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Intercomparison of Force Standards between Korea and Germany

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ABSTRACT

국가간에 힘 측정 또는 힘 측정기기의 교정 결과에 대한 상호 신뢰를 확보하기 위해서는 힘 표준에 대한 상호비교가 필수적이다. 본 논문에서는 한국의 힘 표준에 대한 국제적 신뢰를 확보하기 위하여 세계 여러 나라들과 힘 표준에 대한 국제비교 연구를 수행한 독일연방물리청과 힘 표준의 상호비교를 실시하였다. 비교시험 결과 한국과 독일의 힘 표준의 상대 편차는 100 kN~500 kN범위에서 $\pm 5.5 \times 10^{-5}$이내로 나타났으며, 한국의 힘 표준의 정확도가 국제적 수준임을 확인하였다.

Key Words : Force Standard, Deadweight Force Standard Machine, Intercomparison

1. Introduction

Force is often measured for quality control in production processes, the characteristic evaluation of material and stress analysis of structure which is closely connected with safety and optimal design in the field of engineering. Force is defined as the physical quantity acting on mass to accelerate it. The standard of force obtained on the basis of this principle is realized by means of deadweights of the mass under the influence of local acceleration due to gravity. This deadweight force standard machine is widely used as the force standard in most national institutes of metrology(1). Force measuring equipment should be calibrated with a force standard machine to transfer the standard of force to industrial and scientific institutions.

Whithin the framework of international cooperation in the field of force measurment, the question of the scope within which deviations in the generation of forces agree in different countries and with what uncertainty forces can be realized, has been discussed for several years. This problem is of great interest, as international economic interdependence demands a standardization of the realization of force. It is also necessary to ensure that when calibrating a force measuring device, all national laboratories obtain the same results within the scope of the uncertainties stated. For this reason, the Physikalisch-Technische Bundesanstalt(PTB), Germany, has carried out

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comparison measurements with many countries(2, 3).

In order to estabilish force standards in Korea, three deadweight of 5 kN, 20 kN and 500 kN capacity were installed at the Korea Research Institute of Standards and Science (KRISS). The 500 kN deadweight machine was donated to KRISS as a part of cooperation project between Korea and USA in 1978. The deadweights of the machine were precisely recalibrated to compensate the effect of local gravitational acceleration in 1986(4). The machine was then intercompared with the 540 kN deadweight machine of the National Research Laboratory of Metrology in Japan in 1987. In a previous paper it was shown that the force standards of KRISS were in good agreement with those of NRLM over a range of 15 kN to 500 kN(5). It is very important for KRISS to intercompare the force standards between Korea and Germany as the PTB has much experience in intercomparisons of force standards among other countries.

The objective of this paper is to compare the force standards realized by KRISS and PTB over a range of 100 kN to 500 kN, so that the results of force calibrations performed at one institute are more readily accepted by the other.

2. Force Standard Machines

As the force standard machines intercompared have been described in detail in Refs. (1, 7), only a brief description of them is given here.

2.1 The KRISS 500 kN deadweight machine

A schematic diagram of the 500 kN deadweight machine is shown in Fig. 1. This machine has one stack of ten weights having a nominal of 44 kN(10 klbf), a second stack of nine weights having a nominal value of 4.4 kN(1 klbf), and a loading frame having a nominal value of 13 kN(3 klbf). The large weights are applied to the force sensor as the lifting frame is raised by a hydraulic jack, and the smaller weights are applied as they are lowered onto the loading frame by the screw jackes. The weight applied to the force sensor being calibrated is the sum of the weight applied from the two stacks plus the 13 kN weight of the loading frame. The loading speed and the weight increment are essentially fixed as functions of the machine. The machine is about 15 m high and about 2 m wide. The weights are on the first floor of the laboratory building, the force is applied to the force sensor on the second floor, and the hydraulic jack for lifting the weights is on the third floor. The minimun magnitude of force which can be generated by this machine is about 13 kN.

