ON THE NECESSITY OF DYNAMIC CALIBRATION FOR IMPROVED TRACEABILITY OF MECHANICAL QUANTITIES

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Abstract − Dynamic calibration still poses many challenges for measurement and data analysis. However, we show that without a proper dynamic calibration misleading results are obtained as static calibration approaches to dynamic measurement applications are inappropriate. We illustrate expected improvement in uncertainties when dynamic calibration information is available, and we conclude that further research in this direction is necessary in order to improve measurement capabilities and reliability.

Keywords: Traceability, dynamic calibration, uncertainty evaluation, convolution

1. A DYNAMIC APPROACH IS NECESSARY

With the rapid development of engineering and specifically the automotive industry after the 2nd World War it was discovered that the static approach to the measurement and traceability of mechanical quantities was not sufficient and a dynamic approach was necessary. For example, in the 1960s a guideline document [1] states that "… the frequency response of a force transducer heavily depends on the masses of the whole measurement setup coupled to the transducer…" and "…in order to make statements on the transducer's behavior (in the application) the transducer has to be calibrated along with all coupled masses". As the guideline [1] focuses on the automotive industry it not only considers force, but also dynamic torque, stating that "… due to the analog behavior of translatory and rotatory movement the same basis has to be applied for the dynamic calibration of torque transducers…". The measurement of dynamic torque is essential for power calculations, as well as efficiency determinations of combustion engines and electrical drives, and thus the scope of the guideline [1] is already very broad. In recent years it has become evident that the development of dynamic calibration techniques for mechanical quantities is essential, and this has led to a renaissance of research in this topic.

In particular, the availability of traceable dynamic calibration of pressure and torque is a key requirement in the automotive industry [2, 3]. For instance, measurements at engine test stands often reveal deviations between directly measured dynamic torque and the result of a calculation of torque from measured dynamic pressure in the combustion engine. An explanation of these deviations requires traceable dynamic calibration of pressure and torque.

Dynamic measurements are carried out routinely in many industrial applications [4]. However, owing to the lack of a metrological infrastructure and common guidelines, these are generally not traceable. Where primary dynamic calibration at NMIs is available, often the transfer to industry is deficient, mainly due to the lack of practical guidelines and software tools for the efficient using of dynamic calibration results. Instead approximate analysis of dynamic measurements is carried out by using rule-of-thumb methods, or static methods are utilized and additional uncertainty contributions for dynamic errors are estimated or simply ignored. This has an enormous impact on decisions and further calculations, which are based upon these dynamic measurements.

Several National Metrology Institutes (NMIs) have already started research in the area of dynamic calibration, e.g., in the joint European research projects JRP IND09 "Traceable dynamic measurement of mechanical quantities" and JRP IND16 "Metrology for ultrafast electronics and high-speed communications". However, many challenges still exist, and with new measurement capabilities, such as torque in the range of over 5 MN m, new challenges for dynamic measurements and dynamic calibration will arise.

To foster research in this area of metrology, in this contribution we aim at demonstrating the benefit and necessity of dynamic calibration. Therefore, we briefly introduce the joint research of European NMIs, and we illustrate the effect of neglecting dynamic effects in the measurement analysis.

2. JOINT EUROPEAN RESEARCH FOR TRACEABLE DYNAMIC MEASUREMENT OF MECHANICAL QUANTITIES

The aim of EMRP project JRP IND09 "Traceable dynamic measurement of mechanical quantities" was to establish a foundation for traceable primary calibration of dynamic torque, force and pressure [5]. The project was undertaken from 2011-2014 by nine NMIs and four industrial collaborators. In addition, much support, in terms of official letters of interest, came from the automotive industry, aerospace, production, transport and process control. As an outcome of the project, European NMIs are now capable of

providing more advanced dynamic calibration of torque, force and pressure for a wide range of applications.

However, effective dissemination of dynamic calibrations requires specific advice to industry end users on how to use calibration results to correct measurements for dynamic effects and to demonstrate compliance with the *Guide to the expression of uncertainty in measurement* (GUM) [6]. In addition, to describe the dynamic behavior of the complete application system, it is necessary to gather in-depth-knowledge of all components of the measuring chain including the surrounding environment, cf., e.g., [7]. These topics were out of the scope of the EMRP IND09 project. Hence, although encouraging progress has been made in this project, successful exploitation at the industry level is still challenging. The most important reason for this is the lack of generic mathematical and statistical methods that can be applied effectively and with confidence by industrial end-users, in particular, in the reliable evaluation of uncertainties. Existing methods are often focused on specific applications or have challenging requirements [8-12]. If there is no continued work in these areas, the barrier to the application and further development of dynamic metrology in industry remains. Thus, further investigations are necessary addressing mathematical challenges, e.g. modeling of the complete measuring chain, and practical challenges, e.g. stiffness investigations of torque disc design vs. response characteristics or the traceability of a dynamic bridge standard for carrier frequency (CF).

