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Nondestructive tests of cylindrical steel samples using the ultrasonic projection method and the ultrasound transmission tomography method

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The paper presents some methods of NDT of cylindrical steel samples by means of ultrasonic projection (UP) method and ultrasound transmission tomography (UTT) method. Some ways of scanning were proposed, using different measurement geometries and rendering possible the characterization and visualization of the inner structure of steel samples by projection and tomographic images of measured acoustic parameters.

The measurements proposed in the paper allow us to obtain at the same time the distributions of mean values of a number of acoustic parameters characterizing the structure of samples: the mean amplitude of the ultrasonic wave after running through the sample, the mean runtime on the transmitter-receiver path, and the mean decrease of the ultrasonic wave frequency after running through the sample. These parameters measured in the tomographic scanning setup from many directions around the samples allow us to reconstruct the distributions of the local values of acoustic parameters such as respectively: the ultrasonic wave attenuation coefficient, the group velocity of the ultrasonic wave, the derivative of attenuation coefficient along the frequency. The reconstructed distributions of the local values of acoustic parameters render possible the imaging of the samples' internal structure cross-sections, each of the parameters characterizing different features of the structure.

1 Introduction

By definition based on solid geometry, projection is a transformation, which allows mapping objects in a model with less degrees of freedom (e.g. three dimensional solids on a two dimensional plane). Parallel projection is one of the classes of projection algorithms. In parallel projection (Fig.1a) straight lines are kept parallel, segment length proportions and size relations of plane figures parallel to projection plane are maintained and all projection straight lines go in the same direction. Particular projections, in which the direction of projection lines is perpendicular to the projection plane, are called orthogonal (perpendicular) projections. In case of function values projections (Fig.1b) every single projection can be defined as an integral [1]:

$$F_L = \int_L f(s) ds, \quad (1)$$

where f is a function specified on plane s , and L indicates every straight line belonging to this plane. Line L on the plane can be defined using two numbers: $p \in \mathbb{R}$ and $\psi \in (0;2\pi]$. In that case:

$$L_{p,\psi} = \{(x, y) : x \cos \psi + y \sin \psi = p\}. \quad (2)$$

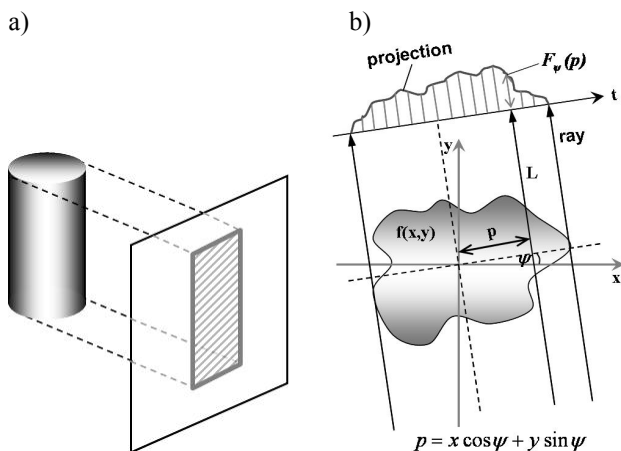


Fig.1. Figure represents: a) geometric orthogonal projection of a cylinder, b) function parallel projection on a plane.

In case of function f specified on a plane, the set of its projections along an infinite number of lines $L_{p,\psi}$ is known as the Radon transform [1]:

$$R\{f(p,\psi)\} = \int_{L_{p,\psi}} f(x,y) ds. \quad (3)$$

The Radon transform is used in various diagnostic methods, e.g. rontgenography, in which the examined structure is x-rayed, and the radiation intensity differences resulting from diversified absorption capabilities are registered on a photographic film or a luminescent screen. Similarly, projection method can be used with ultrasonic waves, where in case of a source generating a flat ultrasonic wave (parallel beam rays) a parallel projection image will be obtained [2, 3]. The projected function in the examined structure section may for example be a distribution of local sound velocity values. Projection of sound velocity c_p on the l - path of the ultrasonic wave ray going through heterogeneous structure can be determined as:

$$c_p = \frac{l}{t_p}, \quad (4)$$

where t_p indicates transit time [2]. If the projection measurements of the distribution of the examined structure section's specified acoustic parameter are performed from a number of directions around, it will be possible to reconstruct the distribution of local values of this parameter in the whole section by determining inverse Radon transform (ultrasonic tomography) [4].

