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Contents

Volume 108
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Research Articles

Smart Sensor for Analyzing Train Vibration in WCR Zone
Alka Dubey and Ashish Verma 1

Design of a Low Cost Smart Dryer Temperature Measurement System for Tea Factories
Utpal Sarma, Digbijoy Chakraborty, Pradip Kr. Boruah 8

Design of a MEMS Capacitive Comb-drive Micro-accelerometer with Sag Optimization
B. D. Pant, Lokesh Dhakar, P. J. George and S. Ahmad 15

Dynamic Characterization of MEMS Scanners
Çağlar Ataman, Hüseyin R. Seren, Harald Schenk, Hakan Ürey 31

Electromagnetic Investigation of a CMOS MEMS Inductive Microphone
Farès Tounsi, Brahim Mezghani, Libor Rufer, Mohamed Masmoudi and Salvador Mir. 40

Study of Thermoelastic Damping in Capacitive Micro-beam Resonators Using Hyperbolic Heat Conduction Model
Ghader Rezazadeh, Armin Saeedi vahdat, Seyed-Mehdi Pesteii,Bahman Farzi 54

Development of Planter Foot Pressure Distribution System Using Flexi Force Sensors
S. L. Patil, Madhuri A. Thatte, U. M. Chaskar 73

Fiber Optic Displacement and Liquid Refractive Index Sensors with Two Asymmetrical Inclined Fibers
H. Z. Yang, S. W. Harun and H. Ahmad 80

Controlling a pH Process Using Feedback & Double Controller Scheme
S. Shobana, A. Srinivasan and Rames C. Panda 89

Time Domain Analysis of Ultrasonic Wave Propagation using an Electromagnetic Acoustic Transducer
Sadiq Thomas, Salah Obayya, Domenico Pinto, D. Dulay, W. Balachandran, Mostafa Darwish 102

Design of a PC Based Mass Flow Indicator of an Electrical Motor Driven Water Lift Pump using Motor Load Current as the Flow Sensing Parameter
S. C. Bera, N. Mandal and R. Sarkar. 116

A Bimorph Moment/Force Actuator for Dynamic Testing
Hou Xiaoyan 128

Instrumentation to Measure the Capacitance of Biosensors by Sinusoidal Wave Method
Pavan Kumar Kathuroju and Nagaraju Jampana 139

Humidity and Electrical Sensing Properties of $CoCr_2O_4$–ZnO–MnO_2 Composites
Regina Mary L., Jeyaraj B. and Nagaraja K. S. 147

AC Response to Humidity and Propane of Sprayed Fe-Zn Oxide Films
Alejandro Avila-García, Manuel García-Hipólito and Yasuhiro Matsumoto-Kuwabara...................... 156

Sn-doped Zinc Oxide Thin Films for Methanol
Rajarshi Krishna Nath and Siddhartha Sankar Nath.. 168

Spray Deposited Pure and CuO Doped ZnO Thin Films for NH_3 Sensing
L. A. Patil, I. G. Pathan... 180

Formulation and Characterization of Cr_2O_3 Doped ZnO Thick Films as H_2S Gas Sensor
A. V. Patil, C. G. Dighavkar, S. K. Sonawane, S. J. Patil and R. Y. Borse.. 189

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Dynamic Characterization of MEMS Scanners

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Abstract: A simple yet precise optical characterization technique for beam scanning devices is proposed. The method uses a single photodetector to measure various dynamic characteristics of scanning devices, including frequency, scan angle, scan phase, and the mechanical quality factor, given that the scan waveform is known. A quantitative performance analysis and a set of experimental characterization results are presented. Experimentally 0.007 % scan angle measurement accuracy is demonstrated and it is shown that it can be improved. *Copyright © 2009 IFSA.*

Keywords: MEMS, Scanner characterization

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1. Introduction

Micro-electro-mechanical system (MEMS) scanning mirrors have proven to be a versatile and effective solution for ultra-small yet high resolution display and imaging systems. This mirror is connected to small flexures allowing it to oscillate vertically and/or horizontally to capture (imaging) or reproduce (display) an image pixel-by-pixel allowing high resolution display and imaging systems. The literature on microscanner technology is very rich with devices targeting head mounted displays [1-2], hand-held projectors [3-4], endoscopic imaging/tomography [5-6], spectroscopy [7], and various other applications. High precision, controllability, and low jitter are essential for high resolution scanning applications; hence precise dynamic characterization and real-time monitoring of device performance is crucial.

