ISSN 1726-5479

SENSORS & TRANSDUCERS

vol. 107
8/09

Sensors and Transducers Applications

International Frequency Sensor Association Publishing

Sensors & Transducers

Volume 107, Issue 8
August 2009

www.sensorsportal.com

ISSN 1726-5479

Editors-in-Chief: professor Sergey Y. Yurish,
Phone: +34 696067716, fax: +34 93 4011989, e-mail: editor@sensorsportal.com

Editors for Western Europe
Meijer, Gerard C.M., Delft University of Technology, The Netherlands
Ferrari, Vittorio, Universitá di Brescia, Italy

Editor South America
Costa-Felix, Rodrigo, Inmetro, Brazil

Editor for Eastern Europe
Sachenko, Anatoly, Ternopil State Economic University, Ukraine

Editors for North America
Datskos, Panos G., Oak Ridge National Laboratory, USA
Fabien, J. Josse, Marquette University, USA
Katz, Evgeny, Clarkson University, USA

Editor for Asia
Ohyama, Shinji, Tokyo Institute of Technology, Japan

Editor for Asia-Pacific
Mukhopadhyay, Subhas, Massey University, New Zealand

Editorial Advisory Board

Abdul Rahim, Ruzairi, Universiti Teknologi, Malaysia
Ahmad, Mohd Noor, Nothern University of Engineering, Malaysia
Annamalai, Karthigeyan, National Institute of Advanced Industrial Science and Technology, Japan
Arcega, Francisco, University of Zaragoza, Spain
Arguel, Philippe, CNRS, France
Ahn, Jae-Pyoung, Korea Institute of Science and Technology, Korea
Arndt, Michael, Robert Bosch GmbH, Germany
Ascoli, Giorgio, George Mason University, USA
Atalay, Selcuk, Inonu University, Turkey
Atghiaee, Ahmad, University of Tehran, Iran
Augutis, Vygantas, Kaunas University of Technology, Lithuania
Avachit, Patil Lalchand, North Maharashtra University, India
Ayesh, Aladdin, De Montfort University, UK
Bahreyni, Behraad, University of Manitoba, Canada
Baliga, Shankar, B., General Monitors Transnational, USA
Baoxian, Ye, Zhengzhou University, China
Barford, Lee, Agilent Laboratories, USA
Barlingay, Ravindra, RF Arrays Systems, India
Basu, Sukumar, Jadavpur University, India
Beck, Stephen, University of Sheffield, UK
Ben Bouzid, Sihem, Institut National de Recherche Scientifique, Tunisia
Benachaiba, Chellali, Universitaire de Bechar, Algeria
Binnie, T. David, Napier University, UK
Bischoff, Gerlinde, Inst. Analytical Chemistry, Germany
Bodas, Dhananjay, IMTEK, Germany
Borges Carval, Nuno, Universidade de Aveiro, Portugal
Bousbia-Salah, Mounir, University of Annaba, Algeria
Bouvet, Marcel, CNRS – UPMC, France
Brudzewski, Kazimierz, Warsaw University of Technology, Poland
Cai, Chenxin, Nanjing Normal University, China
Cai, Qingyun, Hunan University, China
Campanella, Luigi, University La Sapienza, Italy
Carvalho, Vitor, Minho University, Portugal
Cecelja, Franjo, Brunel University, London, UK
Cerda Belmonte, Judith, Imperial College London, UK
Chakrabarty, Chandan Kumar, Universiti Tenaga Nasional, Malaysia
Chakravorty, Dipankar, Association for the Cultivation of Science, India
Changhai, Ru, Harbin Engineering University, China
Chaudhari, Gajanan, Shri Shivaji Science College, India
Chavali, Murthy, VIT University, Tamil Nadu, India
Chen, Jiming, Zhejiang University, China
Chen, Rongshun, National Tsing Hua University, Taiwan
Cheng, Kuo-Sheng, National Cheng Kung University, Taiwan
Chiang, Jeffrey (Cheng-Ta), Industrial Technol. Research Institute, Taiwan
Chiriac, Horia, National Institute of Research and Development, Romania
Chowdhuri, Arijit, University of Delhi, India
Chung, Wen-Yaw, Chung Yuan Christian University, Taiwan
Corres, Jesus, Universidad Publica de Navarra, Spain
Cortes, Camilo A., Universidad Nacional de Colombia, Colombia
Courtois, Christian, Universite de Valenciennes, France
Cusano, Andrea, University of Sannio, Italy
D'Amico, Arnaldo, Università di Tor Vergata, Italy
De Stefano, Luca, Institute for Microelectronics and Microsystem, Italy
Deshmukh, Kiran, Shri Shivaji Mahavidyalaya, Barshi, India
Dickert, Franz L., Vienna University, Austria
Dieguez, Angel, University of Barcelona, Spain
Dimitropoulos, Panos, University of Thessaly, Greece
Ding, Jianning, Jiangsu Polytechnic University, China
Djordjevich, Alexandar, City University of Hong Kong, Hong Kong
Donato, Nicola, University of Messina, Italy
Donato, Patricio, Universidad de Mar del Plata, Argentina
Dong, Feng, Tianjin University, China
Drljaca, Predrag, Instersema Sensoric SA, Switzerland
Dubey, Venketesh, Bournemouth University, UK
Enderle, Stefan, Univ.of Ulm and KTB Mechatronics GmbH, Germany
Erdem, Gursan K. Arzum, Ege University, Turkey
Erkmen, Aydan M., Middle East Technical University, Turkey
Estelle, Patrice, Insa Rennes, France
Estrada, Horacio, University of North Carolina, USA
Faiz, Adil, INSA Lyon, France
Fericean, Sorin, Balluff GmbH, Germany
Fernandes, Joana M., University of Porto, Portugal
Francioso, Luca, CNR-IMM Institute for Microelectronics and Microsystems, Italy
Francis, Laurent, University Catholique de Louvain, Belgium
Fu, Weiling, South-Western Hospital, Chongqing, China
Gaura, Elena, Coventry University, UK
Geng, Yanfeng, China University of Petroleum, China
Gole, James, Georgia Institute of Technology, USA
Gong, Hao, National University of Singapore, Singapore
Gonzalez de la Rosa, Juan Jose, University of Cadiz, Spain
Granel, Annette, Goteborg University, Sweden
Graff, Mason, The University of Texas at Arlington, USA
Guan, Shan, Eastman Kodak, USA
Guillet, Bruno, University of Caen, France
Guo, Zhen, New Jersey Institute of Technology, USA
Gupta, Narendra Kumar, Napier University, UK
Hadjiloucas, Sillas, The University of Reading, UK
Haider, Mohammad R., Sonoma State University, USA
Hashsham, Syed, Michigan State University, USA
Hasni, Abdelhafid, Bechar University, Algeria
Hernandez, Alvaro, University of Alcala, Spain
Hernandez, Wilmar, Universidad Politecnica de Madrid, Spain
Homentcovschi, Dorel, SUNY Binghamton, USA
Horstman, Tom, U.S. Automation Group, LLC, USA
Hsiai, Tzung (John), University of Southern California, USA
Huang, Jeng-Sheng, Chung Yuan Christian University, Taiwan
Huang, Star, National Tsing Hua University, Taiwan
Huang, Wei, PSG Design Center, USA
Hui, David, University of New Orleans, USA
Jaffrezic-Renault, Nicole, Ecole Centrale de Lyon, France
Jaime Calvo-Galleg, Jaime, Universidad de Salamanca, Spain
James, Daniel, Griffith University, Australia
Janting, Jakob, DELTA Danish Electronics, Denmark
Jiang, Liudi, University of Southampton, UK
Jiang, Wei, University of Virginia, USA
Jiao, Zheng, Shanghai University, China
John, Joachim, IMEC, Belgium
Kalach, Andrew, Voronezh Institute of Ministry of Interior, Russia
Kang, Moonho, Sunmoon University, Korea South
Kaniusas, Eugenijus, Vienna University of Technology, Austria
Katake, Anup, Texas A&M University, USA
Kausel, Wilfried, University of Music, Vienna, Austria
Kavasoglu, Nese, Mugla University, Turkey
Ke, Cathy, Tyndall National Institute, Ireland
Khan, Asif, Aligarh Muslim University, Aligarh, India
Sapozhnikova, Ksenia, D.I.Mendeleyev Institute for Metrology, Russia

