

The advantage of aiding mechanisms in measurements with callipers

Emanuel Paquete Correia^{1§} and João A. Sousa²

¹*LREC*

Edifício LREC, Rua de S. Gonçalo, 9500-343, Ponta Delgada, Azores

²LREC, Rua Agostinho Pereira de Oliveira, 9000-264 Funchal, Portugal

E-mail: emanuel.p.correia@azores.gov.pt

Abstract. Making accurate measurements with a calliper is far from a trivial task. It requires control of the positioning and force application during measurement, which can only be achieved by experienced users. Research has been made in order to help the inexperienced user to make accurate measurements and minimize the training that is normally required. The developed techniques consist on the application of a structure to support the calliper, thus minimizing positioning errors, and a force control accessory for the calliper's movable jaw, resulting in an estimated operator's uncertainty of about 40% of the calliper's resolution value.

1. Introduction

The calliper is an instrument for dimensional measuring, frequently used in Civil Engineering tests, and in a wide variety of other applications. In the performance of my job as a calibration technician, I have found out that the calliper is not an easy to handle instrument because its accuracy depends a lot on the user's ability and experience. Considering the factors that make measurements difficult, which subsequently result in a high user measurement uncertainty, some techniques to reduce the measurement uncertainty are described. These were implemented in the Metrology Unit of the Civil Engineering Regional Laboratory of the Azores archipelago. Topics to be covered include the following.

- General characteristics and calliper types;
- Metrological characteristics;
- Common operator errors;
- Calliper calibration structure and force control device;
- Operator uncertainty calculation method and examples resulting from the applied techniques, using the ANOVA method;
- Global uncertainty analysis using the Monte Carlo method.

2. General characteristics and calliper types

Generally, a calliper has the following components (see figure 1):

- 2 jaws for external measurements;
- 2 jaws for internal measurements;

[§] To whom correspondence should be addressed



- 1 depth measuring blade.

It can be either analogue or digital.

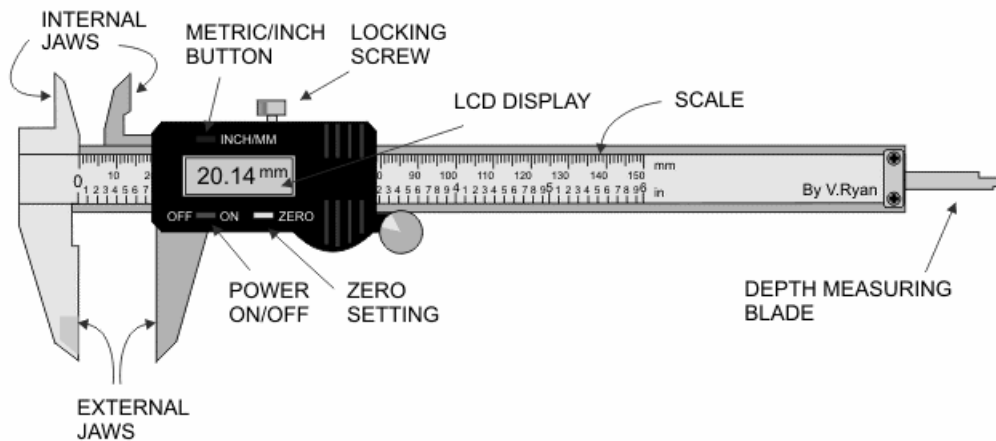


Figure 1. Digital calliper example

3. Metrological characteristics

According to ISO [2], the main metrological characteristics applicable to the calliper's external measurement jaws are the following:

- Partial surface contact error;
- Repeatability of partial surface contact error.

The partial surface contact error is the “error of indication when a partial measuring face contact is employed”.

The repeatability of partial surface contact error may be obtained by the standard deviation of the partial measurements made along the length of the external jaws. The determination of these metrological characteristics includes deviations caused by the:

- Measuring position error (within the measuring range);
- Clearance between the slider and the beam;
- Parallelism and form deviation of the measuring surface of the external jaws.

4. Common operator errors

The most common operation errors caused by an inexperienced user can be divided into the following categories:

- Calliper alignment errors;
- Sliding (measuring) jaw force application error;

The alignment errors can be either horizontal or vertical, as represented in figures 2 and 3, respectively.

