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METHODS FOR ENHANCING REPRODUCIBILITY OF CALIBRATION RESULTS FOR HYDRAULIC PRESSURE TRANSDUCERS

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Abstract: The effects of the calibration procedure on the results are investigated for quartz Bourdon-type hydraulic pressure transducers. A fully-automated system that uses a pressure balance as the standard device has been developed for the calibrations at pressures from 10 MPa to 100 MPa. The effect of the interval between the calibration cycles and the effect of preliminary pressurization are quantitatively evaluated for two kinds of calibration cycles, stepwise and 0-A-0-type calibration cycles. For the stepwise cycle, the interval between the calibration cycles strongly affects the results in the pressure increasing process. The preliminary pressurization reduces the influence of the interval on the results. However, in turn, the waiting time between the preliminary pressurization and the main calibration cycle exerts a strong influence on the results. For the 0-A-0-type calibration cycle, the effect of the interval on the results is almost half of that for the stepwise cycle. Moreover, with preliminary pressurization, the calibration results are rarely affected by the interval. From the results, possible methods for obtaining reproducible calibration results are discussed.

Keywords: pressure standard, pressure gauge, calibration, hysteresis.

1. INTRODUCTION

In the field of pressure calibration, liquid column manometers and pressure balances are most commonly used as both the primary and the reference pressure standards. Recently, however, owing to considerable improvements in quality, electromechanical pressure gauges are also used as reference pressure devices in various industries. Among them, gauges with digital outputs are commonly used due to its usability and versatility. Electromechanical pressure gauges have also been used as the transfer standards in international comparisons. For example, in APMP.M.P-K7 for hydraulic pressure from 10 MPa to 100 MPa, three sets of two digital pressure gauges were successfully used as the transfer standards after detailed characterizations [1].

To appropriately use electromechanical pressure gauges as the standard device, a number of characteristics have to be evaluated in advance. Some guidelines and regulations have been established as references for characterizations [2, 3]. Among such characteristics, the time-dependent behaviour and the effect of the pressurization history are focused in this study. In general, the output of pressure gauges depends on not only the currently applied pressure,

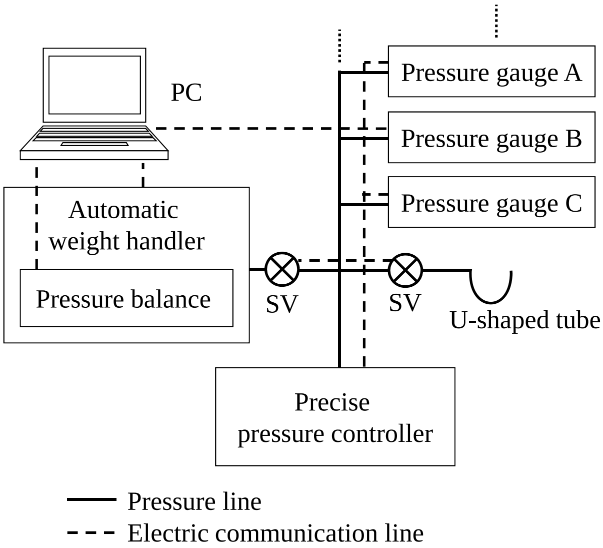

Figure 1: Schematic diagram of fully automated calibration system for pressure gauges. Pressure balance with automatic weight handler is used as the reference device. SV: gas-operated shut-off valve, PC: laptop computer.

but also the timing of the measurement and the previously applied pressures. Accordingly, the calibration results can also be affected by such conditions. The difference in the calibration procedure can lead the different calibration results, and may increase the uncertainty. Then, the effects of the calibration procedure on the results should be quantitatively evaluated.

