10.2478/v10048-012-0022-9



# Long Term Uncertainty Investigations of 1 MN Force Calibration Machine at NPL, India (NPLI)

Rajesh Kumar, Harish Kumar*, Anil Kumar, Vikram

CSIR – National Physical Laboratory, New Delhi, India, *Email: harishkec@gmail.com

**The present paper is an attempt to study the long term uncertainty of 1 MN hydraulic multiplication system (HMS) force calibration machine (FCM) at the National Physical Laboratory, India (NPLI), which is used for calibration of the force measuring instruments in the range of 100 kN – 1 MN. The 1 MN HMS FCM was installed at NPLI in 1993 and was built on the principle of hydraulic amplifications of dead weights. The best measurement capability (BMC) of the machine is ± 0.025% (*k* = 2) and it is traceable to national standards by means of precision force transfer standards (FTS). The present study discusses the uncertainty variations of the 1 MN HMS FCM over the years and describes the other parameters in detail, too. The 1 MN HMS FCM was calibrated in the years 2004, 2006, 2007, 2008, 2009 and 2010 and the results have been reported.**

**Keywords: Force standard machine (FSM), force calibration machine (FCM), hydraulic multiplication system (HMS), best measurement capability (BMC), dead weights, uncertainty of measurement**

## 1. Introduction

NATIONAL PHYSICAL LABORATORY, INDIA (NPLI) is the National Measurement Institute (NMI) of India. It has been the custodian of national standards in India at apex level and maintains / disseminates the national standards to the users, including calibration laboratories and various industries. NPLI maintains the national standards of force through various force standard / calibration machines and precision force transfer standards and disseminates the standards to the user industries and calibration laboratories by means of calibration. The group has force realization facility in the range of 1 N to 3 MN through various force standard / calibration machines. The 1 MN HMS FCM employs the principle of amplification of dead weights by hydraulic means to realize force in higher range. The dead weights are placed on the pan situated on the top of the piston of a smaller diameter piston-cylinder assembly. This piston-cylinder assembly is connected through a hydraulic line to a larger diameter piston-cylinder assembly. Force generated by the larger piston is equal to the force on the smaller piston multiplied by the effective area ratios of piston-cylinder assemblies (Fig.1 and 2) [1-2].

$$F = mg\left(1-\rho_a/\rho_m\right) A/a$$

where,

F = force in newton

A = effective area of the larger piston-cylinder assembly in $m^2$

a = effective area of the smaller piston-cylinder assembly in $m^2$

m = mass in kilogram

g = value of local acceleration due to gravity in $m/sec^2$

$\rho_a$ = density of air in $kg/m^3$

$\rho_m$ = density of material (of dead weights) in $kg/m^3$

The cylinders of both piston-cylinder assemblies are rotated through a motor to maintain a uniform lubricating film of the hydraulic oil between the piston and the cylinder to minimize friction. Two sets of dead weights are being used on the smaller piston-cylinder assembly to generate the forces from 10 kN to 1 MN in steps of 10 kN. Using one stack of dead weights, the forces from 10 kN to 100 kN are realized and the forces from 100 kN to 1 MN are realized using another stack of dead weights. The minimum force that can be applied on the 1 MN HMS FCM is 10 kN. The consistency in the effective area ratios of both these piston-cylinder assemblies has also been confirmed by evaluating this system using a series of force transfer standards (FTS) having a relative repeatability deviation better than ± 0.005 %. The FTS have been used for 40 % to 100 % of their rated capacity and their relative repeatability deviation is found within ± 0.005 % [3].