Kim, Min Young, Kyungpook National University, Korea South
Ko, Sang Choon, Electronics and Telecommunications Research Institute, Korea South
Kockar, Hakan, Balikesir University, Turkey
Kotulska, Malgorzata, Wroclaw University of Technology, Poland
Kratz, Henrik, Uppsala University, Sweden
Kumar, Arun, University of South Florida, USA
Kumar, Subodh, National Physical Laboratory, India
Kung, Chih-Hsien, Chang-Jung Christian University, Taiwan
Lacnjevac, Caslav, University of Belgrade, Serbia
Lay-Ekuakille, Aime, University of Lecce, Italy
Lee, Jang Myung, Pusan National University, Korea South
Lee, Jun Su, Amkor Technology, Inc. South Korea
Lei, Hua, National Starch and Chemical Company, USA
Li, Genxi, Nanjing University, China
Li, Hui, Shanghai Jiaotong University, China
Li, Xian-Fang, Central South University, China
Liang, Yuanchang, University of Washington, USA
Liawruangrath, Saisunee, Chiang Mai University, Thailand
Liew, Kim Meow, City University of Hong Kong, Hong Kong
Lin, Hermann, National Kaohsiung University, Taiwan
Lin, Paul, Cleveland State University, USA
Linderholm, Pontus, EPFL - Microsystems Laboratory, Switzerland
Liu, Aihua, University of Oklahoma, USA
Liu Changgeng, Louisiana State University, USA
Liu, Cheng-Hsien, National Tsing Hua University, Taiwan
Liu, Songqin, Southeast University, China
Lodeiro, Carlos, Universidade NOVA de Lisboa, Portugal
Lorenzo, Maria Encarnacio, Universidad Autonoma de Madrid, Spain
Lukaszewicz, Jerzy Pawel, Nicholas Copernicus University, Poland
Ma, Zhanfang, Northeast Normal University, China
Majstorovic, Vidosav, University of Belgrade, Serbia
Marquez, Alfredo, Centro de Investigacion en Materiales Avanzados, Mexico
Matay, Ladislav, Slovak Academy of Sciences, Slovakia
Mathur, Prafull, National Physical Laboratory, India
Maurya, D.K., Institute of Materials Research and Engineering, Singapore
Mekid, Samir, University of Manchester, UK
Melnyk, Ivan, Photon Control Inc., Canada
Mendes, Paulo, University of Minho, Portugal
Mennell, Julie, Northumbria University, UK
Mi, Bin, Boston Scientific Corporation, USA
Minas, Graca, University of Minho, Portugal
Moghavvemi, Mahmoud, University of Malaya, Malaysia
Mohammadi, Mohammad-Reza, University of Cambridge, UK
Molina Flores, Esteban, Benemérita Universidad Autónoma de Puebla, Mexico
Moradi, Majid, University of Kerman, Iran
Morello, Rosario, University "Mediterranea" of Reggio Calabria, Italy
Mounir, Ben Ali, University of Sousse, Tunisia
Mulla, Imtiaz Sirajuddin, National Chemical Laboratory, Pune, India
Neelamegam, Periasamy, Sastra Deemed University, India
Neshkova, Milka, Bulgarian Academy of Sciences, Bulgaria
Oberhammer, Joachim, Royal Institute of Technology, Sweden
Ould Lahoucine, Cherif, University of Guelma, Algeria
Pamidighanta, Sayanu, Bharat Electronics Limited (BEL), India
Pan, Jisheng, Institute of Materials Research & Engineering, Singapore
Park, Joon-Shik, Korea Electronics Technology Institute, Korea South
Penza, Michele, ENEA C.R., Italy
Pereira, Jose Miguel, Instituto Politecnico de Setebal, Portugal
Petsev, Dimiter, University of New Mexico, USA
Pogacnik, Lea, University of Ljubljana, Slovenia
Post, Michael, National Research Council, Canada
Prance, Robert, University of Sussex, UK
Prasad, Ambika, Gulbarga University, India
Prateepasen, Asa, Kingmoungut's University of Technology, Thailand
Pullini, Daniele, Centro Ricerche FIAT, Italy
Pumera, Martin, National Institute for Materials Science, Japan
Radhakrishnan, S. National Chemical Laboratory, Pune, India
Rajanna, K., Indian Institute of Science, India
Ramadan, Qasem, Institute of Microelectronics, Singapore
Rao, Basuthkar, Tata Inst. of Fundamental Research, India
Raoof, Kosai, Joseph Fourier University of Grenoble, France
Reig, Candid, University of Valencia, Spain
Restivo, Maria Teresa, University of Porto, Portugal
Robert, Michel, University Henri Poincare, France
Rezazadeh, Ghader, Urmia University, Iran
Royo, Santiago, Universitat Politecnica de Catalunya, Spain
Rodriguez, Angel, Universidad Politecnica de Cataluna, Spain
Rothberg, Steve, Loughborough University, UK
Sadana, Ajit, University of Mississippi, USA
Sadeghian Marnani, Hamed, TU Delft, The Netherlands
Sandacci, Serghei, Sensor Technology Ltd., UK
Saxena, Vibha, Bhbha Atomic Research Centre, Mumbai, India
Schneider, John K., Ultra-Scan Corporation, USA
Seif, Selemani, Alabama A & M University, USA
Seifter, Achim, Los Alamos National Laboratory, USA
Sengupta, Deepak, Advance Bio-Photonics, India
Shearwood, Christopher, Nanyang Technological University, Singapore
Shin, Kyuho, Samsung Advanced Institute of Technology, Korea
Shmaliy, Yuriy, Kharkiv National Univ. of Radio Electronics, Ukraine
Silva Girao, Pedro, Technical University of Lisbon, Portugal
Singh, V. R., National Physical Laboratory, India
Slomovitz, Daniel, UTE, Uruguay
Smith, Martin, Open University, UK
Soleymanpour, Ahmad, Damghan Basic Science University, Iran
Somani, Prakash R., Centre for Materials for Electronics Technol., India
Srinivas, Talabattula, Indian Institute of Science, Bangalore, India
Srivastava, Arvind K., Northwestern University, USA
Stefan-van Staden, Raluca-Ioana, University of Pretoria, South Africa
Sumriddetchka, Sarun, National Electronics and Computer Technology Center, Thailand
Sun, Chengliang, Polytechnic University, Hong-Kong
Sun, Dongming, Jilin University, China
Sun, Junhua, Beijing University of Aeronautics and Astronautics, China
Sun, Zhiqiang, Central South University, China
Suri, C. Raman, Institute of Microbial Technology, India
Sysoev, Victor, Saratov State Technical University, Russia
Szewczyk, Roman, Industrial Research Inst. for Automation and Measurement, Poland
Tan, Ooi Kiang, Nanyang Technological University, Singapore,
Tang, Dianping, Southwest University, China
Tang, Jaw-Luen, National Chung Cheng University, Taiwan
Teker, Kasif, Frostburg State University, USA
Thumbavanam Pad, Kartik, Carnegie Mellon University, USA
Tian, Gui Yun, University of Newcastle, UK
Tsiantos, Vassilios, Technological Educational Institute of Kaval, Greece
Tsigara, Anna, National Hellenic Research Foundation, Greece
Twomey, Karen, University College Cork, Ireland
Valente, Antonio, University, Vila Real, - U.T.A.D., Portugal
Vaseashta, Ashok, Marshall University, USA
Vazquez, Carmen, Carlos III University in Madrid, Spain
Vieira, Manuela, Instituto Superior de Engenharia de Lisboa, Portugal
Vigna, Benedetto, STMicroelectronics, Italy
Vrba, Radimir, Brno University of Technology, Czech Republic
Wandelt, Barbara, Technical University of Lodz, Poland
Wang, Jiangping, Xi'an Shiyou University, China
Wang, Kedong, Beihang University, China
Wang, Liang, Advanced Micro Devices, USA
Wang, Mi, University of Leeds, UK
Wang, Shinn-Fwu, Ching Yun University, Taiwan
Wang, Wei-Chih, University of Washington, USA
Wang, Wensheng, University of Pennsylvania, USA
Watson, Steven, Center for NanoSpace Technologies Inc., USA
Weiping, Yan, Dalian University of Technology, China
Wells, Stephen, Southern Company Services, USA
Wolkenberg, Andrzej, Institute of Electron Technology, Poland
Woods, R. Clive, Louisiana State University, USA
Wu, DerHo, National Pingtung Univ. of Science and Technology, Taiwan
Wu, Zhaoyang, Hunan University, China
Xiu Tao, Ge, Chuzhou University, China
Xu, Lisheng, The Chinese University of Hong Kong, Hong Kong
Xu, Tao, University of California, Irvine, USA
Yang, Dongfang, National Research Council, Canada
Yang, Wuqiang, The University of Manchester, UK
Yang, Xiaoling, University of Georgia, Athens, GA, USA
Yaping Dan, Harvard University, USA
Ymeti, Aurel, University of Twente, Netherland
Yong Zhao, Northeastern University, China
Yu, Haihu, Wuhan University of Technology, China
Yuan, Yong, Massey University, New Zealand
Yufera Garcia, Alberto, Seville University, Spain
Zagnoni, Michele, University of Southampton, UK
Zamani, Cyrus, Universitat de Barcelona, Spain
Zeni, Luigi, Second University of Naples, Italy
Zhang, Minglong, Shanghai University, China
Zhang, Qintao, University of California at Berkeley, USA
Zhang, Weiping, Shanghai Jiao Tong University, China
Zhang, Wenming, Shanghai Jiao Tong University, China
Zhang, Xueji, World Precision Instruments, Inc., USA
Zhong, Haoxiang, Henan Normal University, China
Zhu, Qing, Fujifilm Dimatix, Inc., USA
Zorzano, Luis, Universidad de La Rioja, Spain
Zourob, Mohammed, University of Cambridge, UK

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).
Available in electronic and on CD. Copyright © 2009 by International Frequency Sensor Association. All rights reserved.

