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DEVELOPMENT AND EVALUATION OF TUNING FORK TYPE FORCE TRANSDUCERS

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Abstract: Tuning fork type load cells are expected to have better long-term stability than conventional strain gauge type load cells. A new 50 N rated capacity load cell has been developed herein adopting a Double-Ended Tuning Fork (DETF) sensing unit. The performance of two such load cells was evaluated using the 500 N force standard machine at the National Metrology Institute of Japan (NMIJ). The DETF load cells were found to have low creep, low hysteresis and superior long-term stability.

Keywords: tuning fork, sensibility, stability

1. INTRODUCTION

Recently, the traceability of measurements has become more important with the spread of quality control systems required to achieve conformance to international standards such as ISO 9000 and 14000. Therefore, ensuring the traceability of force measurement by national metrology institutes (NMIs) has been demanded by industry and the official trade authorities. International comparisons between NMIs using traveling load cells are required to ensure consistency between these laboratories internationally. Also, comparison calibrations of the force calibration machines used in many calibration laboratories using transfer load cells are required to ensure traceability of force calibration. These comparisons involve uncertainties arising from force standard machines, force calibration machines and also traveling/transfer load cells, particularly their long-term stability of sensibility. Accurate comparisons are better ensured by employing sensitivities of the load cells stable for long periods, usually several months.

At present, traveling/transfer load cells use strain gauges. However, for capacities below 1 kN, the stability of sensibilities of such load cells is insufficient. The size of the elastic bodies used in these load cells reduces with capacity. However, the size of the strain gauges used therein remain almost constant. As a result, low stiffness materials such as aluminum are often employed to make the elastic bodies for these smaller load cells. Unfortunately, such materials generally have inferior elastic stability when compared to that of heat-treated steel. Additionally, the properties of the elastic bodies in these small load cells become more sensitive to machining accuracy. These difficulties are part of the reasons why no international comparison of forces below 1 kN has yet been planned.

A tuning fork type force sensor is a kind of resonator. Load cells with built in tuning fork type force sensors should exhibit superior long-term stability than conventional strain gauge type cells. This is because they directly convert applied force into resonant frequency and this conversion mechanism is insensitive to the inherent characteristics of the elastic bodies in load cells and analog to digital converters [1]. Therefore, it is considered that they would be well suited for use in traveling/transfer load cells and, particularly, for comparison of small forces. However, with the exception of microscopic force detection using Micro-Electrical-Mechanical Systems (MEMS) technologies, it is believed that no practical tuning fork type force sensor has yet been put into practical use.

This paper details the development of a new 50 N capacity tuning fork type load cell with sufficient stability and durability for practical use. The long-term stability of two such tuning fork type load cells was evaluated using a force standard machine at the National Metrology Institute of Japan (NMIJ).

2. EXPERIMENTS

2.1. *Tuning fork type load cells*

Compared to a simple vibration beam, the Double-Ended Tuning Fork (DETF) vibrator eliminates redundant bending vibration modes due to its symmetry and avoids deterioration of mechanical quality factor [1]. However, due to the residual stress and strain caused by assembling and fixing a tuning fork element to a structural body, repeatability remains a problem. Kobayashi et al. solved this problem by integrating the vibrator into a single metal block [2]. An illustration of these monoblock DETF force sensing units is shown in Fig. 1. This structure has the additional advantage in that the elastic fulcrum, to some degree, reduces the transmission of any non-axial components of the applied force. These units have actually been applied in precise electric balances produced by Shinko Denshi Co. Ltd. and also to the shape control system of the 8.3 m concave mirror of the Subaru telescope in Hawaii [3].

