A PROPOSAL FOR AN EVALUATION METHOD OF FORCE STANDARD MACHINES BY USING BUILD-UP SYSTEM

Y.K.Park[1], M.S.Kim[1], J.H.Kim[1] and D.I.Kang[1]

[1]Division of Physical Metrology, KRISS, Korea

ABSTRACT

This paper describes a new method to evaluate a force standard machine by using a build-up system. The sum of three force signals from three force transducers in a build-up system can be used as a reference value for an intercomparison of force standard machines. At the same time, the small amount of differences between force signals from the build-up system can be used to estimate side force components of a force standard machine. This paper explains theoretical derivation and assumptions of the method. One example of using the method is included in this paper. A 500 kN deadweight force standard machine was examined by using the propose method.

1. INTRODUCTION

The unit of force is realised by deadweights of known masses subjected to the effect of local acceleration of gravity. The mechanical structure and apparatus to handle and control such deadweights is known as a deadweight force standard machine. If the local acceleration of gravity is determined accurately and correction is made for the air-buoyancy, the generated force by a deadweight machine is known very accurately with high reproducibility. In the international comparison of deadweight force machines in national metrology institutes by using a single force transducer, the maximum relative deviations were about $\pm$ $5x10^{-5}$ in the worst case while the theoretical uncertainty of a deadweight force machine is less than $1x10^{-5}$. This discrepancy has been ascribed to the interaction between deadweight machines and transfer standards, measurement procedure and parasitic force components of deadweight machines. By using a conventional comparison method employing a single force transducer, the parasitic force components of force standard machines cannot be measured. This limitation requires a new method to evaluate force standard machines absolutely.

A build-up system composed of three equal force-transducers in parallel, provides an efficient method for measuring large forces. The measuring range of the build-up system is three times that of each component force transducer. Build-up systems have been used as large force standards at some national institutes for metrology[1].

If a build-up system is set into a deadweight force machine, and if the build-up system and the deadweight force machine are ideally axi-symmetrical to the gravitational line, then the three force signals from the three force transducers in the build-up system should be same. On the contrary, if the deadweight force standard machine is non-symmetrical to the gravitational line, the force signals from the force transducers should be different each other. Therefore, the difference between the three force signals from a build-up system can play a key role to reveal the asymmetric properties of a deadweight force standard machine. In this paper, a method of quantitatively investigating parasitic force components of deadweight force machines will be proposed. The estimation method of side force components will be given. In order to check the propose method, the method was applied to evaluate a deadweight force standard machine. Measurement results of the 500 kN deadweight force standard machine in Korea Research Institute of Standards and Science(KRISS) will be introduced.

2. SIDE FORCE ESTIMATION

In the build-up system of a deadweight force machine, the scalepan of the machine delivers the load to the force transducers through the spherical cap of the load button. Assuming that the force transducers are identical, and are located at the correct position, and that the normal to the surface-plane of the scalepan coincides with the vertical axis, then the output signals measured from the force transducers must be the same. However, the scalepan is generally tilted. This gives an offset to the loading point of the build-up system. The forces acting on the load button and the middle platen of the build-up system can be represented as in Figure 1. In the figure, F is the force delivered by the force machine and R_A, R_B and R_C are the reactions caused by force transducers A, B and C, respectively. Subscripts X, Y and Z represent the force components along the x, y and z directions, respectively. In the figure, (ξ, η) is the contact position of the scalepan of the force machine. By considering Figure 1, and assuming that no moment is exerted on the build-up system by the force machine, the force equilibrium along the z-axis and the moment equilibrium along the x- and y-axes can be represented as follows.

$$\begin{aligned} &F_Z = R_{AZ} + R_{BZ} + R_{CZ} \ , \\ &\frac{\sqrt{3}}{2} a \frac{R_{BZ} - R_{CZ}}{F_Z} + \xi - \frac{F_X}{F_Z} h = 0 \ , \\ &\frac{a}{2} \frac{R_{BZ} + R_{CZ} - 2R_{AZ}}{F_Z} - \eta + \frac{F_Y}{F_Z} h = 0 \ . \end{aligned} \tag{1}$$