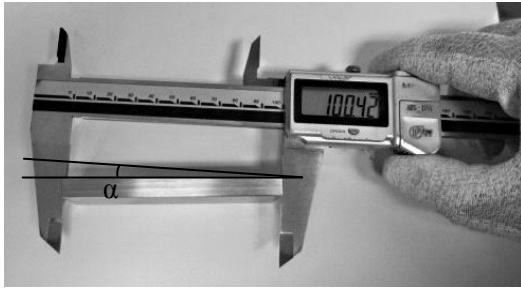


Figure 2. Horizontal alignment error



Figure 3. Vertical alignment error

The sliding jaw force application error is characterized by the deformation of the sliding jaw, caused by the strength exerted by the operator while doing several measurements on the same object. The deformation of the sliding jaw will, consequently, produce inaccurate readings, especially at the tip of the jaws for external measurements. This error occurs because the calliper does not fulfill the Abbe's principle of alignment, due to the existing clearance between the sliding jaw and the calliper's beam. This clearance is inevitable; otherwise it would be impossible to move the sliding jaw, although some callipers allow some mechanical adjustment for the minimization of this clearance.

5. Calliper calibration structure and force control device

A possible solution for the reduction or elimination of calliper alignment errors is the implementation of a structure (see Figure 4), to support the calliper while it is being calibrated, and a force control device to fit on the calliper's beam (see Figure 5).

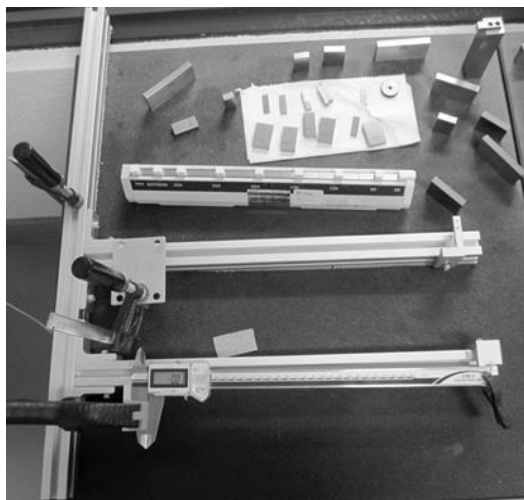


Figure 4. Structure, made in aluminum profiles, to support a calliper – made in LREC (Azores)



Figure 5. Force control device – made in Flexible Measuring Systems (Denmark)

6. Operator uncertainty calculation method

Operator's uncertainty is determined from studies of repeatability and reproducibility. The ANOVA is a method for the analysis of variance, which allows for the combined study of repeatability, reproducibility and the interaction between different operators or between the same operator and time. The two-way ANOVA presented in this paper is based on the method used by Engineered Software [4]. The examples presented in the following sections will characterize the variation of measurements made, by a single operator, in different time periods.

The total measurement system variation is given by equation (1).

$$V_T = \left(\sqrt{R_{ep}^2 + R_{epro}^2 + I^2} + V_O^2 \right)^{1/2} \quad (1)$$

Where R_{ep} , R_{epro} , I and V_O represent, respectively, the repeatability and reproducibility of the measuring system, the interaction between factors A (time) and B (operator) and the operator variation.

The operator's uncertainty will be determined as a rectangular distribution of this total system variation, according to equation (2).

$$u_O = \frac{2V_T}{\sqrt{12}} \quad (2)$$

In the following examples, the null hypothesis for the ANOVA method can be interpreted as:

1. The operator is not a significant source of measurement variability during different time periods;
2. The operator is not a significant source of measurement variability on measurements made on the same time period;
3. There is no interaction between measurements made by the operator through different time periods.

6.1. Operator uncertainty calculation - Example 1

The objective is to evaluate the reduction in the operator's uncertainty after applying a structure to support the calliper (see Figure 4). The procedure consisted on making 2 series of measurements, one in the morning and the other in the afternoon, on a 100 mm gauge block and with a digital calliper (resolution of 0,01 mm). Test data for 3 days is presented on Table 1.

