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FORCE CALIBRATION OF INSTRUMENTED HARDNESS TESTERS

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Abstract – In this paper a methodology for calibration of force transducers used for hardness testers is described. The methodology associates to the standard procedure a method to evaluate and correct other effects such as promptness, creep and hysteresis. After a general description, a practical application is reported.

Keywords: Hardness, Force, Calibration.

1. INTRODUCTION

The problem of calibrating force transducers used for measurement in connection with hardness testers is well known. Nominal forces for hardness testers are usually different from round numbers. This happened in the past mainly for Brinell Scales, but now, being the unit "Kilogram Force" obsolete, is common for each hardness scale.

The problem was important in the past mainly for two reasons:

- force transducers were used for calibration of hardness testers, therefore a high accuracy was required (nowadays, the use of force transducers in hardness testers for generating the test force, therefore with much lower accuracy requirements, is also common);
- metrological characteristics of force transducers were not so good to allow interpolation.

The problem was so important that, to avoid the effects of linearity, creep and hysteresis (much important for Rockwell scales), special Deadweight Machines able to give exactly the loads required by hardness scales were developed [1].

Nowadays the problem is evolved, but not cancelled. We shall face different situations that we can summarise here.

On the one side we can have an advantage in solving this problem because accuracy of force transducer is much increased [2, 3, 4, 5, 6].

On the other side the technological evolution of hardness testers has enlarged the involved sectors:

- the use of force transducers is no more limited to the instruments used for calibration of hardness testers, operation reserved to high quality transducers, but has evolved to drive the force generation within the tester itself, task performed with normal transducers. In both cases creep and, for Rockwell scales, hysteresis effect are not negligible;
- new scales, like Martens Scale and most of the measurement of Instrumented hardness [7], require a continuous measurement of force variation during the indentation, therefore the dynamic characteristics of force transducers, both that used for the force generation of hardness testers and that used for periodical calibrations, are important.

That means that for traditional scales a creep correction shall be defined to control (by the internal force transducer) or measure (by the calibration force transducer) the required levels of force. Moreover, specifically for Rockwell and Martens scales, an hysteresis correction shall be defined to control or measure the minor load after the application of total load. Notice that a measurement cycle that requires to measure with the same transducer and in sequence first a force of about 100 N, thereafter a force of about 1500 N and eventually a force of about 100 N again shall be considered critical.

These problems remain for scales involving a continuous force measurement, adding on problems given by non linearity of the transducers too.

2. PROBLEM DESCRIPTION

As a first approach the attention has been focused on Rockwell Hardness. According to the requirements of international standards [8], the relative uncertainty of the force generated by a Rockwell Hardness secondary standard machine should be less or equal to 0,2% on preloads (i.e. $\leq$ 0,19614 N, for Rockwell C) and less or equal to 0,1% on total loads (i.e. $\leq$ 1,471 N for Rockwell C).

This could create some difficulty for Rockwell Hardness machines with an automated feedback-controlled force generation. In fact it is necessary to utilize a force traducer able to fulfil standard requirements both for the preloads and for the total loads.

For commercial force transducers to be calibrated in force calibration machines, the calibration and classification procedure applied in Europe is that given in the European Standard EN 10002-3 [5]. In order to determine the uncertainty of measurement of the calibration results for a particular class of device, the different contributions to the uncertainty must also be established. However, that standard does not state a procedure for the determination of the uncertainty and the overall uncertainty of the calibration result.

For doing that the EA guide EA-10/04 (ex EAL-G22), "Uncertainty of Calibration Results in Force Measurements" [3] can be used. This guidelines is based on the method of estimation of uncertainty described in document EA-4/02 [4] and in “Guide to the Expression of Uncertainty in Measurements” [6]. A further contribution to appreciate each single factor affecting the overall uncertainty is given in paper [2], where all the effects investigated in the standard procedure are analysed.

In the following sections a procedure for fine calibration of an elastic force transducer used as a transfer standard for the verification of a automatic-force-controlled Rockwell Hardness C machine [9, 10] is described. The same procedure can be equivalently used for the calibration of force transducers used for automatic-force-controlled hardness machines performing measurements on different hardness scales (as, for example, Rockwell, Vickers, Martens or Instrumented Indentation Test).

