# COMPARISON OF EVALUATIONS OF A COMPARATOR TYPE FORCE CALIBRATION MACHINE

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**Abstract:** The paper present examples of evaluation of uncertainty of a comparator type force calibration machine, either by calibration of force calibration machine using transfer standard transducers or via independent traceability of the reference force transducer. Results of evaluations are presented for reference values from various sources, different mounting conditions and different traceability links.

**Keywords:** force, calibration, uncertainty, evaluation

## 1. INTRODUCTION

The paper presents a comparison of different examples of evaluation of a comparator type force calibration machine uncertainty and estimation of its calibration and measurement capability (CMC).

The evaluation procedure is based on EURAMET document cg-4 [1] and guides for calculation and expression of measurement uncertainties [2,3]. The EURAMET cg-4 document describes the procedure for evaluation and calibration of various force calibration machines using transfer standard transducers, and proposes generally two traceability paths, one via traceability link via transfer standards (path A) and one via direct traceability link of generated force (path B).

For comparator type force calibration machines, the reference transducer performance is one of specific uncertainty contributions and needs to be taken into consideration when calculating the uncertainty budget for the generated force and CMC evaluation. Reference transducer calibration, its performance, and its loading and mounting condition, as well as the traceability path chosen, all have an impact on the final achievable uncertainty,

The paper presents examples of evaluation results which are based on experience with measurements, evaluations and experiments on a comparator type force calibration machine developed with the aim to achieve $2\times10^{-4}$ or better force uncertainty.

## 3. THE MACHINE SET-UP

The examples of evaluations were performed on a force calibration machine based on a 600 kN material testing machine Zwick Z600E. The machine is controlled with the standard control electronics, but was upgraded with an external high precision amplifier and high precision reference transducer, mounted axially below the control transducer. The reference transducer is either a 500 kN HBM Z4A transducer with extended load range to 600 kN or a 100 kN HBM Z4A transducer for improved performance in the range up to 100 kN. The example of the set-up is shown in Fig. 1, for compression loading up to 600 kN. The control transducer is mounted below the crosshead and the reference transducer is mounted directly below it. The transfer standard transducers are positioned on the base of the machine, axially below the reference transducer.

For the measurement, the reference transducer and the transfer transducer are connected to a two channel HBM DMP41 measuring amplifier and both indicated values are simultaneously transferred to the measuring software on the PC computer, which is also responsible for the control of the machine. Any control deviation of the force is determined with the reference transducer signal and corrections are applied to the measured results.



Fig. 1. Set-up of the machine for 600 kN range, compression, with control transducer on top, reference transducer mounted below it (in the middle) and transfer standard transducer at the bottom (all 600 kN).

## 3. EVALUATION PROCEDURE

The measurements on the machine were performed according to specified procedure in EURAMET cg-4 with several transfer standards (50 kN HBM Z4A, 200 kN HBM

Z4A and 600 kN HBM Z4A) calibrated in a national force standard machine (NFSM) with expanded uncertainty $2\times10^{-5}$ (PTB Germany), in four rotational positions (0°, 90, 180°, 270°). Evaluation of the generated force was performed according to EURAMET cg-4, as well was the machine CMC calculation, which included contributions specified in the same document.

For traceability path A, the EURAMET cg-4 guide recommends to evaluate the deviation and reproducibility of the generated force (measurements with transfer standard transducers), apply corrections to any established deviation, and then calculate the measurement uncertainty (CMC) for the corrected generated force. In this case, the reference transducer performance such as repeatability, reproducibility, and creep are of value for inclusion in the uncertainty budget. The calibrated values themselves are of secondary importance, as the values for the generated force need to be corrected in most cases, to reduced deviation and improve the uncertainty, and can be as well determined during the calibration of the machine.

For traceability path B, first, the calibrated values of the reference transducer must be known, as they are directly used as values for generated force, and also all other performance parameters of the transducer must be known, for the calculation of the uncertainty of the generated force.

As there are different ways to evaluate the generated force, the same calibration machine was evaluated under different conditions and reference value sources, to compare different possible scenarios:

a) Example of uncalibrated reference transducer values. In this case, there are no calibrated reference values for the reference transducer and no traceability is assured. While the reference values could be assigned during a calibration of the machine, the expected reference values are in this case estimated in advance, simply by linear interpolation between 0 mV/V and 2 mV/V of the transducer range, so that a deviation can later be calculated and shown. Correction needed to be applied to the reference values of the machine must be determined by the calibration of the machine with transfer standard transducers (traceability path A).