Sensors & Transducers Journal

Contents

Volume 107
Issue 8
August 2009

www.sensorsportal.com

ISSN 1726-5479

Research Articles

Authors are encouraged to submit article in MS Word (doc) and Acrobat (pdf) formats by e-mail: editor@sensorsportal.com
Please visit journal’s webpage with preparation instructions: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm

Sensors & Transducers Journal, Vol. 107, Issue 8, August 2009, pp. 1-16

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

Precise Frequency and Period Measurements for Slow Slew Rate Signals Based on the Modified Method of the Dependent Count

Sergey Y. Yurish
International Frequency Sensor Association (IFSA),
C/Llorens Artigas, 4-6, planta 0, Edifici U, Campus Sud, 08028 Barcelona, Spain
Tel: +34 696067716, fax: +34 93 4011989
E-mail: SYurish@sensorsportal.com

Received: 1 July 2009 /Accepted: 15 August 2009 /Published: 25 August 2009

Abstract: This paper describes an application of novel modified method of the dependent count for measuring the frequency (period) of slow slew rate signals (common for the conversion-to-digital of resistance, capacitance, inductance or resistive-sensor–bridge signals based on direct connection to a microcontroller). The AVR 8-bit ATmega168-20PI microcontroller (Atmel), based on advanced reduced instruction set computing architecture, was used. The modified method of the dependent count improves the accuracy of period measurements for the slow slew rate signals of triangular, sine, exponential rise and fall, as well as rectangular waveforms, by 2-to-3 orders in comparison with the accuracy achieved with classical indirect counting in all frequency ranges. The error is evaluated from the statistical characteristics and histograms of measured pulse periods, quantitatively confirming the advantages of the modified method for frequency (period) measurements for non-square pulse signals. Measurements are further improved (becoming about 1.5 times more accurate) for some waveforms when an external Schmitt trigger is used. *Copyright © 2009 IFSA.*

Keywords: Period measurement; Modified method of the dependent count; Frequency measurement

---

1. Introduction

Frequency and period of non-rectangular waveform signals that have a slow slew rate - such as triangular, sine, exponential rise and fall waveform signals - must often be measured. Low frequency measurements (50, 100 and 200 Hz) involving signals with a slow slew rate are common, for example, in the conversion-to-digital of resistance, capacitance, inductance or resistive-sensor–bridge signals based on direct connection to a microcontroller [1, 2]. Such an approach offers a simple low-cost interface between microcontrollers with embedded timer/counter and quasi-digital sensors with a period, time interval or frequency output. The indirect (period) counting method for slow slew rate signals is susceptible to errors because of changes in the input trigger threshold due to several external and internal noise sources. In addition to thermal noise, there are other trigger noise sources that are program dependent [3] or result from interference in the microcontroller power supply [4, 5]. Very often, trigger errors predominate over the inherent quantization error, so that precise frequency or period measurements require the use of an external input signal-forming device, such as an amplifier-limiter with a Schmitt trigger circuit, which yields rectangular waveform impulses from the slow slew rate signal [3]. However, that solution increases the hardware cost and reduces reliability, because the probability of failure is directly proportional to the number of components being used.

Fig. 1 shows a triangular signal whose period is determined by measuring the time interval between consecutive voltage crossings of its leading ramp. In a noiseless system (V_{th} undistorted), the period measured would be T_x and the input trigger points would be at S_1 and S_2. However, noise and interference added to V_{th} shift the trigger points, so that the measured period will be $T_x+\tau_1+\tau_2$. Usually, $\tau_1 \neq \tau_2$ because $\Delta V_1 \neq \Delta V_2$.

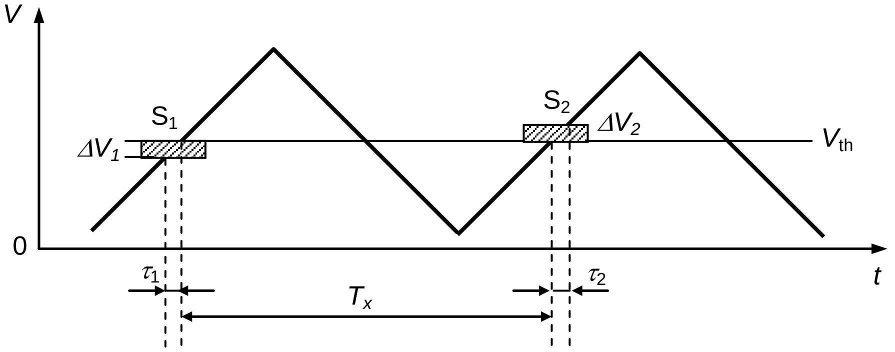


Fig. 1. Error level related to trigger point uncertainty when measuring the period of a triangular signal.

Frequency-to-digital conversions are immune to that error component, because it is not necessary to extract a separate period from the pulse train and $\tau_1=\tau_2=0$, so that we can measure f_x and then calculate the period as $T_x=1/f_x$ [6]. But the standard direct counting method for frequency measurement applied to low frequencies has either a very high quantization error or a long measurement time. For example, in order to have a quantization error below 0.01% at $f_x = 100$ Hz, the conversion time must be larger than 100 s. Advanced methods for frequency measurement, such as ratiometric, reciprocal, M/T, constant elapsed time (CET), single- and double-buffered or direct memory access (DMA) methods, and methods using a non-redundant reference frequency [6] all have a constant quantization error regardless of signal frequency; however, their conversion time is redundant, which increases the dynamic error and the measurement time for all frequencies except the nominal one. It would be preferable to use an alternative method related to frequency (period) conversion, one that would have a constant quantization error over the entire frequency range measured and a non-redundant conversion time.

This paper describes the application of a novel approach to the measurement of slow slew rate signal frequency (period) based on a modification of method of the dependent count; this approach uses the common modern AVR 8-bit ATmega168 microcontroller (*Atmel*), which is based on advanced reduced instruction set computing (RISC) architecture. The main advantages of the microcontroller-based method are the use of the least possible amount of hardware, high reliability and low price. All these factors are very important for applications where resistive, capacitive, inductive or resistive bridge sensing elements are directly interfaced to standard microcontrollers in order to convert appropriate parameters into digital information.

2. Novel Modified Method of the Dependent Count

The modified method of the dependent count combines the advantages of classical and advanced methods and ensures a constant relative quantization error over an entire frequency range and also high speed due to non-redundant conversion time. The time diagram of the modified method of the dependent count is shown in Fig. 2.

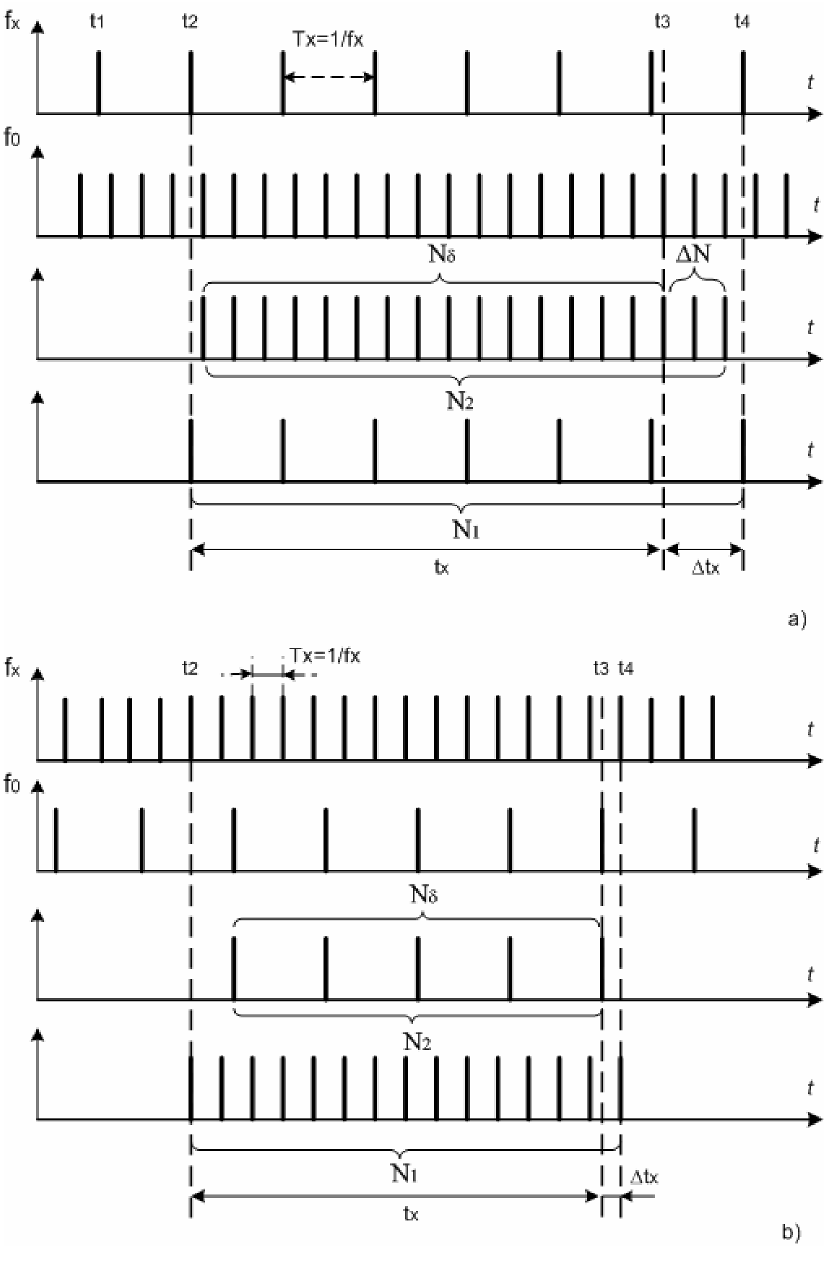


Fig. 2. Time diagrams of the modified method of the dependent count in cases of $f_x < f_0$ (a) and $f_x > f_0$ (b).

