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APPLICATION OF A LOADING FRAME STRUCTURE TO A FORCE COMPARATOR REFERRING TO A TUNING-FORK-TYPE FORCE TRANSDUCER

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Abstract – A loading frame structure and a piezoelectric actuator were applied to a force comparator referring to a tuning-fork-type force transducer. The gravitational force acting on the loading frame was shared between the reference transducer and another transducer under calibration. Introduction of the loading frame structure improved reproducibility of the force transducer under calibration, and the piezoelectric actuator improved force controllability in comparison with that of the previous reported force comparator. Because of the excellent linearity and small hysteresis of the reference transducer, the force comparator showed a capability comparable to dead-weight-type force standard machines.

Keywords: Tuning fork, hysteresis, fine and coarse adjustment

1. INTRODUCTION

There is expected to be a demand for force comparators that are suitable for calibration in the small force range below several hundred Newtons. Conventional dead-weight-type force standard machines (DWMs) show excellent performance in calibrating force transducers, with the smallest uncertainty currently achieved; however, their weights have a complex connection structure and are difficult to handle. In small force calibration, such a complex structure is a disadvantage in terms of manufacturing and mass adjustment. Force comparators, on the other hand, have a simple structure and, when equipped with high-performance force transducers, can show capabilities comparable to conventional DWMs, such as good long-term sensitivity stability, low creep, and small hysteresis. To this end, there have been some trials to develop force comparators operating in the small force range using reference electromagnetic balances [1–4].

In one study, a tuning-fork-type force transducer has demonstrated a relative long-term sensitivity stability of under 3×10^{-5} negligible creep, and relative hysteresis of under 1×10^{-5} [5]. These characteristics make it suitable for the reference transducer of a force comparator. We have already tried to develop a force comparator referring to a tuning-fork-type force transducer [6]; however, the results of force calibration were not satisfactory in terms of reproducibility and short-term stability of the applied force, even though the results were comparable to those obtained with a DWM. In the work described here, to overcome these problems, a loading frame structure and a piezoelectric actuator were applied to the force comparator.

2. DESIGN AND STRUCTURE

In our previous study [6], we installed a reference tuning-fork-type force transducer of 50 N capacity, developed by Shinko Denshi Co., Ltd., into a screw driving type uniaxial testing machine as a loading mechanism of the force comparator. A strain-gauge-type force transducer under calibration was inversely set on the lower side of the crosshead. However, the relative reproducibility of the strain-gauge-type force transducer was 9.8×10^{-5} peak-to-peak using that force comparator, whereas it was 2.0×10^{-5} when calibrated by using the conventional DWM. The

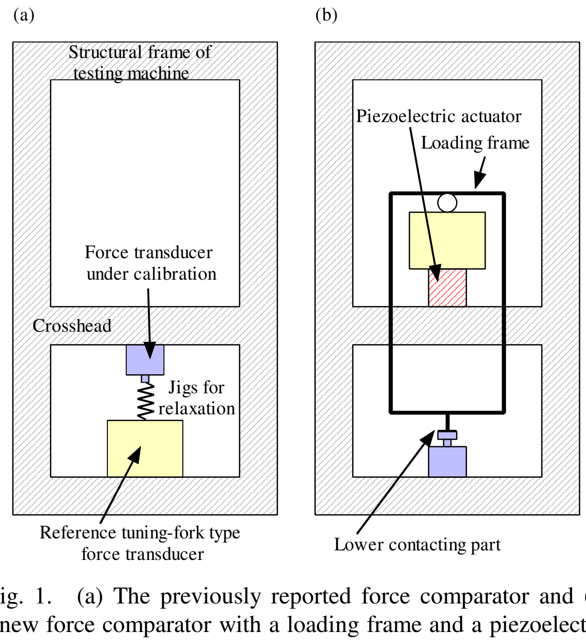

Fig. 1. (a) The previously reported force comparator and (b) the new force comparator with a loading frame and a piezoelectric actuator.

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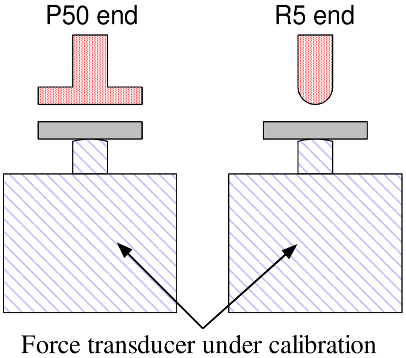

Fig. 2. Two types of lower contacting parts of the loading frame.

deteriorated reproducibility of the force transducer under calibration was suspected to be caused by an eccentric force and parasitic moments due to constraint between the reference and calibrated transducers. Though some inserted jigs can reduce such eccentric force and moments, the constraint is unavoidable if the force comparator adopts a face-to-face structure between the two transducers.

