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Remaining differences among precision strain-gauge amplifiers for force transducers after compensation with reference to a common bridge calibration unit

Toshiyuki Hayashi *, Kazunaga Ueda

National Metrology Institute of Japan (NMIJ), AIST, Japan

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ABSTRACT

In key-comparisons of force standards among National Metrology Institutes, it is a common practice to circulate only strain-gauge force transducers and a common bridge calibration unit and to use each participating laboratory's own precision strain-gauge amplifiers. In this scenario, the amplifiers should be compensated by referring to the common bridge calibration unit; however, in some combinations of force transducers and amplifiers, undesirable differences in the indications were observed even after compensation. This paper reports on experiments to examine the remaining individual differences among six precision amplifiers, revealing that considerable differences remained in some cases. The maximum difference exceeded both the uncertainty of the reference voltage ratio signal from the bridge calibration unit and the instability in the sensitivities of the force transducer and the amplifier. One measure to cope with this problem would be to make an intra-laboratory comparison among multiple amplifiers within the laboratory, prior to conducting inter-laboratory comparisons, if possible.

1. Introduction

International comparisons are important in ensuring equivalence of measurement standards among National Metrology Institutes (NMIs) and in demonstrating their calibration capabilities. Also in the force measurement field, some key-comparison programs have been conducted, and the results have been reported [1,2]. Because force standard machines are fixed in location at the NMI sites and are not portable, generally, they cannot be compared directly. Instead, accurate force measuring instruments have been used as traveling artifacts for international comparisons.

Force measuring instruments consist of a force transducer and an amplifier/indicator. So far, precision strain-gauge type force transducers have been chosen as the best option for traveling artifacts. Consequently, precision strain-gauge amplifiers with an alternating current (AC) carrier have been adopted as the amplifier.

In some cases, both precision strain-gauge type force transducers and a strain-gauge amplifier are transported as a traveling artifact between NMIs. However, in most cases, a bridge calibration unit is transported instead of precision amplifiers, which are kept intact at the NMIs. This is because the precision amplifiers are valuable and essential for the daily work at each NMI, and a bridge calibration unit with inductive voltage dividers is expected to show better sensitivity stability than that of a precision amplifier. Therefore, in typical cases, a precision amplifier possessed by a first NMI (NMI-a) is calibrated by referring to the common bridge calibration unit, before and/or after calibration of the force measuring instrument, consisting of a circulated force transducer and a stationary amplifier at NMI-a, by using the force standard machine(s) of NMI-a. Next, the force transducer and the bridge calibration unit are transported to the next participating NMI (NMI-b), and then the stationary amplifier at NMI-b is calibrated by referring to the circulated bridge calibration unit before and/or after calibration of the force measuring instrument using NMI-b's force standard machine(s). As a result, the participating NMIs can use their precision amplifiers for their daily work even during the period of the international comparison.

Of course, every strain-gauge amplifier has particular individual difference in its indication. The correction method mentioned above was based on the premise that such individual difference could be sufficiently canceled out by calibration with reference to the common bridge calibration unit. This was supported by the results of previous key-comparisons, showing that most deflections of the force transducers recorded using the precision amplifier possessed by each NMI exhibited good equivalence [1,2]. On the other hand, some of the comparison results showed considerable deviations compared with their declared measurement uncer-

* Corresponding author.
E-mail address: t-hayashi@aist.go.jp (T. Hayashi).

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tainties. The causes of such errors may be partially ascribed to force standard machines, calibration procedures and/or data processing. However, to the best of the authors' knowledge, this premise has never been verified.

Accordingly, the authors experimentally tried to verify the compatibility among precision strain-gauge amplifiers after calibrating them by referring to common bridge calibration units.

2. Experimental conditions

The instruments used for the experiments are listed in Table 1. Three bridge calibration units, labeled Cal.A to Cal.C, six precision strain-gauge amplifiers, labeled Amp.A to Amp.F, and two accurate strain-gauge type force transducers, labeled as Tr.A and Tr.B, were prepared for the verification. All of the instruments, except for force standard machines, were manufactured by Hottinger Baldwin Messtechnik GmbH. Cal.A and Cal.B included inductive voltage dividers and had been calibrated by referring to the voltage ratio measurement standard. Cal.C included a precision resistance network in a star configuration, but it had not been calibrated. An excitation voltage of AC 5V/225 Hz was applied to a Wheatstone bridge from the amplifier, and the amplifier was set to use a measurement range of 2.5 mV/V and a low-pass filter of 0.1 Hz. Tr.A had a rated capacity of 2 kN, and Tr.B had a rated capacity of 20 kN. Input resistances of Tr.A and Tr.B were stated as exceeding 690 Ω and 345 Ω, respectively, in the data sheets of the manufacturer.

