Invited paper

Kinematic and Elastically Averaged Joints: Connecting the Past, Present and Future

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Abstract – Exactly constrained mechanisms provide precision, robustness, and certainty of location and design. Kinematic couplings exactly constrain six degrees of freedom between two parts and hence closed-form equations can be written to deterministically predict the structural performance of the coupling. They can also be made active to provide fine positioning and have only just begun to enable a new generation of very high performance machines to be realized. Elastically averaged joints can provide the same type of performance but with the added benefit of higher stiffness and greater load capacity in a small space; although, analyses of their design is much more complex, their use is expected to increase as design analysis models advance.

***Key Words*:** Kinematic, elastic average, interfaces, couplings, servo control

1. Introduction.

Kinematic couplings provide exact constraint because they use six known contact points to locate one component with respect to another. They have long been known to provide an economical and dependable method for attaining high repeatability in fixtures [1-9] and helping to reduce design and manufacturing costs. On the other hand, contact stresses are often very high and no lubrication layer remains between the elements that are in point contact. For high-cycle applications it is advantageous to have the contact surfaces made from corrosion-resistant materials (e.g., stainless steels, carbides, or ceramic materials). When non-stainless steel components are used, one must be wary of fretting at the contact interfaces, so steel couplings should only be used for low-cycle applications. Less well known are dynamic kinematic couplings, which allow for servo controlled fine motion [10-13].

Elastically averaged joints support a system at many points, thus preventing large deformations sometimes associated with supporting a system at only a few points. Many machine components are made far more accurate than any of their components by elastic averaging: Hirth or Curvic couplings use essentially two face gears that are forced together to allow one surface to be indexed with respect to another and achieve an accuracy (number of gear teeth)$^{1/2}$ better than either gear itself, because of the high forces used to preload the gears together Spline-type flexible couplings can eliminate backlash if their elements radially flex to create a preload effect [14]. Of particular interest for the future is the ability of elastically averaged joints to be used in semiconductor systems and devices [15].

2. Servo controlled kinematic coupling alignment system

One example of a successful kinematic interface used in industry is the Perfect Dock™ system developed by Teradyne, Inc. in the late 1990's to provide a robust and accurate and reconfigurable interface between their semiconductor Automatic Test Equipment (ATE) and a wide variety of material handling equipment, including wafer probing stations and package handlers. At the time, state of the art bond pad pitches were 40 microns and advanced microprocessors might have in excess of 5000 electrical connections distributed along the periphery of a 1 cm^2 die. In volume test applications, multiple die may be tested in parallel at typical rates of once/second.

Because of the batch-process nature of volume semiconductor test and packaging manufacturing; equipment is reconfigured and tooling changed at least once per shift by operators who often have little training or education. Contemporary solutions typically used pin and bushing interfaces with manually actuated cam-clamps to lock two sides of the interface; either to align tooling to tester or between two pieces of equipment. The non-repeatability of this design could result in poor gage reliability, damaged tooling and lost yield. Figure 1 shows a typical image of probe needles with a tip diameter of approximately 40 um, and die bond pads with needle scrub marks.

Teradyne developed a reconfigurable interface based on kinematic couplings using modular ball and groove components that also integrated latching, preload, error sensing and alignment [11]. Each module consists of a single ball-groove couple, with two contact points on hardened, gothic-arch ground and polished surfaces to increase contact area and stiffness. Grooves were typically pinned and bolted to the handling equipment on a single plane and balls mounted on the tester. The position of each ball was adjustable in translational 3 axes. Other surfaces of the ball and groove were shaped to help guide them to safely final position while minimizing risk of damage or binding as the tester can weigh more than 500kg and be constrained by a large cable bundle.

Figure 2 shows an example of a single ball-groove couple. Note the outer diameter of the ball has a hardened rim and recess that engages raised walls on the groove. Prior to reaching its final position, this rim-wall interface constraints the motion of the tester to +/- 1mm, and thus reducing the lateral motions during the final compression of electrical connectors. Figure 2 also shows the final version of the production system with covers removed. This version includes a latching pin through the center of the ball that locks to a floating washer in the groove. A DC servo motor and leadscrew are used to apply a fixed preload force and sensors can detect whether the system was accurately latched.