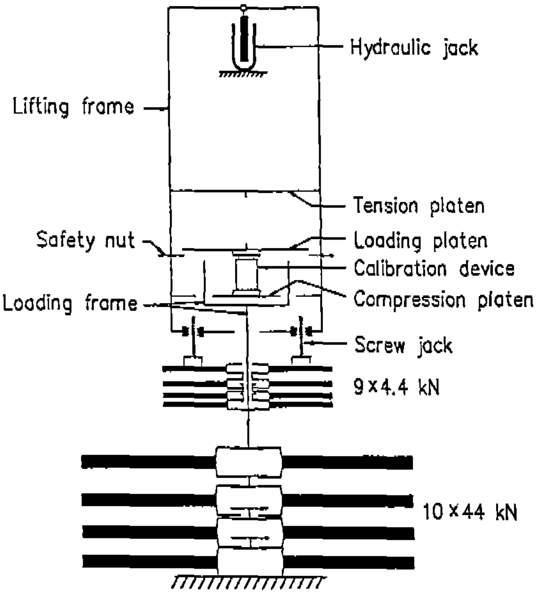

Fig. 1 Schematic diagram of the 500 kN deadweight machine of KRISS.

This machine, fabricated by Emery Co. in the USA, was installed at the National Institute of Standards and Technology, USA, in 1926 and was used as a force standard in USA until the

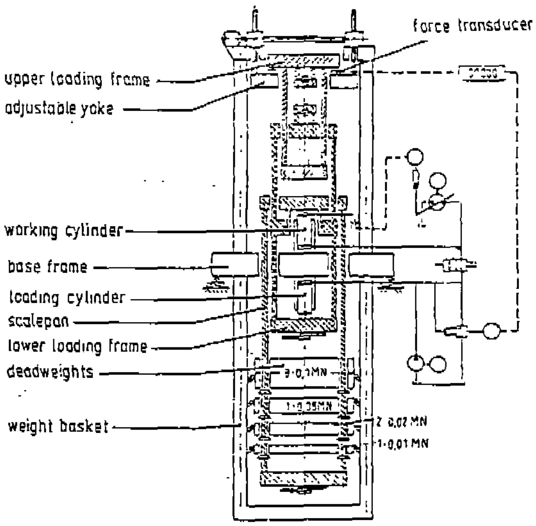

Fig. 2 Schematic diagram of the 1 MN deadweight machine of PTB

beginning of the 1970's. It was then contributed to KRISS as a part of a cooperation project between Korea and the USA in 1978. The weights of the machine were precisely recalibrated by the 1-ton Russel mass comparator and the 5-ton Schoonover mass comparator after the mass value of the weight was adjusted to compensate the effect of local gravitational acceleration⁽⁴⁾.

2.2 The PTB 1 MN deadweight machine

A schematic diagram of the 1 MN deadweight machine is shown in Fig. 2. A base frame supports a vertically adjustable yoke which carries three force transducers for the control system. The force transducers carry the upper loading frame. The loading cylinder exerts pressure upon the lower loading frame. The deadweights participating in the loading are carried by the machine scalepan, and the deadweights which do not participate in the loading are deposited in the weights basket. The weights hang from top to bottom in the following order :

9 weights, each for the generation of 100 kN
1 weight for the generation of 50 kN
2 weights, each for the generation of 20 kN
1 weight for the generation of 10 kN

The deadweight of the loading frame generates a force of 20 kN, which is the first force step; the deadweight of the scalepan also generates 20 kN and constitutes the second force step. The stack of deadweights is placed in a pit 9 m in depth.

3. Force Transfer Standards

Two strain gage type force transducers having capacities of 200 kN and 500 kN were used in the intercomparison. The rated outputs of the force transducers are about 2 mV/V and the repeatability errors are less than 2×10^{-5}. The force transducers have been in use at PTB over a substantial period of time. The behavior of the force transducers is well known as is their long-term stability⁽⁶⁾.

To minimize the uncertainty associated with the indicating instrument, a high-resolution indicator with good stability was chosen⁽⁸⁾.

Prior to the start of the intercomparison, measurements were conducted at KRISS and PTB, using a high precision standard bridge (model no. : BN 100) to ascertain the reliability of the indicator when different main frequencies (50 and 60 Hz in Germany and Korea, respectively) are used. No significant differences were found. Fig. 3 shows the measurement set-up for the KRISS deadweight machine.