3. EXPERIMENTAL DEVICE

The characterized force transducer is a purpose-built uniaxial elastic transducer (see Fig. 1) with a maximum load of 2,5 kN. The acquisition and analysis of output signal have been performed using an electronic control unit HBM DMP40, interfaced with a personal computer. A purpose-built software has permitted to run an on-line analysis of the output signal.

Fig. 1. Picture of the force transducer used as a transfer standard for the verification of the automatic-force-controlled Rockwell Hardness machine.

According to the requirements of international standards for Rockwell Hardness measurements [8], the uncertainty of measurement associated with the force measured by this force transducer should be lower than 0,19614 N on preloads and lower than 1,471 N on total loads.

4. CALIBRATION PROCEDURE

The calibration has been conducted using a deadweight force calibration machine and following standard prescriptions [5]. It must be highlighted that, due to the particular use of the transducer (note that, during Rockwell Hardness measurement cycles, the minor load level is reached by increasing force values, as preload, and decreasing force values as final load), it has been necessary a particular kind of calibration, considering additional effects like hysteresis or similar, which should happen as a consequence of the inversion of applied load sequence. For that reason the calibration procedure has been articulated in the following steps [11, 12]:

- identification of mobility threshold;
- identification of mobility error;
- response promptness and creep analysis;
- construction of the calibration curve and hysteresis analysis.

4.1. Identification of the mobility threshold

This operation consist of individuating the minimal load variation which produces a transducer response. The mobility threshold represents a kind of inertia to small solicitations, and it is substantially due to transducer internal frictions. Referring to the analysed transducer, the mobility threshold has been tested at different levels of the full measurement range, the obtained results have produced values lower than 1,0 mN.

4.2. Identification of the mobility error

The mobility error can be identified reaching the same load value going through increasing and decreasing values of force varying in a small range, and verifying the output signal variation. The mobility error is usually attributed to transducer internal clearances or frictions.

Such as for the mobility threshold, the mobility error has been tested at different levels of the full measurement range using a load input of ± 0,02 N, the obtained values were negligible in comparison to the reading uncertainty of the electronic control unit (± $0{,}5\times10^{-6}$ mV/V).

4.3. Response promptness and creep analysis

Another essential operation for determining the behaviour of a force transducer concerns the response promptness and the creep analysis. To do this it is necessary to induce a step shaped input solicitation (from the practical point of view, a load is suddenly applied at the higher speed) and to analyse the output signal.

If, like in the present case, the transducer calibration force is applied using a deadweight force machine, that is loading a mass having a well-known value (opportunely compensated for the local gravity acceleration), the obtained system (transducer + mass) becomes, as a first approximation, a second-order system, which is described by a second-order differential equation as follows [12, 13].

Applying a terminated-ramp input to this kind of systems, under the condition that the damping coefficient $r \ll 1$, which holds in the analysed case, the output signal can be easily calculated using Duhamel integral [12, 13]. Therefore, we obtain the following expression for the dynamical behaviour of the elastic element:

$$x(t) = C \cdot \left[t - \frac{2 \cdot a}{w^2} + \frac{1}{w} \cdot e^{-a \cdot t} \cdot \left(\cos w_1 t + \frac{a}{w_1} \cdot sen w_1 t \right) \right] \quad (1)$$

if $0 \le t \le T$, and:

$$x(t) = C \cdot \left\{ T + \frac{1}{w} \cdot e^{-a \cdot t} \cdot \left[\left(\cos w_1 t + \frac{a}{w_1} \cdot sen w_1 t \right) + \right. \right.$$
$$\left. \left. - e^{a \cdot T} \cdot \left(\cos\left[w_1 (t-T) \right] + \frac{a}{w_1} \cdot sen\left[w_1 (t-T) \right] \right) \right] \right\} \quad (2)$$

if $T \le t \le \infty$.

The notations appearing in (1) and (2) are:

$C = \frac{M \cdot g}{k \cdot T}$ is a constant of the problem;

M is the inertial constant (total applied mass);

g is the local gravity acceleration;

k is the elastic constant;

T is the ramp terminal instant;

r is the instrument damping coefficient;

$w = \sqrt{\frac{k}{M}}$ is the system characteristic pulse;

$r_C = \sqrt{M \cdot k}$ is the instrument critic damping coefficient;

$a = \frac{r}{2 \cdot M}$ is the reciprocal of the system time constant;

$w_1 = \sqrt{1 - \frac{r}{r_C}}$ is the system damped pulse.

