Dynamic Measurements as an Emerging Field in Industrial Metrology

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1 Motivation

Since its foundation in the fifties of the last century, i.e. for more than six decades, our company has been serving mechanical engineering as a manufacturer of complete measuring chains from sensor through data processing to software. The first products were amplifiers and inductive transducers. In 1955, the company – as the first company in Europe at all – started the production of strain gauges. This turned out to be a huge success story. Today, strain gauge-based reference transducers and precision instruments are used in the static calibration of quantities such as force, torque and pressure, since this allows the lowest possible measurement uncertainty to be achieved for the measuring chain as a whole. So it is no wonder that in 1977, HBM was the first company ever in Germany to be accredited as an official DKD (German Calibration Service), now DAkkS, calibration laboratory.

HBM headquarters in Darmstadt, Germany.

Of course, given our wide range of industrial applications, we have also been among the first to see the emergence of new requirements in terms of measurement bandwidth and, in the last decade, also of dynamic measurement. Germany was among the leaders in addressing these new challenges. For example, Rohrbach in his *Handbook of Electrical Measurement of Mechanical Quantities* [1] issued in the sixties of the last century, having full understanding of the complexity of this new approach wrote: "… the frequency response of a force transducer heavily depends on the masses of the whole measurement set-up 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". This book not only talks force, but even covers torque already "… due to the analogue behaviour of translatory and rotatory movement the same basis has to be applied to the dynamic calibration of torque transducers …" .

2 Industry and Research Joining Together

The complexity of this approach may have been the reason why it has not been followed up in the following decades. Anyway, with the beginning of the new century, it suddenly gained a new urgency [2]. This was due to the fact that processes became faster and, e.g., power and efficiency measurement required that these aspects be looked into as well. In the beginning, dynamic calibration still meant that mechanical quantities were measured only in a state when they were constant over time; however, industrial users needed "a dynamic state" (varying over time-> which is what really happens in the application). For torque, a second phenomenon has to be considered, i.e. the fact that today torque transducers are mounted in calibration machines in non-rotating set-ups, while industrial users are interested in "rotating conditions". Therefore, the actual application is "dynamic". Hence, dynamic calibration is the logical successor to static calibration. However, this approach is new and standards for dynamic calibration still have to be developed.

Project meeting of NMIs in EMRP IND 09 at PTB, Braunschweig, March 2014.

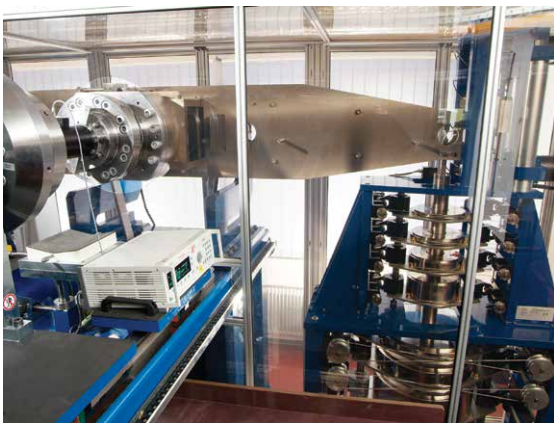
In the field of force transducers, this applies mainly to aerospace and materials testing (e.g. in material testing machines). In the field of torque, automotive and shipbuilding applications are of interest. Here, in-line torque measurement is required, i.e. measurement directly in the drive train of ships. More stringent regulations (e.g. for emission limits) require substantially increased accuracy of torque measurement. Eventually, measurement of both rotational speed and power must be certified.

NMIs, too, were facing these challenging requirements from industry. As a result, attempts have been made to develop the required calibration and traceability infrastructure within NMIs. A major step has been implemented in the framework of EMRP (*European Metrology Research Project*) and EURAMET, the *European Association of National Metrology Institutes*.

HBM booth at the XX IMEKO World Congress in Busan, Korea.

