Status and future of metrology for dynamic measurement in Nordic and Baltic countries

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Abstract. Methods and technologies for dynamic measurements have been developed and used for decades. To enable robust metrological traceability, uncertainty analysis methods for various applications have been derived and published by many scientists. In Europe, several research projects funded within European metrology research programmes (EMRP, EMPIR, Partnership on Metrology) have been focusing in dynamic measurements of mechanical, thermal and electrical quantities to provide new measurement and calibration methods. The European Metrology Network "Mathmet" drives the development of analytical methods related to dynamic measurement applications. The importance of dynamic measurement solutions has been boosted by digitalisation and rapid growth of computer power. Artificial intelligence combined with sensor fusion and sensor networks brings dynamism to wider measurement applications but may hide serious vulnerabilities to time dependent disturbances.At the moment most calibrations are performed under static conditions, i.e. the time dependency of the measurand is considered as a very small contribution to the overall calibration uncertainty. Calibrations at static conditions are often preferred due to practical reasons even if dynamic calibrations are available. In its recent strategy, the European Metrology Network "Smart North" has identified dynamic measurements as a field of regional competence and service development within Nordic and Baltic countries. This paper reviews most relevant research results and currently available calibration services in Europe. The study is focused on measurement needs related to machinery, combustion engines and electrical grids. Potential future needs for NMI level services in the region are analysed by considering specific needs of local industry, societal resilience and northern climate..

1 Introduction

In industry, measurement sensors are mostly used in non-static conditions but often they are calibrated in static conditions. There are many cases where dynamic characteristics of a sensor form a significant limiting factor for achievable measurement uncertainty. With proper calibration and analysis methods, the uncertainty could be significantly improved. The importance of dynamic measurement solutions has been boosted by digitalisation and rapid growth of computer power. Artificial intelligence combined with sensor fusion and sensor networks brings dynamism wider to measurement applications but may hide serious vulnerabilities to time dependent disturbances. In its recent strategy, the European Metrology Network "Smart North" has identified dynamic measurements as a field of regional competence and service development within Nordic and Baltic countries. Metrology related published research results and currently available calibration services are reviewed in this paper to provide a solid basis for strategic decisions in the region.

Eichstädt et al [1] define dynamic measurements as measurements involving at least one dynamic quantity whose value varies with time in such a way that this time dependence must be taken into account to characterize the quantity to the accuracy desired. The main challenges in establising robust metrological traceability for dynamic measurements are: evaluating the measurement uncertainty and calibrating the measurement system in such a way that the time dependency is appropriately taken into account [1 – 3]. Theoretical basis comprising definitions, concepts and analysis methods has been developed to dynamic measurements in general and applied to various fields [1, 4 – 10]. The state-of-the-art methods relevant to mechanical quantities and ultrasound is well described in [11]. When studying measurement challenges in more details, we need to look at different applications separately as the range of applications is very wide and the challenges vary with the application. To match with the needs specific to industry in Nordic and Baltic countries, we decided to focus on three applications fields: machinery, combustion engines and electrical grids. Needs in these application fields are discussed in Section 2. Research results on calibration methods and systems as well as calibration services provided by national metrology institutes are reviewed in Section 3. Using this information with industry landscape in Nordic and Baltic countries we analyse in Section 4

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future needs of dynamic metrology services in this region.

2 Dynamic measurements and application fields

2.1 Dynamic measurements and quantities

Dynamic measurement can be considered as the measurement of time-dependent quantities [12]. As an opposite approach, K.H. Ruhm states in [13] that a system is nondynamic if all quantities in the mathematical model of the measurement process except input and output signals depend only on their present values. However, the time dependency alone is not sufficient to consider a measurement dynamic: otherwise allmost all real-time measurements would fall into this category. It is decisive how the time dependency of the measurand is interlinked with the measurement system and the measurement result. When an instrument output reading show a significant time dependent deviation from the actual measurand values, the measurement should be treated as dynamic measurement. T. J. Esward et al. defines a dynamic measurements 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” [14]. To emphasize that the defining characteristics related to dynamic are not the absolute timescale nor physical application, A. Dienstfrey and P. D. Hale presented the definition as “one in which the measurand varies in time sufficiently fast relative to the response of the measurement system that corrections for finite-bandwidth effects are required to achieve the desired accuracy” [15]. S. Eichstädt et al. extends the definition to measurements involved with several quantities by defining a dynamic quantity as “any quantity whose value varies with time in such a way that this time dependence must be taken into account to characterize the quantity to the accuracy desired” and stating that “Measurements in which at least one of the involved quantities is dynamic are called dynamic measurements” [1].

