

ESTABLISHMENT OF LARGE FORCE STANDARDS BASED ON BUILT-IN FORCE TRANSDUCERS AND BUILD-UP SYSTEM

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Abstract: This paper describes a force calibration machine of 10 MN capacity which consists of a loading frame, built-in force transducers, a hydraulic generating unit and a control unit. This machine is traceable to national force standard as being calibrated by the build-up force transfer standard of 10.8 MN capacity which consists of nine force transducers of each having 1.2 MN capacity which was calibrated using the 498.2 kN deadweight force standard machine and the 2 MN hydraulic force standard machine. It revealed that the relative expanded uncertainty of the force calibration machine is less than 4.0×10^{-4} ($k=2$) in the range of 1 ~ 4.5 MN.

Keywords: force calibration machine, build-up force transfer standard, built-in force transducer.

1 INTRODUCTION

Force measuring devices should be calibrated to guarantee their test results. To establish the force standards in Korea, four deadweight machines of 5 kN, 20 kN, 100 kN and 500 kN capacity and 2 MN hydraulic force standard machine were installed at the Korea Research Institute of Standards and Science (KRISS). As heavy industries in Korea have been developed, force measuring devices above 2 MN should be calibrated to measure large forces in industry precisely. It is, therefore, necessary to establish the large force standards above 2 MN.

Some national institutes of metrology achieve large forces using hydraulic force standard machines which amplify smaller deadweight forces using piston/cylinder systems of different diameters. The hydraulic force standard machine should have large space for installing the machine and are expensive in manufacturing cost and maintenance. A force calibration machine which is traceable to the national force standards by using a build-up force transfer standard may be an efficient method to solve this problem. Debnam et al. [1] established standards of large force up to 30 MN by means of this technique. Gizmajer [2] and Gosset [3] established large force standards up to 10 MN in which a build-up force transducer that is traceable to the national standards is connected in series to a force transducer to be calibrated in a loading frame. Wieringa [4] designed a precise build-up system of 4.95 MN to be used as a transfer standard.

In order to establish large force standards in Korea, we have developed a force calibration machine of 10 MN with built-in force transducers which is calibrated by 10.8 MN build-up force transfer standard with nine force transducers of each having 1.2 MN capacity. This paper describes the structure of the machine, the test results about its characteristics and the result of uncertainty evaluation.

2 DESIGN OF FORCE CALIBRATION MACHINE

A force calibration machine consists of a loading frame, a hydraulic generating unit and a force control system as shown in Fig. 1. The loading frame consists of four columns, a cylinder, a piston, an upper frame, a lower frame and bearing platens. We can select bearing platens to accommodate the various size of a force transducer to be calibrated. Four columns are elongated as the result of reaction forces when compression force is applied to the force transducer by the hydraulic generating system. We can assume that the longitudinal surface strain and the circumferential surface strain in the middle of each column are uniform, respectively. Therefore we made a built-in force transducer with column as a sensing element. To make a built-in force transducer, four strain gages (code: N2A-06-T004R-350) were bonded along the longitudinal direction and the circumferential direction for each column, respectively, by using M-Bond 610 adhesive which is cured at 135 °C for two hours. In order to apply heat to column during bonding strain gages onto the column, a special temperature control

system with maximum temperature of 200 °C which consists of two heat bands, thermocouple, temperature control circuit was designed. A balco gage of 60 W, a nickel-iron alloy, and a copper gage were used to compensate the temperature effects on the sensitivity and the zero output of a built-in force transducer, respectively. The sensitivity of the force transducer is about 0.65 mV/V.

