Nanotechnology 4 (1993) 242–245. Printed in the UK

# Capstans or lead screws? Comparing the performance of diamond turning machines under operating conditions

**David H Youden**

Rank Pneumo, A Division of Rank Taylor Hobson Inc., P O Box 543, Precision Park, Keene, NH 03431-0543, USA

Received 15 December 1992, accepted for publication 17 August 1993

**Abstract.** The cutting performance of diamond turning machines which employ lead screw driven slides is compared to that of similar machines which use capstan drives. Diamond turned parts are compared using Talystep, Form Talysurf, and Zygo Mark 2 interferometer data. Machine contouring performance is compared using a sinusoidal path technique.

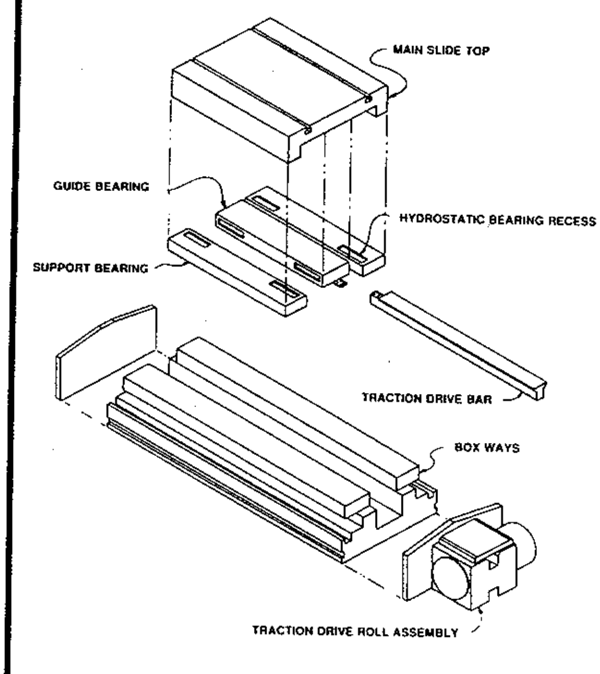
## 1. Introduction

Capstan drives have received a considerable amount of attention over the last several years. A number of well known organizations have invested time and effort designing diamond turning machines that use these drives for slide translation.

Capstan drives are generally felt to be superior to ball screws because they eliminate the cyclic errors often associated with screws and because they lower the frequency of tachometer ripple to a point where it falls within the bandwidth of the servo controller. Capstan drives also have very low Coulomb friction compared to ball screws.

Capstan drives, however, have a low mechanical advantage, which limits the thrust force available from the device. This low mechanical advantage also causes the tachometer signal to be vanishingly small, limiting the usefulness of velocity feedback.

The author has had the unique opportunity to analyse the performance of, and produce diamond turned parts on, two ultra-precision diamond turning machines that are mechanically identical except for the slide drives. One machine has slides that have preloaded ball screw drives and the other has air bearing capstan drives. These drives must be capable of moving the slides of the lathe with accuracy sufficient to produce contoured parts with a form accuracy better than 0.1 $\mu$m. They must also be capable of positioning the slides to an accuracy of $\pm$40 nm.




HYDROSTATIC BOX SLIDE DESIGN

## 2. Capstan drive slide design

The slides on the capstan drive machine are hydrostatic box slides. The traction drive bar is attached to the slide by a small, spring steel reed. The reed serves to decouple the slide from any small vertical motions of the drive bar, and to ease the alignment of the traction drive to the slide in the vertical plane. Figure 1 illustrates the construction of the slide and the location of the traction drive roll assembly.

