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True Moves

Motion control advances for micromachining

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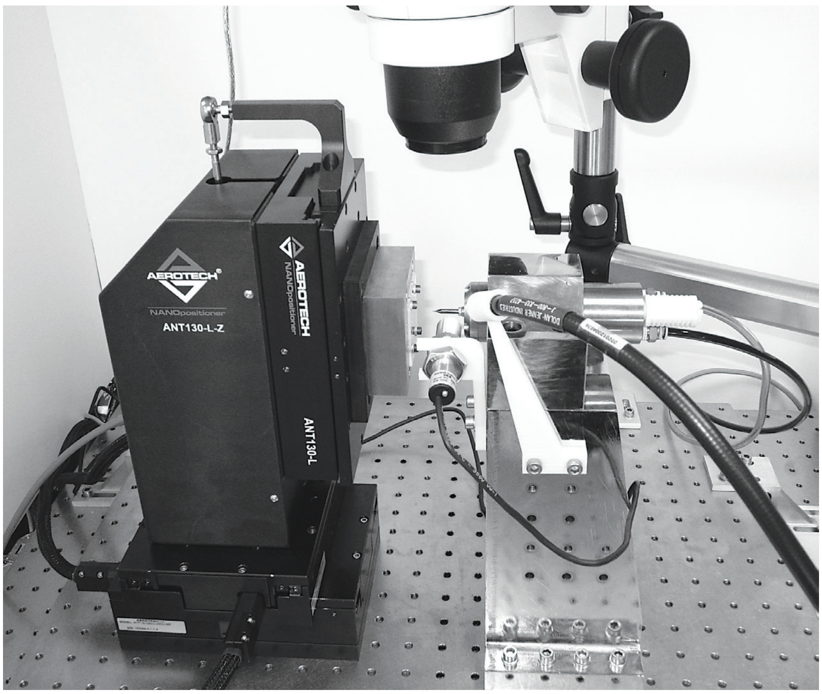

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A high-precision micromachining center with Aerotech stages.

Precise motion control is a key element in mechanical and laser micromachining. With some applications requiring submicron positioning accuracies in a 4- to 6-cubic-inch work envelope, motion control can be the difference between an operation's success and failure.

An advanced micromachining system must have either nanometer positioning capability or incorporate miniature machine tools with equivalent precision. Positioning subsystems must provide nanometer resolution and accuracy, along with travels long enough and speeds high enough to permit machining campaigns of sufficiently short duration to make the application cost-effective. The magnitudes of these speeds and travels are, obviously, dependent on the application.

Key motion requirements for mechanical and laser micromachining systems include high dynamic contour accuracy, repeatability, speed and a flexible, advanced motion controller. These requirements cannot be achieved with a single technology. Rather, success depends on carefully integrating mechanical, electrical, control and software elements. Common motion system components include bearings, motor and drive systems, feedback devices, amplifiers and advanced control.

Aerotech

Aerotech's ANT130-XY is an example of a dual-axis nanopositioning linear stage that uses crossed-roller bearings.

Bearing technologies

Stage selection begins with determining the desired bearing technology for a particular application. Options include recirculating ball bearings, anti-creep crossed-roller bearings and air bearings. Length of travel, dynamics, load and friction considerations all influence the bearing selection.

Recirculating ball bearings offer the greatest flexibility among the options mentioned. Designs can have travels ranging from 25mm to greater than 3m and payloads varying from 2kg to greater than 1,000kg. Applications are usually point-to-point motion or contouring, where contouring dynamics up to several microns are acceptable. Stages can be sealed with a hard cover and tensioned side-seals to help protect the internal components from machining-generated debris. However, the recirculating element of the bearing introduces disturbances to the system as the individual balls enter and leave the recirculating path.

Aerotech

Aerotech's ABL1500WB-B is an example of an air-bearing linear stage with bellows.