4. Measurement procedure

In developing the procedure used to perform the intercomparison, great care was taken to minimize the effects of parameters that are known to contribute to the measurement uncertainty. The following subsections describe

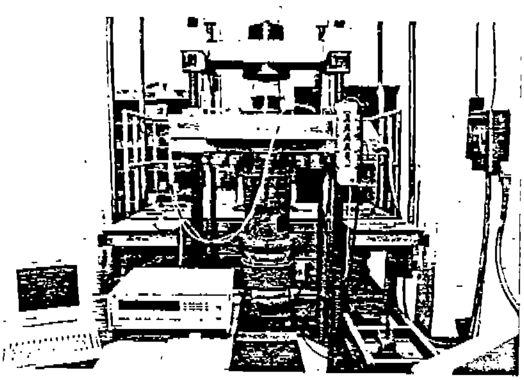

Fig. 3 Scene of measurement for the deadweight machine of KRISS

these parameters and the ways in which their effects were minimized.

4.1 Time Interval

The difference between the output of a transducer at a load and its output when no load is applied represents the response of the transducer to that load. When a load is applied to a force transducer or when the force transducer is unloaded, there are initial mechanical, thermal and electrical responses in the various interconnected elements, followed by a delayed creep response of drift in the output of the transducer as the elements approach a new state of equilibrium. The process may be further complicated by local heating due to electrical power dissipation by the strain-measuring bridge.

Although different force transducers exhibit different creep patterns(7), in general, the creep rate decreases rapidly during the first few minutes following loading or unloading. To minimize the creep effect of the force transducer, the time required to achieve a stable response following loading and unloaing was determined prior to the start of the intercomparison. In most instances it was found that a 3 minute time delay between the start of the loading(or unloading) and the actual reading was adequate(9). A 3-minute time interval was therefore used. Fig. 4 shows the time schedule of loading used for the intercomparison.

In each instance, each set of measurements was repeated once. In all cases a 3-minute time interval was introduced between the completion of the intial set of measurements and the start of the repeat set measurements.

4.2 Machine-Transducer Interaction

Machine-transducer interaction can significantly influence the measurement uncertainty. As normal imperfections in the alignment of loading machines and force transducers may result in considerable deformation components such as bending, shear, and twisting, it is desirable to

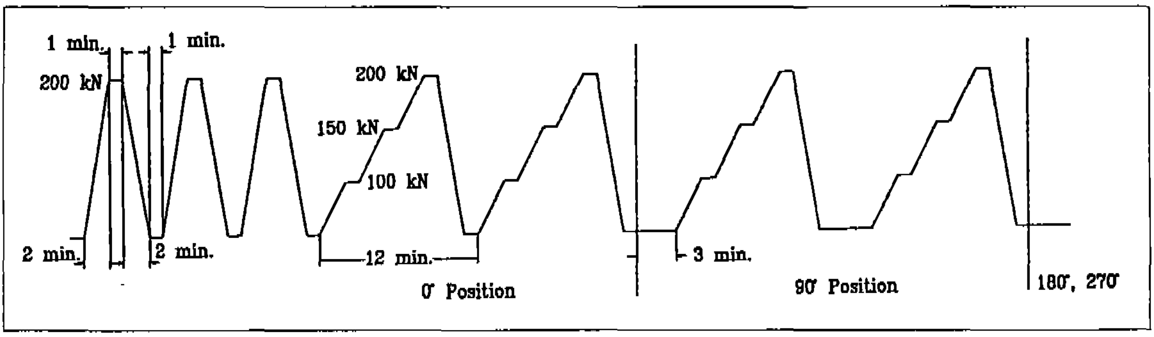

Fig. 4 Time schedule of loading used for the intercomparison.

sample the response of the force transducer at several symmetrically distributed positions(9). For this reason, the output of each force transducer was measured at four positions relative to the axis of the machine (0°, 90°, 180°, 270°).

At the 0° position and prior to the start of a measurement cycle, the force transducer was exercised by applying the maximum test load three times, returning to zero after each maximum load application. After a 3-minute delay, with the force transducer still the same position, two sets of measurements were carried out, separated by a 3-min interval. The force transducer was then rotated by 90° and two new sets of measurements, separated by a 3-minute interval, were carried out, and so on.

