ANALYTICAL STUDY ON THE UNCERTAINTY OF LOAD CELLS CALIBRATED WITH DEADWEIGHT-FORCE-STANDARD MACHINE AND FORCE-COMPARATOR MACHINE

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Abstract

In Thailand, there are two important types of force calibration machines; deadweight force standard machine and force comparator machine. The first machine provides more accurate results, but requires high investment when compared to the force comparator machine that is widely used. However, the quality of calibration from force comparator machine is still questionable due to many factors, such as alignment and loading method.

The purpose of this study was to evaluate the uncertainties of load cells calibrated with deadweight force standard, in comparison to force comparator machines. The calibration results were compared in term of sources of uncertainties, i.e., reproducibility, repeatability, stability of the standard and hysteresis to understand the behavior of both machines.

The results showed that the maximum relative reproducibility errors from the deadweight force standard and force comparator machine are 0.006% and 0.05%, respectively. The relative instability of the deadweight machine (at 10 kN) is less than 0.003% while the comparator machine is 0.07%. Therefore, these data strongly demonstrate that load cell calibration with deadweight force standard machine is better than that of force comparator machine. Moreover, the 0.07% relative instability of the force comparator machine is more than the reported uncertainty (0.0529%), indicating that, the machine requires more realistic evaluation on the uncertainty of the applied forces.

Keywords: force calibration, uncertainty of force measurement, deadweight machine, load cell

1. Introduction

Load cell is an instrument for measuring force in many material testing applications, ranging from small force as testing food products to large force as testing properties of steel for construction. Any mistake of the measuring results of load cells can lead to loss of properties and life. Therefore, it is necessary to calibrate load cells to ensure that they pass the standard requirement and are also traceable to the SI unit. Generally, the calibrations of load cells are carried out according to standard procedure such as ISO 376 [1].

According to the guidance for evaluation of uncertainty of force measurements [2], based on type of force generation, force calibration machine can be categorized into four groups; deadweight, hydraulic amplification, lever amplification and comparator. The applied forces of deadweight force standard machine (DWM) are generated from mass of deadweight multiply with the local gravitational acceleration. For lever amplification machine [4] and hydraulic amplification machine, the applied forces are originally generated from mass of deadweight multiply with the local gravitational acceleration. Then, these forces are amplified using lever mechanism and hydraulic system, respectively. For force comparator machine, test force is applied to both standard and calibrated load cell at the same time, the calibration is carried out by comparing the reading of the calibrated load cell with the reading of the standard one.

Among the types of calibration machines, deadweight force standard machine provides best accuracy and stability. Therefore it is used as a national primary standard in many countries such as Thailand, Japan, Germany, USA, Korea, etc. However, the investment for a large deadweight machine is very high.

In Thailand, only National Institute of Metrology Thailand (NIMT) is capable of calibration load cell with deadweight-force-standard machine for the force larger than 10 kN (Fig.1.). While most of others force calibration services use force-comparator-type machines, which provide less accuracy.

From the previous study on the interlaboratory comparison [3], indicating that, there is a large deviation on the calibration results among the participant laboratories. Therefore, it is necessary to have a study on the quality of load cell calibration for improving force calibration system in Thailand.

In this study, the performance of force comparator machine is investigated by comparing its results with the deadweight machine. Two load cells, HBM-C4-100kN (with indicator HBM-DK38) and GTM-KTN-D-100kN (with indicator HBM-DMP40), were used as artifacts. The deadweight force standard machine 100kN (Maekawa-FSD-10) (Fig.1.) and force comparator machine (Morehouse-UCM-50000kgf) (Fig.2.) were used for calibrating these artifacts.

For easier understanding, the load cell systems were defined as following.

1. LC-A represents the load cell model HBM-C4-100kN (with indicator model HBM-DK38)
2. LC-B represents the load cell model GTM-KTN-D-100kN (with indicator model HBM-DMP40)

The calibration machines were also defined as following.

1. DWM represents the deadweight force standard machine 100 kN (Maekawa-FSD-10).
2. FCM represents the system of force comparator machine (Morehouse-UCM-50000kgf) combined with a reference load cell (LC-B).

