Development of Intellectual Tomographic System of Ultrasonic Diagnostics of Materials

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Abstract—**The principles of development an intellectual tomographic system of ultrasonic diagnostics of materials damage on the basis of registration of the backscattered signal are considered. The model of propagation of elastic waves in a scattering medium is given in the form of an inhomogeneous Lame equation with variable coefficients. The procedure of constructing successive approximations to the solution of the considered model in the case of slowly variable parameters is presented. The expression of backscattered tomography is considered. An algorithm for processing of backscattered signal is presented. The results of UML-modeling and intellectual system structure diagram are presented.**

Index Terms—**intellectual system; damage; ultrasonic backscattered sagnal; tomography.**

I. Introduction

An important problem of technical diagnostics is the evaluation of the state of the metal by ultrasonic methods. Despite the fact that ultrasonic methods have been widely used in nondestructive testing [1] and in medicine, for the evaluation of the defect state of the metal [2], damage [3] is used restrictively and mainly in laboratory conditions [4-6]. To solve these problems, the use of a backscattered signal is adequate [7, 8]. The backscattered signal is noisy. In non-destructive testing, it was practically not used and considered an interference ("structural noise" [4]). Some work was known about the use of a backscattered signal to study the structural characteristics of a material [5, 6, 9]. To develop these methods, it is necessary to ensure the possibility of documenting the parameters of the object of control, the state of the metal, the conditions and results of experimental research. Ensuring this possibility is carried out by developing an intellectual system for ultrasonic diagnostics of materials on the basis of registration of a backscattered signal.

II. The Theoretical of Development an Intellectual Tomographic System of Ultrasonic Diagnostics of Materials Damage

A. *Description of material damage due to Rabotnov, evolutionary damage equation*

The degradation of structural materials in the process of exploitation is accompanied by the emergence of micropores, microcracks, their associations up to the occurrence of macrocrack and destruction of the object

For a quantitative description of material damage, Rabotnow proposed a parameter of damage [3]:

$$D = (S_0 - S)/S_0 \ . \quad (1)$$

S_0 - the cross-sectional area of the undamaged material, S - the "effective area" of this section (excluding the total area of damage), $S_0 - S$ - the area of damage.

For undamaged material $D = 0$. As damage grows D goes up to 1. At the time of destruction $D(t = T_{cr}) = 1$.

For the forecast of the resource of trouble-free operation of the product on the basis of the damage, the evolutionary equation of damage is necessary. On the basis of the law of conservation of mass, the evolutionary equation of damage is obtained in the form of a logistic equation [10]:

$$\frac{dD}{dt} = CD(1 - D). \quad (2)$$

Usually for an undamaged material:

$$D_{t=0} = 0 \ . \quad (3)$$

The criterion of destruction is determined with the condition:

$$D(t = T_{cr}) = 1 \ . \quad (4)$$

The solution of equation (2) is the logistic curve:

$$D(t) = \frac{D_0 e^{Ct}}{1 + D_0 \left(e^{Ct} - 1\right)} \ . \quad (5)$$

Calculation of the remaining resource is made on the basis of the determination of the time to reach the specified damage after equation (5).

B. The model of propagation of elastic waves in a scattering medium

The scattering of elastic waves in a solid takes place on separate scatterers, inhomogeneities of elastic properties, density, boundaries of the medium [11].

A model of a scattering medium is considered which includes two types of scatterers: an inhomogeneous distribution of elastic properties and density and separate scatterers (including defects).

For the model of the propagation of elastic waves in a scattering medium, we accept an inhomogeneous Lame equation with variables (in space) coefficients $\lambda(x, y, z)$, $\mu(x, y, z)$, $\rho(x, y, z)$:

$$(\lambda + \mu)\nabla(\nabla \bullet u) + \mu\Delta u - \rho\frac{\partial^2 u}{\partial t^2} = \\ = \sum_{m\in M} A_m \delta(x - x_m)\delta(y - y_m)\delta(z - z_m) f_m(t) \quad (6)$$

The right side takes into account the influence of individual scatterers, depending on the shape of the probing impulse. Variable coefficients take into account inhomogeneity of density, elastic properties of a material.

let's write (6) in the form:

$$L(c(x, y, z))u = \\ = \sum_{m\in M} A_m \delta(x - x_m)\delta(y - y_m)\delta(z - z_m) f_m(t) \quad (7)$$

$L\bullet$ - operator, $c(x, y, z)$ - set of parameters (coefficients).