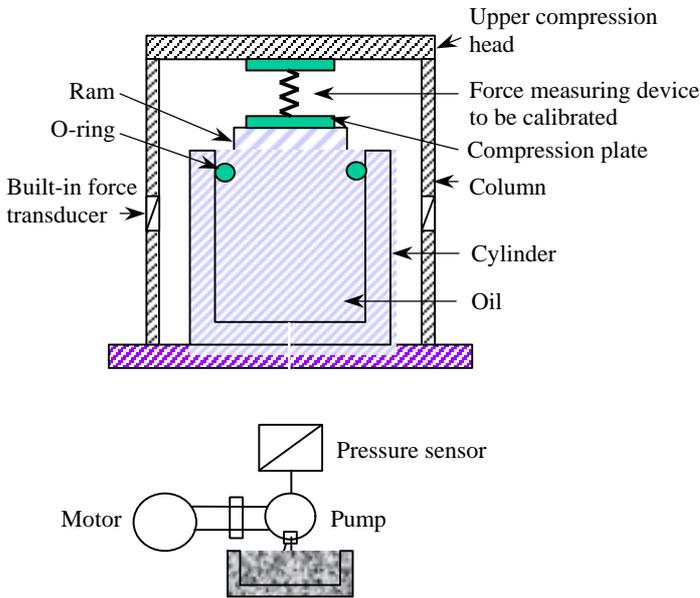


Figure 1. Schematic diagram of 10 MN force calibration machine.

The block diagram of the force control system is shown in Fig. 2. The force generated by the machine can be maintained precisely using a servo valve system. We used the digital measuring unit DK 38 with the built-in force transducer to measure the force being generated by the machine. Since the response time of the DK 38 is slow, an auxiliary DC amplifier with the pressure transducer is used to control the servo valve system. The force calibration machine with a built-in force transducer designed in this study is more compact in structure and convenient for use than a force calibration machine using a build-up force transducer as reference force.

To calibrate the 10 MN force machine, we used the build-up force transfer standard of 10.8 MN capacity. This consisted of nine force transducers of each having 1.2 MN capacity. The force transducers

were calibrated using the 500 kN deadweight force standard machine with uncertainty of 2×10^{-5} and the 2 MN hydraulic force standard machine with uncertainty of 2×10^{-4} . To reduce hysteresis error of the force machine we calibrated the built-in force transducer in increasing mode and decreasing mode; calculated a calibration curve for each mode; input a calibration curve into a computer.

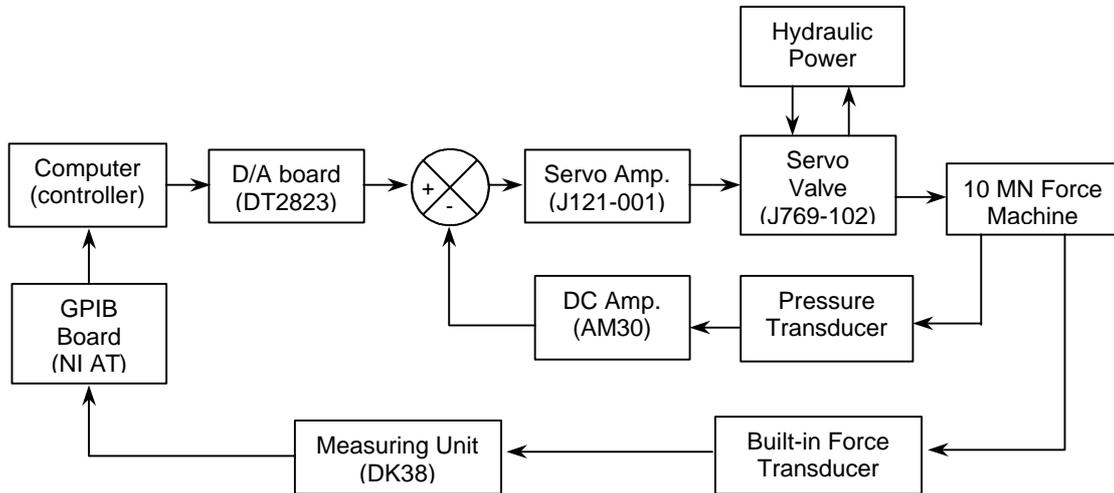


Figure 2. Block diagram of control system.

3 RESULTS AND DISCUSSION

3.1 Characteristics of the force calibration machine

Fig. 3 shows the stability of force control of the machine for five minutes at each test force. The relative deviation decreased from $\pm 0.02\%$ to $\pm 0.001\%$ as the test force increased from 1 MN to 10 MN. We found similar tendency in unloading direction. This behavior is presumably due to the

resolution of measuring unit of a DK 38 and sensitivity of a built-in force transducer in which the output at 1 MN is about 6500 digits being one-tenth of the output at 10 MN. We found that force control system using a servo valve system and a pressure transducer may maintain each force step precisely.

