Design of ultraprecision modular, Freeform® machine tool

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Abstract

The Freeform® 3000 ultra precision machine tool has been developed to satisfy a need for a unified affordable multi-axis machine with the capability of milling, grinding and turning ultra precision surfaces. Demand for a universal ultra-precision machine emerges from developments in grinding and milling conformal optics, lens arrays, grooved patterns and diamond turning. This paper discusses the design challenges of the Freeform® 3000 machine and the culmination of enabling technologies. The final machine configuration was determined by evaluating precision, stiffness and modularity. Ultra precision machine elements have been reinvented to accommodate the new configuration. Finite element models were used to evaluate static and dynamic performance of machine components. A steady state thermal analysis of the machine has been compiled which pinpointed areas for thermal error reduction. A thermal environment has been created to hold the machine temperature stable to less than ±.05 C°(.1 F°). Cutting tests display that the machine is appropriate for milling three dimensional forms, diamond turning axis-symmetric components and grinding in a flood-cooled environment.

Configuration

Several machine configurations have been evaluated for the following criteria: Flood coolant compatible, commonality of parts, ease of build, ability to single point diamond turn, ability to diamond mill, and modularity. It is common to think of machine configurations in a conventional manner, however this can lead the ultra-precision designer down the wrong path. Fundamental to ultra-precision machine design is that relative motion between moving elements be facilitated by a fluid film and be free of contact. The fluid film provides an averaging effect, which in turn produces straightness and truth-of-motion in excess of the individual elements. Contact between moving elements through a seal or service loop produces undesirable forces and error motion. Sealing slides from machining debris must be facilitated through the use of non-contacting labyrinths. Service loops must be supple and the number of cables minimized when ever possible. Finally, cables must be bundled in a manner to provide a neutral axis that remains parallel throughout the slide travel.
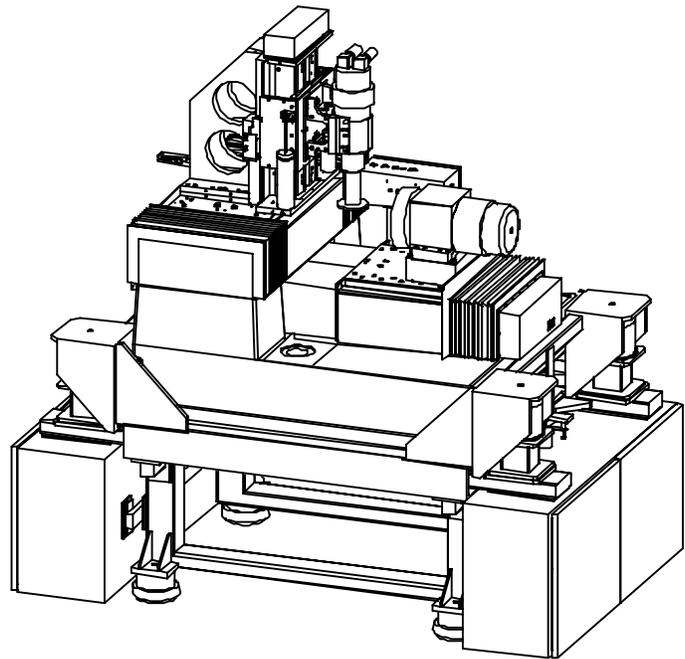

Figure-1
Freeform®-3000 machine
Guards and covers removed

To produce three axes of motion, at least one axis must be mounted onto another. However, if the moving slide way causes a transfer of mass, then a compromise in slide straightness will result. The Freeform® 3000 was designed with a 150 mm vertical slide mounted onto a 350 mm horizontal slide and a third 250 mm horizontal slide mounts orthogonal to the other two slides to produce the final axis of motion. During the conceptual phase of the Freeform® 3000, it was determined that a non-contacting bulkhead design would separate the cutting process from the combination slideways, to provide isolation for flood coolant[1].

