

# Measurement Science and Technology

## Highlights of 2014

Editor-in-Chief: D J S Birch, Strathclyde University, UK



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Dear Colleagues

I am delighted to present the *Measurement Science and Technology* (MST) Highlights of 2014, a selection of the very best research published by the journal in 2014. These highlights show the tremendous diversity of areas covered by the journal. Articles in MST represent the highest quality research in measurement science, and are published following a rigorous peer-review process, which accepts fewer than one in three submissions to the journal.

The articles presented here have been selected by the journal's Editorial Board, with the guidance of our team of expert referees, as some of the highest quality papers we have published in 2014. I hope that you find them interesting.

To read the full-text articles, or to submit your own work to *Measurement Science and Technology*, please go to [iopscience.org/mst](http://iopscience.org/mst). All these articles have been made free to read to the end of 2015.

**Ian Forbes**

Publisher, *Measurement Science and Technology*

### Winner of 2014 Outstanding Paper Award

#### Fluid mechanics

## A combined scanning PTV/LIF technique to simultaneously measure the full velocity gradient tensor and the 3D density field

D Krug, M Holzner, B Lüthi, M Wolf, A Tsinober and W Kinzelbach

#### Abstract

We present a newly developed combined scanning particle tracking velocimetry (SPTV) and scanning laser-induced fluorescence (SLIF) technique. The new method allows for the first time to measure the full velocity gradient tensor and the three-dimensional density field simultaneously in a refractive index matched environment. The data thus obtained will be valuable in investigating the interaction between turbulence, i.e. the dynamics of vorticity and strain, and the density field. In this study, we describe the implementation of the measurement system in detail. As a showcase, the new technique is applied to a gravity current flow and the measured data are validated by imposing various checks. Further results are presented that illustrate the capability of the SPTV/SLIF technique in the investigation of interface dynamics

2014 *Meas. Sci. Technol.* **25** 065301

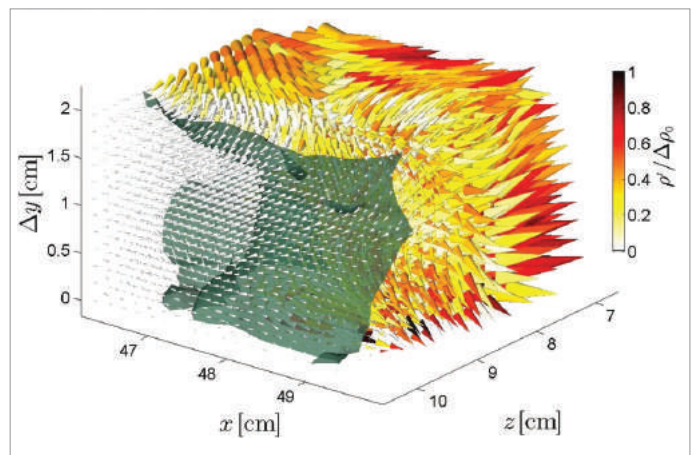


Figure taken from D Krug et al 2014 *Meas. Sci. Technol.* **25** 065301



#### Did you know?

MST is the oldest measurement journal in the world, originally published as *Journal of Scientific Instruments* in 1923

## Bootstrapping de-shadowing and self-calibration for scanning electron microscope photometric stereo

Atsushi Miyamoto, Deshan Chen and Shun'ichi Kaneko

### Abstract

In this paper, we present a novel approach that addresses the blind reconstruction problem in scanning electron microscope (SEM) photometric stereo. Using only two observed images that suffer from shadowing effects, our method automatically calibrates the parameter and resolves shadowing errors for estimating an accurate three-dimensional (3D) shape and underlying shadowless images. We introduce a novel shadowing compensation model using image intensities for both cases of presence and absence of shadowing. With this model, the proposed de-shadowing algorithm iteratively compensates for image intensities and modifies the corresponding 3D surface. Besides de-shadowing, we introduce a practically useful self-calibration criterion by enforcing a good reconstruction. We show that incorrect parameters will engender significant distortions of 3D reconstructions in shadowed regions during the de-shadowing procedure. This motivated us to design the self-calibration criterion by utilizing shadowing to pursue the proper parameter that produces the best reconstruction with least distortions. As a result, we develop a bootstrapping approach for simultaneous de-shadowing and self-calibration in SEM photometric stereo. Extensive experiments on real image data demonstrate the effectiveness of our method.

2014 *Meas. Sci. Technol.* **25** 105402

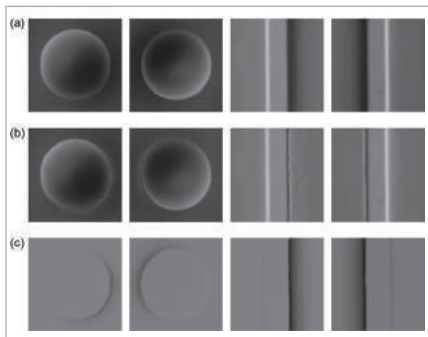


Figure taken from Atsushi Miyamoto et al 2014 *Meas. Sci. Technol.* **25** 105402

## PTB's enhanced stitching approach for the high-accuracy interferometric form error characterization of spheres

Guido Bartl, Michael Krystek and Arnold Nicolaus

### Abstract

The stitching procedure that was presented a few years ago allowed the reconstruction of the real shape of a sphere from the measured data that had been acquired by the sphere interferometer of the Physikalisch-Technische Bundesanstalt. The enhancements described in this paper involve additional information from the measurements that could not be taken into account before. Therefore, not only the determination of the uncertainty of the reconstructed results is enabled, but also the occurrence of large-scale systematic deviations can be prevented. As a consequence, the form

deviations of a sphere can be characterized reliably, which benefits the efforts of reducing the form deviations of the silicon spheres of the Avogadro project. In other fields where spheres are used as references, accurate knowledge of the real form may be helpful for further improvements.

