FINAL PUBLISHABLE REPORT

Grant Agreement number	14SIP08
Project short name	Dynamic
Project full title	Standards and software to maximise end user uptake of NMI calibrations of dynamic force, torque and pressure sensors

Project start date and duration:	July 2015, 36 months	
Coordinator: Trevor Esward, NPL Tel: +44 20 8943 6883 E-mail: trevor.esward@npl.co.uk Project website address: http://empir.npl.co.uk/dynamic		
Primary Supporter: André Schäfer, HBM GmbH Tel: +49 6151 803224 E-mail: andre.schaefer@hbm.com		
Internal Funded Partners: 1. NPL, UK 2. PTB, Germany	External Funded Partners:	Unfunded Partners:

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

TABLE OF CONTENTS

1 Overview

The aim of this project was to maximise uptake, by industry end users and the Joint Committee for Guides in Metrology (JCGM), of the outputs of EMRP project IND09 ‘Traceable dynamic measurement of mechanical quantities’ by providing specific and directed advice on how to make best use of the results of dynamic calibrations provided by NMIs. This was achieved by working with the project’s primary supporter, Hottinger Baldwin Messtechnik GmbH (HBM), who appreciate that dynamic measurements are a key problem for high-value manufacturing and consequently provided data to allow the project to demonstrate the methods developed in the project IND09 in action.

2 Need

Many applications of the measurement of quantities such as force, torque and pressure are dynamic, i.e., the measurand shows a strong variation over time. Transducers are in most cases calibrated by static procedures owing to a lack of commonly accepted procedures or documentary standards for the dynamic calibration of mechanical sensors. However, it is well known that mechanical sensors exhibit distinctive dynamic behaviour and increasing deviation from static sensitivity characteristics as frequency increases.

Previously, the project IND09 sought to establish metrological traceability for the mechanical quantities: dynamic force, torque and pressure. The key output of the project IND09 was the establishment of primary and secondary traceability available at NMIs for the mechanical quantities: dynamic force, dynamic torque and dynamic pressure. However, effective dissemination of such dynamic calibrations requires the provision of specific advice to industrial end users on how to use calibration results to correct measurements for dynamic effects and how to demonstrate compliance with the ‘Guide to the expression of uncertainty in measurement’ (GUM). Therefore, although the outputs of the preceding project IND09 were the development of: (i) general dynamic models for the complete calibration measurement chain; (ii) procedures for uncertainty evaluation of dynamic measurements; and (iii) general procedures for correcting measurements for dynamic effects; these were, unfortunately, not able to be embodied in documentary standards, international guidance or software (used to correct measurements in industrial applications) during the lifetime of that project.

Prior to this project calibration certificates and associated information provided for dynamic quantities by NMIs and accredited calibration laboratories took several forms, therefore, industrial end users urgently needed: (i) guidance on what calibration information to request from NMIs and accredited calibration laboratories; (ii) guidance on how to use this information in their own dynamic measurement applications to ensure GUM-compliance; and (iii) software that demonstrates the guidance in action and provides GUM-compliant uncertainty evaluations.

3 Objectives

The overall goal of the project was to increase awareness and maximise uptake of the outputs of JRP IND09 through papers, input to key documents on uncertainty evaluation, and software.

The objectives of this project were:

1. To provide written advice and guidance to end users, that demonstrates (by means of case studies applied to end user data) methods to evaluate reliable estimates of dynamic mechanical quantities and their associated uncertainties, taking into account the various forms that calibration results may take, as well as correlation effects.
2. To make publicly available validated and tested software for industrial end users to implement the methods described in objective 1.

4 Results

Objective 1: To provide written advice and guidance to end users, that demonstrates (by means of case studies applied to end user data) methods to evaluate reliable estimates of dynamic mechanical quantities and their associated uncertainties, taking into account the various forms that calibration results may take, as well as correlation effects.

