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Assessment of the Metrological Performance of Seismic Tables for a QMS Recognition

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Abstract. Seismic testing and analysis using large infrastructures, such as shaking tables and reaction walls, is performed worldwide requiring the use of complex instrumentation systems. To assure the accuracy of these systems, conformity assessment is needed to verify the compliance with standards and applications, and the Quality Management Systems (QMS) is being increasingly applied to domains where risk analysis is critical as a way to provide a formal recognition. This paper describes an approach to the assessment of the metrological performance of seismic shake tables as part of a QMS recognition, with the analysis of a case study of LNEC Seismic shake table.

1. Introduction

Seismic testing using large infrastructures, such as shaking tables and reaction walls, is performed worldwide using different technical approaches. Measurement and control of these systems is based on complex design of instrumentation, often unique, able to measure and dynamically process several quantities: length and time, electrical (transducers, data acquisition, signal processing and device control), and to provide information of dynamic phenomena under study (e.g., velocity and acceleration). To assure the accuracy of these systems, metrological management should be used, including traceability to SI through calibration procedures and assessment of metrological performance to verify compliance with standards or applications requirements as part of a Quality Management Systems (QMS). The growing importance of conformity assessment in domains of critical risk, leads to the need of promoting the recognition of Research Facilities [1] according to international standards [2-3]. The development of methods to perform the assessment of metrological performance of these infrastructures is, therefore, a relevant contribution to set up the conditions for its implementation. This paper will also describe the procedures and experimental results developed for the assessment of LNEC's shaking table.

2. Seismic Infrastructure of LNEC Earthquake Engineering Research Centre

LNEC Earthquake Engineering Research Centre operates since 1996 as part of the European Seismic Engineering Research Infrastructures, developing research for seismic experimental and analytical modelling of structural systems to seismic hazard and risk analysis applied in the Civil Engineering testing of structures and components. The facilities include a large 3D shake table with a complex set of measuring devices able to measure several quantities (e.g., pressure, force, acceleration, displacement and strain) [4].

The main infrastructure characteristics (metrological and physical) include its large payload capacity (able to support weights up to 400 kN) at extreme testing conditions (near collapse).

The testing platform is made of steel with size of (4,6x5,6) m^2 and weight of 392 kN, 3 axis hydraulic actuators, acquisition system, 8 A/D channels and 96 configurable digital input channels. The operation and control uses in-house based software.

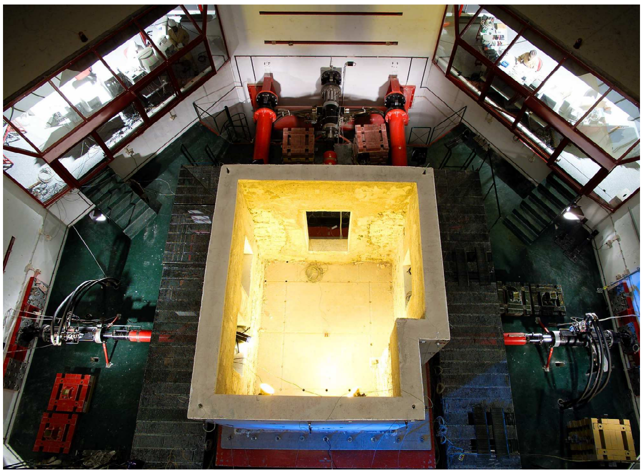

Figure 1 – Top view of LNEC Earthquake Engineering testing room

3. Quality Management System

Quality Systems models, created in the 1950's by Deming, Juran and Crosby, have today huge impact on the Organizations, were integrated Total Quality Management (TQM) has a relevant role establishing management rules of custom-focused organizations. The principles of Management System can be found today in ISO 9000 and ISO 17000 Series standards, highlighting the role of ISO 9001 [2] with the requirements of Quality Management and ISO 17025 [3] with the general requirements for the competence of testing and calibration laboratories. In the first, the aim is to establish recognition to the development of international trade and in the second, to promote competence recognition.