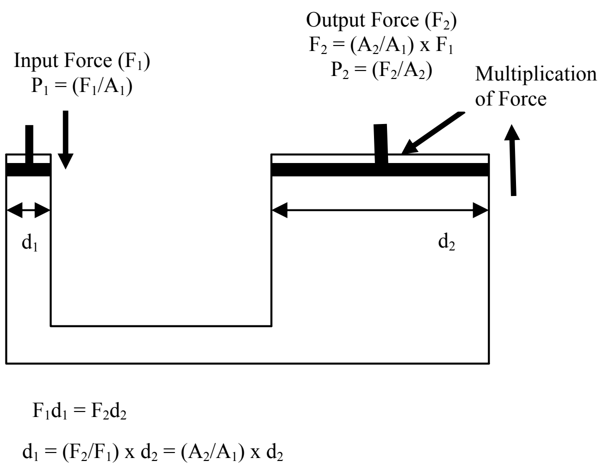


Fig.1. Principle of Hydraulic Multiplication System

An effort has been made in the present paper to address the issues related to systematic characterization study and possible attempts to investigate uncertainty related issues of 1 MN HMS FCM. This paper describes the procedure of learning about the force generated by the hydraulic multiplication system over the range from 100 kN to 1 MN in terms of the drift in its values over a period of time (2004 -2010) using different precision force transfer standards of 100 kN, 500 kN and 1 MN capacities and these FTS have been directly calibrated against the national standards of force at NPLI (Fig.3). The FTS were calibrated in 1994 and 2001 by PTB, Germany, using different force standard machines at PTB, Germany, and the values obtained were used for maintaining the traceability of force in the group. The followed procedure is documented for determination of the reference values of force transfer standards against national standard of force and for determination of best measurement capability (BMC) of FCMs. The BMC of a force calibration machine may be defined as the smallest uncertainty of measurement that a force calibration machine can achieve within its scope while performing routine calibration of nearly ideal measuring instruments designed for the measurement of that quality [3]. The BMC of the 1 MN HMS FCM was calculated by considering two factors, i.e. relative deviation of the reference values with the mean values and repeatability error of FTS at 1 MN HMS FCM. The BMC of 1 MN HMS FCM is found to be within ± 0.025 % ($k$ = 2) [4-5].

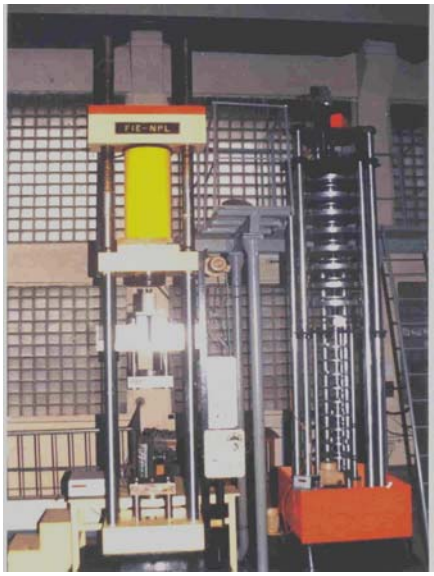

Fig.2. 1 MN HMS Force Calibration Machine in NPLI

Fig.3. 1 MN Force Standard Machine in NPLI

## 2. CALIBRATION PROCEDURE AND UNCERTAINTY EVALUATION

Calibration procedure for determining the reference values of FTS against FSM has been used. The procedure applies to the calibration of the precision FTS in FSM to determine the reference values. The guidelines for achieving the purpose are obtained from EAL – G22. The FTS have been selected with a capacity of 100 kN, 500 kN and 1 MN and have been used for the range of 40 % and 100 % of their nominal capacity. Calibration of the FTS is carried out as per the procedure described on the 1 MN FSM. The sequence of the applied calibration forces is given below [5-7].

a) At 0° position three series of calibration forces with increasing values.
b) At 90° position one series of calibration forces with increasing values.
c) At 180° position one series of calibration forces with increasing values.
d) At 270° position one series of calibration forces with increasing values.
e) The above-described procedure is repeated at an interval of one month to determine the short term drift of the measurement data.

The mean value of the measurement results obtained at all the "n" positions in the increasing force order is the reference value at each force step. For calculating the expanded uncertainty for the reference values $U_{(refv)}$, the following steps were adopted [5-9].