The Freeform® 3000 is based on a modular design. The machine base, oil hydrostatic box slides, frame, electrical and pneumatic cabinets were designed to be common for a family of three separate machine tools, Nanoform® 350, Nanoform® 700 and the Freeform® 3000. The common modular design facilitates economies of scale for the components and an ability to build up the machine subassemblies to a level and then quickly react to customer demands.

Machine Elements

All three linear slideways utilize oil hydrostatic pads, at a supply pressure of 250 psi, and linear motors to produce ultra-precision contouring and positioning. Hydrostatic "box type" slide ways were chosen in each axis for their stiffness and ability to provide straight slide travel.

A small high stiffness vertical slide was developed to mount onto a horizontal axis via an angle bracket. Emphasis for the vertical slide design was placed on reducing the moving mass, which would enable the servo bandwidth to remain high. Several counterbalance design concepts were evaluated for their ability to produce a neutralizing force, be non-influencing, convenient and inexpensive. A counter-balance air piston was chosen because it would <u>not</u> contribute a significant amount of inertia. Other frictionless designs such as a cable mass counterbalance double the moving mass and create a second order harmonic. Finally, the air piston counterbalance would be convenient and inexpensive to implement.

A standard commercially available cylinder was initially used which was rated for a frictional force equal to 1-2% of applied load. During implementation of the cylinders on the vertical slide, it was found that the friction produced an undesirable slide error. Several efforts to reduce the friction resulted in a design of a non-contacting aerostatic piston that was non-influencing[2] (Figure 2).

To avoid reversal error and hysteresis, a design was employed which provides constant pressure to the air piston. The system includes a precision regulator, which maintains constant pressure to a bleed valve. The bleed valve allows an excess of 10 times the volume displaced by the maximum traverse rate, to be exhausted to the environment (Figure-3). The
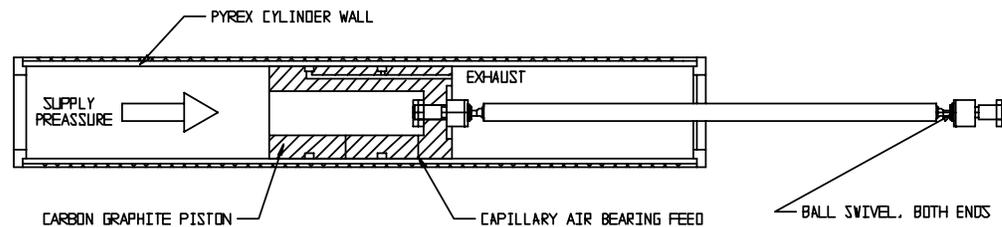

Figure-2
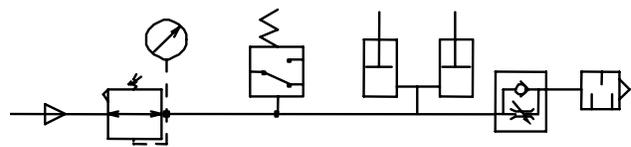**Frictionless air piston counter balance**

Figure-3
Counterbalance air piston schematic

[1] Alexander H. Slocum, "Precision Machine Design", Prentice Hall, 1992, P.
[2] Julius C. Boonshaft, U.S. Patent No. 3,319,534, 1967

constant non-reversing flow through the system reduces variations in force as a function of slide travel direction.

