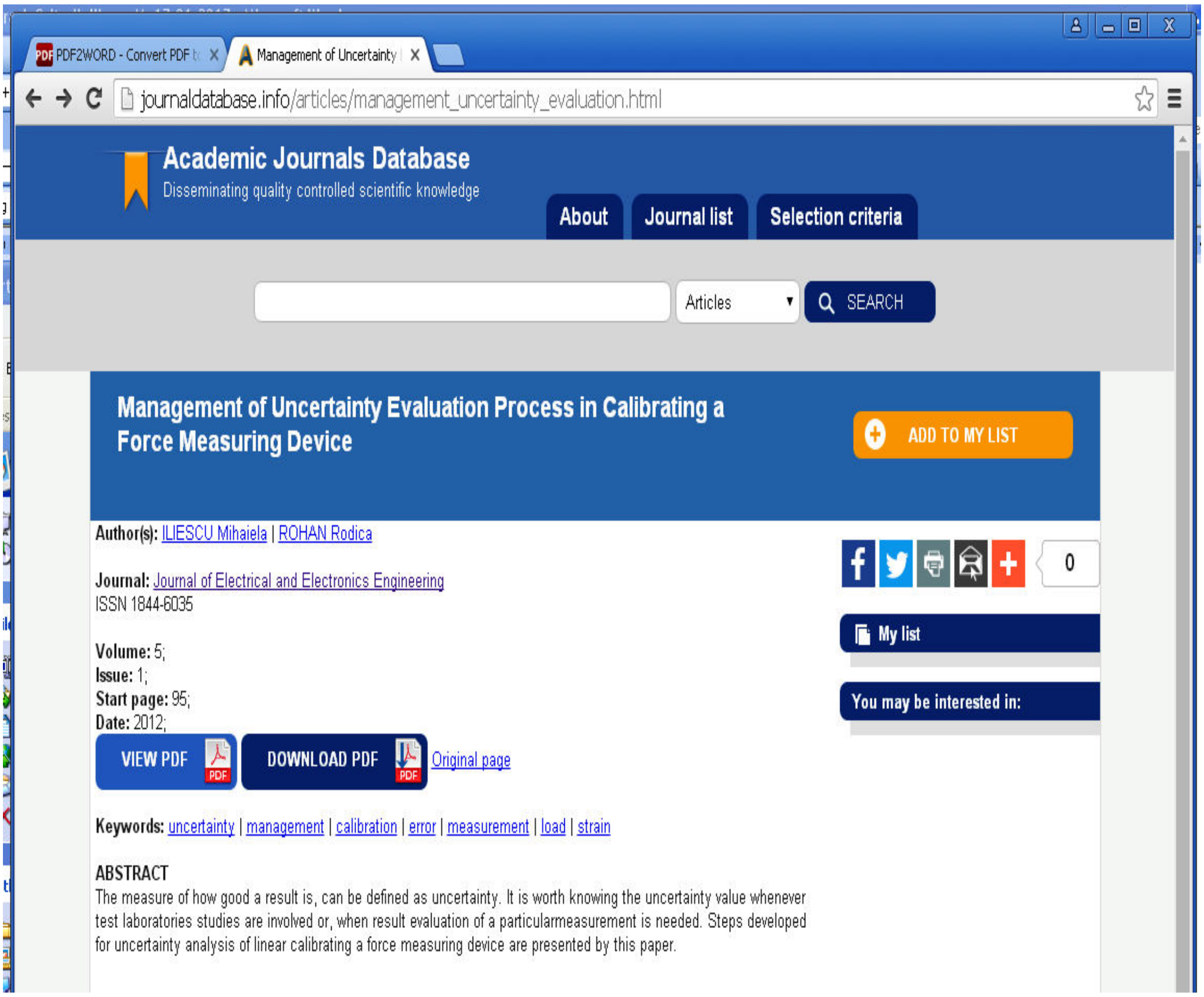

Management of Uncertainty Evaluation Process in Calibrating a Force Measuring Device

Author(s): ILIESCU Mihaiela | ROHAN Rodica

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ABSTRACT

The measure of how good a result is, can be defined as uncertainty. It is worth knowing the uncertainty value whenever test laboratories studies are involved or, when result evaluation of a particularmeasurement is needed. Steps developed for uncertainty analysis of linear calibrating a force measuring device are presented by this paper.