4.3 Ambient Conditions

The measurements were carried out at (22±1)℃. However, a week prior to the start of the measurements, the temperature of the PTB laboratory was increased to (22±1)℃. Both the force transducers and the indicatior were kept at this temperature for a week prior to the start of the measurements.

4.4 Force Steps

The loads selected for the intercomparison of the machines are listed in Table 1. Load selection was dictated by the constraints upon the force standard machines intercompared, and the following criteria :

1. The limiting of the measurement range so that no measurements are made below 40% of the force transducer capacity;
2. The use of only load sequences that can be applied monotonically;
3. The selection of the same loads for each force standard machine intercompared.

The following relationship was used to convert pound force to newtons;

1 lbf=4.448222 N.

5. Measurement Results and Discussion

An attempt was made to select similar loads at PTB and KRISS. However, because of machine limitations, the selected loads, while being similar in some aspects, differed considerably as can be seen in Table 1. For this reason, the KRISS readings were normalized to correspond to the PTB force steps applied, in accordance with the following equation :

$$\text{KRISS normalized indicator reading} = \frac{\text{PTB applied force, kN}}{\text{KRISS applied force, kN}} \times \text{KRISS indicator reading} \qquad (1)$$

Two force transducers having nominal capacities of 200 and 500 kN were used to intercompare the force standards of Korea and Germany. The force steps selected for this intercomparison were 100, 150, 200, 300, 400 and 500 kN.

The measurement variability in each series of measurements at force step and at each force transducer position, expressed as the relative data spread between runs, is given in Tables 2 and 3 for the 200 and 500 kN force transducers, respectively. The relative spread between runs was calculated by taking the difference between the first and second readings

Table 1 Load chosen to intercompare the PTB 1 MN and the KRISS 500 kN force standard machines

Force transducer capacity, kN	Selected load in PTB machine, kN	Selected load in KRISS machine, kN
200	100	102.3901 (23 klbf)
	150	151.2395 (34 klbf)
	200	200.1700 (45 klbf)
500	200	200.1700 (45 klbf)
	300	298.0309 (67 klbf)
	400	400.3400 (90 klbf)
	500	498.2009 (112 klbf)

Table 2 Relative data spread between runs for the 200 kN force transducer as a function of rotational position

Institute	Applied force	Rotational position			
		0°, ppm	90°, ppm	180°, ppm	270°, ppm
PTB initial	100 kN	5	0	10	15
	150 kN	17	3	7	13
	200 kN	10	0	5	5
KRISS	23 klbf	20	5	5	5
	34 klbf	20	3	3	3
	45 klbf	18	5	0	0
PTB final	100 kN	0	20	15	5
	150 kN	13	23	10	13
	200 kN	13	20	10	8

Table 3 Relative data spread between runs for the 500 kN force transducer as a function of rotational position

Institute	Applied force	Rotational position			
		0°, ppm	90°, ppm	180°, ppm	270°, ppm
PTB initial	200 kN	6	25	19	25
	300 kN	8	25	17	13
	400 kN	9	22	19	13
	500 kN	8	20	8	10
KRISS	45 klbf	6	6	6	13
	67 klbf	4	0	0	0
	90 klbf	6	3	0	0
	112 klbf	5	3	0	5
PTB final	200 kN	6	38	25	19
	300 kN	8	29	21	21
	400 kN	3	28	19	22
	500 kN	8	25	15	13

and dividing the result by the initial reading. The relative spread in the data for all measurements performed at KRISS and PTB is less than 5×10^{-5}.

