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High precision ΔE effect measurement with the use of ultrasonic-wave-time-of-flight method

***Abstract**. The paper provides description of very accurate measurement method of ferromagnetic rod Young modulus variations (ΔE effect) as a function of the magnetic field. The Young's modulus variations measurement principle is based on change of sound velocity. The high resolution time of flight of ultrasonic wave measurement was applied. High resolution as good as 15 ps TDC (Time to Digital Converter) implemented in FPGA (Field Programmable Gate Array) was used. This feature allows measuring ΔE with accuracy of about a few ppm. The measurement accuracy mainly depends on resolution of time of flight measurement and sound speed in the tested material. The analog front-end part which is responsible for the time location of the reflected ultrasonic wave is very important part of the measurement system. In the article the results of measurements for different samples made of carbon steel are described.*

***Streszczenie.** W artykule przedstawiono metodę pomiaru zmiany modułu Younga w pręcie ferromagnetycznym pod wpływem pola magnetycznego. Zastosowana metoda pomiaru zmiany modułu Younga polega na wysokorozdzielczym pomiarze czasu przelotu fali ultradźwiękowej. Zastosowano układ TDC (Time to Digital Converter) zaimplementowany w strukturze FPGA (Field Programmable Gate Array) o rozdzielczości rzędu 15 ps, co pozwala mierzyć zmianę modułu Younga z dokładnością kilku ppm. Uzyskiwana rozdzielczość pomiaru zależy głównie od rozdzielczości pomiaru czasu jak i od prędkości rozchodzenia się fali ultradźwiękowej w ośrodku. Ważnym elementem systemu pomiarowego jest analogowy układ do lokalizacji w czasie czoła odbitej fali ultradźwiękowej. Zaprezentowano również przykładowe wyniki pomiarów dla różnych gatunków stali węglowej. (**Precyzyjny pomiar zmiany modułu Younga metodą czasu przelotu fali ultradźwiękowej**).*

Keywords: Young's modulus, ΔE effect, the time of flight measurement, ultrasound, FPGA.
Słowa kluczowe: moduł Younga, ΔE efekt, pomiar czasu przelotu, ultradźwięki, FPGA.

1. Introduction

Young's modulus, also called as elastic modulus, is well known mechanical property of linear, elastic, solid materials and is defined as stress to strain ratio:

$$E = \frac{\sigma}{\varepsilon} = \frac{F}{A} \cdot \frac{l}{\Delta l}, \tag{1}$$

where: E – Young's modulus, σ – stress *(N/m²)*, ε – *strain (m/m)*, Δl – elongation or compression of the object *(m)*, l – length of the object *(m)*, F – *force (N)*, A – area of object *(m²)*.

Employing the classical definition of elastic modulus it is inferred that the elastic modulus of magnetostrictive materials is rather a complicated property. The elastic modulus of magnetostrictive materials is a function of mechanical properties as much as it is a function of magnetic properties. A model for the "ΔE-effect" in magnetostrictive materials was presented in [1].

There are several commonly known methods for determining the elastic modulus:
– static (tensile, torsion, bending test),
– dynamic (resonant frequency method),
– wave propagation methods (ultrasonic echo-pulse method).

Above mentioned methods are suitable for relatively large size and regular shapes samples measurement. Depending on the characteristics of a material, sample dimensions and shape, some different measurement methods may be used. For example, Depth Sensing Indentation (DSI) method is used for relatively small amounts of testing materials and there are no strict requirements for a sample shape [2]. Nanoindentation [3], phase velocity [4], micromechanical cantilever [5] techniques are used for Young's modulus determining in thin film material. In case of small dimension samples interferometric strain/displacement gage (ISDG) technique can be used [6]. Determination of Young's modulus using eddy currents was described in [7]. New method of Young's modulus determination for metallic and composite materials using digital image correlation was described in [8].

2. High resolution Young's modulus determination using ultrasonic echo-pulse method

Presented method of Young's modulus determination is based on ultrasonic echo-pulse method. In this method time of flight of ultrasonic wave measurement is used to determine the sound velocity in the test sample.

In order to accurately determine the speed of sound in the test sample the magnetostriction effect must be taken into account. Magnetostriction is a property of ferromagnetic materials that causes them to change their shape or dimensions when the external magnetic field is applied. Variation of a material magnetization under applied magnetic field changes the material dimension until it reaches its saturation value. This effect was first identified by James Joule in 1842. Magnetostriction λ is defined as a ratio of saturated rod length change under the influence of a magnetic field to nominal rod length when the magnetic field is equal to zero. The nature of this effect is illustrated in figure 1.

