THE DESIGN AND CONSTRUCTION OF A SUB-MICROINCH RESOLUTION LATHE

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For Presentation at the

International Conference
on
Ultraprecision in Manufacturing Technology

May 19-20, 1988

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INTRODUCTION

In an effort to further improve the performance of our diamond turning and grinding machines, Rank Pneumo has been pursuing the development of machine slides which are capable of extreme accuracy. Our success with these slides has led us to the design of a lathe with feedback resolution of Ø.Ø5 microinches (1.27 nm). The design of this machine represents a substantial departure from the design of earlier diamond turning equipment produced by Rank Pneumo.

REASONING

Over the past several years we have received several requests for quotations for the construction of machines with sub micro inch (SMI) resolution. The usual reason cited for needing this resolution is that it allows the compensation of machine and process errors in increments which are too small to be visible in the finish machined surface. Increased resolution reduces the amplitude of the servo "hunting" that goes on when an axis is maintaining a fixed position, and therefore it will make it possible to machine better flat surfaces on two axis machines. Users of diamond turning are serious about SMI equipment and someone is going to fill their requirements. Increased resolution, coupled with our improved hydrostatic slides and newly designed spindle will help make the next generation diamond turning machines capable of day to day performance at a level that can only be achieved with patience and luck using today's machines.

RESOLUTION AND ACCURACY

Increasing the resolution of a machine's servo systems will improve its repeatability provided that the system dynamics are good enough to allow it to achieve its commanded position within a few "counts" of its feedback device. Increasing resolution does not improve the accuracy of the system. A machinists scale that is a millimeter too short is not accurate no matter how fine the graduations. Accuracy is achieved by controlling, or compensating for, the machine geometry and environment (temperature, pressure, and humidity) and accurately knowing the length of our "yardstick" which is the wavelength of the light used in the interferometers. SMI resolution does allow us to command the machine to move in increments which are so small as to be insignificant on the surface of the work piece.

MACHINE DESIGN

Figure 1 illustrates the general design of the new lathe. The spindle is located on the X axis which is mounted on risers so that it spans the Z axis. This arrangement allows the use of hard, non-telescoping way covers which do not influence the slide accuracy and are capable of withstanding a copious flood of coolant. The differing heights of the slide tops provides space for increased swing capacity or a rotary third axis. A large granite block mounted on a self leveling air suspension system forms the supporting structure beneath the slides.