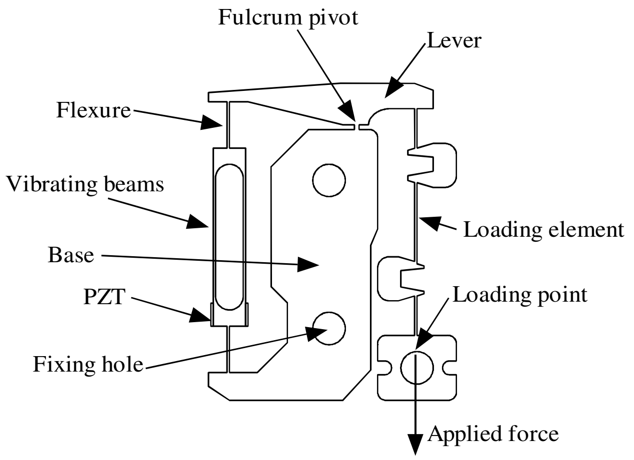

Fig. 1. Illustration of a monoblock DETF force sensor units.

Utilizing the monoblock principle, two 50 N capacity DETF load cells were developed by Shinko Denshi Co. Ltd., shown in Fig. 2. Here forward, these load cells are referred to as ‘instrument 1’ and ‘instrument 2’ respectively. The internal structure of the DETF load cells were similar to that employed in the commercial electric balances. However, these load cells have specially designed load fittings to allow force to be applied while reducing detrimental effects due to any non-axial force components. Three types of load fittings were employed. The resolution of these load cells is 2×10^{-6} relative and the minimum sampling period is 0.2 s.

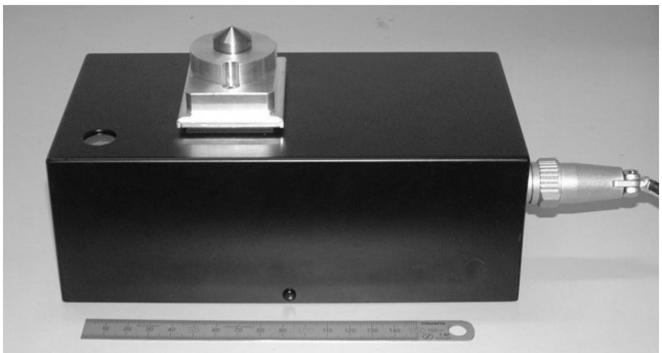

Fig. 2. Outline of a monoblock DETF load cell. A 150 mm scale is shown for reference.

2.2. *Force standard machine*

The 500 N dead weight type force standard machine (500 N DWM) at the NMIJ, outlined in Fig. 3, was used to evaluate the load cells. The 500 N DWM has two series of linkage-weights and is capable of applying accurate forces in 10 N increments. Therefore, the 50 N load cells were calibrated in force steps of 10 N, 20 N ... 50 N. The Calibration and Measurement Capability (CMC) of this force standard machine is 2×10^{-5} relative [4]. Room temperature was usually maintained within a ±1 °C tolerance (actual logs show variance between 22.8 °C and 23.7 °C). However, more unusual conditions were investigated in order to evaluate temperature sensitivity.

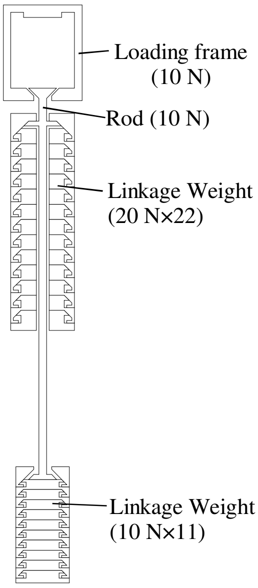

Fig. 3. Outline of the NMIJ's 500 N dead weight type force standard machine (DWM).

2.3. *Loading procedure*

Force measuring instruments are usually calibrated according to the procedure described in the ISO 376 standard [5]. In this paper, the loading procedure described in Fig. 4 was applied to the evaluation of the load cells. Three preloadings and three symmetrical rotations (i.e. 0°, 90°, 180°, 270° due to geometric restriction of the force standard machine) were carried out for each calibration cycle. Calibration data was recorded in two series of increasing and decreasing force for each rotational position. Readings were noted 30 s after the correct force was reached for each calibration step.