1) The expanded uncertainty of the force transfer standard $U_{(fts)}$ calibrated against the 1 MN FSM is determined by considering the input quantities including the relative deviation due to drift during a period of about a month ($\mathbf{a}_{drift}$) and the relative repeatability error of the force transfer standard ($\mathbf{a}_{rep}$), where **a** is the half width of the input quantities. The corresponding estimated variances are given below assuming a triangular probability distribution for drift and a rectangular probability distribution for relative repeatability error.

$$w^2_{(drift)} = \left(a_{drift}\right)^2 / 6 \tag{1}$$

$$w^2_{(mean)} = \left(\left(a_{rep}\right)^2 / 3\right) / 4 \qquad 2)$$

The combined standard uncertainty $w_{c\,(fts)}$ and its expanded uncertainty $W_{(fts)}$ for the coverage factor **k** are determined by the following equations:

$$w_{c(fts)} = \left[u^2_{(drift)} + u^2_{(mean)}\right]^{1/2} \tag{3}$$

$$W_{(fts)} = k.\, w_{c(fts)} \tag{4}$$

2) The expanded uncertainty of the 1 MN FSM $W_{(fps)}$ is also taken into account. The expanded uncertainty for the reference values $W_{(refv)}$ is obtained by combining the two input quantities discussed above and is given as below:

$$W_{(refv)} = \left[W^2_{(fps)} + W^2_{(fts)}\right]^{1/2} \tag{5}$$

Using the procedure given below, the calibration of FTS has been done on the 1 MN HMS FCM. The sequence of the calibration procedure is as follows:

a) At 0° position three series of calibration forces with increasing values.
b) At 90° position one series of calibration forces with increasing values.
c) At 180° position one series of calibration forces with increasing values.
d) At 270° position one series of calibration forces with increasing values.
e) Mean has been taken for series 1, 4, 5, and 6. This mean value represents the values of FTS obtained at 1 MN HMS FCM.

3) $a_{rel-dev}$ Relative deviation between reference values and mean values measured in the FCM with triangular distribution.

Variance of relative deviation is

$$w^2_{(rel-dev)} = \left(a_{rel-dev}\right)^2 / 6 \tag{6}$$

4) $a_{rep-fcm}$ Relative Repeatability deviation of the FTS at 1 MN HMS FCM without rotation of the force transfer standard with rectangular distribution. This is plotted in Fig.4.

Variance of repeatability is

$$w^2_{(rep-fcm)} = \left(a_{rep-fcm}\right)^2 / 3 \tag{7}$$

5) The combined standard uncertainty $\left(w_{fcm}\right)$ of the FCM and its expanded uncertainty $W_{fcm}$ for coverage factor $k = 2$ are determined by the following equations:

$$w_{fcm} = \left[w^2_{rel-dev} + w^2_{rep-fcm}\right]^{1/2} \tag{8}$$

$$W_{fcm} = k\, w_{fcm} \tag{9}$$

Relative deviation of FTS at 1 MN HMS FCM has been calculated by comparing the values of FTS obtained at 1 MN FSM and 1 MN HMS FCM.

Relative Deviation (%) (RD)

$$RD = 100*\left(\frac{FTS_{FSM} - FTS_{FCM}}{FTS_{FSM}}\right) \tag{10}$$

$FTS_{FSM}$ is the value of FTS at 1 MN FSM, while, $FTS_{FCM}$ is the value of FTS at 1 MN HMS FCM.

The relative deviations among the values of FTS at 1 MN FSM and 1 MN HMS FCM are plotted in Fig.5.

The BMC of the 1 MN HMS FCM is computed by the following equation.

$$W_{(bmc)} = \left[W^2_{(refv)} + W^2_{(fcm)}\right]^{1/2} \tag{11}$$

The BMC for different forces of 1 MN HMS FCM has been summarized in form of plot as shown in Fig.6.