0957-4484/93/040242+04$07.50 

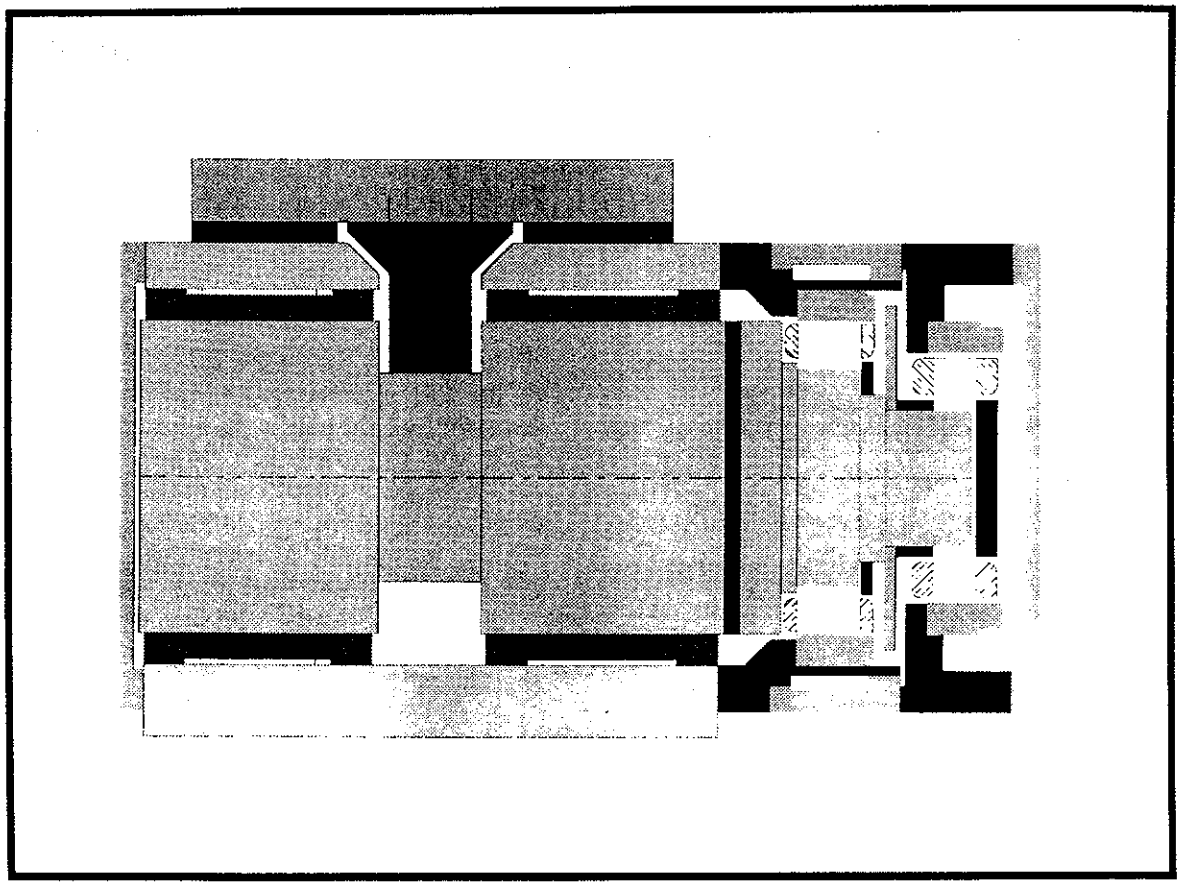


**Figure 2.** Section through capstan drive roll assembly.

The capstan drive bar is tee shaped in cross section. The top of the bar is about 50 mm wide and the bottom is 25 mm wide. The bottom of the bar runs on the drive roll. The bar is preloaded against the drive roll by an air bearing that operates on the top surface of the drive bar, forcing it against the roll with about 1800 N.

The capstan drive roll is supported by two air journal bearings. There is no thrust bearing as the roll is located axially by the drive bar, which, in turn, is located by the slide itself. A DC servo motor and tachometer are mounted on one end of the drive roll. Figure 2 shows the construction of the drive roll assembly.

## 3. Lead screw slide design

The slides used on the lead screw driven machine are similar in appearance to those on the capstan drive machine and the guide way systems are identical on the two sets of slides. The slide drive system is, obviously, quite different. These slides have a 5 mm pitch ball screw with a preloaded nut located below the slide on its centre line. The screw is supported by preloaded ball bearings with the thrust bearings located on the end of the screw nearest to the nut when the slide is in the machining theater. A DC servo motor/tachometer is attached to the screw through a flexible coupling. The ball nut is attached to an intermediate slide. This slide is about 100 mm square in cross section and 300 mm long.