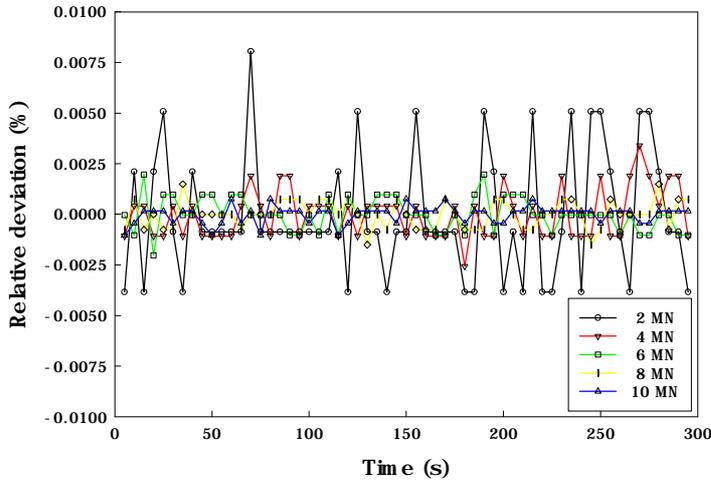


Figure 3. Stability of force control for each force step.

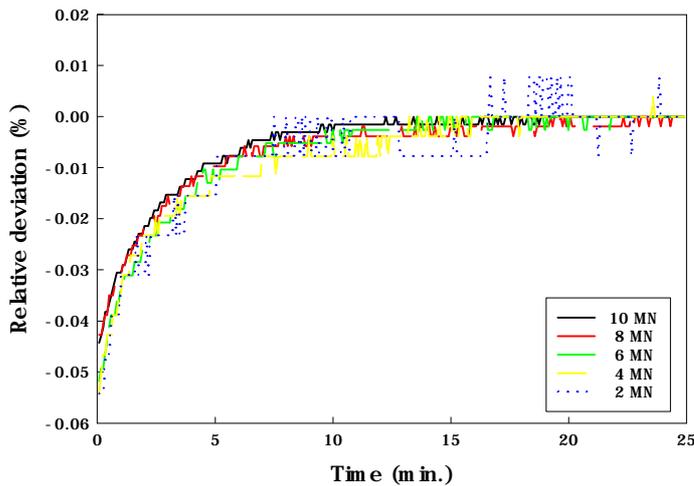


Figure 4. Creep recovery behavior of a built-in force transducer.

Fig. 4 shows the creep recovery of a built-in force transducer after each test force was applied to the machine for 30 minutes. Fig. 5 shows the creep behavior of a built-in force transducer for each test force for 5 minutes. The creep recovery increase with time rapidly, and then converges. But the creep decreases with time rapidly, and then converges. The creep recovery error for each test force for 30 minutes is about 0.05%, in which 80 % of the error for each force appears for initial five minutes. The creep recovery error is so large compared with a precision force transducer.

Fig. 6 shows the relative deviation of the output of a 10 MN force transducer with a column sensing element of 1.75 in ratio of length to diameter according to setting positions of the force transducer on the 10 MN force machine. This behavior resulted from interaction between the force transducer and the force calibration machine. Since the relative deviation is less than $\pm 0.02\%$, we can conclude that the structure of the force calibration machine is stable.

3.2 Uncertainty estimation of the force standard machine

The relative uncertainty of the force calibration machine, w , can be calculated by considering the relative uncertainty of the force transfer standard used for the calibration of the force machine, w_{fs} , and the

relative uncertainty of the force machine oneself, w_{fcm} , as follows:

$$w = \sqrt{w_{fcm}^2 + w_{fs}^2} \quad (1)$$

w_{fcm} can be determined by the following equation:

$$w_{fcm} = \sqrt{w_{zero}^2 + w_{msta}^2 + w_{mro}^2 + w_{res}^2 + w_{creep}^2 + w_{cuit}^2 + w_{temp}^2 + w_{inst}^2} \quad (2)$$

where u_{zero}^2 : zero error of a built-in force transducer (rectangular distribution)

w_{msta}^2 : stability of force control (triangular distribution)

u_{inpol}^2 : rotation error of force machine (rectangular distribution)

u_{res}^2 : resolution of a measuring unit (rectangular distribution)