Management of Uncertainty Evaluation Process in Calibrating a Force Measuring Device

ILIESCU Mihaiela[1], ROHAN Rodica[1]

[1] "POLITEHNICA" University of Bucharest, ROMANIA,
Department of Manufacturing Technologies, Faculty of Engineering and Manufacturing of Technological Systems,
Splaiul Independenței no. 313, 060042 Bucharest, ROMANIA, http://www.pub.ro, iomi@clicknet.ro:

***Abstract* – The measure of how good a result is, can be defined as uncertainty. It is worth knowing the uncertainty value whenever test laboratories studies are involved or, when result evaluation of a particular measurement is needed. Steps developed for uncertainty analysis of linear calibrating a force measuring device are presented by this paper.**

***Keywords:* uncertainty, management, calibration, error, measurement, load, strain**

I. INTRODUCTION

Uncertainty is a measure of the "goodness" of measurement results [1]. Based on its value, it is possible to appreciate the fitness of results as the basis for making decision on studied phenomena.

Each measurement process is "accompanied" by errors. These errors may be generated either by measurand properties, or measuring instrument's characteristics, or measuring process sequence of steps.

As already established [2], an uncertainty statement assigns credible limits to the accuracy of a reported value, stating to what extent that value may differ from its reference value. So, in ISO Guide to the Expression of Uncertainty in Measurement (GUM), uncertainty id defined as "parameter associated with the result of measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand". Uncertainty depends on repeatability of the instrument, the reproducibility of the result over time, the number of measurement of the test result and on all the sources of random and systematic error that could contribute to the "disagreement" between the result and its reference value [1].

The measurement method involves precision, related to random error and bias. While random errors can not be corrected, bias can be corrected or eliminated from the measurement result.

ISO (GUM) approach to classifying sources of error is the one that follows.

◘ Type A error - uncertainty components are evaluated by statistical methods.

Some specific random errors are the next ones:

- time dependent, like short-term (repeatability, imprecision), day-to-day (reproducibility) and long-term (stability) errors;
- errors caused by specific condition of measurement (instrument, operator, temperature, humidity);
- errors caused by material that is not homogeneous

The sources of bias relate to the specific measurement environment like: instruments, operators, configuration, geometries, etc.

◘ Type B error - uncertainty components are not determined by statistical methods.

Some sources of these errors are:

- physical constants used in calculating the reported value;
- environmental effects that can not be sampled;
- reference standards calibrated by another laboratory;
- possible incorrect configuration / geometry in the instrument;
- instrument's lack of resolution.

All the aspects mentioned above prove that evaluation of uncertainty is an ongoing process, time and resources consuming. Still, there are cases when it has to be done, like when laboratories or industries do participate in inter-laboratory studies or, when there are one-of-a kind-measurements [3], [4], [5].

The last mentioned, can be considered the case of a special designed machining forces measuring device. It has been designed and manufactured so that to be used in various types of machining procedures and, therefore, before exploitation, specific calibration equations had to be determined.

So, evaluation of uncertainty had to be done, the case being that of uncertainty in linear calibration.

II. EVALUATING UNCERTAINTY STEPS

The tasks that need to be performed in order to obtain an evaluation of uncertainty associated to measurement results are mentioned next:

- specify measurand, identifying the parameters for which uncertainty is to be estimated
- identifying all sources of uncertainty;
- classifying the sources of errors into type A or B;
- estimating the standard uncertainty for each source of uncertainty;
- computing the combined uncertainty, u_c;
- computing the expanded uncertainty, U;
- reporting the results.

