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Force Generation and Measurement

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Our broad product offerings in miniature, high performance, air bearing linear motor stages have, by virtue of their design, some interesting secondary capabilities of particular value in photonic automation applications. In addition to their traditional roles as point-to-point motion stages and constant velocity systems, the completely non-contact nature of their three primary design elements – motor, bearing, and encoder – permit these stages to function as both high performance generators and measurers of force. Central to this capability is the complete absence of friction in the bearing ways, the perfectly linear relationship between motor coil current and the resulting force, and the availability of high resolution optical encoder position feedback. Together, these make the creation and measurement of milliNewton-level forces a reality in your application, as an added benefit above and beyond the substantial value that they already provide in high precision movement, and short move and settle times.

With conventional mechanical bearing stages, friction in the way elements prevents the accurate generation and/or measurement of small forces. These tasks are effectively impossible if leadscrew and or piezo driven stages are considered. As a result, there is a tendency to mount load cells to the top of these types of stages, which compromises position accuracy and stiffness, while adding unnecessary complexity, cost, and volume. Commercial load cells are optimized for the measurement of high forces, and it is difficult to find models with good signal to noise at the low force levels typical of photonic automation. Our air bearing, linear motor stages provide built-in, high-resolution force generation and low level force measurement rivaling the most sensitive load cells, as a free added benefit to their main task as high precision positioners.

Precision Touch-off

There are a number of potential uses for these added capabilities, particularly in photonic automation. One, referred to as "precision touch-off", is the ability to detect when two parts contact to a very high degree of precision. This can be important in establishing a reference position, from which a predetermined offset is added to place a part very accurately with respect to another. Examples where this capability is useful include manipulating collimator parts a known small distance above a reference surface prior to bonding or laser welding, and providing exact control of an epoxy bond film thickness. In a typical precision touch-off application, the parts are moved at fairly high speed to a position of close proximity. One part is then moved at quite low velocity towards the other, with the integrator term of the position servo loop disabled. The motion controller monitors the following error, and can easily detect the contact point via the change in following error from a very small value to a gradually increasing value as the commanded position continues beyond the contact point (the parts, in contrast, do not). The servo loop DAC output level, which is directly proportional to force, can also be monitored. With typical stage resolutions in the 1 to 20 nanometer range, contact position determinations at or below 100 nanometers can be performed. While this is usually far finer than applications require, the higher accuracy position information comes at no extra cost, and can only help. With the actual relative position of the two parts established, a position offset to a desired location can then be made. Occasionally, concerns are raised about possible damage as the parts "bang into" each other. The actual kinetic energies are amazingly low, however, and with the possible exception of the most sensitive semiconductor parts, this is usually a non-issue.

Kinetic energy equals **½ mv2**; assuming a moving mass of 1 kilogram, and an approach speed of 50 microns per second, the kinetic energy is a vanishingly small 1 nanoJoule.

In the epoxy bonding film thickness case, the two parts are briefly contacted as described above, while dry, to establish their relative positions. The parts are separated, epoxy is dispensed, and the high resolution and repeatability of the stages are then used to “dial in” an exact epoxy gap thickness. This ability to control the epoxy film thickness in the 100 nanometer range affords a new and very useful process variable. In addition to the ability to detect part touch-off at very low force levels, it is also valuable to measure skewing forces due to epoxy curing stresses and or laser welding shifts. In its force measurement mode, our air bearing, linear motor stages perform this task with high precision; the technique is described below. In their force creation mode, our stages can produce force at high precision; this is valuable when squeezing epoxy films, seating solder preforms, and deforming compliant elements prior to laser welding.

