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100 kN Deadweight Force Standard Machine and Evaluation

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A deadweight force standard machine is a mechanical structure that generates force by subjecting deadweights to the local gravitational field. The Korea Research Institute of Standards and Science (KRISS) developed and installed a 100 kN deadweight force standard machine for national force standards. It can generate forces from 2 kN to 110 kN in increments of 1 kN. The uncertainty of the force machine was estimated and declared as 2×10^{-5}. This 100 kN deadweight force machine was compared with the 500 kN deadweight force standard machine at KRISS and the 20 kN and 50 kN deadweight force standard machines at the National Metrology Institute of Japan (NMIJ). The measurement results showed good agreement between the deadweight force machines, and the accuracy level of the 100 kN deadweight force machine was verified.

Key Words : Deadweight Force standard Machine, Uncertainty, Intercomparison, Evaluation

Nomenclature

F : Force
F_{100} : Applied force for 100 kN force machine (kN)
F_{500} : Applied force for 500 kN force machine (kN)
g_{loc} : Local gravitational acceleration
h : Relative humidity
m : Mass of deadweights
p : Atmospheric pressure
T : Temperature of air
u_{xi} : Absolute uncertainty due to xi
w_c : Relative combined uncertainty of deadweight force machine
w_g : Relative standard uncertainty due to gravitational acceleration
w_m : Relative standard uncertainty of deadweight calibration
w_p : Relative standard uncertainty due to inclined baseplate of deadweight force machine
w_s : Relative standard uncertainty due to swing of deadweights
$w_{\rho a}$: Relative standard uncertainty due to density of air
$w_{\rho w}$: Relative standard uncertainty due to density of deadweight
X_{ni} : Normalized indicator reading for 500 kN force machine
X_i : Indicator reading for 500 kN force machine
Δ_i : Relative error components caused by structure of deadweight force machine
Δ_g : Error in gravitational acceleration
$\Delta\rho_a$: Variation of air density
$\Delta\rho_w$: Error in density of deadweight
ρ_a : Density of air
ρ_w : Density of deadweights

1. Introduction

According to Newton's second law, force is a physical quantity that acts on a mass to accelerate it. In many industrial and scientific fields, force is often measured for quality control, characteristic evaluation of materials, and stress analysis of structures. Highly advanced measurement technology is an indispensable foundation for today's

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cutting-edge technologies and industrial applications. The reliability and compatibility of all the measurements related to force quantity are based on the national force standards.

The unit of force is defined by deadweights of standard masses subjected to the effect of the local gravitational field. The mechanical structure and apparatus to handle and control such deadweights is known as a deadweight force standard machine. Because of their high accuracy, deadweight force standard machines are widely used at most national metrology institutes (NMIs), to provide national standards for forces in the range of 50 N ~ 4.5 MN (Weiler and Sawla, 1978). The Korea Research Institute of Standards and Science (KRISS) has installed four deadweight force standard machines with capacities of 5 kN, 20 kN, 100 kN, and 500 kN. Among them, the 100 kN deadweight force machine was developed in 1998 to cover the force range of 2 kN to 110 kN (Kim et al., 1998). The structure and control system of the deadweight force standard machine are described in Kim et al. (1998).

Before a deadweight force machine is used for disseminating force standards, it should be tested and evaluated. This paper deals with the evaluation of the 100 kN deadweight force standard machine. The uncertainty of the machine was estimated theoretically and declared to be 2×10^{-5}. In order to check the performance of the deadweight force machine, it was compared with a 500 kN deadweight force standard machine at KRISS. In the intercomparison, a precision force transducer was installed on the both force machines and the indicator readings were compared when applying the same force to each machine.

Because of increasing globalization, it is becoming very important to establish a cooperative framework for obtaining international compatibility of national measurement standards. Within the framework of international cooperation in the field of force measurement, the question of the range within which deviations in the generation of forces agree in different countries, and what accuracy can be attained, has been discussed for several years (Kang et al., 1994). Intercomparison with other force standard machines at other NMIs is a common method to evaluate a force standard machine. For this reason, NMIs have performed many intercomparisons (Peters, 1989; Yaniv et al., 1991). KRISS also has undertaken several intercomparisons with the Physikalisch-Technische Bundesanstalt (PTB, Germany) (Kang et al., 1994; 1998) and the National Metrology Institute of Japan (NMIJ) (Paik et al., 1989).