2014 *Meas. Sci. Technol.* **25** 064002

## Improving the accuracy of the transient plane source method by correcting probe heat capacity and resistance influences

Yanning Li, Chunfeng Shi, Jian Liu, Errui Liu, Jian Shao, Zhi Chen, Dante J Dorantes-Gonzalez and Xiaotang Hu

### Abstract

The transient plane source (TPS) method is a relatively newly developed transient approach for thermal conductivity measurement. Compared with the steady-state method, it is fast, and applicable to either solid, liquid or gas state materials; therefore, it has gained much popularity in recent years. However, during measurement, the measured power is influenced by the heat capacity of the electrical isolation films as well as the electrical resistance change of the metallic thin wire of the TPS probes. This further influences the measurement precision. Meanwhile, these two factors have been ignored in the traditional model of TPS developed by Gustafsson. In this paper, the influence of both the heat capacity and the resistance change of the TPS probe on the measured power is studied, and mathematical formulas relating the two factors and their respective corrections are deduced. Thereafter an improved model is suggested based on the traditional TPS model and the above theoretical models. Experiments on polymethylmethacrylate (PMMA) standard materials have been conducted using a home-made system, including TPS probes, data acquisition module and analysis software. The results show that the improved model can effectively improve the measurement precision of the TPS method by about 1.8–2.3% as evaluated by relative standard deviation.

2014 *Meas. Sci. Technol.* **25** 015006

## Microwave based method of monitoring crack formation

Sergej Aman, Alexander Aman, Soeren Majcherek, Soeren Hirsch and Bertram Schmidt

### Abstract

The formation of cracks in glass particles was monitored by application of linearly polarized microwaves. The breakage behavior of glass spheres coated with a thin gold layer of about 50 nm, i.e. a thickness that is lower than the microwave penetration depth, was tested. In this way the investigation of fracture behavior of electronic circuits was simulated. A shielding current was induced in the gold layer by the application of microwaves. During the crack formation the distribution of this current changed abruptly and a scattered microwave signal appeared at the frequency of the incident microwaves. The time behavior of the scattered signal reflects the microscopic processes occurring during the fracture of the specimen. The duration of the increasing signal corresponds to the crack formation time in the tested specimen. This time was estimated as particle size divided by crack development speed in glass. An intense emission of electrons occurs during the formation of cracks. Due to this, coherent Thomson scattering of microwaves by emitted electrons becomes significant with a delay of a few microseconds after the initial phase of crack formation. In this time the intensity of the microwave signal increases.

2014 *Meas. Sci. Technol.* **25** 025014

## A multifrequency electromagnetic applicator with an integrated AC magnetometer for magnetic hyperthermia experiments

E Garaio, J M Collantes, F Plazaola, J A Garcia and I Castellanos-Rubio

### Abstract

In the present paper, a lab-made electromagnetic applicator for magnetic hyperthermia experiments is described, fabricated and tested. The proposed device is able to measure the specific absorption rate (SAR) of nanoparticle samples at different magnetic field intensities and frequencies. Based on a variable parallel LCC resonant circuit fed by a linear power amplifier, the electromagnetic applicator is optimized to generate a controllable and homogeneous AC magnetic field in a 3.5 cm<sup>3</sup> cylindrical volume, in a wide frequency range of 149–1030 kHz with high field intensities (up to 35 kA m<sup>-1</sup> at low frequencies and up to 22 kA m<sup>-1</sup> at high frequencies). In addition, a lab-made AC magnetometer is integrated in the electromagnetic applicator. The AC magnetometer is fully compensated to provide accurate measurements of the dynamic hysteresis cycle for nanoparticle powders or dispersions. From these dynamic hysteresis loops the SAR of the nanoparticle samples can be directly obtained. To show the capabilities of the proposed set-up, the AC hysteresis loops of two different magnetite nanoparticle samples with different sizes have been measured for various field intensities and frequencies. To our knowledge, no other work reports an electromagnetic applicator system with integrated AC magnetometer providing such characteristics in terms of frequency and intensity.