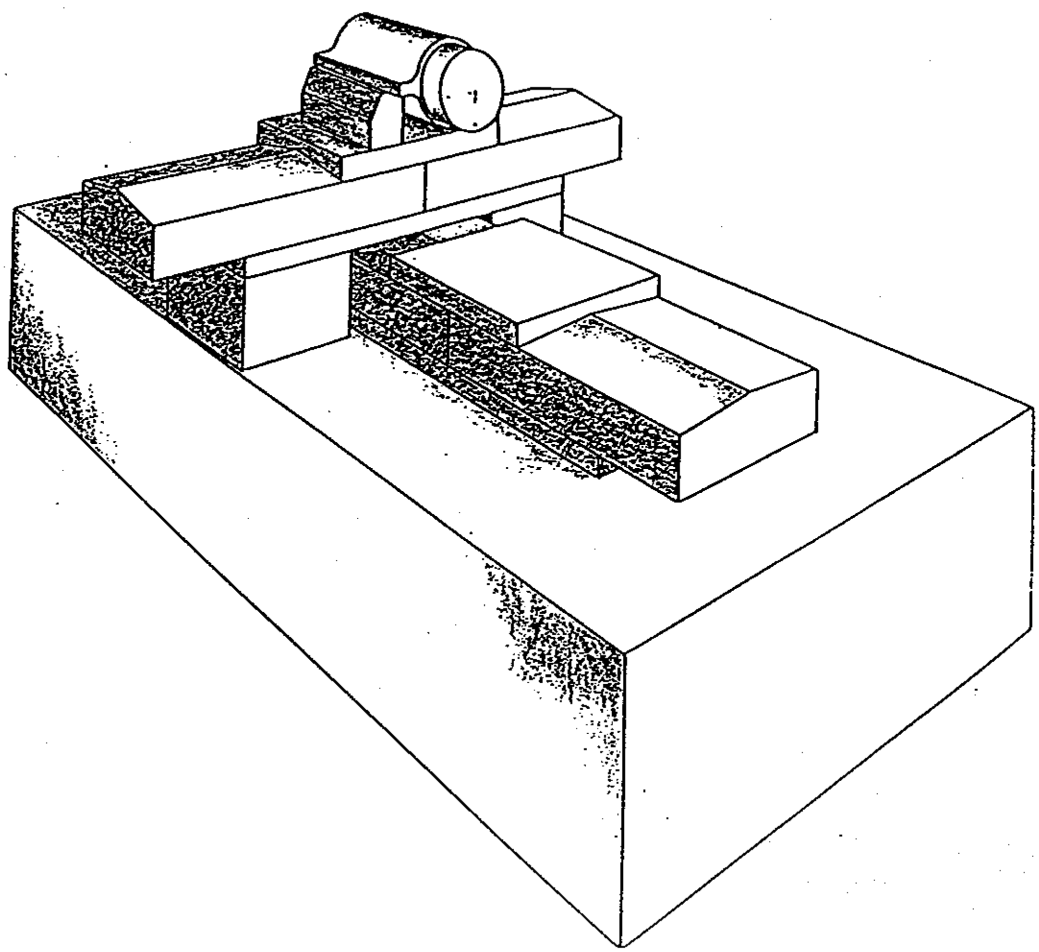


Figure 1

The geometry of our SMI lathe has been improved beyond our previous capability by using modular hydrostatic slides which can be ground to attain straightness of travel better than Ø.5 parts per million without the need for tedious hand lapping. This is twice as good as the specifications on our current machines. Similar improvements have been made in roll, pitch, and yaw. The use of a ball bearing intermediate slide, hydrostatically coupled to the main slide, has allowed us to increase the slide longtitudinal stiffness by almost a factor of four and, at the same time, introduce substantial damping into the system. The increased stiffness and damping are responsible for an improvement in machine dynamics which, in turn, improve the servo performance. The squareness of the axes of the new machine is adjustable after assembly is complete and it can be set it to within a few tenths of an arc second. As the metrology for the Z axis will be located at some distance from the tool tip in the vertical plane, we measure Z axis pitch and correct the axis position for this error in real time.

SLIDES

The slides are modular units which can be employed in various configurations and sizes to construct different types of machines. They utilize hydrostatic bearings in a fully constrained, box way design.

