

Accuracy assessment for a multi-parameter optical calliper in on line automotive applications

G D'Emilia¹, D Di Gasbarro¹, A Gaspari¹ and E Natale¹

¹University of L'Aquila, Department of Industrial and Information Engineering and of Economics, via G. Gronchi, 18, 67100, L'Aquila, Italy

E-mail (corresponding author): antonella.gaspari@univaq.it

Abstract. In this work, a methodological approach based on the evaluation of the measurement uncertainty is applied to an experimental test case, related to the automotive sector. The uncertainty model for different measurement procedures of a high-accuracy optical gauge is discussed in order to individuate the best measuring performances of the system for on-line applications and when the measurement requirements are becoming more stringent. In particular, with reference to the industrial production and control strategies of high-performing turbochargers, two uncertainty models are proposed, discussed and compared, to be used by the optical calliper. Models are based on an integrated approach between measurement methods and production best practices to emphasize their mutual coherence. The paper shows the possible advantages deriving from the considerations that the measurement uncertainty modelling provides, in order to keep control of the uncertainty propagation on all the indirect measurements useful for production statistical control, on which basing further improvements.

1. Introduction

The increasing of the performances of automotive components and systems impose the automotive industry to fulfil more stringent requirements for design and tolerances of mechanical components. On the other hand, the need of reducing scrapes to a near zero level and the production costs in the whole asks for more stringent performances of the measuring systems for productive process control [1], [2].

In many cases the improvement of the measurement characteristics can be obtained by the use of complex measuring apparatuses, allowing to automatically and contemporaneously measure many parameters, depending on their setting. Each parameter that can be measured is a different physical quantity and so, although the measurement system is still the same, the measurement process can change, depending on the chosen parameter to be measured. That means the uncertainty evaluation could be also different.

Typically, only the measurement uncertainty is given by the instrument manufacturer concerning quantities which are directly measured [3]. In facts, indirect measurements imply operating and managerial choices, such as, for example the number of measurement points or the working duration of the measurement, making indirect measurement uncertainty depending in a remarkable way on the specific situation.

Many important applications exist, as the case of coordinate measurements, where the assessment of the real measurement accuracy gains key importance; in order to overcome the difficulty of this task some developed methods exist [4], covering the measurements of different geometrical quantities, but they are difficult to extend to other geometrical measuring systems. Furthermore, it has to be pointed out that in the industrial practice, measurement methods previously adopted may influence the choice



of the procedure to be implemented, thus limiting the possibility of improvements deriving from the use of new and updated measurement systems.

Anyway, a careful preliminary evaluation of the accuracy is necessary, if effective improvements have to be realized, taking into account the requested high level of quality process control in the automotive sector [5], [6]. Also, the planning of measurement strategies could be influenced by this analysis [2]. Being able to measure different parameters according to the possibilities given by the complex measurement systems, the uncertainty evaluation should be specialized for the particular or the possible parameters which are of interest.

Methods to propagate the uncertainty of length inspection based on the uncertainty propagation of coordinates measurement exist, such as Monte-Carlo Simulation and Taylor Series Method [7]. Anyway, the modelling of the uncertainties causes is often difficult, in particular for on-line indirect measurements, and an experimental validation is required. The theoretical and experimental analysis is organized and realized according to the specific industrial practices and procedures but a prompt action may prevent consequences on the production phases.

A structured and recursive approach for uncertainty management could be useful [5], [8], [9].

In this paper, the accuracy of a high performance optical caliper is studied with reference to the measurements of dimensional parameters of turbochargers to be carried out on the production line for quality control. Depending on the chosen measurement procedure, different dimensional parameters could be measured, like turbine profile and angles, turbine/stator clearance, turbine axis alignment with a reference one, relevant plane distance to each other and so on. In order to optimize the working settings for the different parameters to be measured, a model of the measurement uncertainty is developed, depending on measurement and production considerations, in order to get a physical interpretation of the different measurement procedures.

Different models can be set, depending on the specific parameter to be measured, in order to define the best approach in any case. The methodology allows us to identify the main causes of variability together with the possible causes of systematic error, for accuracy improvement.