In this work ultrasonic projection method [2, 3] and ultrasound transmission tomography [5] were used for non-destructive examination of cylindrical steel samples. This method can for example be used to evaluate steel hardness and hardening degree.

2 Methods of sample scanning

The easiest method of scanning of cylindrical steel samples with the use of ultrasonic projection is through adjoined movement of a pair of ultrasonic probes (transmitting and receiving) along a chosen cross-section of the sample (Fig.2). In order to ensure proper acoustic coupling between the probes and the studied sample, the measurement should be performed in a tank filled with clear degassed water or oil. In this measurement arrangement, for each position of the probes during movement, a pulse of the ultrasonic wave transmitted by the sending probe is registered by the receiving probe after it travels over a constant distance between the two probes. The pulse registration allows measurement of projection values of a number of acoustic

parameters, characterising various structure qualities, at the same time. These can include average sound velocity calculated from the measurement of the pulse transit time, ultrasonic wave attenuation coefficient calculated from the measurement of pulse amplitude, frequency derivative of attenuation coefficient calculated from decrease of mid frequency of the pulse [6, 7].

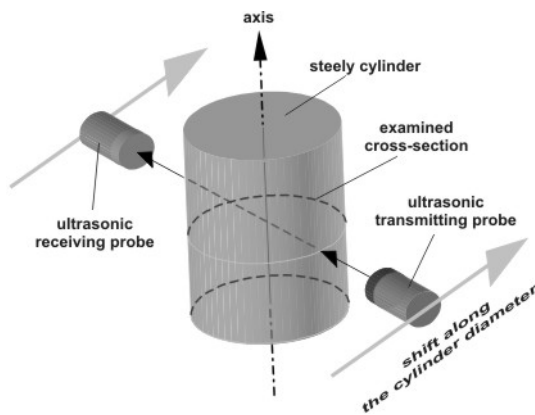


Fig.2. Method of scanning of a cylindrical steel sample with the use of ultrasonic projection.

The use of tomographic scanning in the study of cylindrical steel samples can be realised by the parallel ray projection geometry [4, 6] (Fig.3).

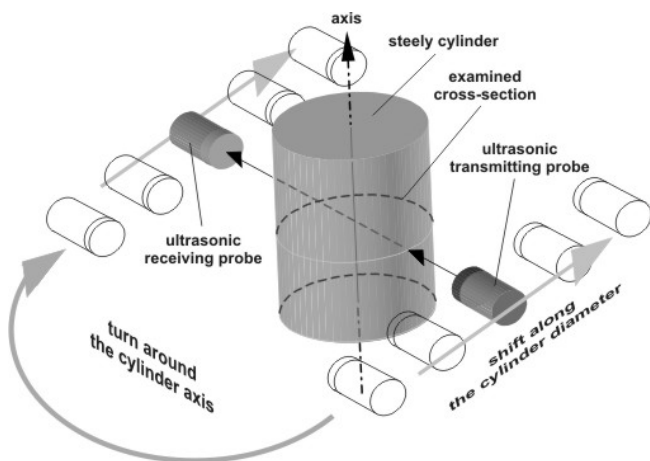


Fig.3. Method of scanning of a cylindrical steel sample with the use of ultrasound transmission tomography.

Similarly to projection method, a pair of ultrasonic probes moves along the cylinder diameter for a chosen section; each time the movement is completed the probes or the cylinder rotate, around the symmetry axis of the cylinder, a predetermined angle $\Delta\varphi = \pi/N$, where N denotes the total number of angle steps in range $[0; \pi)$.

3 Simulation

In the scanning arrangement shown in Fig.2 a simulation was performed of average values (projection) of ultrasonic wave propagation velocity c_p determined after transition through a steel cylinder (diameter $d = 27$ mm) submerged in water. It was assumed that the source and receiver of the ultrasonic wave, the distance between them $l = 100$ mm, are point-size, the source generates an infinitely narrow beam and ultrasonic wave penetrates the structures along a

straight line (no refraction or diffraction). The simulation was performed for temperature $t = 20$ °C, ultrasound velocity in water $c_w = 1482.38$ m/s, ultrasound velocity for longitudinal wave in steel $c_s = 6000$ m/s. The results of the simulation are shown in Fig.4.

