Industrial Dynamic Measurements of Mechanical Quantities within the Inter-American Metrology System (SIM)

Alejandro Savarin¹; Federico Serrano¹; Guillermo Silva Pineda²; Jorge Torres Guzman³; Juan Alberto Arias Prieto³; Ivan David Betancur Pulido³; Akobuije Chijioke⁴; Nick Vlajic⁴; Renato Reis Machado⁵; Rafael Soares de Oliveira⁶

¹ INTI - Instituto Nacional de Tecnología Industrial. Avenida General Paz 5445, 1650, San Martín, Buenos Aires, Argentina
² CENAM - Centro Nacional de Metrología. Km 4,5 Carretera a Los Cués, Municipio El Marques, Querétaro, México
³ INM - Instituto Nacional de Metrología. Av. Carrera 50, no 25-55 int, Bogotá, Colombia
⁴ NIST - National Institute of Standards and Technology. 100 Bureau Drive, Gaithesburg, MD, 20889, USA
⁵ INMETRO - Instituto Nacional de Metrologia, Qualidade e Tecnologia. Av Nossa Senhora das Graças, 50, Prédio 3, Xerêm, Duque de Caxias – RJ – Brasil
⁶ E-mail: rsoliveira@inmetro.gov.br

Abstract. Most industrial measurements of force and torque are performed dynamically, while calibrations are performed mostly in static form. It is evident that the dynamic responses of the instruments are very different from the static responses. The National Metrology Institutes (NMIs) have been requested by industry to develop solutions for this gap in metrological traceability and have recently undertaken activities to do so. The Inter-American Metrology System (SIM) implemented the project “Industrial Dynamic Measurements (from industry to primary standard)”, involving the NMIs: INTI/Argentina, INMETRO/Brazil, NIST/USA, CENAM/Mexico and INM/Colombia. Main backgrounds, findings and outlooks of the project are highlighted in this paper.

Keywords. Dynamic Calibration; Force Metrology; Torque Metrology; Metrological Traceability

1. Introduction
Very many industrial measurements of mechanical quantities, for example force and torque, are performed dynamically, while calibrations are performed almost exclusively statically. Furthermore, it is evident that the dynamic responses of the instruments are often very different from their static responses. Once the demands for the design of products, machines or production and testing processes are improved in the industry, the measurement tolerances become narrower, so there is less leeway to disregard the differences between the behavior of the instrument in the static regime and in the dynamic regime. The National Metrology Institutes (NMIs) have been requested by industry to develop solutions for this gap in metrological traceability and have recently undertaken activities to do so.
There is a growing number of scientific papers published at recent conferences of the Technical Committee for Measurement of Force, Mass and Torque of the International Measurement Confederation (IMEKO TC3) addressing dynamic metrology themes such as traceability and challenges to measure these quantities in the dynamic regime [1].

Another important action was the realization, from 2011 to 2014, of the research program from the European Association of National Metrology Institutes (EURAMET) called “IND09 - Traceable Dynamic Measurement of Mechanical Quantities” [2]. The project of EURAMET had the objective of establishing traceability for three dynamic mechanical quantities: force, torque and pressure, providing the foundation for a European infrastructure for traceable dynamic measurements of these mechanical quantities.

Inspired by this new scenario representing a frontier of knowledge, the Subgroup of Force and Torque of the Metrology Working Group “Mass and Related Quantities” of the Inter-American Metrology System (SIM/MWG-7), under the scope of the Project “Strengthening National Metrology Institutes in the Hemisphere, in support of emerging technologies” with the Inter-America Development Bank (IADB), implemented the project “Industrial Dynamic Measurements (from industry to primary standard)”, involving the following NMIs: INTI/Argentina, INMETRO/Brazil, NIST/USA, CENAM/Mexico and INM/Colombia.

The main objective of the project was to promote the debate around dynamic traceability for these quantities in the SIM region, understand the behavior of the measurement equipment and parts under test in order to advise the industry on how to perform the measurement, and to select the appropriate instruments in usual applications. Traceability at the regional level will allow accredited laboratories to have their own secondary standards and/or perform calibrations of testing machines dynamically.