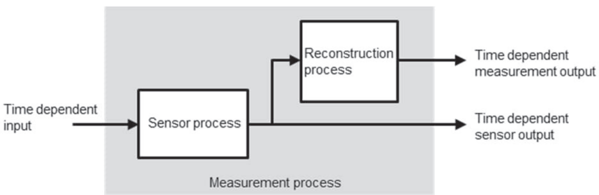

Fig. 1. Scheme of dynamic measurement process in instrument domain

Dynamic measurement process can be described with a block diagram in Fig. 1. In addition to a sensor process giving time-dependent sensor output, the process includes a reconstruction process (also called as estimation process) that generates measurement system output by applying an appropriate mathematical model. Signal processing methodologies are needed for analysing dynamic measurements [12, 16].

The reconstruction process is very sensitive to measurement noise, and the applied method causes systematic errors that cannot be omitted in the uncertainty analysis [12]. Mathematical theory for analysing dynamic measurement results and estimating their uncertainty has been studied in many scientific publications [1, 12 – 26]. A comprehensive overview is given in [11].

2.2 Applications within machinery, combustion engines and electrical grids

To ensure product quality and safety, fatigue tests and other mechanical tests are performed for materials, components and products within manufacturing processes. Dynamic force measurements record varying force acting on materials in tensile testers, compression testers, fatigue testers and viscoelasticity testers etc. [27, 28] Force and torque measurements are important in manufacturing engines and transmissions of ships, automobiles and aircrafts and for operating them in a safe and optimal way. In many cases, measurements are dynamic, which affects significantly the reliability of the recorded measurement data. Requirements for these dynamic measurements are becoming more stringent [28 - 31]. Dynamic torque measurements cover a wide range of applications such as the vibration of engines and motors and impact torque measurement by torque tools [32]. Reliable in-line torque measurement in the drive train of ships are needed for achieving the targets of reduced emissions in seafaring [33]. Regenerative braking in electric vehicles increases the need of dynamic torque measurements with proven quality. Forces acting on materials in press machines and rolling mills are real-time monitored with force transducers.

Another widely applied dynamic mechanical measurement is weighing: when manufacturing products in food, pharma and chemical industry and packaging them for transport and storage, dynamic weighing is commonly an integral part of the processes [34, 35].

According to the Intergovernmental Panel on Climate Change (IPCC), about 15 % of net global GHG emissions came from transport sector [36] in 2019. About 26 % of this is produced by ships and heavy freight vehicles [37]. Combustion engines are expected to continue as the main power source in this sector but the emissions will be reduced further by improving the engine efficiency, e.g. by improving the combustion system, gas exchange and thermal management [38]. More accurate dynamic pressure and temperature measurements are key to reduction of emissions by optimizing the combustion process in real time. Real time monitoring of cylinder pressure and temperature, fuel injection pressure and exhaust pressure and temperature enable optimizing the fuel injection and engine thermal management [39 - 42]. The measurement ranges of interest are from 1 MPa up to 30 MPa and up to 3000 °C [43, 44] with frequency up to a few tens of kHz [39].

Dynamic measurements are also relevant for engines used in light duty vehicles and cars which produce more than 50 % of GMG emissions in the transport sector [37]. However, electrification is expected to reduce the emissions in Nordic countries and the need for dynamic pressure and temperature calibration is not expected to increase significantly in the foreseeable future.