To this end, mathematicians from NPL and PTB together with industrial partners HBM and Rolls-Royce set up a collaborative project in the scope of the EMPIR "Support for Impact" program [13]. The aim of this collaboration is the provision of guidelines specifically targeted at industrial end-users, material for JCGM WG1 to consider in future supplements to the GUM and the development of a comprehensive open source software package [14]. However, to achieve a harmonized treatment of dynamic metrology at the NMI level and the industry level, much greater effort is necessary, taking into account a wide range of applications. There is an imminent need for guidelines that provide a harmonized approach to the analysis of dynamic measurements and the evaluation of dynamic measurement uncertainty.

3. CHALLENGES IN DYNAMIC METROLOGY

The challenges in dynamic metrology have been recognized widely. For instance, the *Bureau Internationale des Poids et Mesures* (BIPM) in 2012 held a workshop which demonstrated that there is a large spectrum of applications with common mathematical and statistical challenges. The report of this workshop states that "there is a need to clarify the terminology, which has to cover diverse quantities" and that "a common approach to the uncertainty evaluation is required from static to dynamic measurement". The current guidelines in metrology, VIM and GUM, are inadequate for this purpose, and even their currently proposed revisions do not cover these areas.

As dynamic measurements play a key role in many areas in metrology and industry, there is a huge number of applications which would benefit from improved calibration facilities and readily available mathematical and statistical methods.

In the automotive industry the development of car engines requires various dynamic measurements, for instance, to ensure that regulations on carbon emissions are satisfied, to validate improvements in engine design and to assess compliance with tolerances in the manufacturing process. The dynamic measurements include time-dependent measurement of torque, force and pressure.

In the aeronautical and space industry the design and characterization of satellite instrumentation involves a number of measurements which are dynamic in nature.

The control of processes in transport of solids and fluids requires reliable flow measurements and dynamic weighing. Often, multiphase flows are involved which often can be measured efficiently by means of process imaging. Improved statistical methods for uncertainty evaluation would enable industrial users to associate reliable uncertainties with such measurements.

In the lighting and display industry measurement of the spectral content of light emitting diodes (LEDs) and related devices requires compensating for wavelength-dependent distortions caused by the measurement device. Improved mathematical and statistical methods would help to increase confidence in the analysis of such compensations.

In the manufacturing of electronic devices the compliance assessment of high-speed electronics typically includes high-speed sampling and real-time oscilloscopes or similar devices which require compensating for dynamic effects caused by insufficient bandwidth of the device. The uncertainties associated with this compensation have a huge impact on the reliability of compliance assessment.

In medical imaging ultrasound devices play an important role and are becoming increasingly important for cancer treatment by high-pressure ultrasound penetration. The characterization of ultrasound devices requires dynamically calibrated hydrophones to compensate for dynamic effects caused by the measurement device. International standards provide an established quasi-static approach for hydrophone compensation. However, their limited applicability compared to a true dynamic approach has been recognized.

Measurements of energy network infrastructure, such as, e.g., PMUs, are important for the assessment of power grid stability and contracting. These measurements are often complex dynamic measurements under non-steady state conditions and evaluation of measurement uncertainties is challenging.

In some industrial areas attempts have been started to overcome the limitations of rule-of-thumb uncertainty evaluation and single-parameter characterization. However, available mathematical and statistical methods are focused mainly on NMI-level applications. Regarding data analysis and evaluation of measurement uncertainties at the industry level, there currently is a lack of best-practice guidelines and practical methods that can be applied by industrial end-users. Developments at industry level for the analysis of dynamic measurements are often based on expert knowledge and simplified approaches. And they lack a generic mathematical and statistical approach and a common

vocabulary. This hinders the exploitation of synergies between application areas and the establishment of documented international standards and guidelines: that is, developments so far have considered only idealized situations or specific applications, whereas a prerequisite for a harmonized and traceable treatment of dynamic measurements is a common vocabulary and generic mathematical and statistical approaches.

