

## **Realization of forces (2N-20N) by primary method**

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### **Abstract:**

The present paper describes the preliminary results of the metrological characterization of the newly design and developed force machine to realize the forces in the range 2N- 20N with an expanded uncertainty of 50 ppm. The characterization of the machine is carried out in compression using two transfer force standards of 5 and 20 Newton capacity. The calibration of the transfer standards directly against the dead weight force machine shows that the repeatability and reproducibility are better than 0.002% and 0.003 respectively, over the full range of measurement.

*keywords: Force Realization, Dead Weight Force Machine, Force Metrology*

### **1. Introduction:**

Recently, there has been a great demand to realize force in the milli Newton range traceable to SI units. Atomic Force Microscope, coordinate measuring machine, stylus system, hardness measuring devices, micro-electromechanical system (MEMS) etc. are commonly used in the modern scientific and hi-tech industrial sectors for precise measurements and to characterize newer materials for potential applications. In all these cases a small load is exerted on the object during the measurement by a sensing probe. To account the deviation, if any in the measurement due to the force exerted by these sensors, it is desirable to know the magnitude of these forces. Though the estimation of these forces were done both theoretically as well as experimentally in the past, it is desirable to know the uncertainty associated with the force-measuring devices. It is therefore necessary to calibrate such devices against the established standard having a lower uncertainty linked to SI units [1-3].

To the best of our knowledge, the facility available to realize the force directly through dead weights world over is only from 10N to 4.4MN [4-6]. The aim to develop a dead weight force machine is primarily to realize the forces in the range of 2N to 20N to bridge the gap between the pico Newton & milli Newton range of measurements to a Newton range traceable to SI unit. Further, it will add to the confidence in estimation of uncertainty as a few force steps which are overlapping

with the existing 50N dead weight machine in the group. Design aspect of the machine and the calibration of two force transducers of 5N & 20N capacity directly against the machine are discussed here.

## 2. Description of the machine:

A two column system is employed in designing the machine as depicted in Fig.1. The main frame of the machine consists of number of the horizontal plates separated by spacers on both the ends. All the weights rest on a spring loaded channel with air ballooning arrangement and a pneumatic system equipped with solenoid valves is used to load and unload the dead weights smoothly. A central pin joined together and screwed on to the loading hanger supports each individual weight. Load is applied to the force transducer through a load-carrying hanger.



Fig.1: 20 N Dead Weight Force Machine

The transducer supports the upper beam of the hanger and the lower beam is directly connected to the loading hanger. 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 operation of the machine is quite flexible so that any weight can be loaded to the hanger from the weight stack or unloaded from the hanger to the to stack. 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 following standard procedures ASTM E-74-2000, ISO 376 –2004 or IS 4169-1988.

The deflection and stress distribution studies of the loading frame are carried out using UG-NX2 software for modeling and Femap- Nastran for analysis. The analysis

is done for static loads up to 40N and is found that the total deflection of the loading frame beam is very much below the accepted limits of deformation, confirming a good mechanical stability of the loading frame. A schematic view of 3D deflection image of the loading frame beam is shown in Fig.2.