Characterization and dynamic control of microscanners require a position feedback. This feedback can be provided through various methods. Piezo-resistive sensors [8], capacitive readout [9], and electromagnetic back-emf monitoring are some of the feedback mechanisms employed in conventional microscanners. Characterizations of such devices only require a monitor device to observe/record the output of the position feedback mechanism. However, most microscanners lack position feedback, since integrating such mechanisms with the device significantly increases device complexity. Experimental characterization of such devices requires complex external optical measurement techniques, such as interferometry [10] or scanning and point-wise vibrometry [11].

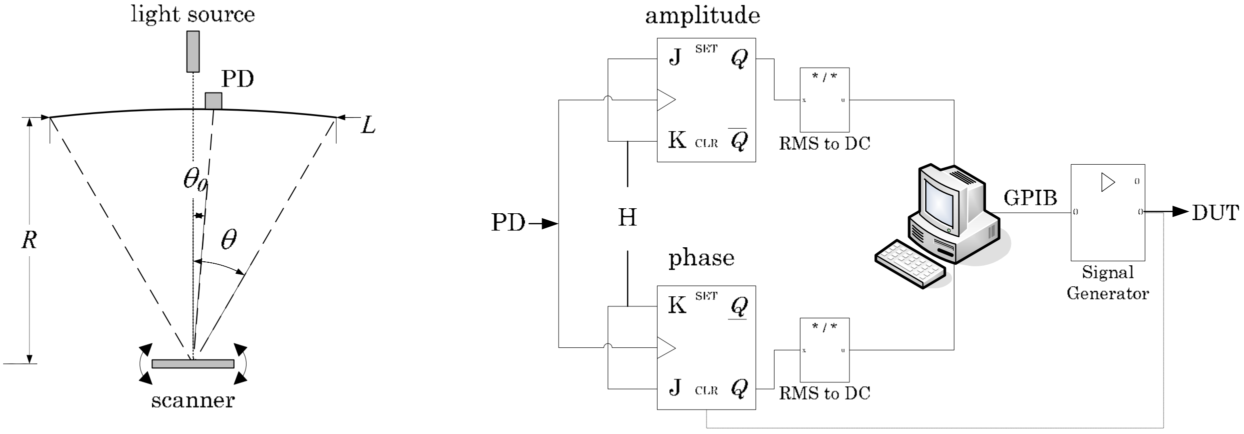
In this paper we present a simple but high precision microscanner characterization technique that needs a single photodetector only to simultaneously measure the frequency, scan angle and scan phase of an oscillating microscanner, assuming that the scan waveform of the scanner is known. This principle can be applied to characterization of microscanners with sinusoidal oscillation or polygon type scanners with linear velocity, and can easily be integrated into miniaturized scanning engines for precise position control. In addition, the same technique can also be used for damping characterization. Section 2 describes the general layout of the measurement system, the measurement principle. Experimental amplitude, phase and damping measurements are also included.

2. Measurement Setup

A simple schematic measurement system is given in Fig. 1a. Fig. 1b shows the layout of the required electronics and the scanner drive. Main measurement device is a Hamamatsu S5049 bi-cell photodetector placed on the scan line of an oscillating microscanner. This is a widely available photo-IC used for print start timing detection for laser printers, and copiers. Each crossing of a laser beam from the detector creates a digital pulse whose rise-time is independent of the size and the speed of the laser beam. While the microscanner is oscillating, the output of the photodetector is a periodic train of short pulses. Fall time of the detector output is independent of scanner frequency, scan-angle and spot size, and is equal to 20 ns. The output of the detector is fed into the clock input of two toggle-mode negative edge-triggered J-K flip-flops, one of which is always active (for scan amplitude measurement), and the other is activated in sync with the scanner drive signal (for phase measurement). Therefore, the amplitude flip-flop changes state at each detector pulse (Fig. 3c), while the phase flip-flop changes state once every two detector pulses (Fig. 3e). Both flip-flops produce a square wave with different duty cycles. Characteristics of device oscillations can be extracted by performing different waveform measurements on the signals produced by the flip-flops. Next we discuss how dynamic response and quality factor measurements for microscanners are performed. For the test measurements, slow axis of a 2D electromagnetically actuated MEMS microscanner developed for a head mounted display application is used (Fig. 2).