Crossed-roller bearings do not include a recirculating element, leading to smoother operation. When coupled with an optimized control system, these stages are capable of nanometer-level precision. Load capacities are generally from 0.5kg to 50kg, with practical travel ranges up to 300mm. Longer travels are limited due to bearing cantilevering, which introduces pitch errors. Additionally, these stages are more difficult to seal against debris.

Air-bearing stages provide near-frictionless motion, and bearing geometric performance (pitch, roll, and yaw error motion) is superior to other bearing types. Practical travels are from 25mm to greater than 3m, with payloads ranging from 1kg to 250kg. Bearing surfaces are large compared to other bearing types, allowing comparatively larger stages.

The frictionless nature of these bearings enables high accuracy and dynamic performance compared to stages that use mechanical elements. Also, their outstanding angular characteristics can yield the lowest possible off-axis errors (e.g., straightness, flatness, pitch, roll and yaw)—in the submicron and sub-arc-second ranges. The biggest disadvantage of using air bearings is that machining debris can damage the bearing surface. Bellows and other protective covers may be employed, but they add friction to the system, partially negating the advantage of air bearings.

Recirculating ball bearings are most commonly used in micromachining systems due to their flexibility and the ease with which they can be sealed. When higher-precision systems are required, crossed-roller bearings or air bearings are often employed, assuming debris generation and removal can be controlled.

Direct vs. screw-based motion

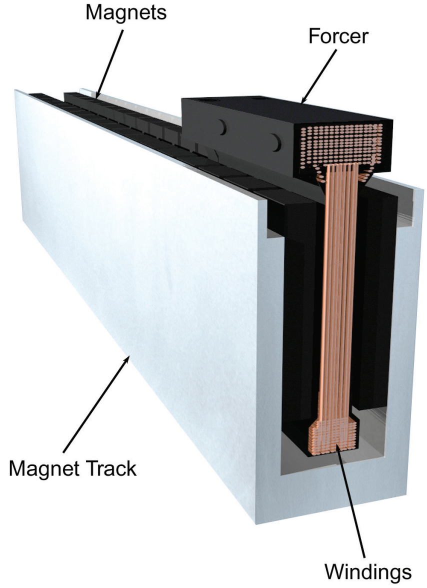
Motion in linear and rotary axes is commonly achieved with either screw-based stages (coupling a rotary motor to a ball screw or worm gear) or with direct-drive solutions. When considering the requirements of most micromachining applications, direct-drive stages offer numerous advantages over screw-based systems.

For example, in high-duty-cycle applications, the screw can wear over time, reducing accuracy and repeatability. Also, backlash in the screw's drivetrain limits its ability to achieve sharp direction reversals or to precisely track complex contours, which reduces system performance and throughput. Direct-drive systems do not exhibit backlash and windup, and they can achieve much higher accelerations and system bandwidth than screw-based systems, thereby increasing part quality. Additionally, the noncontact design of direct-drive systems eliminates wear and requires no maintenance. These advantages make direct-drive motors the obvious choice for micromachining.

Multi-block look-ahead enables the controller to compare future commands against those currently being executed, compensating when necessary to reduce motion errors.

Feedback devices

Micromachining requires feedback devices capable of submicron resolution, which allows the controller to close the servo loop. Common high-resolution feedback devices include linear encoders, laser interferometers, capacitance probes, LVDTs (linear variable differential transformers) and strain gages. While each device has advantages and disadvantages, laser interferometers are prohibitively expensive for most micromachining applications, whereas capacitive probes, LVDTs and strain gages are limited to extremely short travels, making them impractical for most applications. Therefore, in most laser or mechanical micromachining applications, a linear encoder is the clear choice due to its accuracy, speed, range of travel and ease of integration.