Force Generation

The force creation function can be easily described. Since our air bearing stages have no friction, and their linear motors have a precisely linear relationship between coil current and applied force, a D.C. offset in the servo controller DAC output will produce a precise force. To use one stage as an example, our FiberBeam 100 has a motor force constant of 4.0 Newtons per Amp. If we assume a servo amp transimpedance gain of 1.0 Amps per Volt, and a servo controller with standard +/- 10 Volt analog outputs and DAC output resolution of 16 bits, then the minimum DAC output change will be 20/65,536, or 330 microvolts. The servo amp would then have a current resolution of 330 microamps, which corresponds to a force resolution of 1.3 milliNewtons. Grams are a unit of mass, not force, but if it helps, this force would be equal to that exerted by gravity on a 130 milligram mass. This sensitivity can be further increased by limiting the overall force authority, and/or using commercially available motion controllers with 18 bit DACs (Delta-Tau’s Turbo PMAC II, for example). With 18 bit DACs and a total force capability of 1 Newton, the force resolution is a remarkable 8 microNewtons (less than the force of gravity on one milligram). While this is probably well below the actual force resolution most applications require, excess resolution is “a good thing”. Note that the position servo loop integrator term must be disabled when attempting to generate a force, as otherwise the small offset from commanded position will result in the integrator winding up. There are two basic methods by which a force can be generated. In the first, the position servo loop is disabled, and a DC offset is sent to the DAC output. In this case, any DAC value translates directly to force, as described above. If there were mild biasing forces in the application (due, for example, to system cabling), then the DAC output level can be read back just prior to disabling the servo loop, and the new DAC value will be set equal to the sum of the existing DAC value, and the new offset corresponding to the desired force level. While the approach described above works, the disabling of the position loop eliminates the ability to control position; if the compliant load were to “slide over a hump”, exhibiting negative stiffness, then the position could run away. On the other hand, if the target part can be reasonably expected to be either rigid or sensibly compliant, then this approach can be very effective. Generally, after the desired period of force generation, the encoder position is read, and the command position is set to that position before the position servo loop is enabled and the DAC offset is removed. This will prevent a jump in position when the loop is restored.

In the other force generation mode, the position loop is enabled throughout the force generation period. As before, the servo integrator term is disabled. To produce a force, we take advantage of the fact that current, and hence force, is proportional to position error. Accordingly, if we command the moving part to a location slightly past the contact point, it cannot get there, and the resulting error translates to a force. The magnitude of the force is set by the distance past the contact point that we command. This allows just as flexible a control of force as in the former method, but preserves position control. To better understand this mode of operation, refer to Fig. 1.