In many of today's technical activities where measurement results are obtained and needed for the decision process, the growing interest in mutual recognition is due to higher expectations of consumers and the development of international trade. For this purpose, the level of engagement can be established at different levels:

- *Qualification* is a degree that applies examinations to meet specific experience requirements and to comply with Quality Management Systems (QMS).
- *Certification* (organization, person or product) is defined as the compliance with specific requirements, with the assessment made by an external entity;
- *Accreditation* is a formal, third party recognition of technical competence.

The introduction of QMS into activities related to large experimental infrastructures with R&DI is becoming more relevant, considering that technical competence is part of the qualification for testing and measurement. This implies, in many cases, the redefinition of the formal processes of management and the independent assessment of the QMS implementation.

For the development of the QMS based on ISO/IEC 17025 several technical requirements need compliance. In the context of this paper, the interest is focused on the metrological requirements specifically applied to the core equipment that holds the control and measurement of the infrastructure testing facility, namely: traceability and calibration procedures; metrological conformity assessment; measurement correction and uncertainty evaluation; data record management; and data analysis (acquisition & processing of data).

4. Metrological Testing Specifications for Conformity Assessment

The conformity assessment is the basis for the validation of testing specifications, namely, performed by seismic shaking tables (tests and requirements being presented on Table 1). The procedure adopted to conformity assessment compares the target measurement uncertainty (concept defined by [5] *as measurement uncertainty as specified as an upper limit and decided on the basis of the intended use of measurement results*) with the instrumental measurement uncertainty (defined as [5] *component of measurement uncertainty arising from a measuring instrument or measuring system in use*). The procedure was developed according to five stages:

- first stage establishes the measurand quantities to apply the conformity assessment to and the requirements considering the intended use (for R&D&I, testing, or others);
- second stage identifies the instrumentation that support the measurement of quantities needed for the system control and operation;
- third stage establishes the set of tests to be performed:
  - Cross-axis motion
    - Static position – scale accuracy, reversibility, discrimination, repeatability return to zero tests
    - Dynamic mono-axial excitation (response to input sine wave)
  - Rotational motion
    - Mono-axial and combined rotational motion
    - Rotational spurious motion
  - Channels acquisition and transducing (A/D)
  - Amplitude and frequency dynamic response
- fourth stage establishes testing procedures including reference standards and traceability to SI, sampling, statistics to be applied and measurement uncertainty evaluation [6].
- fifth stage performs conformity assessment by a comparison between experimental results and defined requirements based on the intended purposes of testing.

Table 1 – Description of testing set, main characteristics and assessment requirements

Test description	Instrumentation & measurement interval	Function	Reference method & standards	Traceability	Target meas. uncertainty
1 - Cross-axis motion: static position & Discrimination	Inductive LVDT (hydraulic actuators) $l = \pm 120$ mm	Measurement & control	Direct comparison using laser interferometry	IPQ - Instituto Português da Qualidade (NMI)	< 1 mm
2 - Cross-axis motion: dynamic mono-axial excitation	Inductive LVDT (hydraulic actuators) Sine waves	Measurement & control			< 5 %
3 - Rotational motion: Rotational spurious motion	Inductive LVDT (hydraulic actuators) $\theta = \pm 10$ º	System response to stimulus			< 5 º
4 - Channels acquisition and transducing	NI PXI Boards & Controllers 1 Hz – 100 Hz	Measurement	comparison using input signal generator, digital voltmeter and universal time counter	TAP Metrology Laboratory	According with A/D resolution
5 - Amplitude & frequency response	NI PXI Boards & Controllers 0 – 1 V/ 1 Hz –100 Hz	Measurement			< 5 % $< 5 \cdot 10^{-3}$ Hz

In Table 1, the quantities and conformity requirements, related to the 1st stage, are found in column 6, obtained for the common protocol of measurement and control of LNEC shake table. The 2nd stage results are presented in column 2. The 3rd stage defines the set of testing to be applied, described in column 1. The 4th and 5th stages are detailed on next Section. The approach considers that accelerometers (ENDEVCO 7290A to control functions of the shaking table and PCB 337A62 for measurement purposes) used for measurement and control of as well as for measurement of the performance of tested objects, are calibrated under traceable conditions to SI.

