Characteristics and functions of the South African national measuring standard for force

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Abstract. This paper describes the force comparator machine by which a national measuring standard for force is established. The design of the machine is described focusing on the mechanical structure of the force comparator. High-precision strain gauge force transducers are at the heart of the force comparator machine. Characteristics of these force measuring devices are discussed. The process of their calibration for industry using the comparator machine is explained and it is shown that it can be carried out to uncertainties as low as 0.03 %.

1. Introduction

The use of calibrated measuring equipment is very important in industries. In force measurements, there is a variety of force measuring instrumentation within South African industries such as space, mining, aircraft and automobile [1]. Measurement accuracy in these industries can only be determined by calibration against a force standard. In the past, South African industries had to calibrate their force measuring equipment against standards kept overseas. The national measuring standard for force described in this paper was established to support South African industries by providing accurate force calibration against a standard in a timely and cost effective way. This force standard consists of a set of highly accurate force transducers that are periodically calibrated overseas in an internationally accredited force laboratory which is able to perform calibrations with low uncertainties. Calibration is done in a form of a comparison between the standard force transducer and the reference force transducer used in industry.

2. Force comparator measuring system

The South African national measuring standard for force is currently a force comparator machine consisting of the following components: mechanical frame, hydraulic system, force transducer and electronic measuring system.

2.1. Mechanical structure of the force comparator.

The frame of the force comparator structure is made up of forged iron material. The stress permitted in the direction of load application, Y (see figure 1) is 310 MPa and perpendicular to direction of load application (X) is 210 MPa. The total permissible load is 7.8 MN with the breaking load of 14 MN. The extreme stiffness of the mechanical structure ensures that the structure remains rigid and stable up to the maximum operating load.

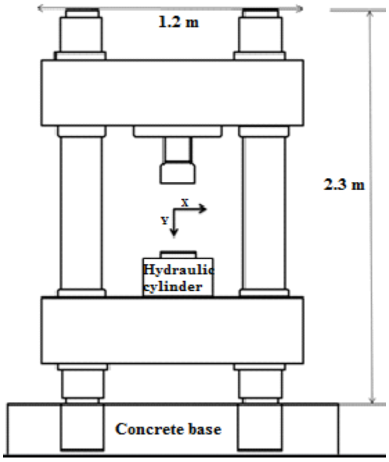

Figure 1. A schematic diagram of the frame of the force comparator machine.

Figure 2. The frame of the force comparator machine.

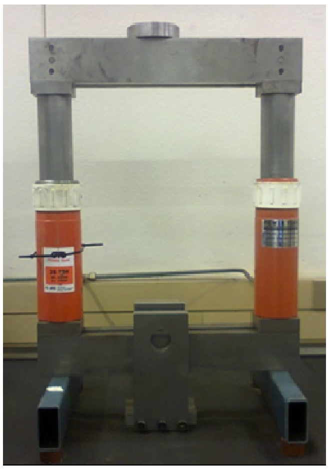

Figure 3. Comparator frame structure used for tensile force measurement.

The frame of the comparator machine shown in figure 2 is used for calibration of force transducer in compression in the range between 2 kN and 4500 kN. For calibration of force transducers in tension, the rig in figure 3 is used. Tensile measurement in the range of 2 kN to 250 kN can be performed (see section 3.1).

2.2. Hydraulic system.
The hydraulic system consists of hydraulic electric pump and a stepper motor coupled to the Budenberg pressure balance (see figure 4). These are used to drive the piston of the hydraulic cylinder and generate force within the comparator machine. The dual action hydraulic cylinder (figure 1) has a capacity to generate up to 4500 kN of force in compression and the double cylinders shown in figure 3 has capacity to generate 250 kN of tensile force. The hydraulic system is operated manually with a hand-pump for movement of the hydraulic cylinders piston up or down to generate force. The stepper motor coupled to the Budenberg pressure balance is used for sensitive and fine applications of force.