Three main international reference standards are taken into account:

- the reference given by the manufacturer in order to define the Maximum Permissible Error (MPE) [10], for coordinate measuring systems;
- the reference to conduct the test uncertainty for the measuring machine [11], where the main contributions to the error of indication are defined (e.g. the calibration error of the material standard of size, the error due to the misalignment, the error due to fixturing the material standard of size, ...);
- the reference for determining the uncertainty of measurement [12], where the uncertainty of the measurement procedure is evaluated through a Type A evaluation (components evaluated by statistical methods).

This approach allowed us to define a set of practical suggestions useful to improve the measurement procedure and the accuracy of data, taking into account the characteristics of the manufacturing process. The effects of on-line applying this improved methodology are also described in the paper, showing that a significant reduction of scrapes and of time devoted to control of production could be achieved [1]. More effective control procedures could then be set, allowing a significant reduction of cost of the control activities.

The paper is organised as follows. In Section 2 the methodology and the test case are described.

The framework is approached by highlighting the scenario, the requirements and the materials used for the analysis, coming from a finer identification of the boundaries for the core analysis itself, which is taken into account [5]. The preliminary description of this, is intended to define the main uncertainty causes that cannot be neglected (*2.1 Uncertainty causes identification*). Then, the uncertainty budget, the indicators for measurement uncertainty and the measurement uncertainty results are provided for two different measurement methods, named *Method 1* and *Method 2*, respectively (*2.2 Measurement uncertainty evaluation: Method 1*, and *2.3 Measurement uncertainty evaluation: Method 2*). Section 3

shows the results obtained comparing the two measurement methods, carrying out a set of measurements by means of the optical calliper on the components of interest. The results are expressed in terms of standard statistical indicators [13], which represent a common practice in the industrial scenario, which is the main field of application of this paper. Short conclusions end the paper.

2. Methodology and test case

2.1. Uncertainty causes identification.

2.1.1. The scenario. The increasing of the performances of automotive components and systems impose to fulfil stringent requirements for both design and production processes. The scenario analyzed refers to the procedure for realization and control of highly-performing turbochargers, by means of advanced and complex measuring apparatuses.

2.1.2. The Requirements. The increasing performance required for turbochargers imposes the fulfilment of more stringent requirements in terms of the mechanical design and tolerances, and consequently also in terms of the performances of the measuring system for productive process control. The reduction of the leakage of fluid under pressure together with the increase in the required power to the new models are the main goals fixed, which are translated into the following:

- a stringent tolerance on the minimum clearance between the turbine wheel and the turbine house, in the order of 0.05 mm,
- the design of a turbine with a longer axial extension, whose outer profile ends with angles between turbine wheel profile and rotation axis, which are larger with respect to the normal axis, in order to exploit the enthalpy gap as far as possible.
- The stability of the improved solution should be also fulfilled, in accord with the need of consolidating it.

2.1.3. The boundaries of the analysis. The guarantee that along the axis of rotation of the turbocharger (the x-axis, in figure 1), there is no interference between the profile of the turbine wheel and the volute of the turbine housing requires that, for each abscissa x , the clearance $g(x)$ is positive but lower than the dimensional tolerance (Eq. 1). Therefore, the true value of $g(x)$, which is defined as the difference between the radius $r_v(x)$ of the volute and the radius $r_g(x)$ of the impeller (Eq. 2), is dependent on the true values of $r_v(x)$ and $r_g(x)$, and this must be ensured along the entire circumference.

The adjustment of the measurement procedure to the new requirements carried out according to the six-sigma approach, led the company to provide 100% control of production, with reference to both dimension B and run-out, since the process resulted not capable.

$$\forall x \in X, g(x) > 0, g(x) < t \quad (1)$$

$$g(x) := r_v(x) - r_g(x) \quad (2)$$

2.1.4. Materials. The above-mentioned developments strain the existing measurement methods, even if based on sophisticated optical gauges [3], [6]. Basically, these systems work on the measurement of two quantities: the distance between the laser head and the measuring item (measurement of the radius) and the axial position of the laser head itself (measurement of the length). The principle of operation of the optical calliper [3] allows us to obtain directly the radius or diameter of the impeller body.