5. Experimental procedures and results

The procedure to evaluate dimensional cross-axis motion and rotational motion across axis performances of the LNEC shaking table was based on interferometry, using a laser interferometer (λ = 633 nm) as reference, being able to perform linear and angular measurements with specific setups of the optical components. The procedure developed had two main parts (setup alignments and data acquisition). The critical contributions to measurement uncertainty found were alignment, synchronization and influence quantities (temperature and pressure). The experimental requirements included error minimization due to misalignment of optical elements with the axis of the actuators both vertical and horizontal (preliminary tests at full range were performed), signal synchronization and compensation of temperature and pressure influence.

Two tests were designed to evaluate scale accuracy and reversibility (test A, see Figures 2 and 3) and discrimination (test B, see Fig. 4). To perform data acquisition, input dynamic series were provided to establish calibration steps of 30 mm with low variance of displacement.

For discrimination, step transitions of 0,5 mm, 0,1 mm and 5 mm were given at 20 mm, 50 mm and 80 mm positions. Calibration was performed by sampling from interferometer and LVDT's data, with at least 500 sampling pairs to have a Gaussian representation of the probability distribution. Two of the geometrical setups are presented in Figures 5 and 6.

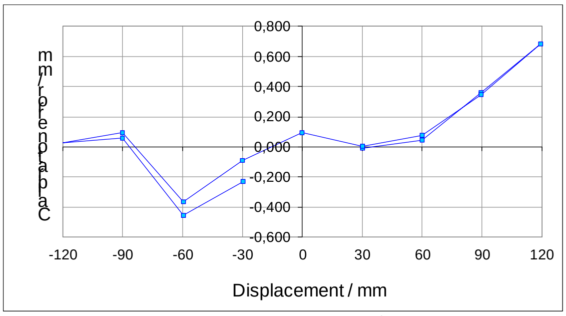

Figure 2 – Static position testing for Axis 1-T-A, scale calibration error with reversibility

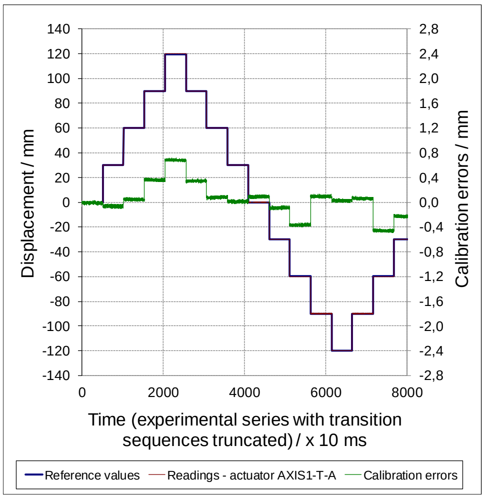

Figure 3 – Cross-axis motion: static position testing axis 1-T-A calibration errors

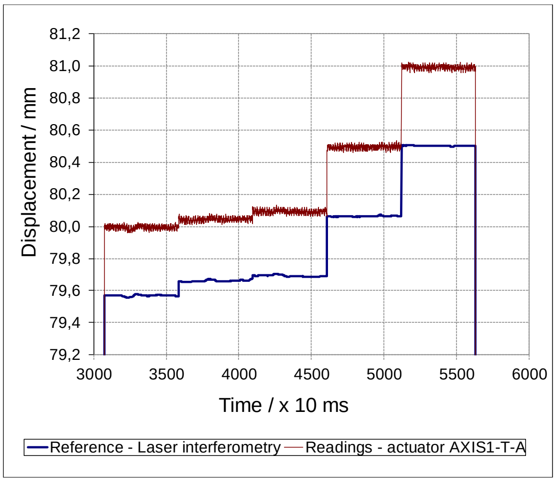

Figure 4 – Cross-axis motion: discrimination testing for axis 1-T-A at reference displacement of 80 mm