Referring to (1) we see that there is a steady-state error of size $\frac{M \cdot g}{k \cdot T} \cdot \frac{2 \cdot a}{w^2}$ [12]. Furthermore the transient error can be no larger than $\frac{M \cdot g}{k \cdot T \cdot w}$ [12].

On the other side, referring to (2), the maximum oscillation around the equilibrium position can be no larger than $\frac{M \cdot g}{k \cdot T \cdot w}$.

Therefore, if k is sufficiently large relative to M, and $r << 1$, the measurement error e_m can be made very small even if the damping is practically nonexistent [12].

Using a terminated-ramp input load and analysing output signal on the grounds of equations (1) and (2), it has been possible to determine the characteristic parameters of the force transducer under analysis. The obtained results confirmed an excellent behaviour of the transducer. In fact the effects related to promptness and creep produce a negligible influence on the output signal.

Therefore, as a consequence of these effects, a relative uncertainty lower than $1 \cdot 10^{-4}$ has been estimated for every load applied for a time interval comprised between 5 s and 10 s. This values can be acceptable for utilising the transducer as a transfer standard for the verification of the system for force application of a secondary Rockwell Hardness standard machine [8].

Fig. 2 shows output behaviour (expressed in mV/V) of the analysed transducer after the application of a smoothed terminated-ramp input load with maximum amplitude of 2,452 kN (note that the small oscillations and the initial and final smoothing of the curve that appear in Fig. 2 are due to the system for the application of loads).

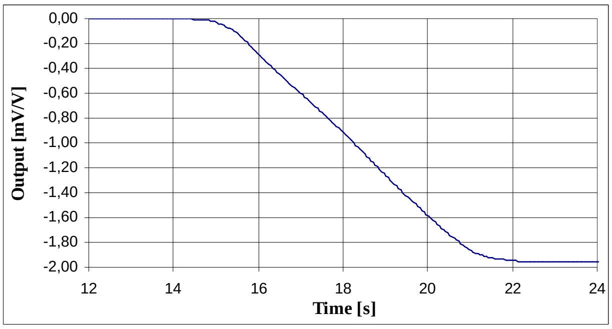


Fig. 2. Output behaviour of the analysed transducer after the application of a smoothed terminated-ramp input load with maximum amplitude of 2,452 kN (the small oscillations and the initial and final smoothing of the curve are due to the system for the application of loads).

Comparing the output behaviour of the analyzed transducer with the input signal, no sensible difference between the two signals can be evidenced.

4.4. Construction of the calibration curve

The last operation consists of the construction of the calibration curve, that is the curve which permits to establish the relation between input signal and output signal.

This operation can be done by applying a series of loads at different levels of the scale. It is usual to use 10 levels between 0 and the full measurement range of the transducer, increasingly applied, and other 5÷6 values in the same range decreasingly applied. This is repeated in 4 different positions of the transducer, turning it around the load application axis, this is done for mediating the effects due to a possible inclination of its loading axis in comparison to the direction of load application.

For each force level, the average value of the four measurement, the calibration factor (obtained from the ratio between the input signal and the average value early mentioned), and the repeatability (obtained from the ratio between the range of the four values early mentioned and their average value) are calculated. In general, we obtained a repeatability lower (for some loads, very lower) than 0,02%. For the decreasingly applied load of 98,07 N the obtained repeatability is lower than 0,08%.

By analysing obtained results, it is possible to individuate and correct possible effects of non-linearity, and, using a linear regression on a second-order polynomial, find the theoretical calibration curve.

For the analysed transducer we obtained the following expression (for the output signal due to increasingly applied loads):

$$U = 79777 \cdot 10^{-8} \cdot F + 855 \cdot 10^{-12} \cdot F^2 \quad (3)$$

where:

U is the output signal (measured in mV/V);

F is the input signal (measured in N).

And for the output signal due to decreasingly applied loads, we obtained:

$$U = 6 \cdot 10^{-5} + 79846 \cdot 10^{-8} \cdot F + 562 \cdot 10^{-12} \cdot F^2 \quad (4)$$

The regression standard uncertainty on the output signal U and the "interpolation deviation" (i.e. the difference between the mean of the measured values and the theoretical ones) have been also analysed.

No "lack of fit" is observable, that means that the obtained quadratic models fit very well the experimental data.

It must be noted that the regression on decreasingly applied loads has been calculated imposing that the two curves respectively described in equations (3) and (4) pass over the same point when the maximum load (2,452 kN) is applied.