As declared by the instrument manufacturer, the system is able to achieve for both diameter and length directions of measurement, a precision in the order of the micrometre, thus resulting appropriate for the use required by the company [6]. Taking into account the previous experience and the preliminary analysis on a new measurement approach, two different possibilities are considered:

- Method 1: As far as for the method 1, it considers the measurement of the abscissa for which the axial profile of the turbine realizes a given diameter, replicating the working condition of a mechanical gauge. This method takes into account the tolerance B, given as an interval along the axial direction (figure 2);
- Method 2: As far as for the measurement method 2, it directly considers the measurement of the radius (or the diameter) of the impeller body. The tolerance acts radially.

It appears evident that the measurement method 1 is physically meaningful for low values of angle α , since in this case axial tolerance practically coincides with a clearance. The problem is maintaining a physical meaning of measurements of parameters to be measured also for higher values of α , linked to technological development of turbochargers.

A set of 30 turbochargers are measured, by means of the optical gauge. The results obtained by using the two measurement methods are compared in terms of their capability indices C_p , C_{pk} , P_p , P_{pk} [13].

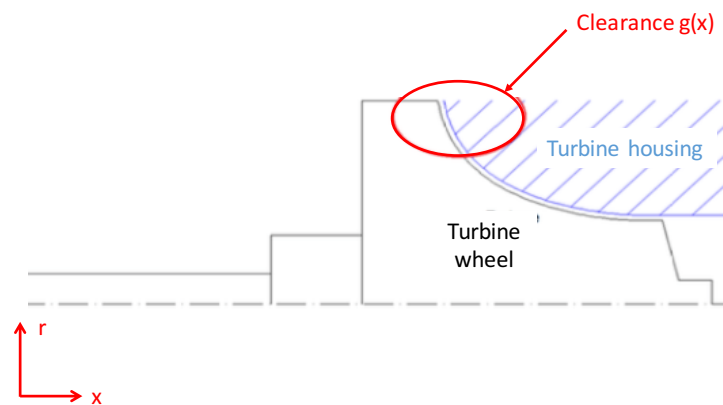


Figure 1. Tolerance on the turbocharger (schematic representation, adapted from [1])

2.2. Measurement uncertainty evaluation: Method 1

2.2.1. Uncertainty budget and test plan. The measurement method 1, reproduce the mechanical verification through a calibrated gauge able to measure the position B along the rotation axis, where the axial profile of the turbine achieves a diameter ϕ_{gauge} of given value, with reference to the plane A (figure 2). Carefully analyzing the method of measurement, the following uncertainty causes are envisaged:

- a lack of significance of the tolerance B: as the angle α increases, the tolerance gradually loses physical meaning and tends to align with the axis of rotation, while the clearance has a radial direction;
- a strong influence of the slope of the turbine profile at the point where the measurement is performed, on the control of the profile itself, performed through a single point identified by a predetermined diameter.

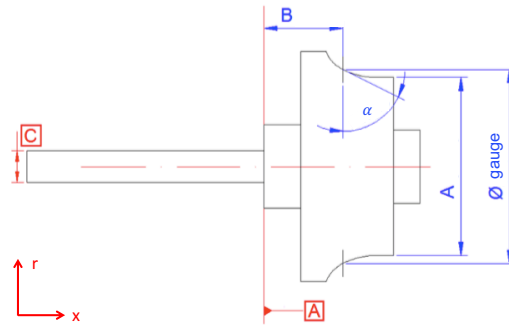


Figure 2. Measurement design for tolerance checking on the turbine wheel, measurement method 1 (schematic representation, adapted from [1])

Thus, the main uncertainty components may be summarised as follows (figure 3):

- the uncertainty of the instrument itself, when measuring an axial distance, dx' ;
- the variability associated to the reference plane, needed to perform the differential measurement, dx_A ;
- the influence of the slope of the profile, at the point where the measurement is performed, $dx(\alpha)$;
- the misalignment between the axis of the component and the reference axis of the measuring system, $dx(\theta)$.

