Indian Journal of Pure & Applied Physics
Vol. 59, August 2021, pp. 537-543

An Investigation on the Techniques used in Force Calibration using Deadweights and Pressure Piston Gauge

Gouda M Mahmoud[a*], Gamal A Aggag[a] & Shaker A Gelany[a]

[a]National Institute of Standards, Tersa St, El-Haram, Box 136 Code 12211, Giza, Egypt

Received 5 June 2021; accepted 7 July 2021

This paper presents two mechanisms for load cell calibrations. The first technique was to use deadweight to generate the required reference load (Applied load). The second method was to use a pressure piston gauge to generate the required calibration force. In both mechanisms, the setup and procedures are described. For verification the results of these methods were compared with international metrology institute calibration results. It was found that deadweight method is the most accurate and the piston gauge is the most realistic at high force values.

Keywords: Force transducer, Repeatability, Reproducibility, Creep, Piston gauge, Pressure balance

1 Introduction

Forces measurements are very important in various industrial and engineering applications. It's accurate and reliable measurement is very important for the crucial investigation of different measurements. The mechanical forces that occurred between or within parts of any mechanical assembly are indispensable to be understood for this mechanisms safety assembly and use of the equipment whether that mechanism is freely working or an integral part of another mechanism[1]. Accurate metrological characterization and measurement of those mechanical forces are important to be understood and monitored[2]. To achieve reliable and accurate measurements of mechanical force it is required to have appropriate measurement techniques in a sound manner. Before proceeding to explain the different techniques, it is required to define mass and force from the metrologists point of view. Mass is defined as the measure of material amount in an object being directly correlated to the type and the number of atoms present in the object[3]. Force is considered as a vector value with both magnitude and direction[4]. Mathematically force is defined as mass multiplied by acceleration[5]. To quantify these forces, force transducers are used. Force transducers have been utilized over the decades for force measurement and to achieve the traceability of force[6]. Many systems and approaches were developed to generate the force required for load cells calibrations[7]. The millstone of these systems focused on obtaining the relevant accuracy. These systems may be mechanical or hydraulic system[8]. Many deadweights standard machines were developed all over the world for this purpose such as PTB (The National Metrology Institute of Germany) 2 kN Force Standard Machine and 5 MN Force Standard Machine with hydraulic amplifications, and 27.1 kN Deadweight Machine at the National Institute of Standards and Technology (NIST)[9,10]. The main idea of these machines is to generate force values with high accuracy and lowest uncertainty to achieve the traceability. The aim of this paper is to review an investigate the difference between two methods (deadweights and pressure piston gauge) to generate this calibration force and to compare the output of those two methods with recognized results obtained from NMI standard machine such as PTB standard machine.

All of these force transducers have to be calibrated in accordance with specified international or national standards and calibration method such as ISO/IEC 376:2011 and ASTM E74:2018[11]. Metrological characterization of these force transducers is very important for accurate measurements. Different techniques were used all over the world to calibrate the force transducers the first method is them direct realization this involves direct comparison with a known gravitational force value on a standard deadweight. The second method is the indirect method where the force can be determined as the measured effects of force on an item and measuring the response due to the force application to an elastic

*Corresponding author (E-mail: goudamohamed15@yahoo.com)

member [12]. In this article two different techniques were investigated thought experimental work. The main target of this investigation is to identify the most realistic and the most accurate method for force transducers calibrations. To verify the accuracy of these two methods, the results of this investigation was compared with the calibration certificate of this force transducer. Where ,this force transducer was calibrated at PTB which is internationally recognized.

2 Experiments Setup

To investigate the difference between these two methods, high precision 1 kN force transducer classified as class 00 in accordance with ISO 376:2011[13], and based on the calibration results of PTB. For force monitoring, DMP 40 reading amplifier was used which is one of the most precise measuring amplifiers for force measurements with accuracy class of 0.0005. The two techniques of this investigation can be explained as follow.