To achieve this objective, project partners NPL and PTB undertook three main activities to address the current lack of guidance relating to dynamic measurements:

1. The preparation and submission of a paper to Metrologia.
2. The preparation and submission of an article to Precision, the magazine of the Institute of Measurement and Control (InstMC).
3. The provision of input to Working Group 1 (WG1) of the JCGM for consideration for inclusion in supporting documents to the GUM.

The journal Metrologia publishes papers on all aspects of measurement and is one of the leading international journals in metrology. The project's paper on "Estimating dynamic mechanical quantities and their associated uncertainties: application guidance" provides general guidance on the use of dynamic measurements. The paper also describes four example applications:

1. Shock calibration of an accelerometer.
2. Compensation of the hysteresis effects of a piezoelectric fibre optic sensor.
3. Compensation of unwanted effects from calibrated hydrophones in the study of medical ultrasound devices.
4. Analysis of invasive blood pressure measurements.

The InstMC magazine Precision presents measurement-related articles and is published six times per year. NPL and PTB, together with the primary supporter HBM, wrote the article "New software for dynamic measurement and calibration of mechanical sensors" introducing the *PyDynamic* software (see Objective 2).

NPL and PTB also co-authored 3 publications in tm - Technisches Messen, Measurement Science and Technology, Journal of Sensors and Sensor Systems.

JCGM-WG1 has responsibility for maintaining the GUM and for developing documents (referred to as "Supplements") that accompany the GUM and aid its use. The list of documents currently being prepared by JCGM-WG1 includes:

- Document JCGM 103 "Evaluation of measurement data – Supplement 3 to the 'Guide to the expression of uncertainty in measurement' – Developing and using measurement models" concerned with modelling. NPL and PTB drafted text that sets out a methodology for developing and using measurement models of dynamic systems and provided it to the chairman of JCGM-WG1 for consideration as input to JCGM 103. A committee draft of the JCGM 103 is expected to be circulated to the eight member organisations of JCGM in late 2018, with the expectation being that the document will be published in 2019.
- Document JCGM 110 provides examples that demonstrate the application of the procedures given in the GUM and its Supplements. The project's Metrologia paper was provided to the chairman of JCGM-WG1 so that, at the discretion of JCGM-WG1, the examples in the paper could be considered for inclusion in JCGM 110. As yet, no date for publication of JCGM 110 has been specified. However, it is intended for drafts of JCGM 110 to be made available during the lifetime of the associated EMPIR project 17NRM05 "Advancing measurement uncertainty - comprehensive examples for key international standards" (2018-2021).

PTB and NPL, together with LNE (France), organised the 9th International Workshop on Analysis of Dynamic Measurements, held in Berlin, Germany in November 2016. PTB also attended a number of conferences to deliver presentations on dynamic measurement.

The publication of a number of journal papers, and the future publication of the Metrologia journal paper and the documents JCGM 103 and JCGM 110, will help to ensure that the issue of dynamic measurements remains highlighted.

Objective 2: To make publicly available validated and tested software for industrial end users to implement the methods described in objective 1.

The provision of software, in the form of source code, which implements algorithms developed during JRP IND09 has a number of benefits:

- Users can see the algorithms in action.
- Users can obtain a clearer understanding of the steps involved in processing measurement data.
- Users may be able to adapt the source code to process their own measurement data or to address similar problems to those addressed by the software.

To make implementations of the algorithms available as widely as possible, the project made the decision to develop software using the Python programming language. Python has several advantages over other languages, e.g., it is free to use and distribute and many (free) integrated development environments (IDEs) are available. *PyDynamic* also encourages interaction with users of the software through requests for assistance, requests for additional functionality, and the provision of example data.