Besides the project entitled IND09 *Traceable Dynamic Measurement of Mechanical Quantities*, I want to write about another project entitled IND16 *Metrology for Ultrafast Electronics and High-Speed Communications* that paved the way for this new approach. In any case, the project IND09 in particular has established a metrological infrastructure for traceable dynamic calibration of the considered quantities at the NMI level.

To cope with the new challenges facing metrology – within the framework of EURAMET – good ways to organize research cooperation with industry were contemplated. HBM, like other industrial providers, regularly takes part in IMEKO events. This covers not only the IMEKO World Congress, but also events of technical committees and several joint meetings. So it was no wonder that HBM was among the first to know when EURAMET started the so-called EMRP calls.



Torque calibration machine at HBM.

Force calibration machine at HBM.

What made the topic of JRP IND09 *Traceable Dynamic Measurement of Mechanical Quantities* outstanding was its vision. Although static calibration still seems to be prevailing in real-life applications, the automotive industry, in particular, is very interested in dynamic calibration research with a focus on mechanical quantities. In our experience, it is always crucial to such projects that not only measurement providers be interested but also "end users". In our case, these were automotive companies and, luckily, Volkswagen AG and Dr. Ing. h.c. F. Porsche AG joined the project as collaborators. Also, under the supervision of mainly PTB, NPL, LNE but also MIKES all initial project partners attached highest importance to asking their end users to contribute support letters to the project. In the end, approximately twenty parties supported the project.

3 Fruitful Dynamic Workshops

A great milestone in the project was the international workshop on *Challenges in Metrology for Dynamical Measurement* taking place at the BIPM (Bureau International des Poids et Mesures) near Paris in November 2012. The event was headed up by Dr. Takashi Usuda and Dr. Thomas Bruns. It was on their initiative that HBM was invited to give one of the main lectures. The workshop was meant to cover talks from both industry and NMI experts, including room for discussion.

The workshop opened with two papers, the first from Dr. Tatsuo Fujikawa of Japan Automotive Research Institute entitled *Requested Reliability of Dynamic Mechanical Measurement in Mobility from Automotive to Humanoid Robot* and the second by HBM (presented by Dr. André Schäfer) entitled *Challenges in Dynamic Torque and Force Measurement with Special Regard to Industrial Demands*. Subsequent presentations, e.g. by Rolls-Royce, UK, picked up on the same topics: "… reduced safety factors demand improvements of measuring uncertainty". Another industry speaker was from Volkswagen do Brasil. The presentations are available for downloading from the BIPM server [3].

The HBM presentation pointed out that foil type strain gauge transducers are most accurate for torque and force measurement and that using measuring bodies from steel and titanium allows measurement of very high force and torque values. HBM described the advantages of offering complete measuring chains to the user. HBM pointed out that, eventually, the dynamic behavior of the complete application system needs to be described while good knowledge of the dynamic behavior of the components (transducers, DAQ units) is the first essential step in the right direction. Subsequently, these components were specified in the project's [4] different work packages. Major conclusions of the workshop were that measuring chains implemented at national level as well as reference transducers have to be as effective as possible and, at industrial level, above all affordable. We were proud to be able to contribute to an overall picture that was created for the first time ever.

The event attracted an international audience and participants developed task lists and further discussed these issues in breakout sessions, contributing to the conclusions drawn at the workshop.To name only a few of the approximately 60 participants from 25 countries' NIMs: France (LNE), China (NIM), United Kingdom (NPL), Germany (PTB), USA (NIST), Japan (AIST), Italy (IMGC), Netherlands (VSL), Spain (CEM), Sweden (SP), Seychelles (NML), Kenya (KBS), Bosnia Herzegowina (IMBIH), Korea (KRISS), Taiwan (ITRI-CMS), Chile (IDIC), Mexico (CENAM), Singapore (NMC), Poland (GUM), Malaysia (SIRIM), Austria (BEV), Switzerland (METAS), Ukraine (Urkme), Egypt (NIS) and Brazil (INMETRO).