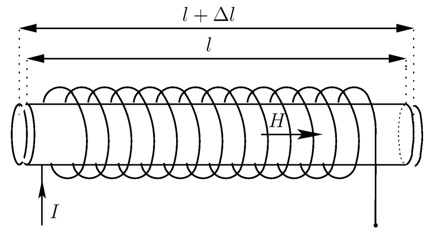

Fig.1. Magnetostriction effect

When the material size decreases while a magnetic field is present, we have a negative magnetostriction, for increasing dimensions, we have a positive magnetostriction. All ferromagnetic materials are basically magnetostrictive. Classical magnetostrictive materials such as iron, mild steel, cobalt, nickel, etc. in wires, tapes, films and bulk alloys shape, have λ values from as low as a few ppb up to a few decades ppm [9]. In the presented measuring system, it is necessary to take into account the rod length changes in order to not significantly degrade measurement accuracy.

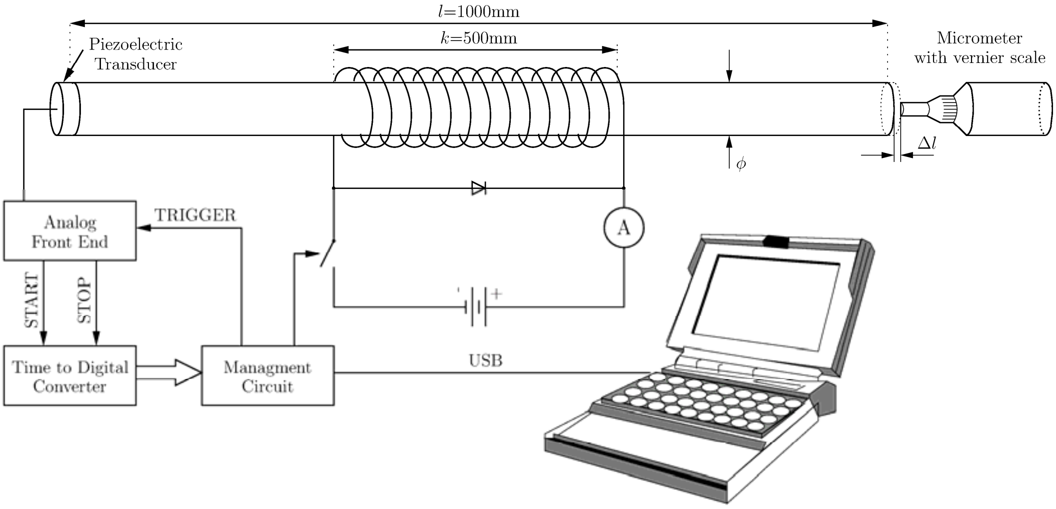

Fig.2. Schematic of the experiment

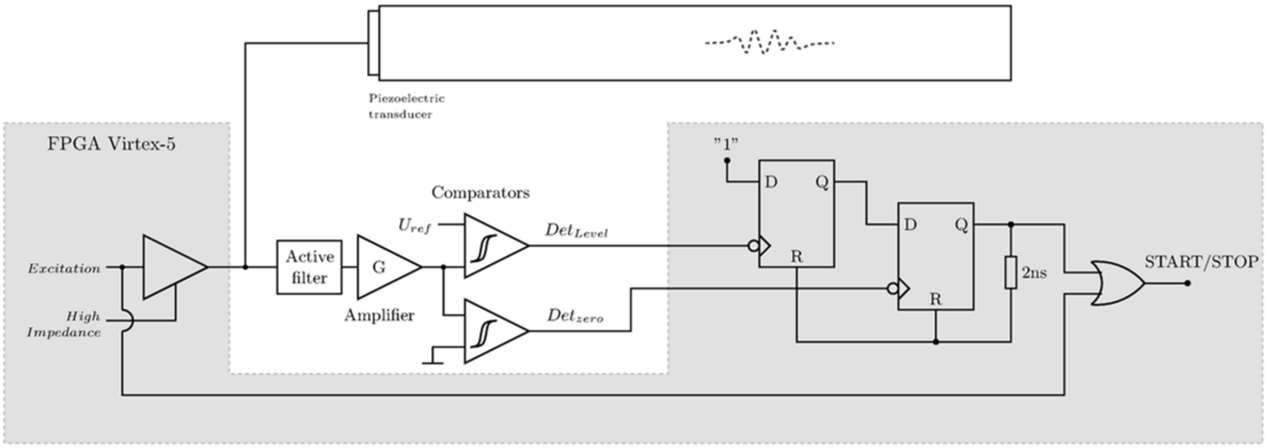

Fig.3. Analog Front End

The measurement system is shown in figure 2. Parameters of the Young's modulus E of a steel rod was determined by longitudinal ultrasonic wave pulse velocity measurement. In general, the Young's modulus E is strongly dependent on temperature. Temperature stabilization is difficult to be met, because the heat is produced by current flowing in the coil. In order to eliminate temperature influence on the "ΔE-effect" measurement magnetic field modulation at a frequency of 0.1 Hz has been implemented (cyclic switching on and off current in the solenoid). This allowed to separate the trend caused by heating of the tested object. Ends of the rods have been planned on a lathe and polished. To effectively transfer energy generated by the piezoelectric element to a metal and vice versa (matching acoustic impedance) same kind of coupling gel was used. In the measuring system 1.98 mm thick, 16 mm diameter disc shape, Pz27 ceramic type piezoelectric transducer with reduced 7 mm electrode diameter manufactured by Ferroperm Piezoceramics was applied. The resonant frequency of this piezoelectric transducers is approximately 1 MHz. The ultrasound waves of such frequency in a steel rod has a length of λ = 5 mm, and propagates rather well. To produce a magnetic field a coil with of length k = 500 mm, which has a 2600 turns was used.