Let us consider two possible cases. In the case of $f_x < f_0$, where f_0 is the reference frequency, time diagrams of the method are similar to the previously proposed method of the dependent count [7] but without the preliminary stage for frequency comparison ($f_x >< f_0$). In other words, a measurement will start at the t_2 moment: thus, beginning from moment t_2 according to the modified method, pulses of both frequencies f_x and f_0 are counted (the numbers N_1 and N_2 respectively). The count continues during the time interval between t_2 and t_4. The reference gate time between t_2 and t_3 is equal to the integer value for the period of the reference frequency f_0 and is determined by the number $N_\delta = 1/\delta$, where δ is the relative error of measurement. The necessary relative error can be chosen at the beginning of each measurement or set up for all measurements at once according to a measuring algorithm. The counts of both frequencies (f_x and f_0) are stopped by the next pulse after an unknown frequency f_x after moment t_3. The number N_2 is the integer number of the period of the reference frequency f_0:

$$N_2 = N_\delta + \Delta N, \tag{1}$$

where $\Delta N = (0 \div \Delta N_{max})$ is the additional value of the period of the reference frequency f_0 counted during the Δt time interval (between t_3 and t_4). In turn, N_1 is the integer value of pulses of unknown frequency f_x. The time of measurement T_{meas} is an integer value of converted periods of the signal with frequency f_x:

$$T_{meas} = T_x \cdot N_1 = \frac{N_1}{f_x} \tag{2}$$

This time interval can also be approximated as:

$$T_{meas} \cong T_0 \cdot N_2 = \frac{N_2}{f_0} = \frac{N_\delta + \Delta N}{f_0} = \left(\frac{1}{\delta} + \Delta N\right) \cdot T_0 \tag{3}$$

From equations (2) and (3) it follows that an unknown frequency f_x and period T_x should be calculated according to the following formulas:

$$f_x = \frac{N_1}{N_2} \cdot f_0 \quad \text{and} \quad T_x = \frac{N_2}{N_1 \cdot f_0}; \tag{4}$$

The quantization error for these measurements results from the fact that the time of measurement $T_{meas} = t_x + \Delta t_x$ is not equal to the integer number N_2 of the period of the reference frequency $T_0 = 1/f_0$:

$$T_{meas} \neq N_2 \cdot T_0 \neq \frac{N_2}{f_0} \tag{5}$$

A change of the frequency f_x between specific limits will change the interval T_{meas}, and the number of counted impulses N_2 will change from $\Delta N = 0$ to $\Delta N = \Delta N_{max.}$, where ΔN_{max} is the number of impulses in the interval $\Delta t_{x\,ma\,x} = T_x$. Taking into account that the period of these input impulses is T_x, we will have

$$\Delta N_{\max} = \frac{T_x}{T_0} = \frac{f_0}{f_x} \tag{6}$$

The maximum quantization error will take place when the number of counted impulses N_2 is minimal and equal to N_δ. Then, the maximum relative error will be

$$\delta_{\max} = \frac{1}{N_{\min}} = \frac{1}{N_\delta} = \delta \tag{7}$$

Hence, the maximum error is determined only by N_δ and does not depend on the measured frequency. The minimum error will be at $N = N_{max.}$ Since $N_{max} = N_\delta + \Delta N_{max,}$

$$\delta_{\min} = \frac{1}{N_\delta + \Delta N_{\max}} \tag{8}$$

Selecting a large $N_\delta = 1/\delta$ reduces the quantization error. The measurement time can be kept short by selecting a large reference frequency f_0.

In the common case the mean-square quantization error will be

$$\sigma_q = \frac{1}{N_\delta \sqrt{6}} = \frac{\delta}{\sqrt{6}} \tag{9}$$

The coefficient of relative error change should be calculated according to the following equation:

$$\alpha = \delta_{max}/\delta_{min} = (N_\delta + \Delta N_{max})/N_\delta. \tag{10}$$

Taking into account a wide frequency range of measurement, the time of measurement $T_{meas} = t_x + \Delta t_x$ should be calculated as

$$\begin{cases} T_{meas} = T_x, & if \quad \dfrac{N_\delta}{f_0} \prec T_x \\ T_{meas} = \dfrac{N_\delta}{f_0} + (0 \div T_x), & if \quad \dfrac{N_\delta}{f_0} \geq T_x \end{cases} \tag{11}$$

The resolution of method in the case of $f_x < f_0$ can be calculated according to the following equation:

$$Q_N = \frac{f_0 \cdot N_1}{N_2 (N_2 + 1)} = \frac{f_x}{(N_2 + 1)} = \frac{f_x}{(N_\delta + \Delta N + 1)}. \tag{12}$$

For the case of $f_x > f_0$, time diagrams of the method are shown in Fig. 2b. N_2 is equal to N_δ ($\Delta N = 0$). Unknown frequency f_x, or period $T_x = 1/f_x$, should be calculated according to equations (4). The relative error $\delta = \delta_{max} = \delta_{min}$ and the coefficient of relative error change $\alpha = 1$. The time of measurement in this case will be

$$T_{meas} = \frac{N_\delta}{f_0} + (0 \div T_x). \tag{13}$$

The resolution of modified method of the dependent count in case of $f_x > f_0$ can be determined as

$$Q_N = \frac{f_x}{(N_\delta + 1)}. \tag{14}$$

In comparison with an earlier-proposed method of the dependent count [7], the new recently patented modified method has high programmable accuracy, scalable resolution, non-redundant time of measurement and a wide frequency range; additionally, it allows us to measure frequency that exceeds the reference frequency ($f_x >> f_0$) without additional hardware or time for preliminary frequency estimation or comparison: ($f_x >< f_0$). In order to measure $f_x < f_0$ or $f_x > f_0$, no additional decision-making procedure is necessary. The calculation is done automatically (see Fig. 2a and 2b respectively).

3. Measurement System Set-up

In order to experimentally validate the advantages of the modified method of the dependent count for frequency (period) measurements of slow slew rate signals with different waveforms, the common modern AVR 8-bit ATmega168-20PI (*Atmel*) microcontroller was used. Fig. 3 shows the measurement set-up.

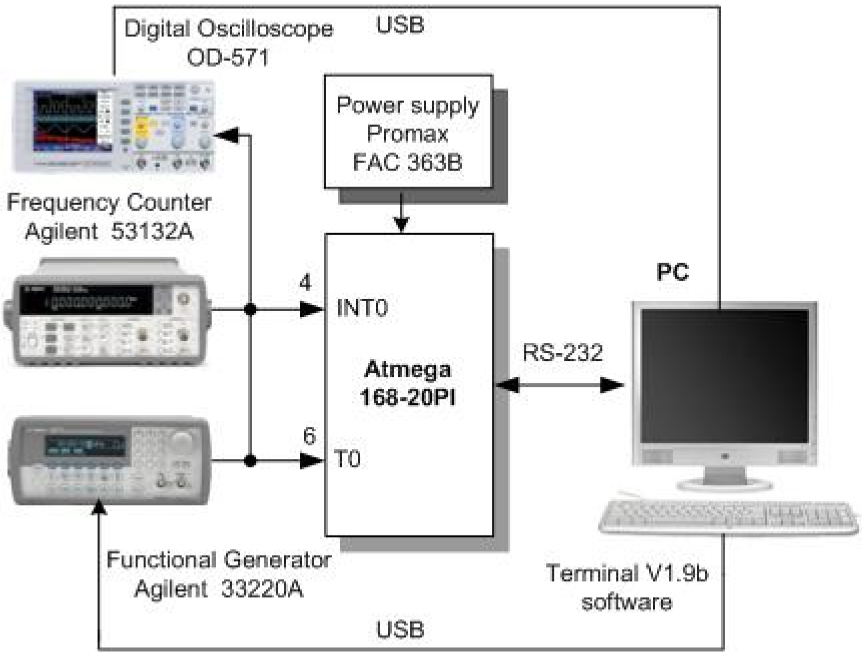
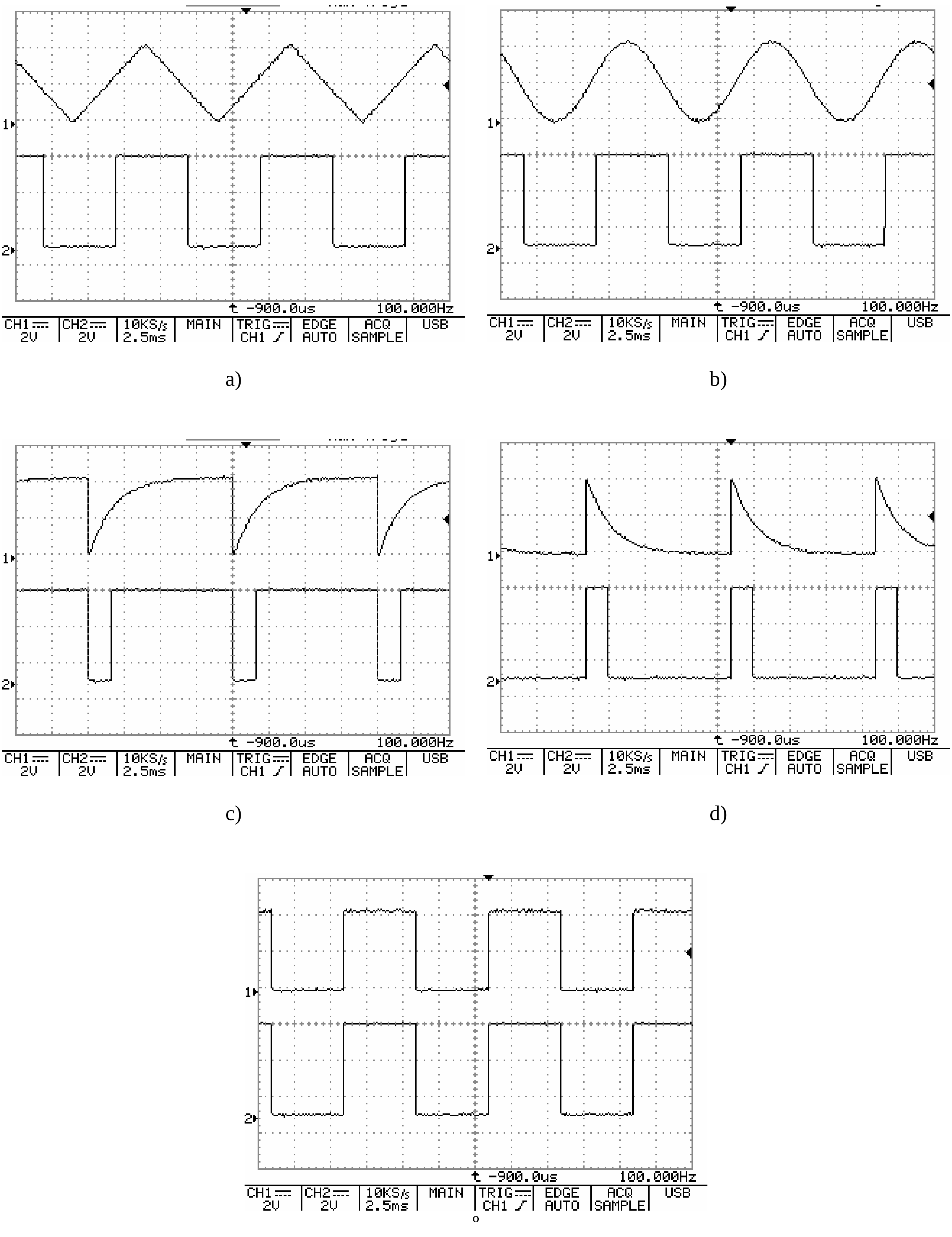


Fig.3. Measurement set-up to determine the period of signals having a slow slew rate.

