



Tools for uncertainty calculations in force measurement

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ABSTRACT

Within the framework of the European Metrology Research Programme (EMRP), tools for the calculation of measurement uncertainties have been developed. The Joint Research Project (JRP) 63 of the “SI Broader Scope II” (SIB) call of the EMRP is entitled: “Force traceability within the meganewton range”. The project was started in July 2013 and had a duration of 36 months. The aim of the SIB63 project was to improve the traceability of the force measurement especially in the meganewton range. This paper presents the results of work package 4 “Improved dissemination of the SI unit of force”. The tools developed by the partners are available from the website of the project.

Section: RESEARCH PAPER

Keywords: EMRP SIB 63; uncertainty; force measurement; calculation tools

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1. INTRODUCTION

The main objective of the research project “Force traceability within the meganewton range” (SIB63) in the European Metrology Research Programme (EMRP) was to improve the traceability of force measurement from primary standards to calibration services and testing laboratories especially in the meganewton range. The project was started in July 2013 and had a duration of 36 months.

The aim of the project was to develop new methods that could be applied by users of measurement devices for large forces in industrial calibration laboratories and applications as well as in testing laboratories. Different work packages (WP) had been defined dealing with build-up systems of force transducers and extrapolation methods of measurement results (WP1), with multi-component measurements (WP2) and with time-dependent effects like creep and hysteresis (WP3).

The present paper describes the work that was undertaken within work package 4 *Improved dissemination of the SI unit of force*

(WP4) during the project’s lifetime.

The key idea of WP4 was to improve traceability by taking various influencing effects into account. This is done by applying corrections to the measurement results based on mathematical models and known parameter values. For the corrected results, measurement uncertainties can be calculated using the tools provided to the users from the project’s website.

The procedure of WP4 was as follows. First, the application conditions and requirements for the calibration depending on the further use of the force measuring instrument were compiled based on an on-line questionnaire. Second, the corresponding technical parameters and coefficients describing the effects of application conditions on the measurement result were collected or defined. Third, for nine of the parameters and coefficients, detailed models and elaborated uncertainty calculation examples were provided. They are publicly available from the website [1]. Fourth, for at least six of the models, online calculations tools were developed. For offline use, a

spreadsheet file, including the same models, was programmed and is also publicly available from the website of the project.

2. APPLICATION CONDITIONS

Force transducers are often calibrated under laboratory conditions. In the later use of these instruments the application conditions must be taken into account if they differ from the calibration conditions to an extent that affects the measurement result. In order to receive feedback from the stakeholders about their application conditions, an online form was generated (Figure 1). It is still publicly available from the web address <http://www.ptb.de/emrp/forcemetrology.html> [1]. All graphics are screenshots taken from the project’s website. If the figures are difficult to read, please open – if available - the website.

As the next step, a survey was undertaken and 66 stakeholders were asked to take part by submitting the filled-in form to the project team. 24 users replied and all the data received was entered into the database and can be found under “Work Packages/WP4.1 Application conditions” on the website.

The intention of the survey was to find out under which conditions and in what ranges (for example, temperatures up to 1100 °C) force transducers are sometimes used. It was not intended to develop methods covering all these ranges so users should be aware that, for example, a temperature coefficient that was measured in the range up to 30 °C may not be useful in the range of 100 °C or above.

3. TECHNICAL PARAMETERS AND COEFFICIENTS

Several parameters or coefficients are already defined in written standards, for example in [2], or in scientific papers. The available information was compiled into one list together with references under “Work Packages/WP4.2 Parameters and coefficients” on the website (Figure 2). All parameters are given with their name, symbol and unit, as well as a description. In some cases, it was necessary to adapt the definition given in the

Part 1 - Parameter and coefficient definitions

Geometrical		
Parameter	Symbol and Unit	Description
Eccentricity effect	$D_{C,E}$ in IU / mm	Output signal of the force transducer at rated force due to a defined displacement of the force action line parallel to the measurement axis. The greatest eccentricity effect in the plane vertical to the measurement axis is to be stated.
Geometrical effects in build-up systems		see Mechanical effects in build-up systems
Mechanical		
Parameter	Symbol and Unit	Description
Torque effect	$D_{C,MT}$ in IU / (N·m)	Deviation of the output signal of the force transducer due to a torque around the measurement axis. The torque is to be stated.
Lateral force effect	$D_{C,FL}$ in IU / N	Deviation of the output signal of the force transducer due to a lateral force. The lateral force shall be applied perpendicular to the measurement axis in the point of force introduction. The greatest lateral force effect and its direction is to be stated.
Bending moment effect	$D_{C,MB}$ in IU / (N·m)	Deviation of the output signal of the force transducer due to a bending moment. The bending moment shall be applied around an axis perpendicular to the measurement axis. The greatest bending moment effect and its direction is to be stated.
Mechanical effects in build-up systems	d_L in %	Relative deviation of the sum of the forces indicated by the single transducers from the introduced calibration force
Multi-component effects		to be delivered by WP2

Figure 2. Parameter and coefficient definitions (part of the table).

guidelines for a better uniformity. This may also serve as a proposal for a future revision of the guidelines.

