# A Theory of Ball-screw Thermal Compensation

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***Abstract*—Thermal growth effects the reliability and accuracy of a machine tool, especially, as it relates to the High Speed Machining (HSM) technology. When axis speeds increase, the effect of thermal expansion of ballscrews will create large positional errors of the axes. In this paper, a piezo-integrated actuator and a load sensor are placed on the machine ballscrews, and the feedback from this arrangement becomes an ideal source for compensation of backlash and thermal expansion. This smart unit provides excellent performance of tolerance, the roundness test report reduced from 18.1µm to 10.00µm, and large cost savings in the manufacture of the machine tool.**

***Index Terms*—Thermal growth, HSM, Compensation**

## I. Introduction

### 1-1 Background

Ballscrew thermal compensation has been proven to be one of the most effective methods to ensure the accuracy of machine tool production [1]. However, two major obstacles limit this application, the effectiveness and reliability of the thermal gathering device, along with the lengthy calibration task that the compensation must be applied [2]. As it becomes difficult to obtain accurate temperature readings from any given source and its' related components, a new solution to the approach of ballscrew compensation is needed to overcome the deficiencies of the current methods.

Most of the tensioning device is provided for the ballscrew. The backlash compensation of a machine tool is set under a no-load situation, and an experienced machine tool technician can extrapolate a good compensation value for a loaded condition with reasonable accuracy. But there still can be up to 12 – 18µm tolerance of roundness [3-4]. This is typically acceptable, but never be perfect in some applications, such as high grade mold and die work, Automobile industries, aerospace etc., these require a higher level of accuracy [5-8]. Fig. 1 shown a Ballbar test report of a traditional pretension placed.

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### 1-2 Ballbar test

This test was done on a Challenger high speed vertical machining center. This machine utilized a linear construction way to meet the higher speed movement application. A ballbar test without thermal compensation is shown in Fig. 1.

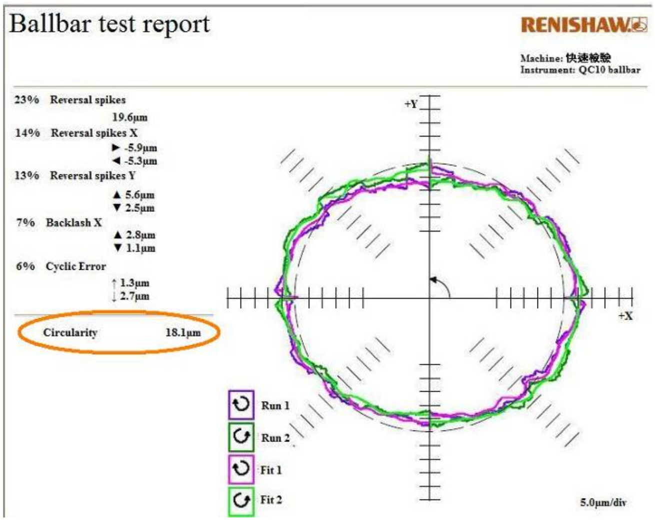


Fig. 1. Ballbar test report of a traditional design.

In Fig. 1, a tolerance of circularity is 18.1µm, which was achieved with a Hollow Shaft Oil Cooled ballscrew system, and pretention placed.

### 1-3 Ballscrew cooling system

Many recent technology uses a cooling system for the ballscrews. A hollow shaft ballscrew is used on the machine. An external chiller unit is plumbed to ballscrew and circulates chilled oil through the screw to maintain a constant temperature [9]. Figs. 2 and Fig.3 show the design of a chilled ballscrew and the joint unit. Fig. 4 shows the accuracy performance of a chilled ballscrew. It gives a nearly 3µm tolerance of a travel in movement distance for 640mm, and the curve shows tolerance across zero point (from plus to minus). This curve tells that the tolerance is far from linear. Although it's pretention loaded and oil chilled.

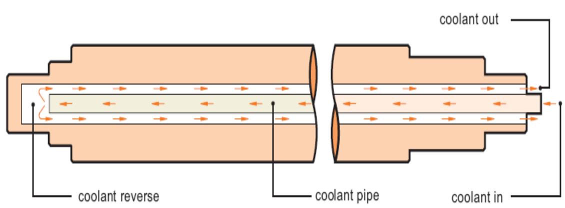


Fig 2. Hollow ballscrew.