We present an approach to finding successive approximations to the solution of system (7) in the case of slowly varying coefficients.

In the formed system of equations, we fix the coefficients and call the inhomogeneous system of equations with constant coefficients originative:

$$L(c = const)u = \\ = \sum_{m\in M} A_m \delta(x - x_m)\delta(y - y_m)\delta(z - z_m) f_m(t) \quad (8)$$

We find solutions of the originative system $u = u^0(x, y, z, t, c)$ with different coefficients $c \in [c_{\min}, c_{\max}]$.

$$u^{(0)} = u^0(x, y, z, t, c(x, y, z)) \quad (9)$$

We will look for the solution of the original system (7) in the form:

$$u = u^{(0)} + u_1 \quad (10)$$

We substitute (10) in (7) and obtain:

$$L(c(x, y, z))u_1 = \\ = \sum_{m\in M} A_m \delta(x - x_m)\delta(y - y_m)\delta(z - z_m) f_m(t) - \\ - L(c(x, y, z))u^{(0)} \quad (11)$$

We find solutions of the originative system $u_1 = u_1{}^0(x, y, z, t, c)$ with different coefficients $c \in [c_{\min}, c_{\max}]$ and construct a zero approximation to the solution (11):

$$u_1{}^{(0)} = u_1{}^0(x, y, z, t, c(x, y, z)) \quad (12)$$

For the first approximation to the solution of the original system (2) we will accept:

$$u^{(1)} = u^0(x, y, z, t, c(x, y, z)) + u_1{}^0(x, y, z, t, c(x, y, z)) \quad (13)$$

Similarly, higher approximations are constructed.

We note that constructed serial approximations are the sum of terms proportional to derivatives of slow variable parameters. Such a representation is successful for formulating inverse problems - finding a spatial distribution of medium parameters based on ultrasonic sounding.

C. The expression of backscattered tomography

Let's consider the features of tomographic reconstruction based on the use of spherical projections. In the problems of defectoscopy the nearest diagnostic technology is a method SAFT [12].

Let's consider a thick plate parallel product. We choose a coordinate system by aligning the XOY plane with the surface of the article. The axis of the OZ is directed perpendicular to the plane of the product.

Let $f(x, y, z)$ is a function that describes the spatial distribution of the inhomogeneity.

The data is collected by scanning the product surface with a direct combined ultrasonic transducer and recording the backscattered ultrasonic signal.

We take the point (x_0, y_0) on the surface of the article and calculate the averaged values of the function $f(x, y, z)$ by parts of spheres with center at the point (x_0, y_0) and radius R:

$$p(x_0, y_0, R) = \frac{1}{\Delta V} \\ \iiint_{(V)} f(\tilde{x}, \tilde{y}, \tilde{z})\delta(\sqrt{(\tilde{x} - x_0)^2 + (\tilde{y} - y_0)^2 + \tilde{z}^2} - R)d\tilde{x}d\tilde{y}d\tilde{z} \quad (14)$$

As a result of data collection, we obtain a set of spherical projections (14).

Tomographic reconstruction is carried out by backprojection on parts of spheres

$$g(x,y,z)=\frac{1}{\Delta S}\iint_{(S)} p\left(x_0,y_0,\sqrt{(x-x_0)^2+(y-y_0)^2+z^2}\right)dx_0dy_0 \quad (15)$$

The total image $g(x,y,z)$ is a low-frequency copy of the searched distribution $f(x,y,z)$.

III. An algorithm for processing of backscattered signal

The time implementation of the registered signal in the form of the A-scan [13] contains several sections: a probing impulse, a prism reverb signal, a signal that is reflected from the boundary of the prism-metal, an "informative signal", the first reflection of the bottom signal, etc.

The informative signal is part of the A-scan from the end of the pulse reflected from the boundary of the prism-metal to the beginning of the first reflected bottom signal.

As a informative parameter on the level of scattered damage, the dispersion of the inverse of the scattered signal is used:

$$S_i=\frac{1}{\Delta_t}\sum_{n=i-\frac{\Delta_t}{2}+1}^{n=i+\frac{\Delta_t}{2}}\left(\frac{s_n-s^0}{A}\right)^2 \quad (16)$$

s_n - registered signal sample, s^0 - constant component, A - signal sweep for a given bit ADC, $\Delta_t=Int\left(\frac{\Omega}{\omega}\right)$ - duration of the probing pulse, Ω - sampling rate, ω - carrier frequency.