In this paper, we adopted a loading frame structure of approximately 52 N to link two force transducers, as depicted in Fig. 1. The loading frame had similar degrees of freedom of motion to those of the conventional DWM, which is expected to improve the reproducibility.

To reduce the constraint between the reference force transducer and the loading frame, a stainless steel ball of 8 mm in diameter was inserted between them. Because there were dimples on the surfaces contacting the steel ball, the ball maintained the alignment between the reference force transducer and the loading frame, while allowing swinging of the loading frame.

Two types of lower contacting parts of the loading frame were prepared, as depicted in Fig. 2. One was a flat plate-shaped end with a diameter the same as that of the loading plate of the force transducer under calibration, namely, 50 mm (called 'P50 end'). The P50 end had an advantage of easily maintaining alignment between the loading frame and the force transducer under calibration. The other type was a spherical end with a radius of 5 mm (called 'R5 end'). The R5 end allowed inclination of the loading frame and reduced the eccentric force and parasitic moments. The force transducer under calibration itself usually has a spherical load button that contacts the loading plate. However, the radii of the load buttons of the force transducers in NMIJ are over 15 mm. It is expected that a smaller radius will reduce the eccentric force and parasitic moments, so long as the contact pressure does not exceed the yield stress. The R5 end is suitable for these conditions and is easily obtainable in the marketplace.

Because the gravitational force applied to the loading frame was shared between the reference force transducer and the force transducer under calibration, the force applied to the force transducer under calibration was sensed by subtracting the reading from the rated capacity of the reference force transducer. The relative hysteresis of the

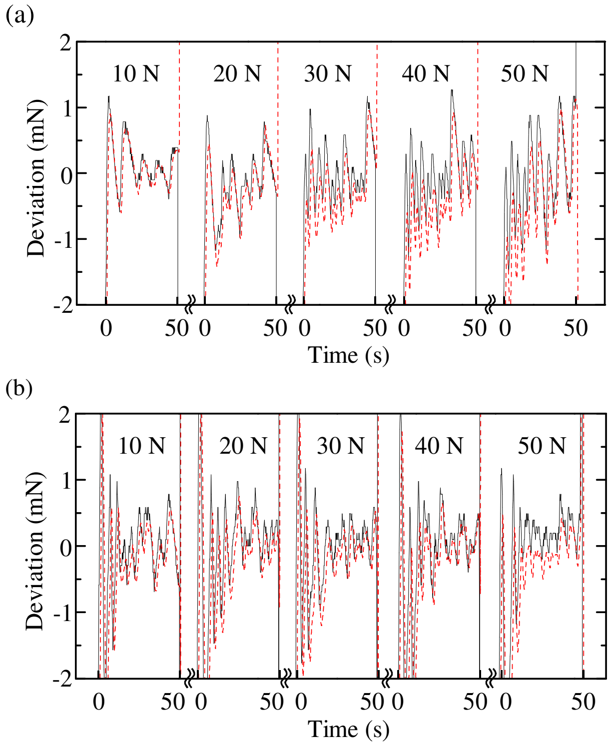

Fig. 3. Residual deviation of readings of the reference and calibrated force transducers obtained with (a) the previously reported force comparator and (b) the new force comparator with the piezoelectric actuator.

reference tuning-fork-type force transducer was under 1×10^{-5}, which was as small as the relative calibration uncertainty of the conventional DWM. Therefore, the tuning-fork-type force transducer was considered suitable for use as a reference standard.

Regarding force controllability, in our previous paper [6], the applied force was controlled only by the screw driving mechanism of the uniaxial testing machine. Although this was advantageous in terms of its simple structure and wide application, like the uniaxial testing machines widely used in industry, the force controllability with such a simple system was poor in comparison with other systems using piezoelectric actuators [1–4]. In this study, therefore, we employed a piezoelectric actuator in addition to the screw driving mechanism of the testing machine, as fine and coarse adjustment, respectively. Although the stroke of the piezoelectric actuator reached 50 μm, applied forces up to 50 N were generated only when using both the piezoelectric actuator and the screw driving mechanism, due to the low stiffness of the loading frame. Control using the piezoelectric actuator started after the screw motor was stopped near the calibration force step.