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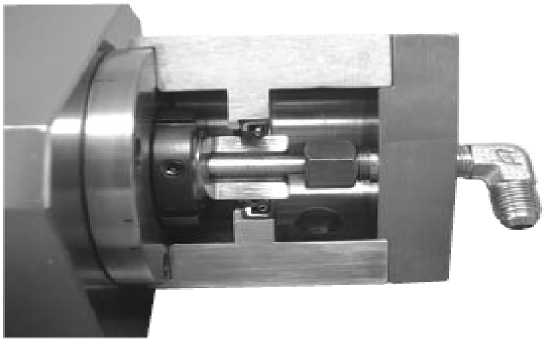

Fig. 3. Joint for hollow ballscrew.

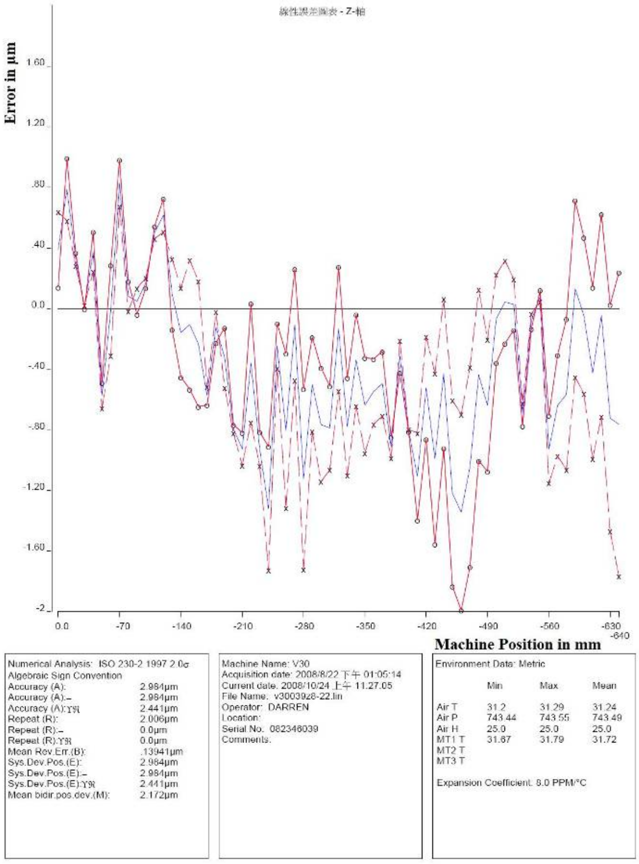


Fig. 4. Laser sample of ballscrew tolerance.

The chilled ballscrew design is effective, but there are several issues that make this model less than ideal value. Coupling issues from the chiller to the ballscrew are unreliable, such as leakage that can be mixed with cutting oils, it will diminish tool life and cause environmental issues [11]. Moreover, the overall costs of the chiller unit and maintenance remain high as well.

1-4 The cost study of chiller unit

Cost considerations of a chiller unit, such as the expensive joint at each ballscrew, the hollow shaft ballscrew cost of 15% - 20% more than a traditional ballscrew, and the chiller unit itself being an expensive item. Service costs is also a large issue with this design. The chiller design will also require experience technician to do properly temperature settings to maintain even temperature control [12]. Cooling oil will also need to be replaced on regular intervals. Table 1 shows the cost breakdown of a chiller system.

Table 1
Component cost of chiller unit

| Item | Hollow Ballscrew with chiller | | Cost US$ |
|---|---|---|---|
| 1 | Hollow Ballscrew | 3 x | 100.00 |
| 2 | Joint & Parts | 3 x | 250.00 |
| 3 | Chiller | | 200.00 |
| 4 | Piping | | 120.00 |
| | **Total** | | **1970.00** |

## II. Model Development & Simulation

2-1 Mechanical layout and load control

An updated technique by putting one measuring unit has been placed at the end of the ballscrew as shown in Fig. 5. Pretension of ballscrew has been removed, which is to ensures that the thermal growth approach is applied to one direction only [13-17]. This will ensure that the PLC compensation can be applied to the entire extention of the ballscrew.