For the purpose of international agreement, we performed an intercomparison of the 100 kN deadweight force standard machine with two deadweight force standard machines of NMIJ. The capacities of the NMIJ deadweight force machines were 20 kN and 50 kN. This paper explains the preparation, procedure, and the result of the intercomparisons. The agreement of the intercomparison was very important in terms of the accuracy evaluation of the 100 kN deadweight force machine.

2. The 100 kN Deadweight Force Machine

The force standard machine is a mechanical unit used to generate an accurate force to provide the national standard of force. The national measurement standard of force is a core component of all measurement activities related to force undertaken within industry, educational organizations, medical institutions, etc. There are several types of force standard machines, such as deadweight, hydraulic amplification, lever amplification, and build-up machines. Among them, the deadweight force standard machine, which generates the force using deadweights and gravitational acceleration, is the most accurate. The force generated by a deadweight can be represented as follows:

$$F=mg_{loc}\left(1-\frac{\rho_a}{\rho_w}\right) \tag{1}$$

where,

m = mass of deadweight

g_{loc} = local gravitational acceleration

ρ_a = density of air

ρ_w = density of the deadweight

In Eq. (1), $\left(1-\frac{\rho_a}{\rho_w}\right)$ allows for the effects of buoyancy.

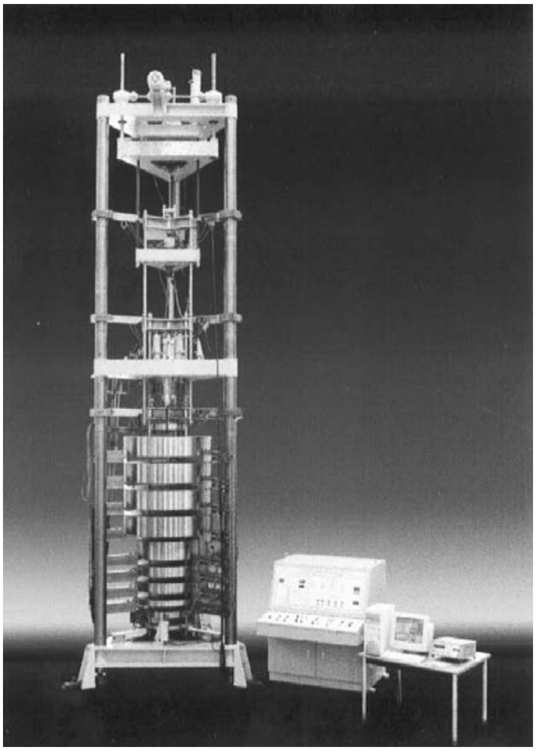

Fig. 1 The 100 kN deadweight force standard machine

KRISS developed a 100 kN deadweight force standard machine in 1998. It generates force in newtons (N). Figure 1 shows a photograph of the deadweight force standard machine. This chapter describes the 100 kN deadweight force standard machine.

2.1 Structure of the deadweight force machine

Figure 2 represents the schematic diagram of the 100 kN deadweight force machine. The machine consists of a framework (A), a lifting frame (B), three force transducers (C), a loading frame (D), a weight supporter (E), an adjustable yoke (F), a tension coupling device (G), weights, a hydraulic supply system, an air supply system, and a control system.

The framework (A) is composed of three columns, an upper crossbeam, a middle crossbeam, and a lower crossbeam. Each column comprises two pieces ; the upper one of length 3340 mm and diameter 150 mm, and the lower one of length 3870 mm and diameter of 150 mm. The three crossbeams are each made of three I-beams that have been welded together, providing the strength required for the machine. The distance between the upper and the middle crossbeams is 3200 mm, and the distance between the middle and the lower crossbeams is 3710 mm.

