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EVALUATION OF DYNAMIC MEASUREMENT UNCERTAINTY FOR INDUSTRIAL APPLICATIONS

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Abstract: Industrial applications are often based on dynamic measurements. The analysis of these measurements, however, is usually based on static analysis. Therefore, many National Metrology Institutes (NMIs) are developing methodologies for the analysis of time-dependent, i.e. dynamic, measurements. This article demonstrates and discusses how industrial applications can benefit from NMI-level measurement analysis and the evaluation of dynamic uncertainties.

Keywords: dynamic measurements, digital signal processing, dynamic weighing, signal analysis

1. INTRODUCTION

Despite of over a decade of active developments and even roots back to the 1960ies [1], the field of dynamic metrology and the analysis of dynamic measurements has still to be divided into National Metrology Institute (NMI) - level expertise and industry-level applications. The European research project "EMRP IND09 Traceable dynamic measurement of mechanical quantities" [2], with HBM as an international supplier of transducers and measuring instruments acting as a collaborator, is an example of a project which attempts to unify these two worlds. In the course of this project primary dynamic calibration for the quantities force, torque and pressure as well as dynamic calibration of bridge amplifiers, together with the correspondingly required mathematical and statistical tools have been developed and investigated. In this way, IND09 laid the foundation for traceable dynamic measurements of these three mechanical quantities and the required amplifiers. Other national and international research projects were carried out on a world-wide basis in order to develop fundamental capabilities at NMIs and dedicated laboratories in the area of dynamic metrology [3]. As an outcome, at least some NMIs can now offer dynamic calibration for a range of physical quantities at least on a research project basis, with the transformation to a standard NMI service being actively developed.
At the industry level, despite of a dynamic measurement environment being the common practice, static calibration of the measuring device remains to be the status quo instead of dynamic calibrations. There are several reasons for this undesired situation: First, one has to consider the tremendous effort necessary for carrying out a dynamic calibration. In addition, there is a lack of guidelines and standards for secondary dynamic calibration; often the practical transfer of NMI-level primary calibration to the industrial application is still a topic of research; the mathematical and statistical methods required for the traceable analysis of dynamic measurements are of course to be pioneered at NMI-level. In this contribution, we want to elaborate on this issue, the applicability of recently developed mathematical and statistical methods for the analysis of industry-level, real-life measurements. As an example, we consider the reduction of undesired dynamic effects in several applications, such as the output of a dynamic weighing instrument together with the assignment and propagation of dynamic measurement uncertainty in order to obtain a traceable measurement result. That is, the analysis methods applied to the raw measured data have to be combined with an uncertainty evaluation in line with the *Guide to the Expression of Uncertainty in Measurement* (GUM) and its supplements [4].

2. CHOOSING HARDWARE ACCORDING TO REQUIREMENTS

In measurement engineering, a measuring chain generally consists of a sensor and a conditioning amplifier. For instance, sensors for kinematic or mechanical quantities, such as force, torque, pressure, acceleration or angular rate usually have to be completed by some conditioning amplifier in order be to further processed or indicated. In order to trace the measurement result back to SI units and to make components exchangeable, one needs to characterize the whole measuring chain – either as a whole or the individual components independently.

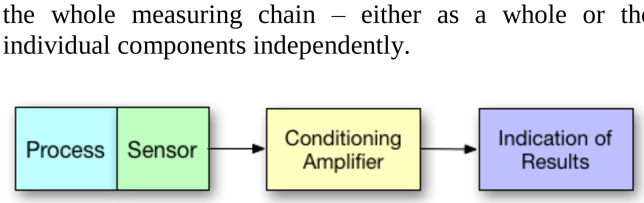

Figure 1: Schematic view of a dynamic measuring chain

The amplifier can be observed separately from the system and therefore can be optimized much easier, especially if it is a stand-alone unit as depicted in Figure 1. This system consideration plays an important role. The transducers behaviour is typically depending on suspension, mounting conditions and other environmental effects, making its optimization challenging. The optimization of the measuring amplifier, on the other hand, as a middle element of the dynamic measuring chain, is much less challenging.

With strain gauge transducers and amplifiers the highest resolution is only reachable with low bandwidth. HBM introduced high precision instruments such as the DMP series as early as 1980. DMP39, the first instrument of the DMP series was developed in close collaboration with the German National Metrology Institute (PTB) to realize an instrument beyond the demands of industry, exploring the physical limits at that time.

Its extreme accuracy, however, was possible only with a slow response, which could no longer be accepted for continuous calibration of e.g. force transducers and led to the MGCplus ML38B amplifier, released by HBM in 2005 [5]. Subsequently also HBMs new flagship precision measuring instrument, the DMP41, released in 2013, allows the physically best possible signal-to-noise-ratio, but also a measuring bandwidth of 0… 50 Hz (with now an applied measuring rate of 225 Hz). In a dynamic calibration, though, the frequency response of the amplifier has to be sufficiently flat over a wide range of frequency. This concern is important for a whole range of applications [6-8].