This study especially focuses on the effect of the interval between the calibration cycles and the effect of preliminary pressurization. These two effects are evaluated for the two common calibration cycles, stepwise and 0-A-0-type calibration cycles. To precisely evaluate the effect of the calibration procedure, it is necessary to obtain highly reproducible data for each investigated procedure. For this, we developed a fully automated calibration system that uses a pressure balance as the standard device. The details of the system and the method of analysis are explained in section 2. Then, the calibration results with different preliminary conditions are shown in section 3. From the results, possible methods and important reminders for obtaining highly reproducible calibration results for hydraulic pressure

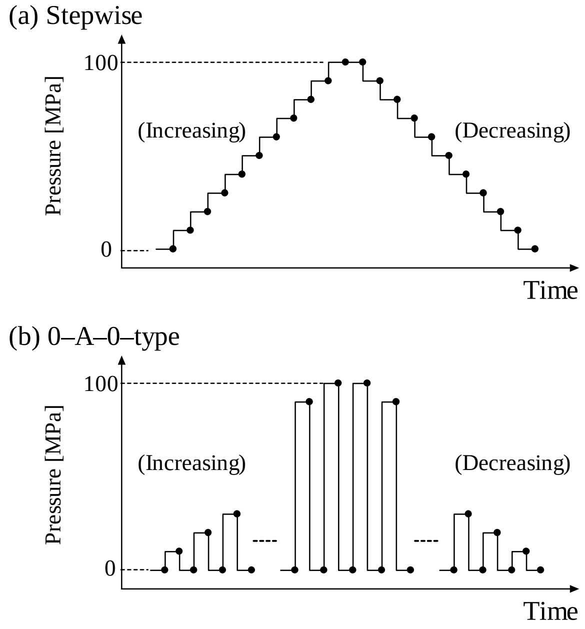

Figure 2: Calibration procedures with (a) stepwise and (b) 0-A-0-type cycles.

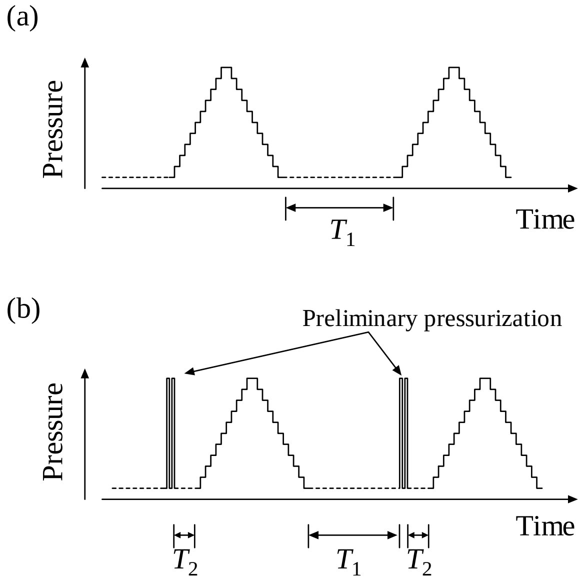

Figure 3: (a) Calibration cycles with time interval T_1. (b) Calibration cycles with preliminary pressurization. T_1 is the interval between the end of the cycle and the beginning of the preliminary pressurization for the following cycle. T_2 is the waiting time between the end of the preliminary pressurization and the beginning of the cycle.

gauges are discussed in section 4. Finally, findings are summarized in section 5.

2. CALIBRATION PROCEDURE

Figure 1 shows the schematic diagram of a fully automated calibration system [4]. Pressure balance with a 1 MPa/kg piston-cylinder assembly is used as the standard devise. The maximum pressure is 100 MPa with the 100 kg weights. The weights are loaded on the piston by the automatic weight handler. The pressure and the piston floating position during the calibration are controlled by the precise pressure controller. The pressure line is connected to the pressure gauges under calibration, and the u-shaped tube, which is used for the pressure release to atmospheric pressure. In this study, pressure gauges containing quartz Bourdon-type pressure transducers are calibrated. Several pressure gauges can be simultaneously calibrated in this system. All of the functions of the pressure balance, weight handler, precise pressure controller, and gas-operated shut-off valves are controlled by the commands from a laptop computer (PC).