NPL and PTB developed software, given the name *PyDynamic*, that demonstrates the methods developed in JRP IND09 in action using end user data. *PyDynamic* allows the propagation of uncertainty for the following problems:

- The application of the discrete Fourier transform and its inverse.
- Filtering with a Finite Impulse Response (FIR) or Infinite Impulse Response (IIR) filter, where the coefficients of the filter are subject to uncertainty.
- The design of a FIR filter as the inverse of a frequency response with coefficients subject to uncertainty.
- The design of an IIR filter as the inverse of a frequency response with coefficients subject to uncertainty.
- Deconvolution in the frequency domain using division.
- Multiplication in the frequency domain.
- The transformation from the representation of a complex quantity expressed in terms of an amplitude and phase to its representation expressed in terms of a real and imaginary part.

For the validation of the propagation of uncertainties, the Monte Carlo method can also be applied, in a memory-efficient way, for digital filtering.

Figure 1 provides an overview of the main modules of *PyDynamic*.

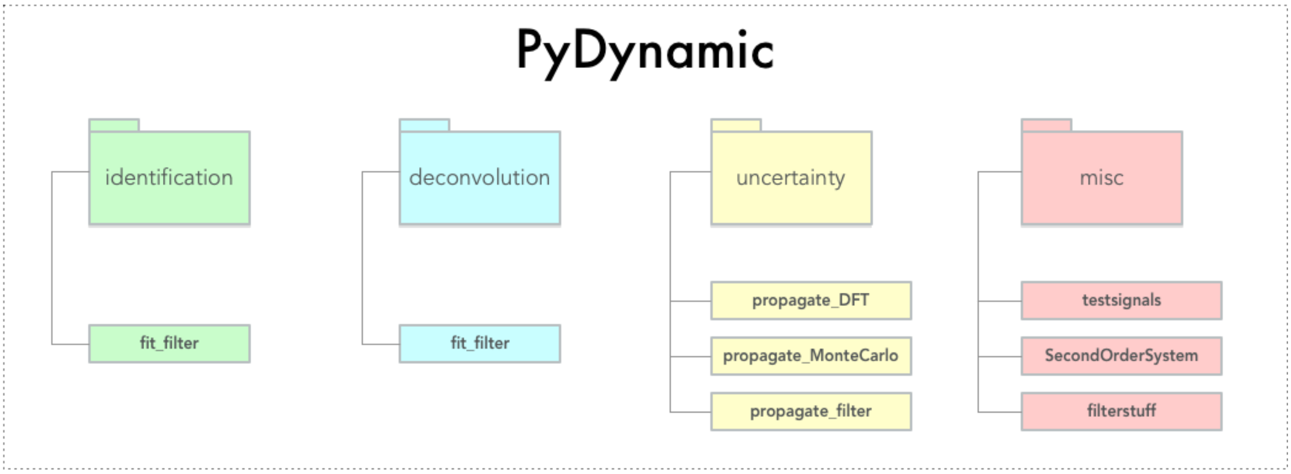

Figure 1: *PyDynamic* modules

PyDynamic, in conjunction with real end user data, has been used by the project to generate case studies for inclusion in both the input to JCGM 103 and the Metrologia paper (see Objective 1).

PyDynamic has been made available as follows:

- On the GitHub software development platform (github.com/eichstaedtPTB/PyDynamic).
- On the PyPi website (pypi.org/project/PyDynamic).

PyDynamic has been downloaded by several metrology experts from National Metrology Institutes (NMIs) after being publicised at the International Workshop on Analysis of Dynamic Measurements workshop held at PTB in November 2016. In particular, it has been used extensively by specialists in mechanical metrology from PTB Braunschweig who have requested a number of enhancements and extensions to the software.

Requests (e.g., for bug fixes, additional functionality, etc.) from users of *PyDynamic* are captured and stored on the *PyDynamic* GitHub website. By the end of the project, sixteen queries had been received and actioned by PTB and NPL. In addition to queries received from PTB Braunschweig, queries have also been received from nCode (a UK subsidiary of HBM), Surrey Automotive (a University of Surrey spin out company) and various attendees at the 9th International Workshop on Analysis of Dynamic Measurements. Beyond the end of the project, PTB will maintain and further develop *PyDynamic*.