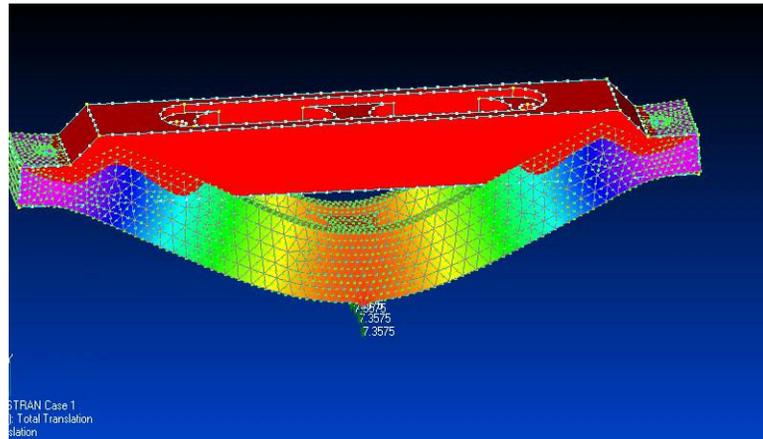


Fig.2 : Stress distribution on the loading hanger beam

The force applied to the load cell is the sum of the weight selected plus the weight of the loading hanger. A minimum force of 2N, which is the nominal load of the calibrated loading hanger, is always included as the first applied force step. The weight stack consists of aluminum masses of different denominations adjusted in its weights by the mass standards group of NPLI, having an expanded uncertainty of  $\pm 1$  ppm, to generate the nominal force value of 0.5N, 1N, 2N and 5N taking in to account the local value of 'g' and the air buoyancy correction. Force transducers of 5N and 20N capacities were calibrated on the machine starting with an initial force step of 2N, which is the weight of the hanger, obtaining the subsequent force steps by the proper selection of dead weights from the stack. The full load can be applied or removed within a predetermined time with negligible oscillations and vibrations ensuring better stability and repeatability.

### 3. Calibration Procedure:

A calibration procedure, NPL-02C based upon IS-4169, 1988, compatible to ISO 376-2004 [7] was adopted during the measurements. Uniform interval of time was maintained while taking the measurements at each force step 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) interfaced with PC through GPIB cord was used throughout these studies. Both the transducers and the indicator were kept near the machine for sufficient time for attaining a better temperature stability. The load was transmitted through a self aligning compression pads supplied by the manufacturer with a suitable flat spacer.

Preliminary loading was performed three times at  $0^\circ$  position in principle to the full-scale value of the transducer and kept for 90 seconds 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 made following a timed loading sequence to minimize the creep and creep recovery and the load time effect. Time duration of 30 sec is found to be adequate from the start to attain the targeted force and to record the observation. After waiting for 90 seconds on returning to zero, another force cycle was started and the same procedure was repeated at each new position of the transducer.

Two force transducers of 5N and 20N full scale having a repeatability of 0.002 % were calibrated in the force machine. In the calibration of each force transducer, after the preloading at  $0^\circ$  position, two series of forces (series 1 & 2) were applied in ascending order. Further, two force series one in ascending order (series 3) and another in descending order (series 4) were taken at  $120^\circ$  position relative to its initial position. Similarly two more force cycles (series 5 & 6), one ascending and one descending, were applied at another new position, i.e.  $240^\circ$  with respect to its initial position.

For the 20N force transducers, in each force series 11 observations were made at force steps of 2, 3, 4, 5, 7, 9, 10, 11, 13, 15 and 20N in ascending order. Besides the force series in ascending order, the observation at force steps of 15, 13, 11, 10, 9, 7, 5, 4, 3, 2 were also taken in descending order at the mounting positions  $120^\circ$  and  $240^\circ$  from its initial position leading to a total of 64 observations per calibration. Similarly, the calibration of force transducer of 5N capacity was also performed at force steps of 2, 2.5, 3, 3.5, 4, 4.5 & 5N in ascending order and at force steps of 4.5, 4, 3.5, 3, 2.5 and 2 N in descending order. The estimated repeatability of 0.002% and the reproducibility (repeatability with rotation) of 0.003% from the calibration of 20N force transducer, directly against the dead weight force machine, is shown in Fig. 3. Similar behavior was observed when the 5N force transducer was compared directly against the force machine. At this moment, we are interested only in relative error and not in the absolute values, so the result of all the values are in indicative units only. 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 with regard to axial load, but also with regard to the generated parasitic components.