In the further course of the project a *Workshop on Analysis of Dynamic Measurements* took place in Torino, Italy in early 2014. It focused not only on the analysis of dynamic measurements, but also on applications. To name only one presentation, *Analysis of Shock Force Measurements for the Model-based Dynamic Calibration* [5] has shown that the results gained from the model-based dynamic calibration of market-relevant (and most of them HBM) force transducers are quite encouraging.

4 Progress Through Exchange of Information

Of course, experts from HBM went to Braunschweig for meetings and experiments in the specific fields during the project. Still, what I want to highlight here is the visit of a PTB working

Participants of the "8th Workshop on Analysis of Dynamic Measurements" May 2014 in Turin, Italy.

group to HBM. HBM's company culture is centered around the concept of dialog for stimulating new approaches and breaking new ground. New impulses come, not only from customers. Moreover, in our endeavor to be innovative we are open to rethinking fundamental aspects. For this reason, it was very much welcomed that the PTB project working group made it possible to come to HBM. More than 20 people, mainly from HBM's R&D department, followed our guests' presentations with keen interest. And, indeed, who could better convey the idea of dynamic calibration than the presentations of our guests Dr. Thomas Bruns, Dr. Michael Kobusch and Dipl.-Ing. (FH) Leonard Klaus? The illustration of this new dimension has been very well received by HBM's developing engineers. HBM project participants received lots of positive feedback over the following months. And for the guests, too, it was interesting to see the laboratories and production lines in our factory. Bearing in mind the new approach, we were able to consider the possible outcome and what will be possible in future.

The second day of the visit focused on specific activities and detailed discussions with our experts for force transducers and torque transducers. Here, design ideas and phenomena were discussed.

Also the resulting approaches for analogue and digital data acquisition items of the talks were indeed very concrete. It can be said that they were completely dedicated to the question of how further requirements can be implemented.

HBM T40B as an example of investigated torque transducers in the project.

The greatest progress made in the project was in the field of data acquisition, since PTB is in need of suitable equipment as a basis for proper investigations at the NMI level for carrying out the work packages of the project. Thus the measurement manufacturer, participating as a collaborator in this project, not only had to come up with suitable sensors, but also conditioning amplifiers [6]. It is a fact that all sensors have to be connected to some kind of conditioning amplifier for further processing or display (a *measuring chain*). To ensure traceability of such a measuring chain and also to make its components exchangeable, it is essential to characterize each of the components of a measuring chain (sensor and conditioning amplifier) independently.

It has been shown that conditioning amplifiers need to provide an even, i.e. flat, frequency response (up to a certain cut-off frequency). On the other hand, the industry requires that DAQ systems fit into an increasingly digital environment. However, such commercially available digital conditioning amplifiers do not have a flat frequency response.

HBM U9B as an example of investigated force transducers in the project.

Thus, as a result of the talks, HBM created a DAQ system with an even frequency response that can claim to be dynamically suitable. To achieve this objective, the digital filter functions of an adequate module have been optimized. The MX410B module – a four-channel highly dynamic universal amplifier of the QuantumX DAQ series – meets this requirement and thus proved to be suitable for dynamic calibration. MX410B is a conditioning amplifier that works with direct current (DC) and 4.8 kHz carrier frequency (CF) while at the same time being fast and universal. The full bridge configuration plays an important role for the mechanical quantities considered here such as force, torque and pressure. The module can either be used with DC excitation for maximum dynamics or with distortion-immune carrier-frequency excitation. The module described above thus could fulfil the requirements of the NMIs participating in the project.

HBM QuantumX MX410B, a versatile and dynamically suitable digital conditioning amplifier.

Needed frequency response of a bridge amplifier.

5 Making Research Results Known Worldwide

One important goal of EMRP is to facilitate closer integration of national research programs and to disseminate the newly gathered knowledge, ensuring collaboration between the National Measurement Institutes as well as with industry, thus reducing redundancy and increasing impact. To put it succinctly: The overall goal is to accelerate innovation in Europe.