Different waveform (rectangular, triangular, sine, exponential rise and exponential fall) signals whose periods were to be measured were fed from a function generator (Agilent 33220A) to inputs INT0 (external interrupt request 0, programmed to interrupt the main program when a rising edge crosses its voltage threshold), and T0 (Timer/Counter 0) of the ATmega168-20 PI microcontroller running on a 20 MHz clock. The microcontroller converted periods of slow slew rate signal to digital by using the modified method of the dependent count implemented by software relying only on the internal functional-logical architecture of the microcontroller. The internal reference frequency was f_0 = 625 kHz with the relative error δ_0 = ±0.0001 %. The programmable relative error of period measurements was chosen as δ = ±0.0005 %. The microcontroller was supplied at +5 V dc by a Promax FAC-363B power supply. The frequency generated by the Agilent 33120A was 100 Hz; its respective period was 10 ms and signals were monitored by a high precision calibrated frequency counter (Agilent 53132A). This frequency was chosen to be the same as in experiments described in [3, 4, 8-10] in order to compare the experimental results. Each slow slew rate signal was measured by the microcontroller directly as well as through an external Schmitt trigger integrated circuit 74HC14D (Fig. 4 a-e). The waveform signal parameters are shown in Table 1. The peak-to-peak amplitude was approximately 5 V. The Promax OD-571 oscilloscope monitored the signal waveforms.

The measured period value was sent to a PC via an RS-232 interface implemented with the ST202D integrated circuit. The user interface was implemented with the help of terminal software (Terminal V1.9b for Windows) [11]. Period measurements were taken every second until a total of 60 measurements had been recorded. The measurement error was evaluated from histograms and appropriate statistical characteristics.



a)

b)

c)

d)

e)

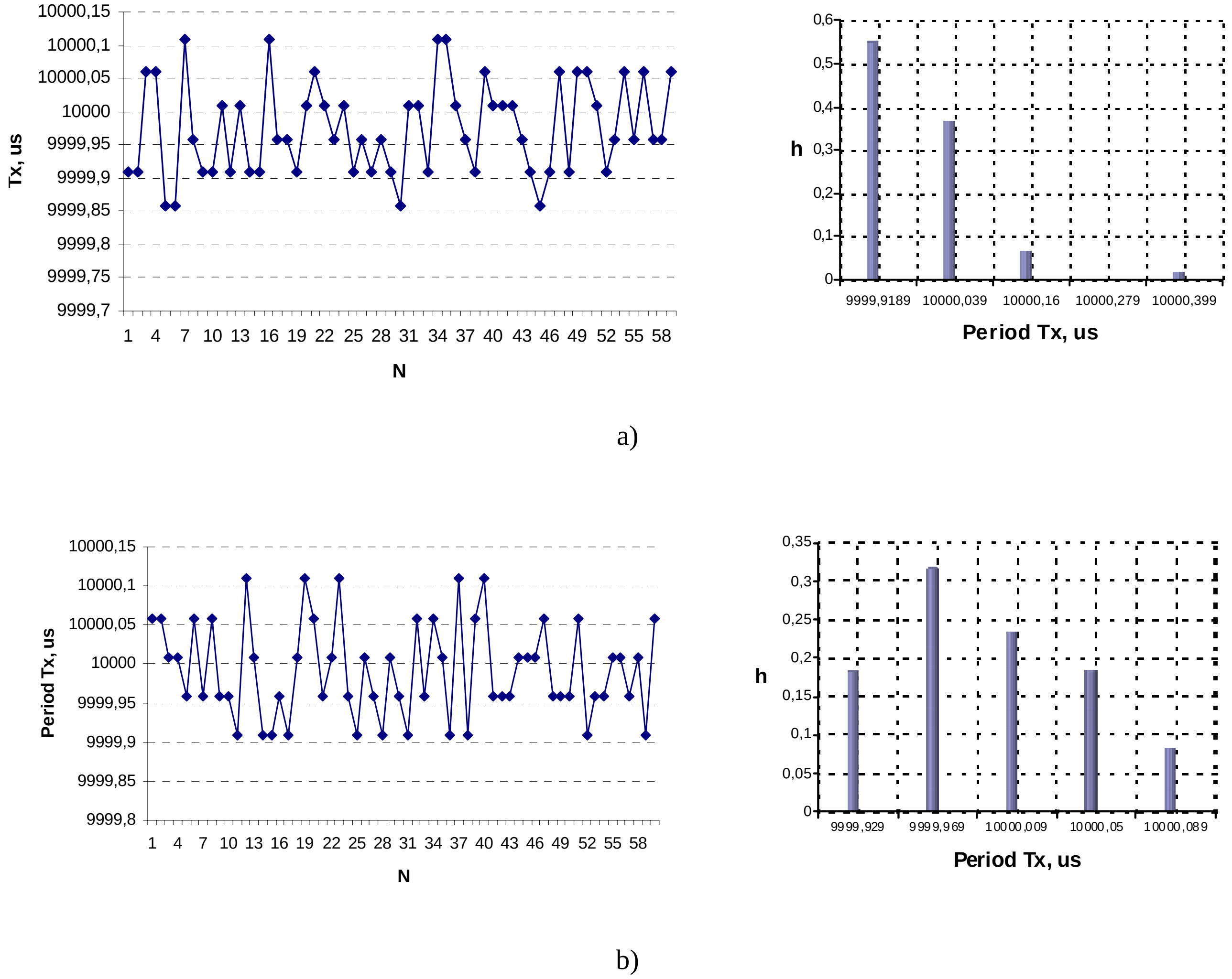
Fig. 4. Input forming device time diagrams: input (1) and output (2) signals for different investigated waveforms.

Table 1. The Waveform Signal Parameters.

	Triangular	Sine	Exponential Rise	Exponential Fall
Rise Time:				
1. Input Signal	3.275 ms	2.82 ms	3.733 ms	78.49 µs
2. Schmitt Trigger Output	78.73 µs	78.73 µs	80.00 µs	81.29 µs
Fall Time				
1. Input Signal	3.3 ms	2.653 ms	75.47 µs	3.273 ms
2. Schmitt Trigger Output	78.73 µs	78.73 µs	81.31 µs	80.00 µs

4. Experimental Results and Discussion

The measured periods and the probability densities for triangular waveform signals of 100 Hz with 50 % symmetry are shown in Fig. 5 (a, b). The statistical characteristics are shown in Table 2. The number of equidistant classes *k* in the probability density function chart for a sampling of 60 measurements was calculated according to [12] and is *k* = 5. The relative error can be reduced 1.53 times by using an external Schmitt trigger.



a)

b)

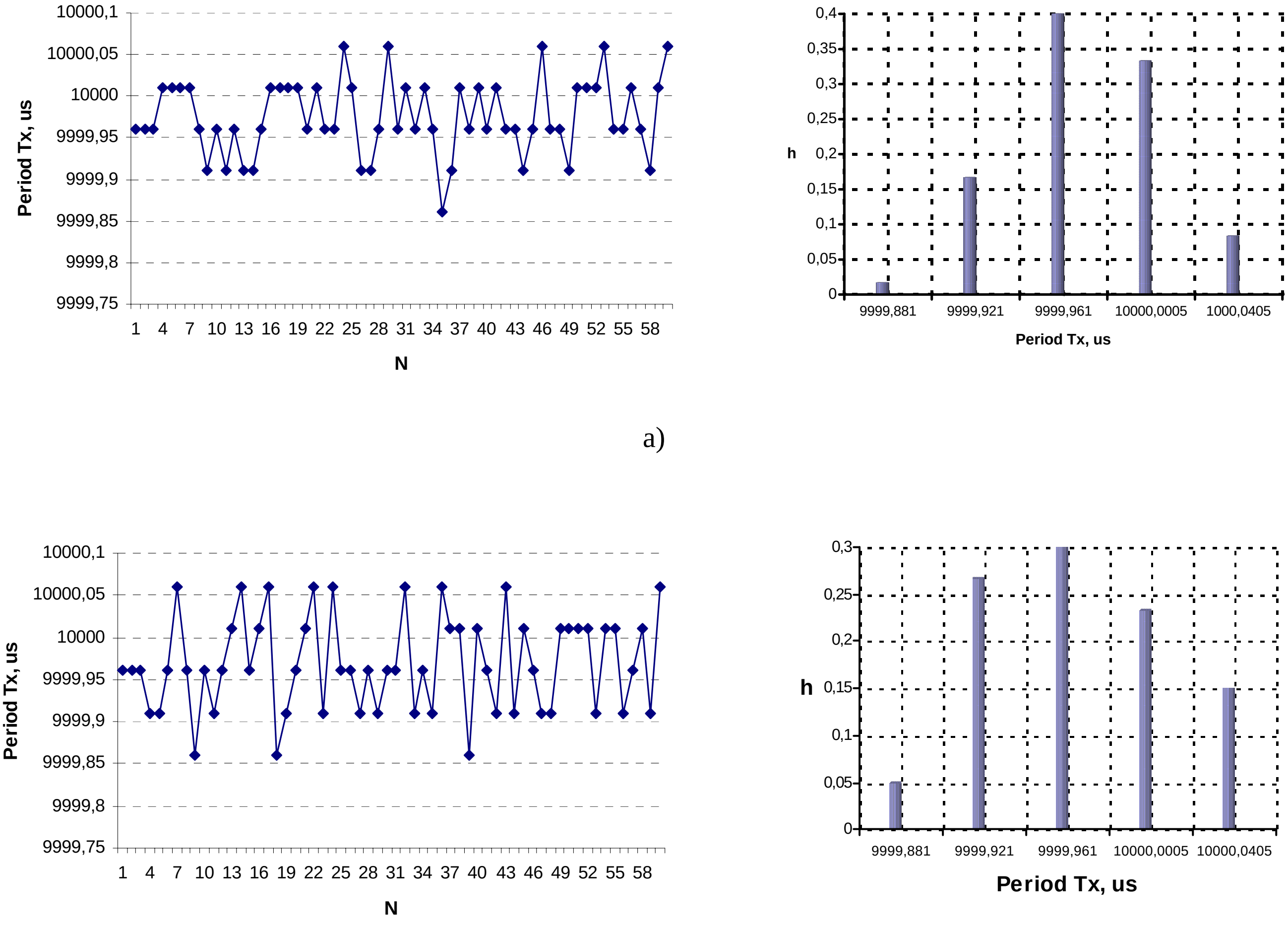
Fig. 5. Experimental results of direct period measurement for a triangular waveform signal and its probability density (a); experimental results and probability density with the use of an external Schmitt trigger (b).