Fig. 1 NIMT's Deadweight force machine 100 kN

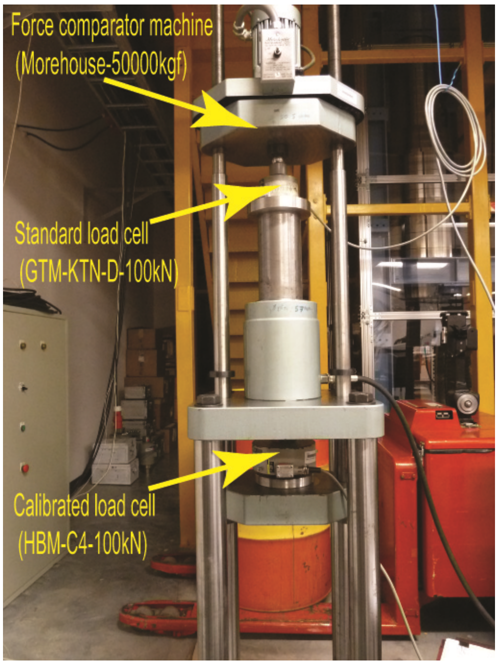

Fig. 2 NIMT's Force comparator machine

2. Protocol

In this study, 6 calibration tests were carried out as followings:

-1st test, using DWM to calibrate LC-A

- 2nd test, using DWM to calibrate LC-B
- 3rd test, using FCM to calibrate LC-A
- 4th test, using DWM to calibrate LC-A
- 5th test, using DWM to calibrate LC-B
- 6th test, using FCM to calibrate LC-A

All the calibration procedures were performed in accordance with ISO 376:2004(e) (see Fig.3.).

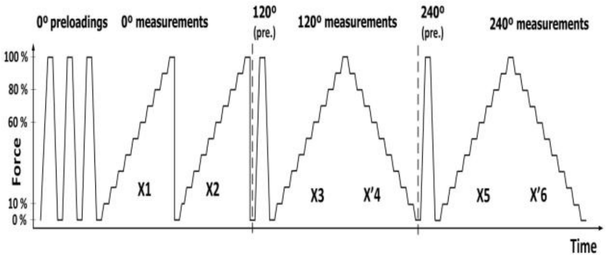

Fig.3. Calibration procedure

As shown in Fig. 3, each calibration contains of 6 calibration series; x1 and x2 are increasing series at 0° angle, x3 and x'4 are increasing and decreasing series at 120° angle, x5 and x'6 are increasing and decreasing series at 240° angle.

According to ISO 376:2004(e), there are 4 classes of load cell; 00, 0.5, 1 and 2. The classification of load cell is categorized by relative error of the load cell's calibration results, in term of relative reproducibility error *(b)*, relative repeatability error *(b')*, relative interpolation error (f_c), relative zero error (f_0), relative reversibility error *(v)* and relative uncertainty of the applied force of calibration machine [1], as shown in Table 1.

Table 1. Classification of load cell - ISO 376:2004

Class	Relative error of load cell (%)					Uncertainty
	reproduce	repeat	interpolation	zero	reverse	of applied F
	b	b'	f_c	f_o	v	k=2, (%)
00	0.05	0.0250	±0.025	±0.012	0.07	±0.01
0.5	0.10	0.0500	±0.05	±0.025	0.15	±0.02
1	0.20	0.1000	±0.10	±0.050	0.30	±0.05
2	0.40	0.2000	±0.20	±0.10	0.50	±0.10

3. Uncertainty calculation

At each calibration force, the combined relative standard uncertainty can be calculated from 8 different sources of uncertainty as seen in Eq. (1).

$$w_c = \sqrt{\sum_{i=1}^{8} w_i^2} \tag{1}$$

Where w_i are relative standard uncertainties associated with sources of uncertainty, which are applied calibration force, reproducibility, repeatability, resolution of indicator, reversibility, drift of zero output, temperature effect and interpolation equation. The expanded uncertainty can be calculated from Eq. (2).

$$W = k \times w_c \tag{2}$$

Where W is expanded uncertainty and k is coverage factor (typically equal to 2)

4. Experiment result

From six calibration tests, the expanded uncertainties of the calibrated load cells (UUC) were calculated and shown in Table 2.