3. RESULTS AND DISCUSSION

3.1. Force controllability

The force controllability of the force comparator was improved using the piezoelectric actuator. Fig. 3 illustrates

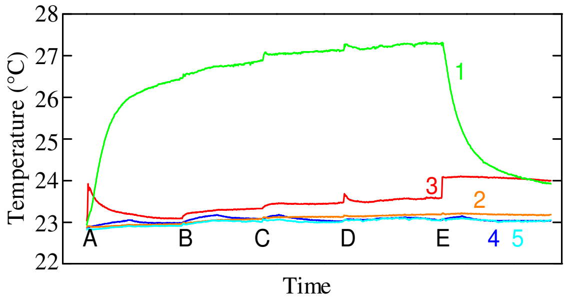

Fig. 4. Temperature drifts (1) in the structure of the testing machine, (2) in the crosshead of the testing machine, (3) in the terminal box of the force transducer under calibration, (4) in the side face of the reference tuning-fork-type force transducer, and (5) in the piezoelectric actuator. Events on the time axis are (A) turning on of the testing machine and setting the force transducer, (B) maintaining alignment at 0° and starting measurement, (C) rotation to 120° and starting measurement, (D) rotation to 240° and starting measurement, (E) finishing measurement and turning off the testing machine. Probe 3 was removed from the force transducer at event E.

examples of a force tracing process in which the force was increased to 10 N, 20 N, 30 N, 40 N, and 50 N in steps. Figs. 3(a) and (b) correspond to examples of the previously reported coarse adjustment and the fine and coarse adjustment demonstrated this time. The solid and dotted lines indicate readings of the reference tuning-fork-type force transducer and the strain-gauge-type force transducer under calibration, respectively. The horizontal axis indicates time after reaching each calibration force, and is divided 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. By employing a piezoelectric actuator, proportional control was applied to the force control. The force amplitude of about 0.3–0.5 mN peak-to-peak obtained in the results was satisfactory, considering that the resolution of the reference tuning-fork-type force transducer is approximately 0.1 mN, though there was some room for improvement.

3.2. Reproducibility and deviation

Two strain-gauge-type force transducers with 50 N capacity were used for comparison with the reference DWM. (These transducers are referred to as 'instrument 1' and 'instrument 2', respectively.) Their nominal radii of the spherical load buttons were 16 mm for Instrument 1 and 18 mm for Instrument 2. However, because slight plastic deformation was observed at the end of Instrument 2, its true radius was a little larger than 18 mm. A DMP-40 amplifier (Hottinger Baldwin Messtechnik GmbH) was used with these instruments.

Calibrations using the reference DWM were carried out before and after the calibration using the force comparator, and the recorded readings were averaged to define the reference values. These calibrations were performed in