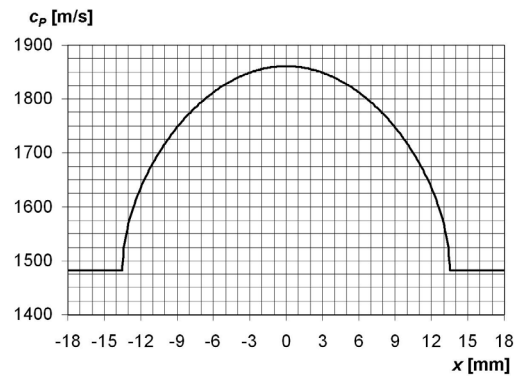


Fig.4. Results of projection calculations of ultrasonic wave propagation velocity for a section of a cylindrical steel sample submerged in water.

The calculations were based on the following formula:

$$c_p = \frac{l \cdot c_w \cdot c_s}{c_s \cdot (l - 2\sqrt{d^2/4 - x^2}) + 2c_w \sqrt{d^2/4 - x^2}}, \quad (5)$$

where $-x_o \leq x \leq x_o$ denotes movement position of the source and receiver along the cylinder diameter in Cartesian coordinate system XOY , whereat outside $(-d/2; d/2)$ range the projection value $c_p = c_w$. Projection measurements allow easy reconstruction of sound velocity in steel cylinder, by means of a suitably modified formula (5).

Fig.5 shows the calculation results for a set of tomographic projection measurements of ultrasound velocity in the parallel ray projection geometry (Fig.3) for a section of cylindrical steel sample submerged in water.

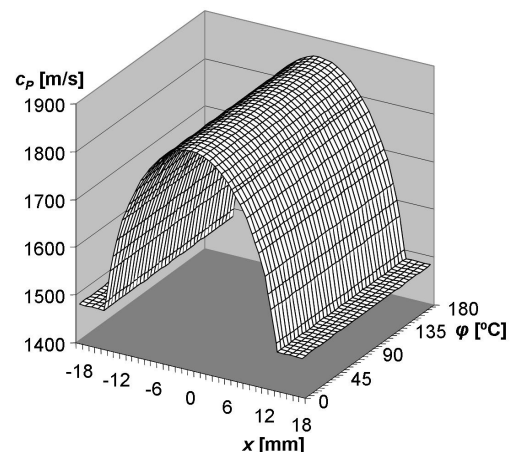


Fig.5. Calculation results for a set of tomographic projection measurements of ultrasound velocity for a section of cylindrical steel sample submerged in water.

The parameters of the tomographic simulation were the same as in case of a single projection (Fig.4). With regard to the assumed homogeneity and axial symmetry of the sample located in the axis of rotation the set of projection values for each rotation angle is the same. On the basis of the simulated tomographic data set, reconstruction of distribution image of local values of ultrasound velocity in

cylindrical steel sample section was performed by means of convolution and back-projection algorithm with the use of universal Ram-Lak convolution function with kernel equalling $E = 1$ [4] (Fig.6).

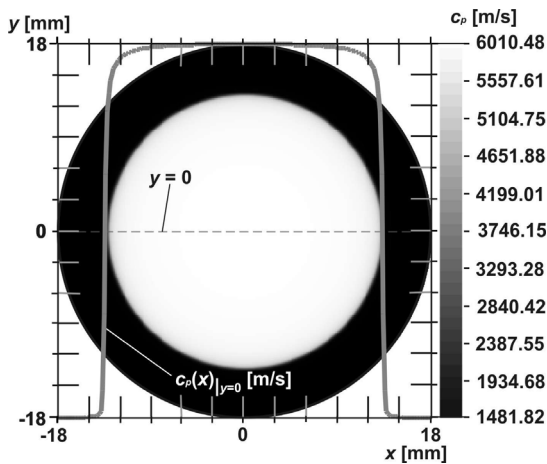


Fig.6. Gray scale tomographic distribution image of local values of ultrasound velocity in a steel cylinder cross-section (XY), reconstructed on the basis of simulated measurement data in the parallel ray projection geometry.