b) Example of reference transducer values from calibration in a force calibration machine (FCM) – example of unreliable calibration results. This case gives an example of a real calibration of the reference transducer according to ISO 376 [4] in a force calibration machine which in retrospect was faulty. Due to large deviation, traceability path B in not possible, so traceability path A must be chosen.

c) Example of reference transducer values from calibration in a deadweight national force standard machine (NFSM) – example of reliable results. In this case the generated force of the machine is directly traceable (it was calibrated in 1 MN deadweight machine at INRiM, Italy, according to ISO 376). The force calibration machine can be either:
   (1) calibrated using transfer standard transducers – traceability path A, or

(2) the performance of the machine is evaluated by comparison with a NFSM, using transfer standard transducers – traceability path B.

d) Example of effect of different mounting of the reference transducer. In this case, the mounting of the transducer from case (a) was changed. It was not loaded via top thread as in case (a), but was fully screwed into the adapter, so that the adapter flange came into contact with the top of the thread baseplate. In this example, modified loading conditions produce large deviation, which needs to be corrected (traceability path A).

The force calibration machine was evaluated for increasing and decreasing force values, for tension and compression, with 600 kN reference transducer and with additional 100 kN reference transducer (both HBM Z4A), for the range from 10 kN to 100 kN. However, for improved clarity, the evaluation of the performance of the machine is only presented for the 600 kN reference transducer in the range from 10 kN to 600 kN for increasing compressive forces.

For the uncertainty evaluation of the generated force and the calculation of machine CMC, the uncertainty components depend on the selected traceability path. For traceability path A, they include the following components:
   - Uncertainty attributed to transfer standard transducers: uncertainty of generated force in national force calibration machine $w_{NFSM}$, uncertainty of calibration of transfer standard in NFSM $w_{ts}$, drift of transfer standard $w_{ts\_drift}$.
   - Uncertainty attributed to the generated force in the force calibration machine: calibration uncertainty of the reference transducer $w_{ref\_tra}$, uncertainty due to reference transducer drift $w_{ref\_tra\_drift}$, standard deviation of measurements with transfer standards in the machine $w_{d\_FCM}$, and uncertainty due to correction of the deviation $w_{corr}$.

For evaluation for traceability path B, the uncertainty evaluation includes the following components:
   - Uncertainty attributed to generated force in the force calibration machine: uncertainty of the reference value of the reference transducer $w_{ref\_tra}$, uncertainty due to reference transducer drift $w_{ref\_tra\_drift}$, uncertainty due to the transducer alignment $w_{axiallity}$, uncertainty due to the control of the machine $w_{control}$. Additionally, the standard deviation of the mean of the measurements with transfer standards in the machine $w_{d\_FCM}$, for machine CMC calculation.

## 4. RESULTS

The results for the determination of the deviation of the generated force are shown in Fig. 2, based on original, uncorrected reference values of the reference transducer. The deviations established by evaluation for traceability path A can later be reduced by correction of reference values.

Results for "uncalibrated" transducer (a) are shown with dotted line, full circle markers.

For comparison, effect of different mounting conditions (d) of the same transducer with the same estimated linear interpolation is shown with dotted line and empty circle

markers and reveals large deviation, highlighting the significant influence of the mounting of the transducer on its reference values. For calculation of the uncertainty budget for cases (a) and (d), the properties of the transducer (repeatability, reproducibility etc.) would have to be estimated as they are not known.

For the case (b), shown with dashed line and full square marker, the results show that reference values from a calibrated reference transducer do not necessarily guarantee small deviations. In the presented case, the calibrated reference values lead to significant deviation. While the calibrated reference values are directly traceable, they are unreliable, and the resulting deviations are larger than the calculated CMC for traceability path B. Calculated $E_n$ values exceed unity and using the direct traceability link is not possible. Therefore, corrections to be applied to the reference values are determined by calibration with transfer standard transducers (traceability path A).
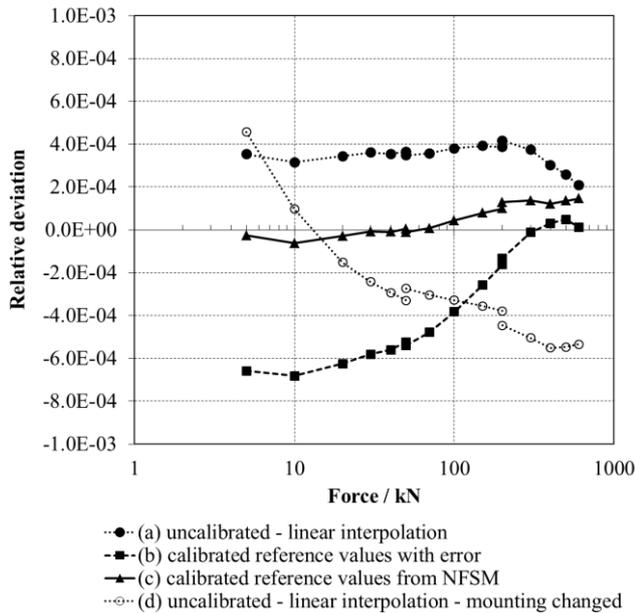