The parameters and coefficients were grouped into Geometrical, Mechanical, Temporal, Electrical and Environmental effects.

For some of the parameters, exact values are given as well. Unfortunately, this list is very short and it does not cover most of the parameters due to a lack of corresponding measurement results. If a user needs to know the exact value of a parameter, then it might be necessary to carry out corresponding measurements. On the other hand, depending on the target uncertainty, it may be sufficient to work with parameter ranges in the form of upper limits of their absolute values from data sheets. For example, the temperature effect on the characteristic value (“sensitivity”) of a C4 force transducer from HBM [3] is not higher than 0.01 % per 10 K temperature change (see Figure 3).

Figure 1. Questions from the on-line questionnaire about application conditions.

Parameter ranges (upper limits of absolute value) from data sheets		
Parameter	Symbol	Range
Temperature effect on characteristic value per 10 K	TK_C	$ TK_C < 0.01 \% / (10 \text{ K})$
Temperature effect on zero signal per 10 K	TK_0	$ TK_0 < 0.015 \% / (10 \text{ K})$
Ambient pressure effect on zero signal per 1 kPa	ρK_0	$ \rho K_0 < 0.015 \% / (1 \text{ kPa})$
Relative eccentricity effect	$d_{E,r}$	$ d_{E,r} < 0.01 \% / \text{mm}$
Relative lateral force effect (lateral force: 10% of F_{nom})	$d_{Q,r}$	$ d_{Q,r} < 0.03 \% / (0.1 \cdot F_{nom})$
Excitation voltage effect on characteristic value	$d_{C,U}$	$ d_{C,U} < 0.1 \% \text{ in the excitation voltage range}$
Excitation voltage effect on zero signal	$d_{S0,U}$	$ d_{S0,U} < 0.5 \% \text{ in the excitation voltage range}$
Temperature effect on characteristic value per 10 K	TK_C	$ TK_C < 0.01 \% / (10 \text{ K})$
Temperature effect on zero signal per 10 K	TK_0	$ TK_0 < 0.015 \% / (10 \text{ K})$
Relative eccentricity effect	$d_{E,r}$	$ d_{E,r} < 0.005 \% / \text{mm}$
Relative lateral force effect (lateral force: 10% of F_{nom})	$d_{Q,r}$	$ d_{Q,r} < 0.03 \% / (0.1 \cdot F_{nom})$

Figure 3. Parameter ranges from data sheets.

4. DETAILED MODELS AND EXAMPLES

4.1. Models

The uncertainty contributions were then evaluated for some of the parameters and their related influencing quantities. In [4] it was shown that the uncertainty calculation can be performed with quite simple software tools.

The various influencing effects are given under “Work Packages/WP4.3 Uncertainty contributions” on the website (Figure 4), arranged in categories. The intention is that the user applies corrections to the measurement results based on the knowledge of the effect, the mathematical model describing the influence and the values of the parameters including their uncertainties.

The models follow directly from the above given definitions of the parameters and coefficients. If new influencing quantities or effects other than those in the list of models have to be considered, the related models can be developed on the basis of the models on the page.

4.2. Calculation examples

For some of the influencing effects from the list in Figure 4, elaborated example calculations are given in the lower part of the WP4.3 page, see Figure 5.

These examples are organized using an accordion element in the graphical user interface of the page. It consists of a vertically stacked list of alternately expandable header items, meaning a maximum of one item can be expanded at a time.

Usually [5], for uncertainty calculations only linearized models are applied and the underlying formula is given in (1):

$$u_c^2(y) = \sum_{i=1}^N \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i). \quad (1)$$

In the case of our form, an enhanced formula (2) is used

$$u_c^2(y) = \sum_{i=1}^N \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) + \sum_{i=1}^N \sum_{j=1}^N \left[\frac{1}{2} \left(\frac{\partial^2 f}{\partial x_i \partial x_j} \right)^2 + \frac{\partial f}{\partial x_i} \frac{\partial^3 f}{\partial x_i \partial x_j^2} \right] u^2(x_i) u^2(x_j). \quad (2)$$

WP4 Improved traceability

WP4 has four tasks. Here we publish the results of these tasks.