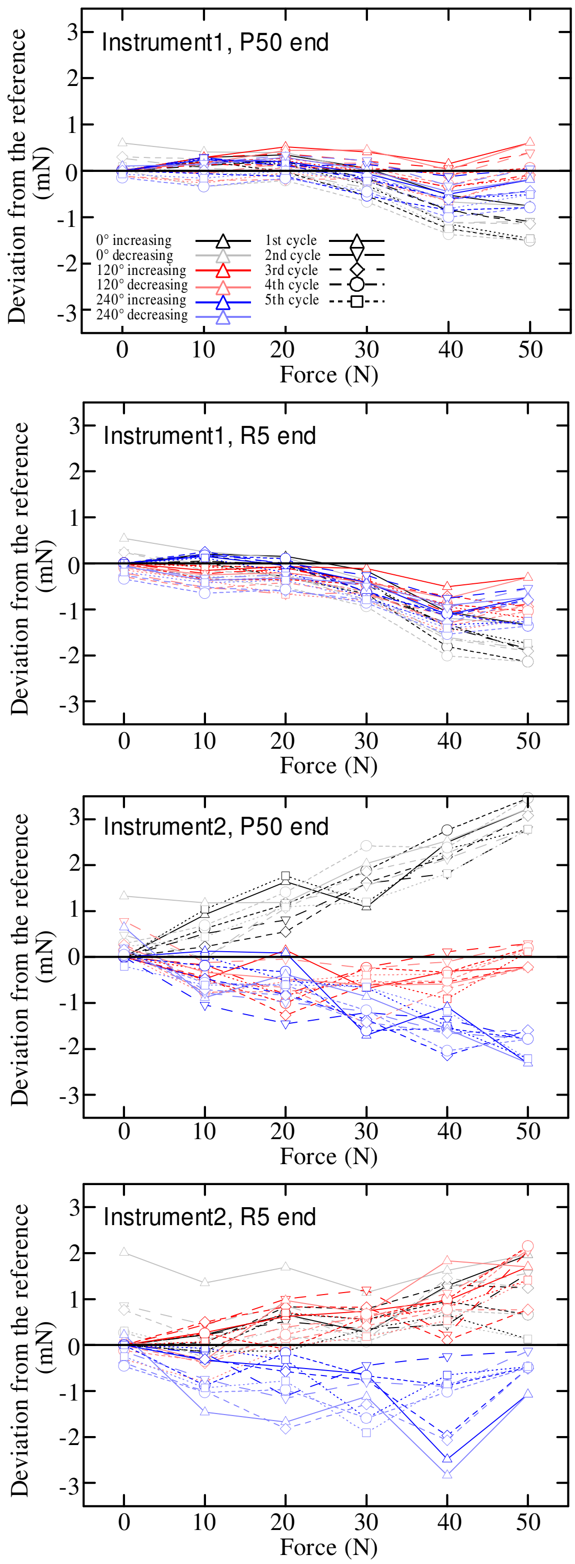

Fig. 5. Deviation of each calibration cycle from the reference value measured by the DWM.

accordance with ISO 376 [7]; briefly, preloadings and two calibration cycles were conducted at three rotational positions of 0°, 120° and 240°. The reproducibilities of Instruments 1 and 2 at the rated capacity of 50 N in the calibration using the DWM were 0.2 mN and 2.2 mN,

Table 1. Reproducibility of instruments at the rated capacity of 50 N.

	Reference DWM	Comparator with P50 end	Comparator with R5 end
Instrument 1	0.2 mN	1.4 mN	0.93 mN
Instrument 2	2.2 mN	5.0 mN	2.2 mN

respectively.

Calibrations using the force comparator were also carried out in accordance with ISO 376, but preloadings and five calibration cycles were conducted at every rotational position for experimental purposes, in contrast to preloadings and only one or two calibration cycles performed at every position in the general calibration. Because the force controllability was not always sufficient, repeat measurements were necessary to clarify the average behavior.

The effect of temperature changes during calibration on the output from the force transducer need to be clarified. Fig. 4 shows the temperature drift of the force transducer under calibration, recorded using resistance thermometers. The degree of drift was less than 0.4 K and it caused a sensitivity drift of less than 0.5 mN at the 50 N force step. Although this was not the main factor in the observed fluctuation, it was a non-negligible one. Nevertheless, the short-term repeatability was not affected by the temperature changes.

Fig. 5 show the calibration results of the force transducers 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. The deviations at increasing and decreasing force steps were evaluated by subtracting the readings from the reference values. The colors of the symbols indicate the different rotational positions of the force transducer under calibration, and the shapes indicate the order of the calibration cycles. In these figures, kinks in the linearity plots and distributions at the same rotational position were mainly due to the force controllability of amplitude 0.3–0.5 mN.

Table 1 shows the reproducibility of the instruments when using the reference DWM and when using the force comparator with the P50 and R5 ends. The reproducibility was improved in comparison with that using the previous face-to-face structure [6], although it was worse than that using the reference DWM, especially in the case of the P50 end. This suggested that there was imperfect parallelism and perpendicularity between the P50 end and the loading frame, even though the P50 end was produced with care and precision. The position of the top center point of the loading frame was maintained by the steel ball, and therefore, eccentric force and parasitic moments caused by asymmetry acted on the force transducer under calibration. On the other hand, the R5 end showed reduced reproducibility in comparison with the P50 end. The eccentric horizontal