The new generation of lens and reflector elements is the free form surface shape, that has no axis of revolution but is instead a surface shape that could be defined by a map of points, an equation, or a computer model represented in solid form[3]. Freeform components require part cuts of up to several days and complete thermal stabilization. The Freeform® 3000 required a thermal enclosure and temperature controller which produced an environment within ±.05 C°(.1 F°)(Figure-4). Key machine elements such as the spindle riser and flycutter wheel were manufactured with Invar-36, a low coefficient of expansion nickel based alloy.
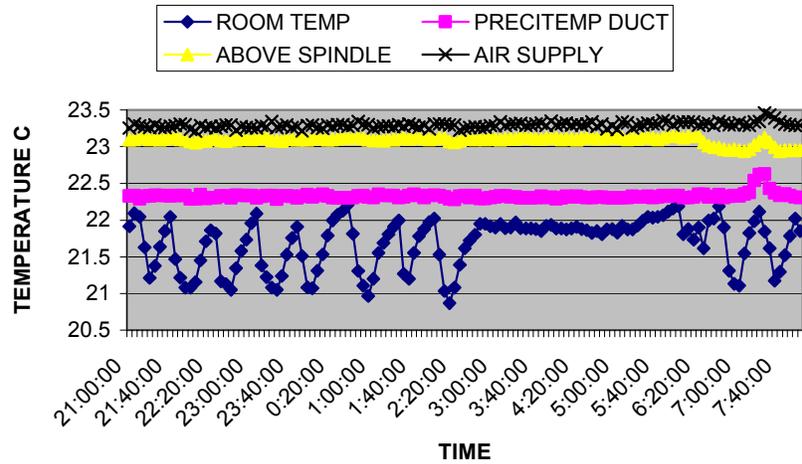
Figure-4
10 Hr machine temperature stability chart

With a diamond tool holder mounted onto the milling spindle riser (Figure-5) and a spindle mounted onto the horizontal slide, the Freeform® 3000 can be configured as a lathe. A tool holder design was evaluated using finite element analysis for stiffness and modes of vibration. Base line design parameters derived from a known diamond turning lathe have a stiffness greater than 150,000 lbs/in and first mode of vibration greater than 700 Hz. Several iterations were required to produce a tool holder, which met these criteria and still maintained a small moving mass. (Figure-6).
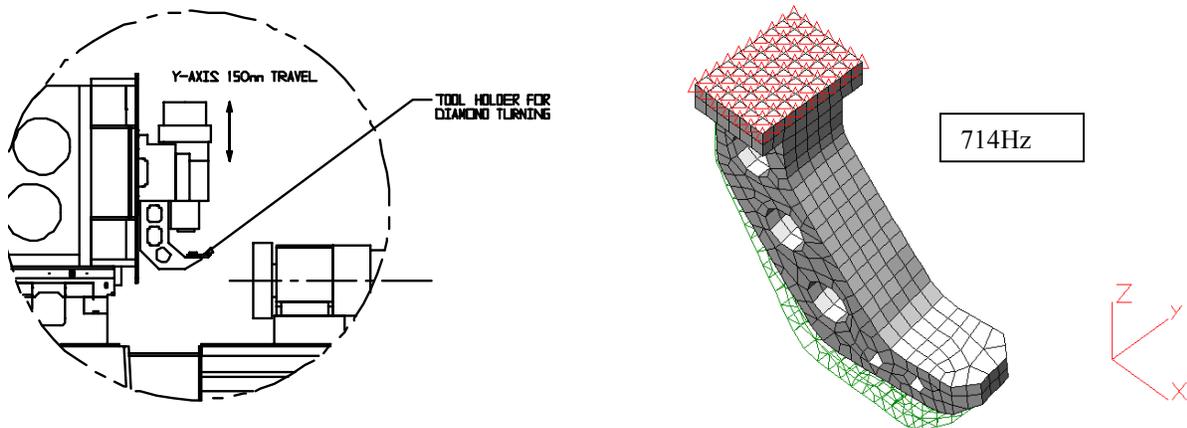
Y-AXIS 150mm TRAVEL

TOOL HOLDER FOR DIAMOND TURNING

714Hz

Figure-6
Tool holder for diamond turning

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[3] P.D.Brehm, The Single Point Diamond Machining of Optical Microstructures and Freeform Surfaces, Euspen Conference Proceedings, Vol. 2, 1999

Machining Results

Diamond milled surfaces have been generated to a form accuracy of 0.204 μm per 1500 mm^2 in an 8-hr cycle with a surface finish of 15 nm RMS. Diamond turned surfaces have been created to a form accuracy of .057 μm P-V with a surface finish of 3nm on a Ø 75mm (250mm convex radius) spherical aluminum part. Peripheral ground parts have been generated to a form accuracy of .214 μm and a surface finish of 4.4 nm RMS. A repeatability test displayed that freeform parts can be created consistently in a 2.5 hr cutting test. Total variation for five part cuts, was 0.038 um P-V.