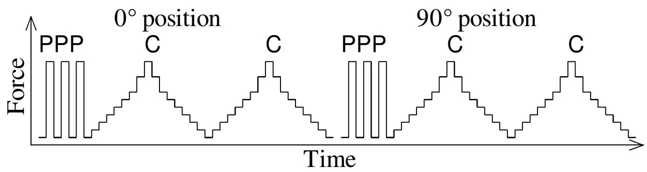

Fig. 4. The loading procedure used to evaluate the load cells. P and C refer to ‘preloading’ and ‘calibration cycle’ respectively. Although this figure only illustrates calibration at 0° and 90° positions, calibration at 180° and 270° positions were performed in a similar manner.

2.4. *Load fittings*

As stated in section 2.1, the monoblock DETF force sensor unit is, to some degree, capable of reducing the detrimental effects of any non-axial components of the applied force. In addition, because electric balances generally employ the Roberval mechanism, load cells used in such balances are not very sensitive to rotation moments created by eccentric loading. However, in the preliminary experiments, it was found that the output of the load cells was scattered disregardably when, similar to normal electric balances, a plain plate was used to attach the load. To generate forces above 20 N, the weights of the 500 N DWM were hung from a rod nearly 2 m in length. This led to a slight but natural swing which, with a plain plate load fitting resisting any slight inclination of the DWM's loading frame, imparted some horizontal force to the load cell. To overcome this problem, three other types of load fitting were employed, illustrated in Fig. 5. All of these fittings allow slight inclination of the loading frame and reduce the detrimental effects of any non-axial force components. Type (a) consists of a convex plate, a concave plate and some steel balls for bearing. It is similar to the eccentric loading removal mechanism employed on an accurate mass comparator. Types (b) and (c) combine a convex plate and a plane (or partially concaved) plate. The former plate is called the 'load button' and the latter is called the 'loading pad.' In many cases, load buttons are utilized for commercial strain gauge type load cells. The radius of the type (b) load button is R30 mm and that of the type (c) button is R1 mm.

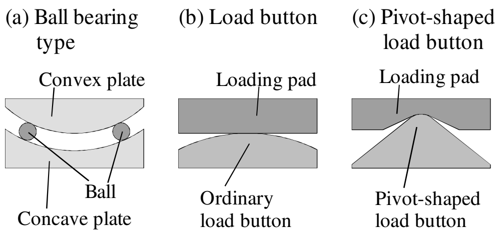

Fig. 5. Illustrations of the load fittings employed herein.

2.5. Evaluated characteristics

ISO 376 defines five types of relative errors, i.e. reproducibility, repeatability, interpolation, zero and reversibility [5]. The interpolation error was not evaluated because only five force steps were used. The creep effect, long-term stability, and temperature dependency were also evaluated. For a performance comparison between tuning fork and conventional strain gauge types, three kinds of 50 N capacity strain gauge type load cells were also evaluated in the same manner. These strain gauge type load cells are often used for transfer standards for comparison calibrations of force calibration machines. A DMP-40 indicator was used for these strain gauge type load cells. The sampling period was 0.2 s.

3. RESULTS AND DISCUSSION

3.1. Characteristics

Four characteristics obtained for the tuning fork type load cells, i.e. reproducibility, repeatability, zero variation and reversibility, are shown in Figs. 6, 7, 8 and 9, respectively. In these figures, the triangle, inverted triangle and circle symbols refer to the ball bearing type, R30 load button type and R1 load button type load fittings respectively. The black square symbol refers to the characteristics of the reference 50 N load capacity strain gauge type load cells.

