffers from excessive moving mass and low frequency structural resonances.

One reasonably efficient solution, referred to as a split-axis design, separates the X and Y axes, one of which carries the payload, with the second axis carrying the tool. While this approach is well suited to compact tools that bear acceleration well, in many cases the tool is prohibitively massive and/or includes sensitive components, and cannot be moved. In this case, the payload must be moved in two axes.

Several decades of evolution in X-Y stage design have converged to yield two related topologies for moving a payload in two axes, commonly referred to as “H” and “T” stages. In both cases, the payload carriage moves in a plane over a very flat surface, supported vertically by a single preloaded planar air bearing.

This bearing constrains movement of the carriage and payload in the Theta X, Theta Y, and Z axes, while providing freedom in the X, Y, and Theta-Z axes. A moving beam with a linear bearing and a linear motor constrains movement in the Y and Theta-Z axes, while controlling movement along the X axis. The distinction between the "H" and "T" design variants is that in the "T" design, this moving X axis beam is rigidly coupled to a bearing that travels along a stationary Y axis beam, and is driven by a single motor. In the "H" design, two motors are used to drive each end of the X axis beam along the Y axis, with a flexible joint between the X beam and the Y axis bearing. Feedback is provided by three linear encoders, supplemented in high accuracy designs by a laser interferometer and a pair of perpendicular flat mirrors mounted to the carriage assembly. For short travel variants, a single planar X-Y encoder can be mounted in the base of the carriage.

While commercially available from a number of suppliers, X-Y stages based on a "H" or "T" design suffer from some fundamental drawbacks, as listed below:

- The mass of the moving X axis beam and its linear motor limits performance.
- The moving X beam is subject to deflection and resonances due to bending moments.
- The payload is closely coupled thermally to the X axis motor coil.
- In "T" designs, cantilevered loads deflect the Y axis bearing.
- In "H" designs, the flexible coupling between the X beam and the Y bearing limits performance.

The above drawbacks manifest themselves in three ways: lower servo bandwidth (due to a low first resonance), limited acceleration (due to high moving mass and motor thermal limits), and thermal deformation of the payload (due to acceleration-induced heating). Attempts to mitigate these effects lead to extensive light- weighting and exotic materials, but for applications which are acceleration-bound, these efforts very rapidly encounter diminishing returns. The use of larger motors might seem helpful, but fails due to the added moving mass of the X axis motor stator. Motor thermal power is equal to $a^2 \sim m^2 / K_m^2$, where a is the acceleration, m is the mass, and K_m is the motor constant (in Newtons per root watt). Since acceleration is what we want, and heat is its undesirable by-product, we can define a figure of merit **K_s**, equal to K_m^2 / m^2, such that stage power equals a^2 / K_s. Motor thermal power is inversely proportional to K_s, and stage designs can be ranked on their value of K_s. Traditional "H" and "T" stages have K_s values that tend to range between 0.05 and 0.25.

The Delta Stage

The Delta Stage (Fig. 1) was developed after attempts to raise the continuous acceleration capability and servo bandwidth on traditional stage designs had reached an impasse.

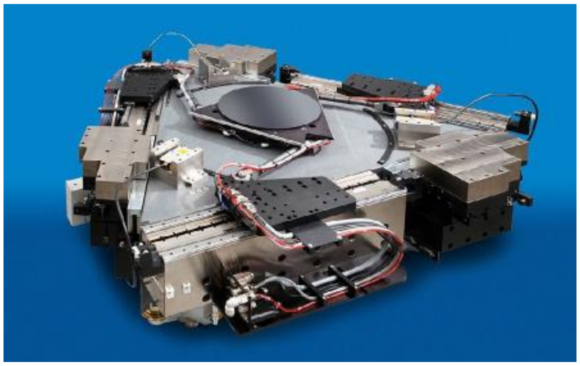

Figure 1*. The Delta Stage*

The Delta Stage utilizes a parallel link architecture, which has been known since the 1800’s to be vastly superior to serial link mechanisms in agility (acceleration per watt) and stiffness [1]. “T” stages are serial link devices, while “H” stages employ a hybrid parallel/serial link design. The basic elements of the Delta Stage are a triangular base (granite in this case, although other materials can be used), three primary linear actuators (one on each side of the granite triangle), three counterforce linear actuators, three tubular silicon carbide drive links, and a vacuum-preloaded central chuck- puck that carries the payload (in the first implementation, a 300 mm silicon wafer). The work area is a 650 mm circle, and the three drive links can rapidly position the chuck-puck anywhere within that circle. Three steel risers support the customer’s optical plate, as well as mounting the fiber-optic interferometer heads.