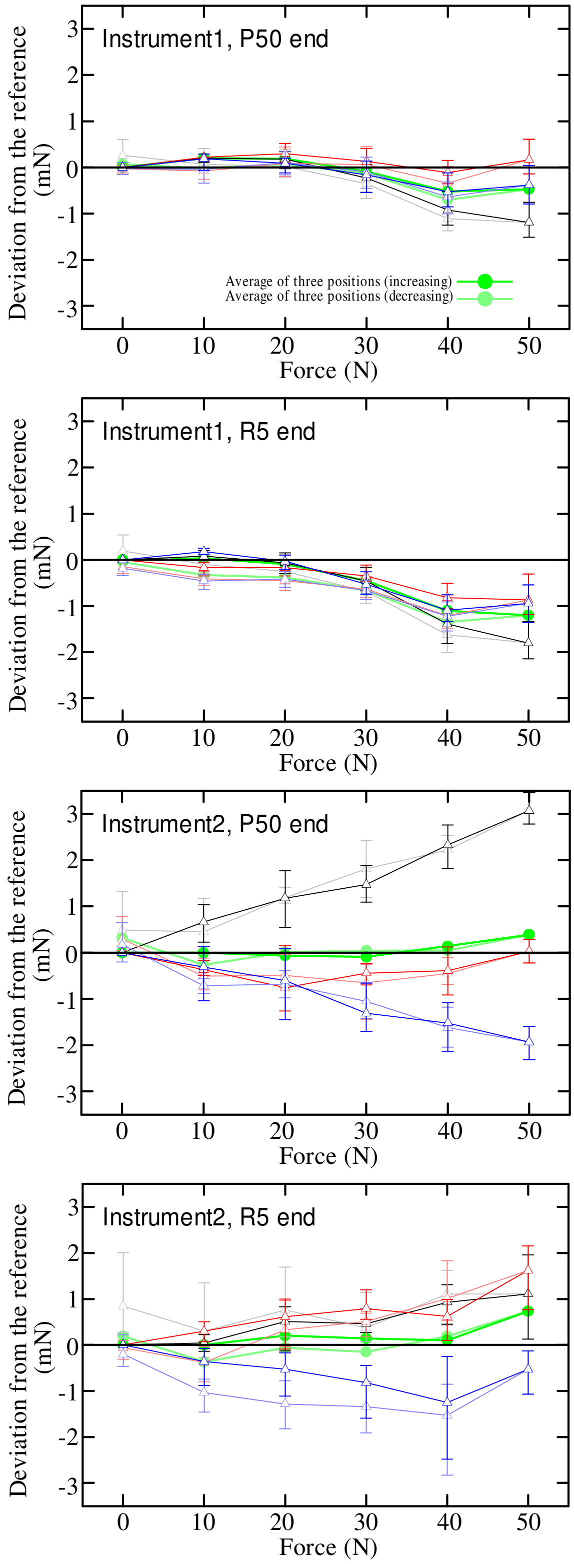

Fig. 6. Mean deviation of each calibration cycle from the reference value.

force and parasitic torsional moment were relaxed by the spherical shape due to loose constraint.

To observe the deviations from the reference values, the mean deviation of five repeat measurements at each rotational position was taken, as plotted in Fig. 6. The horizontal and vertical axes, the symbols and their colors are similar to those in Fig. 5, except for the green lines, which correspond to the average of three rotational positions. The maximum and the minimum values in five repeat measurements are shown as vertical bars at each point. The kinks on the curves are smoother than those in Fig. 5 due to the averaging. However, because of limitations of force controllability, curves as smooth as those obtained with the DWM could not be obtained by averaging only two calibration cycles at the same rotational position, which is the minimum requirement of ISO 376 and also general calibration conditions.

The deviations of the average of three rotational positions from the reference value recorded by the DWM were satisfactorily small, especially when using the P50 end. These maximum values were 0.52 mN for Instrument 1 and 0.39 mN for Instrument 2, where the reference tuning-fork-type force transducer was calibrated by the DWM 48 days before. This shows the excellent long-term stability and reversibility of the tuning-fork-type force transducer and its suitability for use as a reference standard. In the case of the R5 end, the deviation from the reference value was larger than that of the P50 end. It was assumed that variation and misalignment of the contact point between P50 end and the loading plate of the force transducer under calibration caused parasitic bending moments. In future work, we will more closely examine the orientation of the loading frame.

The force comparator using the loading frame structure improved the reproducibility in comparison with the previous face-to-face structure and showed better agreement with the conventional DWM. The tuning-fork-type force transducer was suitable for use as a reference force standard because of its stability of sensitivity and reversibility. Although there is still room for improvement in the design, the loading frame structure will also be useful for developing a new force comparator for the sub-Newton range using a small-capacity reference force transducer.

4. SUMMARY

A force comparator was improved by employing a loading frame structure and a piezoelectric actuator. With these improvements, a tuning-fork-type force transducer could be utilized more effectively 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.

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