ULTRASONIC IMAGING TECHNIQUES FOR THE VISUALISATION IN HOT METALS

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Abstract

The objective of this work was to find most suitable ultrasonic imaging technique for visualisation of objects in hot liquid metals. The imaging systems used for such purposes must operate in very harsh conditions, which significantly restrict the possible architecture of the visualization system and materials, which can be used.

For selection of a most suitable approach, visualisation experiments, using two types of metallic objects (rectangular bar and L-shape profile) were carried out. The experiments were performed using a single 5MHz transducer in pulse-echo mode. The Synthetic Aperture Focusing Technique (SAFT) was selected as a most suitable for demonstration of the possibility of reconstruction of geometrical shape of the objects. The selected approach enabled to reconstruct the geometry of individual elements with a sufficiently high accuracy.

Introduction

The Belgian Nuclear Research Center (SKC*CEN) is engaged in the design of the accelerator driven system MYRHHA with a non-critical fission core. The core will be cooled by a heavy liquid metal (HLM) alloy. For safety and licensing reasons the inspection method of the inner parts of the reactor, submerged in HLM is necessary. For this purpose an ultrasonic visualisation was selected by SCK*CEN.

The complexity of ultrasonic visualization systems varies in a very large range starting from relatively simple ones like position determination systems and up to ultrasonic tomography in medicine and non-destructive testing with a very advanced signal processing [1-5]. The imaging systems used for imaging of the interior of nuclear reactors cooled by liquid metal must operate in very harsh conditions including high temperature, chemical activity of liquid metal and strong radiation [5]. These conditions significantly restrict the possible architecture of the visualization system and materials, which can be used.

For ultrasonic imaging different types of ultrasonic transducer configurations are used. One type of systems uses a single or a small number of physically separated moving transducers and sophisticated signal processing – Synthetic Aperture Focusing Technique (SAFT) or tomography [2, 3, 6]. In another type of systems transducer arrays are used [4, 5].

For imaging of interior of nuclear reactors a best solution would be for transmission and reception of ultrasonic signals to use sparse arrays, consisting of a small number of individual transducers, but enabling to receive simultaneously signals arriving from a few different directions. To our knowledge such an approach was not yet used for imaging purposes, however it looks very promising.

The sparse array may be scanned in space, for example, by a robot arm, thus enabling irradiation of the target from different directions. Applying a signal processing procedure, for example, SAFT it is possible in the second step to get an ultrasonic image of the target with a high resolution. Synthesizing signals obtained at different spatial positions of the array is equivalent to use of a big size array, lateral dimensions of which are equal to the length of scanning path. Therefore, with a relatively small array it is possible to get a high lateral resolution.

Experimental investigations

Purpose of experimental investigations was to prove that using only a single transducer or a small number of physically separated transducers and signal processing (for example SAFT) it is possible to reconstruct shape of objects immersed in liquids.

For experiments the water tank with a scanning system was used (Figure 1). There are two separate scanning systems: 3D linear (*X*, *Y* and *Z*-axis) scanning system and the angular scanner, which are mounted at separate positions. An ultrasonic transducer can be positioned with the scanning step 9μm along all three axes. The scanning step of the angular scanner is 0.015°. The absolute repeatability of the linear scanner is approximately 50μm. Such a high accuracy is necessary for a reconstruction of images from the collected data.

The ultrasonic transducer used during experiments was a conventional disk shape, 5MHz, 12mm diameter damped transducer. It was used as a

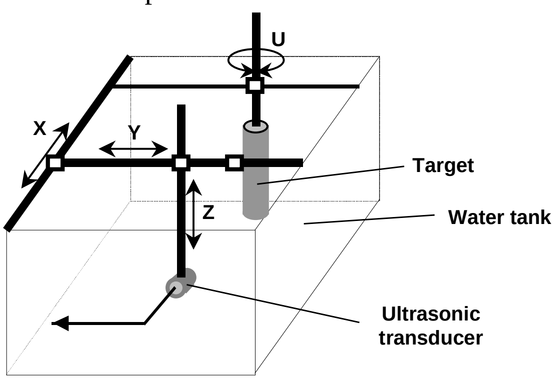


Figure 1: Experimental set-up

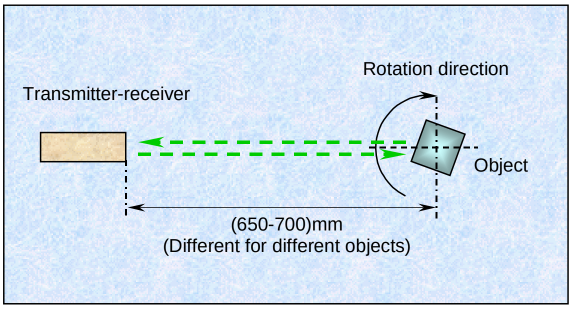


Figure 2: The set-up of the experiments

transmitter and a receiver in pulse-echo experiments.