The reconstruction was done on the basis of $M = 239$ rays (number of simulated values for every single projection – Fig.4), $N = 256$ projections (number of rotation angles in the range of $0 - 180^\circ$), on a 239×239 pixel grid. Tomographic imaging is a quantitative imaging, which means that every pixel of an image represents a reconstructed local value of an acoustic parameter measured in the projection. Fig.6 additionally presents a graph of image pixel values $c_p(x)$ for section line, the coordinate of which is $y = 0$ (along the cylinder diameter). An error associated with the reconstruction process of such a wide range of ultrasound velocity values (water \div steel) results in the values near the cylinder edge being underrated (smoothing), and the maximum value in the axis is overrated (Fig.6).

4 Measurements

In order to analyse the possibilities of using ultrasonic projection and ultrasound transmission tomography in non-destructive examination of cylindrical steel samples measurements were performed (of a chosen section) of steel cylinder shaped drive shafts, some of which were hardened (Fig.7). The measurements were performed in laboratory conditions described in the paper [8] with the use of a pair of ultrasonic probes (transmitting and receiving), which had 5 mm diameter, 5 MHz operating frequency and were moved in $150 \mu\text{m}$ step along a cross-section of the studied drive shafts submerged in water, the temperature of which was 22°C . For each position of the probe pair average value of ultrasound velocity c_p on water – object – water path was measured by means of digital determination of the ultrasonic pulse transit time with uncertainty of 5 ns [5]. The results of projection measurements (Fig.2) of a section of unhardened and hardened drive shaft are shown in Fig.8. The measurement results are not in consistence with calculation results (compare Fig.4 and Fig.8).



Fig.7. Photograph of a studied cylindrical shaped steel drive shafts.

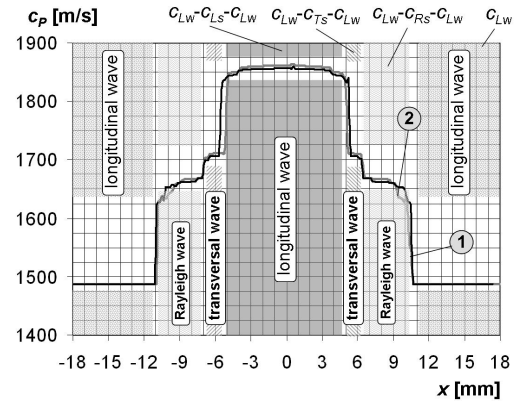


Fig.8. Results of projection measurements of ultrasonic wave propagation velocity for a section of a water submerged steel drive shaft: 1 – unhardened, 2 – hardened.

This inconsistency may result from refraction phenomenon occurring, when ultrasonic wave goes through water – steel and steel – water borders. In order to check that possibility, numerical calculations were performed of refraction angles for an ultrasonic wave ray impinging the surface of a steel cylinder (27 mm in diameter) submerged in water (ray tracing). It was assumed that the ultrasonic wave beam is infinitely narrow (single ray), longitudinal wave velocity in steel $c_{Ls} = 6000 \text{ m/s}$ and transversal wave velocity $c_{Ts} = 3260 \text{ m/s}$. Fig.9 shows the shape of individual rays for longitudinal and transversal wave respectively in the water submerged cylinder during the probe pair movement along the cylinder diameter. The numerical calculations show that due to a significant angle of refraction on the water – steel border, longitudinal wave propagates in the cylinder only in the probes movement range of about $-3 \div 3 \text{ mm}$ (Fig.9a) and transversal wave in the range of about $-6 \div 6 \text{ mm}$ (Fig.9b) (critical angles). The analysis of the phenomenon presented in Fig.9 allows explanation of the complex shape of the graph achieved as a result of measurements (Fig.8). In the probes movement range of about $-5 \div 5 \text{ mm}$ longitudinal wave $c_{Lw} \approx 1488 \text{ m/s}$ propagated in water induces in hardened and unhardened steel longitudinal wave $c_{Ls} \approx 5744 \text{ m/s}$, 5908 m/s and transversal wave $c_{Ts} \approx 3133 \text{ m/s}$, 3202 m/s (calculations were made on the basis projection measurements with the use of formula (5)). Due to higher longitudinal wave velocity value, its transit time is measured for the range of $-5 \div 5 \text{ mm}$ (Fig.10). The range is slightly wider than the one determined in the calculations because of a finite beam divergence value and the size of the receiving probe (the probe also receives some of the refracted marginal rays of the beam, which reach it along elongated paths) [9]. The central ray of the beam penetrates the cylinder without refractions along the diameter only (maximum in Fig.10).