In this proposed model, a Displacement Measurement Meter is placed at the end of the ballscrew [18-20], see Fig. 6. The feedback from this unit will be evaluated for compensating the backlash of the ballscrew. This smart solution offers excellent performance and considerable cost savings in the manufacture of the machine.

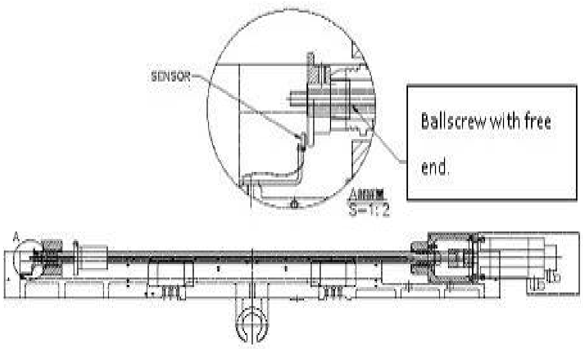


Fig. 5. Free end ballscrew with Sensor layout.

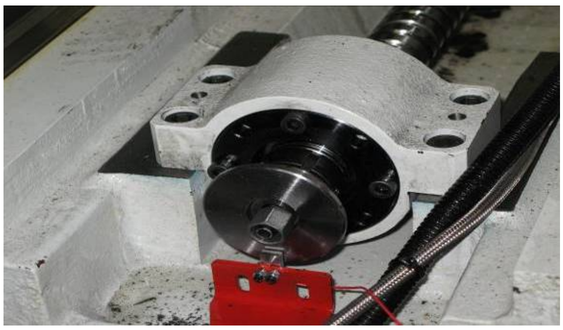

Fig. 6. Ballscrew with a measurement sensor.

2-2 Eddy current

Eddy current is a phenomenon discovered by French physicist Leon Foucault. It says when a conductor moving in the magnetic field generated by a stationary object will experience charges. According to Faraday's law, this relative motion can cause a circulating flow of electrons or current governed by the flowing equation:

$$V_L = L\frac{di}{dt} \quad \text{...(1)}$$

where

$V_L$ is induced voltage in volt

$L$ is the value of inductance in henries.

$\frac{di}{dt}$ is the rate of changes of current in Amp. per sec.

It is extremely important to know the characteristic of the depth of penetration and the density of current. Fig. 7 shows the penetration. It gives a narrow range of area to be measured.

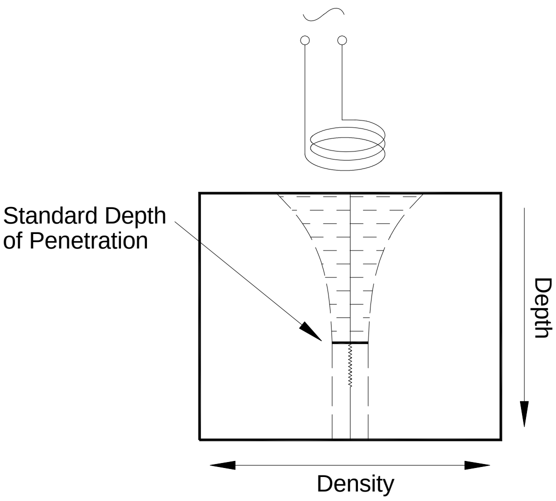


Fig.7. Penetration of Foucault current.

This penetration depth is given by:

$$\delta \approx \frac{1}{\sqrt{\pi f \mu \sigma}} \quad \text{...(2)}$$

where

δ is the depth of penetration (mm).

$f$ is the test frequency (Hz)

μ is the magnetic permeability (H/min.)

σ is the electrical conductivity.

2-3 Logical concept

The parameter has been set for allowing a ballscrew compensation of 2μm when the output voltage changes +0.02V. Since the ballscrew will grow only when the machine starts to run, so the compensation is set '+' only, and the logic chart is shown in Fig. 8.