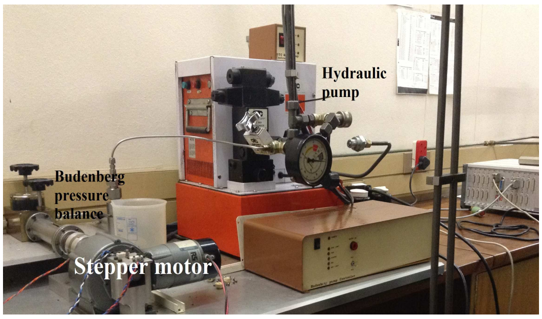

Figure 4. The hydraulic system consisting of the hydraulic pump and a stepper motor coupled to a Budenberg pressure balance.

2.3. Force measuring devices (force transducer).
A force transducer is a device that converts a force or load into a measureable output. There are several types of force transducer but strain gauge force transducer are by far the most common form of force transducer commercially available today [2]. The force transducers that are used with the

comparator machine as standards for force measurements are of accuracy class 0.5 and 00 as classified according to ISO 376 [3]. They are column design and are manufactured at HBM in Germany [4].

2.4. Force measuring devices (The digital measuring unit).

The basic output of strain gauge force transducer is a low level voltage signal (i.e., mV), therefore it must be gained by sophisticated methods. Through the use of signal conditioning and amplifiers, this signal can become a higher level voltage [5]. HBM signal amplifiers model DMP40S2 are used as read out units. Connected strain gauge force transducers are excited with a 225 Hz carrier frequency and the output signal of a selected force transducer is measured, amplified and displayed. The readings can be displayed in any desired unit such as mV/V, kN, kg, etc. [6] [7].

3. Calibration of force transducer using the comparator machine.

3.1. Calibration Setup

During calibration measurements of force transducer in compression (figure 5), the reference force transducer is attached to the upper coupling. The force transducer to be calibrated which is commonly known as the Unit Under Test (UUT) is coaxially aligned with the reference force transducer. This alignment band ensures that the force applied is in alignment with the UUT's principal load axis. In tension measurements (figure 6), the crossbeam is placed on the appropriate piston fittings. The reference force transducer is placed in the centre of the crossbeam and the loading button is placed between the tension to compression rig and the reference force transducer. The tension to compression top half is placed over the reference force transducer and bottom part fastens to the applicable screws. The UUT is fitted with suitable tension bars and attached to the tension rig.

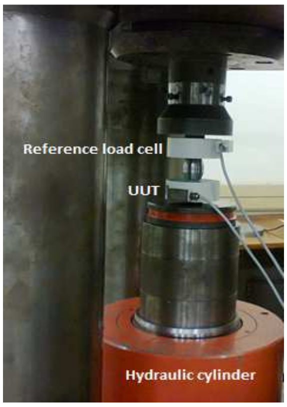

Figure 5. Calibration set up of force transducer in compression.

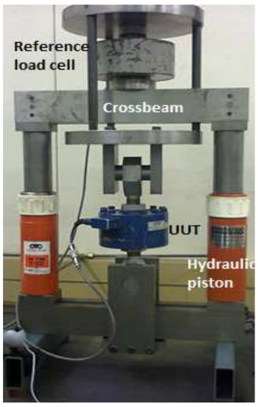

Figure 6. Calibration set up of force transducer in tension.

3.2. Uncertainty of the measurement

Calibration using the force comparator machine consists of applying precisely-known forces to the force transducer under calibration and recording the data from the indicator. At each calibration force, a combined standard uncertainty (u_c) expressed in units of force is calculated using the following equation [3] [8]:

$$u_c = \sqrt{\sum_{i=1}^{8} u_i^2} \quad (1)$$

Where:

u_1 = standard uncertainty associated with the force comparator machine.

u_2 = standard uncertainty associated with reproducibility of calibration results.
u_3 = standard uncertainty associated with repeatability of calibration results.
u_4 = standard uncertainty associated with resolution of readout unit at zero.
u_5 = standard uncertainty associated with resolution of readout unit at measurement point.
u_6 = standard uncertainty associated with creep of the force transducer under calibration.
u_7 = standard uncertainty associated with drift in zero output
u_8 = standard uncertainty associated with temperature.