When the differences among deflections of the force transducers as a result of changing the precision amplifiers were recognized even after compensating the amplifiers by referring to the common bridge calibration unit, a similar phenomenon was also expected to appear when changing the bridge calibration units. It was surmised that the characteristics of the resistance network of Cal.C were more similar to those of the Wheatstone bridge circuit than those of the inductive voltage dividers in Cal.A and Cal.B. Additionally, because the time required for calibration of an amplifier by referring to a bridge calibration unit was obviously shorter than that for calibration of a force transducer by using a force standard machine, it is worth comparing multiple bridge calibration units over a similar time span.

The experiment was carried out as follows. First, Amp.A was calibrated twice by referring to Cal.A and Cal.B, and then its indications were measured by connecting Cal.C. Next, the same procedure was applied to Amp.B to Amp.F one by one. The series of calibrations/measurements using Amp.A to Amp.F was repeated four times. Finally, Amp.A was calibrated an additional two times by referring to Cal.A and Cal.B and was measured with Cal.C.

Calibration of the amplifier by referring to the bridge calibration unit Cal.A or Cal.B was performed by increasing the input from 0.0 to 2.2 mV/V at intervals of 0.2 mV/V. Cal.C was connected and measurement was carried out from 0.0 to 2.0 mV/V with the same increment. A 2.5 mV/V internal calibration signal of the precision amplifier was applied at least three times just before each calibration of the amplifier to ensure stability of the deflection, and the stability was checked based on the repeatability between two incremental measurements. The deflection recorded with Cal.C connected was compensated for by interpolating the calibration results obtained by referring to Cal.A or Cal.B. For example, when the calibration readings of the amplifier were 0.000020, 0.200022, 2.000012, and 2.200010 mV/V with input voltage ratios of 0.0, 0.2, 2.0, and 2.2 mV/V from Cal.A, respectively, two amplifier readings of 0.100000 and 2.100000 mV/V at zero and a certain force step were compensated as 0.099979 and 2.099989 mV/V, and the deflection between the two readings was calculated at 2.000010 mV/V. Individual deviations of Cal.A and Cal.B themselves were determined from their respective calibration certificates. In this study, however, these deviations of the bridge calibration units were not taken into account, because this study focused only on the indication differences of the pairs of amplifiers, not on absolute values. After compensating for deflections measured with Cal.C connected, multiple comparison using the Tukey-Kramer test was applied to find pairs of amplifiers that showed significant statistical differences. The analysis was performed using R version 3.2.3 [3].

From the results of the experiment, as described later in Section 3.2, we identified three pairs of precision amplifiers, i.e., Amp.A-Amp.B, Amp.B-Amp.D, and Amp.A-Amp.D, and investigated their compatibility in the following manner. First, one of the amplifiers was calibrated twice by referring to Cal.A and Cal.B, second, a strain-gauge type force transducer with the amplifier was calibrated by using the dead-weight type force standard machine (DWM) according to the procedure prescribed in ISO 376 [4], and finally the amplifier was calibrated again by referring to Cal.A and Cal.B. A 2.5 mV/V internal calibration signal for the precision amplifier was also applied at least three times just before each calibration of the force transducer. Deflection of the force transducer was calculated from indications noted in three calibration cycles in one calibration by the DWM and was compensated for based on the mean of calibration results of the amplifier by referring to Cal.A or Cal.B before and after the calibration of the transducer. This set of procedures was for one amplifier. The set was repeated for the two amplifiers, alternately. Compatibility between the pairs of amplifiers was evaluated based on the difference between the results.

Table 1
Instruments used for the experiments.

Label	Type
Cal.A	BN100A
Cal.B	BN100A
Cal.C	K3608
Amp.A	DMP40S2
Amp.B	DMP40S2
Amp.C	DMP40S2
Amp.D	DMP40
Amp.E	DMP40
Amp.F	DMP41T6
Tr.A	TOP-Z30 (2 kN)
Tr.B	TOP-Z4A (20 kN)

3. Results and discussion

3.1. Compatibility among the amplifiers by referring to different bridge calibration units

Fig. 1 indicates deviations in readings of the amplifiers when applying certain voltage ratios from the bridge calibration units. Fig. 1(a), (b) and (c) correspond to Cal.A, Cal.B and Cal.C, respectively. The horizontal axes indicate the nominal input voltage ratio. The vertical axes indicate the deviations of the amplifier indications from the nominal input voltage ratio. For example, when the nominal input voltage ratio from the bridge calibration unit and the indication of the amplifier are 1.0 and 1.000010 mV/V, respectively, the deviation in the figure is plotted on the 10 nV/V height. These deviations were not corrected for using the calibration results of the bridge calibration units by using a voltage ratio measurement standard, because application of the corrections only results in uniform shifts of all polygonal lines. The type of marker identifies each amplifier. Calibrations were repeated five or six times for each pair of amplifiers and the bridge calibration units. In the figure, mean values of the deviations in each repetition are