THE UNCERTAINTY OF MEASUREMENT IN CALIBRATION USING A COMPARISON FORCE STANDARD MACHINE

Adrian Gherasimov[1], Eugen Ghita[2]

[1]Romanian Bureau of Legal Metrology, Force Laboratory Timisoara, Romania
[2]"POLITEHICA" University of Timisoara, Romania

ABSTRACT

The paper presents a practical example for the evaluation of the uncertainty in calibration using a comparison force standard machine with a maximum load of 1000 kN, tension and compression mode. The uncertainty of measurement associated with the input estimates is evaluated. It is also presented a way to minimize the uncertainty of the applied force with the view to attaining the necessary value for the calibration of class 1 force transducers, in accordance with ISO 376:1999. For this purpose an evaluation of the loading regime of the force machine is presented. There was identified the main input components influencing the uncertainty in calibrations, such as the force stability during measurements and the metrological characteristics of the reference transducers. Further are presented the practical results of the investigation of the force comparison machine after the optimization, including the technical and economical benefits.

1. INTRODUCTION

In order to provide for the traceability of the force measurements to the International System of Units (SI), Romania possesses, as national force standards, three deadweight calibration machines with the maximum range of 10 kN, 50 kN and 100 kN. The Romanian Bureau of Legal Metrology, through National Institute of Metrology, Force Laboratory Timisoara, keeps the national force standards in Romania [1].

The Romanian legislation of metrology [2] stipulates that the national standards are used only for the reproduction of the SI measurement units as well for their dissemination to the immediate inferior standards. This stipulation represents an important limitation regarding the utilization of the national standards in the whole traceability chain of force measurements. These circumstances conduce to the necessity to enlarge the force standard machine basis. This is because in Romania the owner-laboratory of the national standards is, in the same time, a metrological laboratory where the working standards are calibrated. We consider that this situation is typical also for other national laboratories.

In order to obtain the optimal arrangement for the development of a reference standard system, as a basis for the force measuring traceability, there is imposed the use of some alternatives, which have to be suitable and correct from the viewpoint of their technical and metrological parameters, as well from the viewpoint of a reasonable cost.

The challenge is to keep the uncertainty of the applied force within an appropriate range , necessary for calibration of the force measurement devices, with minimum costs. For the optimization of the basis of standards of the Force Laboratory Timisoara, meeting the requests of the applicants is considered a very important factor.

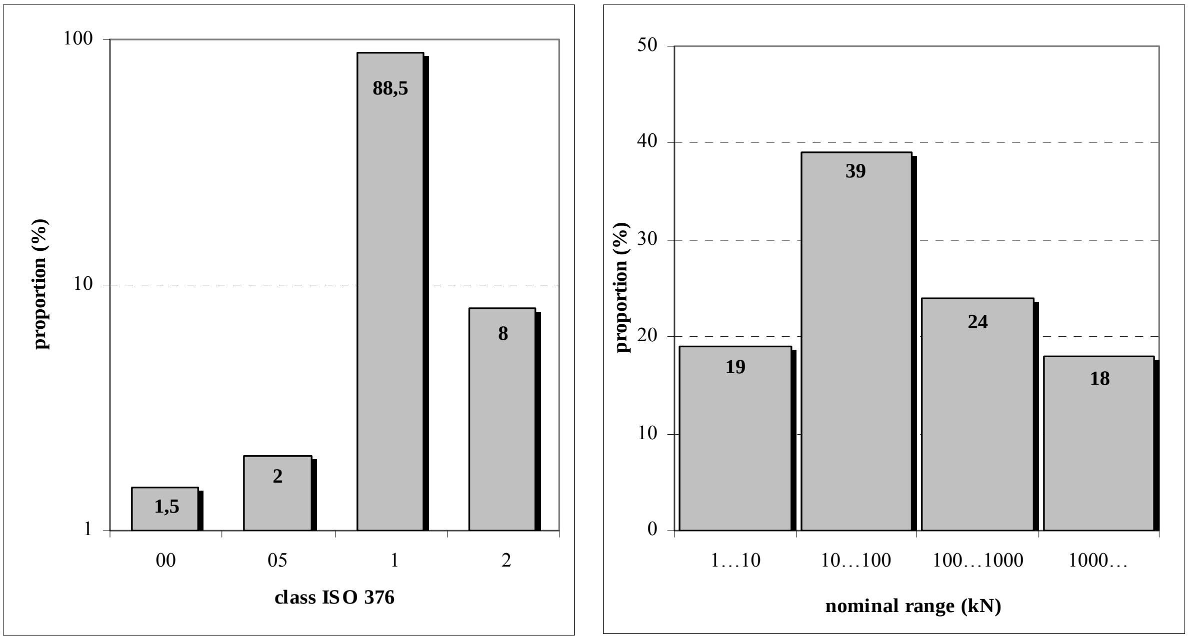
From this viewpoint, for the Force Laboratory Timisoara, using comparison force machines represents an acceptable solution. In order to perform the technical and metrological parameters in accordance with ISO 376:1999 [3] the measuring system of the comparison force machines is based on the characteristics of the component elements (e. g. reference force transducers, force reproduction mechanical system).