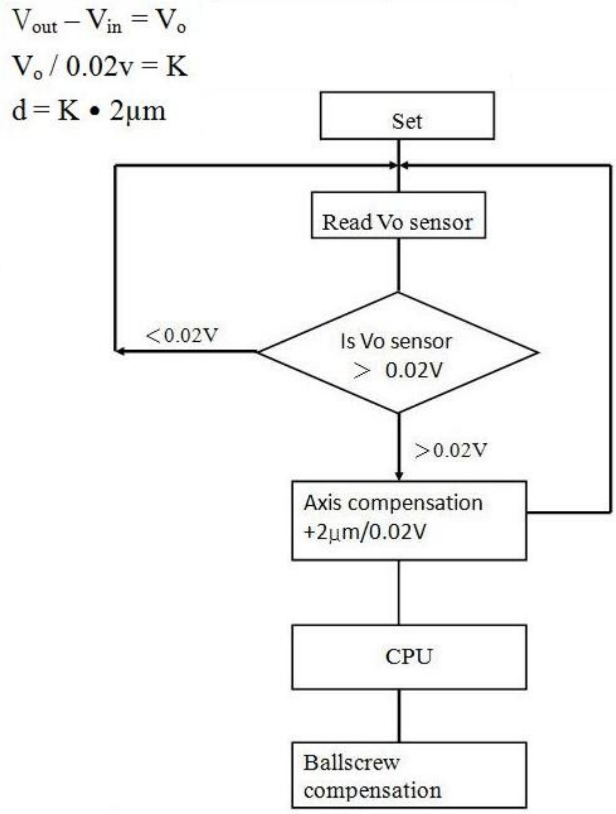


Fig.8. Logic chart.

2-4 Voltage amplifier

A simplified model of the voltage amplifier is shown as Fig. 9 [21].

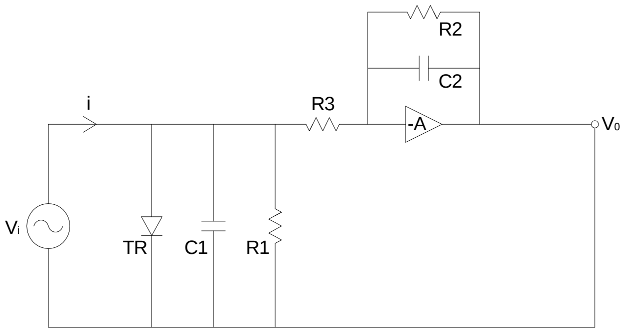


Fig. 9. Simply voltage amplifier.

The Foucault current equation is given as below:

$$i = \frac{V_i}{R_1} = \frac{V_i}{R \sin \omega t} \quad \text{...(3)}$$

where $\omega t$ is the phase at time *t*.

$$V_0 = V_i \times \frac{1}{1 + \frac{1}{AC_2}(C_1 + C_2)} \quad \text{...(4)}$$

The output characteristic of the displacement sensor is shown in Fig.10(a). The load transient response is shown in Fig. 10(b). Functionally, the measuring range of 0.1~0.6 mm is only used, which lies in the linear portion of the curve.