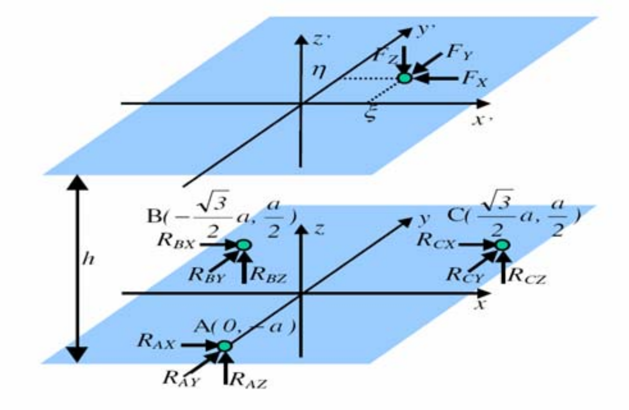

Figure 1 : External force and reactions in components

The upper platen attached to the force machine rolls on the load button by the pendulum motion of the deadweights. In the rolling motion, the friction force can be negligible; therefore the force acting on the build-up system is normal to the contacting surface as shown in Figure 2. In Figure 2, H is the total height between the load button and middle platen of the build-up system, r is the radius of the load button and α is the tilt angle of the force machine along the x-axis. From the geometrical considerations of Figure 2, the following relations can be obtained.

$$h = H - r(1 - \cos\alpha) \ , \tag{2}$$

$$\xi = r\sin\alpha \, , \quad \frac{F_X}{F_Z} = \tan\alpha \ . \tag{3}$$

From a similar consideration in the y-z plane, the following relations can be obtained.

$$\eta = r\sin\beta \, , \quad \frac{F_Y}{F_Z} = \tan\beta \ , \tag{4}$$

where β is the tilt angle along the y-axis.

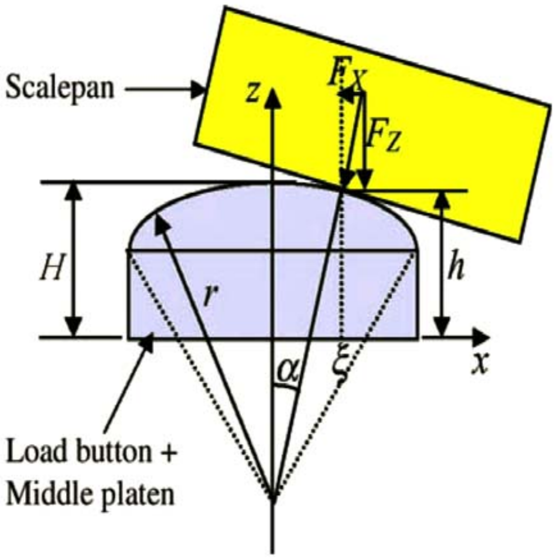

Figure 2 : Oblique external force

By using Equations (1)-(4), the ratios of side forces to normal force can be represented as

$$
\begin{aligned}
\frac{F_x}{F_z} &= \frac{\sqrt{3}}{2}\frac{a}{r-H}\frac{R_{CZ}-R_{BZ}}{R_{AZ}+R_{BZ}+R_{CZ}}\ , \\
\frac{F_y}{F_z} &= \frac{1}{2}\frac{a}{r-H}\frac{R_{BZ}+R_{CZ}-2R_{AZ}}{R_{AZ}+R_{BZ}+R_{CZ}}t\ .
\end{aligned}
\qquad (5)
$$

From Equation (5), one can see that the relative side force components of the force machine can be expressed by using the three reactions of the force transducers of the build-up system.

If the build-up system is perfectly axi-symmetric, one measurement at one fixed direction is enough to evaluate a deadweight force machine. However, real build-up system has some un-symmetric factors such as difference of sensitivity between force transducers, geometrical un-symmetry, small amount of misalignment between force machine and build-up system, etc. Therefore, to minimize the un-symmetric effect, it is desirable to sample the response of the build-up system at several symmetrically and equally distributed positions. The averaged value of the sampled responses can give the correct estimation of the deadweight force machine.

Only the DC component of the force signal is sufficient to estimate the side force components of a deadweight force standard machine. However, the AC component of force signal can be used to analyze the pendulum motion of a deadweight force machine. For the details of the pendulum motion, please see [2, 3].

3. ESTIMATION OF A 500 kN DEADWEIGHT FORCE MACHINE

Figure 3 illustrates experimental set-up to evaluate a 500 kN deadweight force standard machine in KRISS. The experimental set-up consists of a build-up system and a signal processing system. The signals from the force transducers in the build-up system were amplified and sampled simultaneously by a signal-conditioning amplifier HBM MGCplus with ML38 module. The measured signals were transmitted to a personal computer through a LAN interface.
The output of the build-up system was measured at five positions relative to the axis of the

machine(0^o, 90^o, 180^o, 270^o, 360^o). The force step was 200, 300, 400, 500 kN. At the 0^o position, the build-up system was exercised by 3 pre-loadings prior to the start of a measurement cycle. After the pre-loading and a 6-minute delay, two sets of measurements for increasing force were carried out, separated by a 6-minute interval. Then, the build-up system was rotated by 90^o, and one set of measurement for increasing force were carried out. The same procedure was performed at 180^o and 270^o. At 360^o, one set of measurement for increasing and decreasing force were carried out.