Dynamic measurements are crucial for the operation of electrical grids and for ensuring safety and durability of grid components. Measurement and analysis methods in line with principles presented in Section 2.1 are used in lightning impulse and partial discharge measurements, and the measurement quality is ensured by metrologically traceable calibrations. The methods have been implemented in the standard IEC 61083 [45]. Development needs have especially been identified in power measurements related charge-discharge efficiency of electric storage systems [46].

3 State of the art

3.1 Research on traceability of dynamic measurements

3.1.1 Force and torque

Metrological traceability and calibration of dynamic measurement systems in different applications have been studied in various research projects within European metrology research programmes in the last two decades. A traceability chain for metrological services in the field of force measurements was set up in the project ComTraForce [47]. This project delivered improved methods for static, continuous and dynamic force calibrations in a force range from 1 N to 1 MN at frequencies up to 1 kHz. A calibration setup and guidelines were developed for force calibration of testing machines under continuous and dynamic force. A guideline for dynamic calibration of material testing machine was published as DKD-R 9-4 [48]. NIST has developed a system for dynamic force calibrations using harmonic excitation and laser-interferometric acceleration measurement. An uncertainty less than 1.2 % (k = 2) was demonstrated for 2.2 kN and 1.3 kN force transducers [49]. Torque measurements in rotating systems like in wind turbines have been studied in the European research projects MNmTorque [50] and WindEFCY [51]. A development initiated at PTB in the project Dynamic has delivered a calibration system applying an oscillating torque load generating loads up to 20 N m in the frequency band 10 Hz to 400 Hz [52]. Also, a method for dynamic calibration of amplifiers used in conjunction with force and torque transducers was developed in the project Dynamic [53], and the work continued in the project ComTraForce [54]. NMIJ and KRISS have developed primary torque calibration systems applying the Kibble balance principle. NMIJ demonstrated an uncertainty of 0.3 % (k = 2) for a dynamic torque of 20 mN m to 40 mN m at frequencies up to 100 Hz [55]. KRISS expects to achieve an uncertainty level of 0.01 % in static torque calibrations up to 10 N·m. The system will be operating in dynamic calibration mode up to 100 Hz [56].

3.1.2 Pressure and temperature

To enable traceable dynamic pressure measurements, calibration systems applying three principles have been developed within the project DynPT: shock tube, fast opening valve and dropping weight [57]. Pressure and frequency ranges 0.1 – 400 MPa and 1 – 30 kHz, respectively, are covered with the developed setups. The development enabled SI-traceable dynamic pressure calibrations in the range from 5 MPa to 30 MPa, which is important for combustion engine applications. A relative uncertainty of 1 % (k = 2) was achieved with LNE/ENSAM's system combining shock tube and a fast-opening device in the pressure and frequency range up to 5 MPa and 100 Hz. At the frequency of 30 kHz, the uncertainty is about 7 % [58]. When generating the dynamic pressure up to 60 MPa with a drop-weight system developed by VTT MIKES an uncertainty of 1.7 % (k = 2) was achieved [59]. The uncertainty is recently reduced to 0.9 % in the range up to 500 MPa with a new design developed by VTT MIKES. The pulse width is 5 ms [60]. L. Combining a drop-weight test system with a high-speed camera and an accelerometer, Elkarous et al. have developed a dynamic calibration system for ballistic high-pressure sensors up to 350 MPa with a pulse width of 1 – 2 ms and achieved a calibration uncertainty of 2.4 % (k = 2) [61]. KRISS has developed a drop-weight secondary calibration system that generates 3 ms pressure pulses of 10 MPa to 200 MPa [62]. KRISS has also developed a primary dynamic pressure standard using a step pressure generator covering the range 1 MPa to 100 MPa with 1 ms rise time. The reported uncertainty at 70 MPa is 0.51 % (k=2) [63]. SPEKTRA has developed a primary dynamic pressure calibration system using a pistonphone exciter. The system generates sinusoidal pressure with frequencies up to 10 kHz and amplitudes up to 1 MPa (peak to peak). The estimated uncertainty is up to 2 % (k = 2) [64]. Zhang et al. generated a quasi-δ pressure pulse with a pulse width of 8 μs. The maximum static pressure level is 800 MPa and the amplitude 30 MPa. The amplitude-frequency error is estimated to 5 % [65].