PyDynamic has provided a key means to illustrate how the approaches developed during JRP IND09 may be implemented in software. It has already been used by a number of NMI experts and will continue to be added to and updated, including as part of the EMPIR project 17IND12 “Metrology for the factory of the future”.

Key factors in the success of the project has been the collaboration between NPL and PTB, and the engagement and support of HBM. Organisation of the International Workshop on Analysis of Dynamic Measurements, the latest in a series of workshops, required close cooperation between NPL and PTB (as well as LNE). The quality of written material developed during the project was ensured by NPL, PTB and HBM working closely together. The Metrologia paper, for example, benefitted hugely from the inclusion of examples drawn from both NPL and PTB, resulting in a more impactful paper than could have been developed by just one NMI partner. Adopting a collaborative approach to the development of PyDynamic has also helped to ensure its robustness and reliability.

5 Impact

The project built on the outputs of the project IND09 by disseminating those outputs via conference presentations, journal papers and contributions to the Supplements to the GUM, and making freely available software that implements algorithms developed within that project IND09.

The project has published 4 journal papers including a paper in *Measurement Science and Technology* which describes the software package GUM2DFT, a software tool for uncertainty evaluation of transient signals in the frequency domain that will be added to the GitHub software repository for access by end-users. A paper describing the project’s approach has been published in *Technisches Mes*sen and a talk on the same topic was given at the *VDI - Association of German Engineers* expert forum in March 2016. A paper was also published in the Journal of Sensors and Sensor Systems.

The project partners played a major role in the organisation of the 9th International Workshop on the Analysis of Dynamic Measurements, held in Berlin, Germany, in November 2016. The workshop attracted more than 50 attendees, and was the best attended conference in this series to date. The increasing importance of dynamic metrology was illustrated by oral and poster presentations on application areas such as torque, pressure, force, temperature and voltage, and mathematical tools addressing system theory, nonlinear dynamic models and deconvolution. An oral presentation was given by the project to introduce the *PyDynamic* software to stakeholders and potential users.

PTB staff, independent from other PTB project partners, applied *PyDynamic* to their research on the use of open source software tools for data analysis in high intensity shock calibration of accelerometers. The work was presented at the “IMEKO TC3, TC5 and TC22” International Conference 2017 held in Helsinki, Finland, in May/June 2017, and a conference proceedings paper was published.

Other PTB staff, also applied *PyDynamic* to their research on the use of a heterodyne vibrometer in combination with pulse excitation for primary calibration of ultrasonic hydrophones in amplitude and phase.

The outcome of this was published in Metrologia (Volume 54, Number 4) in August 2017, and includes a use case example for which *PyDynamic* was used to undertake analysis.

NPL staff, independent from other NPL project partners, applied *PyDynami*c to the problem of compensating the hysteresis effects of a piezoelectric fiber optic sensor.

The University of Ljubljana, with support from PTB, used *PyDynamic* to process data in relation to their research on dynamic calibration and uncertainty evaluation of invasive blood pressure measurement. This research culminated in the submission of a paper, co-authored by PTB, to the IEEE Transactions on Biomedical Engineering.

The paper 'Estimating dynamic mechanical quantities and their associated uncertainties: application guidance' has also been submitted to Metrologia. Further to this an article on 'Mechanical sensors are dynamic' has been submitted for publication in Precision, the quarterly magazine of the Institute of Measurement and Control.

Vasilewskyi et al. have cited the project's Journal of Sensors and Sensor Systems publication in their recent paper on the evaluation of dynamic measurement uncertainty in the time domain in the application to high speed rotating machinery (https://www.metrology-journal.org/articles/ijmqe/abs/2017/01/ijmqe170021/ijmqe170021.html).

The project's *PyDynamic* software library will be maintained and further developed by PTB beyond the lifetime of this project. In addition, the EMPIR project 17IND12 "Metrology for the Factory of the Future" (Met4FoF) will use and further develop the *PyDynamic* methods.

While not an explicit requirement of the project, a project website was developed and has been populated with information on the main aspects and outputs of the project. Additionally, details of the project are listed on the website of MATHMET, the European Centre for Mathematics and Statistics in Metrology (https://mathmet.org).