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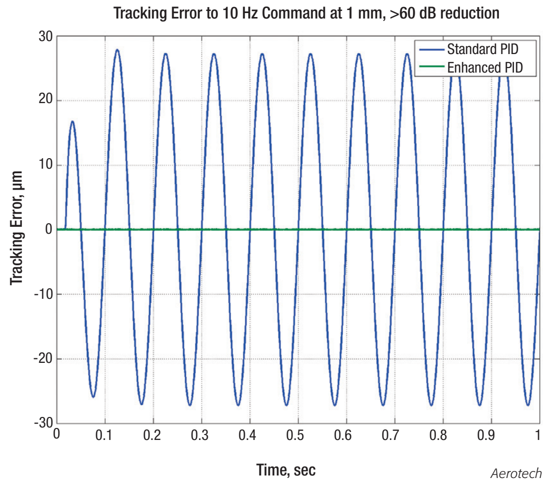
The noncontact design of direct-drive systems, such as this linear motor, eliminates wear and requires no maintenance.

Linear encoders employ a scale with a grating period (distance between graduations on an encoder) and a read head. The optical read head measures the gratings and generates an analog signal whose period is the same as the grating on the scale. Typical encoder periods range from 200nm to 20µm, but advanced controller features can interpolate these fundamental period signals to subnanometer resolution, which is needed for the control system to maintain the required accuracy when micromachining.

The effects of thermal expansion on the encoder scale also must be considered. Linear motors generate heat during operation, which dissipates into the stage and internal components. Stages are typically made from aluminum, which has a thermal expansion coefficient of 24 microns/meter/degree (Centigrade). For example, a 100mm aluminum stage will expand 2.4μm when temperature increases 1° C. While alternative materials with lower thermal expansion coefficients can be considered, manufacturing the entire stage from such materials is often prohibitively expensive and can compromise system stiffness. One technique to maintain performance while minimizing cost is to mount only the encoder scale on a low-coefficient-of-expansion material, isolating it from the thermal expansion experienced by the rest of the stage.



A harmonic cancellation algorithm rejects periodic error motions by canceling the frequency of the error with a cross-axis correction.

Amplifiers and drives

When operating at micron and submicron levels, any disturbance can lead to positional errors that affect part quality. In addition to external disturbances, such as ground vibration or acoustical noise, internal disturbances from electrical noise or power electronics that emit electromagnetic noise can cause instabilities and jitter in the motion system. High-precision systems require advanced amplifier designs to achieve desired results. Amplifiers commonly used for micromachining include the pulse-width-modulated (PWM) amplifier and the linear amplifier.

PWM amplifiers modulate the "on-off" time of the power transistors to control the motor output. PWM amplifiers are efficient because resistance across the transistors is low when in the "on" mode, minimizing power loss across the transistors. This allows high-power amplifiers to be housed in relatively small packages.

Despite their efficiency, PWM amplifiers produce ripple current and electrical noise, making them less suitable for high-precision applications. For example, when controlling systems with resolutions to 50nm, the effect of this ripple current is negligible, but on systems with resolutions below 50nm and, more specifically, lower than 5nm, the ripple can cause system disturbances. This produces poor in-position stability. In other words, the unintended noise current issued to the motors will cause the stage to jitter. This positional jitter can be on the same order of magnitude as the features being machined, and therefore is very detrimental to system performance.

Also, PWM amplifiers exhibit nonzero "dead time" at direction reversals in contours produced by the motion program. When the commanded motion trajectory changes direction, the amplifier requires a small amount of time during which no current is output, reducing the stage's tracking capability.

A linear amplifier operates the power transistors in the linear region, where the device acts as a current amplifier. Linear amplifier voltage and current waveforms have no ripple current, leading to better in-position stability. Linear amplifiers also maintain much better control during motion direction reversals, allowing greater tracking ability.

Linear amplifiers are not without drawbacks. They are large and generate a significant amount of heat. They are also more expensive than PWM drives. As a result, PWM amplifiers are appropriate for some micromachining applications, whereas linear amplifiers are recommended when micron and submicron accuracy is desired.