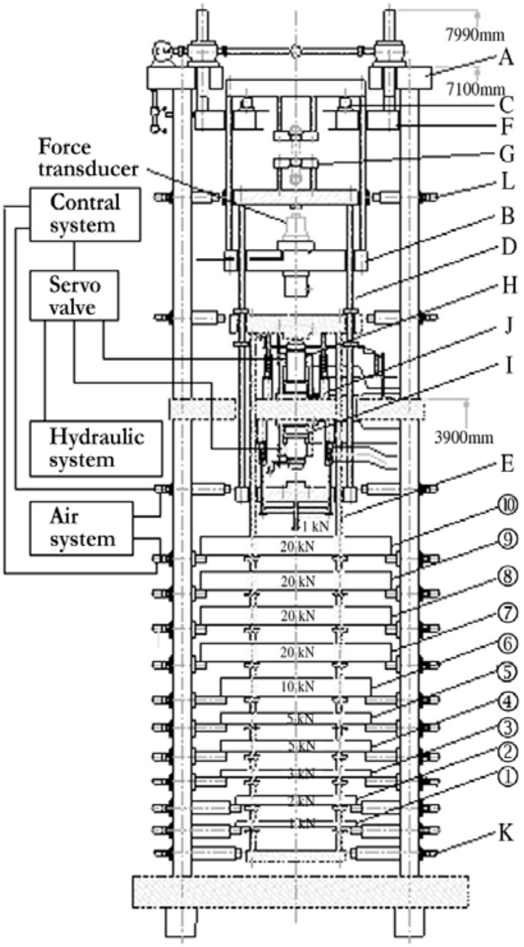

Fig. 2 Schematic diagram of the 100 kN deadweight force standard machine

The lifting frame (B) consists of an upper crossbeam, a lower crossbeam, three columns, and a compression table. The compression table, which holds the force transducer to be calibrated, is mounted on the lower crossbeam, and can be rotated remotely by the operator.

Three force transducers (C), which are used to measure the force generated by the loading frame, the weight supporter, and the weights, were mounted between the adjustable yoke and the upper crossbeam of the lifting frame. The value measured from the force transducers is used as the reference value in the closed-loop control for maintaining the force applied to a force transducer under calibration, while the loading frame (D), the weight supporter (E), and all the weights are moved up by the lifting ram-cylinder (H) when selecting a new weight set.

The loading frame (D) consists of three rods, an upper crossbeam, a lower crossbeam, and six stoppers. Each rod has two adjustable stoppers. The upper stopper contacts the upper crossbeam of the weight supporter when the loading frame is moved up and down when placed on the weight supporter. The lower stopper also contacts the upper crossbeam of the weight supporter, in order to load the selected weight set, to provide the selected force to be applied to a force transducer. The loading frame has a capacity of 2 kN.

The weight supporter (E) consists of three rods, an upper crossbeam, a lower crossbeam, and 30 stoppers. Each rod, which consists of four smaller rods, has 10 adjustable stoppers to support the weights. The adjustable stoppers are in the shape of a 60° cone. The weight supporter has a capacity of 2 kN.

The hydraulic and air systems consist of a hydraulic supply system, an air supply system, a lifting ram-cylinder (H), a loading ram-cylinder (I), three cushion ram-cylinders (J), 30 weight-selecting systems (K), and 12 swing-protecting systems (L).

2.2 Control system of the deadweight force machine

The force standard machine is operated manually and semiautomatically by means of two potentiometers on the control panel. They control two servo valves. One controls the lifting ram-cylinder and the other controls the loading ram-cylinder. The machine can also operate semiautomatically or automatically depending on the specific software controlling the operation PC.

The control system consists of a control panel, a controller, an operation PC, and specific software. The control panel comprises the power control, mode selection, the ram-cylinder manual operator, and the weight selector. It has a screen with a schematic diagram that shows any error messages and indicates the setting conditions and any emergency situations.

The controller consists of a CPU, I/O unit for the input and output modules, a power supply unit for both the CPU and the I/O units. The CPU is connected to the operation PC, the input and output modules, and the stepping motor drive. It receives a command from the operation PC and retrieves information from the input I/O modules, such as: the status of the pumps, any emergency condition, the weight selection, etc. The controller in turn issues commands to the stepping motor drive, the loading pump, the lifting pump, the error message, the schematic diagram, etc. through the output I/O modules.

The operation PC controls the servo valves and the controller. It receives the output signal from the measuring amplifier through a serial interface line, and manages the output signals of the pressure transducer, three force transducers, and two potentiometers through a digital to analog converter.

2.3 Force-generating procedure

The procedure for generating the force is as follows:

(1) apply the force generated by the loading frame (2 kN) to a force transducer;

(2) apply the force generated by the weight supporter (2 kN) through the lower stopper of the loading frame, to a force transducer; and

(3) apply the force generated by the weights through the stoppers of the weight supporter, to a force transducer.

To generate the force of a step produced by all the weights, four steps are needed:

(1) in order to apply a new force to a force transducer, the applied force by the loading frame should be maintained by the loading-ram cylinder;

(2) in order to select a weight set, all the weights should be separated from the weight-selecting systems by raising the weight supporter;

Table 1 Combination of weights in 100 kN deadweight force machine

Load	Loaded weights
20 kN	D+E+①+④+⑥
40 kN	D+E+①+④+⑥+⑦
60 kN	D+E+①+④+⑥+⑦+⑧
80 kN	D+E+①+④+⑥+⑦+⑧+⑨
100 kN	D+E+①+④+⑥+⑦+⑧+⑨+⑩

(3) a weight set for generating the force is selected by the weight-selecting systems; and

(4) the newly selected force is applied to a force transducer by lowering the weight supporter with the selected weights.