2014 *Meas. Sci. Technol.* **25** 115702

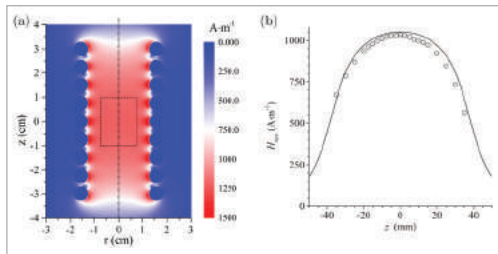


Figure taken from E Garaio et al 2014 *Meas. Sci. Technol.* **25** 115702

## A long-stroke horizontal electromagnetic vibrator for ultralow-frequency vibration calibration

Wen He, Xufei Zhang, Chunyu Wang, Runjie Shen and Mei Yu

### Abstract

A novel long-stroke horizontal electromagnetic vibrator with maximum stroke of 1 m is proposed. To reply to the strong nonlinearity arising from long stroke, a closed double-magnetic circuit with optimal air gap, an electro-viscoelastic-suspension device and a track following device are adopted in the vibrator. Also, a compact moving component with a higher first-order natural frequency is designed to increase the operating frequency of the vibrator. Finally, experimental results show that the vibrator could output low distortion acceleration on its working platform from 0.002 Hz to 100 Hz, which verifies the validity of the proposed technologies and the applicability of the vibrator for an ultralow-frequency vibration calibration system.

2014 *Meas. Sci. Technol.* **25** 085901

## Application of order cyclostationary demodulation to damage detection in a direct-driven wind turbine bearing

Xiaofeng Liu, Lin Bo and Chang Peng

### Abstract

This paper presents a method of fault detection and isolation for a direct-driven wind turbine (DWT) bearing. Computed order tracking is employed to convert the non-stationary envelope signal in the time domain into a quasi-stationary signal in the angular domain by even-angle resampling. Cyclostationary demodulation is then utilized to expose the orders related to fault characteristics in the demodulation spectrum. In order to realize the automatic fault diagnosis and emit a stable alarm about bearing damage, the peak value of the demodulation spectrum is scaled and compared to a defined threshold. The significant advantage of the proposed method is the implementation of an automatic algorithm for DWT bearing diagnostics under randomly varying speed and highly alternating load. Practical applications are provided to show that the proposed approach is able to achieve reliable failure warning in the bearing condition monitoring of a DWT.

2014 *Meas. Sci. Technol.* **25** 025004

## Non-contact test set-up for aeroelasticity in a rotating turbomachine combining a novel acoustic excitation system with tip-timing

O Freund, M Montgomery, M Mittelbach and J R Seume

### Abstract

Due to trends in aero-design, aeroelasticity becomes increasingly important in modern turbomachines. Design requirements of turbomachines lead to the development of high aspect ratio blades and blade integral disc designs (blisks), which are especially prone to complex modes of vibration. Therefore, experimental investigations yielding high quality data are required for improving the understanding of aeroelastic effects in turbomachines. One possibility to achieve high quality data is to excite and measure blade vibrations in turbomachines. The major requirement for blade excitation and blade vibration measurements is to minimize interference with the aeroelastic effects to be investigated. Thus in this paper, a non-contact—and thus low interference—experimental set-up for exciting and measuring blade vibrations is proposed and shown to work. A novel acoustic system excites rotor blade vibrations, which are measured with an optical tip-timing system. By performing measurements in an axial compressor, the potential of the acoustic excitation method for investigating aeroelastic effects is explored. The basic principle of this method is described and proven through the analysis of blade responses at different acoustic excitation frequencies and at different rotational speeds. To verify the accuracy of the tip-timing system, amplitudes measured by tip-timing are compared with strain gage measurements. They are found to agree well. Two approaches to vary the nodal diameter (ND) of the excited vibration mode by controlling the acoustic excitation are presented. By combining the different excitable acoustic modes with a phase-lag control, each ND of the investigated 30 blade rotor can be excited individually. This feature of the present acoustic excitation system is of great benefit to aeroelastic investigations and represents one of the main advantages over other excitation methods proposed in the past. In future studies, the acoustic excitation method will be used to investigate aeroelastic effects in high-speed turbomachines in detail. The results of these investigations are to be used to improve the aeroelastic design of modern turbomachines.

2014 *Meas. Sci. Technol.* **25** 035008



## Laser absorption of nitric oxide for thermometry in high-enthalpy air

R M Spearrin, I A Schultz, J B Jeffries and R K Hanson

### Abstract

The design and demonstration of a laser absorption sensor for thermometry in high-enthalpy air is presented. The sensor exploits the highly temperature-sensitive and largely pressure-independent concentration of nitric oxide in air at chemical equilibrium. Temperature is thus inferred from an *in situ* measurement of nascent nitric oxide. The strategy is developed by utilizing a quantum cascade laser source for access to the strong fundamental absorption band in the mid-infrared spectrum of nitric oxide. Room temperature measurements in a high-pressure static cell validate the suitability of the Voigt lineshape model to the nitric oxide spectra at high gas densities. Shock-tube experiments enable calibration of a collision-broadening model for temperatures between 1200–3000 K. Finally, sensor performance is demonstrated in a high-pressure shock tube by measuring temperature behind reflected shock waves for both fixed-chemistry experiments where nitric oxide is seeded, and for experiments involving nitric oxide formation in shock-heated mixtures of N<sub>2</sub> and O<sub>2</sub>. Results show excellent performance of the sensor across a wide range of operating conditions from 1100–2950 K and at pressures up to 140 atm.

