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METALL MATERIALLARNING SIFATINI ULTRATOVUSH TO‘LQINLARI YORDAMIDA BAHOLASHNING NAZARIY VA AMALIY JIHATLARI

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ТЕОРЕТИЧЕСКИЕ И ПРАКТИЧЕСКИЕ АСПЕКТЫ ОЦЕНКИ КАЧЕСТВА МЕТАЛЛИЧЕСКИХ МАТЕРИАЛОВ С ПОМОЩЬЮ УЛЬТРАЗВУКОВЫХ ВОЛН

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THEORETICAL AND PRACTICAL ASPECTS OF ASSESSING THE QUALITY OF METALLIC MATERIALS USING ULTRASONIC WAVES

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Annotatsiya. Maqolada metal buyumlar va payvand birikmalarida uchraydigan nuqsonlarni buzmasdan aniqlashda ultratovushli nazorat usulining fizik asoslari tahlil qilinadi. Ishning asosini taqdim etilgan o‘quv materiallarida keltirilgan metall nuqsonlarining tasnifi, ultratovush to‘lqinlarining xususiyatlari, piezoelektrik o‘zgartirgichlar, akustik kontakt, to‘lqinlarning aks etishi va so‘nishi, kritik burchaklar hamda aks-impulsli nazoratga oid ma’lumotlar tashkil etadi. Tahlil natijasida ultratovushli nazoratning ichki va sirtga yaqin nuqsonlarni aniqlash, bir tomonlama kirishda ishlash va nazorat natijasini bevosita olish imkoniyatlari tizimlashtirildi. Shu bilan birga, nazorat natijasining ishonchliligiga sirt holati, akustik kontakt, asbobni kalibrlash, nuqson orientatsiyasi va material strukturasining ta’siri ko‘rsatildi.
Kalit so‘zlar: ultratovushli nazorat, buzmasdan nazorat, metall nuqsonlari, ultratovush to‘lqini, piezoelektrik o‘zgartirgich, aks-impulsli usul, akustik kontakt, kritik burchak, so‘nish, aniqlash qobiliyati.

Аннотация. В статье анализируются физические основы ультразвукового контроля, применяемого для неразрушающего выявления дефектов в металлических изделиях и сварных соединениях. Анализ базируется на представленных учебных материалах, охватывающих классификацию дефектов металла, свойства ультразвуковых волн, характеристики пьезоэлектрических преобразователей, вопросы акустического контакта, отражения и затухания волн, критические углы, а также эхо-импульсный метод. Результаты работы систематизируют

возможности ультразвукового контроля в части обнаружения внутренних и подповерхностных дефектов, проведения контроля при одностороннем доступе и получения оперативной информации о результатах проверки. Также рассматривается влияние состояния поверхности, качества акустического контакта, калибровки, ориентации дефектов и структуры материала на достоверность контроля.

Ключевые слова: ультразвуковой контроль, неразрушающий контроль, дефекты металла, ультразвуковая волна, пьезоэлектрический преобразователь, эхо-метод, акустический контакт, критический угол, затухание, разрешающая способность.

Abstract. The paper analyzes the physical foundations of ultrasonic testing for non-destructive detection of defects in metallic products and welded joints. The analysis is based on the provided training material covering metal-defect classification, ultrasonic-wave properties, piezoelectric transducers, acoustic coupling, reflection and attenuation, critical angles, and the pulse-echo method. The results systematize the capabilities of ultrasonic testing for detecting internal and near-surface defects, performing inspection with one-sided access, and obtaining immediate inspection information. The influence of surface condition, acoustic coupling, calibration, defect orientation, and material structure on inspection reliability is also discussed.

Keywords: ultrasonic testing, non-destructive testing, metal defects, ultrasonic wave, piezoelectric transducer, pulse-echo method, acoustic coupling, critical angle, attenuation, resolution.

INTRODUCTION

The service reliability of machines and mechanisms, metal structures, and welded joints is closely associated with the assessment and control of material integrity. In the materials presented, a defect is defined as an individual nonconformity that causes a product to fail to meet the requirements established by relevant regulatory and technical standards. Defects may occur in the form of surface, subsurface, and internal discontinuities [3, 7, 10].

In practice, a range of non-destructive testing methods is employed to detect such defects, including visual, ultrasonic, magnetic particle, penetrant, radiographic, eddy-current, acoustic-emission, and thermal inspection methods. The article demonstrates that ultrasonic testing is based on the reflection and refraction of ultrasonic waves at the interface between two media and is used to detect both surface and internal discontinuities in materials [3, 6, 10].

The aim of this article is to systematically analyze and present the information contained in the source materials on a scientific basis, with particular emphasis on the physical principles of ultrasonic testing, its key parameters, and its practical capabilities for detecting defects in metallic materials.