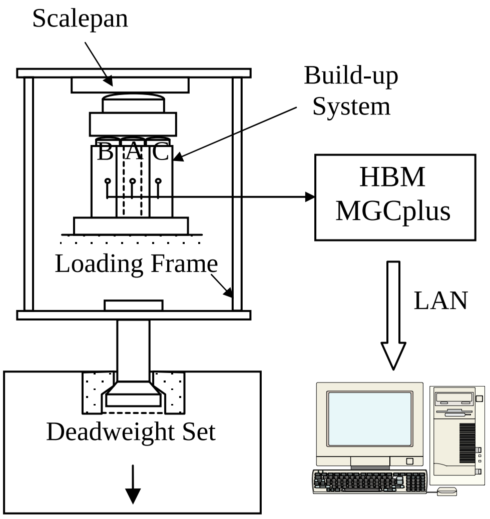

Figure 3 : Experimental set-up for side force components

Figure 4 : Directional characteristic of the side force Measurement

Figure 4 represent the directional characteristic of the measurement when the load is 500 kN. The standard deviation of the Fx/Fz estimation from 90^o to 360^o was about $2x10^{-4}$. The standard deviation of the Fy/Fz was similar to Fx/Fz. The deviation between 0^o and 360^o was about $2.2x10^{-5}$ for Fx/Fz and was $1.6x10^{-5}$ for Fy/Fz. By considering the low deviation, we can confirm the reproducibility of the measurement.

Figure 5 is the averaged relative side force at each load. The average was taken from 90^o to 360^o. The relative side forces with respect to the normal force are represented as vector arrows. Form the figure, one can easily see that the y component decreases with load while the x component remains almost same.

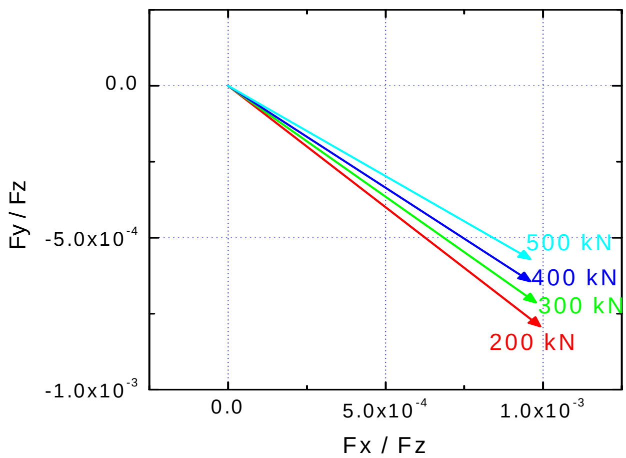

Figure 5 : Side force components of the 500 kN deadweight force machine

4. DISCUSSION AND FURTHER WORKS

In this paper, the authors propose an estimating method of parasitic force components of a deadweight force standard machine. The method uses a build-up system. By considering the small difference between three force signals from the build-up system, the side force components can be estimated.

The sum of three force signals from a build-up system reflects the normal force of a force standard machine. Therefore, a build-up system can be used as a transfer force standard for an intercomparison of force, while the difference between force signals can be used to estimate the side force components of a force standard machine.

As a conclusion, the proposed method can be used to compare the normal force between force standard machines and at the same time it can be used to evaluate some part of parasitic force components of a force standard machine.

However, it needs more improvement for the proposed method to be used in bilateral-intercomparisons or key comparisons. First of all, its reliability to measure the side force components should be checked. It can be done by comparing it with a multi-component force sensor. Second, the effects of build-up system's geometric and mechanical properties must be revealed. Based on this information, optimal conditions of the build-up system can be derived. Third, the stability of the build-up system should be tested. Forth, appropriate measuring protocol should be determined to be used in an intercomparison measurement. Finally, applications of the method to evaluate several force standard machines in several NMIs are necessary. By evaluating various types of force machines, we can examine the applicability of the method.

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Addresses of the Authors:

Yon-Kyu Park, Division of physical metrology, Korea Research Institute of Standards and Science, P.O.Box 102, Yuseong, Daejeon, 305-600, Korea. ykpark@kriss.re.kr
Min-Seok Kim. minsk@kriss.re.kr
Jong-Ho Kim. jhk@kriss.re.kr
Dae-Im Kang. dikang@kriss.re.kr