Measurements were carried out in a pulse-echo mode using one transducer (Figure 2). The mock-up of the object was rotated with the step 0.5° in the clockwise direction and at each position the reflected ultrasonic signal was recorded. Measurements were performed at three different gains of an amplifier: 10 dB, 30 dB and 50 dB correspondingly.

All collected signals, reflected by different objects, where analysed in a few steps. First off all a dynamic range of the acquainted signals was analysed. This was necessary for selection of signals suitable for further analysis. After that analysis of different reflections and their origin was carried out. In the last stage possibilities of the object shape reconstruction from the measured data were analysed. As illustration of this technique the images of the rectangular metallic bar (20×20mm) and L-shape profile (20×3mm) were reconstructed.

Dynamics of the signals

The dynamics of the collected signals can be illustrated using the signal reflected by the rectangular bar. In Figure 3 the signals measured with a different gain are presented. There are two types of the signals: a strong reflection from the planar surfaces and very weak signals caused by edges. In spite of a small amplitude, the edge wave signals are playing a very important role in reconstruction of the reflector shape, because they are related to the position of object edges. As can be seen from Figure 3c, these weak signals can be observed only using a big gain (50dB). In the case of a smaller gain they are “invisible”. Contrarily, the reflections from the planar surfaces of the object can be seen at any of the used gains, but in the case of 30-50dB they are limited by the electronic amplifier. Such signals cannot be used in image reconstruction techniques based on correlation analysis, SAFT or tomography. So, the dynamic range of instrumentation of more than 50dB is necessary for investigation of objects situated at the same distance. In the case when the objects are situated at different distances, or object itself possesses relatively bigger dimensions, the needed dynamic range of electronics is even bigger.

The analysis of different reflections

In this section a more detailed explanation of different reflections is presented. As an example for analysis the B-scan image of the rectangular bar, obtained with the 50dB gain was selected (Figure 4a). In order to enhance small amplitude reflections, the B-scan was formed from the normalised A-scans. It means that each signal was normalised with respect to the maximum amplitude of it. Such an operation enables to improve visibility of low amplitude signals.

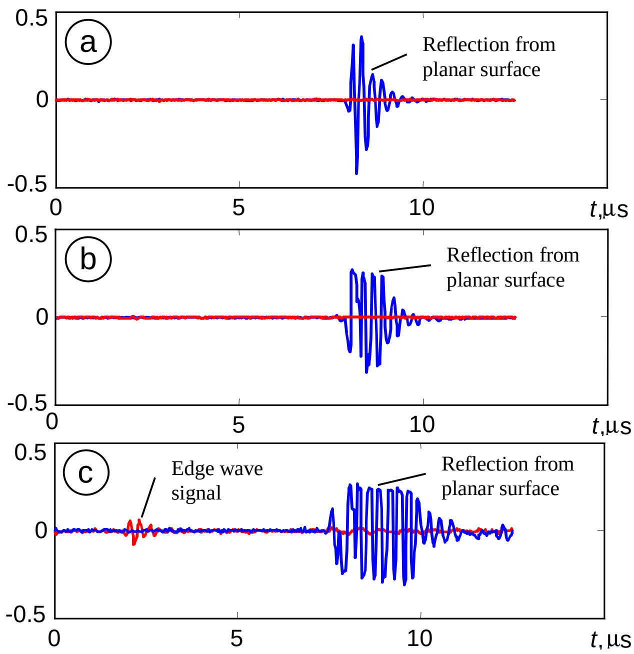


Figure 3: The signals reflected by the rectangular bar and collected using a different gain of amplifiers: a – 10dB, b – 30dB, c – 50dB

In order to explain origin of different reflections, calculation of the expected positions of the reflected signals in the time domain was performed. The following signals were analysed:

- *The signals reflected by a planar surface*. In the case of planar reflections the wave propagation distance was calculated as the length of the perpendicular from the transducer centre to the planar surface of the rectangular bar.
- *The edge wave signals.* The edge waves are caused by a diffraction phenomenon and are generated by the each edge of the planar surface, when an incident wave is reflected by this surface. Therefore, in the case of a rectangular bar they act as point type reflectors. So, the propagation distance of edge waves was calculated as the distance between the transducer centre and the position of a corresponding edge.
- *The longitudinal and shear waves reflected by the opposite corner*. At some angle the opposite corner of the bar reflects back to the transducer the waves refracted by the front wall of the bar. These signals appear at two different time instants, depending on what type of wave - longitudinal or shear wave

was reflected.

- *The specular image of opposite corner.* Very similar signals as in the previous case, only additionally reflected by a side wall of the bar.
- *The surface and leaky wave signals.* The last type of reflected signals included in this analysis are surface and leaky waves. The surface waves are generated on the surface of the bar when the incident waves falls at critical angles with respect to the surface. This surface wave propagates to the edge of the bar and then is reflected by it. This reflected surface wave creates so called leaky wave in water, which propagates to the receiver. It is possible to prove that the propagation time is equal to the propagation time from the transducer to the edge of the bar and back. So, the delay time of these signals was calculated in a similar way as in the case of the edge signals. Usually, there are two critical angles at which surface waves are effectively generated; therefore these signals were calculated for both cases.

In all cases the directivity pattern of the transducer was taken into account. The calculated positions of the signals analysed above are presented in Figure 4b. The character of the calculated and experimental images is very similar. The good coincidence of these two images indicates that presented analysis of the obtained results correctly reveals physics of reflections and transformations of ultrasonic waves.

The reconstruction of the shape of the objects

The SAFT technique was selected for demonstration of the possibility to reconstruct geometrical shape of objects.

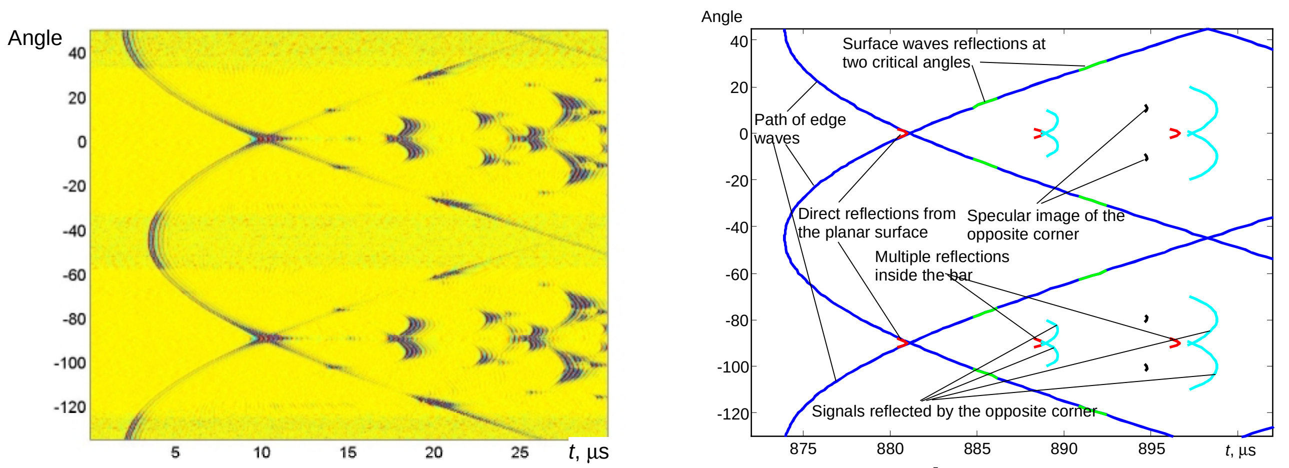
In the case of a conventional transducer array focusing is performed controlling the delay of excitation pulses or/and received signals for different transducer elements.