Fig. 2. Uncorrected relative deviation of generated force for various reference value sources and different mounting conditions

Results for case (c) show small deviations of generated force (below $2\times10^{-4}$), shown with solid line and triangle marker. For this situation, evaluation according to traceability path B is of benefit – case (c2). The deviation is not corrected but evaluated as is and compared to calculated machine uncertainty for determination of $E_n$ values (similar to [5]). In this case, a comparison is performed instead of a

calibration, and a correction based on comparison results cannot be performed, as it would change the traceability link, from path B to path A, and result in situation from case (c1).

In the above examples of evaluation for traceability path A, correction of deviation is required for low uncertainties, as the deviations can be too large compared to the calculated target uncertainty of the machine, leading to CMC values in the range between $5\times10^{-4}$ to $1\times10^{-3}$.

If corrections are applied, the relative deviations can be significantly improved, as shown in Fig. 3, where the residuals from the polynomial fit of the deviation for case (b) and (c1) are shown. The deviation of reference values for case (c2) is also shown, but remains unchanged, as correction based on evaluation data is not appropriate in the case of path B traceability link - it requires additional investigation of the machine performance to reduce it.

As can be seen, the previously large deviation can be improved significantly. After correction, the previous deviation of up to $7\times10^{-4}$ in case (b), has been reduced to below $7\times10^{-5}$, shown with dashed line.

Similarly, the deviation in case (c) can be corrected if path A is chosen, reducing the maximum deviation of $1.5\times10^{-4}$ from case (c2), shown with solid line, to below $2\times10^{-5}$ for case (c1), shown with dash-dot line.
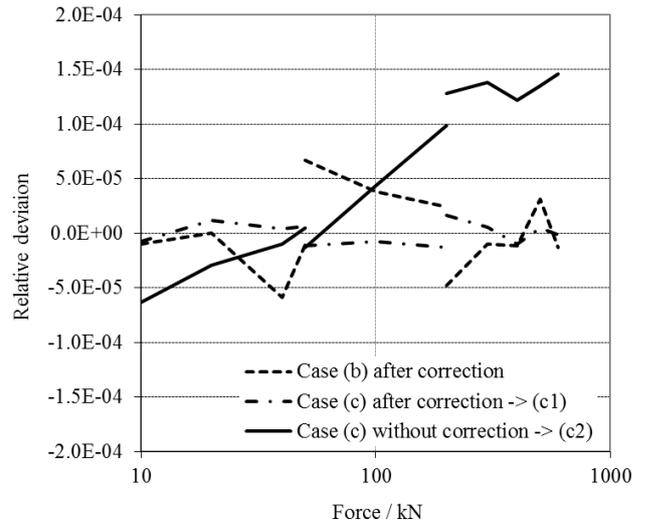


Fig. 3. Relative deviation of generated force after applied correction.

While the application of corrections improves the deviation of the generated force and allows the operation of the machine with improved force uncertainty below $5\times10^{-4}$, traceability path B can be of benefit for reaching the $2\times10^{-4}$ uncertainty goal.

TABLE 1: Example for uncertainty budget calculation for 200 kN force step

| | $w_{ts}$ | $w_{NFSM}$ | $w_{ts\_drift}$ | $w_{d\_FCM}$ | $w_{ref\_tra}$ | $w_{ref\_tra\_drift}$ | $w_{corr}$ | $w_{axiallity}$ | $w_{control}$ | $w_{CMC}$ | $W_{CMC}$ (k=2) | $E_n$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Case (b) - path A** | $1.3\times10^{-5}$ | $1.0\times10^{-5}$ | $4.3\times10^{-5}$ | $6.5\times10^{-5}$ | $7.0\times10^{-5}$ | $5.8\times10^{-5}$ | $3.9\times10^{-5}$ | | | $1.3\times10^{-4}$ | **$2.5\times10^{-4}$** | 0.2 |
| **Case (c1) - path A** | $1.3\times10^{-5}$ | $1.0\times10^{-5}$ | $4.3\times10^{-5}$ | $4.7\times10^{-5}$ | $5.5\times10^{-5}$ | $5.8\times10^{-5}$ | $9.5\times10^{-6}$ | | | $1.0\times10^{-4}$ | **$2.1\times10^{-4}$** | 0.1 |
| **Case (c2) - path B** | | | | $2.4\times10^{-5}$ (*) | $5.5\times10^{-5}$ | $5.8\times10^{-5}$ | | $2.0\times10^{-5}$ | $2.0\times10^{-5}$ | $8.8\times10^{-5}$ | **$1.8\times10^{-4}$** | 0.7 |

