Measurement uncertainty of turbine flow meter calibration used in conformity assessment for water management

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Abstract. Water management is a relevant activity for society, for industry and for consumers, requiring transactions based on measurement. To ensure confidence to all users, a high level of measurement quality is required to enable conformity assessment to be acceptable in the definition of market conditions by the stakeholders. The practical implementation of conformity assessment to equipment requires the definition of decision rules, on acceptance or rejection of its performance, depending on the accuracy of measurements. Liquid turbine flow meters are common equipment used to measure flow velocity and volume of water in many water supply systems. To approve the use of this type of equipment it is necessary to provide measurement traceability and to evaluate and use the measurement uncertainty in the applied decision rules. This paper describes a new framework to use measurement uncertainty obtained by calibration in the definition of decision rules for conformity assessment.

1. Introduction

Water resources management is today of increasing importance, with a large impact on economic and financial relations between entities and consumers, often relying on the quality of measurement in a context of conformity assessment.

The measurement of quantities such as flow rate and volume can be obtained using a wide range of measuring instruments, with selection usually based on the compatibility between metrological performance and requirements of intended applications (fit-for-purpose).

The use of turbine flowmeters is still widely common as measuring device, being able to perform volumetric measures of flow with acceptable accuracy for many water supply providers. There are several studies of the physical behavior of this type of equipment, e.g. [1], including the knowledge of input quantities, mathematical model and sources of error [2], which are mainly due to the mechanical transduction and the nature and behavior of fluids. However, the introduction of the probabilistic concept of measurement uncertainty related to measurands raised the need to redefine the decision rules for conformity assessment [3]. Moreover, in this case there is still an additional interest of assessing the impact on the measurement quality of field installation, often in harsh conditions.

LNEC has a long tradition in making joint research with water service providers and stakeholders in Portugal, aiming at promoting higher levels of measurement quality, and improving the confidence in

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market relations between municipalities, industry and consumers. This resulted in strong cooperation studies combining research with technical applications and experimental testing.

In a different perspective, the recent revision of ISO/IEC 17025 [4] brought to the scope of accreditation the need to make a careful definition of decision rules applied to conformity assessment with a risk based approach. Therefore, it becomes clear the need to provide procedures that include the uncertainty contribution as an updated approach of decision rule criteria for compliance evaluation.

2. Liquid turbine flow meter calibration by a gravimetric method
The calibration procedure of liquid flow meter (for full pipe flow) was developed using LNEC hydraulic test rig (Figure 1), able to generate volume flow rate up to 0.500 m$^3$/s and mass flow rate up to 350 kg/s, for conduits with nominal size between DN80 and DN400 (4 testing lines 15 m long) with a CMC of 0.3% and 0.03%, respectively. The operation of the system includes an underground water supply tank (net capacity of 340 m$^3$), and vertical axis hydraulic pumps with variable speed drive.

The LNEC research infrastructure setup include hot deep galvanised steel pipes and fittings, grooved end quick couplings and full bore shut-off valves at both ends. The primary gravimetric mass flow meter is based on 2 weighing platforms with water weighing tanks measuring apparent mass of water, with net capacities of 1 700 kg and 17 000 kg, secondary standards (electromagnetic flowmeters) and time/frequency counters.

A turbine flow meter (invented by Reinhard Woltman) is an equipment able to perform volumetric measurements. Transduction transfers energy from a flowing fluid to the mechanical motion of a rotor causing it to rotate with angular velocity proportional to the flow rate of the fluid. The measurement chain includes a classic mechanical transfer to a counter or the generation of an electrical signal (typically sine wave), in the latter case the pulse electrical signal and its frequency are counted (pulses by volumetric unit), being the speed of rotation proportional to flow rate. The mathematical model is:

$$\omega_f = \omega_t \cdot \frac{R}{v} = \tan(\alpha),$$  

where, $\omega_t$ is the angular speed of the blade, $R$ is the radius of the blade, $v$ is the average velocity of the fluid and $\alpha$ the angle between the blade and the vertical axis of the rotor. Being $Q$, the volume flow rate and $A$, the effective area of the conduit, a relation between the volumetric flow rate and the angular speed is obtained,

$$\omega_f = \bar{v} \cdot \frac{\tan(\alpha)}{R} = \frac{Q}{A} \cdot \frac{\tan(\alpha)}{R} = \frac{\tan(\alpha)}{RA} \cdot \frac{Q}{k} = \frac{Q}{k}$$  

In this work, the gravimetric start-stand method was used to determine the total flow. Calibration was based on a comparison between the volume measured by the turbine flow meter for a time interval with the volume collected by the gravimetric reference system (including ambient conditions) for the same time interval (input quantities measured are the weight of collected liquid, density of fluid – for the measured temperature – and time interval, allowing to evaluate the related reference volume).