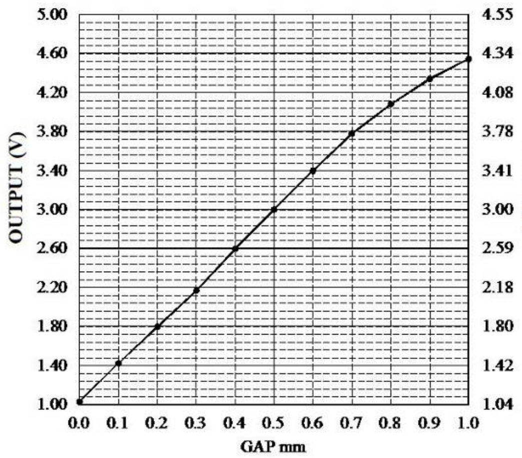


Fig. 10 (a) simulator

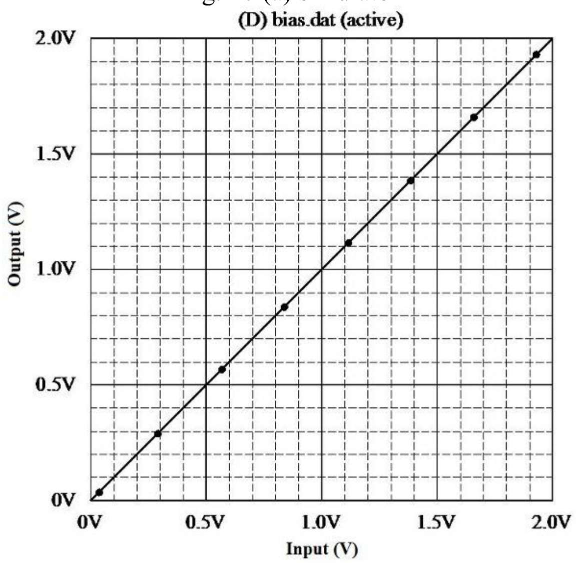


Fig. 10 (b) measured voltage.

Fig. 11 shows the output response of the current and voltage of the amplifier. It shows no timing delay. Thus, the amplifier meets the requirement.

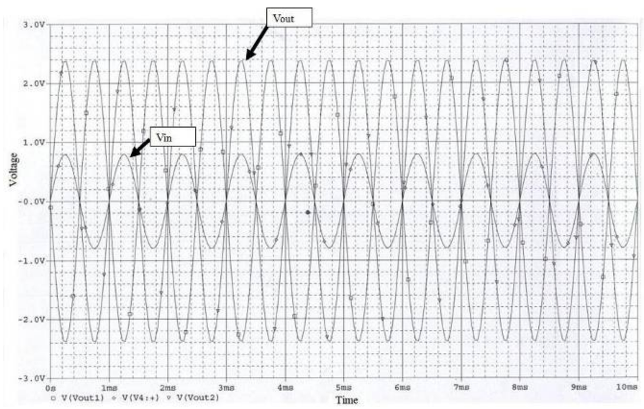


Fig. 11. Voltage and current responses.

## III. Experimental Result

3-1 Ballbar Set-up

Fig. 12 show Ballbar test on a Challenger brand Vertical Machining Center. The new model save a lot of assembly time as there is no ballscrew pretention placed. The free end ballscrew allowed all extension measured by measurement sensor.

Fig. 12. Ballbar set-up

3-2 Ballbar test

Fig. 13 show a roundness value of 10μm, which is measured from the new model, it shows a big improvement of the tolerance.

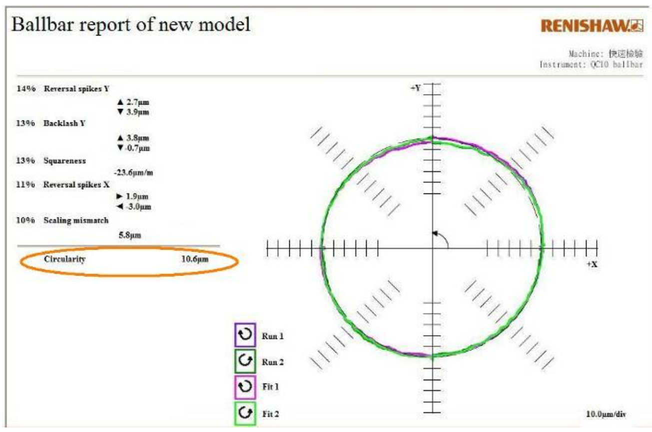


Fig. 13 Ballbar test report of the proposed new model.

## IV. Conclusion

The new model utilizing a Displacement Measurement Meter performed considerably better than traditional chilled ballscrew systems. From the test reports, circularity test results improved from 18μm to 10μm. Additionally, this new model offers considerable cost savings over the traditional hollow screw systems. Table 2 shows a cost saving of US$1,869.00.

Table 2
Components cost comparison

| Item | Hollow Ballscrew with chiller | Cost US$ | New Model | Cost US$ |
|---|---|---|---|---|
| 1 | Hollow Ballscrew 3 x | 100.00 | | |
| 2 | Joint & Parts 3 x | 250.00 | | |
| 3 | | | Reference Ring 3 x | 7.00 |
| 4 | Chiller | 200.00 | | |
| 5 | Piping | 120.00 | Amplifier | 80.00 |
| | **Total** | **1970.00** | | **101.00** |
| Difference at US$1869.00 per machine | | | | |

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