Task 4.3 - Determination of the uncertainty of measurement results in the application of force transducers under real conditions

On this page we provide mathematical models with description and numerical examples for the calculation of uncertainties.

Geometrical	Geometrical effects in build-up systems -> to be delivered by WP1 Eccentricity effect on characteristic value $D_{C,E}$ -> see example below
Mechanical	Torque effect on characteristic value $D_{C,MT}$ Lateral force effect on characteristic value $D_{C,FL}$ -> see example below Bending moment effect on characteristic value $D_{C,MB}$ Mechanical effects in build-up systems -> to be delivered by WP1 Multi-component effects -> to be delivered by WP2
Temporal	Creep effects -> to be delivered by WP3 Storage effect on characteristic value $D_{C,t}$ -> see example below Storage effect on zero signal $D_{z,t}$ -> see example below
Electrical	Excitation voltage effect on zero signal $D_{z,U}$ Excitation voltage effect on characteristic value $D_{C,U}$ -> see example below
Environmental	Temperature effect on zero signal TK_0 Temperature effect on characteristic value TK_C -> see example below Humidity effect on zero signal HK_0 Humidity effect on characteristic value HK_C -> see example below Ambient pressure effect on zero signal PK_0

Figure 4. List of categories and influencing effects.

Detailed models and elaborated examples	
Terminology and abbreviations: Indication - Value indicated by the measuring instrument, also: Output Zero indication - Indication of the unloaded transducer Deflection - Difference between the indication at acting load and the zero indication in mounted state Nominal force - Force the measuring instrument is designed for Characteristic value - Deflection at nominal force Sensitivity - Deflection to force ratio, also: Characteristic value to nominal force ratio (in (mV/V)/N, Hz/N, ...) IU = indicated unit, for example, N, mV/V, kHz	
▶	Eccentricity effect on characteristic value
▶	Lateral force effect on characteristic value
▶	Storage effect on characteristic value
▶	Storage effect on zero signal
▶	Excitation voltage effect on characteristic value
▶	Excitation voltage effect on zero signal
▶	Temperature effect on characteristic value
▶	Humidity effect on characteristic value
▶	Pressure effect on zero signal

Figure 5. Collection of detailed models and example calculations.

One of the advantages of this enhanced calculation method is that additional contributions to uncertainty are taken into account. If, for example, the user works at the same temperature as the calibration laboratory (20 °C, see above), the correction due to the temperature coefficient is zero, but due to a supposed higher uncertainty of the temperature measurement (for example, 0.5 K instead of 0.1 K) the result should also have a higher uncertainty.

In the case of the example shown in Figure 6, the effect of temperature on the characteristic value is calculated when the transducer is used at 35 °C after it was calibrated in an air-conditioned laboratory at 20 °C. The standard uncertainty of measurement is 0.25 %. Due to the known temperature

▶ Temperature effect on characteristic value	
Temperature effect on characteristic value	
$\Delta C = C(T_{app}) - C(T_{cal})$ $\Delta C = (T_{app} - T_{cal}) \cdot TK_C \cdot C(T_{cal})$ with T_{cal} - reference temperature in °C during calibration T_{app} - real temperature in °C during application C - characteristic value in IU ΔC - change of C in IU due to temperature change ΔT in K. The corrected force $F(T_{app})$ can be found from the calibration result $C = C(F)$ (characteristic value as function of the applied force) and its reverse function $F = F(C)$.	
Example	
Calibration with: force $F_{cal} = 1$ MN, standard uncertainty: $u(F_{cal}) = 0.001$ MN temperature $T_{cal} = 20$ °C, standard uncertainty: $u(T_{cal}) = 0.1$ K - Model: $C = C(F, T, \dots)$ - Calibration result: $C(F_{cal}, T_{cal}) = C_{cal} = 2.000$ mV/V, standard uncertainty: $u(C_{cal}) = 0.005$ mV/V i.e. $F_{app}(T_{cal}) = 1$ MN, standard uncertainty: $u(F_{app}) = 0.0025$ MN	
Application with: temperature $T_{app} = 35$ °C, standard uncertainty: $u(T_{app}) = 0.1$ K parameter $TK_C = 0.01$ % / K, standard uncertainty: $u(TK_C) = 0.002$ % / K - Model: $C(F, T_{app}) = (T_{app} - T_{cal}) \cdot TK_C \cdot C(F, T_{cal}) + C(F, T_{cal})$ - Calculation: $C(F, T_{app}) = (35 \text{ °C} - 20 \text{ °C}) \cdot 0.0001 \cdot (2.000 \text{ mV/V}) / \text{K} + 2.000 \text{ mV/V}$ $C(F, T_{app}) = 15 \text{ K} \cdot 0.0001 \cdot (2.000 \text{ mV/V}) / \text{K} + 2.000 \text{ mV/V}$ $C(F, T_{app}) = 15 \cdot 0.0001 \cdot 2.000 \text{ mV/V} + 2.000 \text{ mV/V}$ $C(F, T_{app}) = 0.0015 \cdot 2.000 \text{ mV/V} + 2.000 \text{ mV/V}$ $C(F, T_{app}) = 2.003 \text{ mV/V}$, standard uncertainty (see page bottom): 0.005 mV/V i.e. in the case of linear regression: $F_{app}(2.003 \text{ mV/V}, T_{app}) = 1$ MN, standard uncertainty: 0.00252 MN $F_{app}(C_{cal}, T_{app}) = 0.9985$ MN, standard uncertainty: 0.00251 MN Rule A positive value of TK_C means: a higher temperature results in a larger characteristic value. For the same force, a higher value is indicated. For the same indication, a lower force is acting.	