A short and simplified summary of the general route to evaluation of uncertainty is schematically shown in Fig. 1. It is applicable in most circumstances and the steps involved are “easy” to follow.

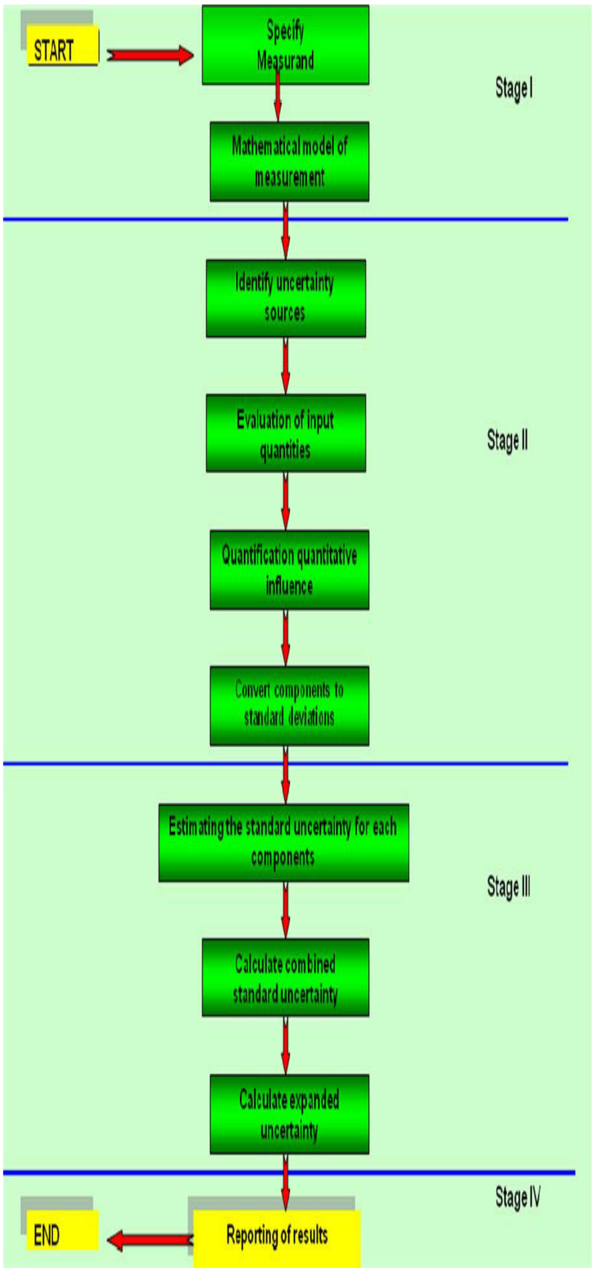


Fig. 1 Steps of the uncertainty evaluation process

III. EXPERIMENTAL CONDITIONS

The special studied device was designed so that to enable measuring of each machining forces’ components, in various machining procedures [6], [7].

It is characterized by elastic element (see Fig. 2) whose shape is a real innovative one.

There are transducers, Hottinger resistive gauges, whose position on the elastic element was established as result of ANSYS simulation.