Figure 2(a) shows the calibration procedure with stepwise cycle, which is commonly used in the pressure calibration field. In this study, one calibration cycle consists of 22 measurements at 11 pressure points: 11 points from 0 MPa to 100 MPa in steps of 10 MPa in the pressure increasing process and 11 points in the pressure decreasing process. At each pressure point, readings of the pressure gauge are obtained in approximately 3 min after the 5 min waiting period for pressure stabilization. The time required to complete a single calibration cycle is approximately 4 h.

Figure 2(b) shows the calibration procedure with 0-A-0-type cycle. The calibration pressure is sequentially increased from 10 MPa to 100 MPa in steps of 10 MPa, and then decreased to 10 MPa. The pressure is decreased to atmospheric pressure (0 MPa) every time after finishing the measurement at the calibration pressure. Both at the calibration pressure and the atmospheric pressure, the pressure is maintained 3 min for pressure stabilization before the measurement. The time required to complete a single calibration cycle is approximately 6 h.

The calibration results are deduced as follows. First, at each calibration pressure, the deviation of the reading of the pressure gauge from the applied pressure is calculated as,

$$DI_p = I_p - p_s,$$

where I_p is the reading obtained from the pressure gauge (average of 18 readings obtained during 3 min) and p_s is the pressure at the reference level of the gauge generated by the pressure balance. The reading at the atmospheric pressure is expressed as DI_0. Then, the calibration results are expressed as the relative deviation of the reading from the standard pressure after offset correction RD_p as,

$$RD_p = (DI_p - DI_0) / p_s.$$

For the stepwise calibration cycle, DI_0 measured at the beginning of the cycle is used for the pressure increasing process, while DI_0 measured at the end of the cycle are used for the pressure decreasing process. For the 0-A-0-type cycle, the average of DI_0 obtained before the calibration pressure and DI_0 after the calibration pressure is, in most cases, used for the offset correction. In this study, however,

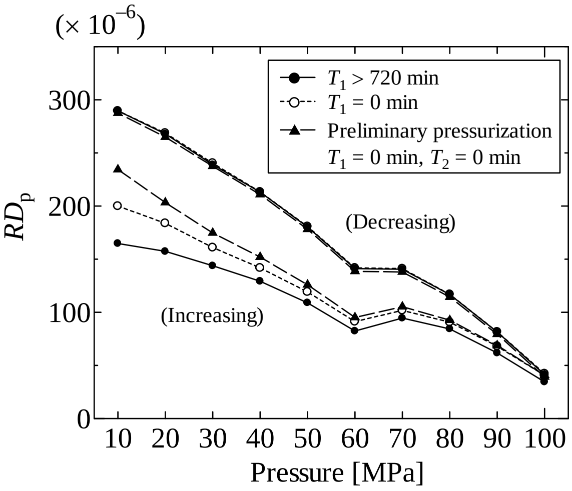

Figure 4: Stepwise calibration results with different conditions before the calibration cycles.

DI_0 measured after the target calibration pressure is used for the offset correction in order to avoid the effect of the previous calibration pressure and to obtain reproducible calibration results with various pressurization conditions.

3. RESULTS

3.1. Calibration with stepwise cycles

The stepwise calibration cycle is commonly used in the pressure calibration field. In usual case, the calibration cycles are repeated three times or more, and then the calibration results are calculated from the average of the data of these cycles. The standard deviation for these data represents the reproducibility of the measurement, and often be treated as the type-A uncertainty in the uncertainty evaluation. To obtain the reproducible data, in addition to the pressurizing procedure during the cycle, the conditions before the cycle should be taken care of. In this study, the effect of the interval between the calibration cycles and the effect of preliminary pressurization are evaluated. Figure 3(a) shows the repetition of stepwise calibration cycles. The interval between the calibration cycles is denoted by T_1. Figure 3(b) shows the calibration cycles with preliminary pressurization. In the preliminary pressurization, the pressure is increased to the maximum calibration pressure (100 MPa), kept for approximately 100 s, and then decreased to atmospheric pressure. This procedure is repeated twice before the main calibration cycle. In this case, the interval between the end of the cycle and the beginning of the preliminary pressurization for the following cycle is denoted as T_1, and the waiting time between the end of the preliminary pressurization and the beginning of the cycle is denoted as T_2.