The evaluation of measurement uncertainty of the calibration was develop following the GUM procedure [5], accounting for the uncertainty related to the reference gravimetric system, the
materialization of the quantity, the metrological characteristics of the calibrated equipment and the computational process of the testing. The combined measurement uncertainty of calibration of 0.50% was obtained considering the following contributions: (i) reference weighing system, with a standard uncertainty of 0.20%; (ii) method, with a standard uncertainty of 0.38% (including the sources of uncertainty related to the stability of flow, piping vibration, geometry influence, isothermal compressibility factor of the liquid and thermal expansion coefficient of the liquid); (iii) and turbine flow meters under calibration, with a standard uncertainty of 0.25% (including the main sources of uncertainty, namely, resolution, non-linearity, temperature effect, pressure effect and repeatability).

3. Conformity assessment and decision rules adopted
Calibration of turbine flow meters has been an activity developed at LNEC to support compliance assessment related to a contract between suppliers and municipalities, according to national legislation and common knowledge about this type of equipment performance. Compliance criteria are commonly based on the performance data of manufacturers, and are used to define tolerance limits in many circumstances for which estimates of calibration errors need to comply. The introduction of measurement uncertainties in this process require a different approach to the procedure of assuring confidence intervals concerning the compliance of tolerances defined by standards, regulations, and legal or contract requirements. These tolerances are related to reference values of flow (minimal, transitional, permanent and overload – see Fig. 2), which allows ± 5% tolerance between $Q_1$ and $Q_2$ and ± 2% between $Q_2$ and $Q_4$. For measurements below $Q_1$ tolerance is not defined, because measurement is considered not valid.

![Figure 2. Tolerances defined by manufacturers.](image)

Usually conformity assessment can follow two main approaches [3], in order to accept or reject calibrated instruments:
- One approach is to consider a test of hypothesis that could be made for each measurement estimate of error and related uncertainty; and
- an alternative approach, is to define guard bands for the tolerance interval, possible if the error estimates have uncertainty of similar amplitude. In this case, conformity assessment should consider only the value of the estimate. Figure 3 shows the typical diagram of an interval tolerance with guard bands (the guard band is simply equal to 95% expanded uncertainty).

![Figure 3. Example of areas defined for a tolerance interval with guard bands.](image)

Legend: $T_U$ – Tolerance upper limit; $G_U$ – Acceptance zone upper limit; $T_L$ – Tolerance lower limit; $G_L$ – Acceptance zone lower limit; $U(y)$ – expanded uncertainty of the measurement.
The guard band interval can be introduced knowing the confidence level needed (usually 95%) and the standard uncertainty of the estimates. In this case, statistical test of hypothesis can be defined in order to determine the size of the guard band. Considering that the test for conformity defines a decision rule for the probability \( P_c \) with the acceptance condition (3),

\[
P_c = P(\eta \leq T_U) = \Phi\left(\frac{U - y}{u(y)}\right).
\]

It follows that, for the lower limit of upper guard band applied respectively to 5% and 2% tolerance, with 95% confidence level, \( 0.95 = P(\eta \leq T_U) = \Phi\left(\frac{5.0-y}{0.50}\right) \) and \( \frac{5.0-y}{0.50} = \Phi^{-1}(0.95) \) will give

\[
y = 5.0 - 0.50 \cdot \Phi^{-1}(0.95) = 5.0 - 0.50 \cdot 1.64 \approx 4.2 \text{ m/s}
\]

\[
y = 2.0 - 0.50 \cdot \Phi^{-1}(0.95) = 2.0 - 0.50 \cdot 1.64 \approx 1.2 \text{ m/s}
\]

4. Experimental results with compliance analysis and conclusion

To study the impact of measurement uncertainty in real cases, a set of 8 turbine flowmeters were calibrated, having different conditions of use (from 10 years installed to new equipment). Steps for the testing were defined according to the recommendations of manufacturers and applications, taking measurement for nominal values of flow velocity of 0.5 m/s, 1.0 m/s and 2 m/s. Tolerances were adopted according with the tolerance found in Figure 2 and a confidence level of 95% required for acceptance. Results obtained for the set of flow meters can be found in Figure 4.

The analysis shows that, introducing the guard band, two of the flow meters (n. 5 and n. 8) would be accepted if the decision rule considers only to the estimate, but rejected if the uncertainty is also taken into account. In fact, the increase of uncertainty implies the growth of guard bands and the increase of risk of rejection of calibrated equipment, thus requiring special care with the accuracy of calibration.

In a broader context of equipment management, this approach can be useful to establish the conditions to promote corrections of the readings after calibration, the definition of calibration intervals, and the metrological conformance.

5. References

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