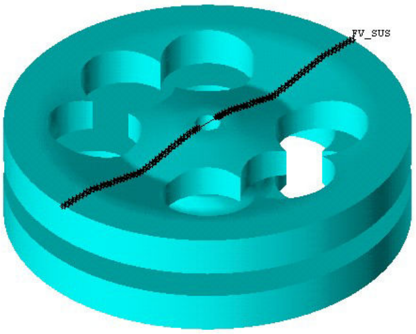
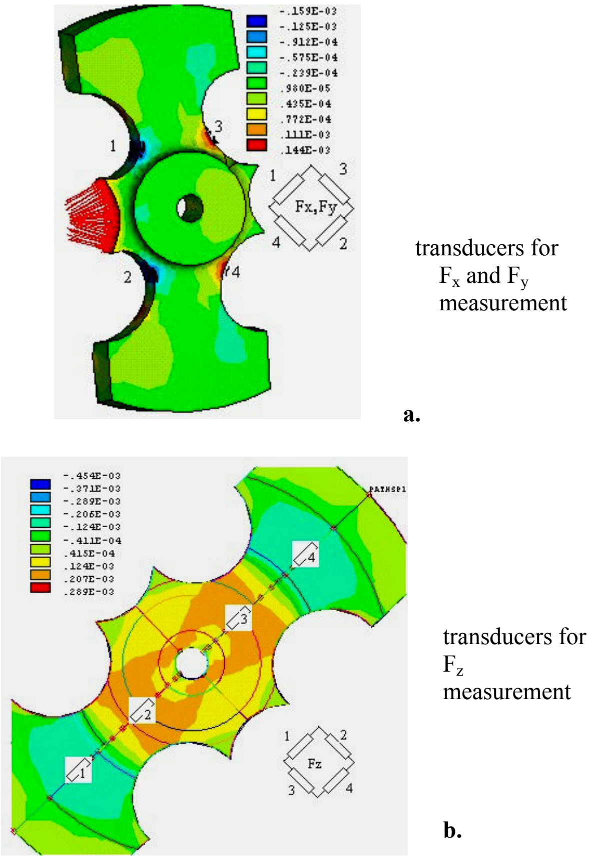


Fig. 2 Elastic element innovative shape, 3D model



transducers for F_x and F_y measurement

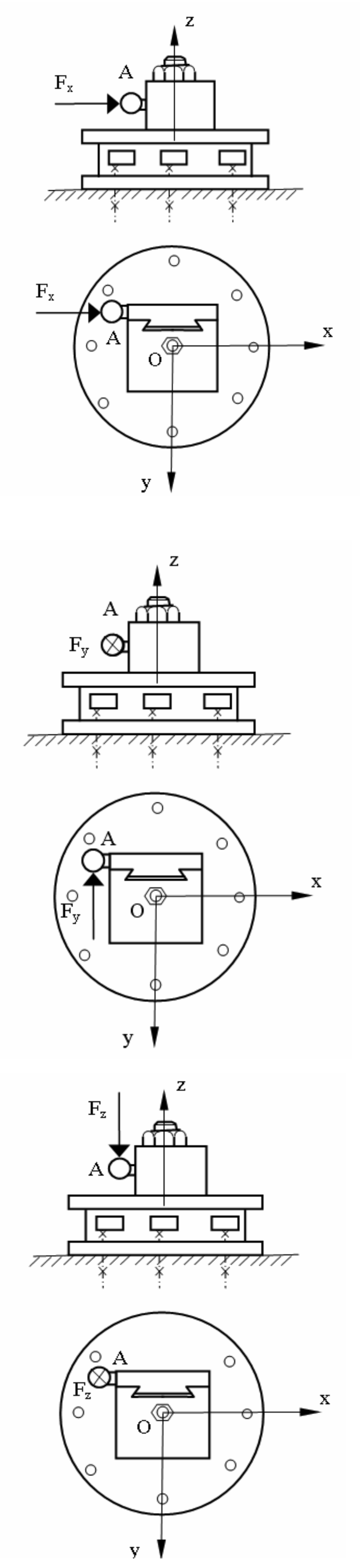
transducers for F_z measurement

Fig. 3 Transducers position and connection

Transducers position and connection, so that all three components of machining force (F_x, F_y and F_z) to be, relatively, independently measured is evidenced by Fig. 3 (a. and b.).