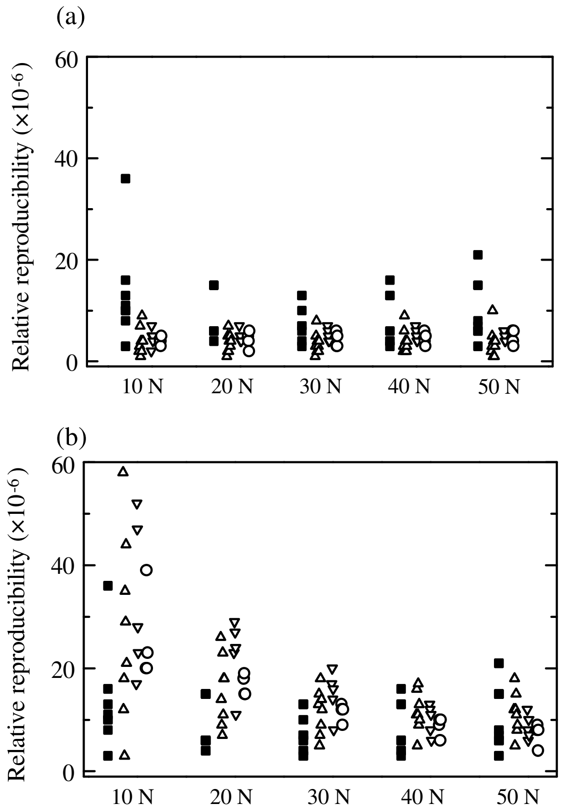

Fig. 6. Load cell reproducibility: (a) instrument 1 and (b) instrument 2.

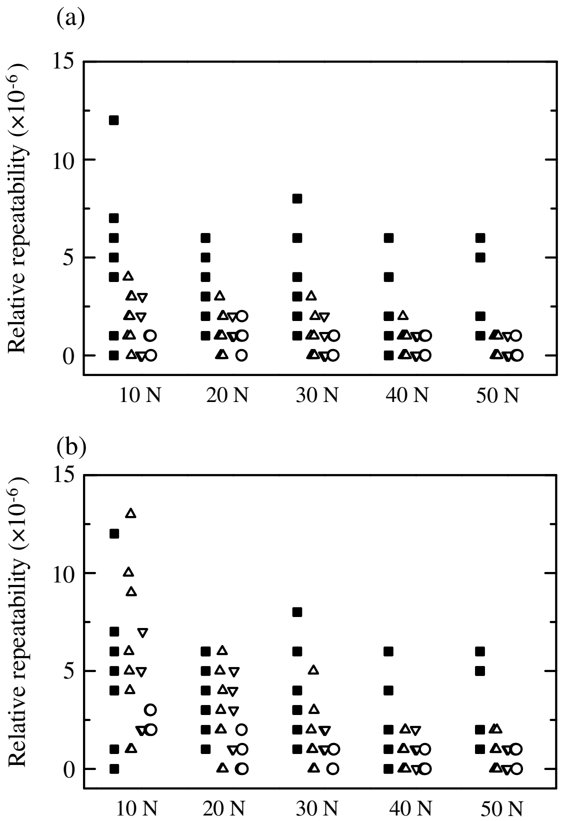

Fig. 7. Load cell repeatability: (a) instrument 1 and (b) instrument 2.

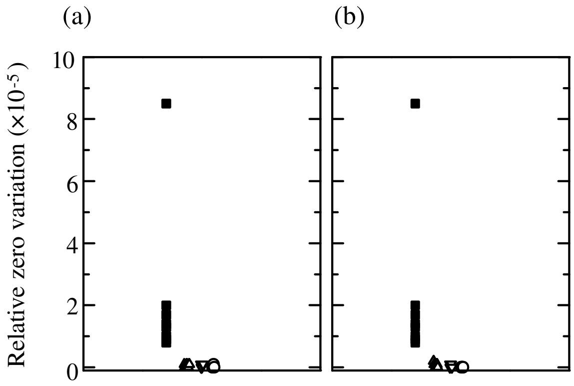

Fig. 8. Load cell zero variation: (a) instrument 1 and (b) instrument 2.