2014 Meas. Sci. Technol. **25** 125103

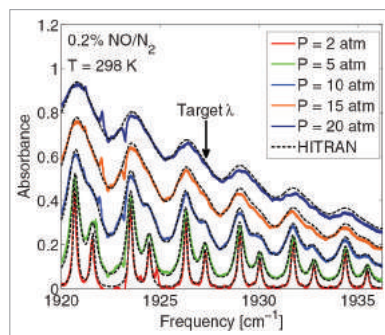


Figure taken from R M Spearrin et al 2014 Meas. Sci. Technol. **25** 125103

## Spatially resolved acoustic spectroscopy for rapid imaging of material microstructure and grain orientation

Richard J Smith, Wenqi Li, Jethro Coulson, Matt Clark, Michael G Somekh and Steve D Sharples

### Abstract

Measuring the grain structure of aerospace materials is very important to understand their mechanical properties and in-service performance. Spatially resolved acoustic spectroscopy is an acoustic technique utilizing surface acoustic waves to map the grain structure of a material. When combined with measurements in multiple acoustic propagation directions, the grain orientation can be obtained by fitting the velocity surface to a model. The new instrument presented here can take thousands of acoustic velocity measurements per second. The spatial and velocity resolution can be adjusted by simple modification to the system; this is discussed in detail by comparison of theoretical expectations with experimental data.

2014 Meas. Sci. Technol. **25** 055902

## Accurate 3D shape measurement of multiple separate objects with stereo vision

Hien Kieu, Tongyan Pan, Zhaoyang Wang, Minh Le, Hieu Nguyen and Minh Vo

### Abstract

3D shape measurement has emerged as a very useful tool in numerous fields because of its wide and ever-increasing applications. In this paper, we present a passive, fast and accurate 3D shape measurement technique using stereo vision approach. The technique first employs a scale-invariant feature transform algorithm to detect point matches at a number of discrete locations despite the discontinuities in the images. Then an automated image registration algorithm is applied to find full-field point matches with subpixel accuracy. After that, the 3D shapes of the objects can be reconstructed according to the obtained point matching and the camera information. The proposed technique is capable of performing a full-field 3D shape measurement with high accuracy even in the presence of discontinuities and multiple separate regions. The validity is verified by experiments.

2014 Meas. Sci. Technol. **25** 035401

## A novel pitch evaluation of one-dimensional gratings based on a cross-correlation filter

Xiaomei Chen and Ludger Koenders

### Abstract

If one-dimensional (1D),  $p$ -period and arbitrarily structured grating position-related topographical signals coexist with noise, it is difficult to evaluate the pitch practically using the center-of-gravity (CG) method. The Fourier-transform-based (FT) method is the most precise to evaluate pitches; nevertheless, it cannot give the uniformity of pitches. If a cross-correlation filter—a half period of sinusoidal waveform sequence ( $p_r$  period), cross-correlates with the signals, the noise can be eliminated if  $p_r \approx p$ . After cross-correlation filtering, the distance between any two adjacent waveform peaks along the direction perpendicular to 1D grating lines is one pitch value. The pitch evaluation based on the cross-correlation filtering together with the detection of the peak's position is described as the peak detection (PD) method in this paper. The pitch average and uniformity can be calculated by using the PD method. The computer simulation has indicated that the average of pitch deviations from the true pitch and the pitch variations are less than 0.2% and 0.2% for the sinusoidal and rectangular waveform signals with up to 50% uniform white noise, less than 0.1% and 1% for the sinusoidal and rectangular waveform signals and 0.6% and 2.5% for the triangular waveform signal if three waveform signals are mixed with Gaussian white, binomial and Bernoulli noise up to 50% in standard deviation, one probability and trial probability, respectively. As examples, a highly oriented pyrolytic graphite (HOPG) with a 0.246 nm distance between second nearest neighbour atoms and a 1D grating with 3000 nm nominal pitch are measured by a ultra-high vacuum scanning tunneling microscope (UHV STM) and a metrological atomic force microscope (AFM), respectively. After the position-related topographical signals are cross-correlation filtered, the 0.240 and 3004.11 nm pitches calculated by using the PD method are very close to the 0.240 and 3003.34 nm results evaluated by the FT method.