The most important metrological parameters of the force transducers, which qualify them to be used as reference standards for the comparison force machines, are as follows: repeatability, reproducibility and stability [4]. There are available on the market some force transducers, which ensure the metrological requirements to be used as reference standards.

2. GENERAL VIEW

The basis of standards, which ensure the traceability force measurements in Romania, is correlated with the requests of the customers.

There is presented in figure 1a) the proportion of the class of accuracy, in accordance with ISO 376:1999, and, in figure 1b), the proportion of the nominal range of the force transducers calibrated in the Force Laboratory Timisoara, function of the applications of the customers. A statistics for three years is presented in figure 1 :



a) b)

Figure 1: Class and nominal ranges proportion from total calibration requests

After the analysis of the data, the class 1 and 2 (ISO 376) transducers in the nominal range up to 1000 kN represent a great share. This is the reason why, the Force Laboratory Timisoara promoted reference force standards in accordance with the customers requests.

The uncertainty of the applied force requested by in order to ascertain the necessary class 1 (ISO 376) transducers, or less accurate, is easy to obtain by using a deadweight force calibration machine (the uncertainty of the applied force into the range of $5 \times 10^{-5}...1 \times 10^{-4}$) and even by using a lever or hydraulic amplification machine ensuring an uncertainty of the applied force into the range of $1 \times 10^{-4}... 5 \times 10^{-4}$. However these machines are expensive and sophisticated to be achieved, especially into the high forces ranges (over 100 kN).

Taking into account the already extant facilities and the economic limitations, the Force Laboratory Timisoara succeeded the following directions:

- keeping and developing the national force standards, the deadweight calibration machines into nominal ranges of 10 kN, 50 kN and 100 kN
- developing reference standards for the calibration of dynamometers into the nominal ranges up to 1000 kN (compression and traction) and 3000 kN (compression)
- assuming by the developed reference standards of some tasks of the national standards

The tasks to be solved were to promote the extant reference force standards to the necessary metrological performances for calibration of the class 1 (ISO 376) force transducers.

For this purpose, the force calibration machines have to be able to ascertain a maximum relative uncertainty of 5 x 10^{-4}. The difference between the uncertainty of the applied force and the uncertainty of calibration has been considered.
The main difference is represented by the following reason: the uncertainty of calibration includes the behavior of the calibration standard during calibration, but the uncertainty of the applied force excludes these important component of the uncertainty. This is the reason why the uncertainty of the applied force is considered very similar with "*bmc*" – the best measurement capability [5].
In order to achieve these purposes, the efforts have been concentrated to the comparison force standard machine of 1000 kN (the most used in the force laboratory). This machine is able to reproduce forces, between the limits of 10 kN and 1000 kN, in tensile and compression mode, by using a wide range of reference force transducers: 50 kN; 100 kN; 200 kN; 500 kN and 1000 kN, with high metrological performances.