Especially important element of the measuring system is the Analog Front End (AFE) (fig. 3). It includes low-noise amplifiers, filter and two high speed comparators. Total gain amplifiers is about 36 dB. The task of AFE is to convert the incoming echo signal from piezoelectric transducer to pulses which are then transmitted to the output STOP. In the next block, time intervals are measured by high resolution TDC between the falling edge at the START input and each falling edge at the (multi-)STOP input.

Analysis of several time intervals for each measurement cycle as shown in figure 4 can efficiently minimize measurement uncertainty caused by the small SNR of ultrasonic incoming wave. Then the "localization in time" of the wave-front is more accurate and it is reasonable to use a high resolution TDC.

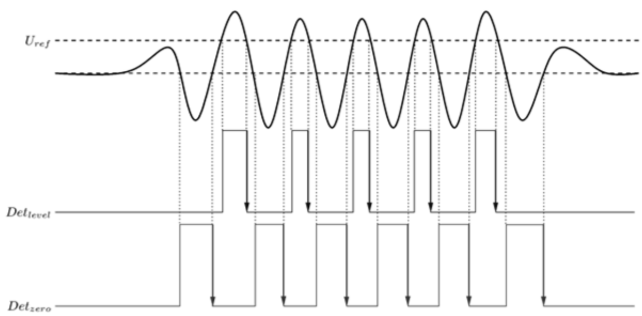

Fig.4. The idea of converting the echo-signal from the piezoelectric transducer

The high resolution TDC for time of flight measure was implemented in Virtex 5 FPGA [10,11]. The multi-segments delay line that uses CARRY elements in FPGA allows for significant resolution improvement. The obtained resolution for this prototype is about 15 ps. Phases of a reference clock signal generated by multi-segment delay line are connected to the D-flip-flop register. Signals START/STOP generated by the AFE are fed to the CLK input of register. Each rising edge of the START/STOP writes the state of the mutually complementing pair register-counter to the FIFO memory. Data from the FIFO memory are then send to application running on a PC computer where are analyzed. TDC circuit, serial communication interface and system management have been implemented in a single Virtex FPGA structure XC5VLX50-1FF676.

3. Theoretical analysis

The dependence of Young's modulus E for a rod is described by relationship: $E = v^2 \cdot d$, where v – is longitudinal wave propagation speed, d – material density. In the echo-pulse method, velocity is measured by time-of-flight T ultrasonic wave in both directions. Then the expression achieves the form:

(2) $$\mathrm{E} = \left(\frac{2\mathrm{l}}{\mathrm{T}}\right)^2 \cdot \mathrm{d} = \frac{4\mathrm{l}^2}{\mathrm{T}^2} \cdot \mathrm{d},$$

where: l – rod length. Absolute value of change in Young's modulus ΔE due to the constant magnetic field is described by the expression:

(3) $$\Delta\mathrm{E} = \frac{\partial \mathrm{E}}{\partial \mathrm{T}} \cdot \frac{\Delta \mathrm{T}}{2} + \frac{\partial \mathrm{E}}{\partial \mathrm{l}} \cdot \Delta\mathrm{l}.$$

