THE DEVELOPMENT OF MACHINE COMPONENTS WITH NANOMETER CAPABILITIES

By

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Machine components designed with the goal of achieving accuracies on the order of nanometers must be simple in form and constructed of stable materials. The design must take into account even seemingly minor, second order effects of forces generated during the normal functioning of the device. Environmental conditions must be recognized and taken into account.

Material selection

The machine slide which I will describe today is such a device. Care has been taken that the critical components are simple shapes which are easy to manufacture. The materials used include cryogenically stabilized tool steel and pearlitic iron; both are materials whose properties and stability are well known.

Slide base

Designing a machine slide as a stand-alone component requires that special attention be paid to the rigidity of the slide sub base so that the accuracy of the mechanism will not be degraded by stresses imposed on the assembly when it is handled after it has been assembled and tested. The base of our slide is machined from continuously cast, iron bar stock. It is designed so that all longtitudinal milling cuts extend completely through the part. The base is unusually thick to withstand the strains placed on it during handling. Machined surfaces provide the operating surfaces for the hydrostatic support bearings, the mounting surfaces for the guide ways, and the mounting surfaces for the ball ways which carry an intermediate slide.

Way design

The hydrostatic ways are located so that the preload forces generated by their operation are either trapped in a single member or, in the case of the ways themselves, operate in opposing directions so that they tend to minimize the deflections which they cause. This design follows the general design of the Colath lathes produced by Philips. By examining figure 1, you can see that this design leaves the slide itself completely free of stresses caused by the operation of the ways. The slide top and the support bearings are made of pearlitic cast iron.

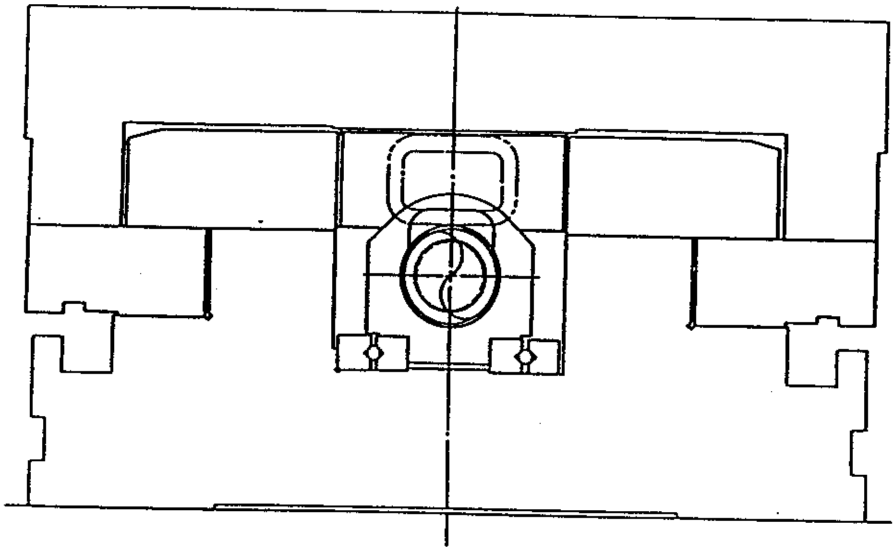


Figure 1

Guide bearing

Extending downwards from the slide top into the gap between the guide ways is the guide bearing. This critical part has, machined into its opposing surfaces, the recesses which form the hydrostatic guide bearings. On one end face, this member has an hydrostatic oil restrictor pin, which supplies metered oil to one half of the hydrostatic thrust bearing, which couples the slide to the intermediate slide. The other end of the guide bearing has provisions for mounting the mirror, or mirrors required for laser interferometric position feedback.

Guide ways

The guide ways themselves are made of A6 tool steel. They are stress relieved and cryogenically stabilized. The geometry of these two parts is crucial to the performance of the slide. The lower and inner surfaces of the guide ways must be flat, and as straight as it is physically possible to make them. In addition the two surfaces must have a fine surface finish and be square to one another within 2.5 microns. Hydrostatic bearings are effective in masking short wavelength disturbances in the straightness of the ways, but disturbances longer than about 25 mm will not be completely eliminated. One secret to success is to grind the opposing surfaces of the guide ways (The vertical surfaces) simultaneously, side by side on the way grinder with the mounting surfaces either facing or opposing each other. In this way, the two guide surfaces, when mounted in position, will have equal and opposite deviations from straight. When the hydrostatic bearings follow ways ground in this manner, they will tend to equalize the clearances on each side of the guide bearing thus cancelling, to a large degree, the error in straightness caused by the way grinder.

Intermediate slide

The intermediate slide carries the ball nut. It also carries a pair of hydrostatic thrust bearings, which transmit the thrust from the ball nut to the main slide. Runout between the ball screw pitch diameter and the ball screw bearing mounting diameters can cause errors in straightness which are cyclic with the ball screw rotation. The intermediate slide prevents these disturbances from affecting the accuracy of the slide

Reaction forces

The cyclic reaction forces caused by ball screw errors can, however, cause the way system itself to deform; therefore they must be minimized, even though the intermediate slide is used. One way of achieving this is to use a ball screw that is about 50 mm longer than required to obtain the desired stroke. By holding the ball nut away from the lead screw support bearings, the forces generated by bearing misalignment are minimized. This results in improved slide straightness.