- u_{creep}^2 : creep error of a built-in force transducer (rectangular distribution)
- u_{cuit}^2 : parallel circuit error of a built-in force transducer (triangular distribution)
- w_{temp}^2 : sensitivity variation of a built-in force transducer with variation of temperature in surrounding air (rectangular distribution)
- w_{inst}^2 : sensitivity drift of a built-in force transducer with time (triangular distribution)

Resolution of a measuring unit is 0.00001 mV/V. In order to reduce parallel circuit error of built-in force transducer within 0.01 %, output resistance of each built-in force transducer in each column was adjusted within maximum deviation of 0.01 %. We assumed that temperature effect on sensitivity of a built-in force transducer is ± 0.002 % of load/ $^{\circ}\text{C}$ and temperature control in laboratory is in the range of $23 \pm 2^{\circ}\text{C}$. The relative uncertainty of the force transfer, w_{fs} , can be determined by the following equation:

$$w_{fs} = \sqrt{w_{zero}^2 + w_{repro}^2 + w_{rep}^2 + w_{res}^2 + w_{creep}^2 + w_{cuit}^2 + w_{temp}^2 + w_{inpol}^2} \quad (3)$$

- where
- u_{zero}^2 : zero error of a built-in force transducer (rectangular distribution)
 - w_{repro}^2 : repeatability error with rotation (U-shaped distribution)
 - w_{rep}^2 : repeatability error without rotation (rectangular distribution)
 - u_{res}^2 : resolution of a measuring unit (rectangular distribution)
 - u_{creep}^2 : creep error (rectangular distribution)
 - u_{cuit}^2 : parallel circuit error (triangular distribution)
 - u_{temp}^2 : sensitivity variation with variation of temperature in surrounding air (rectangular distribution)
 - w_{inpol}^2 : interpolation error (triangular distribution)

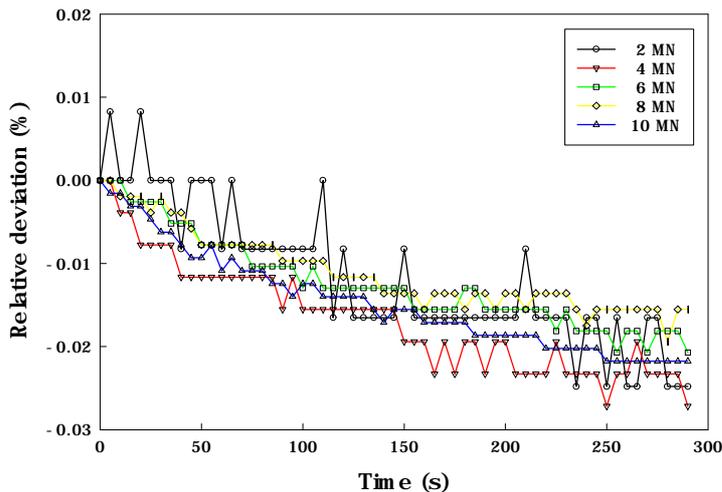


Figure 5. Creep behavior of a built-in force transducer.

Table 1 shows the relative uncertainty components calculated by eq. (2) and eq. (3). The relative expanded uncertainty ($k=2$) of the force transfer standard was less than $\pm 1 \times 10^{-4}$ in the range of 1 ~ 4.5 MN irrespective of loading direction [5]. We will evaluate the characteristic of the build-up force transfer standard in the range of 4.5 MN ~ 10 MN by using 2 MN hydraulic force standard machine. Uncertainty component owing to creep error of built-in force transducer is the biggest component among all uncertainty components. The relative expanded uncertainty ($k=2$) of the force calibration machine is less than 4×10^{-4} in the range of 1 MN ~ 4.5 MN. To improve the accuracy of the force calibration machine, first of all the creep error of the built-in force transducer should

be reduced to the level of a precision force transducer. We will try to compensate creep error of a built-in force transducer using computer program.