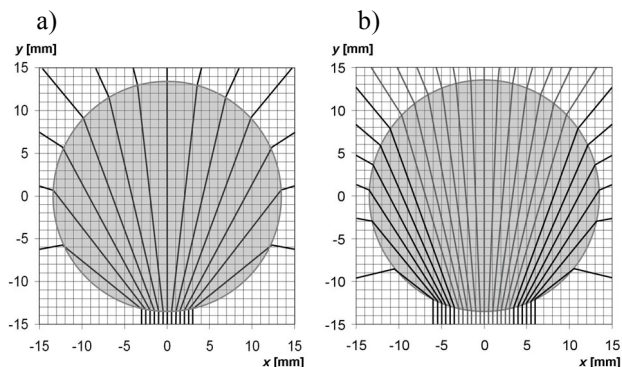


Fig.9. Numerical calculations of angles of refraction (ray tracing) for an ultrasonic wave ray impinging the surface of a steel cylinder (27 mm in diameter) submerged in water: a) longitudinal wave ($c_{Lw} \rightarrow c_{Ls} \rightarrow c_{Lw}$), b) transversal wave ($c_{Lw} \rightarrow c_{Ts} \rightarrow c_{Lw}$).

In the area, where longitudinal wave exists in the cylinder, the real measured ultrasound velocity values are different than the values calculated along straight line rays. It is a result of marginal rays of the beam being refracted. Outside the range of $-5 \div 5$ mm longitudinal wave fades away in the cylinder, as a result of which measurement results in the same transversal wave transit time. The transversal wave transit time, according to numerical calculations should disappear at movement positions outside the range of $-6 \div 6$ mm, however due to beam divergence and overrated value of transversal wave velocity in steel assumed for calculations, transversal wave will disappear outside the range of about $-6.5 \div 6.5$ mm (Fig.8). Next transit time of surface Rayleigh wave is measured ($c_{Rs} = 2971$ m/s, 3053 m/s). The Rayleigh wave disappears outside the movement range of about $-10 \div 10$ mm (Fig.8), because the beam impinging the cylinder border at an angle close to 90° cannot induce it anymore. This results in the cylinder's diameter being seemingly shorter (Fig.8).

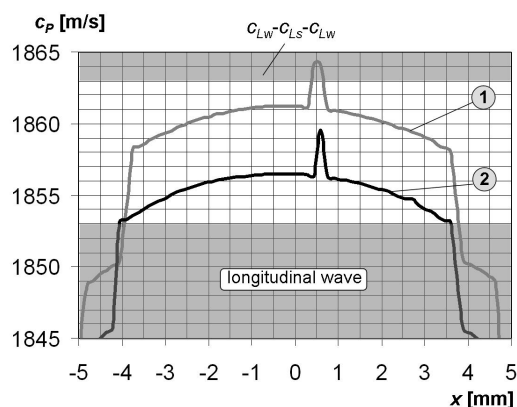


Fig.10. Enlargement of area $-5 \div 5$ mm from Fig.8: 1 – unhardened drive shaft, 2 – hardened drive shaft.

Outside the movement range of $-10 \div 10$ mm diffraction occurs (Fig.11). Wave length in water, for frequency equalling 5 MHz is about 0.3 mm. On the side border of a cylinder, ultrasonic wave beam impinging it at an angle close to 90° does not penetrate the cylinder, but „flow around” a small fragment of its side surface, as a result of which transit time of the wave lengthens, and ultrasound velocity is lower at this location than in water (Fig.11).

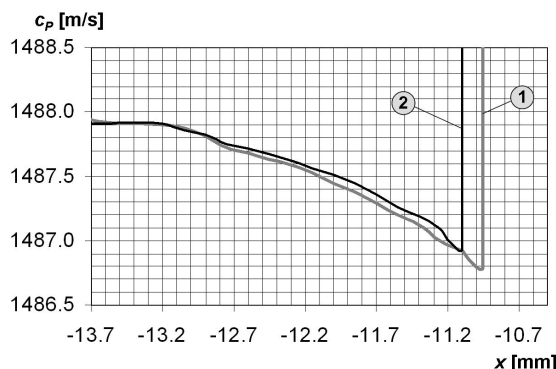


Fig.11. Enlargement of area $-13.7 \div 10.7$ mm from Fig.8: 1 – unhardened drive shaft, 2 – hardened drive shaft.