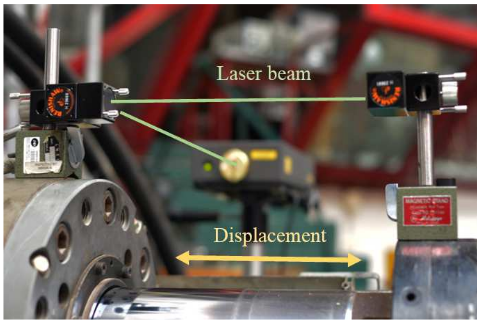

Figure 5 – Geometrical Setup for the cross-axis motion testing

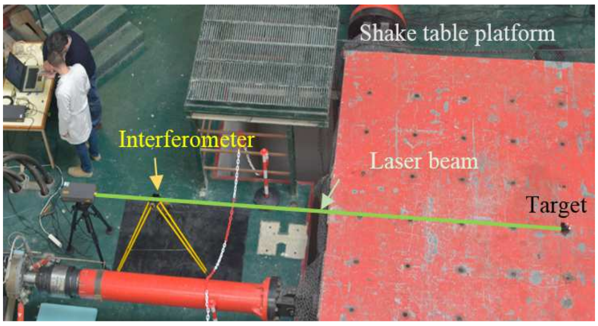

Figure 6 – Geometrical setup for the rotational motion testing

The assessment of the displacement error in dynamic motions were also carried out by imposing a time history of periodic random noise with amplitude of 27,30 mm (RMS=7,94 mm) and a frequency range with a low pass Butterworth filter with a cutoff frequency of 3,333 Hz and 4 poles. An error signal was obtained by taking the difference between the laser interferometer and measuring instrument time history records. In Figure 7 is shown the probability distribution function of the random error. A normal distribution was LSQ fitted to the distribution of the error random variable yielding a mean value of 0,02 mm and a standard deviation of 0,16 mm for the error.

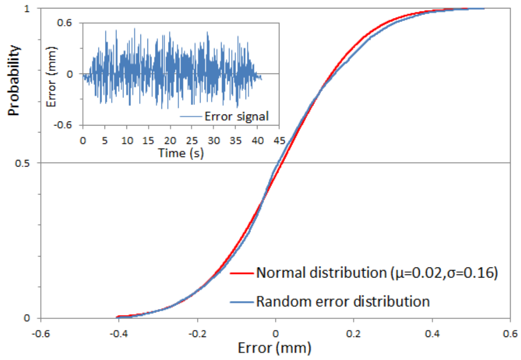

Figure 7 – Random error probability distribution

Figure 8 shows the 1/3 octave Fourier spectra ordinates computed from the laser interferometer and measuring instrument as well as the difference between them which is the error seen in spectral ordinates.

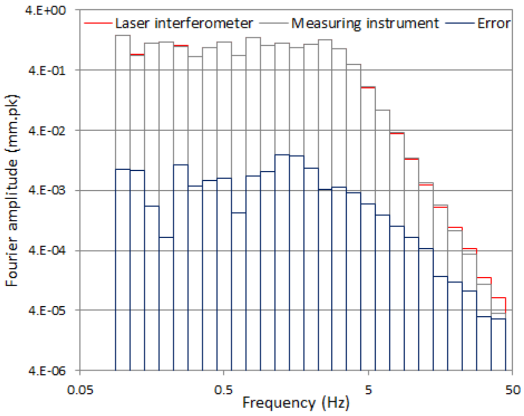

Figure 8 – 1/3 octave Fourier spectra

As can be seen, the error in measurement signals seems to be normally distributed along the time, showing stationarity, although without zero mean, and an expected low standard deviation when compared with the signal RMS (signal to noise ratio around 2%). In fact, from the Fourier spectra error ordinates, it can be seen that below the cutoff frequency the average signal to noise ratio error is around 0.7%, increasing for higher frequencies, above 40 Hz, to 45%. It must be said that for frequencies above the cutoff frequency, the energy content of the signal is greatly decreased which means that the amplitudes are below the resolution of the entire measurement chain of the measuring instrument.

