

Evaluation of Measurement Uncertainty of Universal Calibration Machines

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Abstract

The universal calibrating machines are used extensively in industrial, governmental, and military laboratories for the calibration of various force transducers (load cells, dynamometers, proving rings, and other force measurement devices). There are many important factors that might affect the measurement process. These factors may be summarized as: the possibility of existing friction between moving and stationary parts, the rotational effect of the reference standard load cell, the repeatability of measurements, the effect of the number of runs, the eccentricity effect, hysteresis and drift. The overall uncertainty of a measurement consisting of individual uncertainties was evaluated. A mathematical model is proposed for the estimation of the expanded measurement uncertainty. A numerical example is given to show the application of the proposed method.

1. Introduction

The uncertainties of measurements consist of two types, random (type A) and systematic (type B) uncertainties. The random error is said to be shown when repeated measurements of the same quantity in a certain measurement process give rise to different values. The sign of random errors or errors of observation may be either plus or minus; there is an equal probability that the sign is plus as that it is minus [1]. Systematic errors are attributable to known factors and vary according to these factors. If only the limits of these factors are known with their effects, the systematic

uncertainty for the measurement can be split into different components each one represents the upper and lower limits of the effect of a particular factor. Once the sources of uncertainty (random and systematic with their different contributions) have been specified, the combined standard uncertainty of the output quantity (U_c) can be calculated from the following relation [2]:

$$U_c = \sqrt{\sum_{i=1}^n U_i^2} \quad (1)$$

where U_i is the individual uncertainty contributions of input parameters.

Most National Institutes of Metrology realize

forces using force standard machines of quite different designs. Force transducers which are calibrated with force standard machines are used to transfer the forces to industrial and scientific institutions.

In the present study, the expanded relative uncertainty for the results of calibration of a force transducer (load cell) on a universal calibration machine is evaluated through a numerical example. The different sources of uncertainty included in the results of calibration on the universal calibration machine will be evaluated.

2. Experimental

2.1. Description of the Universal Calibration Machine (UCM)

Figure 1 shows an outline drawing of a universal calibration machine. UCM consists of two main elements, loading frame incorporating loading jack and precision hydraulic pump and a force transfer standard. The machine frame comprises four principal assemblies: a) the stationary frame, b) the movable frame or yoke, c) the hydraulic jack and d) the hand pump assembly.

The performance of UCMs as a force calibration system was evaluated and proven to yield uncertainty in the order of 5×10^{-4} [3]. This figures makes such machines the second best to Force Standard Machines.

2.2. Force Transducers and Scheme of Calibration

Two force transducers are used in the planned set of experiments. The first one is

HBM, type U-1, 1000 N load cell. This one is used as reference standard under compressive

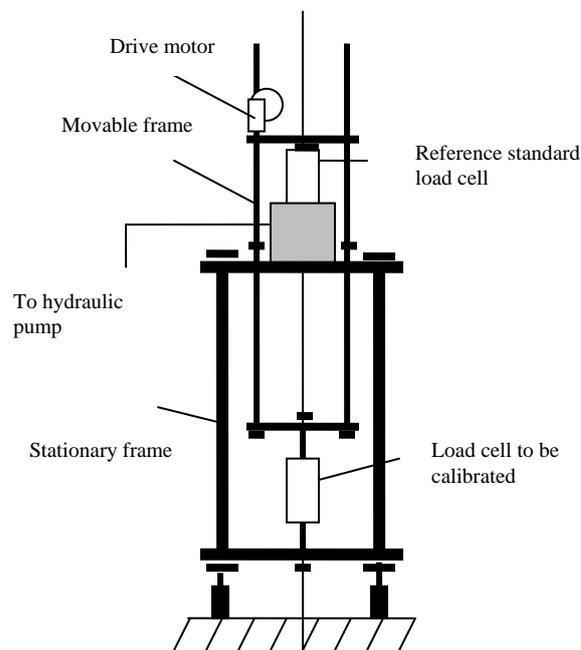


Figure 1. Schematic view of a universal calibration machine.