In order to obtain calibration equation, the device should be submitted to various loading (specific to different machining procedures) and the resulted deformation to be measured. Thus, the F_ρ ($\rho = x, y, z$) loading force does generate the $\varepsilon_{\rho x}$, $\varepsilon_{\rho y}$, $\varepsilon_{\rho z}$ signals to each of “C_x”, “C_y” and, respectively, “C_z” voltage bridge channels.

Schematic representation of F_x, F_y and F_z loading are shown in Fig. 4 (a., b. and c.).



F_x loading

a.

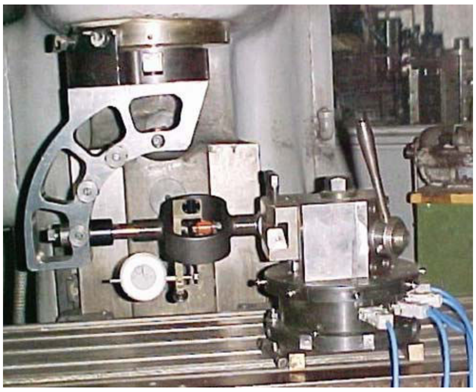
F_y loading

b.

F_z loading

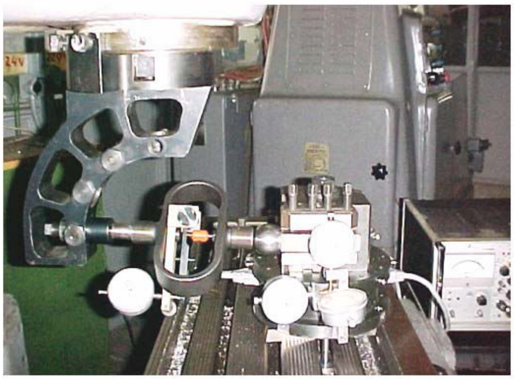
c.

Fig. 4 Schematic representation of force loading - - in calibrating



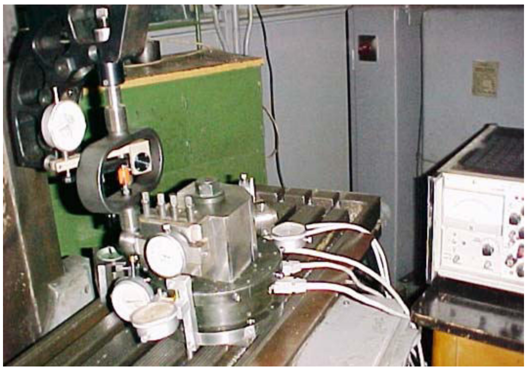
a.

F_x loading



b.

F_y loading



c.

F_z loading

Fig. 5 Images captured while experimenting

Images captured while experimenting can be noticed in Fig. 5 (a., b. and c.). One comment should be about the fact that both, F_x and F_y loadings, are similar ones.

Based on preliminary experimental data analysis, it has been considered that calibration equations are of linear type, such as:

$$\varepsilon_{\rho\theta} = a_{\rho\theta} \cdot F_\rho + b_{\rho\theta} \qquad (1)$$

$$\rho = x, y, z\,, \quad \theta = x, y, z$$

So, considering all the aspects mentioned above, there can be plotted Ishikawa chart of uncertainty sources in device's linear calibration – see Fig. 6.