Furthermore it must be highlighted that the overall calibration uncertainty is obtained by composing the transducer uncertainty (obtained with the contribution of all the calibration phases) with the calibration machine uncertainty. In the practical case here analysed, the expanded relative uncertainty of the utilized calibration machine was $1 \cdot 10^{-4}$.

Sometimes from the practical point of view it is important to know the expression of the real applied load in function of output signal (i.e. $F = F(U)$). This can be easily obtained by inverting F and U, calculating the analogous formula of (3) and (4), and applying the proper corrections.

4.5. Hysteresis correction

A further analysis on the obtained values permits to correct hysteresis effect. This correction is based on the principle for which the distance between two homologous point of two loading-unloading cycles is proportional to the maximum load applied in the relevant cycle.

Therefore for calculating, for example, the hysteresis correction for a cycle in which the prescribed maximum load is F_1, utilizing a force transducer whose hysteresis cycle is known for a maximum applied load F_0, it is necessary to apply the following expression:

$$\frac{\Delta U_{F_0}(F)}{F_0} = \frac{\Delta U_{F_1}(F)}{F_1} \qquad (5)$$

where:

$\Delta U_{F_0}(F) = U_{F_0 loading} - U_{F_0 unloading}$ is the hysteresis correction for each point of the unloading phase for a loading-unloading cycle with a maximum force F_0;

$\Delta U_{F_1}(F) = U_{F_1 loading} - U_{F_1 unloading}$ is the hysteresis correction for each point of the unloading phase for a loading-unloading cycle with a maximum force F_1.

From (5), once known $\Delta U_{F_0}(F)$ values, it is possible to obtain the corresponding ones $\Delta U_{F_1}(F)$.

From the obtained values in the examined case, this correction could be omitted in comparison to the tolerances required by international standards for hardness measurement [8].

In fact, if we suppose to perform a loading and unloading cycle with maximum value 2,452 kN, the hysteresis correction $\Delta U_{2.452}(F)$ is automatically applied by calculating the two different regression models respectively for the calibration curve of increasingly and decreasingly applied loads. Whereas, if we perform a Rockwell Hardness C cycle, the maximum value is 1,471 kN, and this requires to apply a further correction $\Delta U(F)$ to the values obtained in the unloading phase of the calibration cycle (i.e. with maximum value 2,452 kN). $\Delta U(F)$ can be obtained with the following expression:

$$\Delta U(F) = \Delta U_{2.452}(F) - \Delta U_{1.471}(F) \qquad (6)$$

Referring to the analysed transducer, the absolute values of $\Delta U(F)$ are always lower than 0,04%, therefore this correction can be considered negligible in comparison to the tolerances required by international standards for hardness measurement, and it can be incorporated in the overall transducer uncertainty.

4.6. Analysis of temperature effects

For some transducer, it could be necessary to verify that the transducer does not suffer the effect of thermal variations. To do this, it is required to effectuate some tests applying the same load at different temperature values. For the examined transducer, in a thermal range between 293 K and 303 K, the obtained result have not highlighted any deviation of the output signal out of the estimated uncertainty band.

5. CALIBRATION OF A ON-BOARD TRANSDUCER

The calibration of the on-board transducer of an hardness testing machine can be directly done through the comparison with a force transducer calibrated following the already described procedure.

In the present paper we report the results obtained with an automatic hardness machine whose structural scheme is reported in Fig. 3 [14].

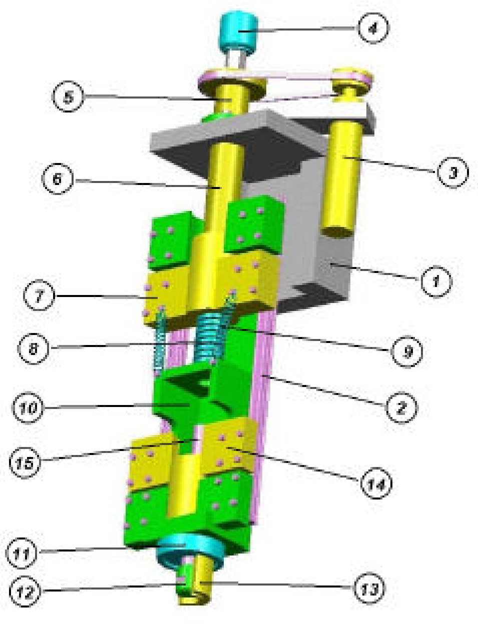
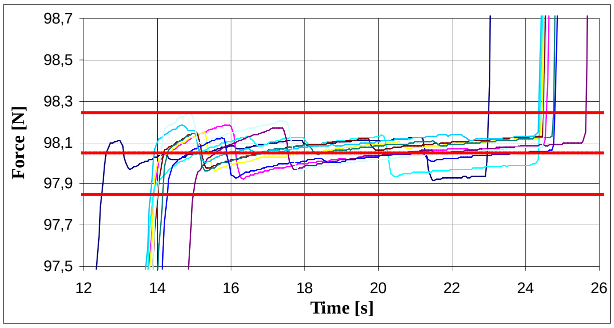