3. EVALUATION OF THE UNCERTAINTY

Generally, the measurand F_{FCM} (the force reproduced by the standard machine FCM) is determined by the input parameters $X_1, X_2...X_n$, according to the functional relation:

$$F_{FCM} = f(X_1, X_2, \dots X_n) \qquad (1)$$

When the force is generated by mechanical devices, and the measurement of the force is performed by reference force transducers (comparison force standard machine), the input parameters are as follows:

- result of the reference force transducer calibration ($F_{Ref\,Tra}$)
- relative long-term drift of the reference force standard ($\Delta_{DriftRef}$)
- relative change in the calibration result due to the temperature change (c_θ)
- relative deviation because of the variation of the applied force during a measurement by comparison process (Δ_{Stab})

The mathematical model followed the relation:

$$F_{FCM} = F_{Re\,fTra} \cdot (1 - \Delta_{Drift\,Re\,f}) \cdot (1 - c_\theta) \cdot (1 - \Delta_{Stab}) \qquad (2)$$

The force value reproduced by the standard machine has to be rectified with the results of the comparison by a deadweight calibration machine FSM. These comparisons conduce to the evaluation of some factors not yet completely defined (e. g. non-linearity, displacements pattern during calibration). The comparison is performed with transfer force standards. The rectification is carried out by the factor (1- Δ_{Tras}), where Δ_{Tras} may be calculated in accordance with the accepted procedure [6].
The mathematical model of the reproduced force becomes:

$$F_{FCM} = F_{Re\,fTra} \cdot (1 - \Delta_{Drift\,Re\,f}) \cdot (1 - c_\theta) \cdot (1 - \Delta_{Stab}) \cdot (1 - \Delta_{Tras}) \qquad (3)$$

The evaluation of the standard measurement relative uncertainty of the reproduced force F_{FCM} begins with the mathematical model, relation (3), assuming that the input values are not correlated. So, the combined relative variance is obtained from the random error propagation law:

$$w(F_{FCM}) = \sqrt{w^2(F_{Re\,fTra}) + w^2(\Delta_{Drift\,Re\,f}) + w^2(c_\theta) + w^2(\Delta_{Stab}) + w^2(\Delta_{Tras})} \qquad (4)$$

where:

$w^2(F_{RefTra})$: the relative variance of the calibration result of the reference force transducer

$w^2(\Delta_{DriftRef})$: the relative variance associated with the drft of the reference force transducer

$w^2(c_\theta)$: the relative variance associated with the change in calibration result due to the temperature variation

$w^2(\Delta_{Stab})$ the relative variance associated with the variation of the force during the calibration

$w^2(\Delta_{Tras})$ the relative variance associated with the relative deviation determined for the generated force, due to traceing it back to the primary force standard machine

The probability of distribution of the input parameters is presented in table 1:

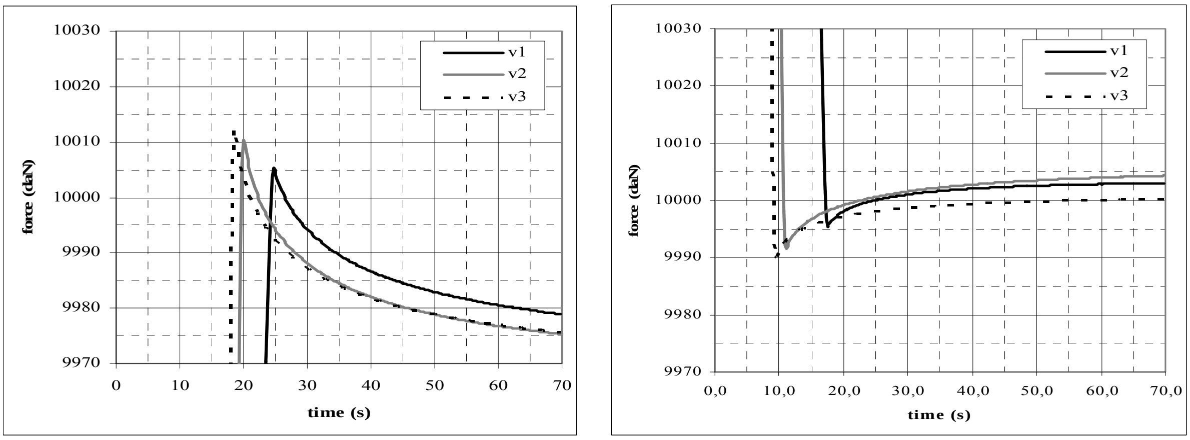
Table 1: The probability of distribution