2.1. Scan Angle Measurement

In the scan angle measurement configuration, the photodetector is placed at an off-center point on the scan line. Hence, the duty-cycle of the square waveform produced by the amplitude flip-flop is not 50 % and depends on the position of the detector on the scan line and the optical scan angle. Assuming oscillations are purely sinusoidal –a very good approximation for MEMS microscanners due to their high quality factors–, the optical scan angle can be computed using angle between the center of the scan line and the photodetector and the flip-flop output waveform parameters.



(a) (b)

Fig. 1. (a) Microscanner Characterization Setup (PD: Bi-cell photodetector); (b) Microscanners are driven by signal generator via the GPIB interface, and frequency, and drive voltage domain response of a microscanner can be obtained automatically.

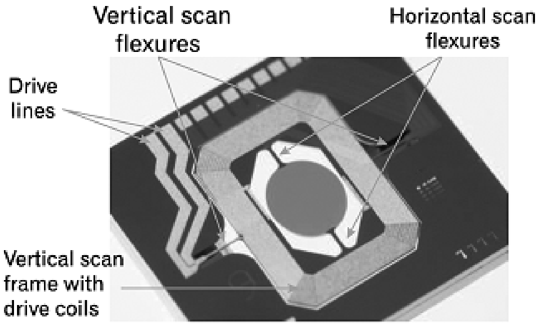


Fig. 2. Electromagnetically driven 2D torsional microscanner [2].

The time required for the beam to travel from the center of the scan line onto the detector (t_0) is given by (the timing convention used for the derivation is shown in Fig. 3):

$$t_0 = \frac{T\left(\frac{1}{2} - \delta_1\right)}{2}, \tag{1}$$

where, δ_1 is the measured duty cycle of the amplitude flip-flop output, and T is the measured oscillation period. The ratio between the detector position (θ_0) and the maximum zero-to-peak optical scan angle (θ) can then be computed using (1) and Fig. 3:

$$\frac{\theta_0}{\theta} = \sin\left(\frac{2\pi}{T} t_0\right) = \sin\left(\frac{\pi}{2} - \pi\delta_1\right) \tag{2}$$

Equation (2) states that the scan angle depends only on the detector angular position and the duty cycle of the amplitude flip flop output square-wave. Therefore, the accuracy of the measurements is determined by the precision of the measurement of these two factors.

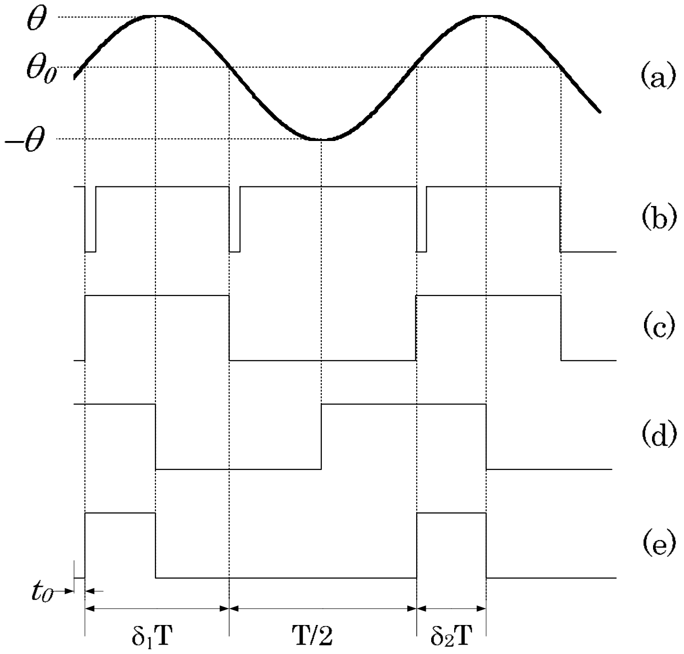


Fig. 3. Timing convention (a) Scanner Position, (b) Bi-cell Photodetector Output, (c) Flip-flop Output for Amplitude, (d) Scanner Drive Sync Signal (e) Phase Flip-flop output for Phase.

Calibration: The size of the scan line and scanner-detector separation (L and R in Fig. 1a) is initially measured manually with a ruler or caliper to determine θ. Then, the detector is placed onto the scan line, close to the center, so that minimum measurable scan angle is minimized. θ_0 is then computed by the software from the measured θ, t_0 and δ_1 using (2). Since a long scan line can be measured quite accurately, the ambiguity introduced by the calibration error is rather small. For integrated measurements, the detector position can initially be set for once with high precision.