Table 2. Expanded uncertainty of UUC

	Expanded uncertainty (k=2) (%)					
Machine	DWM	DWM	FCM	DWM	DWM	FCM
UUC	LC-A	LC-B	LC-A	LC-A	LC-B	LC-A
Force (kN)	test 1	test 2	test 3	test 4	test 5	test 6
10	0.0378	0.0128	0.0447	0.0351	0.0126	0.0529
20	0.0290	0.0089	0.0345	0.0285	0.0089	0.0378
30	0.0229	0.0061	0.0300	0.0223	0.0060	0.0328
40	0.0190	0.0048	0.0263	0.0183	0.0043	0.0318
50	0.0149	0.0043	0.0218	0.0143	0.0035	0.0246
60	0.0118	0.0038	0.0197	0.0109	0.0035	0.0217
70	0.0082	0.0035	0.0178	0.0082	0.0035	0.0201
80	0.0056	0.0035	0.0156	0.0055	0.0035	0.0177
90	0.0035	0.0035	0.0148	0.0035	0.0035	0.0176
100	0.0035	0.0035	0.0138	0.0035	0.0035	0.0154

Table 3 and 4 show relative error and classification of the load cell (LC-A) after calibration with the DWM and FCM, respectively.

Table 3. Classification of LC-A calibrated with DWM (1st test)

Applied	Relative error of load cell (%)					Class
Force	reproduce	repeat	interpolation	zero	reversibility	
(kN)	b	b'	f_c	f_o	v	
10	0.0000	0.0050	0.0002	0.0001	0.0650	00
20	0.0025	0.0000	-0.0005	0.0001	0.0500	00
30	0.0033	0.0000	0.0005	0.0001	0.0392	00
40	0.0025	0.0012	-0.0003	0.0001	0.0325	00
50	0.0010	0.0010	0.0002	0.0001	0.0255	00
60	0.0017	0.0000	-0.0001	0.0001	0.0200	00
70	0.0021	0.0000	0.0001	0.0001	0.0136	00
80	0.0019	0.0006	-0.0001	0.0001	0.0087	00
90	0.0011	0.0006	0.0001	0.0001	0.0039	00
100	0.0010	0.0005	0.0000	0.0001	-	00

Table 4. Classification of LC-A calibrated with FCM (3rd test)

Applied	Relative error of load cell (%)					class
Force	reproduce	repeat	interpolation	zero	reversibility	
(kN)	b	b'	f_c	f_o	v	
10.006	0.0100	0.0050	-0.0047	0.0000	0.0680	0.5
20.006	0.0150	0.0025	0.0038	0.0000	0.0490	0.5
30.005	0.0117	0.0017	0.0016	0.0000	0.0440	0.5
40.004	0.0087	0.0000	-0.0025	0.0000	0.0375	0.5
50.003	0.0110	0.0000	0.0002	0.0000	0.0280	0.5
60.002	0.0108	0.0025	-0.0006	0.0000	0.0229	0.5
70.000	0.0107	0.0014	0.0007	0.0000	0.0182	0.5
79.999	0.0094	0.0025	0.0002	0.0000	0.0124	0.5
89.998	0.0111	0.0011	-0.0001	0.0000	0.0062	0.5
99.997	0.0095	0.0025	-0.0001	0.0000	-	0.5

From Table 3 and 4, the class of the load cell in table 3 is 00 and in table 4 is 0.5. This is because of the expanded uncertainties of applied forces of the DWM, which were less than 0.01%, while that of FCM were more than 0.01%. The major factors are from uncertainties of standard load cell, and loading mechanism of the machine.

5. Comparison result

The relative reproducibility errors indicate the level of variation of reading at difference angle of the load cell. For each force step, these errors were calculated from reading of increasing series at difference orientation (x1, x3 and x5 in Fig.3.)

Fig.4. shows the comparison of the relative reproducibility errors of load cell between each test. It is clearly seen that the results of test 3 and 6, which the load cell were calibrated using FCM, were larger than the result from DWM. For example, at 10 kN force, the result of test 6 was 0.05% and the result of test 4 was about 0.005%.