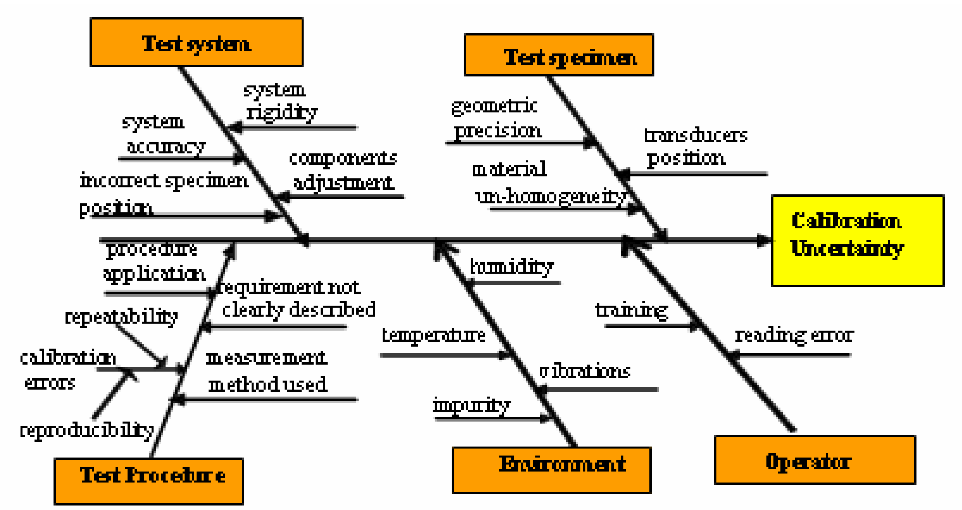


Fig. 6 Ishikawa chart of uncertainty sources

TABLE 1 Tests results

x_1			x_2			x_3			x_4			x_5			F_x loading
0			50			100			150			200			[daN]
y_1			y_2			y_3			y_4			y_5			
r_1	r_2	r_3	r_1	r_2	r_3	r_1	r_2	r_3	r_1	r_2	r_3	r1	r2	r3	
0	0	0	225	233	226	464	476	470	668	678	676	842	854	845	[μm/m]
mean			mean			mean			mean			mean			
0			228			470			674			847			[μm/m]
x_1			x_2			x_3			x_4			x_5			F_y loading
0			50			100			150			200			[daN]
y_1			y_2			y_3			y_4			y_5			
r_1	r_2	r_3	r_1	r_2	r_3	r_1	r_2	r_3	r_1	r_2	r_3	r1	r2	r3	
0	0	0	210	230	205	421	435	425	640	658	646	818	824	821	[μm/m]
mean			mean			mean			mean			mean			
0			215			427			648			821			[μm/m]
x_1			x_2			x_3			x_4			x_5			F_z loading
0			50			100			150			200			[daN]
y_1			y_2			y_3			y_4			y_5			
r_1	r_2	r_3	r_1	r_2	r_3	r_1	r_2	r_3	r_1	r_2	r_3	r1	r2	r3	
0	0	0	210	230	196	486	505	500	682	700	694	868	883	880	[μm/m]
mean			mean			mean			mean			mean			
0			212			497			692			877			[μm/m]

IV. UNCERTAINTY EVALUATION

The model for linear calibration is:

$$Y = aX + b + \varepsilon \qquad (2)$$

there : Y is a measurement on a reference standard;
X – known value of a reference standard;
ε - measurement error
a, b – coefficients to be determined

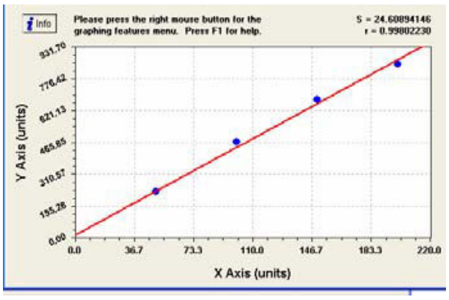
A minimum of five reference standards and a minimum of two measurements on each reference standard is required for linear calibration curve. The repetitions should be separated in time by days or weeks [1].

Basic assumption regarding measurement errors associated with the instrument are the next ones: free from outliers; independent; equal precision; normal distribution.

So, based on all the above, tests have been done and the obtained results are presented in table 1.

There should be mentioned that Y represents the elastic element deformation, Δ [μm/m], while X stands for loading force value, F [daN].

Using a special software, CurveExpert 1.3, there were determined the estimated coefficients value of linear model, meaning (see as example, Fig. 7 – for F_x loading):



Please press the right mouse button for the graphing features menu. Press F1 for help.

