XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6–11, 2009, Lisbon, Portugal

ANALYSIS OF DYNAMIC MEASUREMENTS: NEW CHALLENGES REQUIRE NEW SOLUTIONS

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Abstract − A dynamic measurement can be defined as a measurement where the physical quantity being measured varies with time and where this variation may have a significant effect on the measurement result and the associated uncertainty. New dynamic measurement challenges are arising in a number of metrology areas that have traditionally required only steady state or static characterisation of sensor performance. These challenges may require development of new measurement and calibration methods, as well as new methods for correcting sensor outputs and for the evaluation of uncertainties.

This paper reviews these developments with a particular emphasis on the role and relevance of the Guide to the expression of uncertainty in measurement (GUM) [1] and GUM Supplement 1 (GUM S1) [2].

Keywords: dynamic measurement, uncertainty

1. INTRODUCTION

A dynamic measurement can be defined as a measurement where the physical quantity being measured (the measurand) varies with time and where this variation may have a significant effect on the measurement result (the estimate of the measurand) and the associated uncertainty. The nature of the measurand is dependent on the dynamic application. In some cases the peak value of the measurand over a specified period is of interest. In others, knowledge of the variation of the measurand with time is required. As is pointed out in [3], it is often the irregular and rapidly varying details of the measured signal, together with its maxima and minima, which are difficult to measure. However, the usual purpose of a dynamic measurement is to detect such features. A further complication is that even though many processes are varying in the time domain, a representation by parameters that are constant (i.e., time-independent) is often possible and in practice preferred, especially in acoustics and telecommunication. In terms of such a representation, the measurement problem may then be treated with the same methods as used for time-independent static measurements. For example, a sinusoidally varying time domain signal may be represented in the frequency domain by three constants: amplitude, frequency and phase.

Many industrial measurements are made with sensors and transducers that have been calibrated under static conditions, but in a large proportion of these measurements, the measured signal is varying during the measurement epoch (i.e., under dynamic conditions). The use of a sensor in a different mode from that in which it was calibrated may be a dominant factor affecting the reliability and uncertainty of the measurement result. Furthermore, such contributions may be either underestimated or totally ignored, leading to increased costs and reduced competitiveness, or even impact on human health.

The key feature that distinguishes dynamic from static measurement is the speed of response of the measurement systems as compared to the speed at which the measurand is changing. If the measurement system responds much faster than the rate at which the measurand is changing, it is possible to analyse the measurement and derive its associated uncertainties using a conventional static model of the measurement. If the measurement system responds slowly on the scale of the changes in the measurand then it will be necessary to model the measurement in the time domain using differential or difference equations. The measurement task can then be regarded as dynamic. It is the measurement of measurands related to dynamic signals using dynamic measurement systems that provides new challenges in uncertainty analysis.

A further consequence of many dynamic measurements is that the measurement uncertainty may itself be strongly time dependent. In cases in which the measurand is non-stationary, time-dependent measurement uncertainty cannot be evaluated from conventional calibration certificate information simply because the signals used in calibration will have different properties from those encountered during the measurement [3].

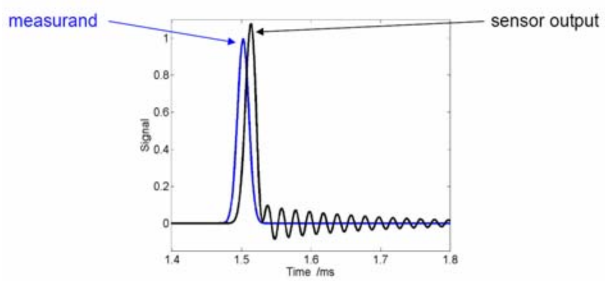

Figure 1: Time domain response of sensor to pulse

Figure 1 demonstrates the uncertainty and error analysis problems that are observed in typical dynamic measurement systems. The sensor response incorporates a delay, it over- or underestimates the height of the peak in the signal, and there may be ringing after the signal has ceased. As a result, the error signal (that is, the difference between the measurand and the sensor output) varies with time and can persist when the measurand is zero. Correcting the sensor output for such effects to obtain estimates of the measurand and assigning appropriate uncertainties to the estimates requires approaches of the kind outlined in section 4 below.

