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Analysis of the Ways of Increasing the Precision of the Isotropic Materials Modulus of Elasticity Measurements

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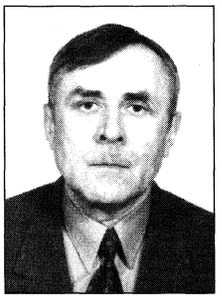

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Abstract

The new ways of increasing the precision of the modulus of elasticity measurement isotropic materials (conductive, dielectric and ferromagnetic) by dynamic method is considered. The of carried out analysis has are established that such factors as the interior material structure defects (point defects, dislocations, pores) and internal mechanical tensions have a direct effect upon the velocity of propagation of ultrasonic waves in a specimen.The increased of precision of the modulus of elasticity measuremenst is achieved by the correction of the methodical error caused by the effect of the interior material structure defects and internal mechanical tensions on the modulus of elastisity value.

Streszczenie

W artykule została przedstawiona problematyka pomiaru metodą dynamiczną modułu sprężystości materiałów izotropowych (przewodzących, dielektrycznych i ferromagnetycznych), które mają defekty struktury wewnętrznej. Przeprowadzono analizę wpływu defektów struktury wewnętrznej i wewnętrznego naprężenia mechanicznego na prędkość rozprzestrzeniania się fal ultradźwiękowych, które powodują powstawanie błędu metodycznego przy pomiarach modułu sprężystości. Z analizy wynika, że wartość błędu metodycznego może wielokrotnie przekraczać wartość błędu instrumentalnego i ma podstawowy wpływ na wartość błędu pomiaru modułu sprężystości. Opisano i analizowano sposoby podwyższenia dokładnosci pomiaru modułu sprężystości materiałów izotropowych metodą dynamiczną, która jest oparta na korekcji błędu metodycznego, spowodowanego wpływem defektów struktury wewnętrznej i naprężenia wewnętrznego mechanicznego na wartość modułu sprężystości. W artykule przedstawiono również schemat blokowy narzędzi do pomiaru modułu sprężystości, w których została zrealizowana automatyczna multiplikatywna korekcja błędu metodycznego.

Keywords: modulus of elasticity, internal structure, defects, error, correction
Słowa kluczowe: moduł sprężystości, struktura wewnętrzna, defekty, błąd, korekcja.

1. Introduction

The modulus of elastisity (ME) is one of the most impotant properties of a solid body, sinse it is directly used in any practical application and in the scientific research of materials. The knowledge of the ME is sufficient to enable a prediction concerning the inner material structural state and its elastic limit and tensile strength make.

The one-axis deformation isotropic body elastic state may be characterized by the following quantites: *modulus of elastisity (Young's modulus)* $E = \sigma/\varepsilon$, *modulus of shear* $G = \tau/g$, *modulus of uniform compression* $K = p/v$ (where σ, τ, p and ε, g, v - mechanical tensions and deformations of the stretched, sheared and uniform compressed body accordingly) and *Poisson's ratio* μ, which are connected by the following equations [1]: $G = \frac{E}{2(1+\mu)}$ and $K = \frac{E}{3(1-2\mu)}$.

It is obvious, that elastic properties of the isotropic body are defined by two independent quantites. Usually, they are E and G, measuring of whith is one of the most important tasks in the experimental materials study.

2. Dynamic method of measuring ME

Measurements of ME of the materials is usually performed by a *dynamic method* [1, 2], which is implemented in two modes:

a) by measuring the specimen's own oscillation frequency of an investigated material (the so-called *resonance method*);
b) by measuring a velocity of propagation of ultrasonic (elastic) waves in a specimen of the investigated material (the so-called *impulsive ultrasonic method*).

To apply a *resonance method* for measuring ME longitudinal or rotating oscillations are excited in the investigated specimen and at the moment of a resonance the frequency of self-oscillation of a specimen is measured, and the value ME of the material is determined by the formulas:

$$E = k_l \rho l^2 f_l^2 \text{ and } G = k_\tau \rho l^2 f_\tau^2, \quad (1)$$

where k_l, k_τ - coefficients, the values of which depend on the shape and geometrical size of an investigated specimen; ρ - density of a material of the specimen; l - length of the specimen; f_l , f_τ - specimen's own longitudinal and transversal oscillation frequency.

