

MACRO MOTIONS WITH MACRO FLEXURES WITH EMPHASIS ON VACUUM COMPATIBILITY

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INTRODUCTION

An admittedly small sub-set of motion systems require Z motions that are perfectly uniform. These are typically applications in semiconductor wafer metrology, primarily as part of systems that involve optical inspection with active auto-focus, ellipsometry, scatterometry or atomic force microscopy. On the “contact allowed” end of the spectrum lies test probing, die attach and other micro-assembly tasks. A smaller sub-set still are those applications of e-beam metrology and the like.

Usually these applications will involve a coarse motion of 10-15mm for load/unload of wafers, and a short travel, fine motion at high bandwidth for auto-focus of optical elements.

The vast bulk of installed systems use a combination of a wedge Z for the macro moves, and then a piezo flexure stage on top that at some point in the focus range takes its position feedback from the analog signal of an auto-focus detector.

The drawback to attempting the strictest auto-focus requirements with a wedge stage alone lies in the kinematics of reacting wedge forces without perturbations in the X-Y plane, and the flexibility of the bearing that takes this reaction. Add to that the general pain of friction and stiction of linear rolling elements and seals that complicate sub-micron moves, let alone moves in the tens of nanometers. Air bearing implementations can cope with the latter, but at great cost.

The former can be dealt with by geometry, using a balanced, differential wedge like our KAOS XZ style stage; though there are limitations to how low manufacturing tolerances of structure and bearings will allow the roll, pitch and yaw to go. An attainable lower limit for higher production stages would be roughly 8-10 arc-sec. The

latter issues of stiction and friction will still make themselves known.



FIGURE 1. KAOS XZ differential Z wedge.

“MACRO FLEXURES”

This is a brief over-view of a Patent Pending long travel flexure based linear guide bearing. The development of this bearing was performed with metrology and vacuum environment as primary goals of the device, with particular effort spent in making yaw, pitch and roll during vertical linear motions as near zero as possible. The basic idea we call “Macro-Flexure”; one product we build using this method is called “SuperZ”.

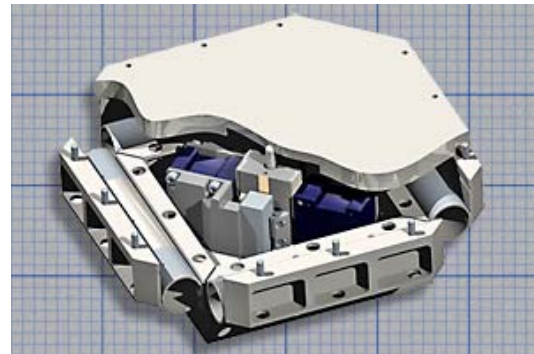


FIGURE 2. SuperZ with NanoMotion drive and Renishaw linear encoder feedback

Why Crack an Arc-second anyway?

Accuracy is all about your error budget. High end encoder scales will allow raw linear accuracies at the sub-micron level. Unless interferometry is used for position feedback at the plane of interest, the bulk of

inaccuracies come from Abbe error, that is, the absolute variation in X, Y and Z at the plane of interest due to the yaw, pitch and roll contribution of all axes. If your Z stage can be “perfect” at reasonable cost, then more error budget can be allowed for the other axes, making their requirements less stringent, and again, lower cost as a result.

Air bearing or crossed roller pillars can have good properties, but are very tall, magnifying Abbe error contributions from the axes below.

What It Is

The Super Z/Macro-Flexure bearing system is a zero back-lash, zero friction linear bearing without rolling elements. With the exception of moment stiffness and overhung load capacity, it has all the advantages of an air-bearing pillar in a previously unattainable package height, and none of the travel limitations of typical flexure stages (usually less than 1mm of travel). Tip and tilt through its travel is limited to an amazing 1 arcsec over its travel range.

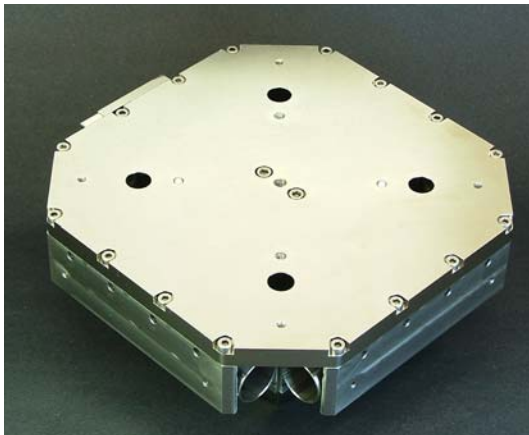


Figure 3. Macro-Flexure SuperZ production unit.

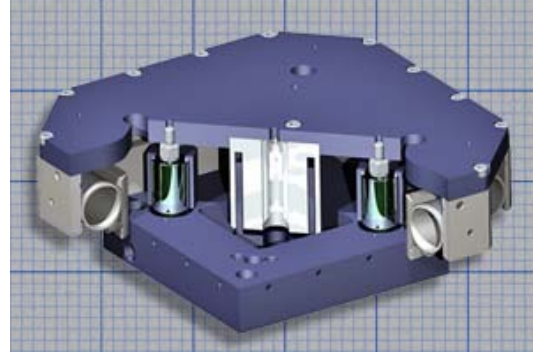


FIGURE 4. Cutaway of SuperZ showing Airpel counterbalance cylinders and voice-coil drive (center).