Each force step can be adjusted by appropriately combining the deadweights. For example, forces of 20, 40, 60, 80, and 100 kN can be generated by the combination listed in Table 1.

3. Uncertainty Estimation

3.1 Mathematical model

The force realization by using a deadweight force machine can be represented as follows:

$$F = m\, g_{loc}\left(1-\frac{\rho_a}{\rho_w}\right)\prod_{i=1}^{n}\cdot(1-\Delta_i) \qquad (2)$$

where m, g_{loc}, ρ_a, and ρ_w are already explained in Eq. (1), and $\Delta_i (i=1, \cdots, n)$ is the relative error component caused by the structure of the force standard machine, such as the error caused by an inclined baseplate of the machine or by oscillations of the deadweights.

3.2 Estimation of standard uncertainty components

In order to estimate the uncertainty of a deadweight force machine, the standard uncertainty due to each component in Eq. (2) should be estimated. This section deals with the estimation of the standard uncertainty components.

The deadweights in the 100 kN force standard machine were calibrated using precision balances and standard masses that are traceable to national mass standard No. 72. The relative standard uncertainty of the calibration of deadweights, w_m, was 1.69×10^{-6}.

The gravitational acceleration at the site of the deadweight force standard machine was 9.7982994 m/s^2. The maximum error in the acceleration due to time variation, height difference, and acceleration measurement was 1.0×10^{-5} m/s^2. By assuming a uniform probability distribution of the error in the gravitational acceleration, the relative standard uncertainty due to the gravitational acceleration, w_g, can be represented as follows:

$$w_g = \frac{1}{\sqrt{3}}\frac{\Delta g}{g} = \frac{1}{\sqrt{3}}\frac{1.0\times10^{-5}}{9.7982994} = 5.89\times10^{-7} \qquad (3)$$

where Δg is the error in the gravitational acceleration.

The density of air can be estimated as follows:

$$\rho_a = \frac{0.464554p - h(0.00252T - 0.020582)}{T+273.15} \qquad (4)$$

where,

p (mm Hg) = atmospheric pressure
h (%RH) = relative humidity
T (℃) = temperature.

At the site of the 100 kN deadweight force machine, the atmospheric pressure varied from 745.7 mm Hg to 765.6 mm Hg, the relative humidity varied from 35.2%RH to 73.0%RH, and the temperature varied from 18.3℃ to 22.3℃ over the period of a year. From this information and by using Eq. (4), the maximum variation of the air density can be estimated as 0.05 kg/m^3. By assuming a uniform probability distribution for the variation in the air density, the relative standard uncertainty due to air density, $w_{\rho a}$, can be represented as follows:

$$w_{\rho a} = \frac{1}{\sqrt{3}}\frac{\Delta\rho_a}{\rho_a} = \frac{1}{\sqrt{3}}\frac{0.05}{1.18} = 2.45\times10^{-2} \qquad (5)$$

where $\Delta\rho_a$ is the variation of air density.

The deadweights of the force machine were made of stainless steel with a density of 7903 kg/m^3. By assuming a relative error in the density of 1% and a uniform probability distribution of this error, the relative standard uncertainty due to deadweights density, $w_{\rho w}$, can be estimated as

$$w_{\rho w} = \frac{1}{\sqrt{3}}0.01 = 5.77\times10^{-3} \qquad (6)$$

To calibrate a force transducer, it should be mounted on the baseplate of a deadweight force machine. The baseplate should be installed horizontally; however, it is usually slightly inclined due to manufacturing limitations and mounting techniques. We assumed that the inclination angle was 0.01°. Because the inclination angle is constant, it is not necessary to consider any probability distribution in its value. Therefore, the relative standard uncertainty due to the inclined baseplate, w_p, can be represented as follows:

$$w_p = 1-\cos(0.01°) = 1.52\times10^{-8} \qquad (7)$$

The deadweights of a force machine often exhibit oscillatory motion that may slightly influence the applied force (Park and Kang, 2000). By assuming the maximum swing angle is 0.03° with a uniform probability distribution, the relative standard uncertainty, w_s, can be estimated as follows:

$$w_s = \frac{1-\cos(0.03°)}{\sqrt{3}} = 7.91\times10^{-8} \qquad (8)$$

3.3 Estimation of the expanded uncertainty

From the mathematical model of force, Eq. (2), the relative combined uncertainty of the deadweight force machine can be represented as follows:

$$w_c = \left\{\sum\left(\frac{1}{F}\frac{\partial F}{\partial x_i}u_{xi}\right)^2\right\}^{\frac{1}{2}} \qquad (9)$$

where F is the force generated by the force machine, and u_{xi} implies an absolute standard uncertainty component due to variation of x_i, which is one of the independent variables in Eq. (2), such as m, g_{loc}, etc. By substituting Eq. (2) into Eq. (9), the relative combined uncertainty can be represented as follows:

$$\begin{aligned} w_c &= \sqrt{\left(\frac{u_m}{m}\right)^2+\left(\frac{u_g}{g}\right)^2+\left[\left(\frac{u_{\rho a}}{\rho_a}\right)^2+\left(\frac{u_{\rho w}}{\rho_w}\right)^2\right]\cdot\left(\frac{\rho_a}{\rho_w-\rho_a}\right)^2+\sum_{i=1}^{n}w_{\Delta_i}^2} \\ &= \sqrt{w_m^2+w_g^2+[w_{\rho a}^2+w_{\rho w}^2]\cdot\left(\frac{\rho_a}{\rho_w-\rho_a}\right)^2+w_p^2+w_s^2} \end{aligned} \qquad (10)$$

From Eq. (10), the relative combined uncertainty was calculated as 4.2×10^{-6}. By increasing the relative combined uncertainty by a factor of 2, the relative expanded uncertainty of the deadweight force standard machine was estimated as 8.4×10^{-6}.

There are additional uncertainty components that have not been considered in this uncertainty evaluation, such as the interaction between the force transducer and the force machine. By considering these unknown uncertainty components, the relative expanded uncertainty of the 100 kN deadweight force standard machine was declared as 2×10^{-5} with a confidence limit of 95.46%.

4. Internal Comparison with a 500 kN Deadweight Force Machine

The 100 kN deadweight force machine was compared with the 500 kN deadweight force machines at KRISS. The schematic diagram of the 500 kN deadweight force machine is presented in Fig. 3. The first weight of 1360.8 kg is constructed in the form of a frame, and its upper part is used as the load platen. In the unloaded condition, 10 weights, each of 4536 kg (the lower weights) rest in conical support sockets that are connected to the building. Nine weights each of 453.6 kg are supported by three threaded rods, which engage bevel seats in plates attached to the tops of the 453.6 kg weights. The lifting frame, which carries the upper or tension platen and the lower or compression platen, is suspended from the center of a hydraulic piston located above. Both platens are

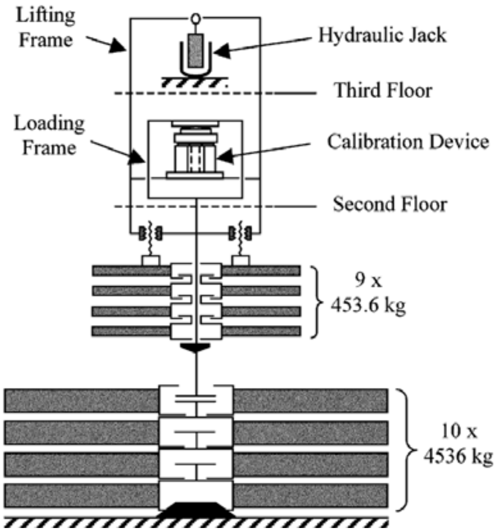

Fig. 3 Schematic illustration of the 500 kN deadweight force machine

independently adjustable to accommodate the size of the particular force sensor. The weight increment is fixed and cannot be varied. The machine is about 15 m high by 2 m wide. The weights are on the first floor of the laboratory building, the forces are applied to the calibration device on the second floor, and the hydraulic jack for lifting the weights is on the third floor (Park and Kang, 1999).

Two strain-gauge-type force transducers having capacities of 50 kN and 100 kN were used in the intercomparison. The force transducer used for the intercomparison is called a force transfer standard. The rated outputs of the force transducers are about 2 mV/V. To minimize the uncertainty associated with the measuring instrument, a high-precision indicator (HBM DMP40) was used, with an indicating resolution of 0.000001 mV/V.

The measuring procedure was carefully determined to minimize the parameters that are known to contribute to the measurement uncertainty. When a loading condition of a force transducer is changed, the transducer experiences changes in its mechanical, thermal, and electrical responses in the various interconnected elements, followed by a delayed creep response leading to a drift in the output of the transducer as the elements approach a new state of equilibrium. Although different force transducers show different creep behavior, the creep rate generally decreases rapidly during the first few minutes following loading or unloading. It was found that a three-minute delay between the start of the loading and the actual reading was adequate (Kang et al., 1994). Therefore, a three-minute interval was used to minimize the creep effect of the force transducer.

