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Performance of force comparator with reference to tuning-fork type force transducer

Toshiyuki Hayashi[1], Yoshihisa Katase[1], Kazunaga Ueda[1],
Tsuyoshi Hoshino[2], Hiroshi Suzawa[2], Masaaki Kobayashi[2]

[1] National Metrology Institute of Japan (NMIJ), AIST
[2] Shinko Denshi Co., Ltd.

Abstract

A force comparator was constructed using a conventional screw-driving type uniaxial testing machine. A tuning-fork type force transducer was used as the reference. A strain-gauge type force transducer was calibrated with the comparator using springs and bearings to relax eccentric forces and moments. In comparison with a conventional dead-weight type force standard machine, deviation of up to only 1 mN at the rated capacity of 50 N was observed. There were still some limitations in terms of force controlability and obstructive eccentric forces; nevertheless, the force comparator exhibited favorable performance for the calibration of commercial force transducers. The tuning-fork type force transducer was suitable as the reference because of its long-term sensitivity stability and small hysteresis.

Keywords: Tuning fork, comparator, testing machine, small force, eccentric force

1. Introduction

Recently, there have been demands for measurement standards and calibration techniques in the small force range in a number of industries, such as biotechnology, nanofabrication, and nanometrology. Up to now, national metrology institutes have generally established national force standards using dead-weight type, hydraulic-amplification type, and build-up type force standard machines. The dead-weight type force standard machines (DWMs) are generally more suitable for relatively small force ranges in comparison with other types; however, it is difficult to construct a DWM for small force ranges below several hundred millinewtons with sufficient measurement uncertainties, for the following reasons. DWMs utilize several weights for generating force, and these weights have to be loaded and unloaded in a certain order, usually while maintaining alignment with a vertical axis of the force transducer to be calibrated to avoid the effects of eccentric tangential forces and bending moments. Therefore, the weights are usually suspended using a linkage structure, a stacking structure, and so forth. Moreover, because the shapes of these weights are not simple, it is difficult to prepare accurate small weights.

Niehe *et al.* [1-2] and Illemann *et al.* [3] at the German Physikalisch-Technische

Bundesanstalt (PTB) demonstrated that the force comparison method of a force transducer was more suitable than the conventional calibration method using a small DWM in the force range below 10 N. They adopted electromagnetic balances having resolutions of 6½ or 7½ digits as the reference. Their method has excellent performance and also paved the way towards continuous calibration of forces. However, it requires complex control because both the actuator control system of the force comparator and the reference electric balance itself have separate feedback loop systems. In principle, the electromagnetic balance is pushed back to its equilibrium position after the actuator applies a certain force, but this shuttle motion breaks the equilibrium of force. Therefore, the actuator control system needs to have a countermeasure for this pushing-back motion.

Unlike the electromagnetic balance, the tuning-fork type force transducer senses force by a slight change in the resonant frequency of a tuning fork and does not have a feedback loop system involving deflection. Therefore, compared with the electromagnetic balance, the control system can be simplified by using a reference tuning-fork type force transducer, and no countermeasure is needed against the pushing-back motion of the reference instrument. Another advantage is elimination of Joule heating normally present in the electromagnetic balance. In the tuning-fork type force transducer, only a short time is needed for thermal stabilization before measurement, and an electric current is needed for driving the tuning fork. As a result, the force transducer under calibration is affected less by heat from the reference instrument.

In this study, a force comparator was set up for evaluation by adopting a tuning-fork type force transducer with a 50 N capacity [4] and a simple control system. A commercially available uniaxial testing machine was used to apply force. This paper reports the performance of this force comparator.