Figure 6. Example of a fully elaborated uncertainty calculation including a corrected result.

coefficient of 0.01 % per 10 K, the characteristic values changed from 2.000 mV/V at 1 MN to 2.003 mV/V.

The uncorrected result has an additional error of 0.15 %. Depending on the application requirements, this can be either low enough to be ignored or it needs to be considered. If the effect is taken into account by applying a correction to the measurement result – which is the preferred way according to the GUM [5], the corrected value has an uncertainty of 0.252 % which is slightly higher than the uncertainty of the calibration result (0.25 %). The increase is mainly caused by the uncertainty in the knowledge of the temperature coefficient T_{KC} .

The example calculations are also used for the test of correctness and validation of the online and offline tools that are described in the following section.

5. ONLINE AND OFFLINE CALCULATIONS TOOLS

The developed online tools can be found under “Work Packages/WP4.4 Software tool” on the website (Figure 7). The user should enter corresponding values into all white input text boxes of the form. After this is done, a click on the “Evaluation” button calculates the results and shows them in the grey text boxes together with a list of contributions and an explanation below the form (Figure 8).

The calculations are performed in the internet browser on the user’s local computer. For this purpose, JavaScript must be supported by the browser and enabled. The use of this tool is free but without any warranty. The source code is accessible and can be checked.

The “Reset” button can be used to delete the current results; the values in the white boxes are not affected. This allows the user to obtain a form without any results but it is not necessary to use this reset function, as any input value can be changed at any time and, by pressing the “Evaluation” button, the results can be re-calculated using these new values. The user should be aware that the indicated results will not correspond to the input values if the latter have been changed without starting a re-calculation using the “Evaluation” button.

The table below the form shows the contributing variances in descending order. In the example of Figure 8 it can be seen that the main contributions come from the uncertainty of the transducer calibration and the uncertainty of the temperature coefficient.

In addition to the online tools, an Excel file is available for offline use. The first sheet in this file contains a short

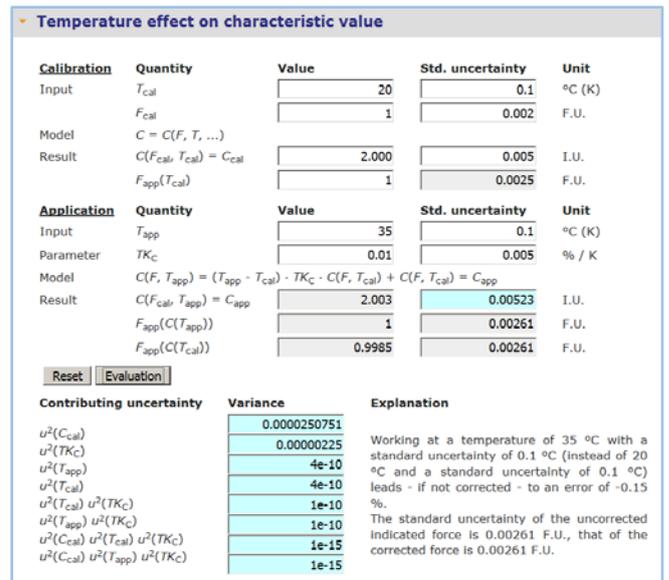


Figure 8. The filled-in form of Figure 7 with calculated results and explanation.

description together with internal links to the other sheets and some settings for the units in which the values are given. The second sheet offers some explanation of technical terms including their units. Each following sheet contains one model and its structure is similar to that on the website. The sheets contain the model and descriptions, input fields (cells) for data, results fields (cells) for the calculation results as well as the “Reset” and “Evaluation” buttons and the contributing variances, and the explanation.

