Influence of Microstructure on Reference Target on Ultrasonic Backscattering

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Abstract

This paper is based on our comments and proposed amendments to the documents, Annex A, Phantom for determining Maximum Depth of Penetration, and Annex B, Local Dynamic Range Using Acoustical Test Objects 87/400/CDV. IEC 61391-2 Ed. 1.0 200X, prepared by IEC technical Committee 87; Ultrasonics. The documents are concerned with the influence of microstructure of reference target material on the ultrasonic backscattering. Previous works on the attenuation due to backreflection and backscattering of reference target materials are reviewed. The drawback to the use of ungraded stainless steel and metallic materials without microstructural data such as, crystal structure, basic acoustic data of sound velocity and attenuation, grain size, roughness and elastic constants has been discussed. The analysis suggested that the insightful conclusion can be made by differentiating the influence arising from target size and microstructure on the backscattering measurements. The microstructural parameters are associated with physical, geometrical, acoustical and mechanical origins of variation with frequency. Further clarification of such a diverse source mechanisms for ultrasonic backscattering would make the target material and its application for medical diagnosis and therapy simpler and more reliable.

Keywords: *Ultrasonic backscattering, Reference target, Microstructare, Backreflection loss, Backscattering crosssection.*

I. Ultrasonic reflection and backs cattering

When a sound wave encounters the material having a different acoustic impedance, a part of sound wave is reflected back to an echo, the rest is absorbed and transmitted. The greater the difference between the impedance of ambient and that of the material, the greater the echo results. The echo from a flat surface after travelling in the direction of the in-cident makes equal angles with the line perpen-dicular to the reflection surface by the law of the specular reflection. However, when the wave is incident on a microscopically rough and nonuniform surfaces, the reflection is in a broad range of directions by scattering and deviates from the specular reflection, called diffuse reflection or back-scattering. The magnitude and mechanism of the scattering loss are dependent on the relationship of wavelength to the dimensions of scatterer.

Surface roughness, nonuniformity of microstru-cture of metallurgical and mechanical inhomogeneity and heterogeneity cause wave scattering in which crystalline defects, grain boundary, height variation and cells in organism act as scatterer. Scattering coefficient, α_s, varies with wavelength relative to the scatter diameter and can be distinguished with

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different behavior of the scattering coefficient in three ranges as follows.

1. Rayleigh scattering region, $\alpha_s \propto D^3 f^4$, where $\lambda \gg D$
2. Stochastic scattering region, $\alpha_s \propto D f^2$, where $\lambda = D$
3. Diffusion scattering region, $\alpha_s \propto 1/D$ where $\lambda \ll D$

where λ is the wavelength, D is the size of the scatterer and f is the frequency. The wavelength boundary is not sharply defined and the transition between the region is known to be gradual. [1]

Ultrasonic reflection or backscattering method of diagnostic assessment of tissue and bone has a number of advantages over X-ray absorption method, such as sensitive change in density and microstructure, and easy adaptability for diagnostic ultrasonic imaging beside it being non-ionizing exposure. The diagnostic images are produced by scanning tissue boundaries and backscattering. Image quality depends on the reliability of the ultrasonic system and microstructure of reference target in a scanning area. Currently, the works on the estimation of size and distribution of scatterer from the backscattering coefficient measurement for diagnostic applications are progressing actively to differentiate abnormal microstructure from a normal one [2,3]

The comparison of the parameters like the maximum depth of penetration and the local dynamic range with results and values obtained from the use of the recommended methods and target provides criteria for the assessments of the system performance in operation. Manufacturers of the ultrasonic imaging system use the reference target to improve the quality of their system and users check its performance according to the relevant standards. Although, requirements for the reference target are not specified in the standard regarding physico-chemical properties including specific attenuation coefficient, the routine performance testing and calibration of the ultrasonic system are carried out with arbitrary target object of various construction yet to be specified.

Various methods of performance testing are proposed by AIUM (1991) [4], AIUM (1995) [5], IEC 60854 (1986, 1993) [6], and IEC 61390 (1996) [7]. However, quantitative evaluations of scattering received with little attention, as evidenced by the intermittent sponsoring of interlaboratory comparison of ultrasonic backscattering coefficient measurement, and attenuation and velocity measurements. [8]

Present work is based on our comments and proposed amendments of the document 87/400/CDV, Project Number IEC 61391-2, Ed 1.0. Circulation date 2008-10-31, concerning the influence of microstructure of reference target material on the ultrasonic backscattering. The convener and reviewer accepted our proposal related to Annex A [9], "Phantom for Determining Maximum Depth of Penetration" and Annex B [10] "Local Dynamic Range Using Acoustical Test Objects" IEC 61391-2 Ed. 1.0 IEC 200x prepared by IEC technical committee 87: Ultrasonics.