2014 Meas. Sci. Technol. **25** 044007

## Scanning magnetic tunnel junction microscope for high-resolution imaging of remanent magnetization fields

EA Lima, A C Bruno, H R Carvalho and B P Weiss

### Abstract

Scanning magnetic microscopy is a new methodology for mapping magnetic fields with high spatial resolution and field sensitivity. An important goal has been to develop high-performance instruments that do not require cryogenic technology due to its high cost, complexity, and limitation on sensor-to-sample distance. Here we report the development of a low-cost scanning magnetic microscope based on commercial room-temperature magnetic tunnel junction (MTJ) sensors that typically achieves spatial resolution better than  $7\ \mu\text{m}$ . By comparing different bias and detection schemes, optimal performance was obtained when biasing the MTJ sensor with a modulated current at 1.0 kHz in a Wheatstone bridge configuration while using a lock-in amplifier in conjunction with a low-noise custom-made preamplifier. A precision horizontal ( $x$ - $y$ ) scanning stage comprising two coupled nanopositioners controls the position of the sample and a linear actuator adjusts the sensor-to-sample distance. We obtained magnetic field sensitivities better than  $150\ \text{nT}/\text{Hz}^{1/2}$  between 0.1 and 10 Hz, which is a critical frequency range for scanning magnetic microscopy. This corresponds to a magnetic moment sensitivity of  $10^{-14}\ \text{A m}^2$ , a factor of 100 better than achievable with typical commercial superconducting moment magnetometers. It also represents an improvement in sensitivity by a factor between 10 and 30 compared to similar scanning MTJ microscopes based on conventional bias-detection schemes. To demonstrate the capabilities of the instrument, two polished thin sections of representative geological samples were scanned along with a synthetic sample containing magnetic microparticles. The instrument is usable for a diversity of applications that require mapping of samples at room temperature to preserve magnetic properties or viability, including paleomagnetism and rock magnetism, nondestructive evaluation of materials, and biological assays.

2014 *Meas. Sci. Technol.* **25** 105401

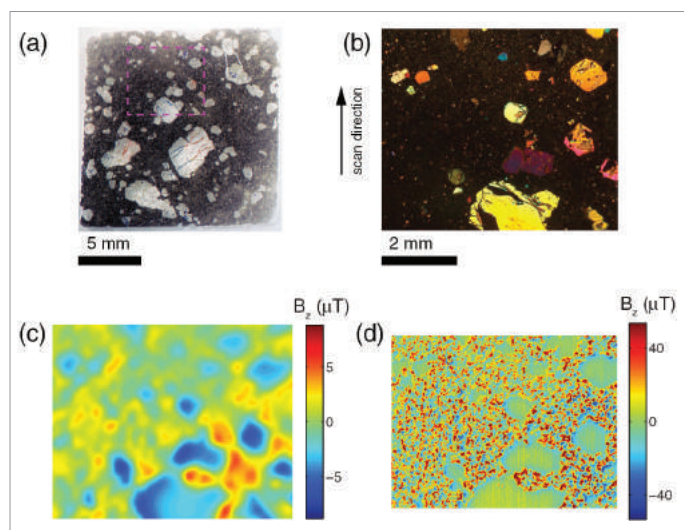


Figure taken from E A Lima *et al* 2014 *Meas. Sci. Technol.* **25** 105401

## A new general approach for solving the self-calibration problem on large area 2D ultra-precision coordinate measurement machines

Peter Ekberg, Lars Stibler and Lars Mattsson

### Abstract

The manufacturing of flat panel displays requires a number of photomasks for the placement of pixel patterns and supporting transistor arrays. For large area photomasks, dedicated ultra-precision writers have been developed for the production of these chromium patterns on glass or quartz plates. The dimensional tolerances in  $X$  and  $Y$  for absolute pattern placement on these plates, with areas measured in square meters, are in the range of 200–300 nm ( $3\sigma$ ). To verify these photomasks, 2D ultra-precision coordinate measurement machines are used having even tighter tolerance requirements. This paper will present how the world standard metrology tool used for verifying large masks, the Micronic Mydata MMS15000, is calibrated without any other references than the wavelength of the interferometers in an extremely well-controlled temperature environment. This process is called self-calibration and is the only way to calibrate the metrology tool, as no square-meter-sized large area 2D traceable artifact is available. The only parameter that cannot be found using self-calibration is the absolute length scale. To make the MMS15000 traceable, a 1D reference rod, calibrated at a national metrology lab, is used. The reference plates used in the calibration of the MMS15000 may have sizes up to  $1\ \text{m}^2$  and a weight of 50 kg. Therefore, standard methods for self-calibration on a small scale with exact placements cannot be used in the large area case. A new, more general method had to be developed for the purpose of calibrating the MMS15000. Using this method, it is possible to calibrate the measurement tool down to an uncertainty level of  $<90\ \text{nm}$  ( $3\sigma$ ) over an area of  $(0.8 \times 0.8)\ \text{m}^2$ . The method used, which is based on the concept of iteration, does not introduce any more noise than the random noise introduced by the measurements, resulting in the lowest possible noise level that can be achieved by any self-calibration method.

2014 *Meas. Sci. Technol.* **25** 055001

## Extending the flash method to measure the thermal diffusivity of semitransparent solids

Agustín Salazar, Arantza Mendioroz, Estibaliz Apiñaniz, Christophe Pradere, Frédéric Noël and Jean-Christophe Batsale

### Abstract

In this work, we extend the classical flash method to retrieve simultaneously the thermal diffusivity and the optical absorption coefficient of semitransparent plates. A complete theoretical model that allows calculating the rear surface temperature rise of the sample has been developed. It takes into consideration additional effects such as multiple reflections of the heating light beam inside the sample, heat losses by convection and radiation, transparency of the sample to infrared wavelengths and finite duration of the heating pulse. Measurements performed on calibrated solids, covering a wide range of absorption coefficients from transparent to opaque, validate the proposed method.