Machine-transducer interaction can significantly influence the measurement uncertainty. A small misalignment between the force machine and transducer may result in considerable deformation components, such as bending, shear, and twisting. Therefore, it is desirable to sample the response of the force transducer at several symmetrically distributed positions (Kang et al., 1994). The output of the force transducer was measured at four positions relative to the axis of the machine (0°, 90°, 180°, and 270°).

Table 2 Loads chosen for intercomparison between the 100 kN and 500 kN deadweight force standard machines

Force transducer capacity (kN)	Selected load in 100 kN force machine (kN)	Selected load in 500 kN force machine (kN)
50	20	22.2411 (5 klbf)
	30	31.1376 (7 klbf)
	40	40.0340 (9 klbf)
	50	48.9304 (11 klbf)
100	40	40.0340 (9 klbf)
	60	57.8269 (13 klbf)
	80	80.0680 (18 klbf)
	100	97.8609 (22 klbf)

The loads selected for the intercomparison of the machines are listed in Table 2. The force unit of the 100 kN force machine is the newton (N). On the other hand, the force unit of the 500 kN force machine is pound force (lbf). Therefore, a direct force intercomparison was not possible, and the force step of the 500 kN force machine was selected to be close to that of the 100 kN force machine. The following relationship was used to convert pound force to newtons:

$$1\ \text{lbf} = 4.448222\ \text{N} \tag{11}$$

Figure 4 shows the time schedule for loading that was used for the intercomparison. In the figure, the solid circle implies the measuring instant. At the 0° position, the force transducer was exercised by preloading before the start of a measurement cycle. Preloading involves applying the maximum test load three times and returning to zero load after each maximum loading. After the preloading and a three-minute delay, two sets of measurements separated by a three-minute interval were carried out. Then, the force transducer was rotated by 90°, and another preloading and one set of measurements separated by a three-minute interval were carried out. The same procedure was performed at 180° and 270°. In the figure, the left vertical axis indicates the load step when using the 50 kN force transfer standard and the right vertical axis applies to the use of the 100 kN force transfer standard.

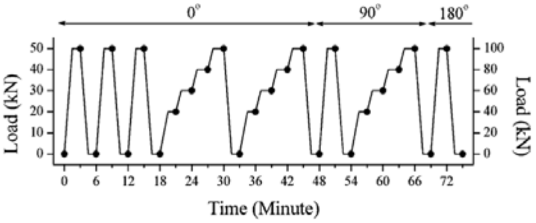

Fig. 4 Loading time-schedule for the intercomparison with the 500 kN deadweight force machine

As already mentioned, the force units of the two deadweight force machines are different. Therefore, the 500 kN force machine readings were normalized to the force steps of the 100 kN force machine as follows:

$$X_{ni} = \frac{F_{100}(\text{kN})}{F_{500}(\text{kN})} X_i \qquad (12)$$

where,

X_{ni} = normalized indicator reading for 500 kN force machine

X_i = indicator reading for 500 kN force machine

F_{100} = applied force for 100 kN force machine (kN)

F_{500} = applied force for 500 kN force machine (kN)

The whole series of measurements was first done on the 100 kN force machine. Then the second set of measurements was done on the 500 kN force machine, followed by a final set done on the 100 kN force machine.

Figure 5 shows the relative deviation between the 100 kN force machine and the 500 kN force machine, where the reference is the 100 kN force machine. The mean value of the two measurements at the 100 kN force machine was used as the reference value. The relative deviation is less than 3×10^{-5} for all the force steps. The relative deviation when using the 100 kN force transducer is higher than the deviation using the 50 kN force transducer. This is because the 100 kN force transducer is unstable, as demonstrated in Fig. 6, which shows the repeatability of the measurement: that is, the difference between the maximum and minimum values of each rotation position. From this internal intercomparison, we could confirm that the 100 kN force machine was in good agreement with the 500 kN force machine within the range 20 kN to 100 kN.