Duty cycle measurement: Frequency, phase and duty-cycle of the flip-flop output may be measured by an oscilloscope or by a PC with DAQ interface. Either way, an analog-to-digital conversion of the waveform is to be performed. Discretization of the waveform introduces an error to the duty cycle measurement. Average error in measuring $\delta_1 T$ product for N measurements is equal to

$$\varepsilon = \pm \frac{1}{N * f_{sampling}} \tag{3}$$

Ambiguity that arises due to this error can be computed using (3):

$$\theta \pm \Delta\theta = \frac{\theta_0}{\sin\left(\frac{2\pi}{T}(t_0 \pm \varepsilon)\right)} \tag{4}$$

Equation 4 indicates that A/D conversion error is related to the scanner frequency and the sampling rate. For small θ_0/θ values, measurement error is relatively high; as θ_0/θ approaches unity measurement error decreases significantly. Averaging is also very effective in reducing the measurement error, especially for characterization purposes, where measurement time is of secondary importance compared to accuracy. Even for real-time applications, averaging is acceptable if time constants of changes (temperature, humidity, pressure) are large in comparison to the averaging time, as it is for displays, spectrometers, and barcode readers.

Discretization is the fundamental source of ambiguity for small scan angle or low sampling rate measurements. The effect of discretization can be eliminated by analog measurement of the duty cycle of the flip flop outputs. A true RMS-to-DC converter IC (Analog Devices AD536A) was employed for analog measurement of the duty cycle. The output of the flip flop was fed to the converter. Then, the duty cycle of the flip flop output was calculated from the measured rms value. In this technique the error limits are determined by the characteristics of the converter, and strongly depend on the peripheral circuitry and the duty cycle of the signal to be measured. Table I is a list of theoretical and experimental measurement errors for different detector positions and sampling frequencies without averaging. For digital sampling method, the measurement error is reduced by increasing the sampling rate and the offset ratio. Accuracy of the analog method, however, does not depend on these factors and is limited only by the measurement error of the RMS-to-DC converter. The measurement accuracy can be improved by using a faster photodetector and by placing the detector near the edge of the scan line. Further improvements are possible by averaging multiple cycles and the signal generated can be used for closed-loop control of the scanner. The accuracy of the scan angle and phase measurement can be increased to be in the order of 1/10,000 as demonstrated in high-resolution printing applications.

Table 1 presents digital and analog noise levels for two different offset ratios and three different sampling rates. The theoretical digital noise levels are calculated using (4). The digital noise is found by measuring the standard deviation of the pulse width in a number of periods and dividing it by the mean pulse width. The analog noise is found by measuring the standard deviation of the mean dc level over a number of periods and dividing it by the mean of the mean dc level. As can be interpreted from the Table 1, the higher the sampling ratio the better the precision is; and as aimed the analog digital level is not affected by the sampling ratio.

Table 1. Theoretical and experimental measurement error for different detector positions and sampling frequencies.

ADC Rate	Offset Ratio	Frequency (Hz)	Digital (theory, N=5)	Digital (exp)	Analog (exp)
1 Ms/sec	0.1	406	0.5 %	0.55 %	0.043 %
2 Ms/sec	0.1	406	0.2 %	0.18 %	0.037 %
5 Ms/sec	0.1	406	0.1 %	0.13 %	0.046 %
1 Ms/sec	0.9	406	0.024 %	0.036 %	0.031 %
2 Ms/sec	0.9	406	0.008 %	0.015 %	0.035 %
5 Ms/sec	0.9	406	0.004 %	0.007 %	0.026 %

Proposed measurement technique can be adapted to different device response characterization experiments. Frequency response of a microscanner device can be obtained by sweeping the scanner excitation frequency quasi-statically with constant or adaptive steps, and recording the scan angle of the device at each step. For excitation-amplitude response experiments, same procedure can also be applied. For both measurements, the user should pay attention to wait long enough before taking data at each step, so that the device reaches steady state after the frequency or voltage is updated.