Note that while parallel link mechanisms have a long history, the particular topology of the Delta Stage is unique, and several patents on the design are pending. Specific details and advantages of the Delta Stage are discussed below.

Three Degrees of Freedom

The Delta Stage is a three DOF system, and positions the chuck-puck in three axes: X, Y, and Theta-Z. The ability to provide Theta-Z positioning with no additional penalty in moving mass, compromised dynamics, overall height, or cost is a distinct benefit in many applications. For the initial application, the chuck-puck rotates 20 degrees during wafer load/unload to minimize the reach required of the wafer handling robot. Future versions of the Delta Stage will redesign the current monolithic chuck-puck as a three DOF Z – Tip – Tilt assembly, providing precise positioning with high dynamics in all six degrees of freedom.

High Specific Stiffness (Stiffness / Mass)

The three linear actuators drive the puck by applying tension and compression forces directly along the drive links. Since there are rotary joints at each end of the links, the links cannot be placed in bending. For a given link length, a tube in tension/compression can be made much stiffer with substantially less material (lower mass) than a beam that must both withstand bending forces and carry a large linear motor.

The time constant **r** for settling after a move is inversely proportional to servo bandwidth, which is in turn proportional to the frequency of the first structural resonance. This first resonance scales as the square root of stiffness divided by mass, so high dynamic performance is a matter of maximizing the system's specific stiffness (stiffness/mass). The replacement of the large mass of the moving X beam and its heavy linear motor stator with a simple cylindrical drive link substantially decreases the moving mass, while the elimination of any bending moments substantially increases the stiffness of this drive method. The result is a much higher ratio of stiffness to mass, and a considerably higher first resonance. In the first-article Delta Stage, a monolithic machined chuck-puck design was chosen, to reduce risk and lead time. With a chuck-puck moving mass of 4 kg, the first resonance (rotation around the Z axis) was 750 Hz, and the second resonance was over 1100 Hz. More aggressive light-weighting (e.g, expanded honeycomb + sheet metal) could achieve a first resonance over 1 kHz.

As stage travel and hence dimensions increase (as is happening in the current move from 300 mm to 450 mm wafers), the stiffness in bending of the moving X-axis beam of an "H" stage decreases with the cube of its length. The stiffness of the Delta Stage drive links, which experience only tension and compression, decrease linearly with length. The dynamic advantages of the Delta Stage, already substantial at 350 mm travel, become even more compelling when the travel grows to 500 mm or more.

High Agility (Acceleration / watt)

The high agility of the Delta Stage results from two factors: low moving mass, coupled with large linear motors. High agility is important in reducing the power dissipation in the motors when performing high-duty cycle moves at high peak acceleration. For a point-to-point move of a prescribed distance and move time, the energy dissipated in the motors during that move will be inversely proportional to the previously defined figure of merit **K_S**.

The Delta Stage (like all parallel link mechanisms) has a dramatic advantage over conventional "H" stages due to the reduction in moving mass of the stage, together with the ability to use very large linear motors with only a modest increase in moving mass (since all three linear motor stators are stationary). In the Delta Stage, Ks varies a bit from place to place, but averages 12, compared to a value of 0.25 for a reasonably aggressive "H" stage. As a result, the Delta Stage is nearly 50 times more efficient, and **will dissipate ~2% of the power that would be dissipated by a conventional "H- Stage" performing the identical motion profile!** During 3G moves at 100% duty cycle, the Delta Stage motor coils dissipate less than 15 watts, and due to their large size, are barely warm to the touch.