(*) Calculated as standard deviation of the mean

Uncertainty calculation for path B traceability differs from path A traceability in the uncertainty contributions that are attributed to the final generated force. In the case of path A traceability link, the uncertainty contribution of the transfer standards must be directly included in the calculation of the final generated force uncertainty, as by definition, the traceability link is provided via transfer standards. Furthermore, the standard deviation of the measurements in the force calibration machines is calculated for the sample and not for the mean.

In contrast, in the case of path B traceability, the uncertainty contribution of transfer standards is attributed to the comparison of force values of the two machines, and the uncertainty of the force calibration machine itself should be calculated in advance from other sources.

An example of uncertainty contributions for path A and path B are presented in TABLE 1 for a 200 kN force step. For case (b) and (c1), the main contributions are the transfer standard transducer calibration, its long-term stability and reproducibility of generated force in the machine, with additional uncertainty contribution from the reference transducer reproducibility and the uncertainty contribution of the correction. For case (c2), the main contribution to the uncertainty of the generated force is the calibration uncertainty of the reference transducer with its long-term stability, and additional contributions due to the construction and the design of the machine.

The final expanded uncertainty of the generated force in the force calibration machine (CMC) is presented in Fig. 4 for the range from 10 kN to 600 kN, for compression loading. It can be seen, that the evaluation for traceability path B for case (c2) results in machine CMC below $2 \times 10^{-4}$ for forces 100 kN and above. If traceability path A is chosen instead, and the deviation is corrected after calibration, the CMC is about $2.1 \times 10^{-4}$ for case (c1). Even with the previously large deviation for case (b), the final CMC value after correction is in the range of $2.5 \times 10^{-4}$.
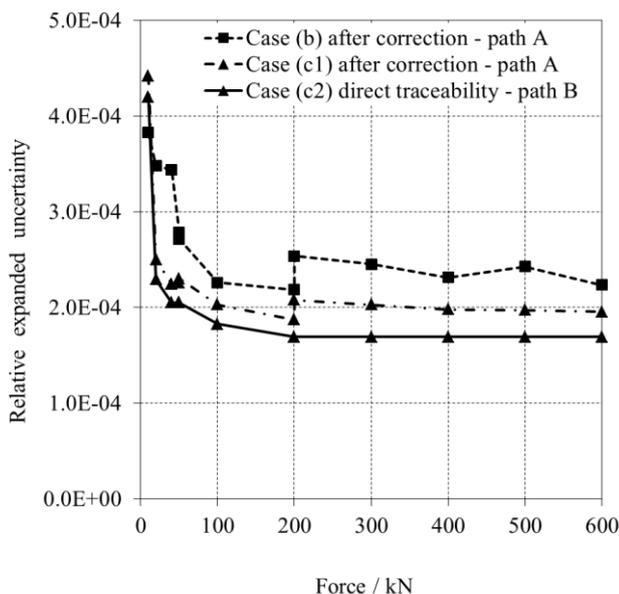


Fig. 4. Comparison of calculated final uncertainty for various evaluation cases

Overall, the evaluation of the force calibration machine for traceability path B results in CMC of $2 \times 10^{-4}$ for increasing forces for tension and compression, in the range from 10 kN to 100 kN with 100 kN reference transducer, and from 100 kN to 600 kN with 600 kN reference transducer.

## 5. CONCLUSION

In comparator type force calibration machines, reference transducer calibration, its performance, and its loading and mounting condition can produce large deviation of generated force. However, during calibration of the machine with transfer standards, these deviations can be determined. With appropriate calibration of the force calibration machine and corrections of established deviations, even machines with originally large deviations, caused by systematic errors, can be employed with low uncertainty values.

However, for lowest uncertainties, traceability path B can be of benefit, but it requires reliable reference values from the calibration of the reference transducer and also reliable machine operating condition (reference transducer loading, the quality of interconnecting elements, etc.) should be assured, to reduce any influences on the reference values.

With the calibrations of the machine with transfer standards (path A traceability link) and appropriate corrections of the deviations, calculated CMCs of the machine below $3 \times 10^{-4}$ were achieved. Path B traceability path resulted in further improvement of the uncertainty of the generated force and calculated machine CMC to the level below $2 \times 10^{-4}$.

## 6. REFERENCES

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