2.2. Phase Measurement

A phase measurement method is developed by using a square wave with 50 % duty cycle, which has the same frequency and the same phase with the driving signal. Such a signal is often available from signal generator trigger outputs. The square wave is fed to the $\overline{Clear}$ input pin of the flip flop. Thus, the output became dependent on both the crossing time of the bi-cell and the fall time of the input signal. The phase difference between the driving input and the microscanner scan angle can be derived from the duty cycle of the flip-flop output.

$$\Phi = \frac{2\pi}{T}\left(\frac{T}{2} - \delta_2 T - t_0\right), \tag{5}$$

where Φ stands for the phase difference between the drive signal and the microscanner scan angle, $\delta_2 T$ is the new duty-cycle and period product, and t_0 is as defined in Eq. (1). The presence of the offset t_0 brings some limitations to the possible measurable phases which can be found as:

$$\frac{2\pi}{T} t_0 < \Phi_{measurable} < \frac{2\pi}{T}\left(\frac{T}{2} - t_0\right) \tag{6}$$

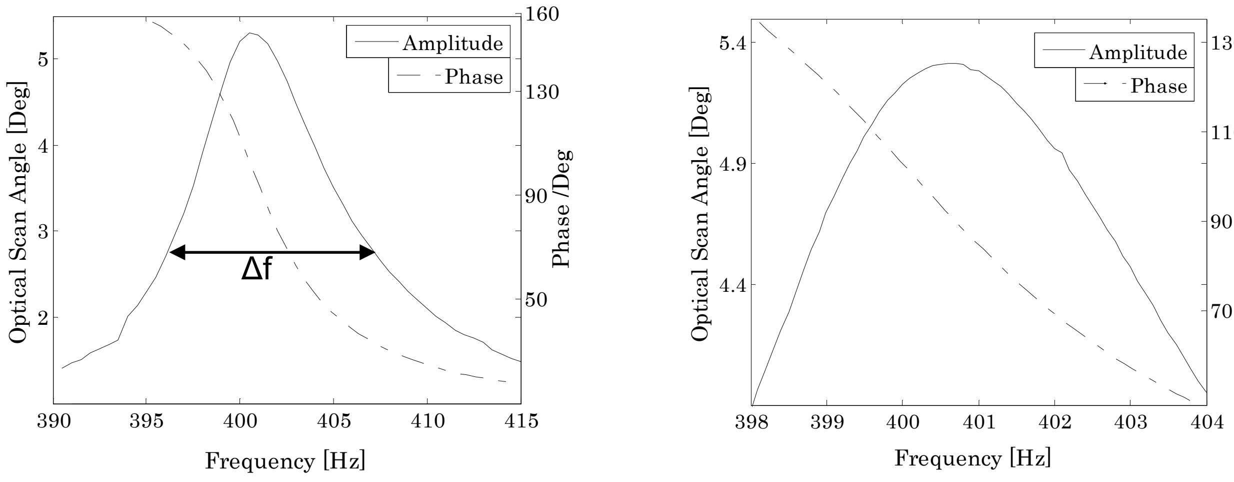
If the amplitude measurement is not required, then the photodetector can be placed in the middle of the scan line, i.e., $t_0 = 0$ and the phase computation can be simplified as:

$$\Phi = \pi(1 - 2\delta_2) \tag{7}$$

For this case, full span, from 0 to π phase difference, can be measured.

This phase measurement technique can be employed for closed-loop control of the scanner using the phase feedback, which allows the control via phase-lock-loop (PLL).

Fig. 4 illustrates the amplitude and phase of the frequency response of a torsional scanner shown in Fig. 2 measured with the proposed technique. The frequency response for nonlinear/hysteretic systems can also be measured with this technique [12].



(a)

(b)

Fig. 4. Amplitude and phase of the frequency response of a MEMS scanner measured with the proposed technique. **(a)** Broad range measurement with offset ratio = 0.1 **(b)** Measurement around the resonance peak with offset ratio = 0.9. The measured device is the slow axis of a 2D electromagnetically actuated MEMS microscanner developed for a head mounted display application [2].

2.3. Damping Measurement

For linear underdamped systems, the easiest method to determine the quality factor of the system is using the 3 dB bandwidth '*Δf*' of the frequency response, illustrated in Fig. 4a. The 3 dB bandwidth and the quality factor are related through the following expression.

$$Q = \frac{2\pi I_m f_0}{b} = \frac{f_0}{\Delta f}, \tag{8}$$

where b is the damping factor and I_m is the effective mass moment of inertia of the scanner [13].