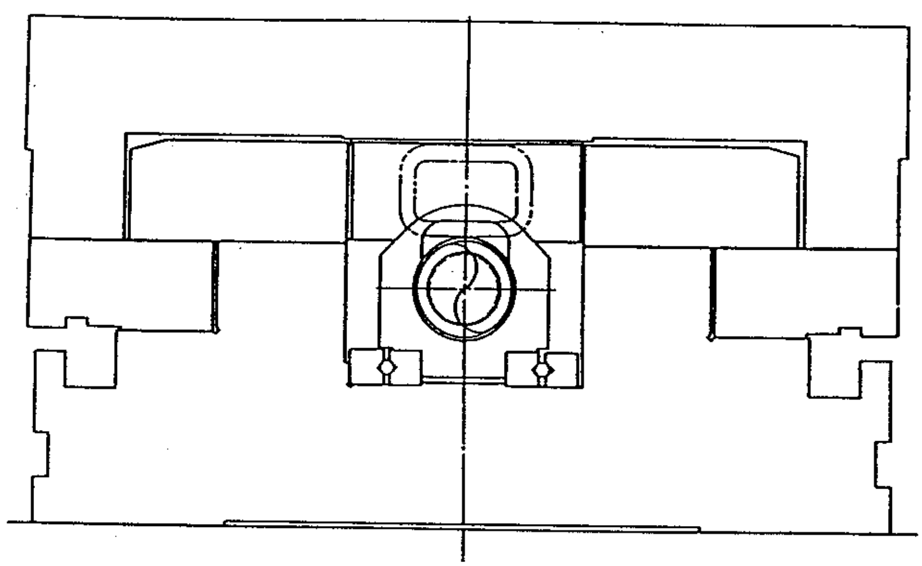
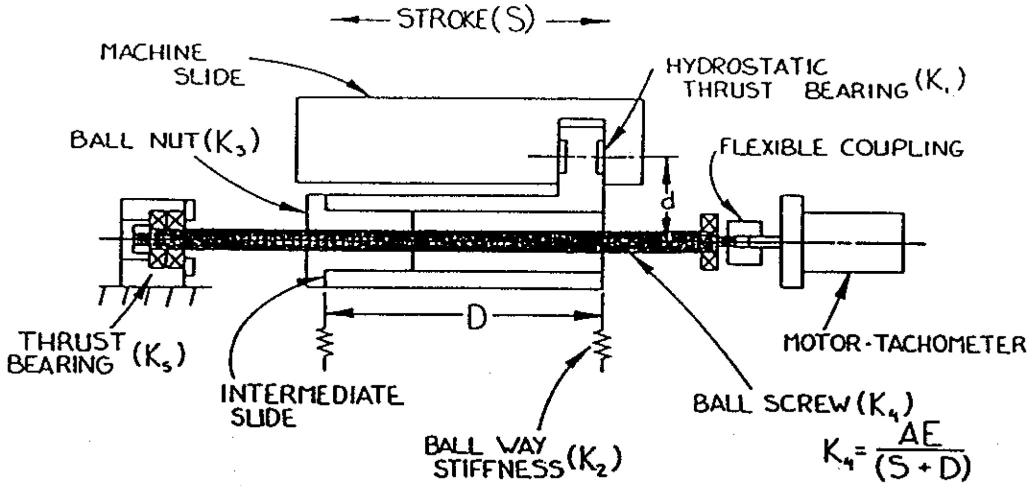


Figure 2



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

Figure 3

The slides are isolated from the lead screws by an intermediate slide which translates on ball ways. This intermediate slide carries the ball nut and a hydrostatic thrust bearing that transfers the thrust force from the ball nut to the main slide. Figure 2 is a cross section through one of the slides and figure 3 shows how the intermediate slide is arranged. By careful design of the thrust bearing it is possible to achieve just the combination of stiffness and damping required to obtain a responsive, yet highly damped system. D. C. servomotors are used to drive the ball screws. The motors are, in turn, driven by linear power amplifiers. Limit switches are non-contacting proximity switches selected to avoid the influence on slide straightness caused by the force needed to actuate conventional switches.

SPINDLE

A new air bearing, hydrostatic spindle was designed for use on the machine. The new spindle is motorized with the rotor of the motor affixed permanently to the spindle. The spindle thrust bearing is located directly behind the front journal bearing to minimize axial drifting of the spindle nose. The span of the journal bearings has been increased over earlier designs and the rotational moment of inertia has been reduced to provide better acceleration characteristics. The spindle housing has its mounting points at the spindle centerline to prevent the centerline from rising as the speed is increased. All of this results in a spindle which is stiffer, runs faster, and is more stable than ever before. Figure 4 is a section through the spindle and illustrates the features of the design.