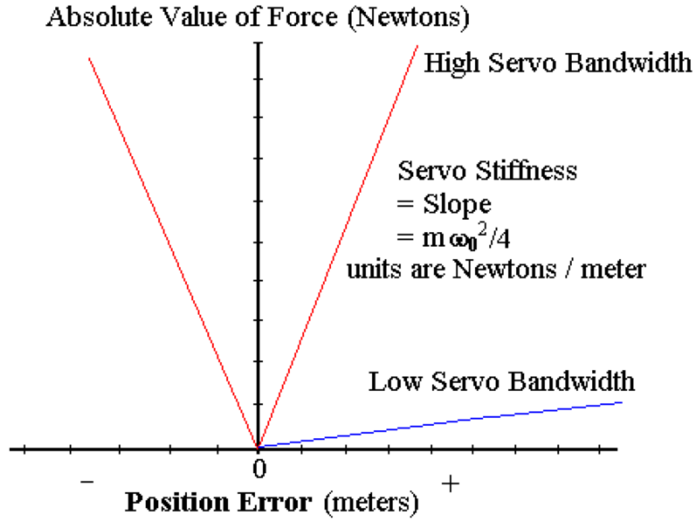

Fig. 1

In this graph, we have plotted the absolute value of force versus position error. With the integrator disabled, the force vs. error graph is linear, as the words "proportional term" would suggest. We can readily calculate the slope of this line, which is the servo stiffness, in units of Newtons per meter. The stiffness is equal to the mass (in kilos) times ω0 2/4, where ω0 is the natural frequency. The servo bandwidth f0, in Hertz, is more commonly used; this is equal to ω0/2π. If a closed loop system is commanded to follow a small amplitude sine wave, and the frequency of that sine wave is varied, the output amplitude will be flat from D.C out to a certain frequency, at which point the amplitude will drop off inversely with the square of frequency. The frequency at which the response has dropped off by 3 dB is the servo bandwidth f0. Typical values of servo bandwidth range from 10 to 100 Hz. If we adopt a typical value of 50 Hz, ω0 will equal 314 rads/sec. With a one kilogram moving mass, the servo stiffness resulting from the above equation comes out at 25,000 Newtons per meter, or 25 milliNewtons per micron. In most positioning applications, maximizing the servo bandwidth is the goal; in that case, the line relating force to error will be as nearly vertical as possible. The practical limit to increased servo bandwidth occurs when phase lag from the systems first resonance leads to instability. When it comes to force generation and/or measurement, however, we are motivated to move in the opposing direction, to fairly low servo bandwidths (the line of lower slope in Fig. 1). This is readily achieved, at enhanced servo stability, by simply lowering the servo tuning parameters. The result of this is to provide an increased ratio between error and force – a fairly small level of force now corresponds to a fairly large position error, which is quite easy to measure. In Fig. 1, for example, lowering the servo bandwidth from 50 Hz. to 10 Hz. will cause a twenty-five fold lowering of the force to error ratio; the value (the servo stiffness) is now 1 milliNewton per micron. To calculate the force resolution that we can achieve, we simply multiply this servo stiffness, in Newtons per meter, by the stage resolution in meters. With an encoder resolution of 10 nanometers, and assuming a 2 count position uncertainty, the force resolution is a remarkable 20 microNewtons. This is in rough agreement with the DAC limited force resolution calculated above. It should now be clear how extremely sensitive a force generator/measurer we have created.

Let's start with an assumption of perfect rigidity in the stationary and moving parts, and use the touch off method to produce gentle contact between the two parts. If we now command the moving part to move 20 microns into the stationary part, it cannot in fact move, but the proportional term "dials in" a force of 20 milliNewtons, (assuming the 10 Hz. bandwidth mentioned above). Our control of the commanded "penetration distance" gives us high precision control over force. If either part is in fact not perfectly rigid, the force will result in a small relative movement between the two parts. In this case, the previous proportionality between distance and force still applies, but the actual distance is not the commanded "penetration", but rather the difference between the commanded position and the current actual position. All modern servo controls provide this value; it is called the following error. If a particular force is the goal, and the part compliance is unknown, one simply moves until the following error is equal to the distance corresponding to the desired force. This resulting distance X, or following error, can be calculated via the formula: $X = F/m(\pi f0)2$, with m in kilograms, F in Newtons, X in meters, and where f0 is the servo bandwidth.

While the above formula can be used to calculate the "penetration distance" needed to create a specific force, it has a drawback: it assumes that the servo bandwidth is accurately known, as well as the moving mass, motor force constant, and amplifier transconductance gain. These are a few too many unknowns. A far more accurate method is to calibrate out the effect of all of these quantities by simply pushing against a force measuring device on one occasion, using a fairly high force level to avoid the need to source a very sensitive transducer. As long as the components remain the same, and the tuning values are preserved, the measured proportionality will persist, even at very low forces. Needless to say, these methods are of no use at all with conventional stages, and require frictionless air bearing, direct drive stages to work. If very low force values are required, specialized magnetic preloading or, better yet, air bearing preload should be selected, and a linear amplifier will prove superior to a pulse width modulated model. A current amplifier is preferred to a voltage amplifier, as otherwise current induced heating in the motor coil will alter the force constant. If limited travel (~20 mm. or less) is adequate, a single phase linear motor designed to have very constant force over full travel will improve force generation accuracy. In addition, multiple readings of the following error can be performed very rapidly by most motion controllers; performing a boxcar averaging on these will produce a "square root of n" improvement in the signal to noise.

Yet another means of generating force exploits the fact that the DAC output is directly proportional to force. In this method, the commanded position is slowly incremented until the desired DAC level is reached. The position is then held at that location for the desired duration of applied force. As before, calibration of the DAC count to force proportionality at higher force levels with an accurate force transducer can be used to achieve absolute accuracy in force.

Force Measurement

With the above material digested, the case of force measurement is quite simple. There are two possibilities: one in which the part on the positioning system is to remain stationary, and another in which it can be allowed to deflect as the external force is applied. In the former case, the servo loop integrator term is left enabled. As the applied force which grows, the linear motor will develop an equal and opposing force, resisting any change in position. To measure this force, the controller is simply interrogated for its DAC output level, which is proportional to force. There is some flexibility with respect to the servo bandwidth. If the force grows very gradually, then a low servo bandwidth is adequate, as long as the integrator term is enabled, and has a reasonable value. If the force is applied abruptly, and very little movement is preferred, a high servo bandwidth is preferred. Since the integrator is present in either case, there is no longer a proportionality between position error and force (in fact, if the integrator is doing its job, there will be no position error). Accordingly, you might as well tune for a fairly high servo bandwidth. The low bandwidth trick outlined above to enhance force sensitivity does not apply in this case. Note, as well, that the integrator limit should be disabled. Care may be required in high force applications to ensure that the motor and amplifier have adequate force and thermal capacity.