II. Influence of target geometry and comparison

The suitability of various material composition and geometry has been studied for an ideal reference target. Hefner and Goldstein (1981) [11] studied backreflection of thin steel wire target for assessing axial and lateral resolution and calibration of distances. They found inadequacies in detecting angular dependence of backscattered intensity for the wire sample. The spherical ball of stainless mounted on the end of a thin rod was used as a target by Ide (1976, 1980) [12, 13] and Chivers and Anson (1982) [14]. However, the target of spherical ball will not be dealt in the present work because of complex variation of backreflection with frequency. The cylindrical rod of absorbing plastic material with a hemisphere and a small cylindrical diameter rod made of stainless steel, tungsten carbide also studied and will be reviewed in the proceeding section.

III. Requirements for ideal target of ultrasonic backreflection

The IEC 1206 (1993) specified following requirements for the ideal reference target of backscattering [15]

1. A plane wave reflection loss in the range 40 dB – 60 dB
2. A plane wave reflection loss that has minimum variation with frequency, any variation being low and smooth over the frequency range of interest.
3. Minimum variation of plane wave reflection loss with angle of incidence.
4. Capable of being supported and mounted in manner, which minimizes problems of spurious reflection from any parts associated with the support of mounting structure of target.

IV. Backreflection loss of reference target

A comprehensive study was made on the frequency dependence of ultrasonic backreflection loss to establish the criterion for ideal target by Preston and Bond (1997) [16]. The material included various prospective materials, such as stainless steel (unspecified grade), PTFE (polytetrafluoroethylene), polycarbonate and tungsten carbide. Geometries included various diameters of spherical ball mounted on rod and flat-ended cylindrical rod soldered onto the rod. Reflection loss, $R(f,r,\theta)$, was calculated by the ratio of the incident and reflected wave amplitudes. [15]

$$R(f,r,\theta) - 20\log_{10}\left|\frac{p_0(f)}{p_r(f,r,\theta)}\right| \quad (1)$$

where $p_0(f)$ is the acoustic pressure amplitude of the incident wave of frequency f at the position of the target r, $p_r(f,r,\theta)$ is the acoustic pressure amplitude of the in the reflected wave at an angle θ.

$$p_r(f,r,\theta) = \frac{1}{2}p_0(f)\frac{ka^2}{r} \times \cos\theta\left(\frac{Z_w\cos\theta - Z_u\cos\phi}{Z_w\cos\theta + Z_u\cos\phi}\right)\left[\frac{2J_1(ka\sin\theta)}{ka\sin\theta}\right] \quad (2)$$

where a is the radius of a flat-ended rod, J_1 is the Bessel function of the first kind, k is the wave number ($k=2\pi/\lambda$), Z_w and Z_u are the characteristic acoustic impedances of water and target material, respectively. θ is the angle between the reflected beam and the target, ϕ is the angle between the normal to the target surface and the beam entering the target.

The figure 3 in the reference [16] shows the backreflection losses of two spherical ball targets mounted on the stainless steel rod of diameter 2.0 mm for θ = 180° and ϕ = 0°, but differ in the way the ball and rod meet. Ball C is the spherical right

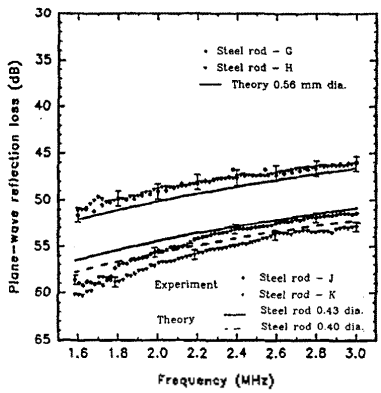

Fig. 1. Plane wave reflection loss for stainless steel cylindrical rods G and H with a diameter of 0.56 mm, J and K with diameters of 0.43 mm and 0.40 mm, respectively. Theoretical results are also shown. Adopted and reconstructed from Preston and Bond (1997) [16].

up to the rod whilst for ball D the rod is flared out to meet the ball. Although the authors claimed that two results follows a similar pattern of reflection loss within ± 3 dB difference, the variation of reflection loss with frequency is complex and fluctuating, no accountable reasons can be found.

The backreflection loss for two cylindrical rods of stainless steel having 0.4 mm diameter J and K measured at θ = 180° and ϕ = 0° (figure 7 in the reference [16]) connected to flat−ended rods and those for cylindrical rod diameter having 0.5 mm diameter with same geometry of connection G and H having same angular alignment (figure 6 in the reference [16]) are shown in Fig. 1. Theoretical predictions of Eq. 2 are also included to see the reproducibility of the measurement and effects of target diameter on the backreflection loss. The size dependence can be accounted by the larger a^2 in $p_r(f,r,\theta)$ of Eq. 2, yielding to the less reflection loss $R(f,r,\theta)$ for the larger diameter.