Activities within this project have aligned with the identified needs of end users. Such end users required specific guidance on how to apply the outputs of the project IND09 to their own measurements of dynamic effects in order to (i) establish confidence in their measurement results, (ii) demonstrate GUM-compliance and best practice in uncertainty evaluation, and (iii) understand how the deconvolution and correction algorithms needed for this purpose can be embodied in validated software.

The project created impact by enabling the efficient application of the methods developed in the project IND09 by disseminating software that demonstrates the methods in action on industrially relevant example data, to industry end users, through the public GitHub software repository. In the longer term, the outputs of the project will assist high-value manufacturing in the optimisation of products and processes where dynamic measurements are necessary. The consortium has identified new potential end-users for the project both in industry and academia (for example, nCode who specialise in software for fatigue analysis and post-processing of time-series measurements, and the automotive engineering department of Surrey University). Furthermore, through these activities the consortium is gaining access to new sources of data and potentially to new case studies that will allow the project to show the benefits of its methods. Figure 2 below shows an example of the benefit of taking dynamic effects into account in a metrologically correct manner and the effect of ignoring dynamic effects. This figure also demonstrates how the use of a statically calibrated sensor produces erroneous results, which becomes evident when compared with the results obtained by a dynamically calibrated sensor. Therefore it is clear to see how this project will enable end users to correct measurements for dynamic effects and hence produce correct estimates of the underlying dynamic signal.

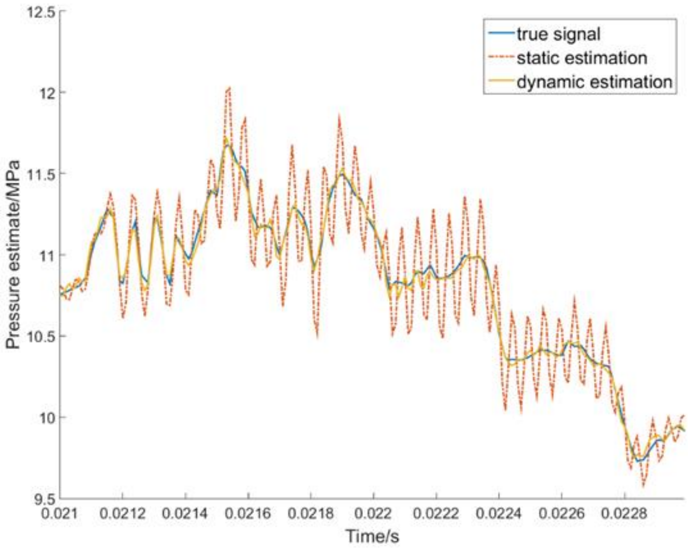

Figure 2: Estimating the value of a dynamic signal. The figure shows the effect of ignoring the dynamic properties of a measuring system compared to taking dynamic effects into account.

6 List of publications

[1]. S Eichstädt, C Elster. Modellierung dynamischer Messsysteme - von stochastischen Prozessen zu praktiblen Messunsicherheiten. tm - Technisches Messen. https://dx.doi.org/10.1515/teme-2015-0098

[2]. S Eichstädt, V Wilkens. GUM2DFT - A software tool for uncertainty evaluation of transient signals in the frequency domain. Measurement Science and Technology. http://dx.doi.org/10.1088/0957-0233/27/5/055001

[3]. S Eichstädt, C Elster, I Smith and T Esward. Evaluation of dynamic measurement uncertainty – an open-source software package to bridge theory and practice. Journal of Sensors and Sensor Systems. http://dx.doi.org/10.5194/jsss-6-97-2017

[4]. T Esward. Investigating dynamic measurement applications through modelling and simulation. tm - Technisches Messen. https://dx.doi.org/10.1515/teme-2015-0128

7 Contact details

For further information about the project, please contact Ian Smith (ian.smith@npl.co.uk).