For an unforced microscanner with sufficient mechanical mode separation and pure velocity dependent damping, the scan angle can be expressed as

$$\theta(t) = e^{-\xi t}\theta_0 \cos(2\pi f_0 t + \varphi), \tag{9}$$

where, ξ is the decay rate of the oscillations, θ_0 is the initial maximum scan angle, f_0 is the damped natural frequency, and φ is an arbitrary phase factor.

Fig. 5 shows the damped oscillations together with the flip-flop output signal when the detector is placed at θ_0. Damping of a scanner can be determined with this setup in two different ways. As θ decreases due to damping, duty-cycle of the flip-flop output shrinks. By evaluating the scan angle using (2) for every period in Fig. 5, a sequence of exponentially decaying angle values are obtained. Decay rate of the oscillations can be computed by fitting a negative exponential to this sequence. Thus, the damped oscillation can be expressed in the form of (9). This method requires the storage and non-real-time processing of flip-flop output. This method is particularly useful in damping characterization of low-Q (e.g., Q<100) devices. Damping measurement result for the same microscanner is given in Fig. 6. The quality factor was measured to be 61.57, while the reference measurement result performed with a Laser Doppler Vibrometer (LDV) is 61.60.

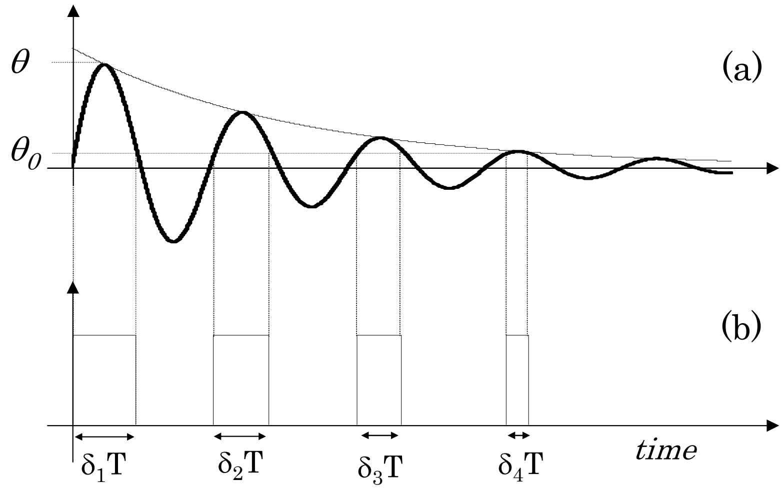


Fig. 5. Damped oscillations of an unexcited microscanner, and corresponding amplitude flip-flop output.

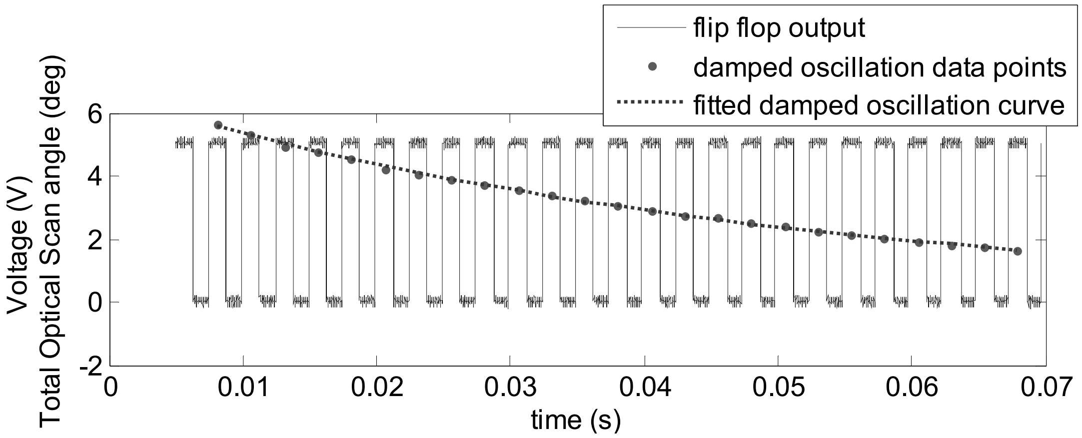


Fig. 6. Experimental damping measurement results. Scanner drive signal is stopped and simultaneously the amplitude flip-flop output is recorded with a data acquisition card. Then, for each period, the scan angle is computed from its duty cycle. This procedure can also be performed in real time using a timer circuit.