Input parameters	Probability distribution	Estimation of variance
$F_{Ref\ Tra}$	normal	u^2
$\Delta_{DriftRef}$	rectangular	$a^2/3$
c_θ	rectangular	$a^2/3$
Δ_{Stab}	triangular	$a^2/6$
Δ_{Tras}	normal	u^2

On the basis of the estimated relative uncertainty, in accordance with the relation (4), the uncertainty of the applied force stipulated by ISO 376, is calculated. In order to decrease the above-mentioned uncertainty for the comparison force machine of 1000 kN, the following opportunities were identified:

- the use of reference standards with high metrological performances (repeatability, reproducibility and stability)
- the accurate knowledge of the metrological characteristics of the reference transducers. The reference standards are periodically calibrated (usually every two years) in accordance with the deadweight calibration machines of PTB-Germany. The components of the hysteresis are evaluated in order to decrease their influence.
- keeping adequate environmental conditions (especially the temperature)
- ascertaining of an adequate stability of the applied force by the control of the loading.

In order to minimize the influence on the uncertainty of the variation of the applied force, the identification of the system represented by the 1000 kN comparison force calibration machine was performed. There is presented in figures 2a and 2b the reply of the system in a free mode, to an input step of 100 kN for compression and respectively tensile force. A variation of the applied force of approximately 0,1% and a “return of the loop” of the pattern are observed. These will modify the metrological performances of the standard force machine.



a) b)

Figure 2: The reply of the FCM to an input of 100 kN in free mode

It comes out that the variation of the applied force depends on the rate of proximity to the ascertain value (kN/s), as well to the deflection of the transducer to be calibrated. The first dependence is direct proportionally, but the second is reversing proportionally.
Taking into account these behaviors and using a suitable automated system, the variation of the applied force decreased to approximately 0,01% and the “return of the loop” of the loading pattern became negligible, (figure 3).

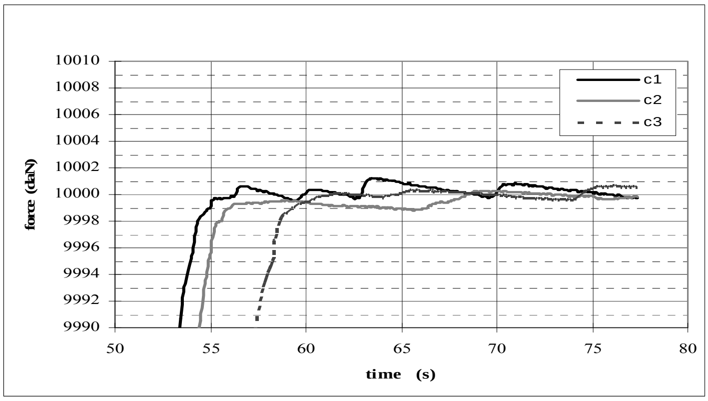


Figure 3: The reply of the FCM to an input of 100 kN in the controlled mode

The uncertainty of the standard comparison calibration machine of 1000 kN has been evaluated in accordance with EA 4/02 [7].
Transfer standard, which were previously calibrated by deadweight force calibration machines of 100 kN and 1000 kN in PTB, have been used. The results of the evaluation of the uncertainty of the applied force of the loading step of 100 kN, are presented in table 2. Some of the input parameters are estimated as a zero value, but have been considered for the uncertainty calculation:

- relative drift of the transfer transducers ($\Delta_{DriftTra}$),
- relative deviation of the force realization by standard machine FSM ($\Delta_{Realization}$),
- relative hysteresis of FCM influenced by the hysteresis of FSM (Δ_{HysFCM}),
- relative drift of the reference transducer ($\Delta_{DriftRef}$),
- relative deviation of the calibration result due to the temperature variation (c_θ),
- relative variation of the applied force during the measurement by comparison (Δ_{Stab}),
- relative deviation of the mean force values determinated between FCM and FSM (Δ_{RelDev})

Table 2. Uncertainty of the applied force for the comparison machine of 1000 kN for the 100 kN force step

