

# BEST MEASUREMENT CAPABILITY OF THE NEWLY DEVELOPED 5 kN DEAD WEIGHT FORCE MACHINE

Kamlesh K. Jain and S.K. Jain

Force & Hardness Standards, National Physical Laboratory,  
New Delhi-110012 (India)

## **Abstract:**

This paper describes the salient features and the results of metrological performance of the newly developed 5 kN dead weight force calibration machine. Two well characterized strain gauge force transfer standards of 2 and 5 kN full capacity having repeatability better than 0.002% in compression mode were used to derive the best measurement capability of  $\pm 50$  ppm. ( $k=2$ ) of the machine.

## **1. Introduction**

The unified system of force measurement at a level, which fully satisfy modern requirements, can only be established with confidence with a sufficient knowledge of the best measurement capability of the force calibration system and some checks on the quality of the force transducer used as force transfer standard. This demands the metrological characterization of the force calibration system which in turn would be used for periodic calibration of the force transducers to generate the confidence in their performance.

In continuation [1] of the efforts made at NPL (India) to lower down the uncertainty in the realization of force using the existing standards upto 1 MN and also to establish new standards to realize force with a lower uncertainty, a fully automatic 5 kN dead weight force machine has been designed and fabricated. The present paper describes the construction, salient features and metrological performance of 5 kN dead weight force machine and its estimated best measurement capability.

## **2. Description of The Machine**

A three column system is employed in designing the machine. The main frame of the machine consists of two triangular plates and one triangular frame joined together by tie rods, so as not to affect the measurement results by buckling load and deflection. The positioning of tie rods minimizes unsupported area of the platen thereby ensuring the stiffness in the structure. This has further been confirmed by stress analysis using PRO-E-2000I and ANSYS 5.4 software done on one of the plates of the main frame. The plates are considered as a free body supported at the three corners and load is applied at the center. Similar analysis done on the loading hanger supports the rigidity of the hanger.

Upper part of the frame can accommodate force transducer in compression mode. Three leveling screws are provided in the bottom plate for the leveling of the machine. The machine can accommodate the force transducer upto a 200 mm height in compression mode. Load is applied to the force transducer through a load-carrying hanger. The transducer supports the upper plate of hanger and the lower end of which is directly connected to the weight stack. The distribution of the mass to the upper and the lower part is such that the center of gravity of the loading frame is situated below the force transducer.

The weights are linked in series to increase or decrease the calibration force sequentially. In the present case a central pin is used to hold a weight with another weight to minimize the error due to non-axiality. Each weight is connected to the other through a central pin.

Guiding taper between pin and weight body helps in achieving better alignment. The top weight is connected to the loading frame in order to apply the load to the force transducer. Each weight is designed to the same thickness and the spacing of 9 mm between the two weights is maintained within a close tolerance of  $\pm 0.5$  mm.

A hydraulic system equipped with a directional solenoid and hydraulic flow control valves for the smooth motion of a linear actuator is used to load and unload the dead weights. All the weights rest on the platform attached to the end of linear actuator, which is flange mounted to the middle triangular frame structure. The adjustment of the flow through a hydraulic - flow control and the micrometer valve makes it possible to reduce the vibration generation and to adjust the speed of loading and unloading of the weights. The weight applied to the force transducer is the sum of the weights selected and the weight of the loading frame.

The minimum force of 0.5 kN, which is the nominal load of the calibrated loading hanger, is always included as the first applied force. The weight stack consists of nine weights and each weight is made up of SS 304. The full load can be applied or removed within a predetermined time with negligible oscillations and vibrations ensuring better stability and repeatability.

The machine is fully automated through a menu driven solenoid valve and the hydraulic flow control valve using a FBLC ( Load cell) as its feed back sensor. A micro controller- based interface with PC makes the operation of the machine interactive with menu driven Windows based display system. The machine operation is quite flexible to have its best performance. The machine operation both in auto or manual mode is selectable on restart up of Windows from the computer. The loading sequence can be programmed and controlled independently. The commands for the pre- loading , number of steps, hold time etc. and for the force series in ascending and descending order are set in the beginning of the calibration process. The calibration process starts automatically upon receipt of commands from PC. Once the force transducer is appropriately placed to carry out the calibration , it is possible to execute the calibration as per any one of the standard procedures ASTM E-74-2000, ISO 376 –2000 or IS 4169-1988.