In order to provide better measuring instruments as tools for all of these applications, HBM, as a result of dynamic testing, was able to create a product with improved transfer function over the wide range of frequencies needed for dynamic measurements. This has been launched as the new HBM QuantumX MX410B conditioning amplifier. In the course of the investigations, dynamic suitability has been verified by PTB [8, 9].

As a next step it is planned to investigate further amplifier types, such as the QuantumX MX 430B, which is able to combine both static and dynamic calibration [10]. As a result, the user can choose from a number of amplifier modules, namely QuantumX MX238B, QuantumX MX430B and QuantumX MX410B in fine steps of very different accuracy-bandwidth combinations, depending on the real needs of the specific measuring task. The existing diversity of modules at HBM alone reflects the wide range of measurement tasks, such as needed on test rigs, to perform efficiently by covering many different measurement principles and aspects.

Based on sophisticated hardware, digital signal processing allows further implementation of improvements. However, this has to be accompanied by fundamental research in measurement science and here NMI and industry are joining forces. The next section shows how this can be applied efficiently with economically very relevant topics.

3. APPLICATION-ORIENTED TREATMENT OF SIGNALS

An economically very relevant key figure for step function applications is the time you need to reach a measured value within a specified range. Since this measured value is often a quality parameter, it must be possible to determine with a sufficiently small measurement uncertainty.

An example for a strong economic impact of dynamic measurements is the manufacturing and packaging of goods, where the time needed to provide analysis results may represent a relevant contribution to the fabrication costs. This makes dynamic weighing, for instance by check-weighers, an especially important field of dynamic applications. Other application fields where a dynamic analysis has a strong economic background are, e.g., automatic slicing devices for goods such as sausages or cheese. A common tool in the post-processing of dynamic weighing measurement data are digital low-pass filters. Generally, Butterworth and Bessel filters can be chosen to achieve low-pass filter characteristics widely used in industry to suppress unwanted higher frequency interferences that lie above a specific cut-off frequency. The filter amplitude response, runtime and step response are dependent on the filter characteristics. The differences between Bessel and Butterworth characteristics are shown in Figures 2. The Butterworth characteristic (blue curve) shows linear magnitude response with a steep drop above the cut-off frequency. On the other hand, an overshoot in the filer's step response of approx. 10 % occurs. The Bessel characteristic (red curve) shows a step response with very small (<1 %) overshooting. The amplitude response, however, drops less sharply than for the Butterworth filter. This behaviour originates from the different filter design criteria used for the filter types; the Butterworth criterion is to reach a flat frequency response in the pass band whereas for the Bessel filter the criterion is a constant group delay in the pass band.

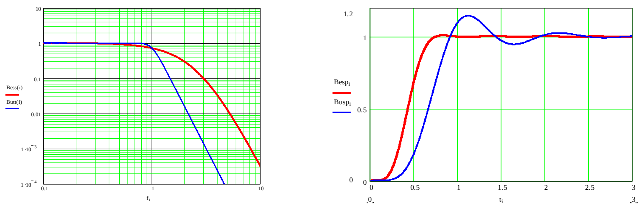

Figure 2. Frequency response (left) and step response (time domain, right) for Bessel (red) & Butterworth (blue) filters of a measuring amplifier

Thus the Butterworth filter fits if, e.g., in a material testing machine sine shape excitation is used, because the magnitude in the required frequency range is given most accurate. The Bessel filter is to preferred for any kind of unknown (stochastic) signals and also for fast transient signals, where overshoot has to be minimized. As a conclusion, for the example application considered here Bessel low-pass filters should be the better choice.

We here focus on check-weighers as our example of choice and carried out a test measurement with three statically measured packages (representing the product to be weighed), which are placed on the check-weighing instrument manually in an approximately equidistant way.

These dynamic weighing measurements were carried out in a small setup that mimics a real-life check-weighing environment as it can be found in many assembly lines at industry. The environment for the here considered test data was not controlled regarding temperature, humidity, vibrations or other possibly disturbing influences. The pieces under test were measured statically with a calibrated scale with an uncertainty negligible for the here considered scenario. Placement of the pieces under test was carried out manually in a close-to periodic way. Movement of the pieces onto and from the weighing active part of the conveyor belt happened uncontrolled, leading to additional dynamic effects in the measured data. Figure 3 shows an example of such a data set measured with the described setup. The three incidents of pieces under test moving onto and from the weighing region clearly can be seen. However, many dynamic effects in this measurement make this data difficult to use without a proper processing of the data beforehand.

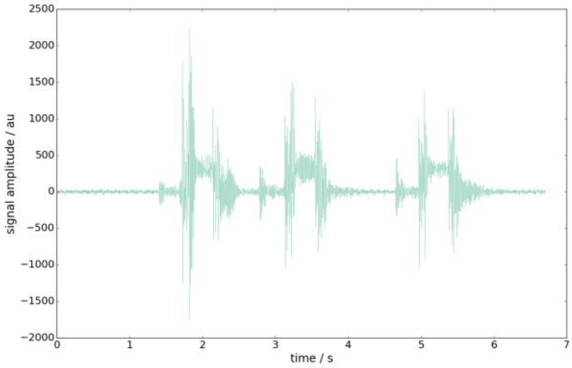

Figure 3 Example measured data acquired from the check-weighing instrument.