Despite the adverse influence of refraction and diffraction, projection method allows detection of ultrasonic wave velocity difference for cylindrical steel samples, which makes it possible to develop an evaluation method of steel hardness and hardening degree. The closer the transmitting and receiving ultrasonic probes are to the sample and the longer the sample's diameter the better is the method's resolution. In case of the distance of 100 mm and cylinder diameter of 27 mm used in this study it can be concluded that it is possible to detect projection value differences of about 0.5 m/s (Fig.10), which translates to differences in values of ultrasonic wave velocity of about 20 m/s (formula (5)). Assuming that the distance between the transmitting and receiving ultrasonic probes is reduced to 67 mm (near field for both probes is about 20 mm), the resolution should improve by half. It is definitely enough, because, as the measurements show, steel hardening results in ultrasonic wave propagation velocity reduction by about 160 m/s.

The images of a section of an unhardened and hardened drive shaft reconstructed from tomographic measurements (Fig.3) are shown in Fig.12 and Fig.13 respectively.

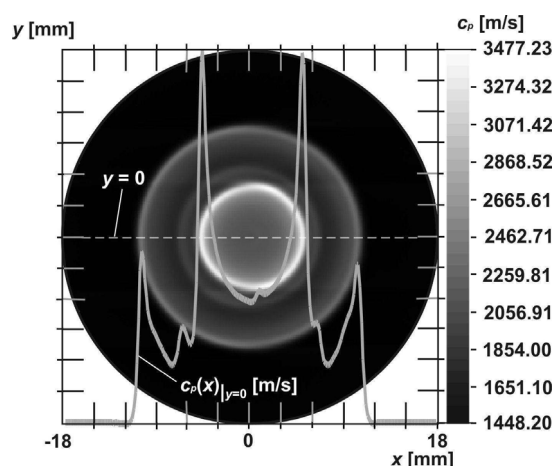


Fig.12. Gray scale tomographic distribution image of local values of ultrasound velocity in an unhardened drive shaft cross-section, reconstructed on the basis of measurements of ultrasonic wave propagation velocity.

Reconstruction was done on the basis of $M = 239$ measurement rays (movement in the range of 36 mm in 0.15 mm steps), $N = 256$ projections, on a 239×239 pixel grid, with the use of a stochastic filter, which minimizes errors caused by refraction [9].

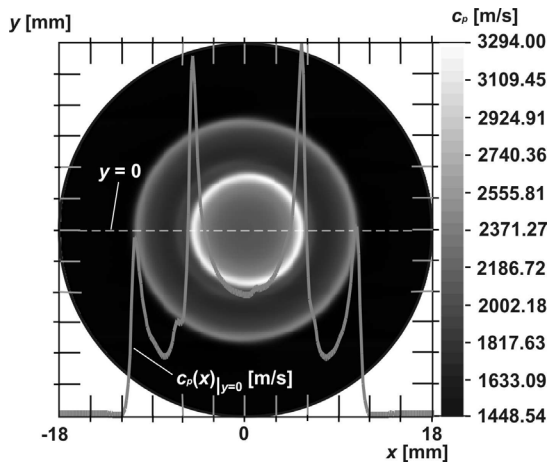


Fig.13. Gray scale distribution image of local values of ultrasound velocity in a hardened drive shaft cross-section, reconstructed on the basis of measurements of ultrasonic wave propagation velocity.

Fig.12 and Fig.13 additionally presents a graph of image pixel values $c_p(x)$ for section line, the coordinate of which is $y = 0$ (along the cylinder diameter). Despite some adulteration of tomographic images resulting from refraction (sound velocity values are significantly underrated), it is easy to distinguish between a hardened and unhardened sample (Fig.14).