The above production systems allow only 'static adjustments', i.e. the final position can be set using a fixture or adjusted in the field by a technician, but there is otherwise no closed-loop, adjustment possible. Aversion with 3 z-axis actuators was also developed that allowed z-axis motion and planarization in the roll and pitch axes. This is useful in probe applications where the prober has the ability to move in the translational and yaw axes. Figure 3 shows an early version of this system.

For most applications, the required accuracy is determined by the mating geometry of a spring-pin (pogo pin) electrical connector and it's mating pad. The budgeted tolerance for this mate is typically 40-200um, though some specialized applications may require <40um repeatability. Test systems typically had large cable bundles, up to 16" in diameter, for power, signals, and cooling, that also apply large lateral and rotational loads on the tester. Field tests were performed with repeatability results well within the required specification, both as a free body and under expected loads, as shown in Table 1.

The Perfect Dock system was applied to the portfolio of Teradyne test platforms and continues to be used today, with many thousands of systems in the field. Furthermore, the general concept of modular kinematic interfaces for macro-docking applications has since gained broad acceptance in the ATE industry and multiple versions of this system have been adopted by competitors.

The challenges of the test industry continue to grow and thus do the opportunities for high repeatability kinematic interfaces. For example, massively parallel testing of memories requires repeatable positioning of high density probe cards and emerging array camera technology will methods to achieve accurate and repeatable positioning of multiple lenses and image sensors during assembly and tests. Modular kinematic interfaces offer a robust and easy to apply solution to reconfigurable and repeatable interfacing of manufacturing equipment.

3. Servo controlled kinematic coupling for advanced machine tools

Next generation precision machines will require ever more rigid elements to achieve the required machining tolerances, yet will require small adjustable alignments [16]. The fundamental importance of these ultra stiff, adjustable machine elements is demonstrated in the design of a grinding machine for 450mm diameter silicon wafers. A new generation of silicon wafer grinding machines is needed to back-grind large (450mm diameter) wafers from the production thickness of up to 1mm down to less than 50μm so as to reduce the cost of Si-wafer based components. The grinding process needs to be done in about 90sec (fine-grinding, e.g. -200micron) to 160sec (coarse grinding, e.g. -600micron). After completion of the fine grinding process the wafer must be flat to 0.1 μ m/□45mm and parallel to 0.6 μ m/450mm diameter. The surface roughness must be less than Rymax 0.1 μ m and Ra 0.01 μ m. Even though the required machining forces are <10N, the machine must be extremely rigid in order to achieve the necessary surface quality with a reasonable grinding feed-rate. Assuming a feed-rate of 5m/min and a total allowable error motion of 5nm, a stiffness of >1N/nm is required, which is many times stiffer than a typical machine tool (0.1 to 0.3N/nm).

In cooperation with industry, this work had the aim of creating a new machine design philosophy, with an example application that focuses on nano- adjustable kinematic couplings and feedback controlled water hydrostatic bearing technology. This new design philosophy is needed to enable the design of a relatively small footprint, compact precision machine shown in Figure 4 [17, 18].

In particular, a ball screw preloaded height adjustable kinematic coupling and a magnetically preloaded hydrostatic thrust bearing were designed and built. The adjustable kinematic coupling allows for up to 8mm of vertical height adjust and 7N/nm stiffness at 26kN preload. By varying the preload on the coupling by +/- 10%, in-process nm to micron height and tilt adjustment at >95% of the nominal stiffness is possible.

Under the assumption of a constant flow supply, the hydrostatic bearing achieves a theoretical stiffness of 1N/nm at a 20micron bearing gap and 7000N combined gravitational and magnetic preload. In practice, the stiffness is limited by the pressure flow characteristics of the supplying pumps. To increase the bearing stiffness to a required 4N/ nm, various control loops have been developed and tested, although we find that there is much room for more advanced pump/control system development [19].

4. Elastic averaging based thermocentric fixturing

Probe cards are used to test semiconductor die and are composed of ~3,000 to 80,000 probes that provide electrical signals from a tester to chips on a wafer to test the functionality and determine subsequent yield of the wafer manufacturing process. One of the main constraints is the Interposer pitch. The role of the interposer is to provide electrical interconnection from the Printed Circuit Board (PCB) to the Space Transformer (SxF). The smaller the interposer pitch, the more signals that can be sent from the PCB to the SxF.