In above formula ΔT means a difference between measured ultrasonic wave flight time with or without magnetic field. Factor ½ was introduced because the coil length is half of the rod length. Changing the rod length Δl caused by the magnetostriction effect causes a change in flight path. This contribution was also added to equation 3 as the second component. The formula is true for small ΔT and Δl changes. The final expression will take the form:

(4) $$\Delta\mathrm{E} = \frac{-4\mathrm{l}^2\mathrm{d}}{\mathrm{T}^3} \cdot \Delta\mathrm{T} + \frac{8\mathrm{ld}}{\mathrm{T}^2} \cdot \Delta\mathrm{l}.$$

The relative change of the Young's modulus caused by magnetic field is:

(5) $$\frac{\Delta\mathrm{E}}{\mathrm{E}} = \frac{-\Delta\mathrm{T}}{\mathrm{T}} + \frac{2\Delta\mathrm{l}}{\mathrm{l}}.$$

Uncertainty in the relative change of Young's modulus is (type B):

(6) $$\delta\left(\frac{\Delta\mathrm{E}}{\mathrm{E}}\right) = \frac{1}{\mathrm{T}} \cdot \delta(\Delta\mathrm{T}) + \frac{\Delta\mathrm{T}}{\mathrm{T}^2} \cdot \delta(\mathrm{T}) + \frac{2}{\mathrm{l}} \cdot \delta(\Delta\mathrm{l}) + \frac{2\Delta\mathrm{l}}{\mathrm{l}^2}\delta(\mathrm{l}).$$

The TDC circuit together with AFE has a measurement uncertainty on the level [12]:

(7) $$\delta(\mathrm{T})[\mathrm{ns}] = 4 \cdot 10^{-3} \cdot \mathrm{T}[\mu\mathrm{s}] + 0.2.$$

The rod elongation caused by magnetostriction was measured by a micrometer with vernier scale. The uncertainty of the elongation measurement is $\delta(\Delta l) = 1\mu m$. Rod length measurement uncertainty is $\delta(l) = 0{,}5mm$. Finally, the uncertainty of the relative change in Young's modulus does not exceed:

(8) $$\delta\left(\frac{\Delta\mathrm{E}}{\mathrm{E}}\right) < 2.6\mu.$$

4. Measurements results

Measurements were done for several various diameters samples of rods made of aluminum, stainless steel and carbon steel. The ΔE-effect and magnetostriction appeared in carbon steel. All rods had the positive magnetostrictive effect. This caused rod length Δl and time of flight ΔT increasing for all samples. Differences in the time of flight ΔT as a function of the magnetic field H is shown in figure 5.

The relative change of the Young's modulus ΔE of carbon steel dependency on the magnetic field value is shown in figure 6.

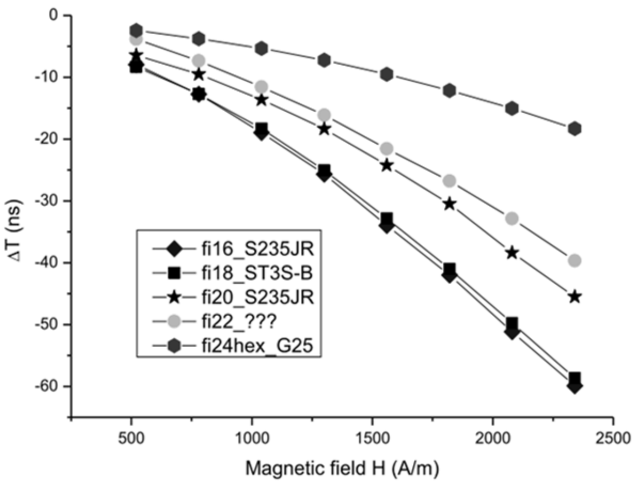

Fig.5. Changes in time of flight for steel rods

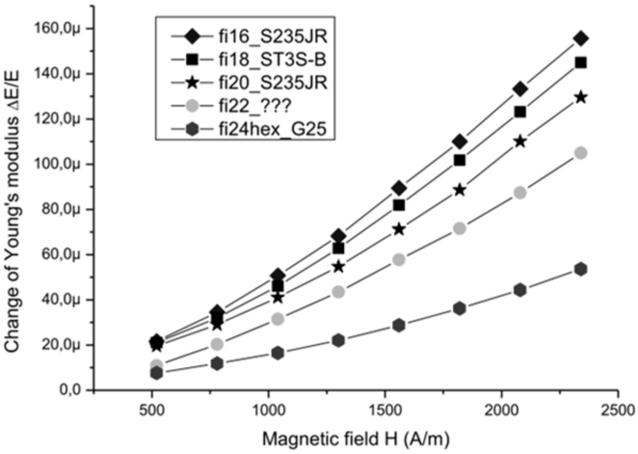

Fig.6. Change of Young's modulus for steel rods

Estimated parameters and uncertainties for the rods made from constructional steel are shown in Table 1.