Advanced control

Micromachining requires an advanced motion controller with algorithms and hardware that minimize disturbance errors, increase tracking capabilities and provide superior in-position stability. Motion errors tend to be the greatest during acceleration or deceleration of an axis. In addition to changing velocities, axes accelerate and decelerate when following curvilinear paths—a frequent occurrence because of the complex contours found in micromachining.

Common motion control features that reduce these errors include acceleration

Using PSO for precise laser positioning

In laser-based micromachining, proper laser pulse spacing must be maintained in a highly dynamic system. When processing with a fixed-frequency laser, maintaining constant vector velocity is required for consistent pulse spacing and process quality. This is often made difficult by the complex contours of laser micromachining, and significant speed and throughput are sacrificed to maintain consistent velocity through the profile.

An option available with Aerotech motion controls is "position synchronized output" (PSO). It removes the speed and throughput limitations by triggering a high-speed output at predefined distances in real-time, based on the actual encoder positions during motion, even while accelerating. This eliminates the need for velocity regulation to maintain consistent processing quality. In addition to fixed-distance firing, array-based triggering allows the user to specify trigger points that are unequally spaced along the travel.

This style of PSO firing can be used to trigger the laser at precise positions along irregular contour operations. PSO can be configured for up to three axes of motion so that the triggering output pulse can be dependent on a vector position in 3-D space, and not simply tied to one moving axis. Additionally, the trigger is based on calibrated encoder positions—not simply the raw data—which further enhances system accuracy.

—J. Johnston, S. Schmidt

limiting and multiple-block look-ahead. Acceleration limiting compares linear and centripetal acceleration commands against predefined thresholds, and if the command exceeds the threshold, the controller decreases tangential velocity to maintain part quality. To optimize this feature, the controller must analyze future motion commands.

Multi-block look-ahead enables the controller to compare future commands against those currently being executed, compensating when necessary to reduce motion errors. For example, if the controller analyzes a future curved path, it calculates the centripetal acceleration and can decelerate over multiple commands so it enters the curve at the correct speed, within the predefined acceleration threshold.

This feature is particularly useful for the short toolpath segments and direction reversals common in micromachining, where the length of a segment may not be sufficient to allow the axes to decelerate at a static, programmed rate without overshooting. Multi-block look-ahead and acceleration limiting also allow the user to maximize throughput by programming higher feed rates, which enables the controller to process at the highest possible feed rate without violating acceleration parameters.

More advanced algorithms can help further reduce motion errors, and increase part quality and throughput. For example, we at Aerotech have developed an algorithm called "harmonic cancellation" that rejects periodic error motions, such as position-dependent wobble in a spindle, by canceling the frequency of the error with a cross-axis correction (see graph on previous page).

And our "enhanced throughput module" increases machine throughput by measuring base motion and appropriately combining this with the servo loop. Another feature, iterative learning control, reduces following error and increases dynamic accuracy by learning and optimizing repetitive move sequences.

System approach needed

Successful mechanical and laser-based micromachining operations require a holistic approach to ensure desired performance and quality specifications are met. One or two components cannot produce precise motion by themselves, but a complete mechatronic system can. Selecting and integrating the appropriate bearing technology, feedback device, amplifier type and control technology helps ensure successful micromachining operations.

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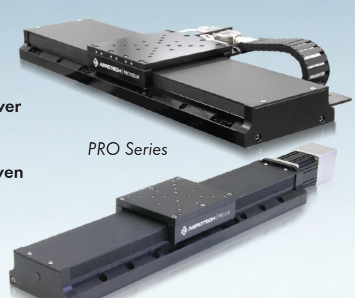

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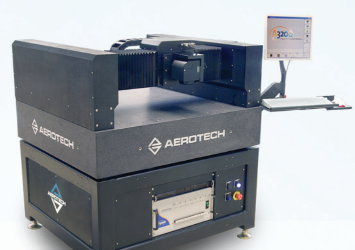

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