Linear vs. Rotary

Is thermal expansion relevant?

A Tech Authority, Inc.
909-972-7520
www.atechauthority.com

Rewritten By Craig D’Ambrosio
A Tech Authority, Inc.
(909) 972-7520
(Based on “Accuracy of Feed Axes" by Dr. Jan Braasch, Dr. Johannes HEIDENHAIN GmbH)

The discussion as to whether linear encoders or rotary encoders are the best solution for measurement on NC machine tools is experiencing quite a comeback. This is due, in part, to the post recession idea that machine tool manufacturer’s need to cut costs to maintain machine sales. Could it be that too much attention has been put on cost, and too much reliance on new technology? Under the pressure of such opinion, one can easily come upon the idea of cutting costs by leaving linear encoders off the lowest-priced models, and then offer them as an accuracy-enhancing optional feature.

This line of thought is reinforced by the drive industry where a large portion of the new servo motors now feature built-in rotary encoders. With this trend, there is now a decision of choosing between a ballscrew/rotary encoder system, or a linear encoder solution for position control. In the heat of such decisions, one should not forget to consider the problems known to be involved with position measurement using a rotary encoder/ballscrew system. In order to make an educated decision, you must first have a general understanding of mechanical feed drive systems.

Although machine tool designs vary, their feed drive systems remain largely standardized (Fig. 1). In almost all cases, the recirculating ballscrew has established itself as the solution for converting the rotary motion of the servo motor into linear slide motion. The ballscrew is normally fixed at only one end with preloaded ball bearings, which take up the axial forces of the slide.

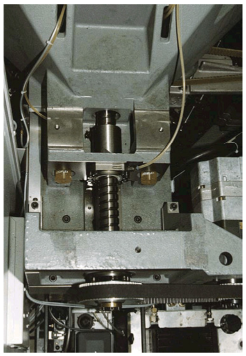


Fig. 1. Feed axis drive on milling machine

A position control loop using a rotary encoder and ballscrew includes only the servomotor (Fig. 2). In other words, there is no actual position control of the slide, because only the position of the servomotor is being controlled. To be able to predict the slide position, the mechanical system between the servomotor and the slide must have a known and, above all, repeatable behavior.

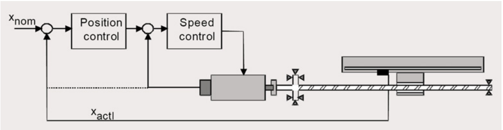


Fig. 2: Typical drive system of a numerically controlled machine tool with linear scale on the slide and rotary encoder on the motor. Unlike in position control with rotary encoder and ball screw, a linear encoder includes the feed drive mechanism in the control loop.

On the other hand, a position control loop with a linear encoder, embraces the entire mechanical feed-drive system. This takes into account all native errors associated with rotary encoder feedback. Plainly put, the linear encoder on the slide gives the control unit a direct indication of it’s position. When using a rotary encoder for linear position of the slide, there are numerous mechanical effects that will cause errors in the positioning accuracy, thus increasing the potential of scrapped parts. These mechanical effects include the following.

- **Kinematic error** results primarily from ballscrew pitch error. This error directly influences the result of measurement because the pitch of the ballscrew is being used as a standard for linear measurement.
- **Reversal error** occurs during positioning from differing directions. The effects are play and elasticity in connection with frictional forces. The so-called pitch loss resulting from a shift of the balls during the positioning of ballscrew can lead to reversal error in the magnitude of 1 to 10 µm.
- **Deformation of feed drive mechanisms** are essentially inertia forces resulting from acceleration of the slide, cutting process forces, and friction in the guideways. They cause a shift in the actual axis slide position relative to the position measured with the ballscrew and rotary encoder.
- **Forces of acceleration**: The mean axial rigidity of a feed drive mechanism as shown in Figure 1 lies in the range of 100 to 200 N/µm. A typical slide mass of 500 kg and a moderate acceleration of 2 m/s^2 result in deformations of 5 to 10 µm that cannot be recognized by the rotary encoder/ballscrew system. Unfortunately, the demand toward faster machines will result in increasingly greater deformation values.
- **Cutting forces** can quite possibly lie in the kN range where their effect is distributed not only in the feed drive system, but also over the entire structure of the machine between the work piece and the tool. The deformation of the feed drive system therefore normally has only a small share in the total deformation of the machine.
- **Forces of friction** in the guideways lies between 1% and 2% of weight for roller guide ways and 3% to 12% of weight for sliding guideways. Therefore, a weight exerting 5000 N results in feed drive deformation of 0.25 to 6 µm.

This brings us to the focus of this article, “Is thermal expansion relevant?” Positioning error resulting from thermal expansion of the ball screw presents the greatest problem for position accuracy and repeatability when using rotary encoders. This is because the ballscrew drive must serve a double function; On the one hand, it must be as rigid as possible to convert the rotary motion of the servo motor to linear feed motion. On the other hand, it must serve as a precision measuring standard. The two-fold function therefore forces a compromise, because both the rigidity and the thermal expansion depend on the preloading of the ball nut and the fixed bearing.