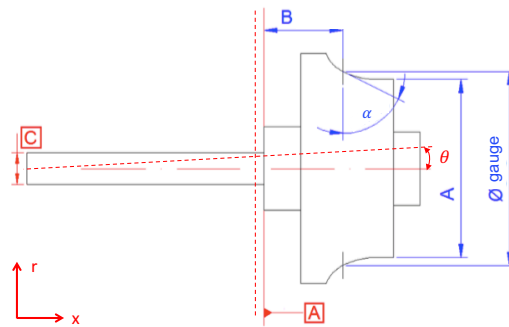


Figure 3. Schematic representation of the main uncertainty causes for measurement method 1

2.2.2. Indicators for measurement uncertainty. If we wish to use the optical instrument to obtain the abscissa for which the turbine realizes a given diameter (as required by the set tolerance, B, in Fig. 3) the instrument is required to provide a differential indication, of the type in equation (3) [1]:

$$dx = dr \tan \alpha \quad (3)$$

where α is the angle of the profile with respect to the normal to the x-axis. It is clearly noted that the variability corresponding to dr is amplified with increasing angle α and that this makes unsatisfactory capability indices calculated with respect to the set tolerance. As far as for the measurement method 1, by applying equation (1), the measurement uncertainty dB for the abscissa B is given by equation (4):

$$dB = dr_g'(x) * \tan(\alpha) + dx_A + dx' + dr(\theta) * \tan \theta \quad (4)$$

2.2.3. Measurement uncertainty results. As far as for the measurement method 1, the analysis of the uncertainty components leads to the following:

- the variability corresponding to dr is amplified with increasing angle α ;
- as the angle α increases, the tolerance gradually loses physical meaning and tends to align with the axis of rotation, while the clearance has a radial direction;
- the control of the profile through a single point is strongly influenced by the slope of the profile itself at the point where the measurement is performed.

2.3. Measurement uncertainty evaluation: Method 2

2.3.1. Uncertainty budget and test plan. As far as for the measurement method 2, it directly considers the measurement of the radius (or the diameter) of the impeller body. The reference axis for the measurement system has been chosen according to the grinding process of the turbine wheels. This measurement method leads to the following uncertainty components (figure 4):

- the uncertainty of the instrument itself, when measuring a radial distance, dr_g' ;
- the influence of the slope of the profile, at the point where the measurement is performed, $dr(\alpha)$;
- the misalignment between the axis of the component and the reference axis of the measuring system, $dr(\theta)$.

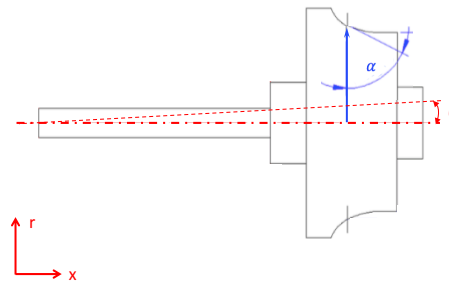


Figure 4. Schematic representation of the main uncertainty causes for measurement method 2

2.3.2. Indicators for measurement uncertainty. On the other hand, the measurement uncertainty of the radius r_g , which is the expected quantity as for the new measurement method, is given by equation (5):

$$dr_g = \frac{dx'}{\tan(\alpha)} + dr(\theta) + dr_g' \quad (5)$$

2.3.3. Measurement uncertainty results. The new measurement method, on the other hand, shows that:

- high values of α reduce the whole uncertainty, since it reduces the effect of the uncertainty of $\frac{dx'}{\tan(\alpha)}$ of the axial positioning of the optical calliper;
- the misalignment between the optical axis of the calliper and the positioning axis of the shaft of the turbocharger is made negligible by the ability of the optical gauge to recreate virtually the rotation axis of the turbocharger, which is the reference axis of the grinding process; the strength of the manufacturing process becomes the strength of the control process as well, being this component of the measurement uncertainty really negligible;

- the profile is the result of an interpolation based on more measurements taken along the profile itself, thus reducing the whole uncertainty, with respect to a single measurement point.

Ultimately, the efficaciousness of the measurement method 2, with respect to the measurement method 1, is proved.

3. Results

A set of 30 turbochargers are measured, by means of the optical gauge. The results obtained by using the two measurement methods are compared in terms of their capability indices C_p , C_{pk} , P_p , P_{pk} .

Tests are carried out at different values of the angle α in order to understand the differences between Method 1 and Method 2, for different geometries of turbochargers.