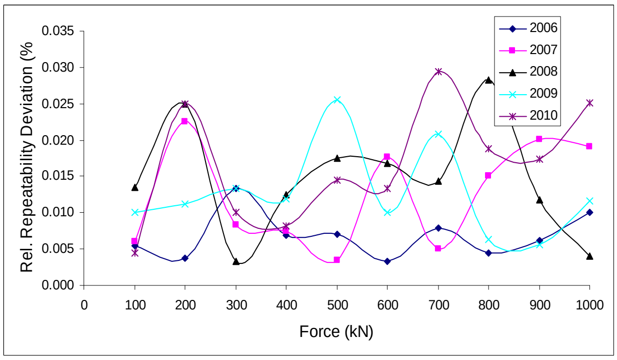


Fig.4. Relative Repeatability Deviation FTS's at 1 MN HMS FCM

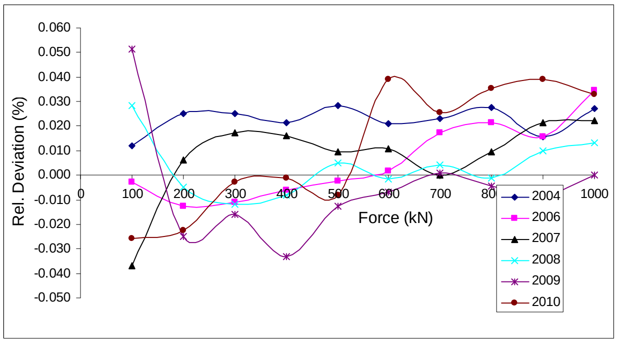


Fig.5. Relative Deviation of Value of FTS's at 1 MN HMS FCM from 1 MN FSM

## 3. RESULTS AND DISCUSSION

The uncertainty of 1 MN HMS FCM has been evaluated as discussed above. The FCM was evaluated in the years 2004, 2006, 2007, 2008, 2009 and 2010. In 2004, the Force and Hardness Standard group went through successful peer review and it was suggested by the experts that 1 MN HMS FCM need to be calibrated every year instead of two years. Hence, up to the year 2004, the 1 MN HMS FCM was calibrated once in two years, but from the year 2006, it has been calibrated every year. The 1 MN FSM has been used for calibration of FTS and has BMC ± 0.003 % ($k$ =2) for dead weight forces 1 kN to 100 kN and ± 0.012 % ($k$ =2) for lever amplification forces 10 kN to 1 MN. The BMC variation curve of 1 MN FCM indicates the variation of the uncertainty of the 1 MN HMS FCM (Fig.6). It indicates that the BMC of the 1 MN HMS FCM has been varying through the years for various forces like 100 kN, 200 kN, etc. The variation does not represent any particular trend. The deviation of the values of FTS's obtained at 1 MN HMS FCM from the reference values obtained at 1 MN FSM has also been measured (Fig.4). Similarly, the relative repeatability deviation of FTS at 1 MN FCM has also been plotted and it has been correlated to the BMC variation of the 1 MN HMS FCM (Fig.5). It is clear from eq. (8) and (9) that major factors that affect the BMC of the 1 MN HMS FCM are relative repeatability deviation and relative deviation from the reference values of force transfer standards.

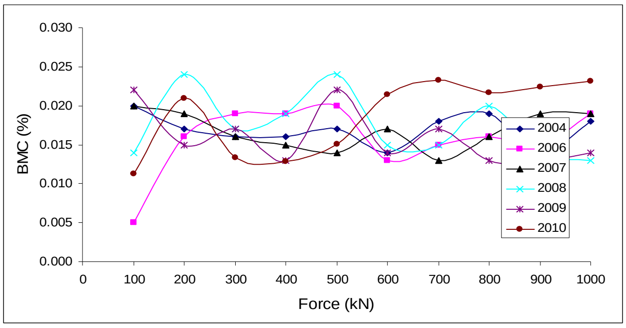


Fig.6. BMC variations at different forces of 1 MN HMS FCM

## 4. CONCLUSION

The present study attempts to discuss the long term uncertainty investigations and related issues of the 1 MN HMS FCM at National Physical Laboratory, India (NPLI). The HMS FCM employs the principle of hydraulic amplification of dead weights. The dead weight forces are amplified by 1:100 ratio. The paper discusses the BMC variation of the 1 MN HMS FCM during 2004 - 2010 for different forces. It also discusses the relative deviation of reference values of FTS's and their relative repeatability deviation, when calibrated at the force standard machine. The variations suggest that the pattern is not uniform and does not present any particular trend. The study may further be extended to study the uncertainty related issues of the HMS FCM and how it is computed.

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Received January 30, 2012.
Accepted August 3, 2012.