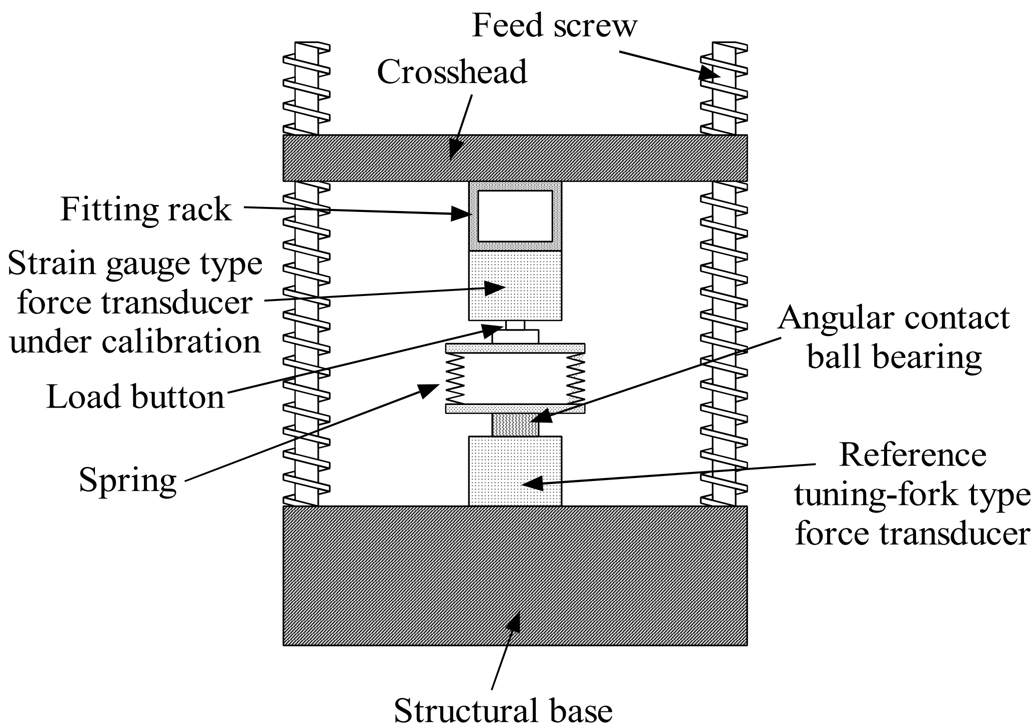
2. Configuration of force comparator

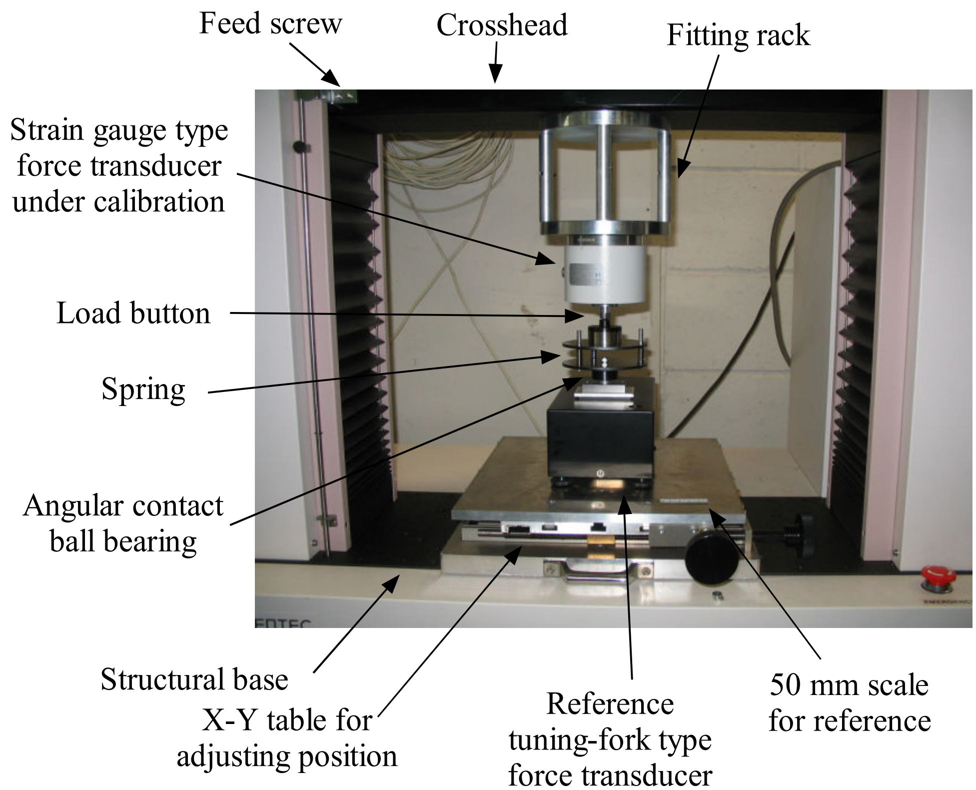
A tuning-fork type force transducer of 50 N capacity (Shinko Denshi Co., Ltd.; model TL-6000) was used for the reference instrument. Details of this force transducer have been described in a previous paper [4]. The resolution of this instrument was approximately 100 μN (5½ digits). A strain-gauge type force transducer of 50 N capacity (Hottinger Baldwin Messtechnik GmbH; model Z30) with a DMP-40 amplifier was calibrated with this force comparator as a trial.