Thermal Isolation

In addition to substantially raising the continuous acceleration capability of the system, the very high efficiency of the Delta Stage reduces thermal coupling to sensitive system components and the payload, and substantially reduces their time and duty-cycle dependent thermal expansion and contraction. Secondary benefits include smaller amplifiers, smaller cables (less cable drag during stage motion), and smaller power supplies. The Delta Stage offers the further benefit of moving the motor thermal dissipation (what little there is) to the periphery of the stage base. In a conventional “H-Stage”, at least one motor will dissipate power immediately under or adjacent to the payload. Given significant power dissipation in the immediate vicinity of the payload, conventional stages are challenged to provide both high precision and high accuracy.

Force Cancellation

In conventional “H” stages, the high moving mass produces large horizontal inertial forces during high acceleration, and the shift in CG during motion produces large and variable vertical forces. Most high accuracy systems require a vibration isolation system that reacts to these large inertial and CG-shift forces, significantly degrading the overall dynamic performance. While the Delta Stage moving mass is considerably lower than a conventional “H” stage to begin with, its three short travel counter-force actuators (only practical in a system with such high efficiency) cancel nearly all horizontal inertial forces. The control law for the counterforce actuators moves their reaction masses in opposition to stage motion, so as to maintain a perfectly fixed and central CG location for the entire X-Y stage sub-system. In many conventional implementations, the full acceleration capability of the stage must be pared back due to interactions with the isolation system; in the Delta Stage, operation at full acceleration imparts negligible forces to the isolation system.

Integral Active Vibration Isolation

Three highly sensitive geophones are built into the base of the Delta Stage. Their signals (resulting from external accelerations) are processed by the system controller, which in turn generates commands to the counterforce actuators that cancel those external accelerations. Unlike conventional active vibration cancellation systems, however, vibration cancellation via the counterforce actuators imparts no forces to the frame, and cannot couple back into the isolation system. Typically, only passive vibration isolation is required with the Delta Stage, and due to the complete lack of CG shifts, active vertical isolation can be effected with the very simple and inexpensive addition (fully supported by the system controller) of three additional geophones and three small solenoids. The cost savings and reduction in overall complexity provided by the

Delta Stage's integral, high-performance active vibration isolation system can be substantial.

Bearings and Motors

The chuck-puck base bearing is a planar, low- noise, vacuum preloaded air bearing. The hinge and pivot joints at each end of the three drive links employ multiple sets of preloaded angular contact bearings. Three long recirculating ball modules with low lateral jitter guide the three primary actuators. Crossed roller ways guide the three counterforce actuators.

Three phase brushless linear servo motors were used to drive both the primary and counterforce linear actuators; K_m for the primary actuators was 23 Newtons per root watt. The motor coil mass is 30% of the total actuator moving mass, compared to 2-5% for traditional "H" stages.

Feedback

Position feedback for each of the primary linear actuators consists of a pair of Heidenhain LIF linear encoders, which provide a sine/cosine output with a 4 micrometer electrical period. The system controller performs advanced interpolation on these signals, with a resolution of 78 picometers. One of the pair is located very close to the center of mass (and drive) of each actuator, while the second is located just below the hinge joint of the drive link. The use of two encoders allows the controller to measure and correct in real time any acceleration-induced yaw of the primary linear actuator. While this proved unnecessary in this first embodiment using mechanical bearings, this capability should be very valuable in subsequent air- bearing iterations of the primary linear actuators.

The exact position of the chuck-puck is determined in real time via closed-loop interferometer feedback, using a pair of plane mirrors integral to the monolithic chuck-puck (see below), and a stationary Renishaw RLE-10 two-axis, plane mirror interferometer, a homodyne position sensor whose native output is sine/cosine. The interferometer's electrical signal period of 158 nanometers is interpolated by the system controller, resulting in a resolution of 3 picometers (well bellow its noise floor), and the Delta Stage's top speed is limited only by the interferometer, which is capable of operating at velocities of up to 1.0 meter/second. Thanks to the exceedingly real-time nature of the RDI based control system, laser firing pulses can be output directly from the interferometer position data, with a timing uncertainty of 1 nanosecond (1 nanometer at 1 meter per second).