The intermediate slide moves on preloaded ball ways. On the opposite end of the intermediate slide (away from the ball nut) is a hydrostatic thrust bearing, which protrudes up above the intermediate slide and engages a recess in the end of the main slide guide way. This bearing serves to transmit thrust from the lead screw to the main slide while effectively decoupling the main slide from pitch, roll, and yaw of the intermediate slide. The technique is so effective that cyclic errors in straightness caused by the ball screw are reduced to less than 10 nm peak to valley. Figure 3 illustrates the construction of the lead screw driven slides.

## 4. LAST test results

Prior to cutting parts, a low-amplitude sine tracking (LAST) test [1] was run on each machine to verify that the machine servos were properly adjusted. In the LAST test, for a 10 nm programming resolution machine, one axis moves in a sinusoidal fashion with a peak to valley amplitude of 500 nm and a period of 60 s while the other slide moves first in one direction and then in the other direction at 2.5 mm $s^{-1}$. The position of the first slide is

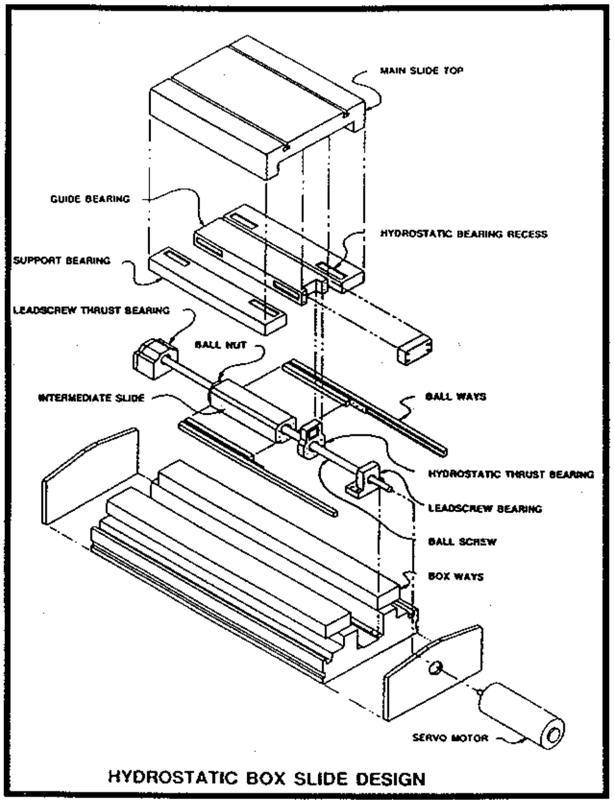



**Figure 3.** Lead screw driven slide assembly.

recorded throughout the three-minute test. Improperly adjusted servos manifest themselves as artifacts on the trace at or near the reversal points on the sine wave. Figure 4 shows the LAST tests on the two machines were very similar in appearance.

## 5. Cutting tests

The parts used for our cutting tests were made of Furukawa A-5486 aluminium, a material which we have found gives excellent results when diamond turned. Each part was 76 mm in diameter and about 25 mm thick. The parts were held on vacuum chucks and a 254 mm spherical radius was turned under the following conditions: spindle speed, 2000 RPM; finish depth of cut, 0.002 mm; feed rate, 2.5 mm $min^{-1}$; coolant, odorless mineral spirits (spray mist).

**Table 1.** Roughness and waviness data from RTH Talystep. Roughness data uses a 0.33 Hz filter. Waviness data uses a 25 Hz filter.

| Part designation | Lead screw drives A | Capstan drives B |
|---|---|---|
| Roughness (nm) | 7.0 | 7.5 |
| $R_t$ | 7.0 | 8.5 |
| | 7.5 | 9.0 |
| Waviness (nm) | 5.9 | 9.6 |
| $R_t$ | 7.3 | 9.9 |
| | 10.2 | 12.6 |

## 6. Results

The parts were measured on an RTH Talystep over a scan length of at least 150 $\mu$m. Roughness data were taken using a filter cut-off of 0.33 Hz and waviness data were taken using a filter cut-off of 25 Hz. The data were assessed over each successive 50 $\mu$m window. The data from two representative parts, one from the capstan driven machine, and one from the lead screw driven machine, are presented in table 1.

The parts were also inspected using an S-5 Form Talysurf which produced the results in table 2.