The testing procedure for the compliance of frequency and amplitude signal response was based on input nominal electrical voltages with a signal generator, at laboratory conditions, and parallel measurement setup using a digital voltmeter reference standard. This allowed to evaluate the compliance of the low-pass filter of the acquisition system for the 8 channels. Tests were performed using sine waves with different parameters and a set of random noise signals.

6. Measurement uncertainties & Metrological conformity assessment

The conformity assessment procedure was based on the comparison of target measurement uncertainties with instrumental uncertainty. This approach, applied to voltage and frequency and the compliance is presented on Table 2 considering a confidence interval of 95 %.

Table 2 – Parameters required for the conformity assessment of voltage and frequency measurements

Quantity	Target uncertainty	Instrumental uncertainty
Voltage	According with A/D resolution	3,0x10-4 V
Frequency	< 5·10-3 Hz	1,0x10-6 Hz

Instrumental measurement uncertainty related to the calibration of the actuators LVDTs was calculated using contributions provided by the several tests presented combined using GUM [6] and assuming moderate nonlinearity of the mathematical model. Table 3 includes these contributions using the uncertainty budget table as defined in the GUM.

Table 3 – Description of testing set, main characteristics and assessment requirements

Quantity	*PDF**	$u(x_i)$ /mm	c_i	$u_i(x)$ /mm	ν
Resolution	R	0,05/√3	1	$2{,}89 \times 10^{-2}$	50
Calibration	N	0,10/2	1	$5{,}0 \times 10^{-2}$	500
Cal. Error correction	R	0,15/√3	1	$8{,}67 \times 10^{-2}$	15
Repeatability	N	0,015/1	1	$1{,}5 \times 10^{-2}$	500
Zero error	R	0,097/√3	1	$5{,}6 \times 10^{-2}$	5
Discrimination	U	0,1/√2	1	$7{,}1 \times 10^{-2}$	14
Reversibility	R	0,08/√3	1	$4{,}6 \times 10^{-2}$	50
Acquisition & proc.	T	0,05/√6	1	$2{,}0 \times 10^{-2}$	500
$u_c(l)$ /mm				$1{,}5 \times 10^{-1}$	
ν_{ef} / k				62 / 2,05	
$U_{95}(l)$ /mm				$3{,}1 \times 10^{-1}$	

* Probability distribution function rectangular (R), Triangular (T), ArcSin (U), Gaussian (N).

In this case the target uncertainty considered was to be lower than 1 mm, which is assured by the instrumental measurement uncertainty of 0,31 mm for a confidence interval of 95%.

7. Final Remarks, conclusion and further development

The metrological assessment of R&DI infrastructures is essential for a better knowledge of the system performance and capability, providing evidence of the compliance with technical and operational requirements. The implementation of QMS in this context leads to an instrumentation management improvement being an asset in promoting confidence and competence recognition. Furthermore, robustness of results is also achieved by its traceability of measurement results to SI and through the evaluation of measurement uncertainty, both needed to establish the conformity assessment in practice.

Further developments include establishing a framework that could be applied to the broader methods used on seismic shake tables testing, e.g., the metrological assessment of these infrastructures with criteria based on the comparison of target uncertainty with instrumental uncertainty. Finally, the same approach can also be applied to similar large testing infrastructures that perform R&DI in other domains of Civil Engineering.

The studies develop for the conformity assessment showed that the seismic simulator complies with the metrological requirements. Further studies will attempt to evaluate the effect of these uncertainties in the measurement process related to the study of physical models under seismic experimental conditions, which is a new approach in this field of knowledge.

8. References

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