Table 2. Statistical characteristics of the results for period measurements (10 ms) of rectangular waveform signal and slow slew rate signals of different waveforms.

Signal Wave Form / **Parameter**	**Rectangular**		**Triangular**		**Sine**		**Exponent Rise**		**Exponent Fall**	
	Directly	**With Schmitt trigger**	**Directly**	**With Schmitt trigger**	**Directly**	**With Schmitt trigger**	**Directly**	**With Schmitt trigger**	**Directly**	**With Schmitt trigger**
Minimal T_x (min), µs	9999.9605	9999.9605	9999.859	9999.90	9999.8605	9999.8605	9999.8582	9999.8582	9999.9587	9999.9587
Maximal T_x (max), µs	10000.0105	10000.0105	10000.4588	10000.1089	10000.0605	10000.0605	10000.1082	10000.0582	10000.0587	10000.0587
Sampling Range, T_x (max) - T_x (min), µs	0.05	0.05	0.5999	0.2	0.2	0.2	0.2499	0.2	0.1	0.1
Median	0	0	0	0	0	0	0	0	0	0
Arithmetic Mean, µs	9999.963	9999.9647	9999.9831	9999.9923	9999.9755	9999.9688	9999.9882	9999.9749	9999.9937	9999.9854
Variance, µs	0.0001	0.0002	0.0088	0.0037	0.0021	0.0032	0.0034	0.0029	0.0009	0.0009
Standard Deviation, µs	0.011	0.0139	0.0936	0.0608	0.0454	0.0569	0.0584	0.0534	0.0295	0.0298
Coefficient of Variation	910206.786	717747.766	106806.024	164427.259	220416.908	175875.618	171370.344	187261.309	338555.832	335849.227
Confidence Interval at probability P=97 %	$T_x \in$ [9999.9599÷ 9999.9661]	$T_x \in$ [9999.9607÷ 9999.9686]	$T_x \in$ [9999.9569÷ 10000.0093]	$T_x \in$ [9999.9752÷ 10000.0093]	$T_x \in$ [9999.9628÷ 9999.9882]	$T_x \in$ [9999.9529÷ 9999.9847]	$T_x \in$ [9999.9719÷ 10000.0046]	$T_x \in$ [9999.9599÷ 9999.9898]	$T_x \in$ [9999.9854÷ 10000.002]	$T_x \in$ [9999.977÷ 9999.9937]
Maximal Relative Error, %	≤ ±0.000031	≤ ±0.00004	≤ ±0.000262	≤ ±0.000171	≤ ±0.000127	≤ ±0.000159	≤ ±0.000164	≤ ±0.00015	≤ ±0.000083	≤ ±0.000084
Distribution low	-	-	-	Uniform	Gaussian	Gaussian	-	Gaussian	-	-

The χ^2 test for goodness of fit test was applied to investigate the significance of the differences between observed data in the histograms and the theoretical frequency distribution for data from a normal, or uniform, population. For the triangular signal, the period of which was measured with the use of a Schmitt trigger as an input device, for five equidistant classes (Fig. 5b) and a probability P = 97 %, according to the χ^2 test, $S < \chi^2_{max}$, where S = 8.6667 is the sum of deviations between the dataset and the assumed distribution; χ^2_{max} = 10 is the maximum possible allowable deviation in the χ^2 distribution. Hence, the hypothesis of uniform distribution can be accepted.

The experimental results for sine wave signal period measurements and the probability densities are shown in Fig. 6 (a, b). In this case the use of an external Schmitt trigger does not improve the relative error (Table 2). There is a small error increase (from 0.000127 to 0.000159 %), but in neither cases does the relative error does exceed the programmable relative error of δ = 0.0005 %. For the sine waveform signal, at five equidistant classes (Fig. 6a) and a probability P = 97 %, according to the χ^2 –Test, $S < \chi^2_{max}$, where S = 3.6821 is the sum of deviations between the dataset and the assumed distribution; χ^2_{max} = 7.0 is the maximum possible deviation in the χ^2 distribution. Hence, the hypothesis of Gaussian (normal) distribution can be accepted. In a case in which a Schmitt trigger is used (Fig. 6b), at five equidistant classes and the same probability P = 97 %, according to the χ^2 test, $S < \chi^2_{\max}$, where S = 4.2002 is the sum of deviations between the dataset and the assumed distribution; $\chi^2_{\max}$ = 7.0 is the maximum possible argument of the χ^2 distribution. Hence, the hypothesis of Gaussian distribution can be also accepted in this case.

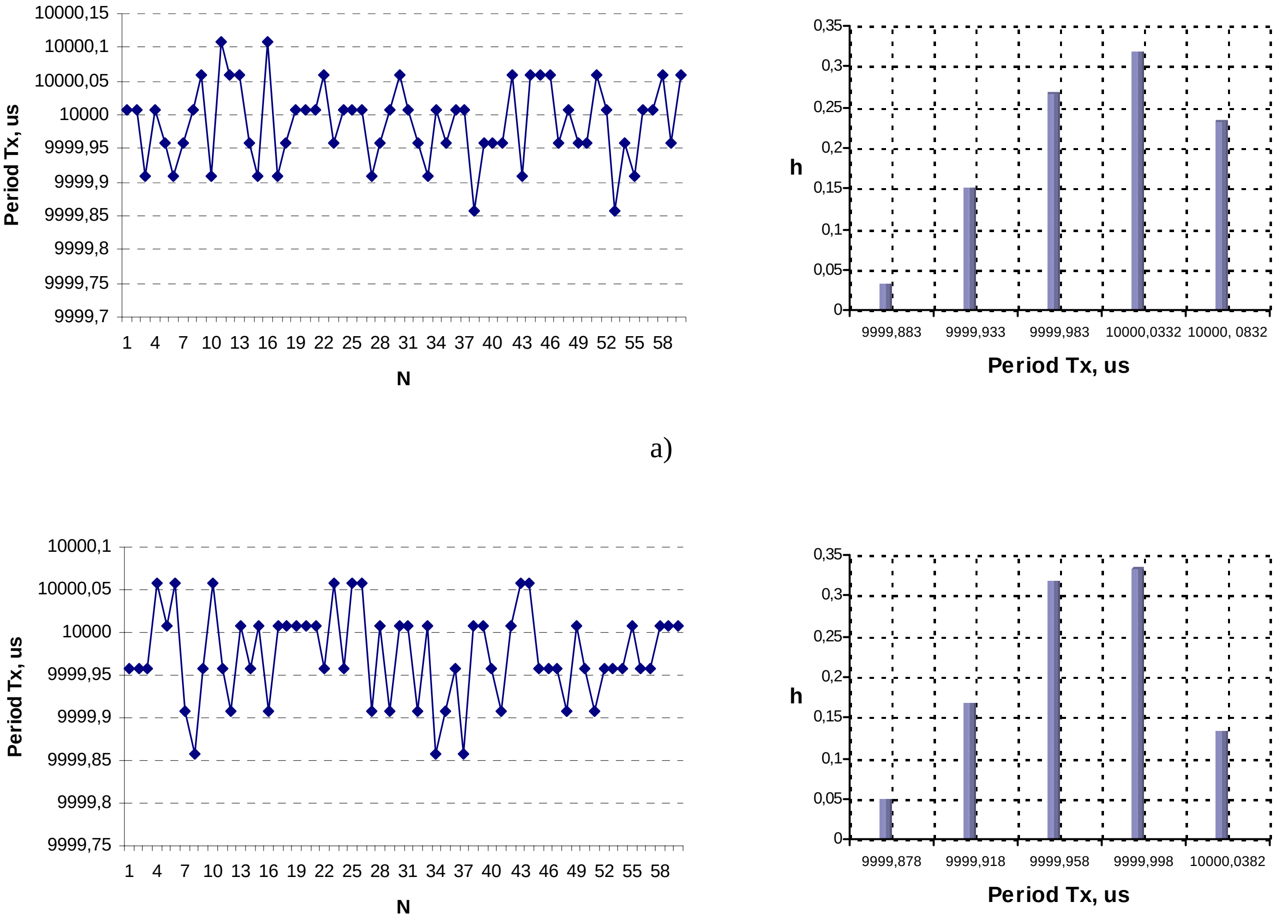


a)

b)

Fig. 6. Experimental results of direct period measurement for sine waveform signal and its probability density (a); experimental results and probability density with the use of an external Schmitt trigger circuit (b).