A portable flame temperature standard was developed by NPL in the European project EMPRESS using the Rayleigh scattering thermometry technique. A relative standard uncertainty of 0.5 % was achieved [66]. The project DynPT resulted in three validated dynamic temperature calibration methods [57]: KTH achieved 3000 °C with a relative uncertainty of 2 % (k=2) using a shock tube setup. RISE developed a system based on a rapid shutter and high temperature blackbodies and estimated the uncertainty of calibration to be 2.2 °C and 4.5 °C at 500 °C and 2200 °C, respectively (k = 2). At NPL, a modified blackbody calibration setup provides traceability to the ITS-90 over a range of dynamic temperature from 800 °C to 2600 °C with a relative uncertainty of less than 1 %.

3.1.3 High voltage

To support testing ultra high voltage equipment, a calibration setup for gas insulated switchgear applications was developed in the European project UHV. This setup generates very fast transient overvoltages and provides robust metrological traceability. The calibration uncertainty (k = 2) is 1.1 % for 100 kV and 6 ns [67]. Several divider designs have been studied and compared for very fast transient measurements [68] and the dynamic effects of test impulse wave shapes were analysed for instrument transformer testing [69]. A Good Practice Guide for measuring ultra high voltage impulses was prepared within the project FutureEnergy. Among other topics, it describes a convolution and deconvolution method for estimate and reduce parameter errors in signal analysis [70]. The main developments achieved with the relevant European projects related to high voltage measurement procedures have been or are in implementation to relevant international IEC standards.

3.2 Measurement and calibration services

In November 2012, a BIPM Workshop on Challenges in Metrology for Dynamic Measurement concluded that developments are needed to clarify the terminology, enable appropriate uncertainty estimation and address specific urgent needs for dynamic measurement especially in the area of mechanical quantities [71]. As described in previous Sections 2.1 and 3.1, significant advancements have been achieved after the workshop. However, a search on CMCs published at the KCDB database by BIPM in January 2025 resulted no dynamic measurement related CMCs for mechanical or thermal quantities. Furthermore, dynamic calibration was only addressed under the theme Pressure in the service category lists of CIPM. In the high voltage area, published CMCs cover well the field of dynamic measurements. In Nordic countries, NMIs in Finland and Sweden cover well the high voltage needs of the region with their CMCs.

As described in Section 3.1, several European NMIs has developed expertise in the field of dynamic force, torque, pressure and temperature measurements within projects of the European metrology research programmes. Although this is has not yet resulted in new CMCs, the NMIs exploit the expertise in their customer service by providing test measurements, prototype instruments and consultancy (see e.g. [59, 72, 73]).

4 Analysis of the needs in Nordic and Baltic countries

Recent strategy documents of CCM and CCEM address the increasing importance of dynamic measurements. Establishing robust SI traceability to dynamic measurements is considered by CCM as one of the main topics for the next decade [74]. According to CCEM, the development of new technologies within e.g. electric vehicles, high frequency communications, renewable energy sources and quantum technology applications requires extending quality control of measurements from steady state to dynamic behaviour [75]. According to the strategic research agendas of the European metrology networks (EMN) Smart Electric Grids, Advance Manufacturing and Mathmet, metrology research in Europe should address the needs of reliable dynamic measurements including the development of relevant uncertainty estimation methods [76 - 78].

Within the stakeholder dialogue of the EMN Smart North, the reliability of dynamic measurements has especially been brought up with manufacturing of heavy duty engines, cars and trucks, measuring instruments and material testing. The needs of the evolving Nordic electric grid have been driving the strong contribution of the Finnish and Swedish national metrology institutes in the high voltage metrology. The electrification of vehicles has been creating needs both in mechanical and electrical measurements. Due to the recent geopolitical development, needs of defence sector have an increasing importance. Dynamic pressure measurements have an important role in testing ammunition.