The uniaxial testing machine was of the screw-driving type, and its load rating was also 50 N. The crosshead of this testing machine was controlled at a constant speed, namely, 2.5×10^{-3}, 5.0×10^{-3}, 1.0×10^{-2}, 2.5×10^{-2}, 5.0×10^{-2}, 0.1, 0.25, 0.5, 1, 2.5, 5, or 25 mm per minute. Continuous change of the driving speed was not possible.

A spring and a bearing were used for decreasing the spring constant and reducing tangential force and twisting moment, as shown in Fig. 1. The spring constant of this component was about 24 kN/m, whereas that of the reference and the calibrated force transducers were about 290 kN/m and 240 kN/m, respectively. A personal computer was connected to the reference tuning-fork type force transducer, the uniaxial testing machine, and the amplifier of the strain-gauge type force transducer. The computer sent commands for changing the driving speed to the testing machine while reading the outputs of the reference tuning-fork type force transducer. To avoid the effect of backlash, the applied force was controlled to approach from one side.

The force controllability of this system was investigated. Repeatability of measurements and reproducibility of rotational position of the force transducer were also evaluated.





3. Results and discussion

3.1 Force controllability

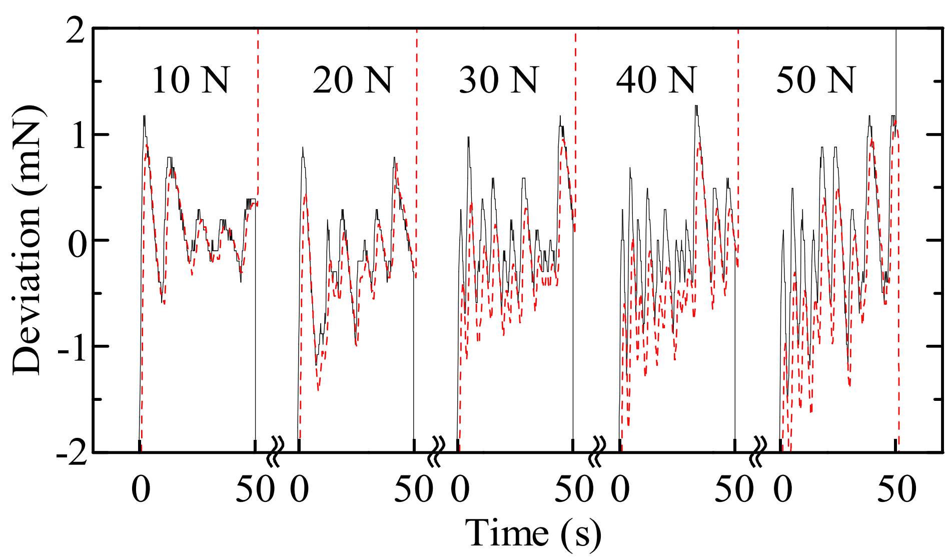


Fig. 2 illustrates an example of force tracing process in which the force was increased to 10, 20, 30, 40 and 50 N in steps. The solid and dotted lines indicate readings of the reference tuning-fork type force transducer and readings of the strain-gauge type force transducer under calibration, respectively. The horizontal axis indicates time after reaching each calibration force step, and is divides into five steps. The vertical axis indicates the deviation of the readings of the reference force transducer from the target value of the force control. Readings of the force transducer under calibration are overlaid on this diagram for comparison; the average of the readings is set as the baseline. To prevent screw backlash, the approaching force was varied in the increasing direction only. It was not possible to employ proportional control due to restriction of the discrete crosshead driving speed. For this reason, while the readings of the reference force transducer were slightly less than the target value, the screws were driven to increase the force using the minimum speed of 2.5×10^{-3} mm per minute, otherwise the applied forces would naturally decrease due to stress relaxation of structural elements even though the screws stopped. These effects are inverted when decreasing the applied force.