Integral, Diamond-turned Interferometer Mirrors

In most X-Y stages equipped with a plane mirror interferometer, two individual glass “stick mirrors”, or a single “L mirror”, are mounted to the upper axis carriage, and present two plane mirror surfaces at 90 degrees that reflect the two interferometer beams. Both of these approaches add substantial cost and mass to the system, and it is a difficult design challenge to clamp these mirrors securely without compromising either mirror flatness or system dynamics. In the Delta Stage, the two mirrors are oriented at 60 degrees, and have been directly diamond-turned into an electrolessnickel coating applied to lightweight ribbed extensions of the monolithic chuck-puck. The top of the mirror surface is 1.5 mm below the top of the wafer, and the mirrors are both diamond- turned and subsequently profiled via interferometry with an active chuck-puck base bearing, ensuring minimal deformation from flatness of the two surfaces in operation. Deviation from flatness is +/- 110 nm over full travel (350 mm), and the mirror first resonance is 1200 Hz. The total incremental moving mass of the integral interferometer mirrors is a mere 150 grams. The simple addition of a column reference mirror in the reference leg of the interferometer eliminates any sensitivity to atmospheric refractive index changes.

Monolithic Chuck-Puck

The monolithic chuck-puck was machined in two halves from aluminum plate, producing a pair of structures with 1 mm hexagonal cell walls and dedicated compressed air and vacuum routing. These two halves were then vacuum braised together, producing a lightweight and stiff chuck- puck assembly.

Dedicated wafer chucks typically add significant cost, mass, and dynamic compromises to traditional X-Y stage solutions. In the Delta Stage, an array of pins in the top of the monolithic chuck-puck forms an integral wafer chuck that provides minimal back-side contact, while ensuring rapid air flow to and from (and across) the vacuum chuck. The Delta Stage vacuum chuck adds no mass, no dynamic complications, and minimal incremental cost to the system, and consists of a large number of features photo-etched into the thin top skin of the monolithic chuck-puck.

Complementing the pin-grid wafer vacuum chuck is an integrated, 6 mm travel, three-post lift-pin assembly. The three moving posts have an internal switched vacuum to grip the wafer, and transport the wafer 6 mm above the vacuum chuck to provide access for a wafer handling robot paddle. The lift-pin assembly is driven by an integrated stepping motor linear actuator, and optical limit switches define the travel range and confirm lift-pin retraction. The total incremental mass of the lift-pin assembly is 75 grams.

Performance

Figure 2 shows the performance of the Delta Stage while performing a typical semiconductor application. The stage is performing a series of operations “on-the-fly”. The operations occur during brief moments when the stage is moving at constant velocity. The stage makes a cycloidal acceleration between the constant velocity segments. Note that the following error during 2.7 G acceleration segments is never more than a few microns, and settles to a few hundred nanometers in under 10 milliseconds after the acceleration transient.

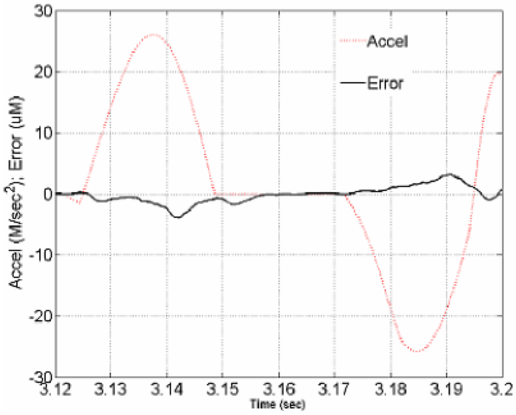

FIGURE 2. Stage acceleration and following error in the X direction during typical semiconductor processing.

Delta Stage Controller

The Delta Stage Controller is implemented with an infrastructure called RDI. RDI (Real-time Data Interface) provides synchronization and communication services in support of high- performance control systems. The Delta Stage Controller consists of a host computer where the application interface is implemented, an embedded real-time computer that executes the time-critical control code, and peripheral devices that interface with encoders, interferometers, amplifiers, galvos, and other application-specific devices.

The host and real-time computers each include an RDI PCI-card. Each card provides four (4) RDLink ports that use Cat6 cables to communicate with other RDI-devices. Each port transmits a 100 MHz clock signal. The receiving port synchronizes to the RDI clock signal and adjusts the phase at the receiver to compensate for transmission delays. The resulting clock on the receiving port exhibits less than 0.1 nanosecond of jitter (3-sigma) and less than 1 nanosecond of skew relative to the clock source. This level of synchronization is critical to achieving nanometer-class precision when operating at speeds approaching 1 meter/sec.