According to our analysis, the first priority in the Nordic and Baltic countries should be given to the development of the dynamic pressure metrology and to the continuation of the relevant high voltage metrology. Also, dynamic force and torque measurements are of interest but it is not clear how the actual customer need will develop in the future. Overall, it is expected that the volume of dynamic calibrations will not increase rapidly within the next 5 years and they will be focused in specific application fields.

It is worth noticing that static and dynamic calibrations represent extremes from the time dependence point of view leaving an area in between whose importance is increasing. The development of uncertainty analysis methods and research on the optimal calibration approaches are needed to address increasing accuracy requirements and complexities in sensor network setups.

5 Summary

We reviewed published needs, research results and currently available NMI level calibration services related to dynamic calibrations. The review was focused in on measurement needs related to machinery, combustion engines and electrical grids because these were initially identified as the most important application fields in the Nordic and Baltic countries. Dynamic pressure calibrations and specific high voltage measurements were identified as the first priority topics of development in the area. It was also noted that the demand for NMI level dynamic metrology focuses on specific applications with limited growth potential.

References

1. S Eichstädt et al 2016 Metrologia 53 S125
2. T. J. Esward, C. Elster, J. P. Hessling, IMEKO 2009
3. A. Schäfer, S. Eichstädt, IMEKO TC3 2017
4. Andrew Dienstfrey and Paul D Hale 2014 Meas. Sci. Technol. 25 035001
5. K. H. Ruhm, Measurement 79 (2016) 276–284

