Arm balancing experiments in the deadweight torque standard machine with adjustable lever-arm lengths.

M-S Kim\textsuperscript{1,2}, M Derebew\textsuperscript{1,2}, Y-K Park\textsuperscript{1} and D-I Kang\textsuperscript{3}

\textsuperscript{1}Mechanical Metrology Center, Korea Research Institute of Standards and Science, Daejeon 34113, Republic of Korea
\textsuperscript{2}School of Metrology, University of Science and Technology (UST), Daejeon 34113, Republic of Korea
\textsuperscript{3}Convergence Research Institute, Daegu Gyeongbuk Institute of Science and Technology, Daegu 42988, Republic of Korea

E-mail: minsk@kriss.re.kr

Abstract. KRISS (Korea Research Institute of Standards and Science) has developed the 20 kN m-capacity deadweight torque standard machine that incorporates a double-arm design for the lever. Such a double-arm structure allows to separate two functions; supporting deadweight loads and determining effective lengths. One arm made of stainless steel supports the loads and the other made of INVAR determines the lever-arm length. Since the INVAR arm bears little loads, we could implement a translation mechanism in the INVAR torque arm to change its length in the range of approximately 6 mm. Using this unique feature of our machine, arm-balancing experiments have been conducted to investigate lever-arm length dependence on applied loads and determine the sensitivity of the air-bearing by intentionally unbalancing lengths on both sides to generate micro-torques under various loading conditions. In this paper, we present our plans of the experiments and discuss them.

1. Introduction
The KRISS (Korea Research Institute of Standards and Science) initiated a project in 2013 to develop a 20 kN·m-capacity deadweight torque standard machine in response to the ever-growing demands for the traceable torque calibration from Korean heavy industries that need high-capacity torque measurements, such as turbines (wind or steam), motors (electrical and combustive) manufacturers [1].

The machine is designed for generating traceable torques from 100 N·m to 22 kN·m with a step of 100 N·m. The relative calibration and measuring capability of the machine is targeted to be better than 5 parts in $10^5$. It weighs about 5 t, not including the weight of all deadweights and has a large size with dimensions of approximately 4350 mm x 3400 mm x 4055 mm in width, depth, and height, respectively. The length of a lever (one side) is 1 m. The size in height includes a depth of underground pits accommodating weight stacks of combination type. This machine can accommodate torque transducers with the maximum cylinder diameter of 130 mm and 1000 mm in length. The machine was installed in the laboratory at KRISS in 2016 as shown in figure 1. The machine consists of mainly four parts; the torque arm assembly, weight stacks, an adaptor assembly accommodating torque transducers including flexible couplings and hydraulic clamps, and a counter bearing assembly [2]. Among these parts, we incorporated a new scheme in the torque arm design, which is so-called a “double-arms” design [3]. This scheme allows to put length adjustable mechanism in the torque arm.
2. Double arm for the lever

The lever arm plays two important roles in producing deadweight torques. One is delivering torque to the transducers by supporting vertical forces generated by deadweight stacks and the other is to precisely define the lever-arm length between the force axis and the rotational axis of the air-bearing to produce torque accurately. Realizing these two functions at the same time requires a stiff lever structure to maintain its effective arm length under high loads at its ends, which leads to inevitable increase in weight of the lever. As the lever weight gets higher, the sensitivity decreases and it can also place a burden on the air-bearing used as a fulcrum. Separating these two functions by using the double-arm design can address this issue [3]. The KRISS adopted this concept to the torque arm design of the 20 kN·m deadweight machine.

2.1. Double arm lever design

The double torque arm consists of a main lever made of stainless steel that delivers torques by supporting loads at its ends and an auxiliary lever made of INVAR (i.e., a steel alloy that has an extremely low thermal coefficient of expansion of 1.8 ppm/°C) that allows to precisely determine the effective length of the lever to be 1 m. The INVAR lever can be designed to be as light as possible because it does not need to bear high loads. This design can reduce the cost of development by using less amount of the expensive material of INVAR. In addition, we can also reduce the weight of the main lever by allowing more deflection under high loads within the elastic limit of the stainless steel. The Young’s modulus and yield strength of the stainless steel are higher than those of INVAR so more stiff structure can be realized with less weight. The design of the double torque arm is shown in figure 2. The invar torque arm pushes the metal band outside about less than 0.5 mm in horizontal directions so that it defines the effective lengths of the torque arm on both sides by allowing round bars attached at its ends on both sides to touch the 450 mm wide metal bands as shown in figure 3.

2.2. Lever-arm length adjusting mechanism

Since the invar torque arm does not bear high loads, we could incorporate translation mechanisms in the INVAR torque arm capable of adjusting lever arm lengths with 1 μm precision. The translation mechanism for each side of the lever arm consists of two double-leaf springs, two precision micrometers and two digital dial gauges as shown in figure 4. These mechanisms can eliminate tricky
steps necessary to achieve target lever lengths. We can set our target lengths of the lever to be 999.9600 mm in-situ while measuring torque arm lengths using a 3-dimensional coordinate measuring machine (CMM) as shown in figure 5. The length of the torque arm for each side was determined by the average of 6 distances measured from 6 points at the round bar equally spaced along the width of the metal band to the axis of rotation as shown in figure 6. The maximum deviation from the target length was less than 5 μm. Considering the repeatability (3 μm) of the CMM used for the measurements, the uncertainty from absolute torque-arm length measurements is expected to be small enough when compared to the overall target relative uncertainty of the torque standard machine (0.005 %). The final lever-arm lengths for right-hand and left-hand sides were determined to be 999.961 mm ± 0.005 mm and 999.957 mm ± 0.005 mm, respectively. Dial gauges are used to monitor the displacements of the round bars. We measured After finishing lever-arm length settings on the 3-D coordinate measuring machine, the translation mechanisms have a locking system to prevent unintended change of its final lengths.

**Figure 2.** Design of the double torque arm.

**Figure 3.** The definition of the effective torque arm length (only one side shown)

**Figure 4.** Design of the lever-arm length adjusting mechanism. Inset (top left) shows the results of finite element analysis of the double-leaf spring

**Figure 5.** In-situ adjustment of torque arm length in the 3-dimensional coordinate measuring machine.
3. Arm unbalancing experiments

The net torque can be generated by unbalancing the lever through unbalanced loads or unbalanced effective lever arm length. Neglecting the second order terms, the relative unbalance torque ($\Delta T/T$) measured by a torque transducer can be expressed in equation (1)

$$\Delta T/T = (\delta_R - \delta_L)/l + (\Delta l_R - \Delta l_L)/l + \Delta F/F - T_{\text{fric}}/T$$

where, $\delta_R$ and $\delta_L$ are deviations of right and left lever-arm lengths from the nominal value of $l$ at zero load, respectively and $\Delta l_R$ and $\Delta l_L$ are length changes under loads for right and left sides, respectively and $T_{\text{fric}}$ is the frictional torque at the fulcrum at the specific load. The notation of these symbols are illustrated in figure 7.

According to the measurement results of the CMM and neglecting the difference in force generated by same dead-weights on both sides, the relative torque unbalance is expected to be 4 ppm. However, due to the load dependency of torque-arm length [4], the relative torque unbalance is expected to vary according to the loads applied. Using the lever-arm length adjusting mechanism, the unbalance due to difference in length at zero loads (i.e. the first term in equation (1)) can be controllable. We expect to find the load dependence along with friction at fulcrum by changing both lever-arm length and forces intentionally.

4. References

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