We note that when a plane-parallel sample is probed by directly separately combined piezoelectric transducer in the case when the reflection coefficient from the "bottom" is near to unity (that is, the large difference in the impedances of the material (metal) being probed and the external medium), then practically the entire energy of the input sounding signal in one cycle (in the time domain from the beginning of the pulse reflected from the prism-metal boundary to the end of the first bottom reflected pulse) returns to the piezo transducer.

We normalize each sample of intensity (16) to this value:

$$S^*_i=\frac{S_i}{\sum_{n=i_0-\Delta/2}^{i_H+\Delta/2}S_n} \quad (17)$$

As a result of the normalization, we obtain the realization of the intensity of the backscattered signal, which has a unit energy taking into account the energy of the reflected bottom signal.

With the help of this procedure, we get out of the influence of the sounding signal level, acoustic contact, amplification of the receiving trakt.

To take into account the influence of attenuation during the propagation it is necessary to additionally adjust each sample:

$$S^{pr*}_i=\frac{S_i}{\sum_{n=i_0-\Delta/2}^{i_H+\Delta/2}S_n\left(1-\frac{\sum_{n=i_0-\Delta/2}^{i-1}S_n}{\sum_{n=i_0-\Delta/2}^{i_H+\Delta/2}S_n}\right)} \quad (18)$$

Δ - duration of the probing radio pulse (contains several periods of the carrier) frequency, i_0 - the sample of the maximum value of the pulse reflected from the boundary of the prism-metal, i_H - sample of the first bottom reflected signal.

As a result, we obtain an estimate of the cross section of the back scattering [14] along the path of propagation of the probing signal.

To estimate the spatial distribution of scattered damage in the material volume, the B-scan is used [13].

The B-scan image can be used to calculate the scattered corruption parameter (1).

IV. UML-modeling and intellectual system structure diagram

The model of the database and knowledge of the intellectual information system of ultrasonic diagnostics of damage of structural materials is developed.

CASE-modeling of an intelligent system was considered (Fig.1).

A. CASE-modeling of an intelligent system

In Fig. 1 is a diagram of classes of the intellectual system is given.

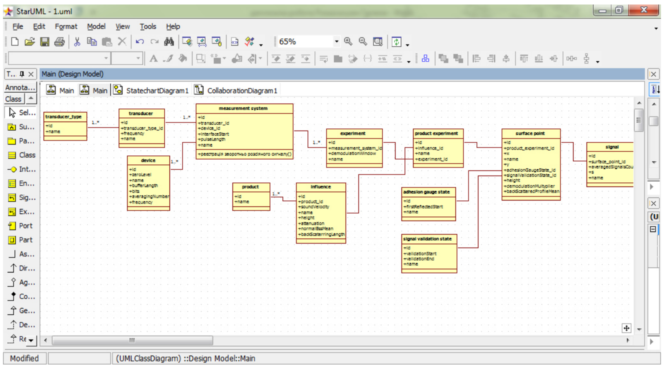

Figure 1. Diagram of classes of the intellectual system

The database and knowledge consists of three main modules: data on the measuring system; a priori data about the object of research, experimental conditions; diagnostic results.

B. Block diagram of the intelligent system

In Fig. 2 the block diagram of the intelligent system is given.

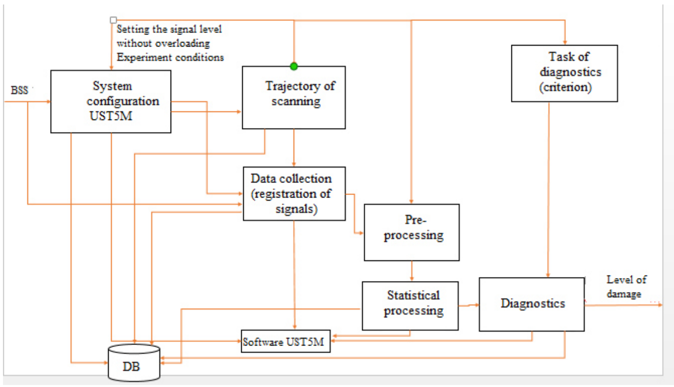

Figure 2. Block diagram of the intelligent system

The intelligent elements of the system include self-adjusting the system by selecting a minimum level of amplification to ensure the correct registration of the backscattered signal with the highest sensitivity to material damage; adaptive evaluation of material damage parameters during scanning in order to identify places with increased damage; forecast of the resource of trouble-free performance of the product on the basis of the logistic equation.