### **3. Calibration Procedure**

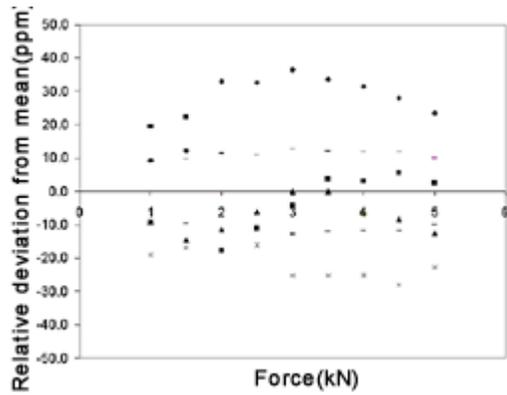
A calibration procedure NPL-02 based upon IS 4169-1988 and compatible with ISO 376 – 2000 was adopted during the measurements to minimize the uncertainty of the mean values due to the influence of the loading process and the creep pattern of the force transducer. A high - resolution indicator (Model DK-38, HBM, Germany) having a resolution and a stability of 5 ppm with a data sampling rate of 50Hz was used throughout these studies and transmitted to a PC through GPIB interface. Both the transducers and the indicator were kept near the machine for sufficient time for better temperature stability. The indicator was put on for two hours before starting the experiments.

Preliminary loading is performed three times in principle to the full-scale value of the transducer and kept for 3 minutes before returning to zero. When it is rearranged to its new position, it is loaded only once to its full scale. All the measurements were done continuously following a timed loading sequence. Time duration of 30 sec was found to be adequate from the start to attain the targeted force and 30 sec. to record the observation. After waiting for three minutes on returning to zero, the same force cycle was repeated at the same position of the force gauge. The same process was followed at each new position of the transducer to record the force series in ascending order only.

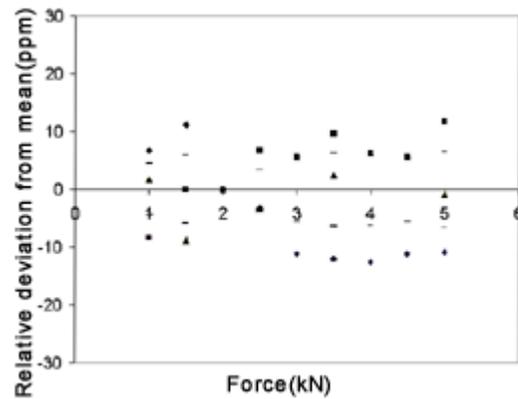
Two well-characterized strain gauge force transducers [3] of 2 kN (ser. No. 01113, manufactured by GTM, Germany ) and 5 kN full scale (ser. No. 01260, manufactured by

GTM, Germany) , having the repeatability better than 0.002% were used to characterize the force calibration system. These are traceable to the reference force standard (PTB, Germany) by their direct comparison.

In each cycle of zero position 13 observations at force steps of 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 4.5, 4, 3.5, 3, 2.5, 2 and 1.5 kN were taken. Only seven observations were recorded at force steps of 1.5, 2, 2.5, 3, 3.5, 4, 4.5, and 5 in each force series taken at different positions leading to a total of 60 observations per calibration. The transducer of 2 kN full-scale is used at force steps 1, 1.5, 2, 1.5 and 1 and in this manner, a total number of 20 observations per calibration were recorded following the same procedure. The deviation from the mean value observed when these transducers were rotated through 360° along its axis is presented in Fig. 1 whereas Fig. 2 represents the repeatability observed in these two transducers kept at zero position.



**Figure 1** Calibration of force transducers of 2 kN and 5 kN full scale at different positions ( increasing force series)



**Figure 2** Calibration of force transducers of 2kN and 5kN full scale at one position ( increasing force series)

- - - relative standard uncertainty

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The maximum relative standard uncertainty due to rotation 10ppm and 13ppm ( Fig.1) are observed when the 2 kN and 5 kN force transducer is used. The repeatability through out the range irrespective of the transducer and its position as observed is always less than 20ppm.

#### 4. Estimation of Uncertainty

In SI units the vertical force exerted by a stationary mass in dead weight force machine in air on its support is given by

$$F = (g - \Delta g) m (1 - \rho_a / \rho_m) \quad (1)$$

where  $F$  is the force in Newton (N), 'm' is the mass in kilogram (kg), 'g' is the local gravity measured near the bottom of the machine,  $\Delta g$  is the variation of the g along the height of the machine,  $\rho_a / \rho_m$  are the densities of air and of the material of the masses, respectively. The variation of g from its bottom to the top of the loading stack is less than a ppm and as a result, the contribution of  $\Delta g$  in the above equation is negligible.

The standard uncertainty  $W(F)$  [2,3] in the force applied by the dead weight machine incorporates the uncertainties associated with the determination of the mass of the dead weight, the acceleration due to gravity and the air density. The component standard

uncertainties are combined to produce an overall value of uncertainty, known as combined uncertainty.