2.1 Deadweights method

In this investigation deadweights up to 1 kN were used to calibrated the force transducer, refer to Fig. 1. The resultant force generated by masses can be calculated from Eq. 1[14],

$$F_1 = m_i\left(1-\frac{\rho_a}{\rho_{mi}}\right)g \tag{1}$$

Where,

m_i is the individual mass value of each weight (kg)

ρ_a is the density of air (kg/m^3);

ρ_{mi} is the density of each weight (kg/m^3); g is the local gravitational acceleration (m/s^2);

2.2 Pressure piston gauge method

The previous reference transducer also used with the same DMP40, refer to Fig. 2. The applied load is generated using pressure piston gauge based on Eq. 2[15],

$$F_2 = p_r\left[A_{0,20}\left(1+\lambda p'\right)\left(\alpha_p+\alpha_c\right)\left(t-20\right)\right]-N_m\ ,$$

$$N_m = m_p\left(1-\frac{\rho_a}{\rho_p}\right)g + C \tag{2}$$

Where:

p_r is the pressure measure using a reference pressure balance (Pa);

$A_{0,20}$ is the effective area of the piston cylinder assembly measure at 20 °C (m^2);

λ is the pressure distortion coefficient of the piston cylinder assembly, (Pa^{-1});

$\acute{p}$ is the approximate pressure (Pa);

$(\alpha_p + \alpha_c)$ is linear thermal expansion coefficient of the piston and cylinder (°C^{-1});

t is the temperature of the piston cylinder assembly during the pressure determination (°C);

m_p is the piston mass value (kg);

ρ_a is the density of air (kg/m^3);

ρ_p is the density of piston (kg/m^3);

g is the local gravitational acceleration (m/s^2);

C is the fluid surface tension correction (N)

2.3 Force proving instrument characterization

The relative errors can be calculated based on the following equations[16]

a. The Reproducibility relative error, R_{prod}

$$R_{prod} = \frac{\left|S_{\max} - S_{\min}\right|}{\bar{S}_r} \tag{3}$$

Fig. 1 — Shows method 1 calibration mechanism: 1. DMP40, 2. Load cell, 3. Deadweights

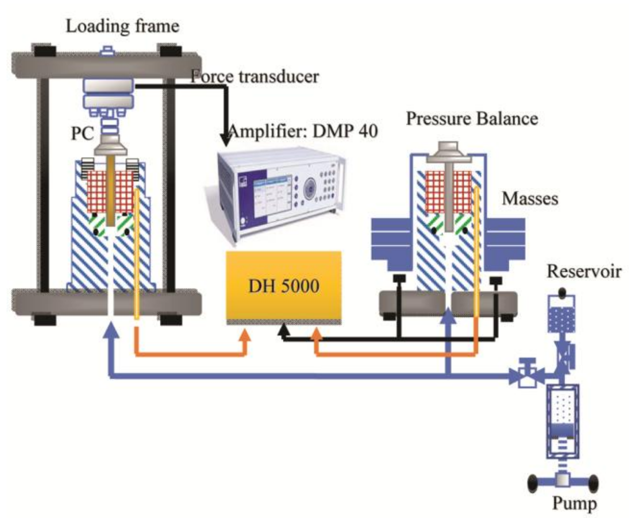

Fig. 2 — Schematic for pressure piston gauge method to generate the calibration forces

Where:

s_{max}: Maximum deflection from loading series 1, 3 and 4 shown in Fig. 1,

s_{min}:Minimum deflection from loading series 1, 3 and 4 shown in Fig. 1,

And;

$$\bar{S}_r = \frac{S_1 + S_3 + S_5}{3} \tag{4}$$

b. The relative repeatability error R_{Rep}

$$R_{Rep} = \frac{|S_2 - S_1|}{\bar{S}_{wr}} \tag{5}$$

And:

$$\bar{S}_{wr} = \frac{S_1 + S_2}{2} \tag{6}$$

Where,

$\bar{S}_r$ Average value of the load cell response with rotation,

$\bar{S}_{wr}$ Average value of the load cell response without rotation.

s_1, s_2, s_3, s_4 are the deflection of the force transducer at increasing mode

a. Interpolation relative error, I_{Int}

$$i_{Int} = \frac{\bar{S}_r + S_a}{S_a} \times 100 \tag{7}$$

s_a: Computed value of deflection obtained from the curve fitting of the calibration results.

b. Zero relative error, z_{eror}

$$z_{error} = \frac{f_r - f_o}{S_N} \times 100 \tag{8}$$

f_r :Reading on the indicator after removal of force,

f_o: Reading on the indicator before application of force,

S_N: Maximum calibration force.

c. The Creep relative error, c_r

The contribution of this item is the maximum relative creep error evaluated.

$$Cr = \left| \frac{f_{300} - f_{30}}{S_N} \right| \times 100 \tag{9}$$

The classification criterion is performed based on Table 1[16].