Table 1. Measurements made using the structure shown in Figure 4 and determination of parameters

Measurements (mm)						Parameter	Value (mm)
Day 1		Day 2		Day 3		Repeatability	0,030
1 st Series	2 nd Series	1 st Series	2 nd Series	1 st Series	2 nd Series		
99,98	100,00	100,01	100,00	100,01	100,01	Reproducibility	0,039
100,00	100,00	100,01	100,00	100,01	100,01		
100,00	99,99	100,00	100,00	100,01	100,00	Interaction (time, operator)	0,000
99,99	99,99	100,00	100,00	100,00	100,01		
99,99	100,00	100,00	100,00	100,01	100,01	Measurement variation (on same day)	0,000
99,98	100,00	100,01	100,00	100,01	100,01		
99,98	99,99	100,00	100,00	100,01	100,01	Total system variation	0,049
99,98	99,99	100,01	100,00	100,01	100,00		
100,00	100,00	100,00	100,00	100,00	100,00	Operator uncertainty	0,028
99,99	100,00	100,00	100,01	100,01	100,01		

Table 2. F-Statistic - Significance and critical points for an operator uncertainty of 0,028 mm

Source of Variation	F Statistic	Degrees of Freedom	Significance	Critical Point ($\alpha=0,05$)
Time	33,3(3)	2	2,39E-8	3,32
Operator	0,87	9	5,59E-1	2,21
Interaction (Time, Operator)	0,95	18	5,31E-1	1,96

Observing the operator's uncertainty value on table 1, it can be concluded that it is about 3 times the calliper's resolution value, which is significant. This means that the structure used to minimize the alignment errors during the measurement is not enough. The next example shows that the force component weighs heavier on the total system variation and consequently on the operator's uncertainty. Observing the calculated values on Table 2, it can be verified that all *F-Statistic* values, with the exception of the *Time* source of variation value, are inferior to the *Critical Point* values and consequently, hypotheses 2 and 3 are accepted and hypothesis 1 is rejected. This means that the operator is a significant source of variability on measurements made on different days.

6.2. Operator uncertainty calculation - Example 2

In the sequence of example 1, the objective is to apply a force control device (see Figure 5) on the calliper and test it on the support structure, just as before. Test data is presented on Table 3.

Table 3. Measurements made using the structure plus force device and determination of parameters

Measurements (mm)						Parameter	Value (mm)
Day 1		Day 2		Day 3		Repeatability	0,007
1 st Series	2 nd Series	1 st Series	2 nd Series	1 st Series	2 nd Series		
99,99	99,99	99,99	99,99	99,99	99,99	Reproducibility	0,000
99,99	99,99	99,99	99,99	99,99	99,99		
99,99	99,99	99,99	99,99	99,99	99,99	Interaction (time, operator)	0,000
100,00	99,99	99,99	99,99	99,99	99,99		
99,99	99,99	99,99	99,99	99,99	99,99	Measurement variation (on same day)	0,000
99,99	99,99	99,99	99,99	99,99	99,99		
99,99	99,99	99,99	99,99	99,99	99,99	Total system variation	0,007
99,99	99,99	99,99	99,99	99,99	99,99		
99,99	99,99	99,99	99,99	99,99	99,99	Operator uncertainty	0,004
99,99	99,99	99,99	99,99	99,99	99,99		

Table 4. F-Statistic - Significance and critical points for an operator uncertainty of 0,004 mm

Source of Variation	F Statistic	Degrees of Freedom	Significance	Critical Point ($\alpha=0,05$)
Time	1,00	2	0,38	3,32
Operator	0,9(9)	9	0,46	2,21
Interaction (Time, Operator)	1,00	18	0,49	1,96

From Table 3, it can be seen that repeatability, reproducibility and uncertainty have decreased in relation to the previous example, which means that operator performance has significantly improved. From Table 4, it can be verified that all *F-Statistic* values are inferior to the *Critical Point* values and, consequently, all null hypotheses are accepted. This means that the operator is no longer a significant source of variability on measurements made on different days.

7. Global uncertainty analysis

Evaluating the global measurement uncertainty associated with the calibration of this type of equipment, might give useful indications on the importance of the operator's uncertainty on the global measuring system. Assuming fixed values for the other sources of uncertainty, namely, (a) working standards uncertainty ($\pm 0,9 \mu\text{m}$, Gaussian); (b) working standards drift ($\pm 0,3 \mu\text{m}$, rectangular); (c) temperature influence ($\pm 0,7 \mu\text{m}$, rectangular); (d) finite resolution ($\pm 2,9 \mu\text{m}$, rectangular), we can

analyse the influence of considering (i) operator uncertainty = $\pm 28 \mu\text{m}$, rectangular, as from Table 1 (0,028 mm), or (ii) operator uncertainty = $\pm 4 \mu\text{m}$, rectangular, as from Table 3 (0,004 mm), using a Monte Carlo method. In the first situation the measurand output is clearly rectangular with an expanded factor $k = 1,66$ for a 95 % level of confidence, as in Figure 6, whereas the smaller value of operator uncertainty will produce a much more Gaussian shape curve (Figure 7), indicating that the conditions of the Central Limit Theorem (CLT) are fulfilled to a much higher degree.