METHODS

The article provides a systematic overview of the principal non-destructive testing methods, the classification of metal defects, the physical parameters of ultrasonic and elastic waves, acoustic coupling, energy reflection and transmission, attenuation, critical angles, reference standards, piezoelectric transducers, the acoustic path, and the pulse-echo method [1–3, 7].

The study employed methods of content analysis, grouping of physical concepts, and identification of cause-and-effect relationships among the considered phenomena. Initially, information concerning metal defects and their origins was identified and systematized. Subsequently, the available materials related to the main parameters of ultrasonic waves, including frequency, wavelength, propagation velocity, amplitude, and attenuation, were generalized. At the final stage, the relationships among the transducer, acoustic coupling, ultrasonic signal, and defect coordinates were analyzed [1, 2, 7].

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One of the fundamental physical relationships considered in the article is the dependence of wavelength on frequency and wave propagation velocity:

$$\lambda = \frac{c}{f}$$

where λ is the wavelength, c is the wave propagation velocity in the medium, and f is the frequency. This relationship was used to systematize and substantiate the physical principles presented in the article.

RESULTS

Metal defects and the need for their inspection

The article classifies metal defects according to their origin into three main groups: metallurgical, manufacturing and technological, and operational defects. Manufacturing and technological defects are associated with processes such as deformation, surface treatment, rolling, and heat treatment. Operational defects may arise as a result of wear, fatigue, corrosion, and improper use or service conditions.

The schematic diagram illustrates the propagation of an ultrasonic signal generated by a piezoelectric transducer through the metal, its reflection from an internal defect, and the subsequent detection of the reflected signal (Figure 1).

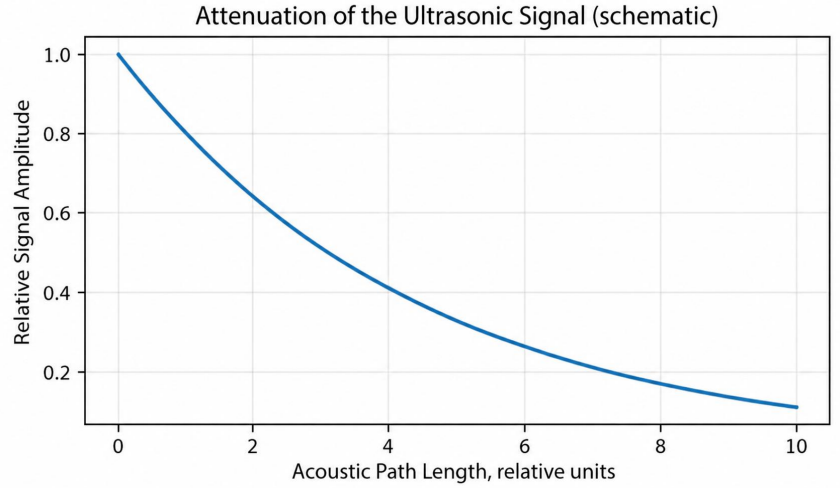

Figure 1. Schematic graph illustrating the attenuation of an ultrasonic signal in a material.

This principle is particularly important when organizing inspection under conditions where access is available from only one side.

Depending on their location, defects are classified as external, surface, subsurface, and internal defects; according to their geometric configuration, they are categorized as point-like, linear, planar, and volumetric defects. Based on their level of severity, defects are classified as critical, significant, and minor.

Such a classification serves as a practical criterion for selecting an appropriate inspection method. In particular, the capability of ultrasonic testing is of considerable importance for detecting internal defects that are not visible to the naked eye.

Key parameters of ultrasonic waves

In the presented material, the frequency range of ultrasonic waves is specified as 20 kHz to 100 MHz. The frequency range of 20 Hz–20 kHz is defined as the audible sound range, frequencies below 20 Hz are classified as infrasound, while frequencies above 100 MHz are referred to as hypersound [1, 2, 7].

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The wavelength is defined as the distance traveled by a wave during one complete cycle and is expressed by the following formula:

$$\lambda=\frac{c}{f}$$

Thus, in a homogeneous medium, an increase in frequency results in a decrease in wavelength. The article distinguishes between longitudinal, transverse, surface, and Lamb waves. For longitudinal waves in steel grade St3, a velocity of 5930 m/s was calculated, while for transverse waves, the corresponding velocity was approximately 3250 m/s (Table 1).