The amplitude of the oscillations was approximately 1 mN, regardless of the target force. This was about ten times greater than the force resolution of the reference tuning-fork type force transducer, namely, 0.1 mN. In this study, it was difficult to further suppress the oscillation due to resonance of additional springs under the restricted conditions for applying force and the response lag between the applied forces and the readings of the reference force transducer. Although the results reported by PTB [3] showed much smaller oscillation than those in the present study, presumably owing to the better resolution of the reference force transducer, the oscillation amplitude of this force comparator is not inferior to ordinary DWMs, and it can be said that the force comparator with the tuning-fork type reference force transducer is feasible for practical calibration of small-capacity force transducers. It should also be noted that the waveform of the readings of the force transducer under calibration was in good agreement with that of the reference force transducer's output, except for a time lag of approximately 1 second between the waveforms of the two force transducers, which may be attributed to a Bessel-type digital filter of 0.45 Hz used in the DMP-40 amplifier.

3.2 Repeatability and reproducibility

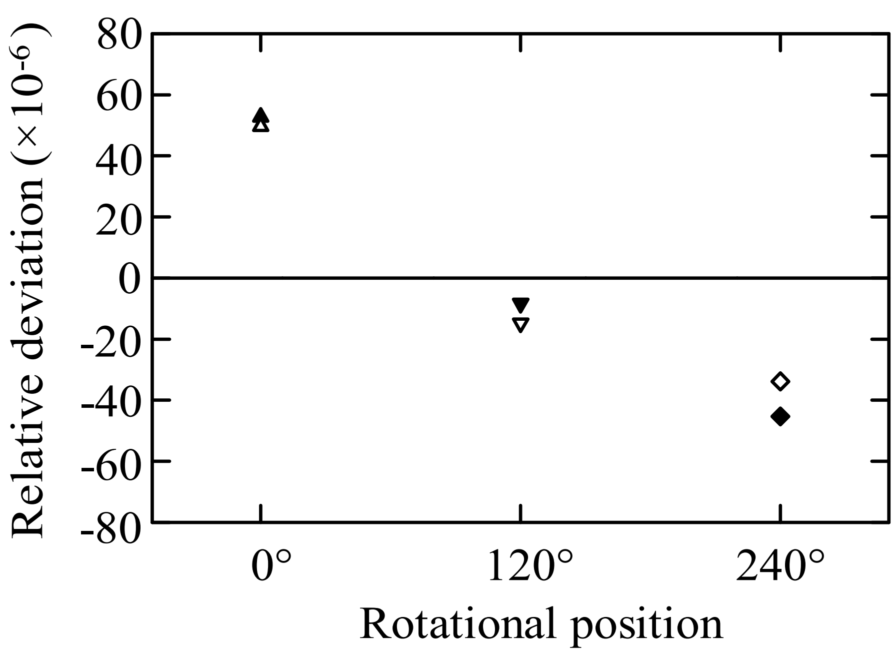


Fig. 3 shows the repeatability of two readings at each of the rotational positions and the reproducibility with changing rotational position of the force transducer under calibration. The horizontal axis indicates rotational position, and the vertical axis indicates the relative deviation. Measurements were performed twice after a preloading at each rotational position of 0°, 120°, and 240°. In Fig. 3, the triangle, inverted triangle, and diamond symbols indicate readings at 0°, 120°, and 240°, respectively. Solid and hollow symbols correspond to readings at 1st and 2nd cycles, respectively. All results were recorded at the rated capacity of 50 N.

The relative repeatability was between 0.3×10^{-5} and 1.2×10^{-5}. As can be seen in Fig. 2, the relative amplitude of oscillation while maintaining the applied force was about 1.5×10^{-5}, these results were within the excepted range. The relative reproducibility was 9.8×10^{-5} peak to peak using the force comparator, whereas it was 2.0×10^{-5} using the conventional DWM. Although the angular-contact ball bearing relaxed the eccentric forces and moments caused by the restrained loading system (relative reproducibility was 6.6×10^{-4} without the bearing), some eccentric forces and moments still remained and affected the reproducibility. However, the degrees of repeatability and reproducibility achieved were satisfactory for calibration of commercial force transducers.