The other case for force measurement is one in which the part is permitted to move in response to the force being measured. In this case, the integrator is disabled, and the choice of a low servo bandwidth enhances force sensitivity, although there will be a potential trade-off between force sensitivity and physical displacement. To measure the applied force, one simply interrogates the servo loop DAC output level, and scales this with the previously calibrated force to DAC counts factor to accurately measure the applied force.

Spring Rate Measurement

There are a number of applications in which the spring rate of a part under test must be determined. Possible examples include keyboard keys, connector contacts, MEMS hinges, etc. As described above, frictionless air bearing stages with direct drive can be very effectively employed in this regard, serving as both the motion axis for the probe, as well as the force transducer itself. Monitoring either the following error or DAC output value vs. time as the spring is approached will reveal the touch point. The servo loop integrator term can be left enabled, with the DAC output value (which is proportional to force) and position monitored as the spring is depressed. If the spring is to be characterized by its force difference for two specific compression distances, then the stage is moved to each of these locations, a delay to allow the position to settle is timed out, and a number of DAC output values are recorded at each location. Averaging a large number of DAC measurements at each location will add a useful “square root of n” noise reduction to the data. The spring rate is then simply the delta in force (proportional to the difference in DAC counts) divided by the delta in position. A more detailed look at the spring characteristics can be derived by collecting position and DAC output data continuously as the stage compresses the spring at constant velocity. Care should be taken to avoid measurements at varying velocities, as the resulting inertial forces may swamp the desired spring-related forces. A more accurate touch point location can also be calculated (if this is of interest) by fitting a straight line to the force (that is, DAC counts) vs. position data, and extrapolating this line backward to the intercept with the zero force level. The slope of this line provides the stiffness, or spring rate. Continuous measurements provide the spring rate as a function of displacement, possibly pointing out non-linear regions of operation to be avoided. The speed of engagement should be sufficiently slow so as to avoid measurement error due to the transient response of the servo loop, or due to inertial forces as the payload is decelerated by the spring. Hardware position capture can also be used to very precisely determine the break and make point in the case of a switch testing application.

Force Generation and Measurement for Vertical Axes

In a number of applications, the axis along which force must be generated or measured will be vertically oriented. In this case, gravity will produce a large force that threatens to swamp the sensitive, vertically directed forces arising from our application. There are several means at our disposal to address this issue. None are as pure as a redirection of the force axis to the horizontal plane, but with proper care, results approaching those of the ideal horizontal case can be achieved. The methods generally include a counter-force that balances the gravitational force. This counter-force can be implemented using pneumatics, springs, or magnetic fields. In the pneumatic case, one can use a precision Pyrex cylinder, undersized graphite piston, precision regulator, and flexural coupling to produce a frictionless counter-force device that is very accurate. Springs can also be used, although their linear region is perhaps 10% of their extended length (restricting their use to fairly short travels), and the resulting spring constant must be measured and taken into account. Finally, magnetic fields can be employed. This is simpler than it seems, and can employ the same linear motor that actuates the stage. The magnetic circuit must be designed in such a way as to allow the stage carriage and payload to be supported without exceeding the motor thermal limit, and coil placement should be considered with an eye to minimizing thermal coupling to the linear encoder. Any resulting thermal expansion of the encoder can degrade the force measurement accuracy. While one can use a DAC offset to bias out the gravitational force using the linear motor, this may reduce the force sensitivity if the gravitational force is much higher than the desired force range in the application. In this case, the servo control can be scaled such that its output range corresponds to the desired force range, with full resolution. An op amp can then be used to sum this voltage with a precision DC offset voltage, the sum being presented to the input of the current amplifier. In this manner, full dynamic range is preserved, while allowing a magnetic counter-force to be employed. Higher precision will result if a dedicated, single phase motor design is chosen, although these motors are best used in fairly short (~20 mm or less) applications.