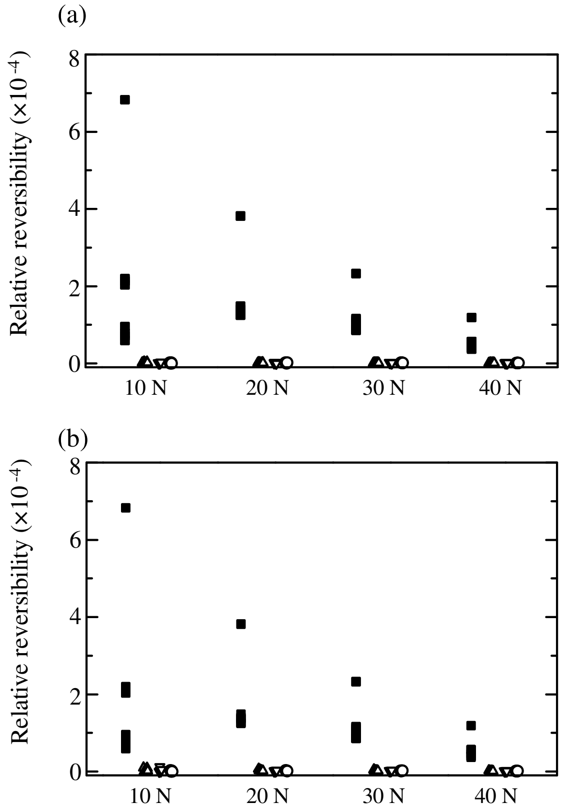

Fig. 9. Load cell reversibility: (a) instrument 1 and (b) instrument 2.

The reproducibility and repeatability of the two tuning fork type load cells were not consistent. For instrument 1, these characteristics were superior to those of the strain gauge type load cells. However, in some cases, for instrument 2, the characteristics were equal to, or slightly inferior to, those of the strain gauge type load cells. The pivot type load fitting had superior reproducibility and repeatability to the other load fittings.

Zero variation and reversibility of the tuning fork type load cells are clearly smaller than for the strain gauge types. The reversibility of the tuning fork type load cells was less than 1×10^{-5}, while values for the strain gauge types were in the order of 10^{-4}. To achieve adequate resolution of strain gauge type load cells, a minimum degree of strain must be generated in the employed elastic bodies. In contrast, because stress variations are sensed through resonant frequency variations, the tuning fork type load cells do not require as much strain. Strain of elastic bodies is generally accompanied by hysteresis. Zero variation and reversibility are directly influenced by this hysteresis. The different sensing principle employed in the two types of load cell account for the differences obtained in zero variation and reversibility. The results show that the tuning fork type load cells are better suited to accurate force measurement, irrespective of stress history.

3.2. Creep

A typical creep plot for the tuning fork type load cells is shown in Fig. 10(a). For comparison, that for a strain gauge type load cell is shown in Fig. 10(b).