Several mathematical and statistical approaches that are required, such as, for example, auto-regressive process modelling, high-dimensional data analysis, MIMO state-space models and regularization of inverse problems, are also topics of research in applied mathematics. However, available methods are typically not ready for their application at the industry-level, e.g., owing to the requirement for application-specific adjustments or the lack of validation using actual industrial applications. Progress towards mathematical methods suitable for dynamic metrology at the industrial level is starting slowly. However, a general applicability and acceptance of these methods requires further research and validation in actual applications.

4. UNCERTAINTY EVALUATION FOR DYNAMIC MEASUREMENTS

The analysis of a dynamic measurement and the corresponding evaluation of measurement uncertainty depend on the approach to the estimation of the measurand. For dynamic measurements of mechanical quantities the mathematical relation between the measurand $y(t)$ and the observed indication values $\boldsymbol{x} = (x_0, \dots, x_N)$ is typically given by a convolution of the measurand with the measuring system's impulse response $h(t)$

$$x_n = (h * y)[n]. \qquad (1)$$

The model (1) corresponds to the assumption that the measuring system can be modelled as a linear time-invariant (LTI) system. The difference between the measurand and the observed system output values depends on the dynamic properties of the system employed. In particular for measurands with a frequency content which is broad compared to the system's bandwidth, the observed system output shows time-dependent deviations. A typical example is signal ringing due to a resonance frequency of the system. Such deviations are called *dynamic effects.*In practice, often the dynamic effects caused by the measurement setup are ignored and the measurement is treated as static. That is, the value of the measurand is estimated as

$$\hat{y}_n = \frac{\hat{x}_n}{\hat{H}_0}, \qquad (2)$$

with H_0 a correction factor obtained from a static calibration of the measuring system. According to the GUM, the uncertainty associated with the static estimate (2) is then given by

$$u^2(\hat{y}_n) = \frac{u^2(\hat{x}_n)}{\hat{H}_0^2} + \frac{\hat{x}_n^2}{\hat{H}_0^4} u^2(\hat{H}_0). \qquad (3)$$

However, such a static analysis ignores the influence of the measurand's frequency content on the measurement

result. As a consequence, the calculated uncertainties do not reflect the actual reliability of the estimated result. This can be seen by taking into account the systematic error, caused by the static estimation (2), in the uncertainty evaluation. In [11] the following upper bound on the dynamic error has been derived:

$$|\Delta| \le \frac{1}{2\pi} \int_{-\pi f_s}^{\pi f_s} \left| G(e^{j\omega f_s}) H(j\omega) - 1 \right| \cdot \bar{A}(\omega) d\omega =: \gamma \qquad (4)$$

with H the frequency response of the measuring system, G the frequency response of the applied estimator and $\bar{A}(\omega)$ such that the amplitude of the Fourier transform $Y(\omega)$ of the measurand $y(t)$ satisfies $|Y(\omega)| < \bar{A}(\omega)$ for all ω. Ideally, the estimator satisfies $G(e^{j\omega f_s}) = H^{-1}(j\omega)$, in which case γ in equation (4) is equal to zero for all $\bar{A}(\omega)$. In practice, this holds true only up to a certain frequency ω_0 owing to the necessity of suppressing noise, see also Figure 1.
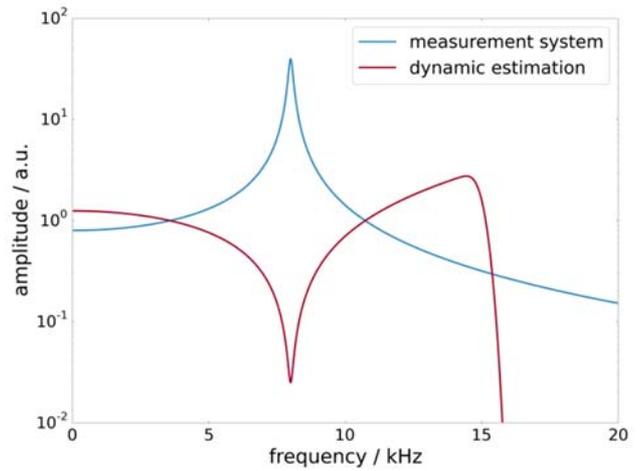

Figure 1 Amplitude of the measurement system frequency response and that of a correponding dynamic estimator

In the case of static estimation, $G(e^{j\omega f_s})$ becomes the constant H_0^{-1} and the corresponding error bound is

$$\gamma = \frac{1}{2\pi} \int_{-\pi f_s}^{\pi f_s} |H_0^{-1} H(j\omega) - 1| \cdot \bar{A}(\omega) d\omega. \qquad (5)$$

The first term of the integrand in (5) represents the deviation of the measuring system from a perfect dynamic behaviour. The second term $\bar{A}(\omega)$ denotes a weighting of the system's imperfection over frequency. That is, the larger the frequency content of $\bar{A}(\omega)$, the larger the error (5).