Figure 4 exemplifies the calibration result RD_p with different conditions before the calibration cycle. The results in the pressure increasing process apparently differ

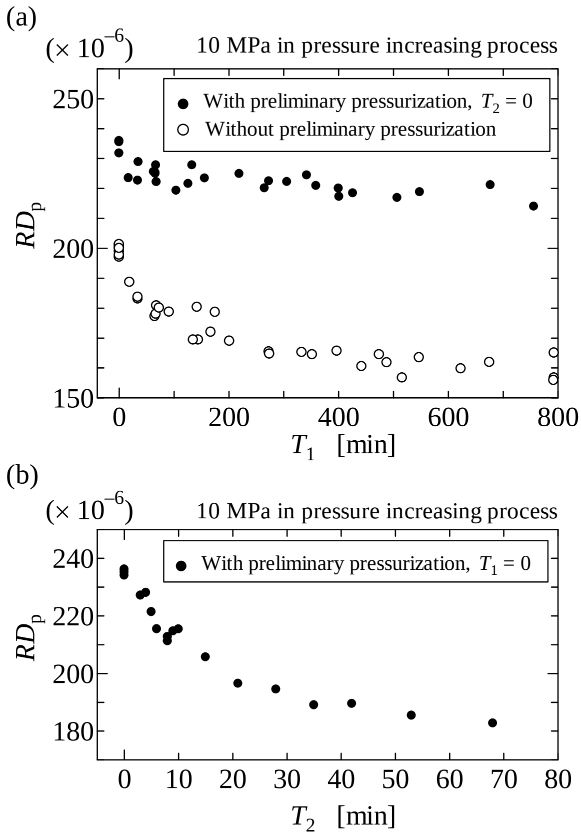

Figure 5: Stepwise calibration results RD_p at 10 MPa in the pressure increasing process under different T_1 and T_2 conditions. (a) T_1 dependence of RD_p, (b) T_2 dependence of RD_p with preliminary pressurization.

depending on the interval and the preliminary pressurization. Filled circles show the results with T_1 of more than 720 min (half a day), while open circles denote those with $T_1 = 0$, which means the cycles are continuously repeated. At 10 MPa, where the results are most affected by T_1, the relative deviation is almost 35 parts per million (ppm), that is as much as the expected expanded (k = 2) uncertainty of the calibration. In addition, the results with preliminary pressurization, shown by triangles, become larger than those without preliminary pressurization; the deviation is as much as 40 ppm at 10 MPa.

The effect of T_1 on the results is extensively investigated for both the calibration with preliminary pressurization and that without preliminary pressurization. Figure 5(a) shows the T_1 dependence of RD_p at 10 MPa in the pressure increasing process, where the results are most affected by T_1, as shown in figure 4. Open circles show the effect of T_1 on RD_p for the calibration without preliminary pressurization. The effect of T_1 is not monotonic. The decreasing rate of RD_p is gradually reduced when T_1 becomes longer. When T_1 is set longer than 250 min, for example, the range of deviation is only within approximately ± 7 ppm. Filled circles show the effect of T_1 on RD_p for the calibration with preliminary pressurization. Waiting time T_2 is fixed to be 0

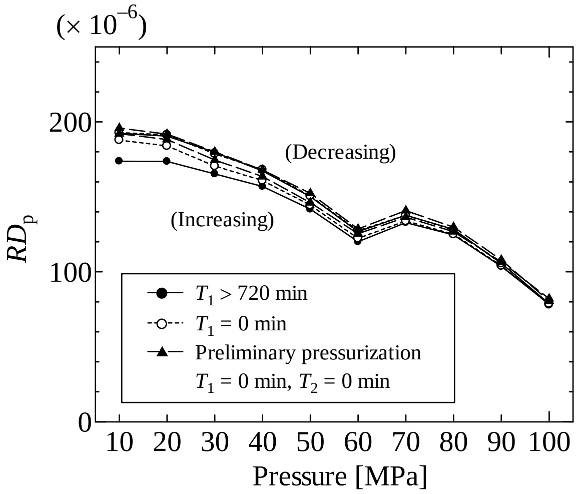

Figure 6: 0-A-0-type calibration results with different conditions before the calibration cycles.