Today, the internet is a powerful tool for reaching this goal. Therefore, the project consortium has thought about how to transfer this knowledge to an international audience. In the framework of the project, a *Best Practice Guide* has been made available on the website [8] of IND09 *Traceable Dynamic Measurement of Mechanical Quantities* to everyone, on an international basis.

Furthermore, ongoing efforts toward setting up DKD guidelines in Germany, which are currently taken by the DKD Technical Committee *Force & acceleration* played an important role, too. Documents such as *Dynamic Calibration of Uniaxially Stressed Force Measuring Instruments and testing Machines* as well as *Calibration of Measuring Amplifiers for the Dynamic Measurement of Kinematic and Mechanical Variables*, which are going to be implemented in the DKD – R 3-2 Directive, have been worked out in collaboration with HBM. Of course, one day, the development of methods, technologies and standards for these important applications will be required and finally a specific GUM supplement will have to be created.

In the meantime, this topic has been explored in other events organized by HBM, e.g. the torque seminar at MPA (State Material Testing Institute) [7] or our in-house event *HBM@home*, both held in Darmstadt, Germany. Talks presented at these

Lecturers at the torque seminar at MPA (State Material Testing Institute) in Darmstadt.

events made contributions to better traceability from the NMI level to secondary calibration laboratories and further down, so far only established under static conditions. Some of the attendees, from secondary calibration laboratories as well as from industry expressed their great interest in the topic by very detailed questions. For this reason, we will continue to disseminate our knowledge on the new approach, as dynamic traceability, especially for mechanical values, as well as traceability of high nominal force and torque values is a requirement for further successful developments in industry.

Simposio de Metrologia, Queretaro, Mexico, October 2014.

The latest proof of the importance was shown at the *Simposio de Metrologia* in Queretaro, Mexico on the occasion of the 20th anniversary of Mexico's NMI, CENAM in October 2014, where the topic of dynamic calibration was dealt with extensively [9, 10].

6 Conclusions

Traceable dynamic measurements were first required by the automotive industry. However, measurements are performed under dynamic conditions in other applications, too, that are served by our company, such as aerospace, production, transport or process control. In addition, increasingly complex measurement configura-

tions require characterization and implementation of mechanical multi-component measurements. High-speed data acquisition and modelling are necessary to develop advanced dynamic and/or multi-component measurements. Our customers increasingly demand traceability for their dynamic measurements and a clear representation of the corresponding measurement uncertainty.

The development of methods, technologies and standards is required for these important applications. As a collaborator in the EMRP project *Traceable Dynamic Measurement of Mechanical Quantities* [8], we can now evaluate, that this topic is subject to an increasing worldwide interest.

Although encouraging progress has been made in the project, successful exploitation at the industry level still is challenging. One 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. This lack may still present a barrier for the application and further development of dynamic metrology in industry. For this reason we think further investigations will be necessary, such as stiffness investigations of torque disk design vs. response characteristics or the development of traceability of a dynamic bridge standard for carrier frequency.

Combining dynamic behavior and larger structures could present another challenge. An example of this is wind energy generation. For torque measurement, the kilonewton metre range is by far insufficient, meganewton metre values are rather required, and still conditions are "dynamic"! Therefore, we strive to make further progress in this field, either by joining new projects or through our own investigations.

We are well aware of the fact that the uncertainties of measurement which can be achieved with dynamic calibration, will – for the time being or, in principle, even for all of time – be markedly more significant than those already attained with static measurements today. It is essential that the expectations raised remain realistic, while at the same time reflecting the industry's requirements. Yet, what we offer is – compared to today's ignorance of these influences – real progress and closer to the "truth".

Users in industry are primarily interested in how mechanical quantities act on the test specimen, to what extent measuring body, electronics, and suspension affect the actual loading, and how this has to be accounted for. The "dynamic dimension" is definitely one of the major emerging fields in the industrial metrology of our century and this project has helped to close the gap between the present and future demands of industry and what NMIs and suppliers can offer.

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