Quantity	Estimation	Relative half-width value *a*	Distribution of probability	Relative standard uncertainty	Sensitivity coefficient	Relative uncertainty contribution
F_{RefTra}	100 kN		normal	5 x 10^{-5}	1	5 x 10^{-5}
$\Delta_{DriftRef}$	0 kN	2,0 x 10^{-5}	rectangular	1,2 x 10^{-5}	1	1,2 x 10^{-5}
c_θ	0 kN	5,0 x 10^{-5}	rectangular	2,9 x 10^{-5}	1	2,9 x 10^{-5}
Δ_{Stab}	0 kN	1,0 x 10^{-4}	triangular	4,1 x 10^{-5}	1	4,1 x 10^{-5}
$\Delta_{Realization}$	0 kN		normal	1,0 x 10^{-5}	1	1,0 x 10^{-5}
$\overline{F}_{FSM}$	100 kN		normal	2,5 x 10^{-5}	1	2,5 x 10^{-5}
$\overline{F}_{FCM}$	100 kN		normal	4,5 x 10^{-5}	1	4,5 x 10^{-5}
Δ_{HysFCM}	0 kN	1,2 x 10^{-5}	rectangular	1,0 x 10^{-5}	1	1,0 x 10^{-5}
$\Delta_{DriftTra}$	0 kN	2,0 x 10^{-5}	rectangular	1,2 x 10^{-5}	1	1,2 x 10^{-5}
Δ_{RelDev}	0 kN	1,8 x 10^{-4}	triangular	7,3 x 10^{-5}	1	7,3 x 10^{-5}
F_{FCM}	100 kN		normal			1,2 x 10^{-4}
Expanded relative uncertainty $W = kw\ (F_{FCM})$ for k = 2						2,4 x 10^{-4}
Specification of the uncertainty of the applied force						5 x 10^{-4}

4. CONCLUSIONS

The comparison force calibration machine with the nominal range of 1000 kN, tensile and compression mode, is used in the Force Laboratory Timisoara as a reference standard to calibrate sevaral force measurement devices. The requests of the applicants impose to achieve a relative uncertainty of the applied force of maximum 5×10^{-4}, which is necessarry to calibrate the class 1 force transducers in accordance with ISO 376:1999. The main factors of influence about the uncertainty of the applied force which may be optimized are: the stability of the applied force and the associated uncertainty of the reference transducers. Through an appropriate control system of the loading force and using a wide range of reference force transducers having high metrological performances, an uncertainty of 5×10^{-4} has been attained. The main advantages regarding the use for calibration of a comparison force standard machine are: a low cost, a relative convenient maintenance and calibration, the sparing of the national force standards for usual calibration purposes.

REFERENCES

[1] A.Gherasimov,E.Ghita,"The state of the art in the Romanian traceability system of force measurements", Proceedings of the 8th International Conference on Flexible Technologies, Novi Sad/Serbia and Montenegro, 2003, pp. 63-64.

[2] Romanian Law 178/2003, Romanian Governmental Order 20/1992, Romanian Low 11/1994.

[3] ISO 376:1999. Metallic materials. Calibration of force-proving instruments used for the verification of the uniaxial testing machines.

[4] BIPM, CEI, IFCC, ISO, IUPAC, IUPAP, OIML,"International vocabulary of basic and general terms in metrology (VIM)", the second edition, 1993.

[5] EA-10/04 (EAL G22):1996. Uncertainty of Calibration Results in Force Measurements.

[6] A.Savla,"Uncertainty scope of the force calibration machines", Proceedings of the XVI IMECO Congress, Vienna/Austria, 2000, pp. 253-258.

[7] EA-4/02 (EAL-R2):1997. Expression of Uncertainty of Measurement in Calibration.

Addresses of the Authors:

Gherasimov Adrian, Romanian Bureau of Legal Metrology, Force Laboratory Timisoara, 64 Crizantemelor Str., Timisoara, Romania. E-mail: agherasimov@yahoo.com drmltm@yahoo.co.uk

Conf.dr.eng. Ghita Eugen, "POLITEHNICA" University of Timisoara, Mechanical Engineering Faculty, Department Strength of Materials, Bd. M.Viteazul nr.1, Timisoara, Romania. E-mail: ghita@mec.utt.ro eghita63@yahoo.com