2014 *Meas. Sci. Technol.* **25** 035604

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## Capabilities and limitations of the self-calibration of angle encoders

Ralf D Geckeler, Alfred Link, Michael Krause and Clemens Elster

### Abstract

At the Physikalisch-Technische Bundesanstalt (PTB), a self-calibration method for the fast and precise *in situ* calibration of angle encoders without recourse to external reference standards has been developed. It relies on a suitable geometric arrangement of multiple reading heads which read out the radial grating of the angle encoder at different angular positions. Fourier-based algorithms are used to analyse the measurement differences of pairs of heads to recover the graduation error of the grating. A comprehensive overview, both theoretical and experimental, of the capabilities and limitations of the self-calibration method is presented, including experimental data obtained with the high-precision primary angle standard of PTB. The evaluation and, where it is possible, correction of error influences due to lateral shifts of the centre of the encoder's grating during its rotation, including its eccentricity, the reading heads' angular positions, and their non-uniform response, are discussed in detail, as well as the resulting uncertainty budget.

2014 *Meas. Sci. Technol.* **25** 055003

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## An examination of polyvinylidene fluoride capacitive sensors as ultrasound transducer for imaging applications

B Reyes-Ramírez, C García-Segundo and A García-Valenzuela

### Abstract

We investigate theoretically and experimentally the performance of low-noise capacitive sensors based on polyvinylidene fluoride (PVDF) piezoelectric films to sense water-borne ultrasound signals for their use in photoacoustic tomography. We derive a mechanical-to-electrical transfer function of a piezoelectric capacitor sensor of infinite lateral dimensions and arbitrary thickness assuming that an ultrasound wave is normally incident. Then, we analyse the response for obliquely incident ultrasound waves on sensors of large but finite area and derive an expression for the angle dependence of the sensor's response. We also present experimental different measurements with home-made sensors and compare with our theoretical model. We present measurements of the sensors' response to harmonic signals of variable frequency in the range from 0.5 to 50 MHz and of the angular-dependence factor at 6 MHz. Additionally, because of the scope of interest in these kinds of sensors, we also tested the sensors' response for photoacoustic perturbations. These are generated by laser pulses from directly impinging on the sensor and from ultrasound perturbations produced on neoprene by the same kind of laser pulses and then travelling through water to the sensor.

2014 *Meas. Sci. Technol.* **25** 055109

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## Procedure and reference standard to determine the structural resolution in coordinate metrology

Jens Illemann, Markus Bartscher, Otto Jusko, Frank Härtig, Ulrich Neuschaefer-Rube and Klaus Wendt

### Abstract

A new procedure and reference standards for specifying the structural resolution in coordinate metrology traceable to the SI unit the metre are proposed. With the definition of the structural resolution, a significant gap will be closed to complete 'acceptance and verification tests' of the coordinate measuring systems (CMSs) which are specified in the ISO 10360 series dealing with tactile sensors, optical sensors, and x-ray computed tomography measurement systems (CTs). The proposed new procedure uses reference standards with circular rounded edges. The idea is to measure the radius of curvature on a calibrated round edge structure. From the deviation between the measured and the calibrated radius, an analogue Gaussian broadening of the measurement system is determined. This value is a well-defined and easy-to-apply measure to define the structural resolution for dimensional measurements. It is applicable to CMSs which are based on different sensing principles, e.g. tactile, optical and CT systems. On the other hand, it has a physical meaning similar to the classical optical point-spread function. It makes it possible to predict which smallest details the CMS is capable of measuring reliably for an arbitrary object shape. The theoretical background of the new procedure is given, an appropriate reference standard is described and comparative, quantitative measurement data of CMSs featuring different sensors are shown.

2014 *Meas. Sci. Technol.* **25** 064015

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## Reduction of chromatic aberration influences in vertical scanning white-light interferometry

Peter Lehmann, Peter Kühnhold and Weichang Xie

### Abstract

Vertical scanning white-light interferometry (SWLI) is a well-established method that is widely used in high precision surface topography measurement. However, SWLI results show characteristic slope-dependent errors due to dispersion effects and lateral chromatic aberrations of the optical imaging system. In this paper, we present methods to characterize these systematic errors related to dispersion and lateral colour. Lateral colour leads to field-dependent systematic discrepancies of the topography data obtained from the envelope position of a low-coherence interference signal and the data resulting from its interference phase. Hence, an erroneous fringe order obtained from the envelope position leads to a  $2\pi$  phase jump and thus to a so-called ghost step in the measured topography. Our first approach to solve this problem is based on the measurement of a surface standard of well-known geometry. By comparison of measurement results related to the envelope position and the phase of SWLI signals, the systematic error is estimated and a numerical error compensation method is proposed. Both experimental and simulation results confirm the validity of this numerical method. In addition, using an improved design of a white-light Michelson interferometer we demonstrate experimentally that lateral chromatic aberrations and dispersion influences can be reduced also in a physical way. In this context, a conventional long working distance microscope objective is used which was not originally designed for a Michelson interference microscope.