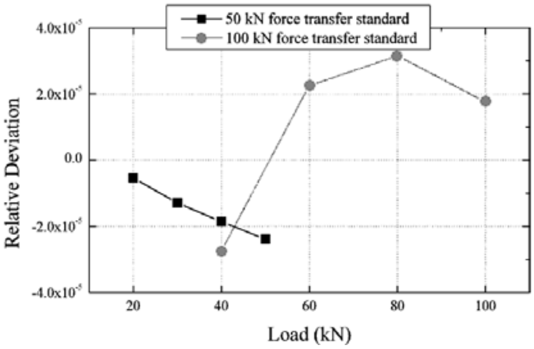

Fig. 5 Relative deviation for the intercomparison with 500 kN deadweight force machine

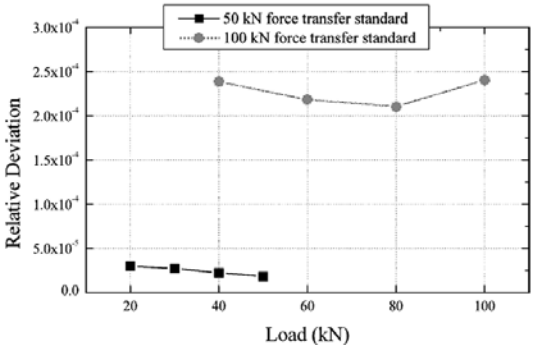

Fig. 6 Repeatability for the intercomparison with 500 kN deadweight force machine

5. Intercomparison with the NMIJ Deadweight Force Standard Machines

By intercomparison with the 500 kN deadweight force machine, the accuracy of the 100 kN deadweight force machine was checked internally. However, to get more general international agreement on the deadweight force standard machine, an additional intercomparison with other force machines at other NMIs was needed. For this reason, we performed an intercomparison at the NMIJ.

NMIJ has 3 kN, 20 kN, 50 kN, and 540 kN deadweight force standard machines. Of these, the 20 kN and 50 kN deadweight force machines were compared with the 100 kN deadweight force machine at KRISS. Transfer standards of 20 kN and 50 kN force were used for the intercomparison with the NMIJ 20 kN and 50 kN force machines, respectively. A high-precision indicator, HBM DMP40, was used to read the values of the force transfer standards. The measurements were carried out at (23±0.5) ℃. Both the force transducer and indicator were kept at this temperature for several days before the start of the measurements.

As already mentioned, the time interval should be decided carefully to minimize the creep effect. A three-minute interval was used. However, the operating time to reach the maximum load from zero and to return to zero from the maximum load was quite long for the NMIJ's force machines because the machines loaded and unloaded each deadweight step by step. Therefore, a five-minute interval was used for the preloading procedure and when returning to the zero point after maximum load. The output of the force transducer was measured at four positions relative to the axis of the machine (0°, 90°, 180°, and 270°) to reduce the effects of machine-transducer interaction. The force steps were 10, 14, 18, and 20 kN for the intercomparison with the NMIJ 20 kN force machine, and 20, 29, 39, and 49 kN for the NMIJ 50 kN machine. The 50 kN deadweight force machine at the NMIJ has a force unit of ton force (tf), instead of newtons. Therefore, to minimize the difference in comparing force levels between the two force machines, force steps of 20, 29, 39, and 49 kN were used instead of 20, 30, 40, and 50 kN. Table 3 shows the loads selected for the intercomparison. The relationship to convert ton force to newtons is as follows:

$$1\ \text{tf} = 9.80665\ \text{kN} \tag{13}$$

As with the internal intercomparison of the 100 kN and 500 kN force machines, the readings of the NMIJ 50 kN force machine were normalized to correspond to the force steps of the 100 kN force machine in a way similar to Eq. (12).

Figure 7 shows the loading time schedule used for the intercomparison. At the 0° position, the force transducer was preloaded three times before the start of a measurement cycle. After the preloading and a five-minute delay, three sets of measurements were carried out, separated by a five-minute delay. Then, the force transducer was rotated by 90° and two further sets of measurement were carried out, and so on until 270°. In the figure, the left vertical axis shows the load steps for the intercomparison with the NMIJ 2 kN force machine, and the right vertical axis shows the load steps for the intercomparison with NMIJ 50 kN force machine.

Table 3 Loads chosen for intercomparison between the KRISS 100 kN and the NMIJ 20 kN and 50 kN deadweight force standard machines

NMIJ force standard machine (kN)	Selected load in 100 kN force machine (kN)	Selected load in NMIJ force machines (kN)
20	10	10
	14	14
	18	18
	20	20
50	20	19.6133 (2 tf)
	29	29.4200 (3 tf)
	39	39.2266 (4 tf)
	49	49.0333 (5 tf)

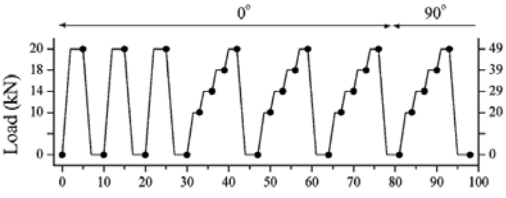

Fig. 7 Loading time-schedule for the intercomparison with NMIJ deadweight force machines

The first measurement was done at the 100 kN force machine at KRISS, then the second one was done at the 20 kN and 50 kN force machines at NMIJ. The final measurement was done at the 100 kN force machine at KRISS again.