The equations for calculating each of the above standard uncertainties are derived and stated on the ISO 376 document which is an international standard for calibration of force transducer [3].

3.3. Calibration Procedure.

Force transducer are attached to their respective readout units and energised for about 30 minutes. Before the calibration forces are applied in a given mode (tension or compression), the maximum force is applied to UUT three times to exercise it. Two runs of increasing calibration forces are applied to the UUT and readings are recorded and used to calculate the repeatability uncertainty. The UUT is then rotated symmetrically on its axis to positions 120˚ and 240˚ and a run of increasing calibration forces is applied at each position and readings recorded to calculate the reproducibility uncertainty. The zero point is recorded before and after each run approximately 30 s after the force has been completely removed from the UUT. This is to calculate the uncertainty due to drift in zero for the force transducer. After the final zero reading is taken, the change in UUT output 300 s after removal of the calibration force is recorded to calculate creep. Laboratory temperature is recorded before and after the calibration is completed to calculate uncertainty of measurement due to change in temperature.

This procedure is followed during the calibration of force transducer to disseminate traceability in force measurement to South African industry. For the determination of the calibration measurement capability (CMC) of the comparator machine, reference standard force transducers of the force lab that have been calibrated by an internationally accredited NMI were calibrated against each other using the comparator machine following the above procedure. To determine the CMC of the machine in the range 2 kN to 20 kN, reference standard force transducer HBM Z4A (serial number: 184830136) of capacity 20 kN and class 00 was used to calibrate reference standard force transducer HBM C4 (serial number: 35178) of class 00 with capacity 20 kN in compression mode.

3.4. Calibration Results.

The calibration data obtained from HBM C4 (serial number: 35178) force transducer calibrated using HBM Z4A (serial number: 184830136) force transducer is shown in Table 1. The procedure as stated in section 3.3 was followed to perform the calibration. The temperature of the lab before and after the calibration was recorded and was found to be 18˚C and 19˚C respectively. The readout unit DMP40S2 connected to the HBM C4 force transducer indicated the measurements in mV/V units with resolution of 0.000001.

Using calibration data from Table 1, uncertainty contributors to the force measurements expressed in the units of force, kN can be calculated using equations as derived from the ISO 376 standard document. Table 2 shows values calculated of all uncertainty contributors. The machine uncertainty is taken as the combined standard uncertainty as quoted on the recent calibration certificate of the HMB Z4A force transducer issued by an internationally accredited NMI. The uncertainty due to reproducibility, repeatability, resolution of the readout unit for both at zero and at the point of measurement, creep and drift at zero are calculated using equations derived in the ISO 376 document. The uncertainty contribution of temperature to measurements is also calculated.

Table 1: Calibration data received from HBM C4 (serial number: 35178) load cell in compression mode.

Ref force	Pre loads			Run 1	Run 2	Run 3	Run 4
kN	**mV/V**	**mV/V**	**mV/V**	**mV/V**	**mV/V**	**mV/V**	**mV/V**
0,0	-0,000002	0,000030	0,000034	0,000002	0,000010	0,000011	0,000001
2,0				0,199938	0,199948	0,199927	0,199926
4,0				0,399857	0,399866	0,399855	0,399858
6,0				0,599760	0,599765	0,599774	0,599792
8,0				0,799647	0,799647	0,799684	0,799727
10,0				0,999519	0,999515	0,999582	0,999659
12,0				1,199376	1,199371	1,199471	1,199585
14,0				1,399217	1,399216	1,399348	1,399504
16,0				1,599045	1,599053	1,599213	1,599412
18,0				1,798858	1,798883	1,799067	1,799307
20,0	1,998662	1,998618	1,998628	1,998658	1,998709	1,998908	1,999187
Force indicated at zero 30 seconds after the removal of the maximum load.				0,000070	0,000060	0,000020	0,000040
Force indicated 300 seconds after the final maximum load has been removed (Creep effect)							-0.000030

Table 2: Calculated values of uncertainties contributors in force measurements by HBM C4 standard force transducer.