The backreflection loss of 0.4 mm diameter decreased with frequency from 61 dB ~ 59 dB at 1.6 MHz to 52 dB ~ 53 dB at 3 MHz with a smooth variation of about 2 dB at all frequencies. The backreflection loss of 0.56 mm diameter decreased from 51 dB at 1.6 MHz to 46 dB at 3 MHz, indicating the reflection loss of larger diameter 0.5 mm is less than those of 0.4 mm diameter. The results can be accounted for by the a^2 term involved in $p_r(f,r,\theta)$ of Eq. 2, leading to reduced reflection loss $R(f,r,\theta)$ in Eq. 1 for greater diameter. The results also suggest that cylindrical target of stainless steel is reproducible and meet the requirements specified in the IEC 1266 (1995) [15] for ideal target.

The figure 8 in the reference [16] shows the backreflection loss with frequency for cylindrical rod of tungsten carbide with flat−ended connection of the diameter 0.595 mm, 0.5 mm and 0.41 mm, respectively, with their respective theoretical predictions.

The agreements between measurements and theoretical prediction are within ± 0.1 dB with a smooth variation with frequency, even better than those of stainless steel target in respect of reproducibility.

Backreflection loss at θ = 180° alone is not sufficient to describe the full characteristics, hence further information required to evaluate influence of geometry, material density and distribution of scatterer can be attained by angular dependence of reflection loss. The figure 11 in the reference [16] shows the variation of reflection loss with angle at 2 MHz for the stainless steel rod of 0.56 mm diameter, showing a wider angular variation of reflection loss than that for the off axis of θ > ± 10° required for 1 dB difference from its value at on axis θ = 0°. However, a much narrower profile of angular dependence (figure 12 in the reference [16]) was observed for PTFE of a smaller diameter of 2 mm than the diameter of the same connecting rod, three times more sensitive than that for the stainless steel.

V. Comments on the work by Preston and Bond (1997)

Reflection loss with frequency was measured in the frequency range 1.6 MHz to 3.0 MHz to establish a criteria for ideal reference targets for spherical ball, hemispherical rods and flat−ended rods made of stainless steel, PTFE, polycarbonate and tungsten carbide. The variation of reflection loss was greatest in the case of spherical ball targets and least for flat−ended targets. They are in favour of tungsten carbide targets of a long rod with a diameter of 1.6 mm tapered down to a cylindrical flat−ended with a diameter of 0.4 mm, 0.5 mm and 0.6 mm to provide the best performance; a smooth variation of reflection loss between 60 dB and 40 dB with frequency and an angular variation of < 1 dB at 10° off axis. Thus, they considered tungsten carbide target to be an ideal target to meet the requirements of IEC 1266 (1995). Furthermore, tungsten carbide (WC) contains equal amount of tungsten and carbon atoms, without involving complexity and obscurity caused by a generic term like stainless steel. However, the influence of the size and number of grains on the sample surface of tungsten carbide, surface roughness, wave number and beam diameter are not considered on the backreflection loss measurements. These variables are not expected to be the same for the tungsten carbide of different diameters.

3.1. Types and grade number of stainless steel

Both Preston and Bond (1997) and Lubbers and Graaff (2006) tested "stainless steel" for a prospective target material without specifying grade number in their work. However, a stainless steel is not a single specific material, a generic term for various grades of steel that contain Cr < 30 % and Fe > 50 % with other varying addition of alloying elements with low carbon contents to improve corrosion resistance and physico-chemical properties. Stainless steel is graded on the basis of its metallurgical composition, microstructure and property that they display. There are about 150 different grades of stainless steel of a good availability with wide range of choice. Therefore, stainless steel without specifying grade number is an obscure expression and inappropriate, concealing metallurgical microstructure, regarding composition, property and crystal structure. The most commonly used grading is the SAE (Society of Automotive Engineering) designated by the Series Numbers of Types. Sometimes, the constitutive ratio of stainless steel is specified directly.

1. Authentic stainless steel, Series 100-300.
   Low carbon content and non-magnetic, comprises over 70 % of total stainless steel production. Type 304 or 18/8 (18 % Cr and 8 % Ni) is most common grade.
2. Martensitic stainless steel, Series 400.
   Cr (15.5 % - 17 %) - Fe alloy, hardenable by heat treatment, but are brittle and difficult to form, magnetic. Type 420 is a typical one.
3. Ferritic stainless steel, Type 430
   Cr (10.5 % - 27 %) - Fe alloy and very little nickle, less expensive, but reduced corrosion resistance and magnetic. Type 439 is a typical one.