The necessary requirement of realization of equalities (1) is a high ratio between length l and diameter d of an investigated specimen ($l/d \rangle 10$), whith complicates the practical embodying of a resonance method, as it is not always possible to ensure the above mentioned requirement. According to [1], the relative error of measuring ME by a resonance method does not exceed 1%.

The *impulsive ultrasonic method* of measuring ME is based on the dependences of the velocities of propagation of longitudinal v_l and v_τ transversal (shearing) elastic or ultrasonic waves (USW) in an isotropic material from the material modulus of elastisity [1, 2]:

$$v_l = \sqrt{\frac{E}{\rho} \cdot \frac{1-\mu}{(1+\mu)(1-2\mu)}} \text{ and } v_\tau = \sqrt{\frac{G}{\rho}}. \quad (2)$$

In the investigated specimen, transversal size or the diameter d is much smaller than the length of an elastic wave λ, whics propagates in it, i.e. under the condition of $d \langle\langle \lambda$, the expression (2) becomes simpler up to $v_l = \sqrt{E/\rho}$, whence we can gain a working formula for defining ME by an impulsive ultrasonic method:

$$E = \rho v^2. \quad (3)$$

Measuring instruments, in which the impulsive ultrasonic method of measuring ME is implemented (hereinafter we shall consider only the modulus of a normal elasticity E, because the following analysis is also valid for the case of measuring of the modulus of shear G), usually built under the block diagram shown in fig. 1, and they contain the ultrasonic channel (USC) for measuring a velocity v of propagation USW in the investigated specimen S and the block of an evaluation of the module (MEE).

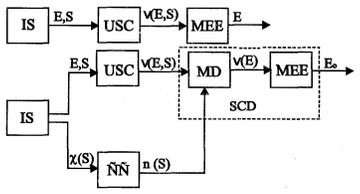

Fig. 1. The block diagrams of the measuring instruments realizing an impulsive ultrasonic method of a modulus of elasticity measurements: without correction (a) and with correction (b) of a methodical error.

3. Errors of a ME measuring by an impulsive ultrasonic method

The impulsive ultrasonic method of ME measuring at the present stage of the developments in measuring techniques ensures the utmost split-hair accuracy of ME measuring. A relative error δ_E of ME measuring according to the references [1] makes up a tenth long of percent and less. However it is necessary to mark that the authors of the known operations take into account only an instrumental error $\delta_{E,I}$, i.e. accept that $\delta_E = \delta_{E,I}$, which with the account of (3) is equal to $\delta_{E,I} = \delta_\rho + \delta_v$, where δ_ρ - is a relative error of measuring of density ρ of a material of the specimen; δ_v - is a relative error of measuring of a velocity v of propagation of USW in the specimen.

However the requirement $\delta_E = \delta_{E,I}$ is wrongful, since herein the effect of the interior structure of the IS material on the velocity of USW propagation and, accordingly, on the ME value, is not taken into account (in fig. 1 the effect of interior structure of the IS material on the value of its physical properties is designated by the letter S).

The carried out analysis established that such factors as the interior material structure defects (ISD) i.e., point defects, dislocations, pores and interal mechanical tensions have an immediate effect to a ME value. For example, owing to the driving of dislocations caused by mechanical tensions affixed on a specimen, the measured ME value can be 1 % smaller then the real value* [3]. The modification of interior mechanical tensions at the material state passing from the tempered to the released state causes magnification of ME value up to 1,5...2 %. The presence of vacancies reduces in a diminution the ME value, and the presence of inter-knotted atoms causes magnification of ME up to 5...10% per 1% of atoms. At a research of high-melting metalceramic materials [2], which practically always have a residual porosity, the variance between the measured and the real ME values can make up a few percent.

Let us consider the effects of ISD of a specimen material on ME measurement accuracy by an impulse ultrasonic method more in detail. As a matter of fact, the measured velocity v of USW propagation in an actual specimen having ISD always differs from the velocity v_0 of USW propagation in the specimen free from defects by the magnitude Δv, i.e. $v = v_0 + \Delta v$, i.e., the real value of ME of E_0 the defectless material, which is equal to $E_0 = \rho_0 v_0^2$, (here ρ_0 is the theoretical density of the defectless material) also always differs from the measured value E by the magnitude of $\Delta E = E - E_0$, i.e. there is a ME methodical measuring error $\delta_{E,M}$, equal to $\delta_{E,M} = (\Delta E / E_0) \cdot 100\%$.