min. Even when the interval T_1 is changed from zero to approximately 800 min, the range of deviation of RD_p is only 20 ppm; that is almost half of that without preliminary pressurization. Thus, the effects of T_1 are suppressed by the preliminary pressurization.

For the calibration with preliminary pressurization, the calibration results depend not only on T_1, but also on T_2 since the preliminary pressurization itself induces a considerable pressure change to the pressure gauge within a short amount of time. Figure 5(b) shows the T_2 dependence of RD_p at 10 MPa in the pressure increasing process. Waiting time T_1 is fixed to be 0 min. When waiting time T_2 is changed from zero to 70 min, the range of deviation reaches 60 ppm; the changing rate of RD_p with T_2 is more than 10 times larger than that with T_1. Thus, T_2 should be determined with high precision to obtain reproducible data.

3.2. Calibration with 0-A-0-type cycle

Figure 6 exemplifies the calibration result RD_p with 0-A-0-type calibration cycles. As in case of stepwise cycles, calibration results with three different conditions before the calibration cycles are compared. At almost all pressure points, the results obtained with 0-A-0-type calibration cycles differ from those with stepwise cycles. In particular, the hysteresis, the difference between the results in pressure increasing and decreasing processes, is considerably reduced. That is mostly because the pressure gauge is restored to the initial condition by the pressure release after each measurement. Filled circles in the figure show the results with T_1 of more than 720 min (half a day), while open circles denote those with T_1 = 0. Deviations between them are much smaller than those for the stepwise cycles. At 10 MPa in the pressure increasing process, for example, the deviation is at most 20 ppm, which is almost half of that for stepwise calibration. Moreover, it appears that the preliminary pressurization rarely affects the results; RD_p

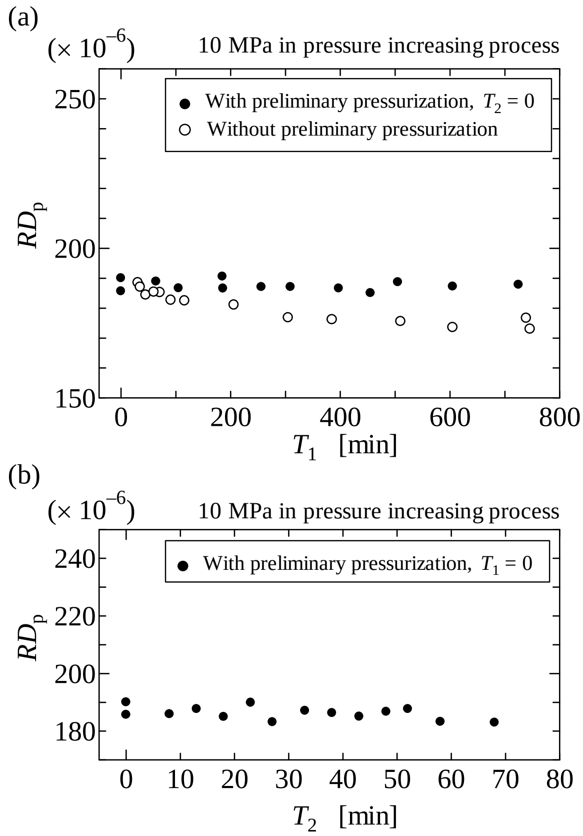

Figure 7: 0-A-0 calibration results RD_p at 10 MPa in the pressure increasing process under different T_1 and T_2 conditions. (a) T_1 dependence of RD_p, (b) T_2 dependence of RD_p with preliminary pressurization.

with preliminary pressurization, shown by triangles, is almost the same value with those without preliminary pressurization. From the small hysteresis, it is expected that the results with 0-A-0-type calibration is less affected by the previous calibration pressure during the cycle. The similar results can be obtained even when the calibration is performed with different maximum calibration pressure, or in arbitrary orders of calibration pressures.