The differences between the two measurement methods are evaluated by means of the indices for statistical process control. With reference to the former specification of the tolerance B (Method 1), in figure 5a and figure 6a the process capability evaluation data for a turbine profile with a small angle α are given, with a lower tolerance specification limit (LSL) of 20.1 mm and an upper tolerance specification limit (USL) of 20.2 mm. Data processing allows us also to predict, based on these performance values, the out-of-specification value, which resulted unsatisfactory.

With reference to the latter specification of tolerance and the general profile form (Method 2), the data of the process capability evaluation for a turbine profile with a low angle α are shown, with an LSL of 0 mm and a USL of 0.1 mm, are shown in figure 5b and figure 6b. The performance indices are greatly improved [20].

Similar satisfactory results are obtained with reference to the potential capability (within-capability) data and the overall capability data in terms of C_p and C_{pk} and in terms of P_p and P_{pk} , for a turbine profile with a large angle α [20].

The actions realised demonstrated that the measurement uncertainty reduction can be seen as a contribution to the knowledge of the system, also in respect to other competence areas.

The analysis of differences between the presented methods in terms of SPC indicators aims at predicting possible improvements in terms of the following productive advantages:

- a reduction in the necessary controls;
- a reduction in the dedicated manpower;
- a reduction in the observed scrapes, which are often false alarms;
- a reduction in the time taken for the operation.

4. Conclusions

In this work, with reference to the online control procedure of the critical geometrical dimensions of a high-performance turbocharger for automotive applications, the uncertainty budget and the modelling of the measurement process are carried out for two different measurement methods, both implemented on the same high-performances optical calliper.

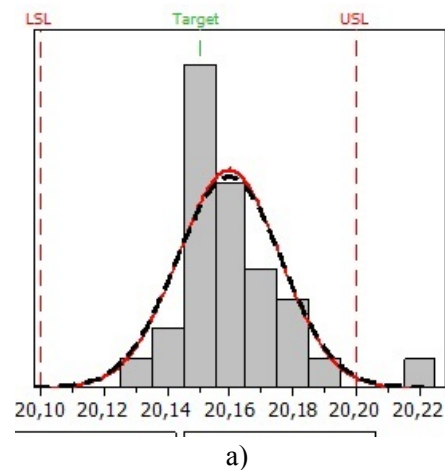
The preventive analysis of the uncertainty budget of both methods allowed to correctly address the use of the calliper, depending on the dimensional characteristics of products (e.g. low/high values of angle α), basing the uncertainty budget on the modelling of the uncertainty causes and their effects for each measurand.

The construction of the uncertainty model requires to take into account measuring, production and operating topics. Furthermore, the following aspects have been achieved:

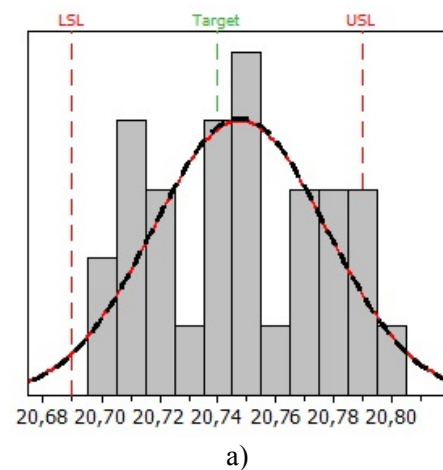
- concepts translation in order to interpret them from a physical perspective;
- studying the past actions for tolerances designing;
- tolerances re-designing;
- exploiting the force of the technological processes to define measurement references.

In conclusion, a structured and iterative approach supports the possibility of both addressing some

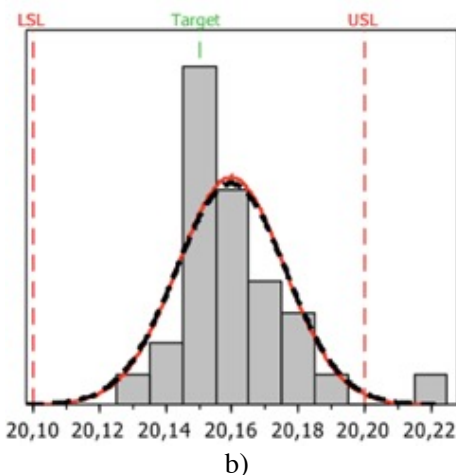
improvement actions and of validating their effects. This is expected to reduce the randomness of opportunity of further actions, that is the “uncertainty” of the improvements themselves.