2. Methodology

As the studies on dynamic traceability are in their early stages, the project’s methodology focused mainly on leveling the knowledge between the NMI participants through the execution of knowledge transfer and learning activities such as technical visits, meetings and workshops.

Current and prior interactions with industry and calibration customer sectors were evaluated in order to quantify and qualify demands of force and torque transducers on measurement applications that involve or potentially involve significant dynamic effects on the measured quantity. From this very brief survey, several different sectors were identified and here we can highlight some as follows: mechanical tests (fatigue of metallic materials); environmental (vehicles emissions); energy (wind power); biomedical tests (fatigue implantable medical components); vehicle braking performance and drivetrain efficiency; motor performance; and dynamic tools (pneumatic & hydraulic tools in automobile sector).

Also, the NMIs were able to present their technical background, with the most recent research they were developing that could attend to these demands either in application-specific ways, or in more general forms reaching different applications.

This paper presents a milestone to the knowledge of metrological traceability applied to dynamic measurement in the SIM. This was a kick-off opportunity and, henceforth, further discussions on these topics must be facilitated.

3. Background

This session presents the highlights of the technical activities already achieved or under development by some NMIs, with a research envelope encompassing the range from primary standardization to test machine calibrations. Presentations on these technical activities allowed participants to observe points of convergence between the activities and objectives of the different NMIs, and the extent towards which current activities may address the industrial needs for traceability.

3.1. Primary standard for harmonic force calibration

The system, developed at NIST, allows the dynamic calibration of force transducers using harmonic excitation.
The force applied to the transducer is produced by the acceleration of an attached load mass, and is determined according to Newton’s second law. The acceleration is measured by laser interferometry and a bandwidth of 2 kHz with force amplitudes up to 2 kN, with an uncertainty level of 1.2 %, could be reached [3].

The primary standard for harmonic force calibration is at the top of the traceability chain for dynamic force, so its results can be used in other research under this approach, such as the dynamic calibration of fatigue test machines. For example, the same principle can be adopted to evaluate the dynamic behavior of the dynamic calibration device (DCD) (see section 3.3) isolated from the test machine, which will contribute to a better characterization of this device.

It was noted that the harmonic standard provides the primary calibration for base-driven harmonic dynamic force measurements, such as for force transducers used to measure mechanical mobility. For other types of dynamic force measurements, such as impacts and top-driven-base-supported configurations, the harmonic standard supports traceability as a verification system for the force transducer, but not as a direct calibration system. It was also noted that the approximation of a uniform acceleration within the load mass starts to break down as the operating frequency increases, and Newton’s second law \( F = m a \) must be replaced by its distributed integral over the load mass.

There are several opportunities for improvement of this standard and reduction of its uncertainty, which provided the scope for a three-month technical exchange between INTI, Argentina and NIST, USA. In this technical exchange, the focus was on real-time measurement of dynamic tilting, which can thereby be compensated, reducing the uncertainty of the obtained dynamic force in the harmonic standard. Implementation of this real-time measurement by photodetection and also by using accelerometers was investigated, providing increased opportunity for such measures to be implemented by different NMIs.

![Figure 1. Scheme of the Primary Harmonic Force Standard of NIST.](image)

A calibration system developed at CENAM to calibrate dynamic force transducers with piezoelectric sensing crystals which are used mainly in shock and vibration applications mostly required for the automotive industry. The documentary reference standards are ISO 16063-11 for primary calibrations using laser interferometry and ISO 16063-21 for secondary calibrations in comparison to a reference transducer. The primary calibrations according to ISO 16063-11 can achieve an uncertainty of the transducer sensitivity of about 0.5% in the frequency range from 1 Hz to 10 kHz; and the secondary calibrations according to ISO 16063-21 an uncertainty in the transducer sensitivity of about 1% in the same frequency range. The next Figure 2 shows the implementation of the primary and secondary calibrations of these dynamic force transducers with piezoelectric sensing crystals.
3.2. Continuous force

The continuous measurements aim to perform calibrations of industrial instruments in short times compared to static calibration and with simpler equipment than in dynamic calibration. This can be considered an intermediate step between static and dynamic methods, and therefore deserves special attention.