3.3 Comparison with DWM

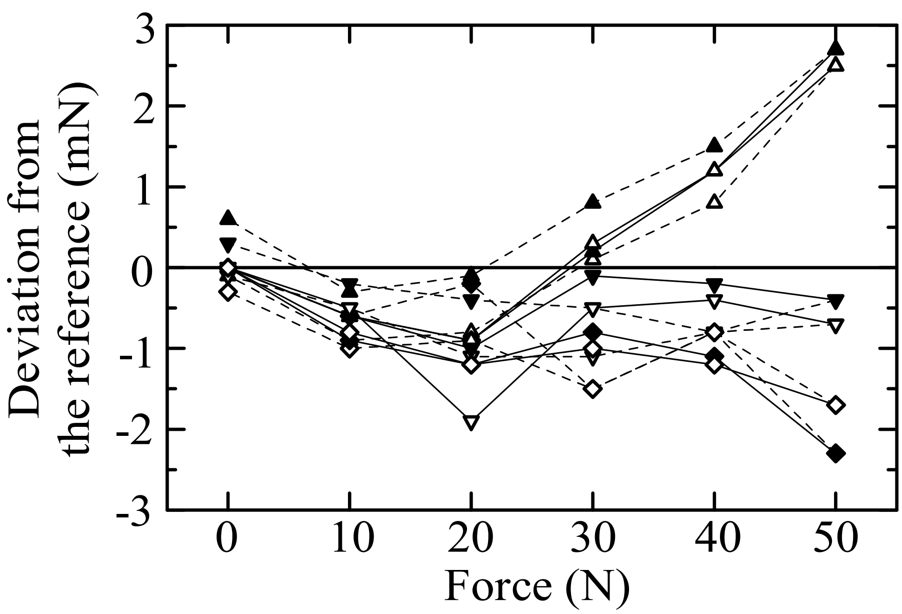


Fig. 4 shows calibration results of the force transducer using the force comparator, in comparison with those using the conventional DWM. The horizontal axis indicates calibration force steps, and the vertical axis indicates deviation from the reference values obtained by the calibrations using the DWM. Solid and dotted lines indicate increasing and decreasing forces, respectively. The symbols have the same meaning as those in Fig. 3. The calibrations using the DWM were carried out before and after the calibration using the force comparator, and the readings were averaged to define the reference values. The deviations at increasing and decreasing force steps were evaluated by subtraction from the reference values.

The average of reading at three rotational positions at each force step differed by up to 1 mN from the reference calibration results. This could not be fully accounted for by the sensitivity drift of up to 0.7 mN between the initial and the final calibrations using the DWM; the eccentric forces and moments accounted for the remainder. Additionally, there was a loading time difference between the force comparator and the DWM. In the force comparator, 20 - 30 seconds was required to increase or decrease to the next force step, whereas only several seconds was required in the DWM. This time difference caused a slight sensitivity change due to a creep effect. However, because the difference in the sensitivity was relatively small compared to the reproducibility, adequate uncertainty could still be achieved for practical use.

The hysteresis differences between the force comparator and the DWM were up to only 1 mN. This was caused by the hysteresis of the reference force transducer, which was up to 300 μN, and the loading time difference between them. The tuning-fork type force transducer exhibited little hysteresis, and therefore, its performance was satisfactory for practical use.

The reproducibility at the force steps close to the rated capacity was larger than that near zero. It was suspected that this problem was caused by the undesirable effect of friction in the ball bearing. In future, to solve this problem, the relaxation mechanism of the eccentric forces and moments will have to be improved.

In addition, it is also necessary to improve some other basic characteristics, such as the controllability of the loading system and the force resolution of the reference transducer. Although there were still some problems, this force comparator was able to calibrate the force transducer with sufficient uncertainty. Since the tuning-fork type force transducer exhibits little creep, as reported in a previous study [4], it may be suited to not only quasi-static calibration but also to continuous calibration.

4. Summary

A force comparator has been manufactured for calibration trials of small-capacity force transducers. The force comparator employs a tuning-fork type force transducer of 50 N capacity as a reference, a commercially available screw-driving type uniaxial testing machine for applying force, and a simple control system for maintaining the force. Although there is some room for improvement in resolution for controlling the applied force and in removing or relaxing the eccentric force and moment, the tuning-fork type force transducer was found to be suitable as a reference due to its excellent long-term stability and small hysteresis characteristics. The force comparator with the tuning-fork type reference force transducer will be suitable for calibration of force transducers, especially in small force ranges and/or in continuous calibration.

References

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Figure captions:

Figure 1: (a) Illustration and (b) photograph of the force comparator.

Figure 2: Residual deviation of readings of the reference and the calibrated force transducers.

Figure 3: Repeatability and reproducibility of the force transducer under calibration.

Figure 4: Deviation between the force comparator and the conventional DWM.