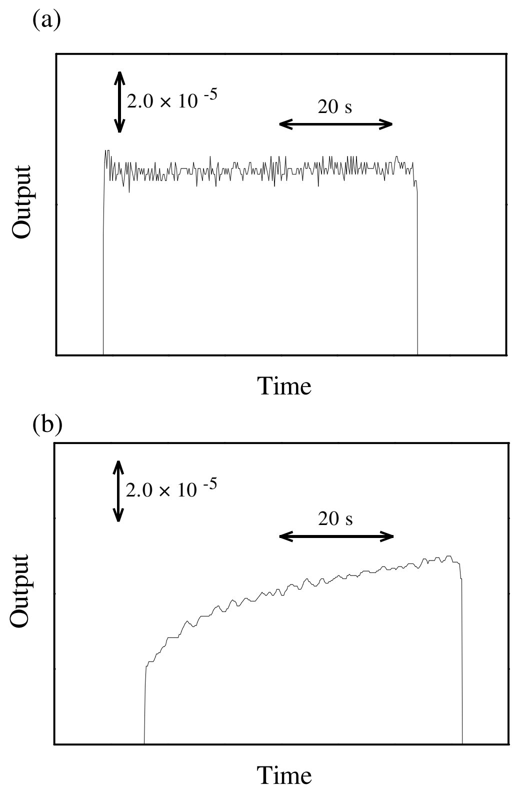

Fig. 10. Typical load cell creep effect: (a) tuning fork type and (b) strain gauge type.

The output of the strain gauge type load cell gradually changes under constant applied force conditions of 50 N. In contrast, the output of the tuning fork type load cell displays no discernable creep characteristic. However, it is unstable initially and also shows fluctuations due to the relatively low force resolution.

Similarly to the explanation for the performance differences relating to zero variation and reversibility, it is considered that, for the creep effect, the superior performance of the tuning fork type load cells is also due to the different sensing principle. At present, readings are generally recorded at least 30 s after the calibration force is applied. This is because the obvious creep effect of ordinary strain gauge type load cells appears immediately after applying the force. The tuning fork type load cells, which are not as susceptible to creep, have a potentially shorter waiting time before recording.

3.3. Long-term stability

Changes in sensitivity over a year are illustrated in Fig. 11. These sensitivities were recorded for force of 50 N. Error bars are omitted, however, each value has a relative uncertainty of 2.0-2.1×10^{-5} on the vertical axis. The uncertainty is expressed with a coverage factor of k = 2. No significant differences in sensitivity between the three types of the load fittings are evident. The load cells were mounted onto the FSM and then dismounted for each calibration. Thus, the observed changes in sensitivity include not only the load cell instability, but also the effects of human error in setting up the equipment.

(a)

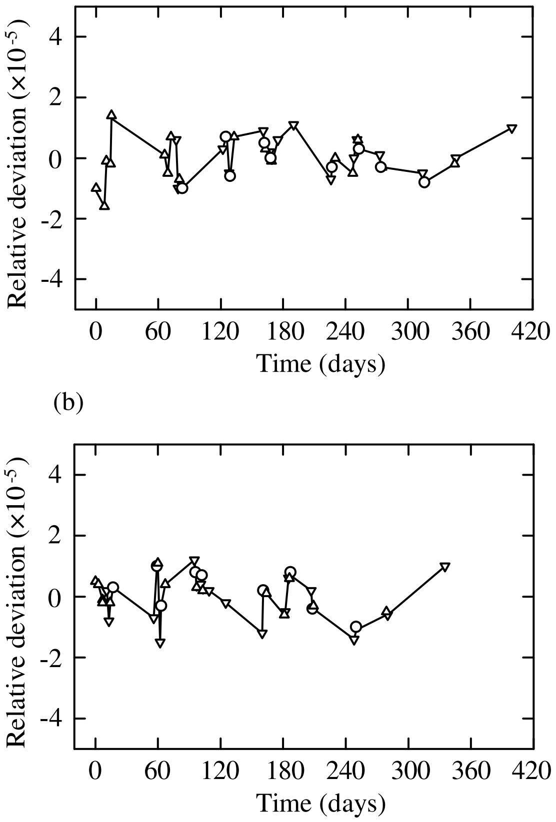

Fig. 11. Load cell sensitivity change: (a) instrument 1 and (b) instrument 2.

Although the evaluation period was only a year, the change in sensitivity of the tuning fork type load cells was about 3×10^{-5} relative. Though some of the highest quality strain gauge type load cells show comparable stability, the long-term stability of these types of load cells with small capacities is usually over 1×10^{-4}. It is therefore considered that the tuning fork type load cells have an obvious advantage over the strain gauge types with respect to long-term stability. Therefore, they are well suited to reference standards and transfer standards in the traceability system for force measurement.