Further testing was done using a Zygo Mark 2 interferometer with a phase measuring attachment. This instrument produced the data shown in table 3.

Although these parts are all within the machine performance specification, it is clear that the parts cut on

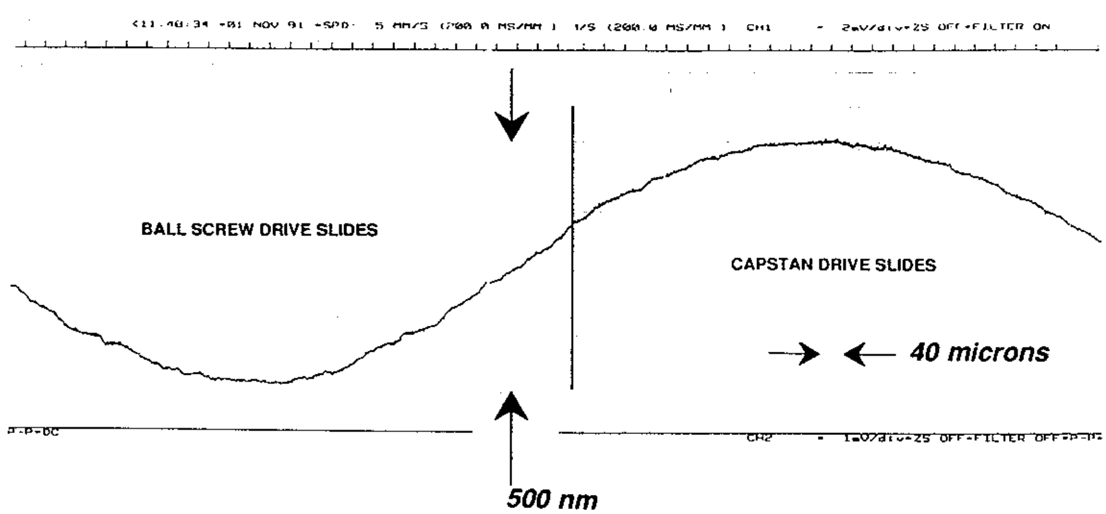



**Figure 4.** Sections of LAST test data from two different slides.

**Table 2.** Data collected using an RTH S-5 Form Talysurf.

| Part designation | Lead screw drives A | Capstan drives B |
|---|---|---|
| $R_a$ (nm) | 4.3 | 6.1 |
| $R_t$ (nm) | 33.6 | 66.6 |
| $W_a$ (nm) | 5.3 | 5.4 |
| $W_t$ (nm) | 23.8 | 26.3 |

**Table 3.** Data collected using a Zygo Mark 2 Interferometer with a ZyMOD phase measuring attachment.

| Part designation | Lead screw drives A | Capstan drives B |
|---|---|---|
| P–V $\lambda$ | 0.15 | 0.16 |
| RMS $\lambda$ | 0.022 | 0.030 |

the machine with lead screw driven slides are somewhat superior to those cut on the other machine.

In addition to part cutting tests, there is the question of drive system stability under different operating conditions. The machine slides have a mass of about 180 kg and the mass of the spindle is about 135 kg making the total moving mass of the $X$ axis just over 300 kg. The work piece can add up to 125 kg of additional mass. It was found that capstan drives were more sensitive to changes in the driven mass than lead screw drives. In order to maintain peak performance, the servo drives required retuning if massive work pieces were to be machined to the accuracy obtainable on the machine used for the test cutting.

## 7. Conclusions

Retuning the servo drives is not a long nor a complex task. The requirement that it be done, however, in addition to the fact that there is no improvement in cutting results, has led us to the decision to continue to use lead screw drives until such a time when the advantages of capstan drives can be more clearly demonstrated.

It should be noted that these results are valid only for this particular application of the slide drives tested. In other applications, and with different drive designs, the results might well favor one type of drive over the other more emphatically.

## References

[1] Gerchman M C and Youden D H 1991 An evaluation of ultra-precise machine tool contouring performance: the low amplitude sine tracking (LAST) test *Proc. 6th Int. Precision Engineering Seminar; Proc. 2nd Int. Conf. on Ultra-Precision in Manufacturing Engineering* (Berlin: Springer) pp 124–7