

Establishment of a 10 kN Dead Weight Force Machine at NPL, India

Kamlesh K. Jain, H. N. P. Poddar and M. K. Chaudhuri

Force Standards, National Physical Laboratory, New Delhi (India)

Abstract

This paper describes the preliminary results of the performance of the newly developed 10 kN dead weight force machine at the National Physical Laboratory, India that would serve as national reference force standard with an expanded uncertainty lower than 30 ppm. Two well-characterized strain gauge transfer force standards of 5 kN and 10 kN full scale, having an uncertainty of 0.02% in the measured forces and repeatability better than 0.002% were calibrated in the machine. The observed results were analyzed with particular reference to repeatability, hysteresis, machine interaction etc that are well below the stated uncertainty.

1. Introduction

In most of the National metrological laboratories the generation and realization of forces with highest possible accuracy are made by the application of the dead weights under the influence of local gravitational field. A dead weight force-generating machine provides a convenient means of selection and application of precisely known static forces in the form of dead weights directly on the force-measuring device being calibrated. Presently, a maximum of 4.4 MN force can be realized by the direct application of the dead weights at NIST, USA. Economic considerations, machining components parts and space limitations limit the use of such machines in the extended range. An alternative to dead weight force machine, dead weight cum lever multiplication machines are being used to

realize the forces in the higher ranges. Recently the strain gauge controlled leaf spring joints [1] instead of the conventional knife-edges are used in these machines to lower down the uncertainty in the force measured both in compression and tension. The hydraulic multiplication of dead weight force machine and build up system are also commonly used to realize forces over a wide range but with higher uncertainty.

At present, NPL (India) has embarked upon a comprehensive plan to lower down the uncertainty in the realization of force by the existing standards up to 1 MN and also to establish new standards to realize force with lower uncertainty by the direct application of the known dead weights and acceleration due

to gravity, traceable to the standards of mass, length and time.

A first step in this direction is to establish a 10 kN dead weight force primary standard with an expanded uncertainty of ± 30 ppm or lower. The present paper describes the construction, salient features of the 10 kN dead weight force machine and the calibration results of two, 5 kN and 10 kN transfer force standards (herein after termed as transducer) over whole of the range.

2. Description of the Machine

The main frame of the machine consists of three triangular plates joined together by tie rods as shown schematically in Figure. 1. The center of tie rods lie at the vertex of an equilateral triangle. Such positioning of tie

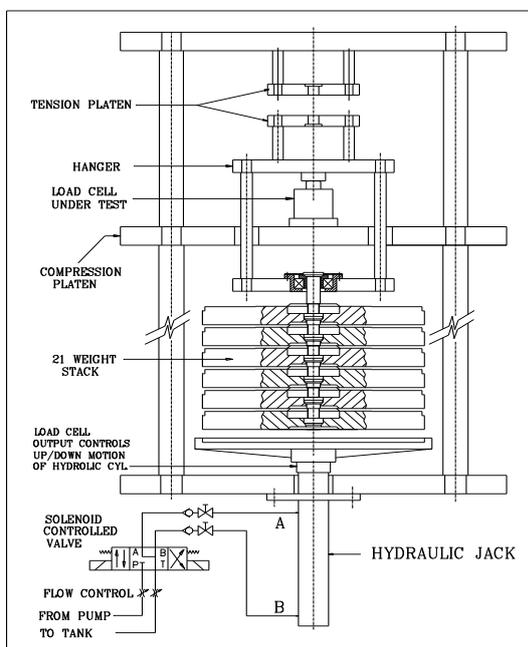


Figure 1. Schematic diagram of force

rods minimizes unsupported area of the platen rods minimizes unsupported area of the plate

thereby ensuring the stiffness in the structure. Upper part of the frame can accommodate force transducer both in tension and compression mode. Loading pad on which the force transducer is made to rest are hardened to HRC 58 and grounded to an average surface roughness of 0.2 micron. The concentric circles are made on the loading pad to ease the centering of the transducer. Three leveling screws are provided in the bottom plate for leveling of the machine. The machine can accommodate the force transducer of 300 mm and 500 mm in compression and tension mode respectively. The height from the point of measuring the value of 'g' to the top of the weight stack is approximately 2.5 meters. Load is applied to the transducer through a load-carrying hanger, triangular in shape. The