3.4. Temperature dependency

Though changes to the room temperature were restricted to only 6 °C due to limitations in the air conditioning system, the temperature dependency of the load cells was evaluated. Fig. 12 shows the sensitivity changes for several room temperatures varying between 19.8 °C and 25.9 °C. These sensitivities were recorded for a force of 50 N. Error bars are omitted, however, each value has a relative uncertainty of 2.0-2.1×10^{-5} on the vertical axis and 0.09 K on the horizontal axis, respectively. The uncertainties are expressed with a coverage factor of k = 2. No obvious temperature dependencies for the tuning fork type load cells were observed. However even the highest class strain gauge type load cells exhibited a temperature coefficient of 1×10^{-5}/K. Successful materials selection and compensation by a processor [2] are partly responsible for the low temperature sensitivity of the tuning fork type load cells.

(a)

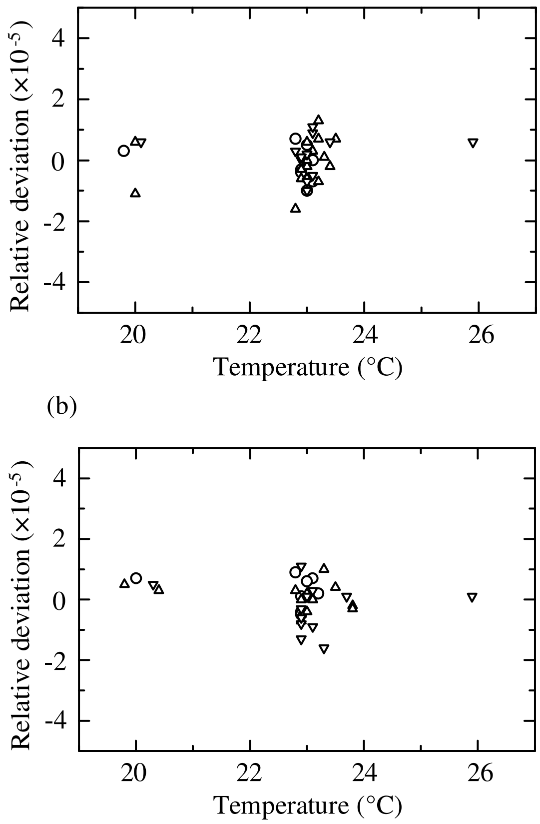

Fig. 12. Load cell temperature sensitivity: (a) instrument 1 and (b) instrument 2.

4. CONCLUSION

A tuning fork type load cell has been developed for practical use in high precision force measurement. Two tuning fork type load cells have been evaluated and compared with three high quality strain gauge type load cells.

The tuning fork type load cells showed obvious advantages with respect to the hysteresis, creep and long-term stability characteristics. Repeatability and reproducibility were comparable to those for strain gauge type load cells. Tuning fork type load cells do still have some weaknesses requiring further development such as their larger size and inferior time resolution in comparison to strain gauge type load cells. However these load cells are stable and are clearly well suited to traveling standards of international comparisons between national force standards and transfer standards for calibrating force calibration machines and testing machines.

REFERENCES

[1] R. M. Langdon, "Resonator sensors-a review," J. Phys. E: Sci. Instrum. Vol. 18, pp. 103-115, 1985.

[2] M. Kobayashi, "Precision balances applying tuning fork vibrators," Proc. of 1993 JSME Int. Conf. on Advanced Mechatronics, pp. 23-28, Tokyo, 1993.

[3] http://www.vibra.co.jp/eng/TFSENSOR/subaru.html

[4] http://kcdb.bipm.org/AppendixC/default.asp

[5] ISO 376, "Metallic materials - Calibration of force-proving instruments used for the verification of uniaxial testing machines," 2004.