Thus, as a matter of fact, the error of ME measurings by an impulsive ultrasonic method have got two components i.e. instrumental error and methodical error, i.e. More over, , which, as it was shown above, can make up a few percent, i.e. it is much larger than, and has a prevailing effect on the value of the error of ME measurings.

Hence, the diminution of the methodical error is a rather important problem, since it permits to considerably increase ME measurement accuracy using the impulse ultrasonic method. Let us consider this problem more in detail.

* Hereinafter the *real* or *conventionally true* ME *value* of the investigated material is the ME value determined after correction of a methodical error. It differs from a ME *true value* of the material by the value of ME instrumental measuring error.

The real ME value E_0 of the investigated material) can be presented as follows:

$$E_0 = \rho_0 v^2 n^2, \tag{4}$$

where $n = v_0 / v$ is the coefficient (the scale) of modification of the velocity of USW propagation.

The coefficient (the scale) n displays the how many times the velocity v of USW propagation in an actual specimen having imperfections of the interior structure, is smaller than the velocity v_0 of USW propagation in an ideal defectless material, i.e. it shows the effect of the factors of the IS interior structure on the velocity of USW propagation in it and, hence, on the ME value.

With the account of (3) and (4) the ME methodical measuring error is equal to:

$$\delta_{E,M} = \left(1 - \frac{n^2}{\vartheta}\right) \cdot 100\%, \tag{5}$$

where $\vartheta = \rho / \rho_0$ - is the relative density of the IS material.

Thus, knowing the value of the coefficient n under the formula (4) it is easy to define the real ME value E_0 of the investigated material and, thus, to eliminate a methodical error $\delta_{E,M}$, which, as is seen from (5), appreciably depends on the value n and on the relative density ϑ. of the specimen.

4. Principal physics of the correction of ME methodical measuring error

To define the coefficient n it is necessary to perform the measuring of some IS physical property, which, on the one hand, would represent the factors of its interior structure, i.e. would be a structuraly – sensitive property of the IS material, and, on the other hand, would be interlinked with the measurands, i.e. with the velocity of USW propagation in the specimen and with the ME value.

In this connection, it is necessary to analyze the correlations between physical properties and the interior structure of the material. So, for this purpose we shall take the main positions of the theory of consolidation [4], which envisages the unity of the properties of the solid body having the defects of the interior structure (ISD).

According to [4], it is necessary to consider tothe physical properties of the solid body having ISD, as conditional performances of some construction consisting of a compact defectless material and particular defects (pores, point defects, dislocations etc.), the properties of any compact spatial element of the solid body having ISD being identical to the relevant properties of the defectless material. In such a construction the velocity of propagation of any process (for example, transmission of the mechanical, electromagnetic or thermal energy) always differs from the velocity of propagation of the same process in the defectless material. The degree of modification (contortion) velocity is defined by the *scale factor* l/l_0 (here l is the actual length paths of a particular process in the specimen having ISD; l_0 - are nominal or the least length paths of the same process in the defectless specimen), which displays how many times is the actual path l of propagation of any process through compact elements of the specimen with ISD larger than the nominal paths l_0 in this specimen, or how many times is the velocity v of the process propagation, for example, of the elastic or ultrasonic waves, in the specimen with ISD, smaller than a nominal velocity v_0 of propagation of the same process in the defectless specimen, i.e. $l/l_0 = v_0/v$.

Another major parameter of the solid body having ISD, is the dimensionless contact cut α, which is equal to the ratio of the actual contact cut of the specimen with ISD to the nominal cut of the defectless specimen. The numerical value α lies in the limits from 0 up to 1. According to [4], the small mechanical tensions (smaller than the limit of elasticity) in the solid body having ISD, practically completely concentrate in critical contact cut α, which is in fact a dimensionless active part of the cut of the body having ISD, in which the

directional tensions or processes concentrate. It allows to establish the fundamental relations defining the unity of physical properties of the solid body having ISD: $E/E_0 = \alpha$ and $(v/v_0)^2 = \alpha$.

Between two basic dimensionless parameters (scale factors) l/l_0 and a in one and the same specimen with ISD there exists a unique dependence - $\sqrt{\frac{\alpha}{\vartheta}} = \frac{1}{l/l_0}$, which enables to solve a problem of defining the correlations between different physical properties in this specimen.