Surface finish for freeform machining is defined by the cusp height of the interrupted cut. Thermal stability of the machine is required for long part cuts. Surface finish can be predicted using the following equations:
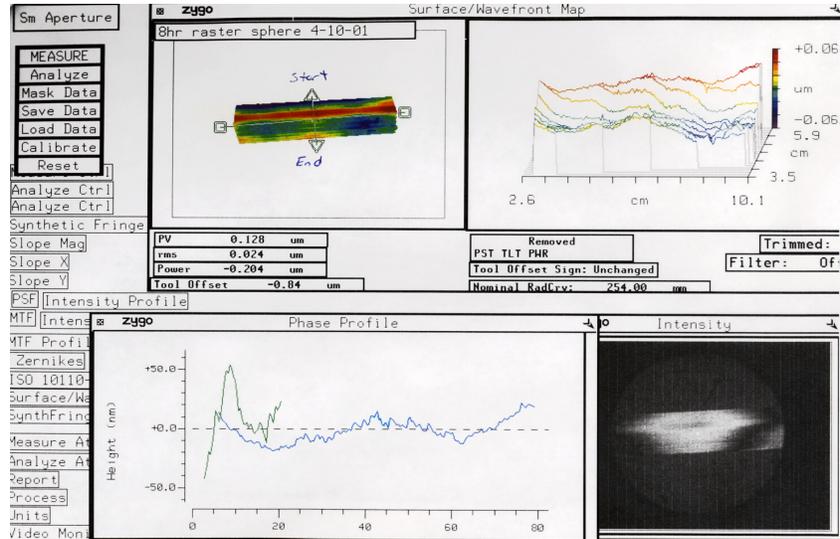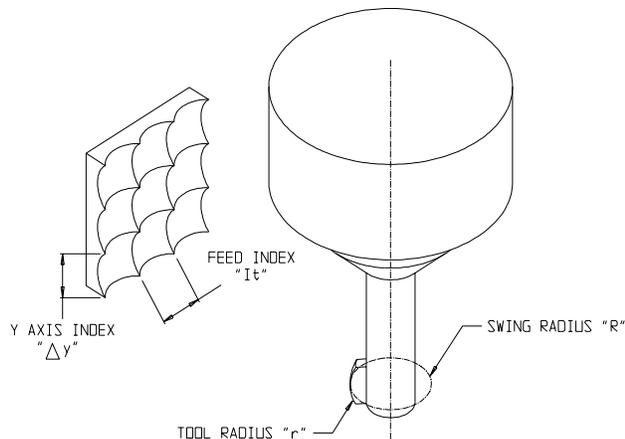

Figure-8
Freeform Cutting results

Cusp height in X feed direction.

$$Hcx := R - \frac{1}{2} \cdot \sqrt{4 \cdot R^2 - \left(\frac{Fx}{S}\right)^2}$$

$$Hcx = 5 \cdot 10^{-6} \cdot mm$$

Index (Δy) so that index cusp matches feed cusp.

$$\Delta y := 2 \cdot \sqrt{Hcx \cdot (2 \cdot r - Hcx)}$$

$$\Delta y = 0.014 \cdot mm$$

Tool Advance:

$$It := \frac{Fx}{S}$$

$$It = 0.014 \text{ mm/rev}$$

Surface finish (rms)

$$Rq := \sqrt{\frac{It^4}{720 \cdot R^2} + \frac{\Delta y^4}{720 \cdot r^2}}$$

$$Rq = 2.09 \cdot 10^{-9} \text{ rms}$$

Figure-9
Cusp height definition

Conclusion

The Freeform® 3000 establishes an ultra precision diamond machining platform which is versatile in configuration, thermally stable, and easy to operate. The machine has been developed to meet the need for conformal freeform optics, lens arrays and grating patterns, while maintaining utility as a turning/grinding platform. Precision engineering disciplines have been applied to produce a cost-effective robust design. Machining results have produced components that exceed initial expectations.