2. KEY APPLICATION AREAS

The physical quantities of concern include, but are not limited to, mechanical applications such as pressure, force, torque, length, temperature and acceleration and various types of high and low power electrical measurements. Dynamic regimes of interest range from shock and impact processes, to cyclic and continuous or repetitive processes. In each of these areas new challenges arise in the design of sensors and their associated instrumentation, the design of suitable calibration standards and processes, and in traceability and uncertainty evaluation.

An example application area currently being tackled by the National Physical Laboratory (NPL), UK, the Physikalisch-Technische Bundesanstalt (PTB), Germany, and the Technical Research Institute of Sweden (SP) is the calibration of sensors that are employed to understand pressure changes in internal combustion engines. Internal combustion engines provide an environment with extreme operating conditions for reliable sensor operation. Engine development requires high frequency and amplitude measurements, e.g., 'knocking' produces in-cylinder pressure fluctuations with a duration of ~0.05 ms resulting in a bandwidth of about 20 kHz. Fuel injection pressures up to 200 MPa are used in direct injection engine research. Pressure measurements are made during engine development to optimise fuel efficiency and reduce toxic emissions. Knowledge of the response of a sensor and its associated equipment (e.g., processing electronics, connectors and pipe work) is needed for the dynamic range of the measured parameter. Sensors can be supplied directly from the manufacturer with traceable calibrations but their response, at best, is only determined for an idealized transient pressure change of limited variation and is unlikely to be evaluated at the environmental conditions and signals encountered in an engine.

The engine developers need to be confident that sensors are reproducible and consistent, provide accurate measurements of peak pressures (especially for in-cylinder measurements), have a bandwidth (when connected with pipe-work and processing electronics) that is significantly higher than the pulse frequency (which can be up to 5 kHz) and have a sufficiently short response time to resolve the detailed behaviour of the injectors. To meet these requirements new calibration standards and new methods of delivering traceability, correction and well-defined measurement uncertainties are needed.

3. DYNAMIC METROLOGY AS A CONCEPT

The aim of dynamic metrology is to bridge the gap between calibration as a discipline practised by metrology institutes and specialist calibration laboratories and scientists, engineers and designers who are facing new demands for more accurate and precise characterisation of dynamic systems. The concept includes:

- Methods for transferring the results of dynamic calibrations to measurements of interest;
- Dynamic calibration methods for various quantities and measurement systems;
- System analysis of complex measurements;
- Optimization of measurement systems;
- Dynamic correction of time-dependent measurements;
- Evaluation of time-dependent measurement uncertainty.

Dynamic metrology is inherently multi-disciplinary. It employs a wide range of mathematical and statistical techniques from signal processing, sampling and information theory, digital filter design, systems identification, correlation analysis and control engineering and it is the need to combine methods from this range of disciplines that makes dynamic metrology both interesting and challenging.

4. PROPOSED METHODOLOGIES

Techniques currently being studied by the authors include time, frequency and Laplace domain methods for estimating the measurand and evaluating its associated uncertainty and for evaluating and correcting measurement errors, with a view to designing optimal correction methods that may be directly applied to the measured signal. Monte Carlo methods are also being studied both for simulating dynamic measurement systems to help in system design and in understanding the propagation of uncertainties through dynamic measurement systems. These methods are useful for the evaluation of uncertainty but they cannot supply means of dynamic correction, which in many cases are of interest for improving the performance.

Hessling [4,5] has proposed a method to synthesise digital signal correction filters to be used in an extended general dynamic calibration service. These are devised to recover the signal of interest. The method is applicable to all linear time invariant systems. The required processing is performed off-line, after the output signal has been acquired, allowing for an ideal stabilization by means of time-reversed filtering. By necessity, the measurement uncertainty will be time-dependent as the level of excitation of the system changes in time. As has been demonstrated [6], digital filters may likewise be utilized to derive the time-dependent sensitivities to input parameters, from which the dynamic measurement uncertainty can be determined. An approach to deriving the upper bounds of the dynamic error in the time domain, provided the complex-valued frequency response of the system is known, has also been proposed [7]. The methods have been demonstrated successfully on force and pressure transducer systems and on accelerometers.