VI. Backscattering cross-section of target material

Analyses of backscattered signals are known to provide the information regarding microstructure of tissue and bone, such as inhomogeneities of scatterers [17, 18]. Backscattering coefficient is defined as the differential cross-section for 180° scattering from a volume of the sample normalized to that volume. Lubbers and Graaff (2006) [19] investigated the differential scattering cross-section, σ, which is proportional to the square of the sound pressure, expressed by the backscattered cross-section per unit space angle, as a measure of target performance,

$$\sigma = r^2 \frac{p_s^2(r,f,\theta)}{p_0^2} \tag{3}$$

where r is the distance to target in the far field, $r > D^2/4\lambda$, p_0 is the incident sound amplitude on the target of frequency f and p_s is the scattered amplitude at r in a direction with angle θ with the normal to the flat target surface.

$$\sigma = \frac{k^2 D^4}{64}\left(\frac{Z_m \cos\theta - Z_w \cos\phi}{Z_m \cos\theta + Z_w \cos\phi}\right)^2 \left[\frac{2J_1(kD\sin\theta)}{kD\sin\theta}\right]^2 \tag{4}$$

k is wave number, D is the target size, Z_m and Z_w are the acoustic impedances of target and water, respectively. θ is the angle between the axis of target cylinder and direction of incoming beam. The dB value of the backscattered cross-section per unit area, σ_{dB}, was calculated by considering amplifier gain and various loss mechanism of incomplete reflection at the reflector, beam width effect and attenuation in water.

The target had a normal diameter ranging from 0.05 to 3.2 mm; two target sizes of 3.2 mm and 1.6 mm machined from stainless steel rod of unspecified grade. The sizes 0.8 to 0.1 mm were from spring steel of again not specified grade. The smallest size 0.05 mm was a wire of Karma alloy of 20 % Cr in Ni.

The σ_{dB} relative to unit area for the flat ended target diameter at 2.4 MHz, 4.8 MHz and 9.6 MHz with respective theoretical predictions for $\theta = 0$ are shown in the figure 5 in the reference [19]. Consistency of the measurements and results can not be checked as they are, since the values of λ, velocities and densities for various sample species with different diameters are not accessible, $k^2 = (2\pi/\lambda)^2 = (2\pi f/v)^2$, where $v = \sqrt{Y/\rho}$.

The figure 9 in the reference [19] shows diameter dependence of the backscattering cross section on the flat ended wire sample of various diameters at 2.4 MHz, and compared with theoretical diameter dependence of D^4 and D^6.

In their model of the backscattering cross section arising from the cross-sectional diameter D^4 and squared frequency dependence, f^2, are considered, not the scattering arising from microstructural inhomogeneity (size and distribution of scatterers), roughness and grain boundaries. The results are rather fortuitous not to notice the difference between D^4 and D^6 plots. Since the authors did not give the velocities of these materials tested by unexplained reasons. The wavelengths of target materials tested of unspecified stainless steel, spring steel and Karma alloy can not be determined.

The figure 7 in the reference [19] is the backscattering at 4.8 MHz with respective to the backscattering at $\theta = 0°$ as a function of the angle of the target axis with the direction. Data include those of four targets diameters of 1.595 mm, 0.387 mm, 0.237 mm and 0.096 mm. The σ_{dB} of the largest diameter, 1.595 mm designated by the open diameter, decreased sharply with the angle of incidence θ and sharpness of σ_{dB} decreased markedly as the target size decreased. Diffraction dependency may account for the behavior, however, no account or elucidation is given by the authors.

VII. Comment to the work by Lubbers and Graaff (2006).

Differential backscattering cross-section, σ, proportional to the intensity of the reflected sound pressure by squaring of the sound pressure was studied for variety of flat ended prospective reference target materials over the frequency range 2 MHz to 10 MHz. The testing target materials included unspecified grade of stainless steel and spring steel, and Karma alloy (20 % Cr in Ni) of cylindrical target with different diameters ranging 0.05 mm to 3.2 mm. The informations regarding acoustic and materials variables, such as beam diameter and sound velocities of target materials, grain size and roughness of the flat-end sample, are not provided in this work [19]. Backscattering of ultrasound depends on the ratio of the wavelength and obstacle size, however it is impossible to have the wavelength without wave speed. Therefore, the frequency dependent scattering region can not be identified. These drawbacks make the authors could not differentiate the roles of target size and microstructure in the backscattering mechanism by overlooking the degree of metallurgical and mechanical heterogeneity and non-uniformity.

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