Table 1

The main parameter of ultrasonic testing

Parameter	**Content Stated in the Source**	**Significance in Testing**
Frequency	Ultrasonic frequency range: 20 kHz–100 MHz	Affects wavelength and accuracy
Wave velocity	In St3 steel: longitudinal wave ≈ 5930 m/s; transverse wave ≈ 3250 m/s	Necessary for evaluating the location based on distance and time
Critical angles	27.5° and 57.5°	Related to oblique incidence and the generation of transverse waves
Acoustic coupling	Oil, glycerin, solidol, and other coupling media	Improves energy transmission
Attenuation	Consists of absorption (δ_yut) and scattering (δ_soch) components	Limits the detection distance of the signal
Pulse-echo	One-sided access and recording of the reflected signal	Makes it possible to evaluate the coordinates and characteristics of internal defects

Acoustic Coupling and Energy Reflection

The effective transmission of ultrasonic waves into the test object depends on the acoustic coupling between the transducer and the object. The study shows that, under normal incidence at the steel–air interface, only 0.002% of the energy is transmitted, whereas approximately 12% is transmitted at the water–steel interface and approximately 25% at the organic glass–steel interface [1, 2].

$$E_i=E_t+E_r$$

Here, E_i represents the incident energy, $E_t$represents the transmitted energy, and E_r represents the reflected energy. Based on the energy balance, the transmission coefficient is defined as the ratio of the transmitted energy to the incident energy, while the reflection coefficient is the ratio of the reflected energy to the incident energy. The use of a coupling medium between the transducer and the test object improves ultrasonic wave transmission..

Ultrasonic Attenuation

As a wave propagates through a material, its energy decreases. In the article, attenuation is expressed as the sum of the absorption and scattering coefficients:

$$\delta=\delta_{abs}+\delta_{scat}$$

Here, δ_{abs} - represents the absorption coefficient, δ_{scat} - represents the scattering coefficient, δ – represents the total attenuation coefficient. the sum of the scattering and absorption coefficients. During the absorption process, acoustic energy is converted into heat, whereas during scattering, the energy is dispersed in different directions. Differences in attenuation characteristics are observed in fine-grained and coarse-grained materials [2, 7, 8].

This indicates that the microstructure of the material must also be taken into account in ultrasonic testing. The article identifies the difficulty of inspecting coarse-grained structures as one of the limitations of the method.

Oblique testing and critical angles

When ultrasonic waves are introduced into a test object using an angle-beam transducer, the relationship between the angles of incidence and refraction is of great importance. The article discusses Snell's law, wave transformation, and the generation of longitudinal and transverse waves at the interfaces of solid media [2, 11].

The material specifies the first critical angle as 27.5° and the second critical angle as 57.5°. It is shown that transverse waves can be generated using an angle-beam wedge within the range of 27.5°–57.5° (Figure 2).

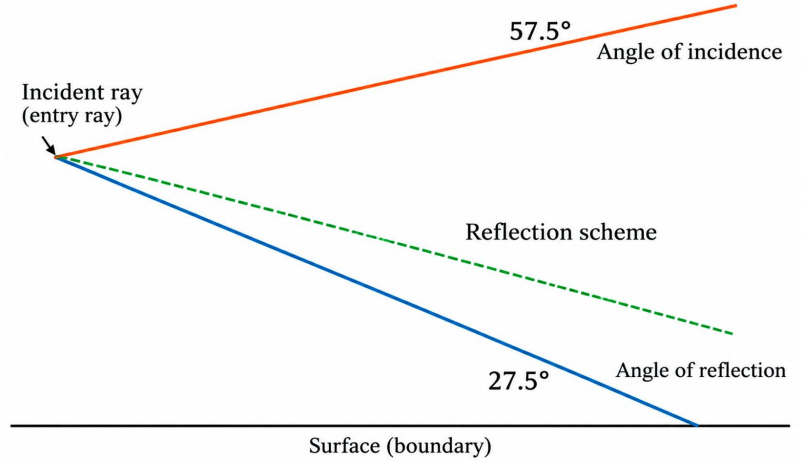

Figure 2. Chematic representation of ultrasonic refraction and critical angles at the interface between media.

Piezoelectric transducer and acoustic path

The piezoelectric transducer is a key component used to generate ultrasonic waves and receive the reflected acoustic signal. The device consists of several components, including a piezoelectric plate, damper, protective layer, induction coil, conductors, housing, cable, wedge, and screen [1, 2, 8].

The division of the acoustic path into near-field and far-field zones is important for understanding the spatial characteristics of the signal. The article indicates that the central beam carries the main acoustic energy, while the intensity is non-uniform in the near field and attenuation occurs relatively uniformly in the far field. The length of the near field depends on the diameter of the piezoelectric element, operating frequency, and wave velocity in the medium.

Pulse-Echo Method

The pulse-echo method is based on detecting reflected ultrasonic pulses to obtain information about defects.

The article demonstrates that the method can be applied with one-sided access and enables the determination of the size, coordinates, and characteristics of a defect (Figure 3).