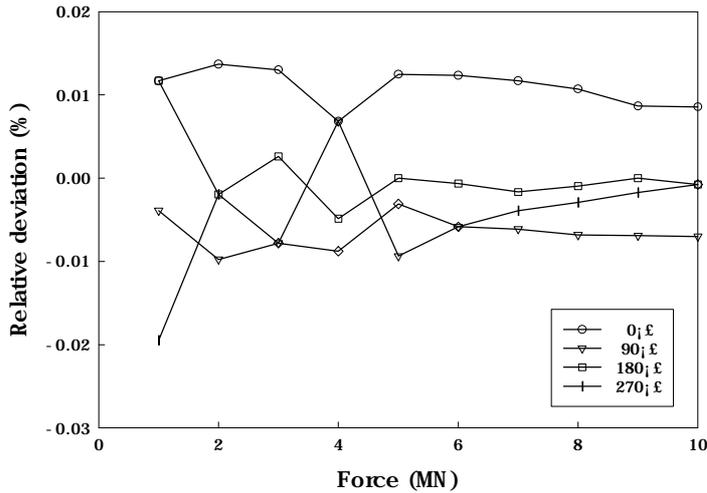


Figure 6. Relative deviation of the output of the 10 MN force transducer.

4. CONCLUSION

In this study, we have developed a force calibration machine of 10 MN for establishing large force standards in Korea. The relative deviation calculated from the stability of force control of the machine for 5 minutes is $\pm 0.02\%$ at 1 MN and $\pm 0.001\%$ at 10 MN. The creep recovery error of the built-in force transducer for each force step for 30 minutes is about 0.05%. The relative deviation resulted from the variation of setting position of a force transducer on the machine is less than $\pm 0.02\%$. The expanded uncertainty ($k=2$) of the force calibration machine is less than $\pm 4 \times 10^{-4}$ in the range of 1 ~ 4.5 MN.

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Table 1. Uncertainty components of 10 MN force calibration machine.

Force (MN)	w_{ts}^2	w_{zero}^2	w_{msta}^2	w_{mro}^2	w_{res}^2	w_{creep}^2	w_{cuit}^2	w_{temp}^2	w_{inst}^2	w_c
1.0	3×10^{-9}	2×10^{-9}	7×10^{-9}	8×10^{-9}	1.7×10^{-10}	1×10^{-8}	8.3×10^{-10}	5.3×10^{-10}	4.2×10^{-10}	1.97×10^{-4}
1.5	2×10^{-9}	2×10^{-9}	7×10^{-9}	8×10^{-9}	7.5×10^{-11}	1×10^{-8}	8.3×10^{-10}	5.3×10^{-10}	4.2×10^{-10}	1.76×10^{-4}
2.0	2×10^{-9}	2×10^{-9}	2×10^{-9}	8×10^{-9}	4.3×10^{-11}	1×10^{-8}	8.3×10^{-10}	5.3×10^{-10}	4.2×10^{-10}	1.61×10^{-4}
2.5	2×10^{-9}	2×10^{-9}	7×10^{-11}	8×10^{-9}	2.7×10^{-11}	1×10^{-8}	8.3×10^{-10}	5.3×10^{-10}	4.2×10^{-10}	1.55×10^{-4}
3.0	2×10^{-9}	2×10^{-9}	7×10^{-11}	8×10^{-9}	1.9×10^{-11}	1×10^{-8}	8.3×10^{-10}	5.3×10^{-10}	4.2×10^{-10}	1.55×10^{-4}
3.5	2×10^{-9}	2×10^{-9}	7×10^{-11}	8×10^{-9}	1.4×10^{-11}	1×10^{-8}	8.3×10^{-10}	5.3×10^{-10}	4.2×10^{-10}	1.55×10^{-4}
4.0	2×10^{-9}	2×10^{-9}	7×10^{-11}	8×10^{-9}	1.1×10^{-11}	1×10^{-8}	8.3×10^{-10}	5.3×10^{-10}	4.2×10^{-10}	1.55×10^{-4}
4.5	1×10^{-9}	2×10^{-9}	7×10^{-11}	8×10^{-9}	8.4×10^{-12}	1×10^{-8}	8.3×10^{-10}	5.3×10^{-10}	4.2×10^{-10}	1.55×10^{-4}