In a dynamic estimation one determines an approximation to the reciprocal of the system's frequency response. That is, the estimation function G is determined such that

$$G(e^{j\omega f_s}) \approx H^{-1}(j\omega) \qquad (6)$$

for a certain frequency range [12]. In this way, the dynamic error caused by the measuring system can be reduced. Figure 2 illustrates the difference between a dynamic and a static estimation for an example of a system with a single resonance frequency.

Following [10], the uncertainty contribution of the dynamic error (4) is given by

$$u^2(\gamma) = \frac{\gamma^2}{\sqrt{3}}, \qquad (7)$$

which follows by assigning a uniform distribution on $[-\gamma, \gamma]$ as a state-of-knowledge probability distribution for the dynamic error. The overall uncertainty associated with the static estimate (3) is then given by

$$u^2(\hat{y}_n) = \frac{u^2(\hat{x}_n)}{\hat{H}_0^2} + \frac{\hat{x}_n^2}{\hat{H}_0^4} u^2(\hat{H}_0) + \frac{\gamma^2}{\sqrt{3}}. \qquad (8)$$
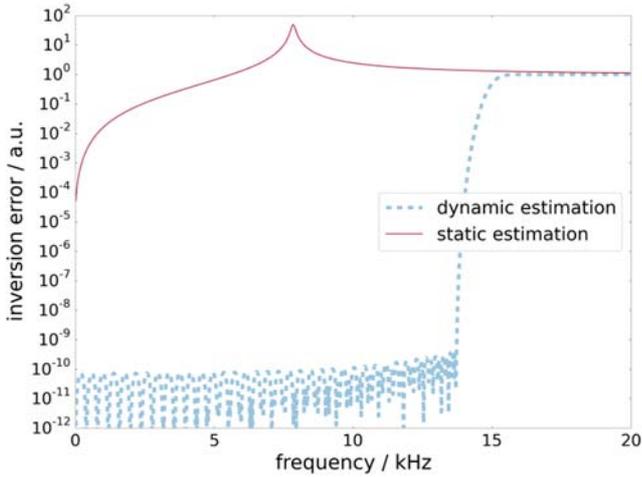

Figure 2 Example of inversion error corresponding to first term in equation (4) for static and dynamic estimation

Thus, the uncertainty associated with the static estimate increases with increasing dynamic error. That is, for measurands with large bandwidth a static estimation results in a significantly larger uncertainty. This is illustrated in Figure 3 for a measurand which resembles a Gaussian pulse and the measuring system from Figure 1.
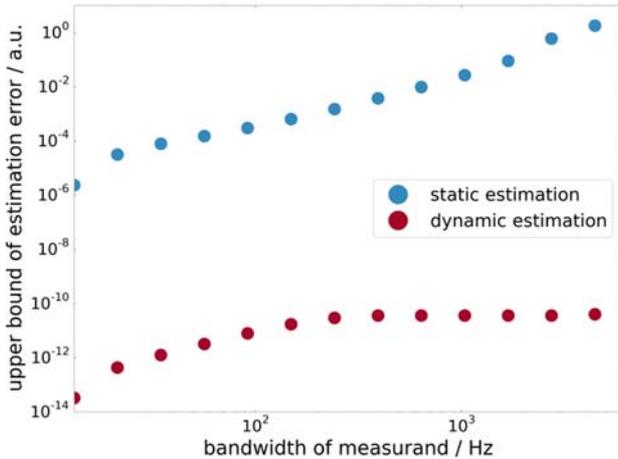

Figure 3 Dynamic error (4) depending on the bandwidth of the measurand for a system with resonance frequency at 8 kHz.