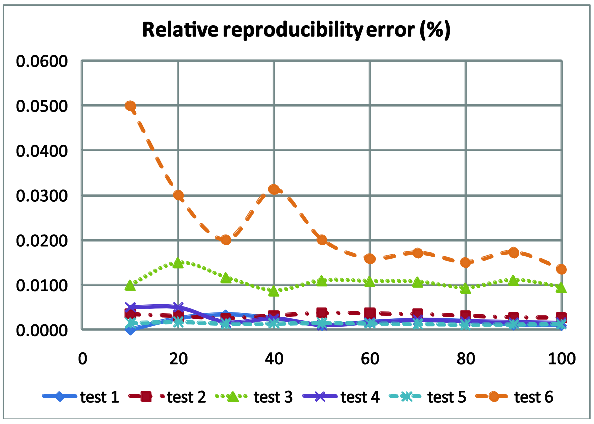

Fig.4. Comparison of relative reproducibility error

Fig.5. shows the comparison result of relative repeatability which is calculated from reading of increasing series of same orientation (x1 and x2). The relative repeatability errors of the 6th test were larger than others, indicating that, the FCM had an alignment problem during the test.

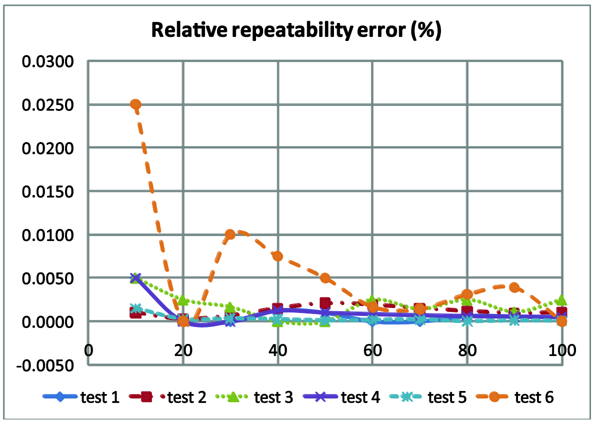

Fig.5. Comparison of relative repeatability errors

Fig.6. presents the relative interpolation errors, which indicate how good of the prediction results (from interpolation equation) compared to the experimental results (from the average of x1, x3 and x5). The results from the 3rd test had largest variation of the errors.

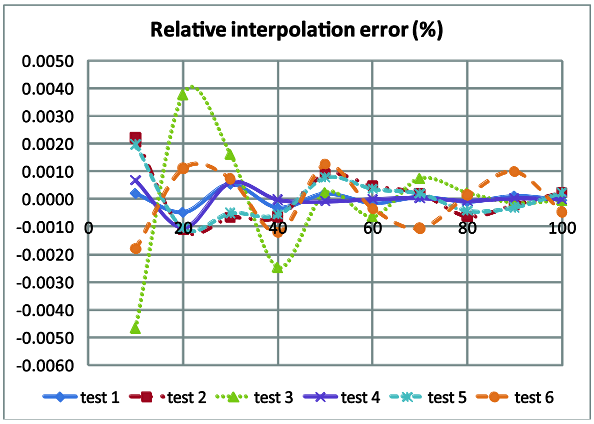

Fig.6. Comparison of relative interpolation errors

Fig.7. shows comparison of relative reversibility error of all the tests. For example, at 10kN force, the relative reversibility errors of the 2nd and 5th tests (LC-B calibrated with DWM) were about 0.02%. The results from the 1st and 4th tests (LC-A calibrated with DWM) were about

0.06%. The results of the 3rd and 6th test (LC-A calibrated with FCM), were also 0.06%.