The experimental results for exponential rise waveform signal period measurements and the probability densities are shown in Fig. 7 (a, b). The similar signal waveform is often used in resistance, capacitance and resistive bridge-to-time interval conversion at the direct sensor-to-microcontroller interfaces based on a charging or discharging capacitor. In case in which an external Schmitt trigger is used (Fig.7b) a small decrease in relative error is observed (Table 2). In this case at five equidistant classes and the probability P = 97 %, according to the χ^2 test, $S < \chi^2_{max}$, where S = 1.9434 is the sum of deviations between the dataset and the assumed distribution; χ^2_{max} = 7.0 is the maximum possible deviation of the χ^2 distribution. Hence, the hypothesis of Gaussian distribution can be accepted.



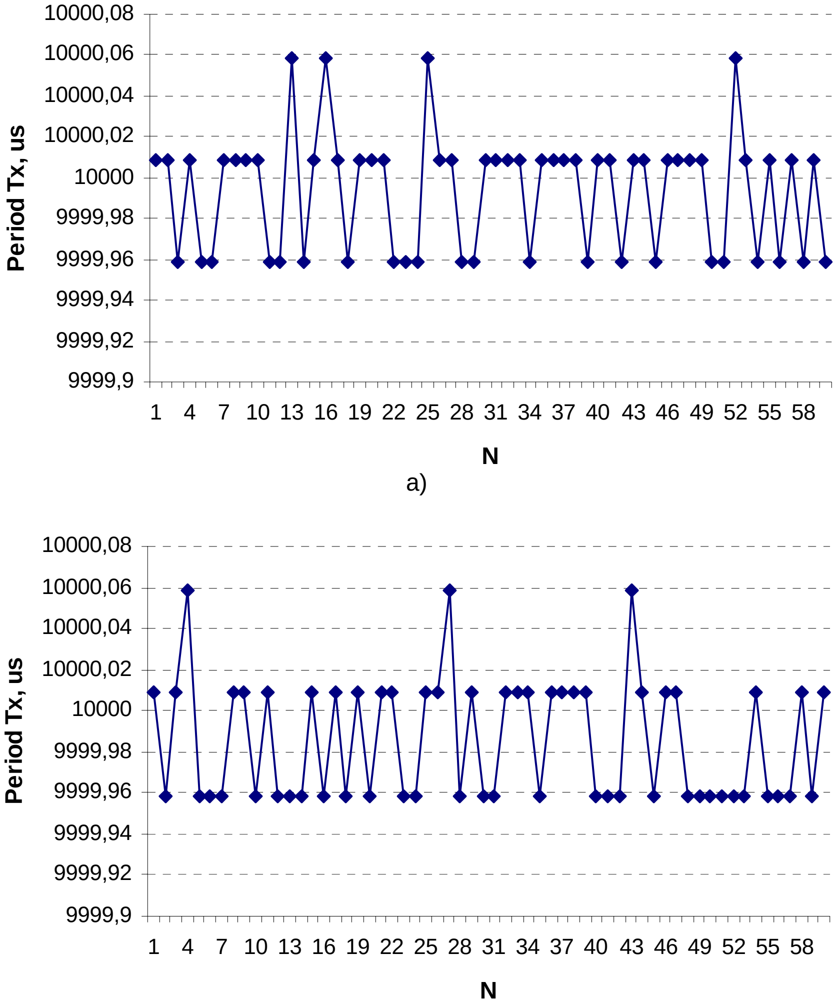
a)

b)

Fig.7. Experimental results of direct period measurement for an exponential rise waveform signal and its probability density (a); experimental results and probability density with the use of an external Schmitt trigger circuit (b).

The experimental results for exponential fall waveform signal period measurements and the probability densities are shown in Fig. 8 (a, b). The use of an external Schmitt trigger as a forming device does not give any relative error improvement (Table 2).

In the case of the rectangular waveform signal, the relative error of period measurements is minimal in comparison with non-rectangular slow slew rate signals and less in 2/8.5 times (Table 2). Nevertheless the use of an external Schmitt trigger decreases the pulse rise time from 24.25 ns to 21.75 ns (Fig. 9), and the use of an external Schmitt-trigger circuit in this case is not recommended (due to the increase in relative error) because the level of internal noises (thermal noise, interference in the IC power supply, etc.) is greater than the microcontroller's internal noises. Most significant deviations from the arithmetic mean in experimental period measurement results for square wave signals are determined by so-called program-related quantization effects, such as an interrupt response shift in time and interrupt response delay because the interrupt response time depends on the instructions executed by the microcontroller [6]. However, the total relative error does not exceed the programmable one.



a)

b)

Fig.8. Experimental results of direct period measurement for an exponential fall waveform signal (a); experimental results with the use of an external Schmitt trigger circuit (b).

These experimental results were compared with those obtained in [3, 8-10] for a 100 Hz triangular signal when measuring the period using the indirect counting method. From the counting results of 10 003 μs and 10 006 μs reported in [3, 9, 10] and 10 003 μs and 10 004 μs reported in [8], the maximum quantization errors were (0.03 ÷ 0.06) % and (0.03 ÷ 0.04) % respectively. When measuring the same frequency and waveform but applying the modified method of dependent counting implemented with the ATmega168-20PI microcontroller, the maximum relative error was below 0.000262 % (Table 2). In the case of a 100 Hz square wave signal, the relative error reported in [8] was (0.01 ÷ 0.03) % in comparison with the maximum relative error obtained in described experiments which did not exceed ±0.000031 % (Table 2).

With regard to the conversion speed, for a 0.016 % relative error, neither of the two methods exceeds one period T_x. Of course, increased accuracy in the case of the modified method of the dependent count will require increasing conversion time, but, in any case, this time will be non-redundant for the proposed modified method. The reference frequency increase of up to $f_0 = 20$ MHz will significantly reduce the conversion time in the proposed modified method of the dependent count performed with the ATmega168-20PI microcontroller. So, for the relative error $\delta = 0.0005$ % the conversion time will not exceed one period $T_x = 0.01$ s, which corresponds to the 100 Hz input signal.

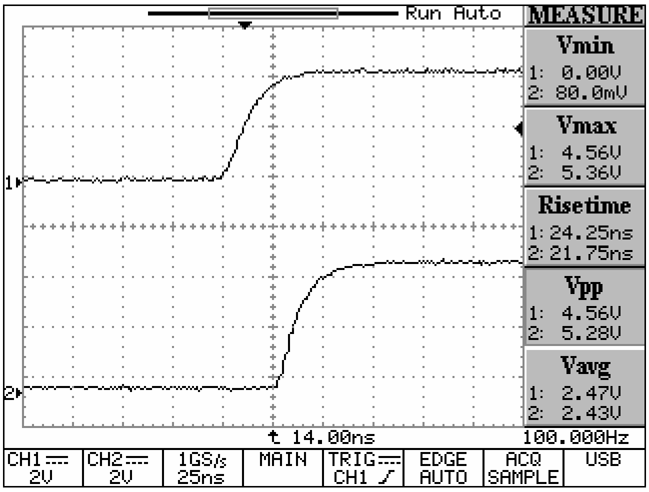


Fig. 9. Rectangular pulse wave front without a Schmitt trigger circuit (1) and with a Schmitt trigger circuit (2).

Even though the relative error can also be reduced slightly by using an external Schmitt trigger, it is not expedient to use this device at a programmable relative error $\geq \delta = 0.0005$ %, because, as is evident from the Table 2, for any investigated signals the relative error without the Schmitt trigger does not exceed the programmable relative error of $\delta = 0.0005$ %. If the modified method of the dependent count described in this article is used, it is also not necessary to use other uncertainty reduction techniques, such as sleep and capture modes for a microcontroller, which are described in [8, 9].

Numerous experiments with the microcontroller-based period measuring systems for rectangular and slow slew rate signals of different waveforms based on the proposed advanced method for frequency (period) and the common ATmega168-20PI microcontroller have also confirmed the high measurement performance of this approach in all frequency ranges possible for this type of microcontroller. Thus, precision frequency (period) measurements with a relative error that does not exceed ±0.0005 % programmable error are possible for the frequency range from 0.03 Hz to 7.5 MHz with the ATmega8-16PI microcontroller and 0.05 Hz to 9.1 MHz with the ATmega168-20PI microcontroller. Experimental results of frequency measurements of rectangular waveform pulses at the limits of the measuring range of the ATmega168-20PI microcontroller are shown in Fig.10 (a, b). Absolute and relative errors for measurements of a minimum possible frequency 0.05 Hz are shown in Fig. 11 (a, b) respectively. Thus, the relative error for high 9 MHz frequency does not exceed 0.00043 % and relative error for infra-low 0.05 Hz frequency does not exceed 0.00009 %.

5. Conclusions

The modified method of the dependent count for frequency-time measurements and the indirect counting method for period measurement can be easily implemented by common one-chip microcontrollers. For signals with non-square waveforms, conversion errors due to internal and external trigger noise predominate, particularly in the low frequency range (slow slew rate). Program-related quantization effects yield errors even for relatively fast input signals.