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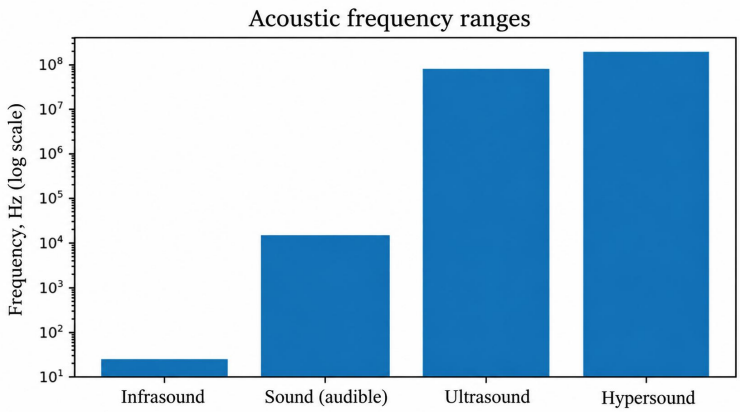

Figure 3. Diagram of the frequency ranges of ultrasound and other acoustic ranges on a logarithmic scale.

On the inspection screen, the initial pulse, back-wall echo, and defect echo are distinguished. The temporal positions and amplitudes of signals received from defects located at different depths and orientations vary. Therefore, the arrival time of the signal is used to estimate the location of a defect, while the signal parameters are used to characterize the defect [1, 3, 4, 7, 11].

Resolution is defined as the ability to detect two closely spaced defects as separate indications. The article shows that a short pulse provides better resolution, whereas a long pulse results in poorer resolution. This characteristic is particularly important for the inspection of welded joints, especially when testing is performed from one side (Table 2).

Table 2

Advantages and limitations of the method

Criterion	Advantages	Disadvantages
Internal defects	Ability to detect internal planar defects	Signal interpretation can be difficult
Accessibility	Can be used with one-sided access	A special transducer is required for certain geometrical shapes
Speed	Results are obtained during the inspection process	Regular calibration is required
Material	Can be used on metal and non-metal materials	Inspection becomes more difficult in coarse-grained materials
Surface	Internal defects can be inspected from the outside	Surface preparation is required

DISCUSSION

The results demonstrate that ultrasonic testing should not be regarded merely as a simple process of monitoring reflected signals, but rather as an integrated physical and engineering system encompassing the generation of ultrasonic waves, their propagation through the material, reflection and refraction at interfaces, attenuation, and subsequent conversion into an electrical signal by the transducer [1–3, 7, 11].

The relationship between frequency and wavelength is of critical importance for understanding the spatial resolution of ultrasonic testing. However, increasing the frequency cannot be regarded as a universally optimal solution for all materials, since high-frequency waves are subject to scattering and absorption associated with the material's microstructure. The discussion of attenuation in coarse-grained materials presented in the article clearly illustrates this limitation [1, 2, 7].

Another important aspect of ultrasonic testing is the orientation of defects. The orientation of a planar defect relative to the ultrasonic beam can significantly affect the detectability and amplitude of the reflected signal. Therefore, the use of angle-beam transducers and scanning from different directions contributes to improving the completeness and reliability of inspection. The article specifically addresses angle-beam transducers and the range of critical angles.

Calibration is also an integral part of the ultrasonic testing procedure. The article describes procedures involving SO-1, SO-2, and SO-3 standard reference blocks for determining the transducer exit point, wedge delay, depth, surface and beam-path distances, refracted angle, and sensitivity [2, 11].

Thus, the reliability of ultrasonic testing results depends not only on the performance of the flaw detector itself, but also on a combination of factors, including transducer selection, operating frequency, acoustic coupling, material microstructure, defect orientation, calibration accuracy, and the operator's ability to correctly interpret the detected signals..

CONCLUSION

Based on a systematic analysis of the presented materials, it has been established that ultrasonic testing is a physical non-destructive testing method that enables the detection of internal and near-surface defects in metal products and welded joints without causing damage to the tested components. The essence of the method lies in the propagation of ultrasonic waves through the material and the detection of reflected signals generated when these waves encounter a defect or another acoustic interface [1–3, 7, 11].

The practical effectiveness of ultrasonic testing depends on the combined influence of such factors as frequency, wavelength, propagation velocity, attenuation, acoustic coupling, transducer type, critical angles, and signal duration. The pulse-echo method is of particular practical significance because it enables inspection with access from only one side of the test object.

At the same time, proper surface preparation, instrument calibration, consideration of the influence of material structure on the ultrasonic signal, and accurate interpretation of reflected signals are essential for obtaining reliable inspection results. Since the presented article does not provide actual experimental results, numerical indicators of experimental effectiveness were not included in this study. In future research, validating the theoretical conclusions through measurements on real test specimens would enhance the practical significance and applicability of research in this field.

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