Figure 3 shows the result of a positioning test as per ISO/DIS 230-3 on a vertical machining center (built in 1998) equipped with linear encoders. The machine was driven to three locations on the 1 meter long axis 100 times at 10 m/min. Taking the standstill periods to acquire the measured value into account, the mean traversing speed during the test was approximately 4 m/min. In addition to the two positions at the ends of traverse as recommended in the standard, a third position at the midpoint of traverse was measured. Figure 3 shows the position values with respect to their initial values. At first the ballscrew/rotary encoder system was used for position control. In a second test, under otherwise identical conditions, linear encoders were used. The comparator system was a VM 101 from HEIDENHAIN.

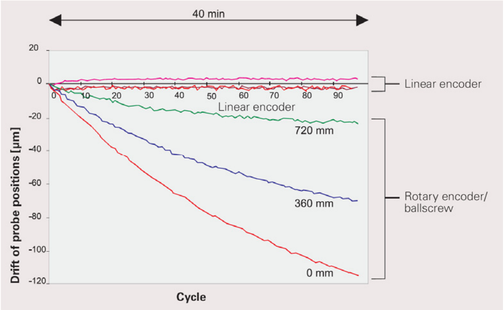
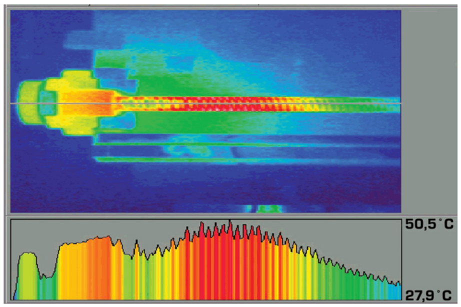


Fig. 3: Drift of three positions during measurement in accordance with ISO/DIS 230-3 with a large number of repetitions on a machining center with ball screw in fixed/floating bearings. Position measurement via rotary encoder and ball screw shows a significant drift of positions due to the thermal growth of the screw.

In spite of the moderate feed rate of 10 m/min (rapid traverse 24 m/min), the position farthest from the fixed bearing of the ball screw shifted by more than 110 µm within 40 minutes. It is interesting to note that the drift increases dramatically, shortly after cycle start. Any change in the mean feed rate in a production process therefore immediately affects positioning accuracy. Similar results were published by Schmitt [5].

Some manufacturers offer hollow ballscrews that conduct coolant to prevent thermal expansion. Circulation of the coolant through rotating ballscrews, requires rotary lead throughs near the ballscrew bearings. Besides the obvious sealing problems, this method assumes the availability of a temperature-controlled coolant, which is usually not the case. Also, it reduces the rigidity of the ballscrew in the direction of traverse. Typically, the cost of this feature is greater than the cost of linear encoders.



Local heating of a recirculating ball screw in the traverse range of the ball nut after six hours of reversing traverse at 24 m/min between two points 150 mm apart [6]. For this thermographic snapshot, the machine table was moved aside at the end of the traverse program. The illustration shows the higher temperatures of the belt drive, locating bearing, and ballscrew.

Therefore, the primary problem involved with position measurement using rotary encoder and ballscrew, is the thermal expansion of the ballscrew. With typical machining times of 1 to 2 hours, thermal expansion causes a positioning error in the magnitude of 100um, depending on the nature of the part program. After every new part program, the ballscrew requires approximately 1 hour to attain a thermally stable condition. The same principle applies for interruptions in machining. A rule of thumb for thermal expansion is that over the entire length of a cold 1 meter ballscrew, the ballscrew grows by approx. 0.5 to 1 µm after every double stroke. This expansion accumulates during the machining process.

As requirements for machine tool accuracy and velocity increase, the role of linear encoders for position measurement grows increasingly important. This should be taken into consideration when deciding to upgrade to a linear encoder feedback system.

To receive a complete technical write-up on this subject contact A Tech Authority at (909) 972-7529 or bill@atechauthority.com.

Literature:

1. Schrîder Wilhelm, ,,Feinpositionierung mit Kugelgewindetrieben, Fortschrittsbericht" VDI Series 1 No. 277, Düsseldorf: VDI publishing house 1997
2. VDW report 0153, ,,Untersuchung von Wälzführungen zur Verbesserung des statischen und dynamischen Verhaltens von Werkzeugmaschinen"
3. Weule Hartmut, Rosum Jens, ,,Optimization of the friction behaviour of ball screw drives through WC/C coated roller bodies", Production Engineering Vol. 1/1 (1993)
4. Golz, Hans Ulrich, ,,Analyse, Modellbildung und Optimierung des Betriebsverhaltens von Kugelgewindetrieben", Dissertation for the University of Karlsruhe, 1990.
5. Schmitt Thomas, ,,Modell der Wärmeübertragungsvorgänge in der mechanischen Struktur von CNC-gesteuerte Vorschubsystemen", Shaker publishing house, 1996.
6. A. Frank, F. Ruech, Position measurement in CNC Machines ... Lamdamap conference, Newcastle 1999
7. Jan Braasch, Dr. Ing., Accuracy of Feed Axes, HEIDENHAIN technical article, published 10/2004