2014 *Meas. Sci. Technol.* **25** 065203



### Did you know?

Papers to MST are currently accepted on average in three calendar months from receipt



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## 3D reconstruction of hollow parts analyzing images acquired by a fiberscope

Octavio Icasio-Hernández, José-Joel Gonzalez-Barbosa, Juan B Hurtado-Ramos and Miguel Villesid-Alonso

### Abstract

A modified fiberscope used to reconstruct difficult-to-reach inner structures is presented. By substituting the fiberscope's original illumination system, we can project a profile-revealing light line inside the object of study. The light line is obtained using a sandwiched power light-emitting diode (LED) attached to an extension arm on the tip of the fiberscope. Profile images from the interior of the object are then captured by a camera attached to the fiberscope's eyepiece. Using a series of those images at different positions, the system is capable of generating a 3D reconstruction of the object with submillimeter accuracy. Also proposed is the use of a combination of known filters to remove the honeycomb structures produced by the fiberscope and the use of ring gages to obtain the extrinsic parameters of the camera attached to the fiberscope and the metrological traceability of the system. Several standard ring diameter measurements were compared against their certified values to improve the accuracy of the system. To exemplify an application, a 3D reconstruction of the interior of a refrigerator duct was conducted. This reconstruction includes accuracy assessment by comparing the measurements of the system to a coordinate measuring machine. The system, as described, is capable of 3D reconstruction of the interior of objects with uniform and non-uniform profiles from 10 to 60 mm in transversal dimensions and a depth of 1000 mm if the material of the walls of the object is translucent and allows the detection of the power LED light from the exterior through the wall. If this is not possible, we propose the use of a magnetic scale which reduces the working depth to 170 mm. The assessed accuracy is around  $\pm 0.15$  mm in 2D cross-section reconstructions and  $\pm 1.3$  mm in 1D position using a magnetic scale, and  $\pm 0.5$  mm using a CCD camera.

2014 *Meas. Sci. Technol.* **25** 075402

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## Nondestructive indication of fatigue damage and residual lifetime in ferromagnetic construction materials

Ivan Tomáš, Ondřej Kovářík, Gábor Vértesy and Jana Kadlecová

### Abstract

A new revolutionary attitude toward investigation of fatigue damage in cyclically loaded steel samples is reported. The measurement is based on the method of magnetic adaptive testing, which—in contrast to traditional magnetic hysteresis investigations—picks up the relevant information from systematic measurement and evaluation of whole minor magnetic hysteresis loops and their derivatives. Satisfactory correlations between nondestructively measured magnetic descriptors and actual lifetime of the fatigued material were found. The presented method is able to serve as a powerful tool for indication of changes, which occur in the structure of the inspected objects during their industrial service lifetime, as long as they are manufactured from ferromagnetic materials.

2014 *Meas. Sci. Technol.* **25** 065601

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## Multiple wavelength interferometry for distance measurements of moving objects with nanometer uncertainty

R Kuschmierz, J Czarske and A Fischer

### Abstract

Optical measurement techniques offer great opportunities in diverse applications, such as lathe monitoring and microfluidics. Doppler-based interferometric techniques enable simultaneous measurement of the lateral velocity and axial distance of a moving object. However, there is a complementarity between the unambiguous axial measurement range and the uncertainty of the distance. Therefore, we present an extended sensor setup, which provides an unambiguous axial measurement range of 1 mm while achieving uncertainties below 100 nm. Measurements at a calibration system are performed. When using a pinhole for emulating a single scattering particle, the tumbling motion of the rotating object is resolved with a distance uncertainty of 50 nm. For measurements at the rough surface, the distance uncertainty amounts to 280 nm due to a lower signal-to-noise ratio. Both experimental results are close to the respective Cramér–Rao bound, which is derived analytically for both surface and single particle measurements.

2014 *Meas. Sci. Technol.* **25** 085202

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## Design and testing of a four-probe optical sensor head for three-axis surface encoder with a mosaic scale grating

Yuki Shimizu, Takeshi Ito, Xinghui Li, WooJae Kim and Wei Gao

### Abstract

This paper presents a design study of a four-probe optical sensor head for a three-axis surface encoder with a mosaic scale grating. As the mosaic scale grating, multiple two-dimensional reflective-type scale gratings are aligned in a matrix on a plane so that measurement ranges of the three-axis surface encoder along the X- and Y-axes can be extended. An optical layout for a four-probe unit, which consists of a laser diode and two beam splitters, was designed based on *geometrical* optics so that four probes aligned in the matrix can be generated. The designed four-probe unit was integrated into the optical sensor head of the three-axis surface encoder. Interference signals generated by the superimposition of diffraction beams from the XY gratings were utilized in the three-axis surface encoder so that the translational displacement motions of the mosaic scale grating along the X-, Y- and Z-axes can be detected simultaneously by each probe in the four probes. Experiments were carried out to verify the feasibility of both the designed four-probe optical sensor head and the proposed concept of the mosaic scale grating for expanding the measurement range of the three-axis surface encoder along the X- and Y-directional primary axes of motion. Measurement sensitivity of each probe was compared, and its compensation was carried out by linear matrix calculations. Measurement resolution and nonlinearity of each probe were also investigated. In addition, XYZ-directional translational motions of a linear stage when a long-range translational motion along the X-axis was given to the mosaic scale grating were measured by stitching the measured results by the four probes.