S = 24.60894146
r = 0.99802230

Fig. 7 Data analysis with CurveExpert 1.3 – for F_x loading

- F_x loading case

$$\tilde{Y} = 4.28X + 15.8 \tag{3}$$

where: s = 24.6089 is the standard error
r = 0.9980 is the correlation coefficient

- F_y loading case

$$\tilde{Y} = 4.15X + 7.2 \tag{4}$$

s = 14.9699 and r = 0.9992

- F_z loading case

$$\tilde{Y} = 4.68X + 8.8 \tag{5}$$

s = 31.6944 and r = 0.9969

Calibration of future measurements can be done by obtaining predicted values, y_{ipred}. The CurveExpert 1.3 software was also used for estimation, obtained results being presented in table 2. It is Fig. 8 that shows an example of one predicted value (for F_x loading case).

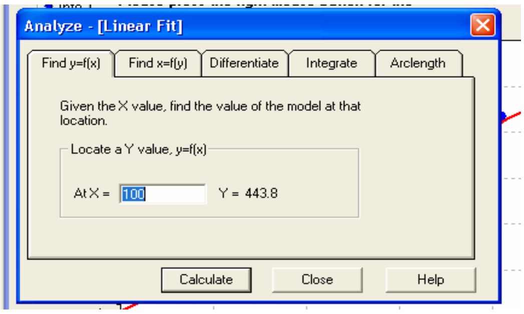
TABLE 2 Predicted values

x_1	x_2	x_3	x_4	x_5	F_x loading
0	50	100	150	200	[daN]
y_{1pred}	y_{2pred}	y_{3pred}	y_{4pred}	y_{5pred}	
15.8	228	470	674	847	[µm/m]
x_1	x_2	x_3	x_4	x_5	F_y loading
0	50	100	150	200	[daN]
y_{1pred}	y_{2pred}	y_{3pred}	y_{4pred}	y_{5pred}	
8.4	215.6	422.8	630	837.2	[µm/m]
x_1	x_2	x_3	x_4	x_5	F_z loading
0	50	100	150	200	[daN]
y_{1pred}	y_{2pred}	y_{3pred}	y_{4pred}	y_{5pred}	
8.8	232.2	455.6	679	902.4	[µm/m]

Based on further statistical calculi, the uncertainty value is being evaluated - see relations below.

$$s_y = \sqrt{\frac{\sum_{i=1}^{N=5}\left(y_i - y_{ipred}\right)^2}{N-2}} \tag{6}$$

$$s_{x_0} = \frac{s_y}{a} \tag{7}$$



Analyze - [Linear Fit]

Given the X value, find the value of the model at that location.

Locate a Y value, y=f(x)

At X = 100 Y = 443.8

Fig. 8 Data prediction with CurveExpert 1.3

$$x_0 = \frac{y-b}{a} \tag{8}$$

$$s_{xx} = \sum_{i=1}^{N=5}\left(x_i - \bar{x}\right)^2 \tag{9}$$

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N=5} x_i \tag{10}$$

$$u(x_0) = s_{x_0}\sqrt{\frac{1}{p} + \frac{1}{N} + \frac{\left(x_0 - \bar{x}\right)^2}{s_{xx}}} \tag{11}$$

$$U(x_0) = k \cdot u(x_0) \tag{12}$$

where: a, b represent linear regression model's coefficients;
p - the number of measurements for x_0;
$u(x_0)$ - the combined uncertainty
$U(x_0)$ - the expanded uncertainty;
k – the coverage factor, selected on the basis of required confidence level.

For a normal probability distribution, the most generally used value for coverage factor is 2, which corresponds to a confidence interval of 95% .

The values of the above mentioned parameters are presented in table 3.