The net mean force transducer outputs measured during the KRISS measurements, the initial and final PTB measurements, and those obtained by averaging the initial and final PTB measurements are presented in Table 4. The values in Table 4 are in indicator units. The relative differences between the average indicator readings at PTB and the corresponding average indicator readings at KRISS are listed in Table as a function of force transducer and force step. The values shown in Table 5 were obtained by taking the mean reading at KRISS, subtracting it from the corresponding mean reading at PTB, and then dividing the result

Table 4 Force transducer outputs measured at KRISS and PTB.

unit : mV/V

Transducer kN	Force step kN	PTB initial	PTB final	PTB mean	KRISS
200	100	0.999439	0.999447	0.999443	0.999426
	150	1.499191	1.499201	1.499196	1.499247
	200	1.999000	1.999030	1.999015	0.999121
500	200	0.799218	0.799199	0.799207	0.799232
	300	1.198924	1.198894	1.198909	1.198937
	400	1.598646	1.598607	1.598627	1.598669
	500	1.998406	1.998356	1.998381	1.998435

Table 5 Relative differences between the PTB and KRISS readings for the force transducers tested in the deadweight machine of KRISS and the deadweight machine of PTB.

Transducer kN	Force step kN	PTB initial ppm	PTB final ppm	PTB mean ppm
200	100	13	21	17
	150	-37	-31	-34
	200	-61	-46	-53
500	200	-18	-41	-31
	300	-11	-36	-23
	400	-14	-39	-26
	500	-15	-40	-27

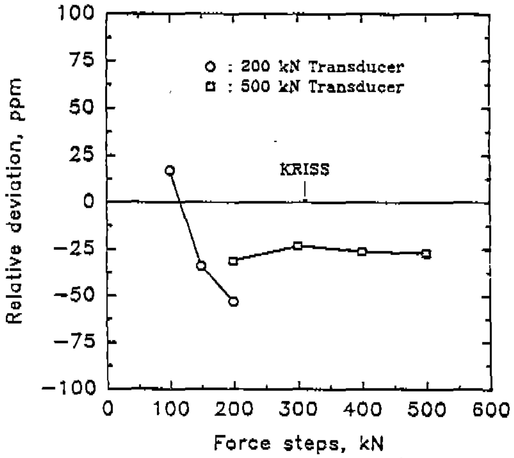

Fig. 5 Relative deviation between the force standards of PTB and KRISS.

by the mean reading at KRISS. The values shown are rounded to the nearest ppm.

The average deviations in the mean PTB data relative to the mean KRISS data for all force transducers and all force steps examined are given in Fig. 5. The 200 kN force step was measured with two different force transducers, reslting in different values. This difference is due to the overlapping effect which depends on the stiffness of the force transducer and the rotation effect as a result of deadweight machine - force transducer interaction(2). The relative deviation in the range of 100 kN~200 kN from the results of 200 kN force transducer is rapidly increased as the test force is increased. This behavior which may be ascribed to the interaction between the machine and the force transducer appears occasionally in the intercomparisons(2). Fig. 5 shows that the relative deviation between the force standards of Korea and Germany over a range of 100 kN to 500 kN is less than $\pm 5.5\times10^{-5}$. Peters(9) has reported that the theoretical uncertainty in the force realized by deadweight machines is in the order of 2×10^{-5}. Also Peters has reported that the deadweight force standard machines intercompared exhibit relative deviations from the PTB machine of $\pm 5\times10^{-5}$ or less(2). The disagreement between the theoretical uncertainty of the deadweight machine and the relative deviations of force standards from the intercomparisons is ascribed to the long-term stability of the force transfer standards, machine-transducer interaction and the measurement procedure. According to these, for the 100 kN to 500 kN force range, the agreement between the force realized at KRISS and PTB is close to what is theoretically achievable. It is also in good agreement with the results of the PTB intercomparisons with the national laboratories of 15 countries(2).

6. Conclusions

The force realized by the KRISS deadweight machine was compared with that realized at PTB. The results of the comparison show that the deviation between the force standards of Korea and Germany is less than ±5.5×10^{-5} over a range of 100 kN to 500 kN. It is well known that the theoretically attainable uncertainty of a deadweight machine is about 2×10^{-5} of generated force. From the intercomparison tests the deadweight force standard machines exhibit relative deviations from the PTB machine of ±5×10^{-5} or less. Therefore the agreement between the force realized at KRISS and PTB for the 100 kN to 500 kN force range is close to what is theoretically achievable. It may therefore be concluded that the force standards realized by KRISS in Korea are maintained on the international level of accuracy.

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