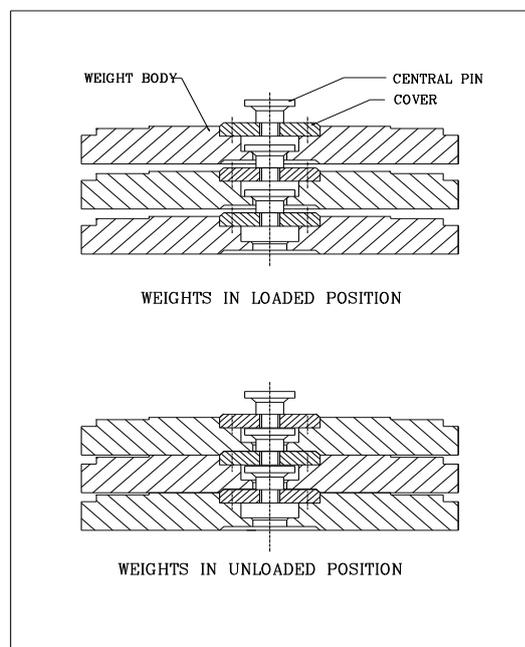


Figure 2. Two positions of weight stack

and the lower end of which is directly connected to the weight stack.

In general the weights are stacked together either by using the three couplings around the circumference or by using a special type of conical coupling [2]. However, 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 (Figure 2). All the weights rest on the platform attached to the rod end of linear actuator, which is flange mounted to the bottom plate of frame. A reproducible transducer [3] of 10 kN full scale of good long-term stability is mounted between weight table and rod end of linear actuator, to control loading steps. Loading and unloading of dead weights is carried out manually through a solenoid controlled directional valve using a pushbutton station. On gradual lowering of actuator the loading hanger picks up predetermined dead weights one after another thus loading the transducer and vice versa. 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 twenty-one weights, each adjusted to the nominal force value of 0.5 kN taking in to account the value of 'g' (local gravity) at the location and the air buoyancy correction. Further, the machine can be used to evaluate the hysteresis if needed by the application of the load both in ascending and descending order. The 5 kN and 10 kN full scale force transducers in 0.5 kN steps or in multiplication of 0.5 kN steps with a minimum step of 0.5 kN can be calibrated

using this machine. The full load can be applied or removed within a predetermined time with negligible oscillations and vibrations ensuring better stability and repeatability.

2. Estimation of Uncertainty

The accuracy in the force realized by the dead weight force machine, depends upon the number of corrections applied to both the mass and the value of 'g', acceleration due to gravity, at the location and is defined as

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

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, Δg is the variation of the g along the height of the machine ρ_a, ρ_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 such the contribution of Δg in the above equation is negligible.

It is evident from the above equation that the over all uncertainty in the force realized at a particular location depends on the uncertainties in the determination of m, g, ρ_a and ρ_m .

The value of the local gravity as experimentally determined near the base of the machine is $9.79123 \text{ m/s}^2 \pm 0.00002 \text{ m/s}^2$. The air density as calculated is $1.18 \text{ kg/m}^3 \pm 0.003 \text{ kg/m}^3$ and the nominal density of the weights as determined is $7827 \text{ kg/m}^3 \pm 8 \text{ kg/m}^3$. The

masses of the austenitic 304 stainless steel is calibrated by NPL (India) mass metrology group traceable to NPL kilogram (BIPM copy No. 57) standard by the substitution method with an over all measurement uncertainty better than 5 ppm. Based upon air density, mass density and the local gravity, each loading part (hanger and the weights) is adjusted to generate the nominal load of 0.5 kN within ± 0.00001 kN. It is estimated that the maximum difference between the actual air density in the laboratory and the calculated air density, and the density of stainless steel out of the big weights and other smaller parts forming the part of applied load would not result in a difference in the applied force greater than 0.0005%.

The uncertainty in the load adjustment and when combined with hysteresis, machine interaction and parasitic components of force, a total expanded uncertainty of the vertical components of force applied over the whole range of the machine on conservative basis is $\pm 0.003\%$. The uncertainty in the application of the load can further be lowered to better than $\pm 0.002\%$ by taking in to account the corrections in the nominal value of air density by measuring the values of the air pressure, temperature, humidity and the actual adjusted mass of each weight.

4. Performance

Lack of long-term stability of transfer standard, interaction between the dead weight machine and the transfer standard, the measurement procedure and the force parasitic components of the dead weight machines

restricts the affirmation of its theoretically derived uncertainty.