load and is mounted on the hydraulic jack. The second one is of the type Rice Lake Weighing Systems, 1000 N load cell. It is calibrated in tension against the first one as shown in Fig. 1. Each load cell is connected with digital read out device model P-3500, Measurements group Inc. of 2×10^{-4} mV/V resolution. The calibration setting is maintained at 20 ± 1 °C for two hours before calibration as well as during the calibration. Seven series (runs) of load application are carried out covering the full range of the reference standard and the force transducer to be calibrated in an ascending order. These seven series are completed successively without any changes to the set up. They are followed by three further runs; each one with the force transducer to be calibrated rotated

symmetrically on its axis 90°, 180° and 270° successively.

3. Uncertainty of Force Transducer Calibration Results

The following model of evaluation analysis of uncertainty for the presented experimental example follows the methods given in “the Guide to the Expression of Uncertainty in Measurement” [4] and “The Expression of Uncertainty and Confidence in Measurement-M 3003”[5].

3.1 Type A Uncertainty

3.1.1. Standard Relative Uncertainty due to the Repeatability Effect (U_{rep})

The effect of the number of runs or repetition on the uncertainty is investigated. The repeatability effect in the present work is studied by taking two, three, five and seven runs of loading into consideration. It can be seen from Fig. 2 that calibration with two runs gives a relatively high values of U_{rep} . Increasing the number of runs leads to decreasing the value of U_{rep} for any applied load value. This may be attributed to the fact that the random errors are random in its nature and have a tendency to compensate one another. It may also be concluded from Fig. 2 that calibration with five or seven runs gives small and more or less equal values of U_{rep} . Thus, it can be concluded that increasing the repetitions leads to decreasing the values of U_{rep} till certain limit, then no significant further improvement would be obtained. This conclusion can easily be observed from Fig. 3,

where the average value of the standard relative uncertainty (U_{rep}) is plotted against the number of runs.

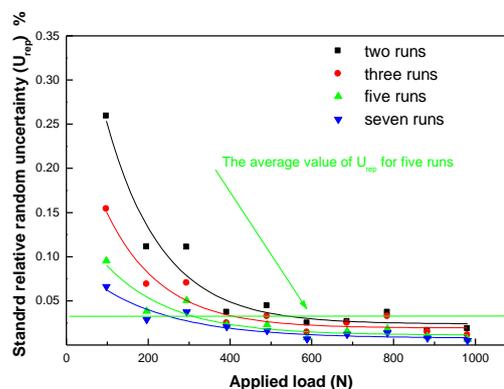


Figure 2. Relationship between the applied load and U_{rep} for 1000 N load cell.

This given example shows that five runs of loading on the universal calibration machine are quite sufficient. The values of U_{rep} in the present work are calculated from the relation [5]:

$$U_{rep} = \frac{s(R)}{1} \quad (2)$$

assuming normal distribution, where $s(R)$ is the standard deviation of the repeated values divided by the number of repeated values.

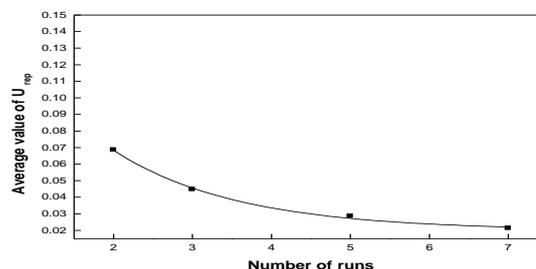


Figure 3. Relationship between the Number of runs and the average value of U_{rep} for 1000 N load cell.

Applying the above equation for the results

obtained from the experimental studied example (as shown in Fig. 2) yields an average value of the standard relative uncertainty due to the repeatability effect (for five runs) about $\pm 0.03\%$. However, repeatability for each applied load may be considered separately.