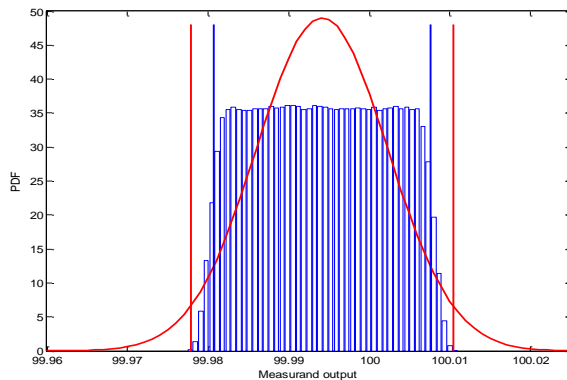


Figure 6. Measurand output for an operator uncertainty of 0,028 mm

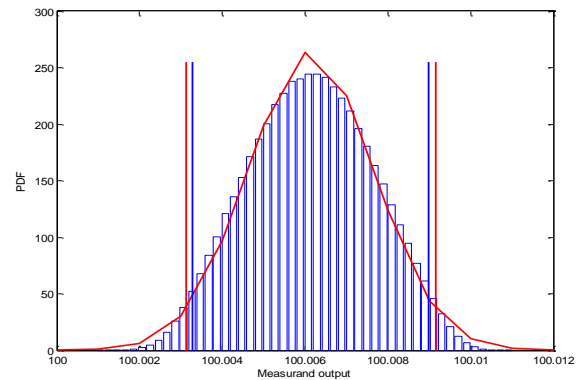


Figure 7. Measurand output for an operator uncertainty of 0,004 mm

These findings are in line with those stated in the EA-4/02 document [5], of mandatory nature for accredited calibration laboratories. The case represented in Figure 6 is typical of situations where there is one dominant source of uncertainty of rectangular shape ($k = 1,65$ according to EA [5], page 49, section S8.2). The case represented in Figure 7, on the other hand, shows that even when the conditions of the CLT are followed (to a degree), the use of the law of propagation of uncertainty might entail an approximation, in cases where not all input quantities are Gaussian. The degree of that approximation is hard to predict *a priori*, and in this particular case a $k = 1,90$ was found (instead of $k = 1,96$) to obtain the same 95 % confidence interval.

8. Conclusions

In the sequence of the techniques here presented, it is possible to conclude that the application of both a structure for supporting the calliper and a device for controlling the force on the calliper's sliding jaw, has significantly reduced the operator uncertainty to about 40 % of the calliper's resolution value. It has been shown by both ANOVA and Monte Carlo methods that the operator's uncertainty is significant and has a dominant effect on the global calibration uncertainty, when there is no force control on the measuring process.

The advantages in the implementation of these techniques are the following:

- Easier, quicker and stress free measurement operations;
- Better accuracy and repeatability on measurements;
- Lower training and test execution costs.

Moreover, it is important to have a full knowledge on the consequences, in terms of uncertainty evaluation, of having a large source of uncertainty associated with the operator handling skills, compared to the rest of the sources considered for the uncertainty budget, or having a much smaller value and therefore much more evenly distributed values for all the uncertainty sources.

References

- [1] Prins J, McCormack D, Michelson D and Horrel K 2012 *e-Handbook of Statistical Methods*. NIST/SEMATECH Albany, NY chapter 7.4.3.7; [accessed december 2013]. Available from: <http://www.itl.nist.gov/div898/handbook/>
- [2] ISO 2011 *ISO 13385-1 Geometrical product specifications (GPS) – Dimensional measuring equipment – Part 1: Callipers; Design and metrological characteristics*. ISO copyright office Geneva
- [3] JCGM 2012 *International vocabulary of metrology – Basic and general concepts and associated terms (VIM)*. JCGM
- [4] Engineered Software Inc. *Repeatability and Reproducibility*. Engineered Software, Inc. Belleville; [accessed december 2013]. Available from: http://www.engineeredsoftware.com/papers/msa_rr.pdf
- [5] EA 2013 *EA-4/02 M:2013 Evaluation of the Uncertainty of Measurement in Calibration*, European Accreditation. Available from: [www.-european-accreditation.org](http://www.european-accreditation.org).