Table 1. Measured parameters of sample rods

Specification	Velocity [m/s]	Density [kg/m3]	Young's modulus [GPa]
roller, Φ=16mm, S235JR	4798 ± 5	7820 ± 107	180 ± 2.9
roller, Φ=18mm, ST3S-B	4745 ± 5	7800 ± 94	176 ± 2.5
roller, Φ=20mm, S235JR	5002 ± 5	7800 ± 90	195 ± 2.5
roller, Φ=22mm, unknown type	4980 ± 5	7840 ± 77	195 ± 2.3
hexagon, Φ=28mm, G25	5200 ± 5	7820 ± 40	211 ± 1.5

5. Conclusions

System which can measure the time of flight with high resolution was presented. Applied method allows for precise estimation of absolute Young's modulus E value.

It is also possible to measure the change of Young's modulus ΔE even at low static magnetic fields. The knowledge of accurate characteristics of the changes ΔE in the function of magnetic field H may assist in material identification. Using the proposed method it is possible to measure the dynamic effect of change in time of flight ΔT. The tests performed on several rods made of carbon steel confirmed the effectiveness and accuracy of the measuring method. An additional method advantage is the requirement of access to the sample from one side only.

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REFERENCES

[1] Marcelo J. Dapino, Ralph C. Smith, Alison B. Flatau, Model for the ΔE effect in magnetostrictive transducers, *Proc. SPIE 3985, Smart Structures and Materials 2000: Smart Structures and Integrated Systems*, (2000)

[2] Gubicza J., Determination of Young's modulus from depth sensing Vickers Indentation Tests, *Solid State Phenomena*, Vol. 56, (1997), 195-200

[3] Pharr G. M., Oliver W. C., Measurement of hardness and elastic modulus by instrumented indentation: Advances in understanding and refinements to methodology, *J. Mater. Res.*, 19 (2004), n.1, 123-127

[4] Vaz F., Carvalho S., Rebouta L., Silva M. Z., Paul A., Schneider D., Young's modulus of (Ti,Si) N films by surface acoustic waves and indentation techniques, *Thin Solid Films*, 408 (2002), 160–168

[5] Akiko N. Itakura, Masaya Toda, Koji Miyake, Renate Forch, Rudiger Berger, Effective Young's Modulus Measurement of Thin Film Using Micromechanical Cantilever Sensors, *Japanese Journal of Applied Physics*, 52 (2013), 110-111

[6] Sharpe W. N., Bin Yuan Jr., Vaidyanathan R., Edwards R. L., Measurements of Young's modulus, Poisson's ratio and tensile strength of polysilicon, *Proceedings of the Tenth IEEE International Workshop on Microelectromechanical Systems*, (1997), 424-429

[7] Kwaaitaal Th., Schoofs A. J. G., Determination of Young's modulus or Poisson's ratio using eddy currents, *Experimental Mechanics*, 19 (1979), n.12, 450-455

[8] Zeeshan M. Siddiqui, Fawad Tariq, Nausheen Naz, M. Fahad Ahmed, Determination of Young's modulus of metallic and composite materials by digital image correlation, *Journal of Space Technology*, 1 (2012), 18-25

[9] Hristoforoua E., Ktenab A., Magnetostriction and magnetostrictive materials for sensing applications, *Journal of Magnetism and Magnetic Materials*, 316 (2007) 372–378

[10] Grzelak S., Czokow J., Kowalski M., et al. Ultrasonic flow measurement with high resolution, *Metrology and Measurement Systems*, 21 (2014), 305-316

[11] Grzelak S., Kowalski M., Czokow J., et al., High resolution time-interval measurement systems applied to flow measurement, *Metrology and Measurement Systems*, 21 (2014), 77-84

[12] Zielinski M., Kowalski M., Chaberski D, et al., Measurement system of oscillators' phase fluctuation and its applications, *Przeglad Elektrotechniczny*, 84 (2008), 259-264