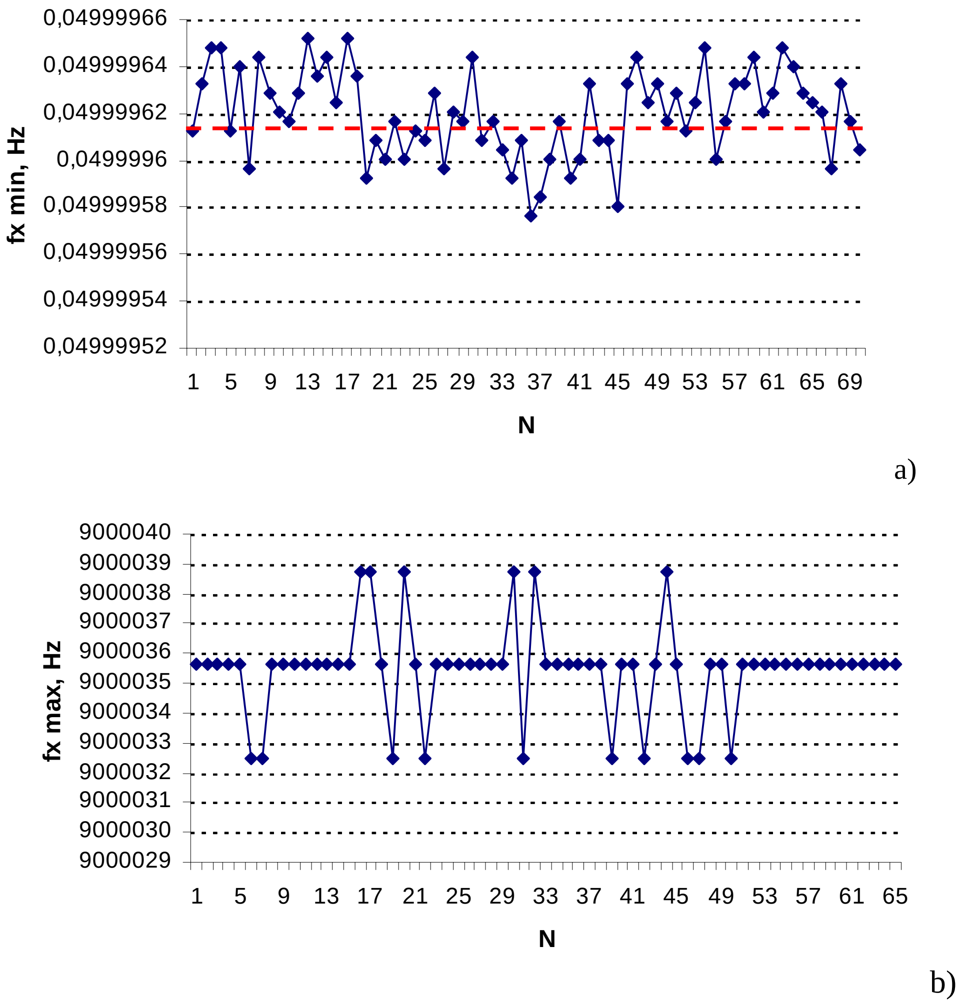


Fig. 10. Experimental results of 0.05 Hz frequency measurements (a); experimental results for 9 MHz frequency measurements (b).

For period measurements of rectangular as well as slow slew rate signals (triangular, sine, exponential rise and exponential fall), the modified method of the dependent count increases the accuracy by 2- to 3-orders as compared to the classical indirect counting method because that method is related to frequency measurement rather than period or single time interval measurements (see time diagrams in Fig. 2). Therefore, components of error, such as trigger uncertainty (Fig. 1) due to internal noise, are either excluded or substantially reduced.

Period measurement is suitable for low frequency measurements due to its non-redundant conversion time. The modified method of the dependent count also has a non-redundant conversion time and for a conversion error ≥ 0.0005 % at reference frequency f_0 = 20 MHz, its conversion time is the same as for the indirect conversion method: a single period T_x.

For the type of microcontroller used in the experiments described here, the ATmega168-20 PI, precision frequency (period) measurements are possible for the frequency range from 0.03 Hz to 9.1 MHz, with a relative error that does not exceed ±0.0005 %.

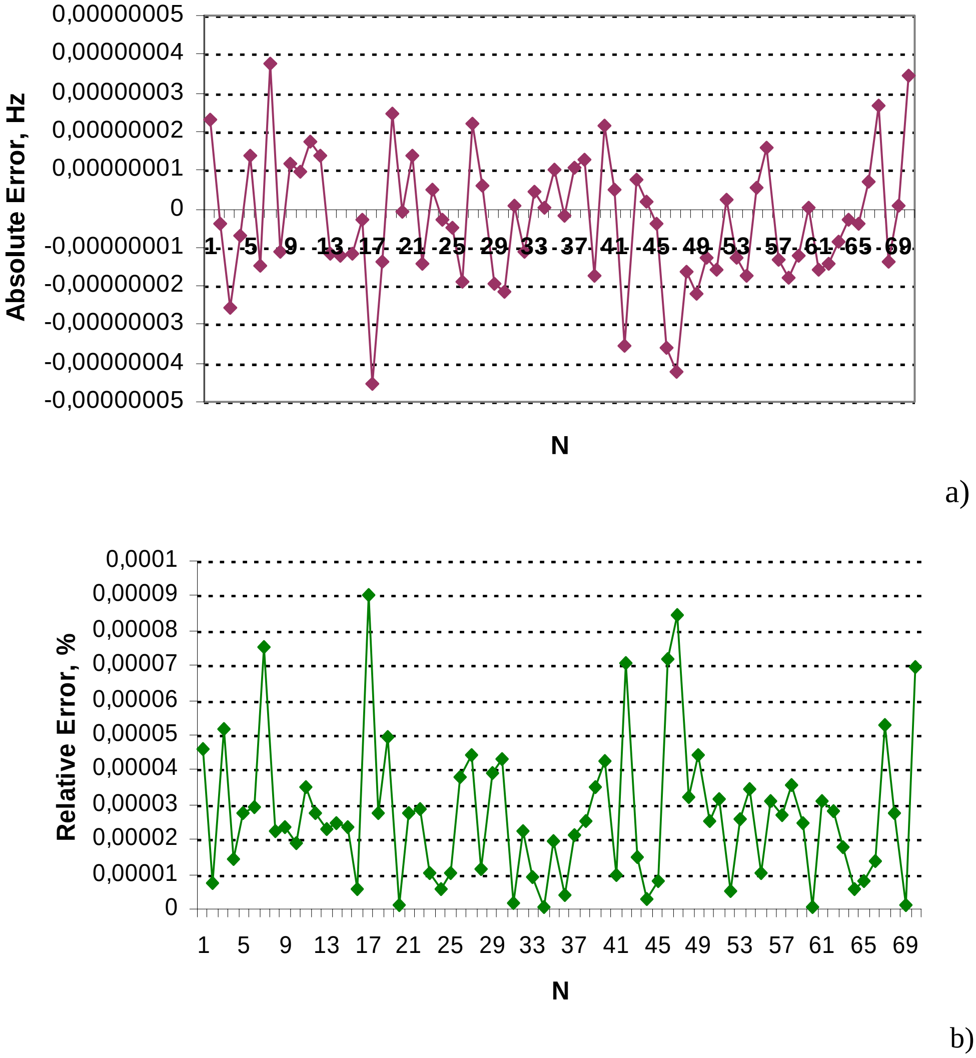


Fig.11. Absolute (a) and relative (b) errors of measurement for 0.05 Hz (0.049999617 Hz) frequency measurements.

Acknowledgements

This research was supported by the European Commission, though the Marie Curie Chair (EXC) project MEXT-CT-2005-023991 SMARTSES.

References

[1] R. Pallàs-Areny, J.G. Webster, Sensors and Signal Conditioning, 2nd ed., *John Wiley & Sons*, New York, USA, 2001.

[2] M.A. Atmanand, V. Jagadeesh Kumar, and Vempati G. K. Murti, A Microcontroller-Based Quasi-Balanced Bridge for the Measurement of L, G and R, *IEEE Transactions on Instrumentation and Measurement*, Vol. 45, No. 3, June 1996, pp.757-761.

[3] F. Reverter, J. Jordana, R. Pall`as-Areny, Program-Dependent Uncertainty in Period-to-Code Converters Based on Counters Embedded in Microcontrollers, in *Proceedings of the 20th IEEE Instrumentation and Measurement Technology Conference (IMTC´ 03)*, Vail, Colorado, USA, 20-22 May 2003, Vol.2, pp.977-980.

[4] F. Reverter, O. Casas, J. Jordana, R. Pallàs-Areny, Trigger Uncertainty in Period-to-Code Converters Based on Counters Embedded in Microcontrollers, *Sensors and Actuators A*, Vol. 110, 2004, pp.439-446.

[5] F. Reverter, M. Gasulla, R. Pallàs-Areny, Analysis of Interference Rejection in Period-to-Code Converters, in *Proceedings of the 21st IEEE Instrumentation and Measurement Technology Conference (IMTC 2004)*, Como, Italy, 18-20 May 2004, pp.839-842.

[6] N. V. Kirianaki, S. Y. Yurish, N. O. Shpak, V. P. Deynega, Data Acquisition and Signal Processing for Smart Sensors, *John Wiley & Sons*, Chichester, UK, 2002.

[7] N. V. Kirianaki., S. Y. Yurish, N. O. Shpak, Methods of Dependent Count for Frequency Measurements, *Measurement* , 29, (1), 2001, pp. 31-50.

[8] F. Reverter, R. Pallàs-Areny, Uncertainty Reduction Techniques in Microcontroller-based Time Measurement, *Sensors and Actuators A*, Vol. 127, 2006, pp.74-79.

[9]. F. Reverter, R. Pallàs-Areny, Direct Sensor-to-Microcontroller Interface Circuits. Design and Characterization, *Marcombo S. A.*, Barcelona, Spain, 2005.

[10] F. Reverter, Microcontroller-Based Interfaces for Quasi-Digital Sensors, *PhD Thesis*, Universitat Politecnica de Catalunya (UPC-Barcelona), 2004.

[11] http://www.sensorsportal.com/DOWNLOADS/Terminal.exe

[12] P. V. Novitskii, I. A. Zograf, Measurement Errors Estimation, *Energoatomizdat*, Leningrad, 1991.

Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 8-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

Advertising Information

Advertising orders and enquires may be sent to sales@sensorsportal.com Please download also our media kit: http://www.sensorsportal.com/DOWNLOADS/Media_Kit_2009.pdf