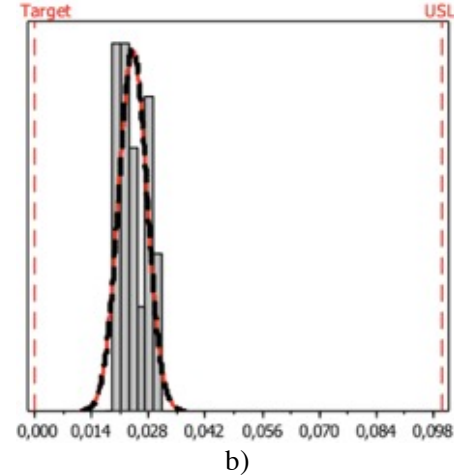
a)



a)



b)



b)

Figure 5. SPC of turbocharger – P_{pk} with a low α angle: Method 1 (a) and Method 2 (b) – redrawn from [1].

Figure 6. SPC of turbocharger – P_{pk} with a high α angle: Method 1 (a) and Method 2 (b) – redrawn from [1].

References

- [1] D’Emilia G, Di Rosso G, Gaspari A and Massimo A 2015 Metrological interpretation of a six sigma action for improving on line optical measurement of turbocharger dimensions in the automotive industry *Journal of Automobile Engineering* **229-2** pp. 261-269
- [2] Kiraci E, Franciosa P, Turley G A, Olifent A, Attridge A and Williams M A 2016 Moving towards in-line metrology: evaluation of a Laser Radar system for in-line dimensional inspection for automotive assembly systems *International Journal of Advanced Manufacturing Technologies* DOI 10.1007/s00170-016-9696-8
- [3] Jenoptic, HOMMEL-ETAMIC opticline C300, [Online]. Available: <https://www.jenoptik.com/us-optical-shaft-metrology-hommel-etamic-opticline-c300> [Accessed 05 16 2016]
- [4] Śladek J 2016 A Coordinate Metrology, Measurement Uncertainty and Requirements of Production System. *Selected Issues of Measurement Uncertainty Theory Springer Tracts in Mechanical Engineering* Springer-Verlag Berlin Heidelberg DOI 10.1007/978-3-662-48465-4_2
- [5] Gaspari A 2016 Measurement-uncertainty: an innovative management tool in modern engineering systems *Ph.D. Thesis, University of L’Aquila (Italy)*

- [6] D’Emilia G, Gaspari A 2016 Measurement-uncertainty as an innovative management tool in modern engineering systems *14th IMEKO TC10 Workshop on Technical Diagnostics 2016: New Perspectives in Measurements, Tools and Techniques for Systems Reliability, Maintainability and Safety* pp. 197-202
- [7] Baia O, Jamshidib J, Kiracib E, Williams M A, Galettoa M, 2017 Measurement strategy impact on dimensional inspection by portable camera-based measuring systems, *Precision Engineering* **47** pp. 516–527
- [8] JCGM – 100:2008 Evaluation of measurement data — Guide to the expression of uncertainty in measurement
- [9] ISO 14253-2:2011 Geometrical product specifications (GPS) - Inspection by measurement of workpieces and measuring equipment - Part 2: Guidance for the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product verification
- [10] ISO 10360-8:2013 Geometrical product specifications (GPS) - Acceptance and reverification tests for coordinate measuring systems (CMS) – Part 8: CMMs with optical distance sensors
- [11] ISO/TS 23165:2006 Geometrical product specifications (GPS) -- Guidelines for the evaluation of coordinate measuring machine (CMM) test uncertainty
- [12] ISO 15530-3:2011 Geometrical product specifications (GPS) - Coordinate measuring machines (CMM): Technique for determining the uncertainty of measurement - Part 3: Use of calibrated workpieces or measurement standards
- [13] Montgomery D C and Runger G C 2003 *Applied Statistics and Probability for Engineers*, 3rd Ed., John Wiley and Sons, Inc.