This experiment resembles a real-life application of dynamic measurements in several ways. The main challenge compared to NMI-level examples is that the measuring device is not identified in detail, making an ideal correction of systematic effects challenging. In particular, the check-weighing instrument could not bee calibrated dynamically beforehand. Additionally, the dynamic effects due to the movement of the pieces under test onto and from the weighing region of the line can typically not be described by standard NMI-level modelling approaches for dynamic systems. In practice, the dynamic disturbances in the check-weighing output data are attenuated by means of the application of digital low-pass filters. That is, one utilizes the fact that the desired measurement information about the mass of the pieces under test remains constant while the piece is moving along the weighing region of the setup. A low-pass filter is thus applied to reduce dynamic effects, such as signal ringing, caused by the dynamic response of the check-weigher.

4. DATA ANALYSIS AND PROPAGATION OF UNCERTAINTIES

For the analysis of the measured data from the dynamic weighing experiment, we consider the application of a finite impulse response (FIR) low-pass filter and the application of an infinite impulse response (IIR) low-pass filter. Data analysis is carried out in the open-source Python package *PyDynamic*, developed by the Physikalisch-Technische Bundesanstalt (PTB, Germany) and the National Physical Laboratory (NPL, UK) [11].

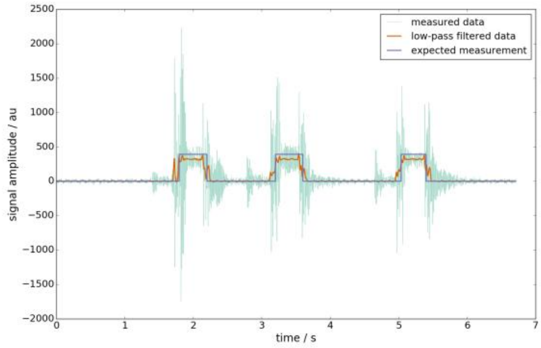

Figure 4 Result of the application of a low-pass filter with cut-off frequency of 20 Hz and the expected measurement based on the static weighing of the pieces under test.

The propagation of uncertainties requires associating an uncertainty with the raw measured data. Therefore, independent noise measurements were carried out with the measurement setup to determine the statistical properties of the measurement noise.

4.1 Application of an FIR low-pass filter

An FIR-type low-pass filter is applied to the raw measurement data with different cut-off frequencies to investigate the effect of the low-pass filter on the height of the region of interest in the resulting output data. For the propagation of the uncertainty associated with the raw measurement data through the application of the filter, the *PyDynamic* routine *FIRuncFilter* is applied. In a first step, we assume a fixed cut-off frequency for the filter. Then, we consider an uncertainty associated with the cut-off frequency, propagate this uncertainty to the filter coefficients using the GUM Monte Carlo method and propagate this uncertainty to the filter output using again *FIRuncFilter*. In addition, we consider taking into account systematic effects in the measurement based on the static calibration of mass. With these approaches, the signal characteristics can be improved whilst maintaining traceability.

4.2 Application of an IIR low-pass filter

An IIR-type low-pass filter is applied to the raw measurement data in the same way as the FIR-type filter. For the propagation of uncertainties, the *PyDynamic* routine *IIRuncFilter* is applied, which implements a transformation of the filter to a state-space system, followed by a GUM-compliant on-line propagation of uncertainties through the linearized state-space system [12]. Similar to the FIR filter case, we consider fixed cut-off frequencies as well as an uncertainty associated with the cut-off. Also, we consider taking into account systematic effects based on the static calibration of mass.

The different filter types can then be compared with respect to their deviation from the static mass measurement taking into account the uncertainty associated with the measurement result.

5. SUMMARY AND CONCLUSION

Using *PyDynamic*, NMI-level data analysis can be employed in practical applications to easily propagate uncertainties through the application of digital filters [13]. For the here considered case study, the availability of the filter outcomes with their associated uncertainty allows for a quantitative assessment of their quality. The possibility to associate an uncertainty with the low-pass filter cut-off frequency provides a convenient and traceable way to express uncertainty in the correct low-pass filter design. For the approximate deconvolution filter, the lack of actual dynamic calibration data can be expressed in an uncertainty associated with the filter itself. The propagation of this uncertainty to the filter output can then, again, be carried out easily using *PyDynamic*. Thus, traceability can be retained and propagated through the data analysis even for dynamic measurements and basic digital signal processing. In this way, it is possible to quantitatively assess the signal processing chain which follows the acquisition of raw measured data in industrial application.

Traceable dynamic measurements have first been required by the automotive industry [16]. However, measurements are performed under dynamic conditions in other applications, too, such as aerospace, production, transport or process control. High-speed data acquisition and modelling are necessary to develop advanced dynamic measurements. The analysis and measures considered in this work help to reach an improved accuracy and reduce the time needed to provide it. As they could have direct impact on the packaging speed and well as a proper weight of goods, it is of high economic relevance. This is why further investigations are planned at industry as well as at NMIs.

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