Machine Uncertainty (kN)	Reproducibility (kN)	Repeatability (kN)	Resolution Zero (kN)	Resolution @ Point (kN)	Creep (kN)	Drift @ Zero (kN)	Temperature (kN)
u_1	u_2	u_3	u_4	u_5	u_6	u_7	u_8
0,00000	0,00003829	0,00000000	0,000004	0,000004	0,0000	0,0002	0,0000000
0,00011	0,00003811	0,00005868	0,000004	0,000004	0,0000	0,0002	0,0001559
0,00020	0,00000768	0,00004920	0,000004	0,000004	0,0001	0,0002	0,0003118
0,00027	0,00009355	0,00002601	0,000004	0,000004	0,0001	0,0002	0,0004677
0,00032	0,00022987	0,00000117	0,000004	0,000004	0,0001	0,0002	0,0006235
0,00040	0,00040340	0,00002258	0,000004	0,000004	0,0002	0,0002	0,0007794
0,00048	0,00060558	0,00002851	0,000004	0,000004	0,0002	0,0002	0,0009353
0,00049	0,00082784	0,00000919	0,000004	0,000004	0,0003	0,0002	0,0010912
0,00056	0,00106166	0,00004510	0,000004	0,000004	0,0003	0,0002	0,0012471
0,00063	0,00129852	0,00014411	0,000004	0,000004	0,0003	0,0002	0,0014030
0,00070	0,00152997	0,00029758	0,000004	0,000004	0,0004	0,0002	0,0015588

At each reference force applied, u_c was calculated from all the uncertainty contributors as listed in section 3.2 and calculated and shown in table 2 using equation (1) and the results are shown in table 3. Expanded uncertainty (U) in measurements is derived by multiplying the u_c by the coverage factor of $k = 2$ and dividing by the magnitude of the reference force applied and reporting the results in percentages at the confidence level of approximately 95 % [8].

The CMC of the machine is then taken as the highest expanded uncertainty calculated in percentage rounded up to two decimal points. Therefore the CMC for the Comparator force machine in the range of 2 kN to 20 kN is 0.03 % when HBM C4 force transducer is used as reference standard in the machine to perform calibrations. The CMC for the machine in the other force ranges was also determined following the same method of calibrating two reference standard force transducer using the Comparator force machine. The CMC in the range of 20 kN to 200 kN was found to be 0.03 % in both compression and tension. From 200 kN to 1000 kN in compression only, the machine has the CMC of 0.04 % and 0.08 % in 1000 kN to 4500 kN range.

Table 3: Determination of the expanded uncertainty (*U*) in measurements of HBM C4 standard force transducer

Reference force	Combined uncertainty	Coverage factor	Expanded uncertainty	Expanded uncertainty
F_R	u_c	k	U	U
kN	**kN**		**kN**	**%**
2,000	0,00027	2	0,001	0,027
4,000	0,00042	2	0,001	0,021
6,000	0,00059	2	0,001	0,020
8,000	0,00077	2	0,002	0,019
10,000	0,00100	2	0,002	0,020
12,000	0,00124	2	0,003	0,022
14,000	0,00149	2	0,003	0,023
16,000	0,00176	2	0,004	0,024
18,000	0,00205	2	0,005	0,025
20,000	0,00235	2	0,005	0,026

4. Conclusions

The calibration capability of the Comparator force machine depends primarily on the force transducer used as the reference standard to measure the force generated by the machine. Precision strain gauged force transducers of high accuracy connected to signal amplifier of high resolution are used as the main components of the Comparator force machine. Therefore the forces generated by the machine can be precisely measured and transferred during the process of calibration. The CMC expressed as the expanded uncertainty of the measurement was found to be 0.03 % in the range of 2 kN to 20 kN for the Comparator force machine.

5. References

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