The interrelations between physical properties of a different nature (mechanical, electrical, magnetic etc.) in the specimen with ISD have only correlative character grounded on the effect of the factors of the interior structure of the same specimen on the scales of a modification of the velocities of propagation of all the processes in it irrespective of their physical nature. In this connection, it is possible to speak about the correlations only of conditional or normalized performances of the specimen, which should be considered as a function of the quantities describing the interior structure of this sample, i.e. $\chi(S)/\chi_0 = f(\alpha;\vartheta)$, where $\chi(S)$ and χ_0 is the value of physical properties (elastic modulus, velocity of USW propagation, mechanical tensions, electrical conductivity, relative dielectric or magnetic permeability etc.) accordingly for the specimen with ISD and defectless material (letter S here designates ISD of the specimen on the value of the relevant properties).

It is possible to use a requirement of unity of physical properties of the solid body having ISD, to define the values of these properties.

5. Analysis of correlations between ME and electromagnetic properties of the investigated materials

A structural - sensitive property of the investigated material, which can be used in defining the coefficient n of a modification of the velocity of USW propagation in the specimen, is the electrical conductivity γ for the conductors, relative dielectric permeability ε for dielectrics, and relative magnetic permeability μ for ferromagnetics.

Let us consider in detail the correlation between the coefficient n of a modification of a velocity of USW propagation and the electrical conductivity γ in the same specimen. For this purpose, we shall take advantage of the limiting equations for the normalized properties of the solid body having ISD, for which the relation $\alpha = \vartheta^3$ is valid [4]. Then, with the account of (6), we shall get, that $v/v_0 = \sqrt{\alpha/\vartheta}$, and, considering the electrical conductivity γ of the specimen, as an electrical conductivity of the cube of the unit volume with transversal cut α, i.e. $\gamma/\gamma_0 = \sqrt{\alpha\vartheta}$, we shall define that the coefficient n of a modification of a velocity of USW propagation in the specimen having ISD, is equal to [5] - $n = \frac{v_0}{v} = \sqrt{\frac{\gamma_0}{\gamma}}$, and the real ME value of the conductive material from which the IS is manufactured with the account of (4)

$$E_0 = \rho_0 v^2 \frac{\gamma_0}{\gamma}, \tag{6}$$

where γ is electrical conductivity of the specimen having ISD; γ_0 is electrical conductivity of the defectless material.

It is similarly proved that in the case of dielectric materials the coefficient of a modification of a velocity of USW propagation in the specimen having ISD, $n = \sqrt{\varepsilon_0/\varepsilon}$, while the real ME value of a dielectric material, from which the IS is manufactured, is equal to [6]:

$$E_0 = \rho_0 v^2 \frac{\varepsilon_0}{\varepsilon}, \tag{7}$$

where ε is relative dielectric permeability of the specimen having ISD; ε_0 is relative dielectric permeability of the defectless material.

Also, it is proved that in thew case of ferromagnetic materials, the coefficient of a modification of a velocity of USW propagation in the specimen having ISD, $n = \sqrt{\mu_0/\mu}$, while the real ME value of a ferromagnetic material, from which the IS is manufactured, is equal to [7]:

$$E_0 = \rho_0 v^2 \frac{\mu_0}{\mu}, \tag{8}$$

where μ is relative magnetic permeability of the specimen having ISD; μ_0 is relative magnetic permeability of the defectless material.

Thus, the essence of the offered procedure of defining the real ME value E_0 of the investigated material as well as of a method of raising the ME measurement accuracy based upon it is that simultaneously with measuring the velocity v of USW propagation in the specimen having ISD it is necessary to measure one of the structural - sensitive properties $\chi(S)$. Such a succession of operations permiys to eliminate a methodical error $\delta_{E,M}$ ME measurings and to considerably increase the ME measurement accuracy using the impulsive ultrasonic method.