d. Uncertainty Estimation

The combined uncertainty can be calculated using the below equation

$$u_c = \sqrt{\sum_{i=1}^{7} u_i^2} \tag{10}$$

Where

u_i can be as follow;

$$u_{prod} = \frac{R_{Prod}}{100 \times \sqrt{3}} \tag{11}$$

u_{prod} is considered the relative standards uncertainty of the reproducibility

$$u_{rep} = \frac{R_{Rep}}{100 \times \sqrt{3}} \tag{12}$$

u_{rep} is considered the relative standards uncertainty of the repeatability

$$u_{int} = \left| \frac{\bar{S}_r - S_a}{\bar{S}_r} \right| \tag{13}$$

u_{int} is considered the relative standards uncertainty of the interpolation

Table 1 — Classification criteria mentioned in ISO 376:2011

Class	Relative error of the force-proving instrument %				
	Reproducibility R_{Prod}	Repeatability R_{Rep}	Interpolation i_{int}	Zero $z_{error} f_0$	Creep cr
0	0, 05	0, 025	±0, 025	±0, 012	0, 025
0, 5	0, 10	0, 05	±0, 050	±0, 025	0, 050
1	0, 20	0, 10	±0, 100	±0, 050	0, 100
2	0, 40	0, 20	±0, 200	±0, 100	0, 200

$$u_{zero} = \frac{Z_{eror}}{100} \tag{14}$$

u_{zero} is considered the relative standards uncertainty of the drift in zero output the amplifiers/indicators.

$$u_{cr} = \frac{cr}{100 \times \sqrt{3}} \tag{15}$$

u_{cr} is considered the relative standards uncertainty of the creep of the instrument.

$$u_{\mathrm{Res}} = \frac{r}{\sqrt{6}} \tag{16}$$

u_{Res} is considered the relative standards uncertainty of the resolution of the amplifiers/indicators.

u_{ref} is considered the relative standards uncertainty of the applied loads by the standards calibration machines or dead weights machines on the force proving instruments (force transducers).

$$u_{\exp} = u_c \times k \tag{17}$$

U_{exp} The expanded uncertainty for each calibration step can be calculated as the combined uncertainty multiplied by the coverage factor k where (k =2), refer to Equation 17.

3 Experimental work procedure

During this investigation, the force transducer is calibrated at four increasing load series using the previous described two methods. After three preloading (from zero to max load), two series at zero position (s_1, s_2). Then rotating the force transducer to 90 ° and record full calibration series (s_3), then rotate the force transducer to 180 º and record the full calibration series (s_4). One preloading is conducted between each rotating series, 30 sec is required for reading stability at each load value (see Fig. 3).

4 Results and discussion

After force transducer calibration the following results were recorded and calculated based on equations from 3 to 9. The results obtained from calibrations are fitted to find the best fit for these results and hence obtaining the calibration equations (18, 19, 20, 21). The calculated responses stated in the below tables are calculated from equations 19 and 21. All the effective relative errors are calculated in accordance with equations from 3 to 9. The classifications criterion for the calibrated force transducer utilize the calculated relative errors for this classification as described in Table 1. The uncertainty

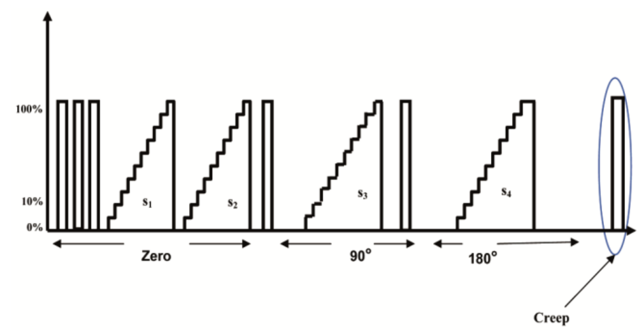

Fig. 3 — Shows the procedure of calibration used

Force proving instrument produced Equations

Force =A * Response + B * Response^2 +C* Response^3 (18)

Where

A	494.5231118	B	-0.042510701	C	0.050647255

Response =X * Force + Y * Force^2 +Z * Force^3 (19)

Where

X	0.00202215	Y	3.50232E-10	Z	-8.45413E-13

Force proving instrument produced Equations

Force =A * Response + B * Response^2 +C* Response^3 (20)

Where

A	494.4945396	B	-0.391041711	C	0.159124794

Response =X * Force + Y * Force^2 +Z * Force^3 (21)

Where

X	0.002022267	Y	3.2366E-09	Z	-2.66444E-12

estimation for measurements are calculated using equation from 9 to 17. The obtained calibration results are compared with PTB calibration results to detect the most accurate and the most realistic results refer to Table 6.