A novel application of Hessling's approach to a challenging dynamic measurement task is the study of the vibrations experienced by bus passengers as a bus drives over road humps of the kind that are advocated by many traffic engineers as a means of reducing vehicle speeds. By considering the geometry of road humps and the mass and axle separation of buses, Hessling and his collaborators were able to 'calibrate' a moving vehicle by measuring the response of front and rear axles as it drove at various speeds over road humps of known height. The approach allows for analysis and optimisation of road hump geometry [8,9] but also vehicle design if a longer road profile instead of a single hump is considered. It has led to the development of a software tool that can be used to study the dynamic relationship between the road profile and vehicle motion in the time domain. The software uses digital filtering to obtain the vehicle response to a given road profile or conversely, the ideal road profile to give a required vehicle response.

Elster, Link and colleagues have applied methods of system identification to accelerometer measurements, supplemented by an uncertainty evaluation [10,11]. Similar to the approach of Hessling and also based on digital signal processing tools, Elster and Link suggested a method for constructing a correction filter applicable to a general linear time-invariant system [12,13]. While the resulting correction filters are causal and thus may be employed on-line, their construction is more involved than the procedures given by Hessling.

A further development has been a method for the evaluation of the dynamic uncertainty associated with the time-dependent estimate of the measurand, which is obtained by applying the correction filter [12,13]. This method is consistent with GUM and GUM S1, and it has been successfully applied to accelerometer calibration measurements [14].

In a recent paper [15] Link and Elster developed a method for evaluating the uncertainty associated with the output signal of an IIR filter when the input signal is corrupted by noise and the filter coefficients are uncertain. The method may be viewed as a direct application of the GUM for this task. A state-space approach is utilized to facilitate a first-order Taylor series expansion, and the derived calculation scheme enables real-time applications.

Georgakopoulos and colleagues developed a dynamic force standard for laboratory use that can provide traceable measurements of dynamic force for use in the calibration of fatigue testing instruments [16]. Such instruments are characterised by means of a combination of DC and AC electrical signals with specific amplitudes and frequency content. These signals are intended to simulate the electrical output of the strain gauge bridges used to monitor the forces applied to the sample under static (DC) and dynamic (AC) conditions. The authors describe how the required electronic instrumentation was made traceable to UK national electrical standards.

5. MONTE CARLO METHODS

Monte Carlo methods have an important contribution to make to the analysis of dynamic measurement systems and their associated uncertainties. GUM S1 addresses the use of Monte Carlo methods in uncertainty evaluation [2]. The advantages of Monte Carlo methods are that they are applicable regardless of the nature of the measurement model, i.e., whether it is linear or non-linear, they make no assumptions about the distribution of the output quantity, calculation of sensitivity coefficients is not required and they can tackle complicated measurement models.

An example of recent work in which Monte Carlo methods have been applied successfully to the analysis of dynamic measurement problems is the simulation of a lock-in amplifier measurement system reported by NPL [17]. An executable version of the simulation software can be downloaded from the NPL web site [19].

Wübbeler and colleagues have examined the evaluation of measurement uncertainty using the Monte Carlo method and compared the results with a conventional GUM approach [18]. The paper concludes that the Monte Carlo method is well suited to uncertainty calculation and should be employed when the assumptions made in the conventional method of the GUM do not apply. However, a limitation of current Monte Carlo approaches is that they can generally only be applied off-line and are unsuitable when real time on-line results are required.

6. EURAMET COLLABORATION

The authors have recently established a EURAMET (European Association of National Metrology Institutes) interdisciplinary metrology project entitled "Development of methods for the evaluation of uncertainty in dynamic measurements" (EURAMET Technical Committee for Interdisciplinary Metrology project no. 1078). The goal of the project is to develop methods for the evaluation of measurement uncertainty and related aspects in dynamic measurements. The methods are intended to align with the Guide to the expression of uncertainty in measurement [1]. The output of the project will include methods for improving the analysis of dynamic measurements demonstrated by means of example applications. The project holds regular workshop meetings to discuss and publicise new research and participation in these events is invited.

Presentations from the November 2008 meeting are available online [20].

7. CONCLUSIONS

New developments in dynamic measurement are presenting some apparently complex problems of correction and uncertainty evaluation. Many of these can be tackled through modelling, simulation and system identification methods, which provide powerful methods of wide applicability. Monte Carlo methods are a useful and general tool for understanding dynamic problems. In addition, new sensors, transducers and calibration methods may be also be a key to progress in this rapidly developing area of metrology.