Thus, on the basis of ultrasonic sounding, multiple registration and statistical processing of backscattered ultrasonic signal, the reconstruction of the spatial distribution of the ultrasonic backscattered cross-section in the bulk of the material in the form of a B-scan or tomographic image are detected places of increased damage and determined an experimental evaluation of the parameter of material damage in volume of product that is used to predict the product of the trouble-free performance of the product on the basis of the logistic equation.

V. CONCLUSION

The principles of constructing an intellectual tomographic system of ultrasonic diagnostics of materials damage on the basis of registration of the backscattered signal are stated. The model of the propagation of elastic waves in a scattering medium with two types of scatterers (density and elastic inhomogeneity and discrete scatterers) is considered in the form of a inhomogeneous Lame equation with variable coefficients. The procedure of constructing successive approximations to the solution of the considered model in the case of slowly variable parameters is presented. Consecutive approximations are the sum of members proportional to derivatives of slow variable parameters. Such a representation is convenient for formulating inverse problems - finding a spatial distribution of medium parameters based on ultrasonic sounding. Tomographic relations on the backscattered signal.and an algorithm for processing backscattered signal are considered. The results of UML simulation and structural scheme of intellectual tomographic system are considered.

REFERENCES

[1] J. Krautkrämer, H. Krautkrämer G Ultrasonic Testing of Materials. 4th ed. Berlin: Springer-Verlag, 1990.

[2] V.M. Rodyushkin. From the search for defects to the search for a predefective state // Bulletin of scientific and technological development. - 2009. - №4. - P.51-56 (in Russian).

[3] L.V. Stepanova, S.A. Igonin. Description of the scattered failure: the parameter of Y.Rabotnov's damage: historical information, fundamental results and the current state // Bulletin of the SSU - Natural Science Series. - 2014, No. 3 (114). - P.97-114 (in Russian).

[4] R. Miralles. Material grain noise analysis by using higher-order Statistics // Signal Processing. – 2004. – P. 197-205.

[5] Ville E Kananen. Discriminating pores from inclusions in rolled steel by ultrasonic echo analysis // Meas. Sci. Technol. – 2011, 22. – P. 105704 (7 p.).

[6] V.L. Busov. Scattering of ultrasonic waves on microcracks in fragmented polycrystals // Acoustical Visnik. - 2007, v. **10**, No. 3. - P. 19-24 (in Russian).

[7] A.S. Birring, M.L. Bartlett, K. Kawano. Ultrasonic Detection of Hydrogen Attack in Steels // Corrosion (National Associition of Corrosion Engineers). – 1989 , v. 45, № 3.

[8] I.D. Iofin, V.L. Busov, I.V.Shishkin On the installation of fatigue tests of steel samples using nondestructive acoustic control method // News of Donbass State Power Engineering Academy. - 2008, No. 3E (14). - P. 61-65 (in Russian).

[9] R. Thompson, F.J. Margetan. Use of elastodynamic theories in the stochastic description of the effects of microstructure on ultrasonic flaw and noise signals // Wave Motion. – 2002, 36. – P. 347-365.

[10] A.V. Kashtanov, Yu.V. Petrov. Energy approach to the definition of instantaneous damage // Journal of Technical Physics. - 2006, **76**, issue 5. - P.71-75 (in Russian).

[11] R. Truell, C. Elbaum., B. Chick Ultrasonic Methods in Solid State Physics. New York, London: Academic Press, 1969.

[12] R. Thompson. Transverse and longitudinal resolution of the synthetic aperture focusing technique // Ultrasonics. – 1984, January. – 9-15 p.

[13] I.N. Ermolov, N.P. Aleshin, A.I. Potapov. Nondestructive Testing. Book 2. Acoustic methods of control: practical textbook / Ed. V.V. Sukhorukov. - Moscow: Higher School, 1991. - 283p. (in Russian).

[14] A.Ishimaru. Propagation and scattering of waves in randomly inhomogeneous media. - M.: Mir, 1981.