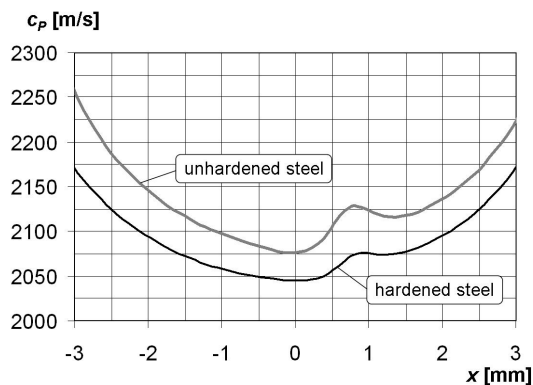


Fig.14. Image pixel values $c_p(x)$ from Fig.12 and Fig.13 for section line, the coordinate of which is $y = 0$ (along the cylinder diameter) enlarged for range $x = -3 \div 3$ mm.

Due to imaging errors and time measurements take, using the tomographic method in examining cylindrical steel samples seems less beneficial than in case of ultrasonic projection method.

5 Conclusions

On the grounds of studies and calculations it is possible to state that ultrasonic projection method as well as ultrasound transmission tomography method can be used for non-destructive examination of cylindrical steel samples. These methods can especially be used to evaluate steel hardness and hardening degree. Ultrasonic projection method produces very good results, and it requires only one movement of the probe pair along a chosen sample section, which reduces measurement time significantly. This time can be further reduced to fractions of a second using a pair

of multi-element linear ultrasonic probes with synchronised switching of elementary transducers [10].

Measurements and numerical calculations showed that during a measurement of an average value of ultrasonic wave transit time along the diameter of a cylindrical steel sample submerged in water, as a result of refraction, longitudinal wave, transversal wave and surface wave successively disappear in the sample, which is manifested by measured ultrasonic velocity value jumps (down shifts). Diffraction on the border of the sample causes a slight decrease of ultrasonic velocity values in this area. In order to increase measurement resolution it is important to set the smallest distance between the transmitting and receiving transducer. It must, however, be remembered that the examined sample should be outside near field. For projection scanning method (Fig.2), longitudinal wave propagates in a steel cylinder submerged in water in the range of about $x \in [-d/9 ; d/9]$ and this is the best analysis area.

References

- [1] J. Radon, „Über die Bestimmung von Funktionen durch ihre Integralwerte langs gewisser Mannigfaltigkeiten, *Berichte Sachsische Akademie der Wissenschaften, Math.-Phys. Kl.* 69 (1917)
- [2] K. J. Opielinski, T. Gudra, “Biological structure imaging by means of ultrasonic projection”, *Acoustical Engineering*, Polish Acoustical Society, Krakow, Poland, 97 - 106 (2004)
- [3] K. J. Opielinski, T. Gudra, “Computer Recognition of Biological Objects’ Internal Structure using Ultrasonic Projection”, *Computer Recognition Systems*, Springer, Berlin, 645 – 652 (2005)
- [4] A. B. Dobrucki, K. J. Opielinski, "Adaptation of Image Reconstruction Algorithm for Purposes of Ultrasound Transmission Tomography (UTT)", *Archives of Acoustics* 25, 4, 395 - 422 (2000)
- [5] K. J. Opielinski, T. Gudra, "Multi-parameter Ultrasound Transmission Tomography of biological Media", *Ultrasonics*, 44, 295 – 302, (2006)
- [6] A. C. Kak, M. Slaney, "Principles of Computerized Tomographic Imaging", *IEEE Press*, New York (1988)
- [7] M. Stapper, G. Sollie, „Characterization of Biological Tissues by Means of Ultrasound Transmission Tomography using Personal Computer, *Ultrasonics International '87 Conference Proceedings*, 321 (1987)
- [8] K. J. Opielinski, T. Gudra, “Three-dimensional Reconstruction of Biological Object’s Internal Structure Heterogeneity from the Set of Ultrasonic Tomograms”, *Ultrasonics*, 42, 705 – 711, (2004)
- [9] K. J. Opielinski, T. Gudra, “Ultrasound Transmission Tomography Image Distortions Caused by the Refraction Effect”, *Ultrasonics*, 38, 424 – 429, (2000)
- [10] T. Gudra, K. J. Opielinski, A. B. Dobrucki, “Model of multielement probes for ultrasound transmission tomography”, *Proc. of the Fifth ECUA*, 2, 1423 – 1428, France (2000)