6. S. Eichstädt, B. Arendacká, A. Link, C. Elster, EPJ Web of Conferences, 77, 0000 (2014)
7. S Eichstädt, K Ruhm, A Shestakov, Journal of Physics: Conf. Series 1065 (2018) 212018
8. Trevor Esward et al 2019 Metrologia 56 015002
9. O. Vasilevskyi et al, Proc. of SPIE Vol. 10808 108082E-1
10. I. Markovsky, Control Engineering Practice 43 (2015) 85–93
11. S. Eichstädt (ed.) Dynamic Measuring Systems: Fundamentals and application of time-dependent measurements, Berlin, Boston: De Gruyter Oldenbourg, 2024. https://doi.org/10.1515/9783110713107
12. S Eichstädt et al 2018 J. Phys.: Conf. Ser. 1065 212018
13. K.H. Ruhm, Measurement 79 (2016) 276–284
14. Esward T J, Elster C and Hessling P 2009 Analysis of dynamic measurements: new challenges require new solutions Proc. 19th IMEKO World Congress (Lisbon, Portugal, 6–11 Sept.) pp 2307–10
15. Andrew Dienstfrey and Paul D Hale 2014 Meas. Sci. Technol. 25 035001
16. Eichstädt S 2012 “Analysis of Dynamic Measurements - Evaluation of Dynamic Measurement Uncertainty”, PhD Thesis, TU Berlin
17. Elster C and Link A 2008 “Uncertainty evaluation for dynamic measurements modelled by a linear time-invariant system”, Metrologia, 45(4), 464-473
18. P. Hessling, “A novel method of dynamic correction in the time domain”, Meas. Sci. Technol. 19, 075101 (10pp), 2008.
19. P. Hessling, “A novel method of estimating dynamic measurement errors”, Meas. Sci. Technol. 17, pp. 2740-2750, 2006
20. J P Hessling 2011 Meas. Sci. Technol. 22 105105
21. Elster C, Eichstädt S, and Link A 2009 Uncertainty evaluation of dynamic measurements in line with the GUM Proc. 19th IMEKO World Congress (Lisbon, Portugal, 6–11 Sept.) pp 2311–14
22. O. Vasilevskyi et al, Proc. of SPIE Vol. 10808 108082E-1
23. Trevor Esward et al 2019 Metrologia 56 015002
24. S. Eichstädt, B. Arendacká, A. Link, C. Elster, EPJ Web of Conferences, 77, 0000 (2014)
25. S Eichstädt et al 2016 Meas. Sci. Technol. 27 125009
26. A. Link and C. Elster, “Uncertainty evaluation for IIR filtering using a state-space approach”, Meas. Sci. Technol. 20, 055104 (5pp), 2009.
27. H. Dizdar, B. Aydemir, C. Vatan, Evaluation of the effect of dynamic verification on different types of force sensors, Joint IMEKO TC3, T5, TC16 and TC22 International Conference, 2022, DOI: 10.21014/tc3-2022.012
28. Mitra Djamal, Kazuhide Watanabe, Kyohei Irisa, Irfa Aji Prayogi, Akihiro Takita, Takao Yamaguchi and Yusaku Fujii, Metrol. Meas. Syst., Vol. XXI (2014), No. 1, pp. 59–66, DOI: 10.2478/mms-2014-0006
29. Nicholas Vlajic and Ako Chijioke 2016 Metrologia 53 S136, doi:10.1088/0026-1394/53/4/S136
30. Misaki Hamaji, Atsuhiro Nishino, Koji Ogushi, Measurement: Sensors 18 (2021) 100183
31. A. Tao Li, B. Xianglong Ma, Zhiqiang Qiao, Negative step dynamic torque calibration machine, Physics Conference Series, vol. 1740, no. 1, pp. 208-212, 2016
32. Misaki Hamaji et al 2022 Meas. Sci. Technol. 33 115901, doi.org/10.1088/1361-6501/ac8441
33. André Schäfer, Dynamic measurements as an emerging field in industrial metrology, PTB-Mitteilungen 125 (2015), No. 2, pp 62-67
34. Y. Yamakawa, T. Yamazaki, Simplified model of mass measurement system with consideration of variation of fulcrum position, Joint IMEKO TC3, T5, TC16 and TC22 International Conference, 2022,
35. André Schäfer, Sascha Eichstädt, Evaluation of dynamic measurement uncertainty for industrial applications, IMEKO 23rd TC3, 13th TC5 and 4th TC22 Int. Conf., 30 May to 1 June, 2017
36. IPCC, 2023: Sections. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647
37. IEA, Statista 2024
38. R D Reitz et al., IJER editorial: The future of the internal combustion engine, International J of Engine Research 2020, Vol. 21(1) 3–10, DOI: 10.1177/1468087419877990
39. Jan Hjelmgren, Dynamic measurement of pressure - a literature survey, SP Report 2002:34, 64p. ISBN 91-7848-925-3
40. Felix Leach, Gautam Kalghatgi, Richard Stone, Paul Miles, The scope for improving the efficiency and environmental impact of internal combustion engines, Transportation Engineering 1 (2020) 100005, DOI: 10.1016/j.treng.2020.100005
41. Dahham, R.Y.; Wei, H.; Pan, J. Improving thermal efficiency of internal combustion engines: recent progress and remaining challenges. Energies 2022, 15, 6222. doi: 10.3390/en15176222
42. Erick Garcia, Strategies for improving efficiency and emissions in heavy-duty diesel engines, PhD dissertation, The University of Michigan 2021
43. J Salminen et al 2020 Metrologia 57 045006, doi: 10.1088/1681-7575/ab8fb9