The RDLink data paths transmit data bidirectionally at 500 Mbit/sec. All connections are transformer isolated to eliminate ground loops. Each link can be up to 10 Meters in length. RDI allows components to be distributed throughout a system, without compromising timing precision. RDI extends the industry trend towards distributed motion control to the realm of nanometer precision and sub-nanosecond timing jitter.

The host and real-time computers transmit data over the RDLink cable using real-time DMA transfers. Each RDI card includes 8 DMA engines that can be scheduled to transmit data packets at specific points in time relative to the servo period. Data from a peripheral card that is responsible for encoder or interferometer input is scheduled to arrive a few microseconds before the start of a servo period. The peripheral card transmits a packet of data directly into the memory of the real-time computer. When the servo period begins, the real-time computer finds the data packet in memory and begins calculations immediately. At the end of the servo calculations, the real-time processor writes output values to a fixed location in memory. A scheduled DMA transfer transmits the output data to a peripheral connected to amplifiers. Note that since all data transfers are performed by the RDI hardware using DMA transfers, the real-time processor is free to focus exclusively on servo calculations. Typical packet transfers between servo-related peripherals and the real-time controller require less than 2 microseconds to complete.

The real-time computer in the Delta Stage Controller consists of an industry-standard PC mainboard with a Pentium 4 processor operating at 3.4 GHz. All PC peripherals (USB, LAN, RS232) and all interrupts are disabled in the real-time computer since the RDI hardware provides all communication services. The entire Delta Stage control program fits within the on-chip cache of the Pentium processor. With no other peripherals on the PCI bus, the RDI card is able to use the PCI bus exclusively for packet transfers. Since the Delta Stage Controller runs without using interrupts, the on- chip memory cache remains coherent between servo periods contributing to improved calculation performance. Typical performance exceeds 1 Gigaflop of double-precision operations per second.

The host computer sends commands to, and receives status from, the real-time computer using DMA transfers over the RDLink connection. In the Delta Stage Controller, the host application computes trajectories that the stage is to follow. Each entry in a trajectory specifies positions, velocities and accelerations as well as application-specific control settings corresponding to a single time-step of the servo. In some applications, the trajectories are computed and stored in a file before the actual motion occurs. In other applications, the trajectory must be computed while the stage is moving. In either case, the RDI hardware handles the transmission of trajectory packets from the host to the real-time computer without processor intervention on either side of the link. There is no practical limit to the duration of a trajectory that the Delta Stage can follow without stopping.

A state-space controller implemented using the RDI infrastructure controls the Delta Stage. The host processor specifies trajectories in a user- specified Cartesian coordinate system. The real-time processor performs all necessary transformations (geometric and kinematic) to transform the trajectory into a body-centered coordinate system.

The state-space controller closes the servo loop in the body coordinate system. The controller output is transformed into the actuator coordinate system where it is sent to the servo interface hardware in a DMA packet.

Sensor inputs are transformed from sensor coordinates to body coordinates and combined with body forces in the state observer to update body states. The state outputs are also used to project the vector of following error onto the nominal path of the stage. The component of error in the direction of motion is converted to an equivalent error in time. The time-based adjustment is used (in the Servo Interface FPGA) to correct nominal trigger times of signals that coordinate external devices with stage motion. Thus, the stage precision in the direction of motion for on-the-fly operations is limited only by the precision of the stage metrology (in this case, a laser interferometer), not by servo performance.

The trajectory planner executing on the host computer is responsible for deriving trajectories that are continuous through 3 derivatives (continuous acceleration, finite jerk) and within the performance capabilities of the stage (position, velocity, acceleration and voltage limits). The planner uses cycloidal motion profiles to link any vector position and velocity to any other vector position and velocity. Using acceleration feedforward from the trajectory, the stage typically will execute a 3G acceleration move with less than 2 microns of deviation from the trajectory during the acceleration phase. The stage settles within a few milliseconds after an acceleration transient to under 0.25 micron following error during a continuous velocity segment. Note that the timing of an external event with the stage motion is corrected for any following error, yielding noise-limited precision in the direction of stage motion.

REFERENCES

[1] Merlet J.-P., Parallel Robots, 2nd Edition. Springer. Dordrecht, The Netherlands: 2006.