Optimization

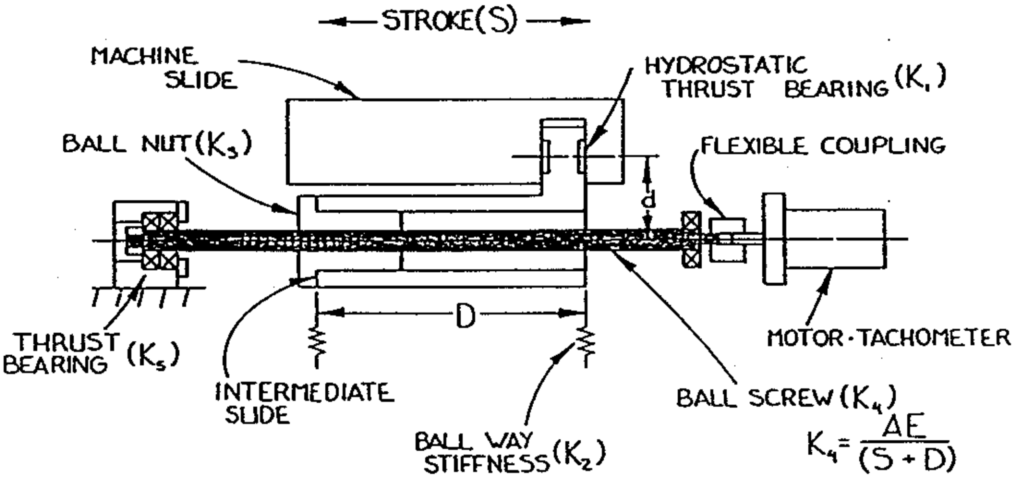
There is an optimum length for the intermediate slide. Figure 2 illustrates schematically the slide and its associated translation mechanism. It can be seen that, if the intermediate slide is too short, its resistance to the overturning moment in pitch is diminished whereas, if it is longer than necessary, the system rigidity is reduced by the compliance associated with an overly long ball screw. Figure 3 shows the formula for optimizing the intermediate slide length, and also indicates the general shape of the length versus stiffness curve.

Ball screw details

One should note that, in this design, the ball screw thrust bearings are located at the end of the screw away from the servo motor. The ball nut is located at the end of the intermediate slide away from the motor. This was done to maximize the rigidity of the slide when it is farthest away from the motor. The reasoning for this is that, in most cases the motors are located away from the area of the machine where metal cutting takes place, and therefore the longtitudinal rigidity of the slide should be maximum at the end of its travel nearest to the cutting area.

Bearing design

The hydrostatic bearings used to support and guide this slide are designed for maximum rigidity. They are also designed to consume the smallest possible volume of oil consistent with good design practice. A low flow rate through the bearings implies that a great deal of power is not needed to pump the working fluid. In general our hydrostatic bearings do not require heat exchangers to control the oil temperature as the oil resides in the supply lines long enough to dissipate any temperature increase into the local environment.



$$K_{\text{SYSTEM}} = \frac{1}{\frac{1}{K_1} + \frac{2d^2}{D^2 K_2} + \frac{1}{K_3} + \frac{(S+D)}{AE} + \frac{1}{K_5}}$$

Figure 2

Operating fluid

The oil used as the working fluid is a low viscosity spindle oil. It was chosen to minimize hydrodynamic effects which occur during rapid positioning moves and cause changes in the slide position which decay over the first few seconds after the slide has stopped moving. The use of a low viscosity fluid works counter to our desire to keep the flow rate low, but engineering often involves compromises, in fact engineering is the art of making appropriate compromises.

$$K_{SYSTEM} = \frac{1}{\frac{1}{K_1} + \frac{2d^2}{D^2 K_2} + \frac{1}{K_3} + \frac{(S+D)}{AE} + \frac{1}{K_5}}$$

IS MAXIMIZED WHEN

$$D = \sqrt[3]{\frac{4AEd^2}{K_2}}$$

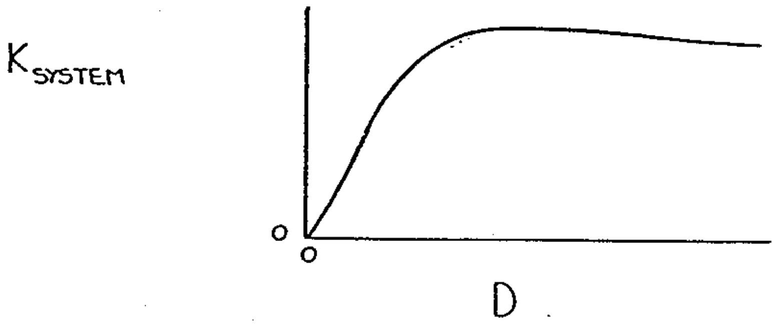


Figure 3

Restrictor design

Our bearings use laminar flow restrictors, which operate like capillary tubes. Figure 4 illustrates the design of these restrictors. To manufacture a restrictor, a cylindrical pin is held in a vice while a flat is ground parallel to its' axis. The depth of the flat and its length, as well as the diameter of the pin, determine the resistance to fluid flow.