The uncertainty contribution of neglecting the dynamic effect increases significantly for a measurand with large bandwidth, cf. Figure 3. In contrast, the remaining dynamic error after a dynamic estimation mostly consists of numerical artefacts. Moreover, Figure 3 illustrates that neglecting the dynamic error in the uncertainty evaluation results in an unreliable uncertainty budget associated with the estimated result. That is, the estimation error, which remains after a static estimation, as shown in Figure 4, is usually much larger than the uncertainty associated with the static estimate when not taking into account the dynamic behaviour of the measuring system.
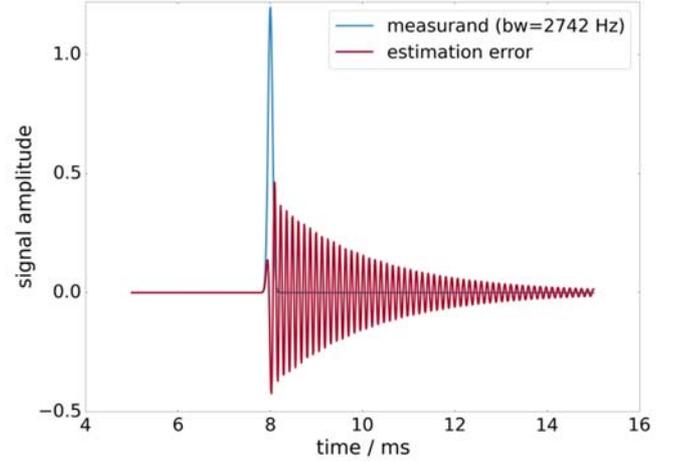

Figure 4 Example estimation error for static estimation of a measurand with bandwidth of about 2.7 kHz.

A prerequisite for a dynamic estimation is the knowledge of the measuring system's frequency response $H(j\omega)$, cf. [11]. It has to be obtained from a dynamic calibration of the measuring system. Typical calibration signals for dynamic calibration measurements are sinusoidal excitation or shock excitation. In both cases the excited frequency range has to cover the range of frequencies likely to be excited in the application. This poses a challenge for NMI-level primary calibration and often requires the development of completely new approaches to calibration. For instance, a calibration setup suitable for static calibration of torque transducers cannot be utilized for a dynamic calibration, because the calibration setup is designed to generate defined static torque values.

5. CHALLENGES IN THE ANALYSIS OF DYNAMIC MEASUREMENTS

Apart from the measurement challenges in dynamic metrology described in section 3, there are a number of mathematical and statistical challenges in the analysis of dynamic measurements.

Mathematical approaches for dynamic measurements differ significantly from their counterparts in static measurements (e.g. inverse problems instead of algebraic equations and noise process modelling instead of simple variances). Current developments in dynamic metrology are very problem-specific whereas the underlying mathematical and statistical models are quite generic. The prerequisite for a harmonized treatment of dynamic measurements is thus joint work incorporating different quantities and industrial

applications. This cannot be carried out by a single NMI, but requires international collaborations.

Statistical modelling approaches have to be developed that allow the evaluation of metrology compliant uncertainties associated with time series, spectral measurements, images and high-dimensional data sets. This includes the translation of knowledge about quantization errors, jitter noise, instrumentation and sensor properties etc. to reliable uncertainties and the practical determination of correlations between measured values for high-dimensional data. Practical signal processing methods for dynamic metrology have to be developed together with mathematical and statistical methods for the corresponding evaluation of measurement uncertainty.

Analysis of dynamic measurements requires practical approaches to regularization in deconvolution tasks, which are applicable to time series as well as multi-dimensional data sets, including spectral measurements, images, as well as 3- and 4-dimensional representations of objects, engineering components and their behaviour.

Finally, mathematical and statistical methods for the transfer and use of calibration results are needed in order to enable traceability in dynamic metrology. For non-parametric calibrations, such as impulse response calibration, this poses the requirement for methods for the treatment of very large covariance matrices and their compact representations, whereas the utilization of parametric dynamic calibration of mechanical quantities typically requires the incorporation of the calibrated sensor model into a model of the applied measuring system.

6. CONCLUSIONS

Research on dynamic calibration has recently gained much attention and good progress has been made in some areas. However, to date dynamic metrology is mainly applied at the NMI level, and there is a lack of guidelines and reliable methods for industrial users. To this end, new research is required as well as an awareness of the benefits of dynamic metrology.

We have demonstrated that neglecting the dynamic nature of a mechanical system can lead to significantly larger or even unreliable uncertainties in measurements with that system. The negative effect of neglecting the dynamic nature of the measuring system increases with the bandwidth of the measurand. Only a fully dynamic estimation of the measurand can reduce the uncertainty contribution of the dynamic error. However, the prerequisite for that is a dynamic calibration of the whole measuring system.

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