Continuous calibration of force transducers is already addressed in some standards, such as the German guideline DKD R-9 [4]. A continuous measurement involves measuring in real time a variable that varies continuously (usually with a constant rate of change). For the quantity force, the changes are slow enough that inertial forces can be neglected. Therefore, the laws of statics continue to be valid. However, the dynamic effects related to creep and hysteresis, as well as those related to digital amplifiers (filters, integration times, etc.) must be taken into account.

INTI has been working on the study of the application of continuous calibration in force. First, two transducers were mounted in series on a 100 kN deadweight force standard machine (DWFSM), to characterize them according to the DKD-R9 guideline and the PT-ST [5] method. Next, they were assembled with the same configuration, to maintain the same extreme force application conditions, in a reference force comparator machine (RFCM). In this machine, two ascending-descending step-by-step runs according to ISO 376 [6] were performed, and then several continuous ascending-descending runs with different force application speeds were performed.

Figure 3 shows the assembly of the transducers in the RFCM and the measurement sequence.

Because the desired uncertainty when using this method was set at 0.1%, only the results obtained at speeds up to 20 % FS / min (5 minutes to reach full scale) are compatible with this uncertainty.

The graphs obtained from the measurements show problems in the synchronization of different amplifiers. Therefore, it is estimated that higher speeds and even better results can be obtained if multi-channel amplifiers are used, for example with a data acquisition of at least 20 samples/s.

The ratio between speed rate and force in kN/s / kN decreases with the force, so the errors decrease strongly with increasing force. One solution could be to use a fixed kN/s / kN parameter, but this would only be achievable in equipment specifically designed and/or adapted for this purpose, thereby sacrificing the desired simplicity of the method.

INM is working on a comparison analysis between a 100 kN direct loading machine and a 1 MN hydraulic reference machine, in the common range from 20 kN to 100 kN. The purpose of the comparison is to verify the incidence of calibrating an instrument with a static force (direct load) and a continuous force (hydraulic reference machine), in order to determine if they are comparable. To develop the analysis, the creep correction of the transducer used for comparison was performed, since the value is known through the characterization in a direct loading machine so the correction due to this
effect can be performed. Currently, the study is in the data analysis stage, when some statistic tools can be applied. The NMI intends to publish results soon.

Figure 3. (Left) Transducers mounted in series. (Right) Different load profiles comparing ISO 376 with varying speed continuous calibration.

3.3. Dynamic calibration of fatigue test machines

In a fatigue test, the main influencing parameters for errors due to dynamic are the frequency range, the force amplitude/range and the different combinations of compliance of the test specimens. So, the verification/calibration of this type of machine must involve the variation and mapping of these parameters.

The standard ISO 4965 part 1 [7] describes a procedure for the calibration of the uniaxial force of fatigue test machines. Basically, the standard states that different dynamic configurations should result in different amplitudes of motion and that the relationship between the force amplitude ($\Delta F$) applied to a test specimen must be compared to the force amplitude indicated by the testing machine ($\Delta F_M$).

A Dynamic Calibration Device (DCD), comprised of a force sensor and some mechanical parts attached to provide compliance to the whole assembly, is used to obtain a reference force value. The standard’s procedure states that there must be a frequency sweep to a pre-determined force range. The error between the force range $\Delta F_M$ and the force range indicated in the DCD ($\Delta F_{DCD}$) is the calibration result.

Figure 4. (Left) DCD mounted in a uniaxial fatigue machine and (Right) errors for DCDs with three different compliances in the frequency range up to 15 Hz.
Figure 4 shows the DCD mounted in a fatigue test machine and the error plot for analyzing three DCDs with different compliances in a frequency range up to 15 Hz. INMETRO has been working on the research for the implementation of this Standard in recent years, and for more details on the description of the calibration procedure of ISO 4965-1 and other results achieved by this research, see reference [8].

3.4. Dynamic calibration of torque transducers

The dynamic traceability of torque is under research at INMETRO. The proposed principle adopts Newton’s second law applied to rotational movements. The reference inertial torque ($T_{ir}$) is generated by the product between the angular acceleration ($\dot{\omega}$) and a known mass moment of inertia ($\theta_r$), which is attached to the torque transducer to be calibrated. Angular acceleration pulses are applied, through the derivative of angular speed ramps. The torque measured in the transducer ($T_{tl}$) can be compared to the calculated torque $T_{ir}$ (Figure 5).