44. Alberto Sposito, Dave Lowe, Gavin Sutton, Int. J. Turbomach. Propuls. Power 2020, 5, 31; doi:10.3390/ijtpp5040031
45. IEC 61083
46. https://e-treny.eu/objectives/
47. Final Publishable Report, 18SIB08 ComTraForce, https://www.euramet.org/
48. DKD-R 9-4 Dynamische kalibrierung von werkstoffprufmaschinen, doi: 10.7795/550.20240606
49. Nicholas Vlajic and Ako Chijioke 2016 Metrologia 53 S136, doi:10.1088/0026-1394/53/4/S136
50. Final Publishable Report, 14IND14 MNmTorque, https://www.euramet.org/
51. Final Publishable Report, 19ENG08_WindEFCY, https://www.euramet.org/
52. Leonard Klaus, Michael Kobusch, Measurement: Sensors 18 (2021) 100149, doi: 10.1016/j.measen.2021.100149
53. Leonard Klaus et al 2015 Metrologia 52 72, doi:10.1088/0026-1394/52/1/72
54. L. Klaus, ACTA IMEKO, December 2020, Volume 9, Number 5, 200-204, ISSN: 221-870X
55. Misaki Hamaji et al 2022 Meas. Sci. Technol. 33 115901, doi: 10.1088/1361-6501/ac8441
56. MyeongHyeon Kim, IEEE Transactions on Instrumentation and Measurement, Vol. 70, 2021, 1005207
57. R. Högström et al., Development of measurement and calibration techniques for dynamic pressures and temperatures – results and achievements, Joint IMEKO TC3, T5, TC16 and TC22 International Conference, 2022, doi: DOI: 10.21014/tc16-2022.005
58. Christophe Sarraf 2021 Meas. Sci. Technol. 32 015013, doi: 10.1088/1361-6501/aba56a
59. J Salminen et al 2020 Metrologia 57 045006, doi: 10.1088/1681-7575/ab8fb9
60. Richard Högström et al., Measurement: Sensors, https://doi.org/10.1016/j.measen.2024.101686
61. Lamine Elkarous, Cyril Robbe, Marc Pirlot, Jean-Claude Golinval, Int. J. Metrol. Qual. Eng. 7, 201 (2016), doi: 10.1051/ijmqe/2016004
62. Rudi Anggoro Samodro; In-Mook Choi, Rev. Sci. Instrum. 90, 095111 (2019); doi: 10.1063/1.5108865
63. In-Mook Choi et al., Measurement: Sensors, https://doi.org/10.1016/j.measen.2024.101684
64. Thomas Platte, Measurement: Sensors 18 (2021) 100252, doi: 10.1016/j.measen.2021.100252
65. Yu Zhang, Jing Zu, Hong-Yan Zhang, Measurement 45 (2012) 1981–1988, doi: 10.1016/j.measurement.2012.04.024
66. Gavin Sutton, Alexander Fateev, Miguel A. Rodríguez-Conejo, Juan Meléndez, Guillermo Guarnizo, International Journal of Thermophysics (2019) 40:99, doi:10.1007/s10765-019-2557-6
67. Final Publishable Report, 15NRM02, www.euramet.org
68. A.-P. Elg, S. Passon, J Meisner and J. Hällström, “High voltage topologies for very fast transient measurements”, 21st International Symposium on High Voltage Engineering (ISH 2019), 26-30 August 2019, Budapest, Hungary, https://doi.org/10.5281/zenodo.3244216
69. A.-P. Elg, “Quantifying a transient recorder for traceable measurements of very fast transients”, Proceedings of Conference on Precision Electromagnetics Measurements (CPEM 2018), July, 8-13, 2018, Paris, France, https://doi.org/10.5281/zenodo.1473323
70. J. Hällström et al., Good Practice Guide on characterisation methods for UHV lightning impulse (LI) dividers, Deliverable Technical Report, 19ENG02 FutureEnergy, www.euramet.org
71. T. Usuda et al., Report on the BIPM workshop on challenges in metrology for dynamic measurement, Rapport BIPM-2013/01, www.bipm.org
72. www.ri.se/en/expertise-areas/test-demo/dynamic-pressure-testing
73. www.ume.tubitak.gov.tr/en/laboratuvarlarimiz/infrastructure-1
74. Strategy 2022-2032. Consultative Committee for Mass and Related Quantities (CCM), Version 1.8, 14 March 2022, www.bipm.org
75. Strategy 2020-2030 Consultative Committee for Electricity and Magnetism (CCEM), 18 May 2021, www.bipm.org
76. European Metrology Network Smart Electricity Grids - Strategic Research Agenda, Version 1.0 (04/2023), www.euramet.org
77. Strategic Research Agenda. European Metrology Network for Advanced Manufacturing, Version Live on JNP sharepoint, downloaded on 07.03.2024, www.euramet.org
78. European Metrology Network for Mathematics and Statistics - Strategic Research Agenda 2023 - 2033, Version 1.0 (07/2023), www.euramet.orgJ. Couturier, Y.H. Abou and E. Grolleau, Element of nuclear safety, (EDP Sciences, Les Ulis, 2019)