ACKNOWLEDGMENTS

T J Esward of NPL acknowledges the assistance of Stephen Downes and Andy Knott of NPL's Mass and Dimensional Group.

REFERENCES

[1] BIPM, IEC, IFCC, ISO, IUPAC, IUPAP and OIML 1995 "Guide to the Expression of Uncertainty in Measurement" (Geneva, Switzerland: International Organization for Standardization) ISBN 92-67-10188

[2] BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML 2007 "Evaluation of Measurement Data—Supplement 1 to the 'Guide to the Expression of Uncertainty in Measurement'—Propagation of Distributions Using a Monte Carlo Method" Joint Committee for Guides in Metrology, Bureau International des Poids et Mesures, JCGM 101

[3] J.P. Hessling, "A novel method of evaluating dynamic measurement uncertainty utilizing digital filters", Measurement Science and Technology, (20) 2009, 055106

[4] J.P. Hessling, "Dynamic metrology – an approach to dynamic evaluation of linear time-invariant measurement systems", Measurement Science and Technology (19) 2008, 084008

[5] J.P. Hessling, "A novel method of dynamic correction in the time domain", Measurement Science and Technology (19) 2008, 075101

[6] J.P. Hessling, "Digital filtering for dynamic uncertainty", Advanced Mathematical and Computational Tools in Metrology and Testing – ENS Cachan (Paris, France, June 23-25 2008)

[7] J.P. Hessling, "A novel method of estimating dynamic measurement error", Measurement Science and Technology (17) 2006, 2740-2750

[8] J. P. Hessling and P. Y. Zhu, "Analysis of Vehicle Rotation during Passage over Speed Control Road Humps", ICICTA 2008, International Conference on Intelligent Computation Technology and Automation, Changsha, China, Oct. 20-22, 2008

[9] P.Y. Zhu, J.P. Hessling and D.S. Liu "Optimal road hump design for comfortable speed reduction", 4th International Symposium on Precision Mechanical Measurements. Proceedings of the SPIE, Vol 7130, 71304L-71304L-6, 2008

[10] A. Link, A. Täubner, W. Wabinski, T. Bruns and C. Elster, "Calibration of accelerometers: determination of amplitude and phase response upon shock excitation", Measurement Science and Technology (17) 2006, 1888-1894

[11] A. Link, A. Täubner, W. Wabinski, T. Bruns and C. Elster, "Modelling accelerometers for transient signals using calibration measurements upon sinusoidal excitation", Measurement (40), 2007, 928-935

[12] C. Elster and A. Link, "Uncertainty evaluation for dynamic measurements modelled by a linear time-invariant system", Metrologia (45) 2008**,** 464-473

[13] C. Elster and A. Link, "Analysis of dynamic measurements: compensation of dynamic error and evaluation of uncertainty", Advanced Mathematical and Computational Tools in Metrology and Testing – ENS Cachan (Paris, France, June 23-25 2008)

[14] C. Elster, A. Link and T. Bruns, "Analysis of dynamic measurements and determination of time-dependent measurement uncertainty using a second-order model", Measurement Science and Technology (18) 2007, 3682-3687

[15] A. Link and C. Elster, "Uncertainty evaluation for IIR (infinite impulse response) filtering using a state-space approach", Measurement Science and Technology (20), 2009, 055104 (5pp)

[16] D. Georgakopoulos, J.M. Williams, A. Knott, T.J. Esward and P.S.Wright, "Dynamic characterisation of the electronic instrumentation used in the calibration of fatigue testing machines", IEE Proceedings - Science, Measurement and Technology, 153(6), 2006, 256-259

[17] P. Clarkson, T.J. Esward, P.M. Harris, K.J. Lines, F.O. Onakunle and I.M. Smith. "A software simulation tool to evaluate the uncertainties for a lock-in amplifier", AMCTM 2008, Paris, June 2008

[18] G. Wübbeler, M. Krystek, and C. Elster, "Evaluation of measurement uncertainty and its numerical calculation by a Monte Carlo method", Measurement Science and Technology (19) 2008, 084009

[19] http://www.npl.co.uk/server.php?show=ConWebDoc.2644

[20] http://www.npl.co.uk/server.php?show=ConWebDoc.2966