6. Basic outcomes of the performed studies

The relative error δ_E of the ME measurings of isotropic materials by the offered method is practically determined by an instrumental component $\delta_{E,I}$ and, according to (6), (hereinafter we shall consider only the ME measuring error of conductive materials because the following analysis is also valid for the cases of ME measuring of dielectric and ferromagnetic materials) it is equal to:

$$\delta_E = \delta_{E,I} = \delta_{\rho_0} + 2\delta_v + \delta_{\gamma_0} - \delta_\gamma, \tag{9}$$

where $\delta_{\rho_0}, \delta_v, \delta_{\gamma_0}, \delta_\gamma$ are relative errors of measurings of the quantities $\rho_0, v, \gamma_0, \gamma$.

Let us consider more in detail the limiting values of the component ME measuring error included in the formula (9). The limiting value of the error $\delta_{\rho_0,\max}$ at defining the investigated material density ρ_0 using the most precise pycnometric method is equal to $\pm 10^{-4}$%, and the limiting value of the error of defining the material electrical conductivity γ_0 by modern precise measuring instruments does not exceed $\pm 0{,}01$%. Then, the error δ_E of the ME measuring is practically determined by the errors δ_v and δ_γ of measuring the velocity v and electrical conductivity γ, the limiting values of which $\delta_{v,\max}$ and $\delta_{\gamma,\max}$, as displays the analysis [5, 8], do not exceed, accordingly, $\pm 0{,}1$% and $\pm 0{,}3$%. Thus, the limiting value of the relative error $\delta_{E,\max}$ of the ME measurings by the offered method does not exceed $\pm 0{,}5$%, i.e. in the present case the ME measuring accuracy of isotropic materials increases 5-10 times in comparison with the known analogues.

The above conclusions concerning the impulsive ultrasonic method of ME measuring are also valid for a resonance method, since the velocity v of USW propagation and the oscillation frequency f are interlinked by the wavelength λ, i.e. $v = \lambda f$, and it is easy to proceed from the formula (3) to the formula (1) upon the condition that the length of the investigated specimen $l = \lambda/2$.

Measuring instruments, in which the above surveyed method of ME measuring of isotropic materials is realized, except for the basic ultrasonic channel USC (see fig. 1b) contain an additional channel of correction (CC) for measuring the structural - sensitive property $\chi(S)$ of an IS material and for developing a correcting signal $n(S)$, as well as the multiplying device (MD) for performing a correcting action, i.e. in these measuring instruments there is carried out a self-acting multiplicative correction of a methodical error. The multiplying device MD and the block of evaluation of the module MEE can be united in the specialized computing device SCD, for example, in a personal computer.

Under the block diagram shown in fig. 1b, the instrument for ME measuring of isotropic materials designated by [8], in which simultaneously with measuring the time t of USW propagation along the IS necessary for definiting the velocity v, the measurements of the electrical resistance R of the specimen, necessary in defining its electrical conductivity γ are carried out. The range of ME measuring of the instrument is from 100 to 1000 GPa, and the limits of permissible intrinsic relative error $\delta_{E,\max} = \pm 0{,}5\%$.

7. Conclusions

1. The interior material structure defects (point defects, dislocations, pores) and internal mechanical tensions have a direct effect upon the velocity of USW propagation in a specimen and, hence, on a ME value of the investigated materials, i.e. they cause the increase of a methodical error, which has a prevailing effect on the resulting ME measuring error.
2. To correct the methodical error, it is necessary, simultaneously with the measuring of the velocity v of USW propagation in an investigated specimen to measure one of the structural - sensitive properties $\chi(S)$ (electrical conductivity $\gamma$for conductive materials, relative dielectric permeability ε for dielectrics or relative magnetic permeability μ for ferromagnetics), and the real ME value of the investigated material should bedetermined according to the formulas (6), (7) or (9).

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Tytuł: Analiza sposobów zwiększenia dokładności pomiaru modułu sprężystości materiałów izotropowych metodą dynamiczną

Artykuł recenzowany

RECENZJE

cd. Recenzji ze strony 52

Część 4 - **Systemy pomiarowe (Instrumentation Systems)** - to rozdziały 26-35. Omówiono w nich podstawy konstrukcji przyrządów elektronicznych i mechanicznych, technikę pobierania próbek, telemetrię, wizualizację i rejestrację wyników pomiaru, aparaturę pneumatyczną, niezawodność, kompatybilność i bezpieczeństwo aparatury kontrolno-pomiarowej oraz zarys historyczny rozwoju systemów pomiarowych. Zarys ten obejmuje też najnowsze rozwiązania sprzętu i oprogramowania stosowane w przemysłowych komputerowych sieciach kontrolno-pomiarowych.