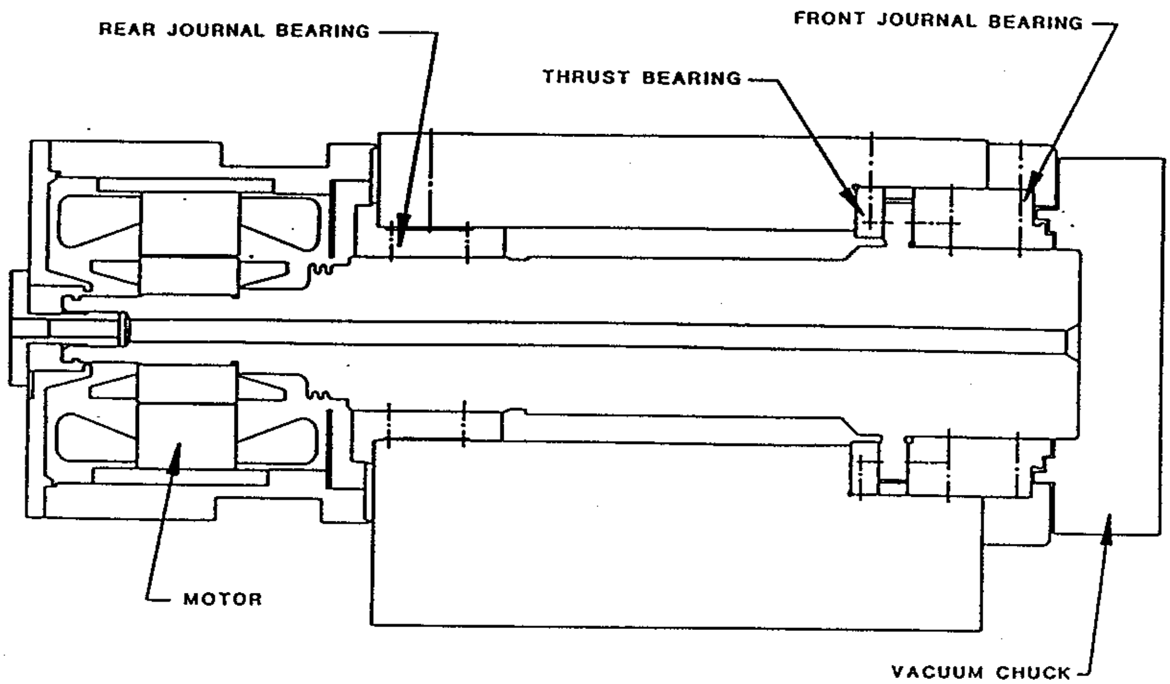


Figure 4

ENVIRONMENT

While the environment is not strictly part of the machine tool in the usual sense, it controls the ability of the machine to produce quality parts. Any improvement in the environment results in improved machine accuracy. In order to be able to even document the geometry of an SMI lathe, we will need an environment where the temperature is controlled to within a few tenths of a degree Fahrenheit and the relative humidity is held within a percentage point. We are currently preparing a small (16'X 16') room to enclose the prototype machine.

WAVELENGTH OF LIGHT

The velocity of light and thus its wavelength is dependent on the medium through which it is passing. While it is possible to enclose all of the interferometry in a vacuum, it is expensive and entails maintaining the vacuum pump and its accessories. The metal bellows usually used to enclose the variable length portion of the light path exert substantial force upon the machine slides. This force and its effects can be avoided. Rather than use a vacuum, our design employs a refractometer to measure the refractive index of the air and correct, in real time, for the errors induced by locally changing conditions. The refractometer is located behind the Z axis slide and close to the surface of the granite machine base.

INTERFEROMETRY

With the expiration of the patents surrounding the Hewlett Packard laser technology there has been a recent flurry of activity resulting in several new products which have come to market within the last several months. Among these is an offering by Zygo Corporation which uses an acousto-optic modulator to generate a dual frequency laser beam with a 20 Mhz. frequency split. This is an order of magnitude greater than that used by HP and others who manufacture similar products. The result is that the Zygo double pass interferometers have a resolution of 0.05 micro inches and will function at up to 0.5 meters per second. The output data is in the form of a 32 bit parallel word which can be delivered at up to 2 Mhz. The cost of the Zygo equipment is comparable to the cost of similar HP equipment. Figure 5 shows the layout of the interferometry on the machine. It can be seen that the X axis beam path is at spindle centerline height and located immediately to the rear of the vacuum chuck.