The calculations in this spreadsheet file are based on macros. For the full functionality of the files macros must therefore be allowed. Depending on the settings of the local programme, the user may be asked to allow macros to be executed by the programme.

The last sheet of the file offers a graphical representation of the different contributing uncertainties (Figure 9).

The user can select which effects and influences should be

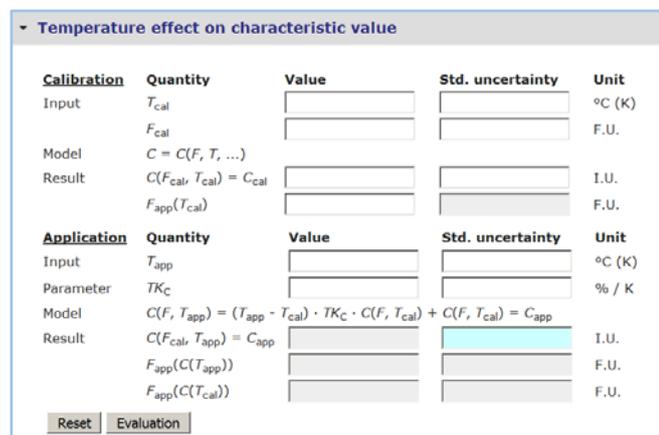


Figure 7. Example of an online tool form.

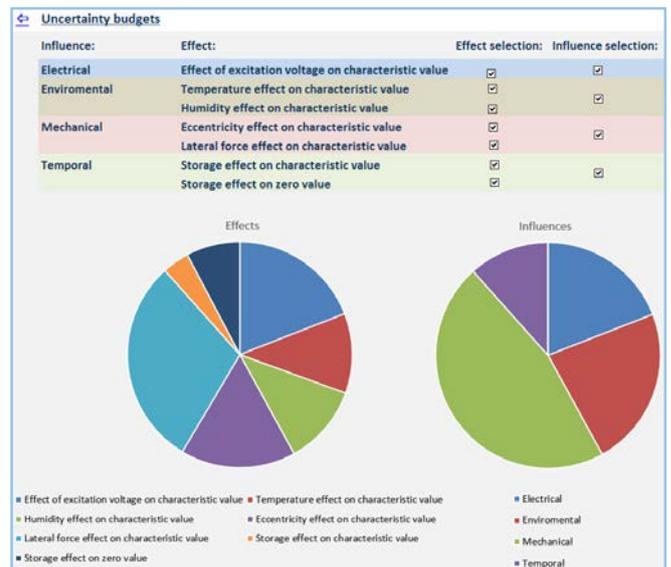


Figure 9. Pie charts of the contributing effects and influences (Source: Excel file [6]).

taken into account by checking or unchecking the corresponding checkbox in the table above the charts. The graphics will be updated accordingly.

6. CONCLUSIONS

The methods and tools developed within this work package should help the users of calibrated force transducers to better estimate the measurement uncertainty with less effort, thus improving the traceability of force measurement. It should be noted that the methods and tools described in this paper are limited neither to the meganewton force measuring range nor indeed to the quantity force, so they can equally be applied to torque or pressure measurements.

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REFERENCES

- [1] EMRP SIB63 "Force traceability in the meganewton range", [Online], <http://www.ptb.de/emrp/sib63-home.html>.
- [2] VDI/VDE/DKD 2638 Kenngrößen für Kraftaufnehmer – Begriffe, 2008-10, (German and English versions in one document), https://www.vdi.de/richtlinie/vdivdedkd_2638-kenngroessen_fuer_kraftaufnehmer_begriffe/.
- [3] HBM C4 Force Standard Data Sheet, Special features, <http://www.hbm.com.pl/pdf/b0663.pdf>.
- [4] D. Röske, "Uncertainty Calculations Using Free CAS Software Maxima," in IMEKO 22nd TC3, 12th TC5 and 3rd TC22 International Conferences, Cape Town, South Africa, February 2014, <http://www.imeko.org/publications/tc3-2014/IMEKO-TC3-2014-016.pdf>.
- [5] BIPM JCGM 100:2008, Evaluation of measurement data - Guide to the expression of uncertainty in measurement, http://www.bipm.org/utis/common/documents/jcgm/JCGM_100_2008_E.pdf.
- [6] Excel file for offline calculation of measurement uncertainties, http://www.ptb.de/emrp/fileadmin/documents/forcemetrology/WorkPackages/WP4/uploads/WP4.4_Spreadsheet_tool_v1.0.1.xlsm.

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