Część 5 - **Inne informacje techniczne i naukowe** (rozdziały 36-43) zawiera zwarte opisy: funkcji trygonometrycznych i innych podstawowych zależności matematycznych, zasad statystyki, wielkości i jednostek, podstaw fizycznych elektrotechniki, promieniowania optycznego i jądrowego, budowy przyłączy (connectors) oraz szumów i zakłóceń transmisji.

W **Dodatkach** podano: zaktualizowany zestaw 20 podstawowych książek anglojęzycznych tematycznie związanych z Poradnikiem wraz ze spisem ich treści; wykaz pomiarowych organizacji i stowarzyszeń inżynierskich międzynarodowych, brytyjskich i amerykańskich oraz z kilku innych krajów; a ponadto - szczegółowe informacje o dwu stowarzyszeniach: brytyjskim - Institute of Measurement and Control i amerykańskim - Instrument Society of America.

Treść Poradnika ma bardzo zwarty, praktyczny charakter, a liczba wzorów została zminimalizowana. Objęto w nim niemal cały zakres podstawowych informacji o technice pomiarowej stosowanej w laboratoriach, przemyśle i w eksploatacji. Natomiast nie zawiera on między innymi pomiarów środowiska.

Jest to już trzecie, częściowo zaktualizowane wydanie tego Poradnika opracowanego przez brytyjskich specjalistów wywodzących się głównie z przemysłu oraz z uczelni i placówek badawczych. Poprzednie dwa brytyjskie wydania (1988, 1995), opracowane pod redakcją B.E. Noltingka, są mało znane w Polsce, a cieszyły się tak ogromnym powodzeniem, że były wznawiane (ostatni reprint w 2000 roku). W przedmowie do obecnego, amerykańskiego wydania jego nowy redaktor zaznacza, że jest ono w dużym stopniu oparte na poprzednich edycjach, lecz zostało „umiędzynarodowione". Uwzględniono w treści normy nie tylko brytyjskie, ale też międzynarodowe IEC, amerykańskie ANSI i inne. Wprowadzono też kilka odnośników bibliograficznych do internetowych stron WWW. Rozszerzono listę autorów i zmieniono numerację rozdziałów i stron na jednolitą dla całego tekstu (poprzednio była ona osobna dla każdej części). W wielu rozdziałach są to niestety jedyne zmiany, a ich bibliografia szczegółowa kończy się na pozycjach bądź z 1985, bądź z 1996 roku. Niektóre ilustracje przedstawiają rozwiązania konstrukcyjne też z tamtych lat. Istotnie rozszerzono jedynie treść rozdziałów o pomiarach przepływu, poziomu i ciśnienia. Usunięto zaś, ze szkodą dla treści, występujący w poprzednim wydaniu rozdział „Przetwarzanie sygnałów", jeden z najlepiej tam opracowanych. Natomiast poprzedni rozdział o przyrządach wirtualnych został wchłonięty przez nowy rozdział 34 „Historia systemów instrumentalnych". Usunięto też z nazw dwu rozdziałów przymiotnik „smart", będący amerykańskim synonimem angielskiego - „inteligent", a mający u Brytyjczyków pewien pejoratywny odcień.

Pomimo powyżej podanych mankamentów omawiany Poradnik zawiera w ogromnej większości treść o charakterze podstawowym, aktualną, oraz bardzo przydatną i dziś w praktyce pomiarowej. Rozdziały są na ogół napisane prostym językiem, zrozumiałym również i dla „non native speakers". Forma edycyjna jest też wzorowa, a cena wydaje się być umiarkowana.

Poradnik techniki pomiarowej „Instrumentation Reference Book", wyd. 3 pod redakcją W. Boyesa można z pełną odpowiedzialnością polecić zarówno konstruktorom aparatury pomiarowej jak i wszystkim jej użytkownikom, oraz nauczycielom akademickim i studentom dysponującym pewną minimalną znajomością angielskiego i terminologii pomiarowej w tym języku.

Na zakończenie autor tych słów pragnie serdecznie podziękować kierownictwu A.B.E. Marketing Warszawa i przedstawicielowi Elsevier Science Europe za przekazanie tuż po Targach Książki egzemplarza Poradnika, co umożliwiło tak szybkie opracowanie niniejszej recenzji.

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