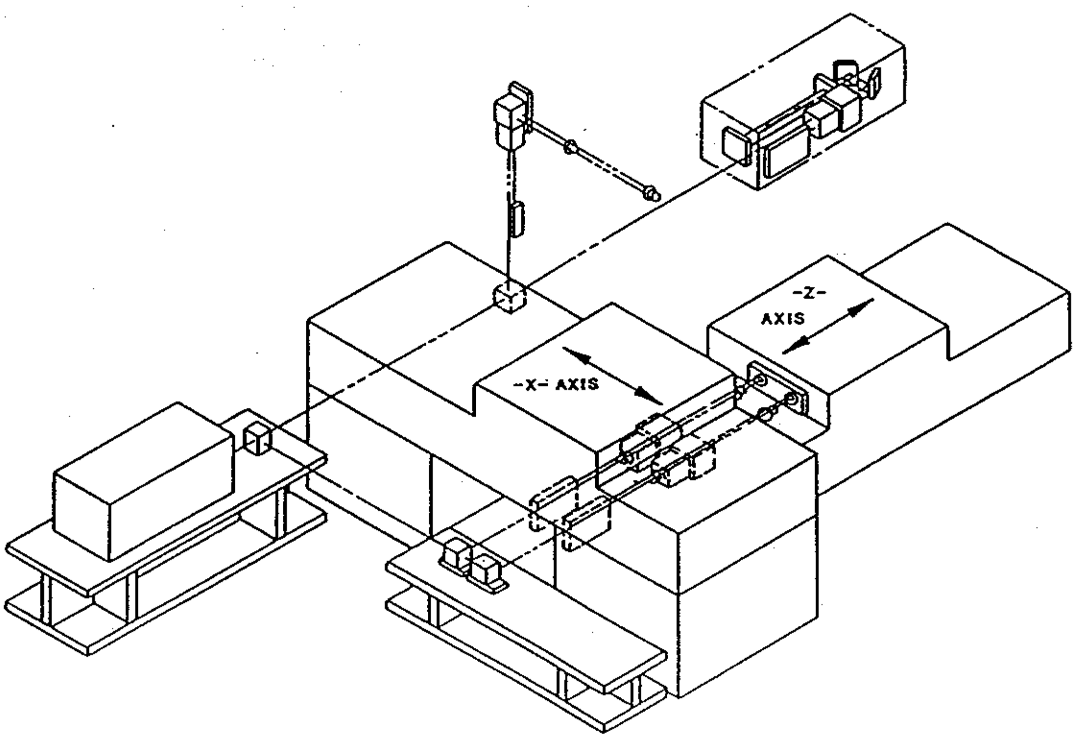


Figure 5

The Z axis has two interferometers, one to measure the displacement of the slide and the other to measure the pitch. This allows us to correct for Abbe errors introduced because the beam paths are below the slide way covers. The location of the interferometry on the Z axis was chosen to prevent the measuring system from interfering with workpieces and tooling.

CLOSING THE SERVO LOOPS

To complete the machine, there must be a controller which can accept the 32 bit parallel data from the interferometers, process this data at a high rate, and close the servo loops. What is required is more of a computer than the typical CNC machine controller. Ideally, this same computer will be able to generate the commands necessary to machine an optical surface given only the equation which describes that surface as input. We have located such a device. It is manufactured by a division of CUPE called Cranfield Precision Systems (CPS). The CUPROC-16 controller is currently used by several other machine tool manufacturers, both in the US and the UK. The cost of the CUPROC-16 is competitive with the cost of our current Allen-Bradley controller.

FUTURE WORK

There are a number of accessories that can be made available in the near future. A fast tool servo has been designed and constructed which will make it possible to machine parts which are not rotationally symmetric. This device is capable of moving the tool at up to 5 KHz. with an amplitude approaching 25 micrometer. Additional testing must be done before the device is ready for the market but we are getting closer. A second spindle is contemplated for the machine. This spindle will have a lower speed range but will be significantly more powerful and will have oil hydrostatic bearings with higher stiffness and damping than its air bearing counterpart.

SUMMARY

Increasing the feedback resolution is only one factor which contributes to making a more capable machine. Attention must be paid to the overall machine design, the environment in which it must operate, and the peripheral electronics which control it. For the first time, lasers and controllers are available to combine with our unique machine design background to build a truly superior diamond turning machine.

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