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## Array-based satellite phase bias sensing: theory and GPS/BeiDou/QZSS results

A Khodabandeh and P J G Teunissen

### Abstract

Single-receiver integer ambiguity resolution (IAR) is a measurement concept that makes use of network-derived non-integer satellite phase biases (SPBs), among other corrections, to recover and resolve the integer ambiguities of the carrier-phase data of a single GNSS receiver. If it is realized, the very precise integer ambiguity-resolved carrier-phase data would then contribute to the estimation of the receiver's position, thus making (near) real-time precise point positioning feasible. Proper definition and determination of the SPBs take a leading part in developing the idea of single-receiver IAR. In this contribution, the concept of array-based between-satellite single-differenced (SD) SPB determination is introduced, which is aimed to reduce the code-dominated precision of the SD-SPB corrections. The underlying model is realized by giving the role of the local reference network to an array of antennas, mounted on rigid platforms, that are separated by short distances so that the same ionospheric delay is assumed to be experienced by all the antennas. To that end, a closed-form expression of the array-aided SD-SPB corrections is presented, thereby proposing a simple strategy to compute the SD-SPBs. After resolving double-differenced ambiguities of the array's data, the variance of the SD-SPB corrections is shown to be reduced by a factor equal to the number of antennas. This improvement in precision is also affirmed by numerical results of the three GNSSs GPS, BeiDou and QZSS. Experimental results demonstrate that the integer-recovered ambiguities converge to integers faster, upon increasing the number of antennas aiding the SD-SPB corrections.

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## Knock detection in spark ignition engines using a nonlinear wavelet transform of the engine cylinder head vibration signal

Ning Li, Jianguo Yang, Rui Zhou and Qingsheng Wang

### Abstract

This paper reports an investigation of knock detection in SI engines using a nonlinear wavelet transform based on the engine cylinder head vibration signals. The nonlinear wavelet transform employed in the current research is constructed by the redundant lifting scheme with an update-first framework, which has the ability to select an optimal wavelet function for each transform sample. The feasibility of applying a nonlinear wavelet transform to detect knock signatures from the vibration signals of the cylinder head is studied. The experimental results verify that the proposed method is capable of detecting knock signatures, even during the initial stages. More importantly, it is found that knock in each cylinder of a multi-cylinder gasoline engine can be detected using just one vibration sensor. Consequently, this is a simple and cost-effective way for knock detection in SI engines. Derived from the above method, we have developed a novel knock intensity factor and investigated the relevance of the proposed criterion for characterizing different levels of knock.

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## Particle image velocimetry correlation signal-to-noise ratio metrics and measurement uncertainty quantification

Zhenyu Xue, John J Charonko and Pavlos P Vlachos

### Abstract

In particle image velocimetry (PIV) the measurement signal is contained in the recorded intensity of the particle image pattern superimposed on a variety of noise sources. The signal-to-noise-ratio (SNR) strength governs the resulting PIV cross correlation and ultimately the accuracy and uncertainty of the resulting PIV measurement. Hence we posit that correlation SNR metrics calculated from the correlation plane can be used to quantify the quality of the correlation and the resulting uncertainty of an individual measurement. In this paper we extend the original work by Charonko and Vlachos and present a framework for evaluating the correlation SNR using a set of different metrics, which in turn are used to develop models for uncertainty estimation. Several corrections have been applied in this work. The SNR metrics and corresponding models presented herein are expanded to be applicable to both standard and filtered correlations by applying a subtraction of the minimum correlation value to remove the effect of the background image noise. In addition, the notion of a 'valid' measurement is redefined with respect to the correlation peak width in order to be consistent with uncertainty quantification principles and distinct from an 'outlier' measurement. Finally the type and significance of the error distribution function is investigated. These advancements lead to more robust and reliable uncertainty estimation models compared with the original work by Charonko and Vlachos. The models are tested against both synthetic benchmark data as well as experimental measurements. In this work,  $U_{68.5}$  uncertainties are estimated at the 68.5% confidence level while  $U_{95}$  uncertainties are estimated at 95% confidence level. For all cases the resulting calculated coverage factors approximate the expected theoretical confidence intervals, thus demonstrating the applicability of these new models for estimation of uncertainty for individual PIV measurements.

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## Underground localization using dual magnetic field sequence measurement and pose graph SLAM for directional drilling

Byeolteo Park and Hyun Myung

### Abstract

With the development of unconventional gas, the technology of directional drilling has become more advanced. Underground localization is the key technique of directional drilling for real-time path following and system control. However, there are problems such as vibration, disconnection with external infrastructure, and magnetic field distortion. Conventional methods cannot solve these problems in real time or in various environments. In this paper, a novel underground localization algorithm using a re-measurement of the sequence of the magnetic field and pose graph SLAM (simultaneous localization and mapping) is introduced. The proposed algorithm exploits the property of the drilling system that the body passes through the previous pass. By comparing the recorded measurement from one magnetic sensor and the current re-measurement from another magnetic sensor, the proposed algorithm predicts the pose of the drilling system. The performance of the algorithm is validated through simulations and experiments.

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