3.2. Type B Uncertainty

3.2.1. Standard Relative Uncertainty for Reference Standard Load Cell System (U_{cal})

The reference standard load cell system consists of a transfer standard and its read-out device. The expanded relative uncertainty of the calibration results (in the present study) included in the calibration certificate of the reference standard used is $\pm 0.06\%$. The probability distribution for U_{cal} is assumed to be normal. The divisor in this case is 2. The standard relative uncertainty U_{cal} is estimated from the following equation and it is found to be 0.03% :

$$U_{cal} = \frac{\pm a_{cal}}{2} \quad (3)$$

where a_{cal} is the expanded relative uncertainty of the reference standard load cell system.

3.2.2. Standard Relative Uncertainty due to the Drift Effect (U_{drift})

For the application of the reference standard load cell the influence of the drift has to be incorporated by a further relative uncertainty contribution as follows [6]:

$$U_{drift} = \frac{\pm a_{drift}}{\sqrt{3}} \quad (4)$$

where a_{drift} is the relative uncertainty due to the

drift effect. The value of U_{drift} in equation 4 is estimated by a rectangular distribution. The value of a_{drift} can be evaluated either by the manufacturer's specifications or by the long-term observations of the calibration results of the reference standard load cell [7]. Through observing the reference standard load cell used in the present evaluation, it was found that each one year period makes deviation not exceeding 500 ppm of the results from the previous year. The standard relative uncertainty U_{drift} is estimated to be 0.03% from equation 4.

3.2.3. Standard Relative Uncertainty due to Rotation (U_{rot})

To minimize the influence of the load eccentricity and/or the unsymmetric loading conditions for the calibrated load cell, the mean of the results for several rotational positions (of the calibrated load cell) uniformly spaced around its axis has to be estimated. To estimate the standard relative uncertainty due to the rotation effect, rectangular probability distribution is assumed and the value of U_{rot} can be estimated from the following relation:

$$U_{rot} = \frac{\pm a_{rot}}{\sqrt{3}} \quad (5)$$

where a_{rot} is the relative uncertainty due to the rotation effect. The maximum possible error due to this effect can be represented by determining the maximum deviation of the results for all rotational positions at each applied load. The average of these maximum errors would then represent the relative rotational uncertainty. Through the present study it is observed that a_{rot} lies within the

range of $\pm 0.05\%$ which leads to U_{rot} less than $\pm 0.03\%$.

3.2.4. Standard Relative Uncertainty due to Temperature Variation (U_{temp})

The universal calibration machines are usually placed in standard force metrology laboratories where the temperature is maintained within $20-25\text{ }^{\circ}\text{C} \pm 1\text{ }^{\circ}\text{C}$. The variation of the load cell resulting from this small range of temperature variation (assuming rectangular distribution) shall be considered as follows [7]:

$$U_{temp} = \frac{\pm k_{temp} \times \Delta t}{\sqrt{3}} \quad (6)$$

where k_{temp} is the temperature coefficient of sensitivity per $1\text{ }^{\circ}\text{C}$ of the calibrated load cell (specified in the manufacturer's manual) and Δt is the half of the expected temperature variations range during the calibration. Referring to the present numerical experimental evaluation (using equation 6) the value of U_{temp} for $\pm 1\text{ }^{\circ}\text{C}$ temperature variation is found to be less than 0.006% .

3.2.5. Standard Uncertainty due to Resolution of Load Detection System (U_{res})

The limit of the ability of the read out to respond to small changes in the applied load, referred to as load resolution, is treated as a systematic component of uncertainty. In a digital instrument it can be considered as ± 0.5 the least significant digit to which the instrument responds on the range in use. The resolution effect is usually predominant at

small loading values. However, the presence of electrical noise causing fluctuations in read-out readings will commonly determine the usable resolution. The value of the standard uncertainty due to resolution U_{res} can be estimated from the following equation [5]:

$$U_{res} = \frac{\pm a_{res}}{\sqrt{3}} \quad (7)$$

where a_{res} is the relative uncertainty due to resolution of read out of the load cell to be calibrated (assuming rectangular distribution). U_{res} is found to be $\pm 1\text{E-}4\text{ mV/V}$ based on ± 1 digit fluctuations. So, the uncertainty U_{res} will be different for each applied load.