Two well-characterized strain gauge force transducers [3] of 5 kN and 10 kN full scale, having an uncertainty of $\pm 0.02\%$ in the measured forces and better than 0.002% in the repeatability were used in these experiment. These are traceable to the national reference force standard by their direct comparison. A high - resolution indicator (Model DK-38, HBM, Germany) was used throughout these studies having resolution and stability of 5 ppm. Both the transducers and the indicator were kept near the machine for more than two days for better temperature stability. The indicator was put on for two hours before starting the observations.

The machine interaction due to misalignment of the applied force on a force transducer can significantly affect the accuracy of measured values; it is therefore desirable to observe the response of the force transducer at several symmetrical positions relative to its vertical axis. Therefore the transducers were rotated symmetrically on its axis to three positions uniformly distributed over 360^o. A calibration procedure NPL-1 based upon IS 4169 and compatible to ISO 376 was adopted during the measurements.

Initially, the force transducer is preloaded three times to its maximum range and kept for 3 minutes before returning to zero and when it is rearranged to its new position, it is loaded only once to its full scale. All the measurements were made following a timed loading sequence to minimize the creep and

the load time effect. Time duration of 180 sec is found to be adequate from the initiation of the loading to the actual reading taken.

In the calibration of force transducers, five-force cycles were carried out. In one cycle the force was increased in steps of 10 % within the range of 50-100% range of the transducer and then decreased in similar steps from 100% to 50 % before bringing it to zero force. After waiting for three minutes on returning to zero, the same force cycle was repeated at the same position of the transducer. Two cycles of the observations following the same force sequence, were taken after rotating the transducer through 120°. After rotating transducer again through 120° from its previous position fourth cycle was carried out and then the transducer was brought back to its initial position to take the fifth force cycle. In one force cycle 11 observations were taken, leading to a total of 55 observations per calibration. The transducer of 5 kN full scale is used from its 40%-100% range and as such a total number of 65 observations recorded following the same procedure. As at this stage we are interested in relative error and not in the absolute values and as a result all the values are in indicative units only. The rotational error in all the five force cycles with respect to the first cycle in ascending as well as in descending force series is shown in Figure. 3. It is evident (Figure 3) that the maximum rotational error of 27 ppm and the hysteresis within 18 ppm over 20% to 100% range of the machine. Similar scatter in the calibration data of 5 kN full-scale transducer, when it is

calibrated under identical conditions is observed and is also shown in Figure 3.

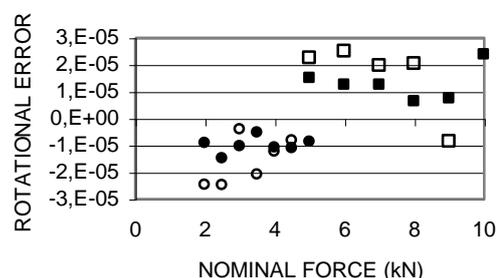


Figure 3. Calibration of load cells of 5 kN and 10 kN full scale for five cycles of increasing and decreasing forces (■) 10 kN increasing; (□) 10 kN decreasing; (●) 5 kN increasing; (O) 5 kN decreasing

However, to visualize the degree of closer in the realization of force in the overlapping region, the results obtained with transducer of 10 kN full scale are compared with those obtained with transducer of 5 kN full scale in Figure 3. Difference of less than 25 ppm, in the overlapping region is observed. This is in good agreement and is well within the estimated uncertainties of the transducers and the dead-weight force machine.

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5. References

- [1]. Fank S., Sawla A. and Ozbay H., *Long term observation of newly developed 110 kN/1.1 MN lever amplification dead weight force standard machine at UME, IMEKO Proceedings "Force, Torque and Mass", 2000.*
- [2]. Sawla A., H. Gassmann and W. Kuhn, *The design concept of a new 20 kN force standard machine, PTB- Mitt., 1994. 104, 237-242*
- [3]. Kamlesh K. Jain and Kumar A., *Intercompatibility of the transfer force standards upto 100 kN*, Measurement, 2001 (To be published)

Contact Person for Paper:

Kamlesh K.

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

Tel: 91-11-5744369

Fax: 91-11-5781850 , 91-11-5852678, 91-11-5764189;

e- mail kkjain4@yahoo.com