A 20mm vertical travel is possible in a package that is only 60mm tall, and horizontally traversing guides are possible with greater than 300mm of travel using this method. The bearing can be made from low magnetic permeability or non-magnetic materials, which is of particular interest in e-beam metrology or other charged particle processes.

Motion is constrained to a single degree of freedom by rolling shear members that are quite wide, providing resistance to shear and moment loads, even though they're very thin, 0.003", as an example. A minimum of three flexure sub-assemblies arranged in a closed polygon foot-print provide a single degree of freedom for the payload.

After moment loads are applied, the guide restores itself to flatness perfectly.

Primary features are its low profile nature, negligible particle generation capability and inherent vacuum compatibility. No lubricants or maintenance are required, and it can be supplied with voice-coil, piezo-electric or screw type drives.

What It Is Not

At first glance, the mechanism might seem similar to a marvelous invention of Donald Wilkes' called the "Rolamite".

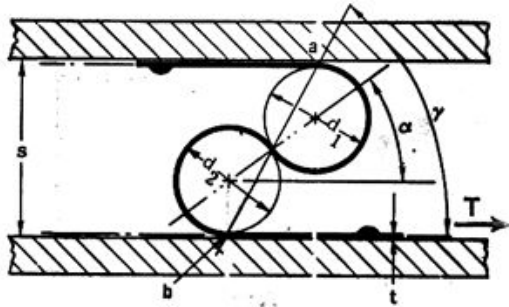


FIGURE 5. Wilkes Rolamite [1]

While the two devices have rolls and bands in common, they differ in the most important ways with respect to precision linear motion.

Both can be arranged in multiple fashion to provide a single degree of freedom. The MacroFlexure though has no actual rolling contacts to perturb motion, and as will be discussed later, is insensitive to a variety of geometric errors in the manufacture of the elements. The bands in a Rolamite, if used as a non load-bearing guide as we do here, will experience motion perturbations due to their lines of rolling contact. Particularly distressing if one wants extreme parallelism between plates maintained is the Rolamites sensitivity to:

- Roundness of the rolls
- Thickness of the bands
- Flatness of the side plates

In a practical sense, it is unrealistic for a Rolamite to be used for precision linear motion, as all flat surfaces and rolls would have to be unrealistically true for it to work well.

The Basic Macro-Flexure Elements

Flexure sub-assemblies can take one of two forms. We'll call them Simplex and Duplex. A common feature to both is an air gap between the roll/band and the guide plates, discussed below.

Flexure bands are laser spot welded to guide plates in a fixture that maintains a uniform tension across the width of the bands, as well as securing the bands to the rolls at points near the limits of travel.

Simplex Flexure



Figure 6. Simplex element, guide plate removed for clarity.

Simplex has a single guide plate adjacent to the roll, and each roll is configured as a spindle.

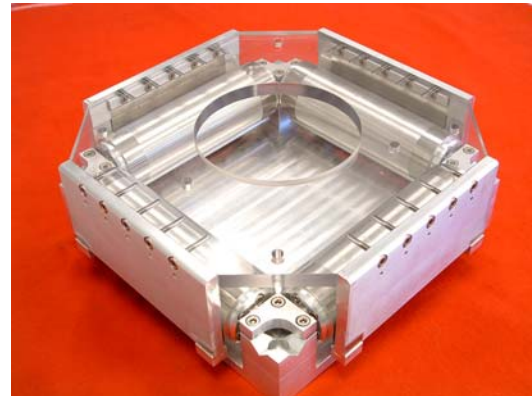


FIGURE 7. A simplex Z stage.

Simplex flexure elements are usable for mechanisms not examined here. The simplex style wrapped band as a rotary to linear force converter has been used for centuries; the difference here being that we are making it quite wide and asking it to act as a rolling shear panel to resist shear and moments in the plane of the bands.

It was determined early on that the downside of the simplex configuration for the strictest linear motion was:

- Sensitivity to roll out-of-roundness
- Sensitivity to roll taper
- Sensitivity to roll centerlines not falling on parallel planes
- Sensitivity to radial bearing run-out

Acceptable results can be obtained from the simplex with reasonable manufacturing processes; e.g., center-less grinding of rolls and providing V-seats for the spindle shafts; however the bearing-less nature of the Duplex style is far more compelling.

Duplex Flexures

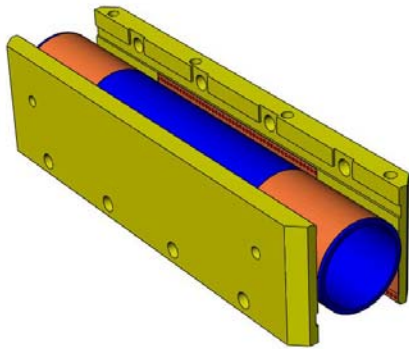


Figure 8. Duplex Flexure Element

Air Gap Examined

As mentioned before, flexure elements have an air gap between rolls/bands and their guide plates.