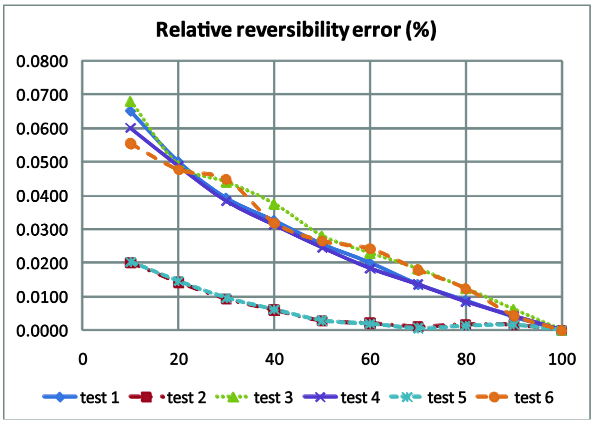

Fig.7. Comparison of relative reversibility errors

Fig.8. shows the comparison result of relative reading errors compared with ideal values of reading. For example of ideal values in this case, if the applied forces are 10, 20, 30,…,100 kN, the ideal reading will be 0.2, 0.4, 0.6,…, 2.0 mV/V, respectively. From Fig.8., the results of the 1st test were very close to the 4th test. The results from the 2nd test were also close to the 5th test. These results indicate that, the DWM was very stable. For FCM, the results from reading of the 3rd test were not close to the 6th test, presenting that the system of the machine had problem on stability. The factors affect machine stability can be alignment, human error and loading mechanism.

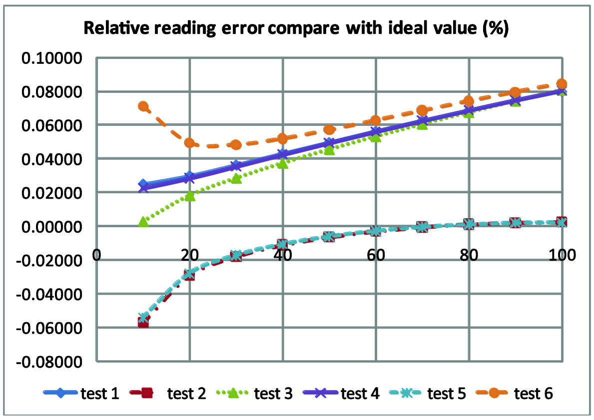

Fig.8. Comparison of relative reading errors

Fig.9. shows system instability which is calculated from the sensitivity change between similar setup. It was easily calculated from the difference of values in Fig.8. From Fig.9., the label of Test1-4 is the relative difference of reading between the 1st and 4th test. It is clearly seen that the results of Test1-4 and Test2-5 were close to zero because they were calibrated with DWM that was very stable. The result of Test 3-6 at 10kN was equal to 0.07%, convincing that, the system of FCM is not stable.

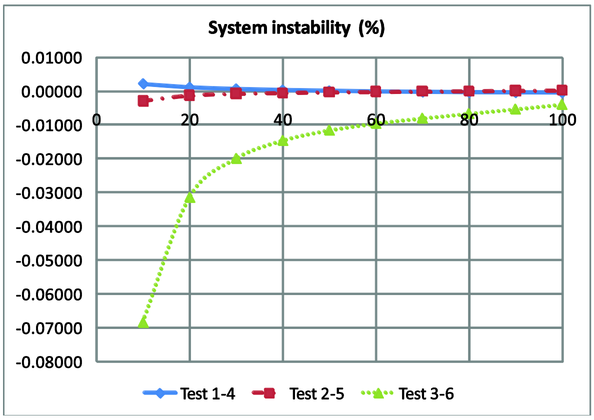

Fig.9. Comparison of relative different of reading

From experiences, it is easier to operate DWM than FCM, because the loading mechanism of DWM is self alignment by hanging the deadweight directly and freely on the top of the calibrated load cell. Contrarily, operating of FCM is difficult because of many factors as following.

1. Difficulty to maintain the applied forces during calibration because of leaking in hydraulic system
2. Difficulty to align two load cells (two spherical joints) on the machine
3. Difficulty to record the reading from two load cell at the same time

6. Conclusions

1. The applied forces from deadweight force standard machine were more stable and accurate than that from force comparator machine.
2. The results from DWM were better than FCM in many aspects such as repeatability, reproducibility and interpolation error.
3. The results from force comparator machine show that, the system had problem of instability. The sources of the problem could be from alignment, human error and loading mechanism of the machine.
4. The instability of the FCM at 10 kN was 0.07%, which was more than the reported uncertainty (0.0529%). The uncertainty from the machine should be re-evaluated to have more realistic results.
5. Further study on how to reduce the instability problem of force comparator machine is necessary to improve the quality of calibration with this type of machine.

7. References

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