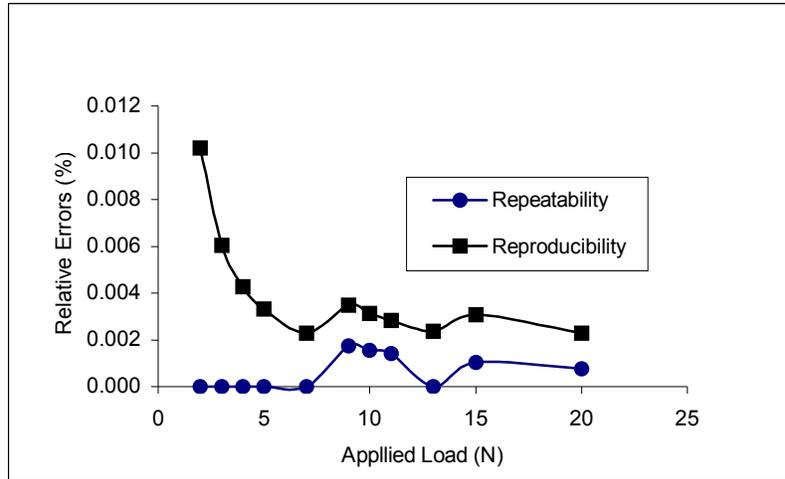


Fig.3 Relative repeatability and reproducibility errors of 20 N load cell

#### 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

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

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. It is evident from eq (1) that the overall uncertainty in the force realized by the dead weight force machine at a particular location depends upon the uncertainty of the individual parameters of equation (1). Taking the variants from equation (1), neglecting the term  $\Delta g$  in the above equation, as the variation of  $g$  from its bottom to the top of the loading stack is less than one ppm, the values of the differentials, their uncertainties, and the fractional uncertainties in force measurements for the force machine are listed in Table 1.

Table 1. Expanded uncertainty in measured force by 20 N dead weight machine

Parameter ( $x_i$ )	Value	Parameter uncert. a	Probability distr./Divisor	Rel. Stand Uncer.	Sensitivity Coeff.	Rel.Uncert. Contr. to force
$M$	2.04264kg	9.8 E-7	Rect./1.732	5.7 E-7	1	5.7E-7
$g_l$	9.791244ms <sup>-2</sup>	1 E-6	Rect./1.732	5.8 E-7	1	5.8E-7
$P_a^*$	1.15kgm <sup>-3</sup>	8 E-2	Rect./1.732	4.6 E-2	1.3 E-4	5.98E-6
$P_m$	2700kgm <sup>-3</sup>	45	Rect./1.732	26	1.8 E-8	4.68E-7

*\*(The density of the air is indirectly determined by measuring the actual temperature (within  $\pm 0.1$ ), relative humidity ( $\pm 5$  %) and the barometric pressure ( $\pm 4$  kPa) in the room and following the equation mentioned in BIPM document no. [8]. 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  $\pm 0.0005\%$ .) [8].*

The total expanded uncertainty associated with the force realized by the machine is  $\pm 0.0012\%$ . 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 uncertainty in the measurement comparison. To be more practical in deriving the uncertainty associated with the realization of the force, a proper weightage should be given to the factors like the long term stability or the drift of the transfer gauge, interaction between the machine and the force transfer standard, the measurement procedure with particular reference to creep and creep recovery, the loading regime and the force parasitic components of the dead weight machine. Treating all these different influencing input quantities as discussed elsewhere [9] and following the suggestion made by Sawla [10], a total expanded uncertainty of the vertical components of force applied over the whole range of the dead weight force machine on conservative basis is 0.005% which is used to calibrate the load cell of 5N and 20N capacity. Further efforts are on to bring down the uncertainty to a level of 20-30 ppm by using the transfer standards having a better repeatability and reproducibility, an indicator with higher resolution and by carrying out the inter-comparison exercise. The poor reproducibility observed with the 20N load cell in the lower range of measurement may perhaps due to the fact that the transducer is not so accurate below 20-30% of its maximum capacity.

## **5. Conclusions:**

A low cost dead weight force machine capable of calibrating force transducers of 5N, 10N & 20N capacity has been indigenously designed and developed. Calibration of the force transducer can be carried out in compression following any one of the internationally accepted calibration procedures to the highest possible accuracy class. This would facilitate the process to link the sub Newton forces to the SI units.

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