3.2.6. Standard Relative Uncertainty due to the Effect of Load Hysteresis (U_{hys})

The effect of hysteresis can be seen clearly by comparing the difference of the response of the calibrated load cell at certain applied load with increasing force and with decreasing force. The values of the expected expanded relative uncertainty due to hysteresis a_{hys} associated with different types of calibration machines are stated in reference 6; maximum a_{hys} on universal calibration machines is stated to be $\pm 0.07\%$. This value refers to the lowest force of the force range applied. So, the standard relative uncertainty due to hysteresis U_{hys} is estimated (assuming rectangular distribution) from the following equation [4]:

$$U_{hys} = \frac{\pm a_{hys}}{\sqrt{3}} \quad (8)$$

The value of U_{hys} is found to be $\pm 0.04\%$.

3.2.7. Uncertainty due to Curve Fitting

Equation (U_{fit})

Using the calibration equation of the calibrated force transducer there will be some sort of uncertainty. This is due to that the actual response of the calibrated force transducer, under certain load, is slightly different than that expected from its fitted calibration equation. The relative interpolation error a_{fit} can be estimated, at each applied load, from the following equation [8]:

$$a_{fit} = \frac{1}{2} \frac{\bar{X} - X_a}{X_a} \times 100 \quad (9)$$

where \bar{X} is the average response of the calibrated force transducer and X_a is the computed response from the fitted equation. In this case the standard uncertainty due to the curve fitting approximation (U_{fit}) can be estimated from the following relation (assuming triangular distribution):

$$U_{fit} = a_{fit} / \sqrt{6} \quad (10)$$

In the given numerical example, the values of U_{fit} are found to be equal to 0.05, 0.02 and 0.002 % at applied loads 10, 30 and 50 % of the force transducer full capacity.

4. Calculation of Overall Uncertainty

The combined relative standard uncertainty for calibration of load cell, on a universal calibration machine can be determined from equation 1 which can be written in the form:

$$U_c = \sqrt{U_{rep}^2 + U_{cal}^2 + U_{drift}^2 + U_{rot}^2 + U_{temp}^2 + U_{res}^2 + U_{hys}^2 + U_{fit}^2} \quad (11)$$

The values of the degree of freedom of the combined standard uncertainty (v_{eff}) for the

three previously mentioned load ranges are estimated from Welch-Satterthwaite equation [5]:

$$v_{eff} = \frac{U_c^4}{\sum_{i=1}^n \frac{U_i^4}{v_i}} \quad (12)$$

where v_i is the degree of freedom for the individual standard uncertainty U_i . The expanded uncertainty values are calculated from the following equation [5]:

$$U_{EXP} = k_{95} \times U_c \quad (13)$$

where k_{95} is the coverage factor at 95% confidence level. The coverage factor is obtained from the t-distribution table and depends on v_{eff} . Applying the above equations, the relative expanded uncertainty is found to be about 0.28%, 0.18% and 0.14% at applied loads 10, 30 and 50 % of the force transducer full capacity.

5. Conclusion

In force laboratories it is recommended to follow certain procedure for evaluating and expressing the uncertainty budget for the calibration of force transducers on universal calibration machines. In the present study it is concluded that the main factors that affect the relative expanded uncertainty of the calibrated force transducer significantly are: the repeatability of the calibration results, the uncertainty of the reference standard force transducer, the drift of the reference force transducer, the rotation effect of the calibrated force transducer, the temperature variation during the calibration process, the resolution of read out device, the curve fitting interpolation

error of the calibrated force transducer and the reversibility or hysteresis effect. This study presents a guide to show how to calculate the expanded relative uncertainty using the recommended calculation procedure. The contribution of each affecting factor depends on the conditions of the calibration process.

6. References

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