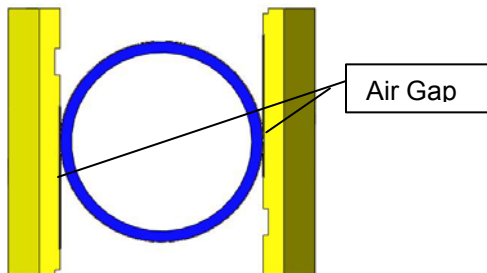


FIGURE 9. Air gaps, typically .003" (.076mm) allow rolls to float.

This feature makes the roll truly float between guide plates and removes high manufacturing tolerance requirements for:

- Side plate flatness
- Perpendicularity of guide plates
- Roll roundness
- Roll taper

There is however a relationship between air gap and shear stiffness of the stage. Shear forces make the rolls "toe in" or "toe out" in response to the force, to the limits of this air gap.



FIGURE 10. Mapping shear stiffness with laser interferometer and force gage.

For most metrology applications in which there are no contact forces, the only concern with lateral stiffness will be the frequency response of the stage and its effect on horizontal stability.

The best roll, pitch and yaw performance is attained when the rolls are truly floating. Yet, as much as 20X greater shear stiffness is possible when the air gap is driven to zero, with the attendant perturbations that come with rolling or intermittently rolling contact. The ideal case for horizontal natural frequency is to have just enough air gap to prevent contact in the travel range.

Oddly, stiffness increases with extension on flexures with an air gap. The flexure element becomes stiffer as the tangent point of the bands approaches their securing laser spot welds on the rolls, effectively increasing resistance to the "toe in/out" of the rolls during shear forces.

Band Preload

All performance metrics were determined with two values of band preload, 26 lbf (116N) and 52 lbf (232N). In general, the doubled preload translated into roughly 50% higher moment and shear stiffness.

Strictly speaking, any system with N number of flexure units can be over-constrained, but reasonable machining tolerances and proper laser weld fixturing are such that assembled misalignments can be kept within the elastic limits of the flexures and their preload value.

Performance in Brief

The depicted SuperZ unit has the following properties (ranges are for up vs. down):

Shear Stiffness	.7-1.1 $\mu\text{m}/\text{N}$
Moment Stiffness	4-5 arc-sec/N-m
Yaw, Pitch and Roll	1 arc-sec
Friction	Zero
Vertical Stability and Repeatability	25nm

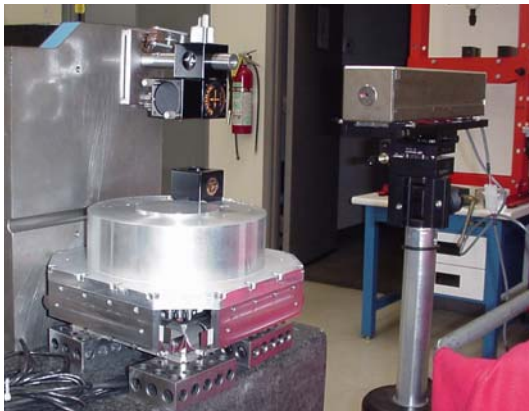


FIGURE 11. Interferometry set-up with payload simulator.

Friction in a classical sense is zero, however there are some losses owing to the hysteresis in the flexure bands, manifesting itself as damping behavior. This makes for a nice situation; nanometer moves can be made as with a frictionless system, yet the stage will remain where it is on power-off, and counter-balance setting is allowed some range of imperfection.

Stability and repeatability cited was performed with a Delta Tau PMAC Turbo with 4096X interpolation of a Renishaw (20 μm pitch) analog encoder (4.8nm

effective resolution), Trust Automation linear amplifier and Renishaw interferometer.

Materials

The unit depicted in this report has flexure elements that are all 304 stainless steel. High vacuum E-beam applications may require all guide elements to be made of Titanium. No changes other than material selection are required.

Counter-Balancing

Counter-balancing for vertical axes in an atmosphere is handled by Airpel style graphite piston pneumatic cylinders with a fast acting regulator, in order to make the payload neutrally buoyant, with an acceptably linear force. This is particularly important when using voice-coil actuators or when attempting high bandwidth corrective or auto-focus moves using piezo drives. Vacuum applications would require a low constant spring or spring/cam, or physical counter weight. Counterweight issues are of course largely unnecessary when using a screw drive.

Size Limitations

Large scale horizontal motions are possible, on the order of 300mm plus, again with an eye toward semiconductor wafer positioning in vacuum or atmosphere. Scan stages for Atomic Force Microscopy or Stylus Profilometry could allow full wafer width line scans.

Units with horizontal motion exhibiting pitch, roll and yaw performance in the sub arc-second regime are envisioned, all without lubrication, rolling contact, rubbing elements, air bearings, or magnetic fields.

Keywords: flexure, frictionless bearings, air bearings, voice-coils, vacuum bearings, metrology stages, Z stages

References:

1. Walton, H., March 1966, Frictionless Machines from Rollers & Bands, *Popular Science*.