From the previous Tables 2-5, the values of the calibration results of the two methods under investigation were presented. All the sources of errors were calculated for each method, separately. The classifications for the force transducer were identified and compared with PTB results as shown in Table 6. From Table 6 it was noted that the calibration using deadweights method is the most

It was found that the dead weights calibration method is the most accurate method, since it is the closest to the reference values in terms of the result and classification. The main drawback of this method is to use it at high calibration range due to weights stability and huge mechanical system is required. For piston gauge method, it is the least accurate as its results being far from the reference value in terms of values and classification, but it is the most used, especially for high ranges force measurements.

Table 2 — Shows the calibration results for the force transducer using deadweights calibration based on Fig 2.

Calibration Results

Applied Load N	Average of s_1,s_2 mv/v	Average of s_1,s_3,s_4 mv/v	Calculated Response s_a mv/v
97.91539	0.19801300	0.198012	0.198002
195.8304	0.39602900	0.396019	0.396006
293.7457	0.59401550	0.594006	0.594007
391.6608	0.79199000	0.791990	0.792000
489.5762	0.98997000	0.989963	0.989981
587.4913	1.18795600	1.187955	1.187945
685.4068	1.38592150	1.385888	1.385888
783.3219	1.58381700	1.583816	1.583803
881.2373	1.78166950	1.781686	1.781688
979.1522	1.97952100	1.979531	1.979535

Table 3 — The calculated relative error for the force transducer calibration using deadweights calibration

Calibration Results

Applied Load N	Relative Repeatability Error % R_{rep}	Relative Reproducibility Error % R_{Prod}	Relative Interpolation Error % i_{int}	Class	Relative Expanded Uncertainty %
97.9154	0.001010	0.002525	0.005111	0.0	0.044749
195.8304	0.008585	0.013636	0.003465	0.0	0.045411
293.7457	0.012626	0.012963	0.000077	0.0	0.045428
391.6608	0.010859	0.008460	0.001304	0.0	0.045057
489.5762	0.011313	0.011718	0.001866	0.0	0.045243
587.4913	0.012458	0.013132	0.000793	0.0	0.045363
685.4068	0.008009	0.013349	0.000002	0.0	0.045385
783.3219	0.007577	0.009092	0.000782	0.0	0.045050
881.2373	0.006791	0.007296	0.000102	0.0	0.044982
979.1522	0.008588	0.009043	0.000212	0.0	0.045050

Table 4 — Shows the calibration results for the force transducer using pressure piston gauge based on Fig 4.

Calibration Results

Applied Load N	Average of s_1, s_2 mv/v	Average of s_1, s_3, s_4 mv/v	Calculated Responses$_a$ mv/v
94.8615	0.1918270	0.1918247	0.1918622
192.7820	0.3898880	0.3899173	0.3899578
290.7032	0.5880150	0.5880853	0.5880875
388.6249	0.7861405	0.7862533	0.7862357
486.5473	0.9842785	0.9844277	0.9843879
584.4702	1.1823910	1.1825637	1.1825285
682.3936	1.3804660	1.3806317	1.3806425
780.3174	1.5784855	1.5786667	1.5787148
878.2420	1.7764770	1.7767043	1.7767314
976.1670	1.9745040	1.9747110	1.9746761

Table 5 — The calculated relative error for the force transducer calibration using pressure piston gauge.

Calibration Results

Applied Load N	Relative Repeatability Error % R_{rep}	Relative Reproducibility Error % R_{Prod}	Relative Interpolation Error % i_{int}	Class	Relative Expanded Uncertainty %
94.8615	0.001043	0.029193	0.019560	0.0	0.047828
192.7820	0.003078	0.020517	0.010387	0.0	0.046328
290.7032	0.019047	0.014114	0.000365	0.0	0.045525
388.6249	0.030147	0.011574	0.002248	0.5	0.045226
486.5473	0.040741	0.018894	0.004039	0.5	0.046331
584.4702	0.048038	0.022578	0.002972	0.5	0.046738
682.3936	0.046071	0.021150	0.000787	0.5	0.046372
780.3174	0.043523	0.016850	0.003051	0.5	0.045922
878.2420	0.043006	0.013733	0.001526	0.5	0.045571
976.1670	0.042745	0.016813	0.001766	0.5	0.046035