For high-Q scanners, a simpler technique can be used. It takes many cycles for this type of devices to settle. Therefore the time required for θ to scale down to θ_0 can be approximated by the number of periods of the square-wave times the damped oscillation period. This method introduces a fractional time measurement error in the order of 1/Q. For high-frequency scanners, Q is often large and the error is negligible.

3. Conclusions

A simple yet precise characterization technique is demonstrated for microscanners to measure scan amplitude and phase, damping, and frequency response assuming the deflection waveform is a sinusoid. The setup utilizes a single photodetector and a data analysis interface. For laboratory experiments, this interface may be GPIB or DAQ. Proposed measurement method can also be integrated with a miniaturized scanning engine, in which data analysis can be simply performed by a microcontroller. Main advantages of the technique are simplicity, spot-size independent detection, and flexibility. In addition to scanner characterization, the technique can be used to provide amplitude or phase feedback for closed-loop control of scanning systems. The accuracy of the scan angle and phase measurement can be increased to be in the order of 1/10000.

Acknowledgements

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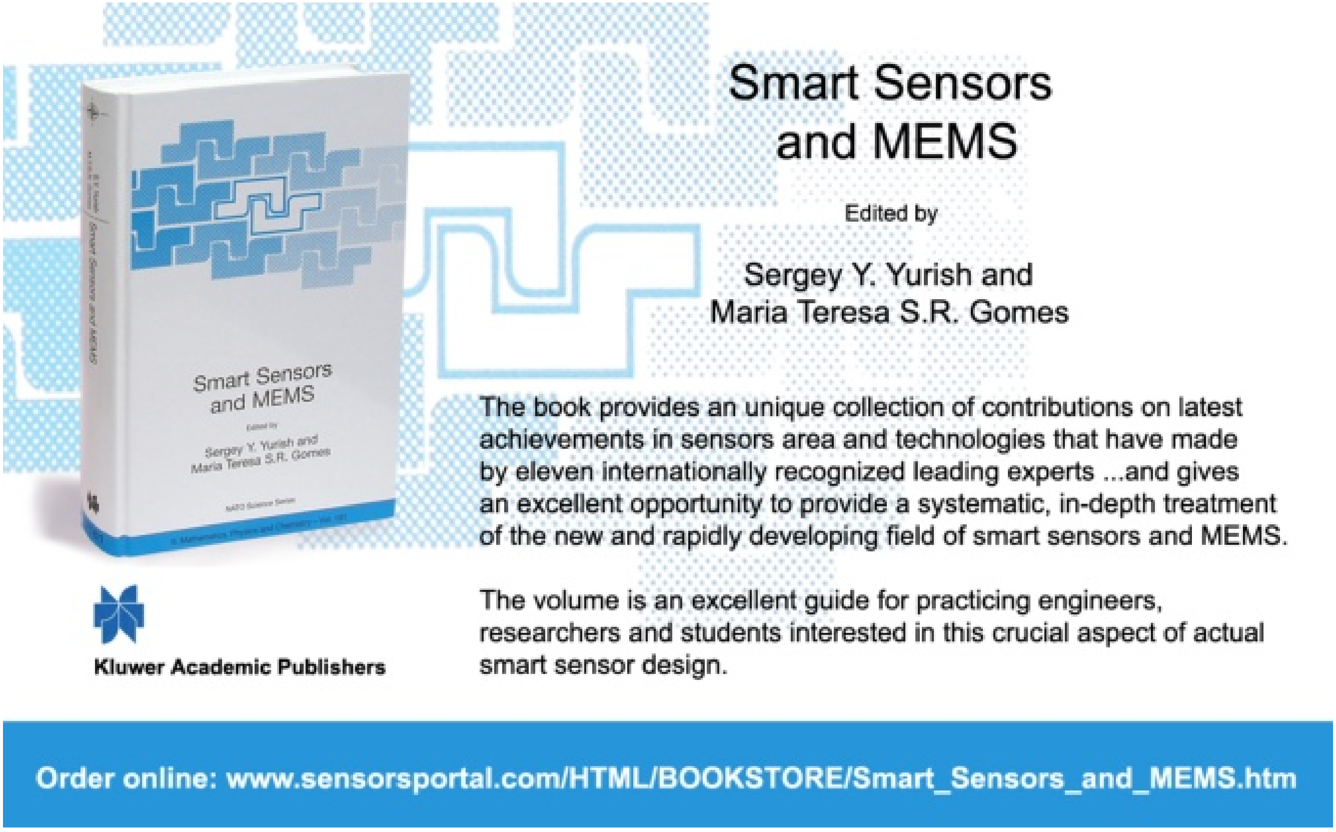