The challenge is to make sure that 60,000-80,000 interposers make connection to electrical pads on the PCB and the SxF. The connections must be reliable, for the life of the probe card as it is thermally cycled over a wide temperature range: from -40°C to 150°C. The native machining tolerances in the PCB or SxF can not provide sufficient accuracy and therefore it was decided to use an elastically averaged connection such as described in [15], but applied to PCB manufacturing.

As shown in Figure 5, posts were added to a PCB and flexure slots to the SxF. The flexure slots provide radial degrees of freedom for differential thermal expansion between the PCB and SxF. The flexure slots also have lateral stiffness and are designed to provide alignment between the parts and lateral stiffness. The accuracy of location is about the accuracy of any post/slot pair divided by the square root of the number of posts/slots.

The solution was implemented on Formfactor Inc.'s SmartMatrix™ and TouchMatrix™ probe card products that are used to test semiconductor chips. Alignment accuracy is <50μm and Alignment Repeatability is <2μm. The cards can be assembled quite easily, without special tooling, therefore enabling field repair. Furthermore, this solution has enabled us to reduce interposer pitch by a factor of 2; thereby providing 4x the number of signals per area compared to previous solutions. This allows for an increase in test parallelism and enhances customer's manufacturing throughput.

5. Conclusions

There are many applications of deterministic design that can be found in the use of kinematic couplings and their reciprocal, elastically averaged interfaces. The key is to keep an open mind and try both options to find the best solution to use for a given problem (opportunity).

6. References

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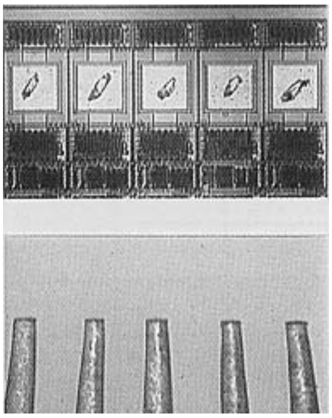

Figure 1: Bond pads and probe needles

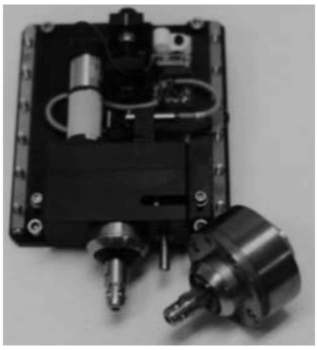

Figure 2: Z axis servo controlled cinematic coupling unit

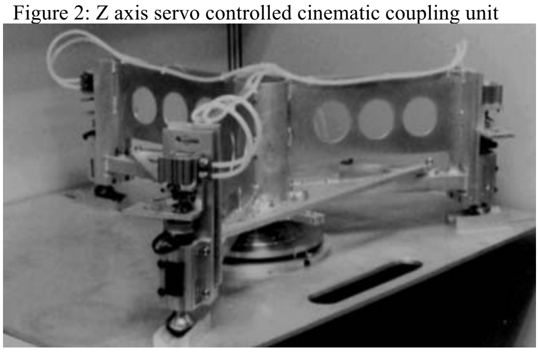

Figure 3: “Perfect Dock” three Z axis servo controlled cinematic coupling units for adjusting height and tilt

Figure 4: Servo kinematic coupling height and tilt adjustable wafer grinding machine.

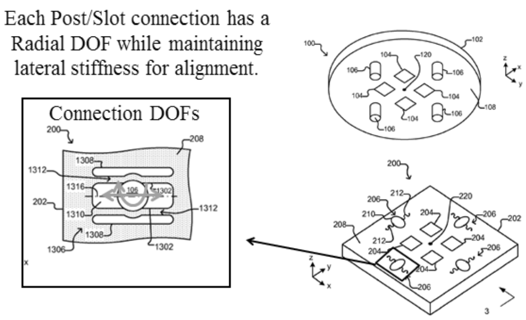

Figure 5: elastic slots and pins used in multitude for thermocentric design

Table 1: Perfect Dock adjustable kinematic coupling test results

Condition	X (in.)	Y (in.)	Z (in.)	θx (arc-sec)	θy (arc-sec)	θz (arc-sec)
No external loads	.0004	.0002	.0002	2	2	2
Side Cable Load	.0006	.0014	.0006	13	13	27
Longitudinal Cable Load	.0032	.0019	.0019	25	40	14
Vertical Cable Load	.0027	.0006	.0009	16	11	16