INMETRO has been working on this research and the proposed system and methodology have the objectives of evaluating the time-dependency of the quantity, prioritizing the application of torque rates, evaluating the differences between the values read from the transducer and those generated in the reference, and observing the susceptibility of the sensor to different kinematic conditions. More details on the measurement sequences and results achieved, showing the dependency of the torque measurement on the time and the torque profile region, can be found in [9].

![Proposed assembly for the dynamic calibration of torque transducer under the application of angular acceleration pulses.](image)

**Figure 5.** Proposed assembly for the dynamic calibration of torque transducer under the application of angular acceleration pulses.

The Mexican regulations related with the environmental protection request that all the vehicles have to be verified every six months to check the gas emissions are below the limits set by Mexican National Regulations. The vehicle under is placed on a chassis dynamometer and speed up to 40 km/h and then a constant brake torque is applied and the gas emissions from the vehicle are measured (Figure 6).

![Vehicle’s gas emission test when a known brake torque is applied.](image)

**Figure 6.** Vehicle’s gas emission test when a known brake torque is applied.
The transducer used to measure the applied brake torque to the vehicle has to be calibrated, in dynamic conditions, and traceable to national measurement standards. CENAM has developed the calibration techniques to calibrate the torque transducers used for these testing.

4. Discussion and Outlook
The presented background brought to light the overlap of needs within this SIM project, with the main objective of the activity being to discuss the progress and work at each NMI regarding dynamic measurements and how the whole group could use this information. Some of the main takeaways were:

- All dynamic experiments showed the need for different signal processing methods compared to those used in static calibration methods. For instance, dynamic measurements require higher acquisition rates and digital filtering. The group concluded that it is important to acquire an adequate knowledge to start working in this field. Some future activities of SIM should include the theme of digitization, synchronization and signal processing applied to mechanical quantities.

- The continuous calibration process can be very useful for rapid checking of machines and standards, being quite beneficial in reducing time, effort and cost. The proposed assembly is not too complex and the NMIs are able to reproduce the tests with easy adaptation of secondary force comparison machines. So, in the near future it will be possible to have a pilot study for comparison between NMIs for this type of calibration methodology.

- The results achieved in researching the calibration of fatigue test machines can be used by all NMIs. The standard ISO 4965 will soon undergo a revision process and fortunately has the participation of SIM representatives in its technical committee. Also, the results achieved in the primary standard for harmonic force can be introduced to the best use and design of the DCDs, characterizing the transducer’s dynamic response for the application setting.

- As a next step, a survey form to run inside the Regional Metrology Organization will be formulated. The idea is to approach the industry on the specific needs for dynamic measurements in the material testing field.

- The presented primary standard for harmonic force and the presented calibration of torque transducers, both realize calibration by primary methods. These approaches are more challenging to be reproduced in all NMIs but it is important that they keep a routine of following the international technical forums, where there is a continuous dissemination of knowledge for this field.

- The NMIs which work directly with industry, designing systems to measure the quantities in the field and not in the lab, must have experience on considering the dynamic effects of mechanical components and structures in order to quantify how their measurements are affected. So, even with a static traceability of their sensor, the NMIs are urged to question these values and to include necessary corrections and considerations, for example, rearranging the sources for the uncertainty of measurement.

Each activity brought the opportunity to approach new proposals and technologies for the implementation of diverse forms of realization of the dynamic regimes of the mechanical quantities involved.

All the main findings were described during the discussions, refining the first impressions and information passed at the beginning of the project and defining the points to be addressed and developed by the NMIs in the near future.

The NMIs are encouraged to get closer to industry and observe its needs for providing traceability under time dependency, with high variation rates or transients. Static calibration results must be compared to and complemented with dynamic calibration outcomes.

The group also identified that there is an excellent potential for dynamic studies in the Pressure quantity, which should be addressed in future opportunities for interaction and co-operation.
Once this target is achieved, the reliability of measurement processes will be improved and production will reach another step in quality.

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