Figure 8 shows the intercomparison result with the NMIJ 20 kN deadweight force machine. In the figure, the upward triangle represents the relative deviation between the NMIJ 20 kN force machine and the KRISS 100 kN force machine where the reference is the first measurement at the 100 kN force machine. The downward triangle represents the relative deviation where the reference is the final measurement in 10 kN force machine. The difference between the two data sets implies a drift in the force transducer during the intercomparison. The drift is less than 2×10^{-5}. The right rectangle shows the relative deviation where the reference was the mean value of the first and final measurements in 100 kN force machine. This deviation was less than 1.6×10^{-5}, which is less than the theoretical uncertainty of the deadweight force machines: 2×10^{-5}. The 100 kN force machine was in good agreement with the NMIJ 20 kN force machine within the range of 10 kN to 20 kN.

Figure 9 shows the intercomparison with the NMIJ 50 kN deadweight force machine. The structure of the figure is same as that of Fig. 8. The drift of the force transfer standard during the intercomparison was less than 2×10^{-5} and the relative deviation between the NMIJ 50 kN and KRISS 100 kN deadweight force machines was less than 1×10^{-5}. The deviation is within the theoretical uncertainty of deadweight force machines in the range of 20 kN to 50 kN.

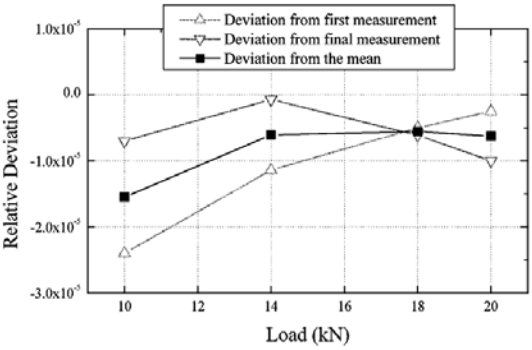

Fig. 8 Relative deviation for the intercomparison with the NMIJ 20 kN deadweight force machine

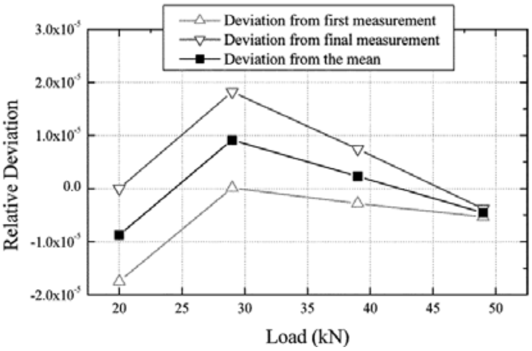

Fig. 9 Relative deviation for the intercomparison with the NMIJ 50 kN deadweight force machine

6. Conclusions

We have introduced a 100 kN deadweight force standard machine that we developed. The machine can generate forces from 2 kN to 110 kN with force steps of 1 kN by combining a binary set of deadweights. Its uncertainty was estimated theoretically and declared as 2×10^{-5}.

The 100 kN deadweight force machine was compared with a 500 kN deadweight force standard machine internally at KRISS. The two deadweight force machines showed good agreement, considering the stability of the force transducers used for the intercomparison.

Over recent decades, there has been much collaboration between NMI force metrology communities from different countries. As a result of this, the force calibrations performed at one institute are now more readily accepted by the others. Moreover, intercomparison of force standard machines with other NMIs is the most common method to verify a force standard machine. For this reason, we compared the 100 kN deadweight force machine with the 20 kN and 50 kN deadweight force standard machines of NMIJ. The relative deviation was less than 1.6×10^{-5}, and we conclude that the 100 kN force standard machine utilized by KRISS in Korea are maintained at the international level of accuracy.

In 1999, directors of NMIs all over the world signed the Mutual Recognition Arrangement (MRA). As a part of the MRA, several key comparisons that are part of a round intercomparison between NMIs, are occurring. The 100 kN force standard machine will participate in a force key comparison in the range of 100 kN. In order to get good agreement in the key comparison, we are making a concerted effort to preserve the high accuracy level of the force machine.

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