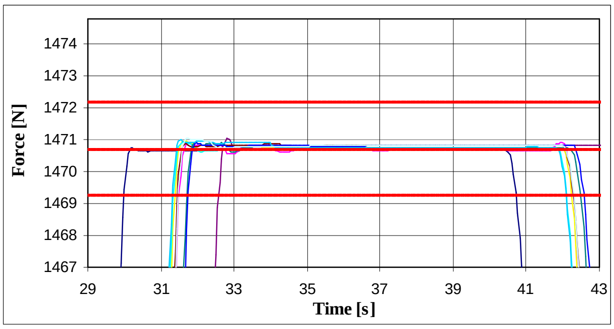
Fig. 3. Scheme of the automatic hardness machine whose force transducer has been tested.

Referring to Fig. 3 the single components are:

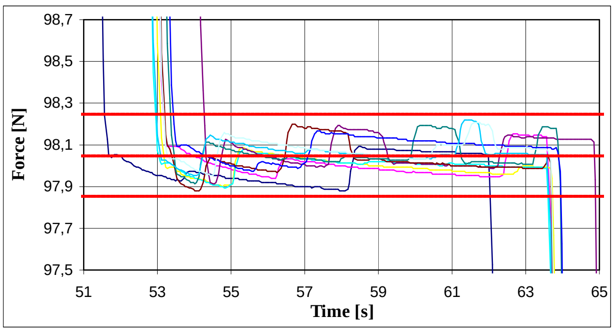
1) bearing structure,
2) ball bearing guide,
3) servomotor,
4) encoder,
5) epicycloidal reducer,
6) screw,
7) mobile cross-beam,
8) uncoupling spring,
9) holding springs,
10) rigid structure for force loading,
11) force transducer,
12) indenter,
13) section of the reference pawl,
14) laser support,
15) laser.



Initial preload force: 98,07 N.



Total force: 1,471 kN.



Final force: 98,07 N.

Fig. 4. Force behaviour during the three phases of a Rockwell C hardness test cycle. The horizontal lines represent the tolerance limits imposed by international standards, the curves represent 10 cycles conducted at 23°C on a 44 HRC hardness block.

The results are related to a Rockwell C test. This calibration has been performed by positioning the reference transducer under the hardness specimen. To avoid eccentricity effects, the transducer has been positioned using apposite centrings so as to have the symmetry axes of the indenter coinciding with the transducer one.

In a set up phase, 10 cycles of force applications have been performed using a 44 HRC hardness block. The results are reported in Fig. 4.

It must be said that in this analysis we imposed a time of load permanence of 10 s, higher than what is prescribed by standards, this has been done with the aim of better controlling the device stability.

Analyzing the obtained results, it is possible to conclude that no disturbing effect is identifiable in any of the four configurations.

The curves reported in Fig. 4 evidence a good behaviour of the hardness testing machine in every phase of force application. The applied force respect the standard tolerances in every level. Some steps are present, due to the intervention of the controller, this behaviour can be, however, further refined by acting on the apposite software.

6. CONCLUSIONS

In the present paper a fine calibration methodology for force transducer of hardness measurement machines is described. The particularity of the methodology is that it associates to the standard procedure a method to evaluate and correct other effects such as promptness, creep and hysteresis. A practical application of the method to a calibration transducer has been conducted. The obtained results have evidenced that the analysed transducer can be properly used as a force transfer standard for the calibration of force transducer of automated hardness measuring machines.

The same procedure can be easily extended to the direct calibration of elastic force transducers used for automatic-force-controlled hardness machines performing measurements on different hardness scales (as, for example, Rockwell A, B and C, Instrumented Indentation Test, or Vickers).

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