Guide for Contributors

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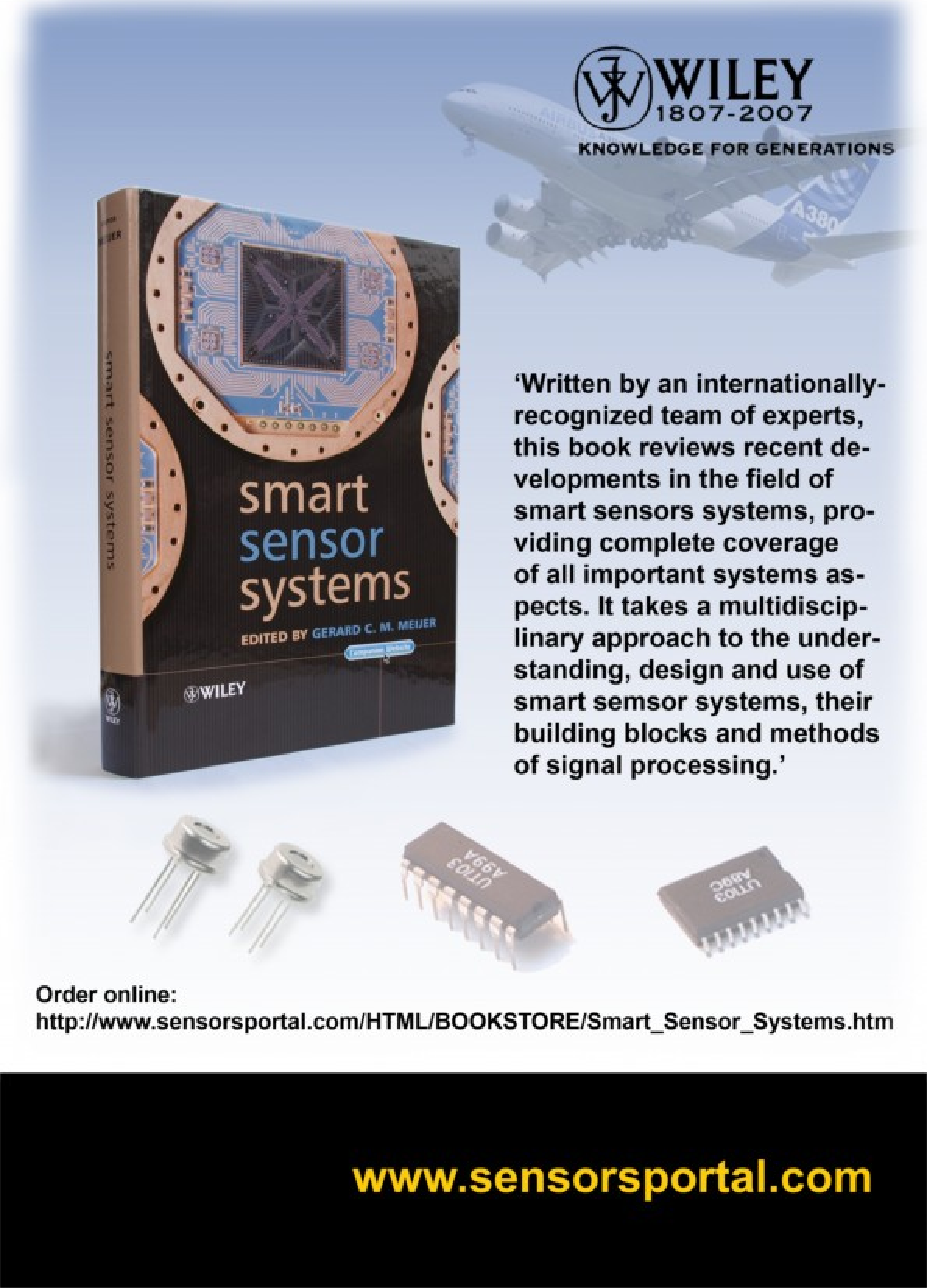
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