Table 6 — Show the summarized calibration results of the two methods compared with PTB results

Results obtained from PTB certificate		Experimental results			
		Deadweights method		Piston gauge method	
Measured value (N)	Class	Measured value (N)	Class	Measured value (N)	Class
0.199886	0.0	0.198002	0.0	0.1918622	0.0
0.399866	0.0	0.396006	0.0	0.3899578	0.0
0.599910	0.0	0.594007	0.0	0.5880875	0.0
0.799856	0.0	0.792000	0.0	0.7862357	0.5
0.999857	0.0	0.989981	0.0	0.9843879	0.5
1.199866	0.0	1.187945	0.0	1.1825285	0.5
1.399856	0.0	1.385888	0.0	1.3806425	0.5
1.599562	0.0	1.583803	0.0	1.5787148	0.5
1.799565	0.0	1.781688	0.0	1.7767314	0.5
1.998967	0.0	1.979535	0.0	1.9746761	0.5

5 Conclusion

The article presents two procedures for force transducer calibration. The first method was to utilize the deadweights and the second method to use the pressure piston gauge to generate the actual force on the force transducers. The generated applied load values (reference values) were used to identify the different relative errors produced from these calibrations. These calculated relative errors were used as classification criterion for the force transducer under investigation. From this investigation, the followings are the conclusive points.

- Based on the results shown above it was noted that dead weights method is the most accurate compared with PTB results where the deadweights are considered as a direct application and generation for the applied force through newton's first low, so it is the most accurate method for verifying the performance of the force transducers.
- Pressure piston gauge mechanisms are not the most accurate procedure compared with the deadweights method as it is derived in relation to generating the applied force.
- One of the most drawbacks of deadweights methods are at high forces as it is possible that instability may occur.
- It is also necessary to provide systems for the application of forces that maintain the centrality of these weights and also to handle them in a manner in which this accuracy can be preserved, which requires extremely high costs, especially when calibrating the high forces.
- Pressure piston gauge is the most realistic at high forces calibrations as it is the best and easiest way for loads magnifications while maintaining adequate accuracy.

References

1 Bièvre P J D, *Accreditation Qual Assur*, 17 (2012) 231.

2 Possolo A & Elster C, *Metrologia*, 51 (2014) 339.

3 Hall R S, Desmoulin G T & Milner T E, *J Biomechanics*, 41 (2008) 3492.

4 Castro R M, Pereira M, Sousa A R, Curi E I M, Izidoro C L & Correa L C, *J Phys: Conf Ser*, 733 (2016) 012048.

5 Olmi G, *Experimental Techniques J*, 40 (2016) 1147.

6 Mahmoud G M, Osman S M & Hegazy R S, *Int J Metrol Qual Eng*, 12 (2021).

7 Park Y K, Kim M S, Kim J H, Kang D I & Song H K, *J Mech Sci Technol*, 20 (2006) 961.

8 Chesnutwood K L & Samuel L H, Automation and Upgrade of the 27.1 kN Dead Weight Machine at the National Institute of Standards and Technology, NIST, Interagency/Internal Report (NISTIR) 2006.

9 Kumme R, Kahmann H, Tegtmeier F, Tetzlaff N & Röske D, PTB'S NEW 200^{KN} Deadweight Force Standard Machine, IMEKO 23rd TC3, 13th TC5 and 4 th TC22 International Conference , Helsinki, Finland, 2017.

10 Prilepk M Y, Sc D & Lysenko V G, *J Phys:Conf Ser*, 998 (2018) 012025.

11 Hayashi T, Katase Y, Maejima H, Yamaguchi Y & Ueda K, *Measurement* , 46 (2013) 4127.

12 Beekmans S V & Iannuzzi D, *Surf Topogr Metrol Prop*, 3 (2015) 025004.

13 Mahmoud G M & Gelany S A, *ASM Sci J*, 14 (2021) https://doi.org/10.32802/asmscj.2020.702.

14 ASTM E74 - 18e, Standard Practices for Calibration and Verification for Force-Measuring Instruments, 2018.

15 Hashad A S, Ehlers S, Jusko O & Sabuga W, *Measurement*, 131 (2019) 723.

16 ISO 376:2011, Metallic materials — Calibration of force-proving instruments used for the verification of uniaxial testing machine.