TABLE 3 Uncertainty parameters values

F_x loading						
s_y	s_{x_0}	x_0	s_{xx}	$\bar{x}$	$u(x_0)$	$U(x_0)$
9.1221	2.1313	106.122	25,000	100	1.5586	3.1172
F_y loading						
s_y	s_{x_0}	x_0	s_{xx}	$\bar{x}$	$u(x_0)$	$U(x_0)$
15	3.6145	101.1566	25,000	100	2.6397	5.2794
F_z loading						
s_y	s_{x_0}	x_0	s_{xx}	$\bar{x}$	$u(x_0)$	$U(x_0)$
31,6944	6.7722	104.3162	25,000	100	4.9490	9.8980

Experimental obtained values have been further processed, based on relation (1) and, also, on CurveExpert 1.3 software. So, the force measuring device's calibration equation has been determined as:

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} 0{,}2402 & -0{,}0052 & -0{,}0218 \\ -0{,}0092 & 0{,}2443 & -0{,}0181 \\ -0{,}0100 & -0{,}0237 & 0{,}2361 \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_x - 6{,}200 \\ \varepsilon_y - 17{,}600 \\ \varepsilon_z + 4{,}000 \end{bmatrix} \tag{13}$$

or, equivalently :

$$\begin{aligned} F_x &= 0{,}2402 \cdot \varepsilon_x - 0{,}0052 \cdot \varepsilon_y - 0{,}0218 \cdot \varepsilon_z - 1{,}4849 \\ \mathrm{F_y} &= -0{,}0092 \cdot \varepsilon_x + 0{,}2443 \cdot \varepsilon_y - 0{,}0181 \cdot \varepsilon_z - 4{,}3150 \\ \mathrm{F_z} &= -0{,}0100 \cdot \varepsilon_x - 0{,}0237 \cdot \varepsilon_y + 0{,}2361 \cdot \varepsilon_z + 1{,}42352 \end{aligned} \tag{14}$$

These equations above, allow each of the machining force's components (F_x, F_y anf F_z) to be independently determined.

So, for example, the measurement results and their corresponding uncertainty are mentioned next:

- machining force's component, F_x

  464 ± 3.117 [daN]
- machining force's component, F_y

  421 ± 5.279 [daN]
- machining force's component, F_z

  486 ± 9.898 [daN]

An image taken while using the designed device in a real machining process (exterior cylindrical turning) is shown in Fig. 9.

Fig. 9 Exploitation of the force measuring device

IV. CONCLUSIONS

Measurement uncertainty is the basic parameter that characterizes result's quality of measurements.

More and more often, specially in industrial environment and in test / calibration laboratories, the measurement's quality is a requirement that according to quality management system, facilitates information exchange and cooperation between laboratories testing / calibration and harmonization of standards, procedures and other regulations specific to measuring process.

The objective of measurements quality assurance is to reduce measurements errors to tolerable limits and to provide a mean of ensuring that the measurements results have a high probability of acceptable quality.

Management of uncertainty evaluation process so that to provide confidence in measurement results involves some important steps, as: method development and validation; validating data; reference measurements; production of reference materials; inter-laboratory comparisons; training, etc

For the study presented by this paper, some relevant conclusions can be considered the ones below.

- Evaluation of measurement uncertainty provides the starting points for optimizing test procedures through a better understanding of the test process
- Statement on expanded uncertainty can represent a direct competitive advantage by adding value and significance to the measurement result
- The knowledge of quantitative effects of single quantities on the test result improves the reliability of the test procedure. Corrective measures may be implemented more efficiently and hence become more cost-effective.
- Calibration costs can be reduced if it can be shown from the evaluation that particular influence quantities do not substantially contribute to the uncertainty.
- Proper evaluation of uncertainty is good professional practice and can provide laboratories and customers with valuable information about the quality and reliability of the result.
- Calibration of a special designed forces measuring device is essential, as it provides trustful information on the interest characteristic that is machining force components' values.

Once calibration equation determined the measurement results can be trusted, as uncertainty value proves to be small enough.

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