Operating pressure and flow

The bearings operate at a pressure of 17 bar. The pressure in the recesses is 50% of the supply pressure. Oil flows thru the bearings at 152 cc/min (total for all recesses). The bearing clearance is 12 microns.

Positioning tests

Positioning tests were done on the completed slide using an ADE Microsense probe for data acquisition. The positioning loop was closed by a laser interferometer with a resolution of 2.54 nanometers. Figure 5 shows the results of a series of moves which include several direction reversals.

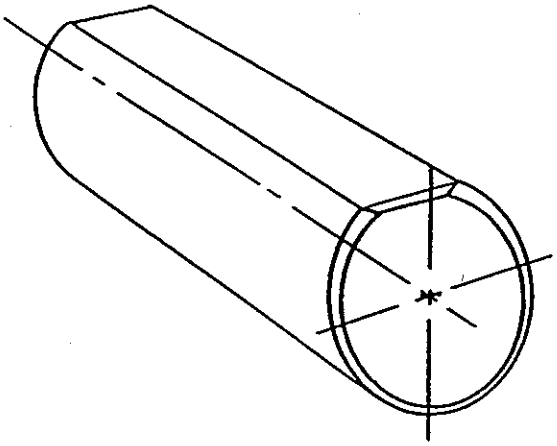


Figure 4

SUMMARY OF TEST SLIDE PERFORMANCE

Characteristic	Measured value
Horizontal stiffness	890 N/micron
Vertical stiffness	950 N/micron
Longtitudinal stiffness	123 N/micron
Horizontal straightness	0.09 micron
Vertical straightness	0.11 micron
Roll	0.3 arc sec
Pitch	0.35 arc sec
Yaw	N. A.
Longtitudinal Fn	155 Hz
Mass of moving parts	128 Kg
Dimensions of slide top, L x W	460 X 380 mm

Table 1

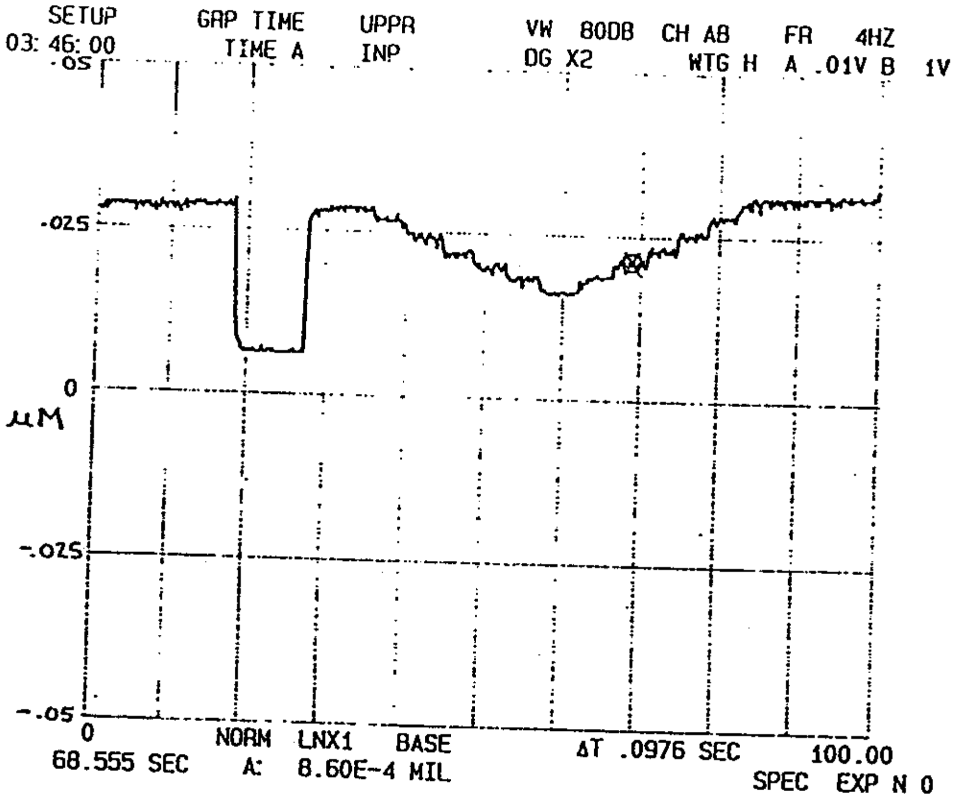


Figure 5

Conclusions

By careful attention to detail, a high degree of accuracy can be obtained from modular machine components which can be used to construct machines with nanometer accuracies.