The value of the local gravity near the base of the machine and the nominal density of the weights are determined experimentally. However, the density of the air is indirectly determined [4] by measuring the actual temperature ( within  $\pm 0.1\text{K}$ ), relative humidity ( $\pm 5\%$ ) and the barometric pressure ( $\pm 4\text{ kPa}$ ) in the room .The masses of the austenitic 304 stainless steel are calibrated by NPL (India) mass metrology group. Each loading part (hanger and the weights) is adjusted to generate the nominal load of 0.5 kN within  $\pm 0.00001\text{ kN}$ . It is estimated that the maximum difference between the actual air density in the laboratory and the calculated air density, would not result in a difference in the applied force greater than  $\pm 0.0005\%$ .

The overall fractional uncertainty in the force measured at the location by the machine ( $F_m$ ) can be expressed as the root – mean square of the total differentials of the individual parameters,  $x_i$

$$\delta F_m / F_m = [ ( 1 / F_m ) \delta F_m / \delta x_i \{ \delta x_i \}^2 ]^{1/2} \quad (2)$$

The values of the differentials , their uncertainties, and the fractional uncertainties in  $F_m$  for the NPL-02, are listed in Table 1. The over all estimated uncertainty at 300 K and at 5 kN is  $\pm 17\text{ ppm}$  ( $k= 2$ ).

**Table 1. Expanded uncertainty in the force measured by 5000 N dead weight force machine**

| $x_i$    | Value                     | Parameter uncert. a | Probability distr./Divisor | Rel. Stand. Uncer. | Sensitivity Coeff. | Rel.Uncert. Contr. to force |
|----------|---------------------------|---------------------|----------------------------|--------------------|--------------------|-----------------------------|
| $m$      | 510.735 kg                | 9.8 E-6             | Rect./1.732                | 5.7 E-6            | 1                  | 5.7E-6                      |
| $g$      | 9.791244 $\text{ms}^{-2}$ | 1 E-6               | Rect./1.732                | 5.8 E-7            | 1                  | 5.8E-7                      |
| $\rho_a$ | 1.15 $\text{kgm}^{-3}$    | 8 E-2               | Rect./1.732                | 4.6 E-2            | 1.3 E-4            | 6.0E-6                      |
| $\rho_m$ | 7891 $\text{kgm}^{-3}$    | 38                  | Rect./1.732                | 22                 | 1.8 E-8            | 4.0E-7                      |

The uncertainty as calculated assumes that there are no parasitic components in the applied force and also there would not be any machine interaction when the force transducer is calibrated directly against the machine. This is the ideal condition and is not true in most cases. Hence, there is always a limited amount of deviation between the uncertainty as calculated above and the observed deviation in the direct calibration of the force transducer against the machine. The differences are perhaps due to the parasitic effects (side forces & moments) which are always present together with the axial forces in these machines. To realize the practical situation and to derive the best measurement capability of the force calibration system, the term traceability ( $1 - \Delta\text{traceability}$ ) is introduced in equation (1) as a product [5], when the force transfer standard is first calibrated in the force standard machine and then in force calibration machine. The standard uncertainty due to traceability comprises of the standard uncertainty of different influencing input quantities such as hysteresis( hys), drift ( dri), relative deviation (rel dev), realization ( rel), force calibration machine and force standard machine etc. Based on the standard uncertainty of each and individual parameter and following the method suggested by Sawla [5], the derived best measurement capability of the force calibration machine is  $\pm 0.005\%$  through out the range.

## 5. Conclusions

A low cost accurate dead weight force machine capable of calibrating force transducers of 5 kN capacity has been developed. The calibration of the force transducer can be carried out in compression mode following any one of the internationally accepted calibration procedures to the highest possible accuracy class as per the requirement of standard.

The observed small relative deviation between the direct calibration of the 5 kN force transducer against the dead weight force machine ( $F_m$ ) and the dead weight force standard machine (maintained at PTB, Germany)  $F_s$  ( $\pm 25$  ppm at  $k=2$ ) over the measurement range between 40-100 % of full scale of the force transducer generates confidence in the precision achieved in the fabrication of the machine and hence in the derived uncertainty associated with the applied forces.

The closeness between the repeatability at any one position and at different angular positions would additionally generate the confidence that the machine is stable and repeatable not only as regards axial load, but also as regards the generated parasitic components.

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## Contact Person for Paper:

Dr. Kamlesh K. Jain,  
Force & Hardness Standards,  
National Physical Laboratory,  
New Delhi-110012( India)

e- mail [kkjain4@yahoo.com](mailto:kkjain4@yahoo.com)  
Tel : 91-11-5744369  
Fax: 91-11-5781850, 91-11-5852678