The effects of T_1 and T_2 on the results are extensively investigated also for the 0-A-0-type calibration cycles. Figure 7(a) shows the T_1 dependence of RD_p at 10 MPa in the pressure increasing process. The range of the vertical and horizontal axes in the figure is set to be the same with figure 5 for comparison. Open circles show the effect of T_1 on RD_p for the calibration without preliminary pressurization. The effect of T_1 on RD_p for the 0-A-0-type calibration cycles is much smaller than that for the stepwise cycles. Filled circles show the effect of T_1 on RD_p for the calibration with preliminary pressurization. The preliminary pressurization before the 0-A-0-type cycles almost eliminates the effect of T_1 on the results. Even when T_1 is changed from zero to 800 min, the range of deviation of RD_p

is only 10 ppm, which is slightly larger than the repeatability of RD_p with the same condition before the calibration cycles.

Figure 7(b) shows the T_2 dependence of RD_p at 10 MPa in the pressure increasing process. Contrary to the results for the stepwise cycles in figure 5(b), the results at 10 MPa are within ± 5 ppm even when T_2 is changed from zero to 70 min. From these two experiments, RD_p for the 0-A-0-type calibration cycle with preliminary pressurization is not affected by either T_1 or T_2.

4. DISCUSSION

From the results with different previous conditions, possible methods for obtaining the highly reproducible calibration results are discussed in this section.

The pressurization conditions before the calibration cycle should be appropriately controlled. When the calibration cycles are repeated, the difference in time interval T_1 between the calibration cycles leads the difference of the results in pressure increasing process. The effect of T_1 is gradually reduced when T_1 becomes longer. Thus, the interval should be determined according to the time-dependent characteristics of the gauge, the efficiency of the calibration and the maximum allowable uncertainty.

The preliminary pressurization before the calibration cycle reduces the effects of the interval between the cycles. However, it is necessary to precisely determine the waiting time between the preliminary pressurization and the calibration cycle because it exerts a strong effect on the results.

In comparison with stepwise calibration results, the results with 0-A-0-type cycles show much smaller hysteresis, and are less affected by the interval between the cycles and the preliminary pressurization. Owing to the high reproducibility without depending on the pressurization history, this method can be a useful way to calibrate pressure measurement devices using pressure gauges as the reference devices.

The use of digital pressure gauges as the reference devices continues to expand in the pressure calibration field. Based on the characteristics of respective gauges against the pressurization history and calibration conditions, the appropriate calibration procedures should be selected according to the efficiency of the calibration and the intended use.

5. SUMMARY

The effects of the calibration procedure on the results are investigated for quartz Bourdon-type hydraulic pressure transducers. A fully-automated system that uses a pressure balance as the standard device has been developed for the calibrations at pressures from 10 MPa to 100 MPa. Two kinds of calibration cycles were applied: stepwise and 0-A-0-type calibration cycles. For the both cycles, the effect of the interval between the calibration cycles and the effect of preliminary pressurization are quantitatively evaluated. For the stepwise cycle, the interval between the calibration cycles, ranging from 0 to 800 min, strongly affects the results in the pressure increasing process. The effect on the results is the largest at 10 MPa. The preliminary pressurization before the calibration cycle reduces the influence of the interval on the results. However, in turn, the waiting time between the preliminary pressurization and the main calibration cycle exerts a strong influence on the results. For the 0-A-0-type calibration cycle, the effect of the interval between the cycles on the results is almost half of that for the stepwise cycle. Moreover, with preliminary pressurization, the calibration results are rarely affected by the interval. From the results, possible methods for obtaining reproducible calibration results are discussed.

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