In the case of the SAFT technique the signals are collected separately by a single transducer at different positions. The focusing is performed artificially by software creating B-scan image and because of that it operates like a virtual or “soft” transducer array. The each element (point) in a conventional B-scan image **B**(N,M) is $b(k,t_j)=u_k(t_j)$, where $u_k(t_j)$ is the amplitude of the k-th measured signal at the instance t_j. The $k\in[1,N]$ is the number of collected signals, $t_j\in[t_{start},t_{end}]$, N is the total number of signals and M is the number of samples in the signal. The each point of the B-scan image in the SAFT technique is obtained as $b_{\mathrm{SAFT}}(x,y)=\sum_{k=1}^{N}u_k(t_k)$, where $t_k=\dfrac{2\cdot d_k(x,y)}{c}$, $d_k(x,y)$ is the distance between a transmitter-receiver and the point (x,y), c is the ultrasound velocity in the medium.

In our case the image is reconstructed from 720 signals collected at different positions with a single transducer rotating the object around its axis.

As illustration of this technique the reconstructed images of the rectangular bar and L-shape profile are presented in Figures 6 and 7. The images are obtained from the signals measured using the 10dB gain. It can be seen that the external profile of the objects is reconstructed correctly except some lines extending object wall near the edges. This may be explained by the fact that in this case the image is reconstructed mainly from the planar reflection signals and the exact positions of edges cannot be determined. Inside the object, many artefacts can be seen. They are caused by various reflections, analysed in the previous section. There is a lot of hidden information about the object in these artefacts, but extraction of this information requires development of new reconstruction techniques and algorithms.

Very strong corner reflections in Figure 6 can be seen also. These reflections do not project into a single point and possess a butterfly type shape. For



a b

Figure 4: a - The normalised B-scan image of the rectangular bar in the case of the 50dB gain; b - distribution of different analysed signals in the time domain

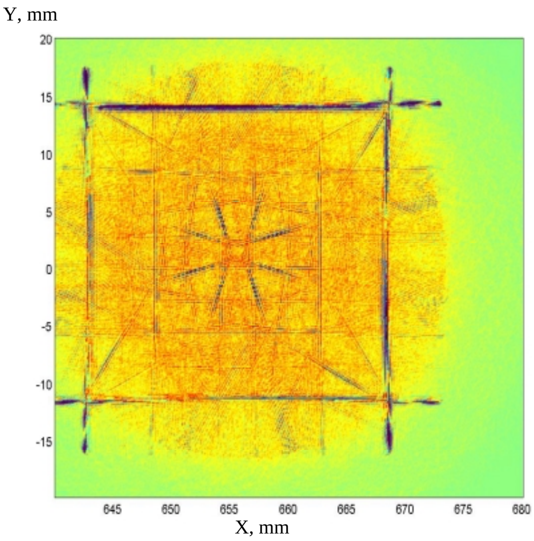


Figure 6: The reconstructed image of the rectangular bar obtained from the data with the 10dB gain

reconstruction of corners probably the tomographic approach and more precise selection of parameters should be used.

It is difficult to recognize the reconstructed edge wave image in Figures 6 - 7, therefore in order to reveal imaging possibilities of edge waves the reconstruction was performed using only edge wave signals. The result is presented in Figure 8, in which four points correspond to the positions of reconstructed edges. That indicates that edge waves enable to determine very precisely positions of sharp edges.

Conclusions

The analysis of the image reconstruction techniques, such as SAFT had shown that even from the data measured by a single transducer scanned around the object, it is possible to reconstruct the approximate shape of single objects. The shape of the objects in obtained images at the moment can be recognized only visually, because the object in the image is blurred and presented by dashed lines.

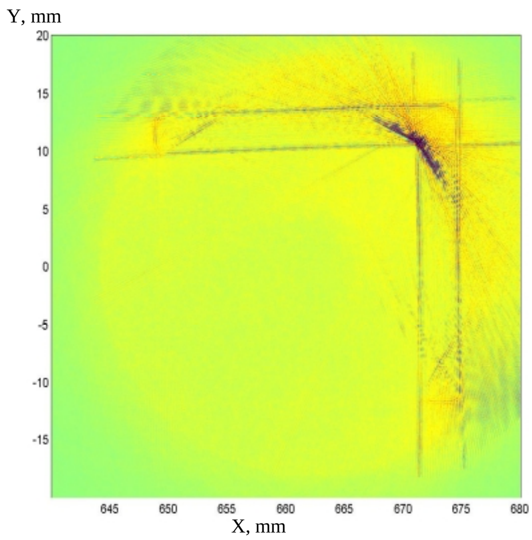


Figure 7: The reconstructed image of the L-shape profile obtained from the data with the 10dB gain

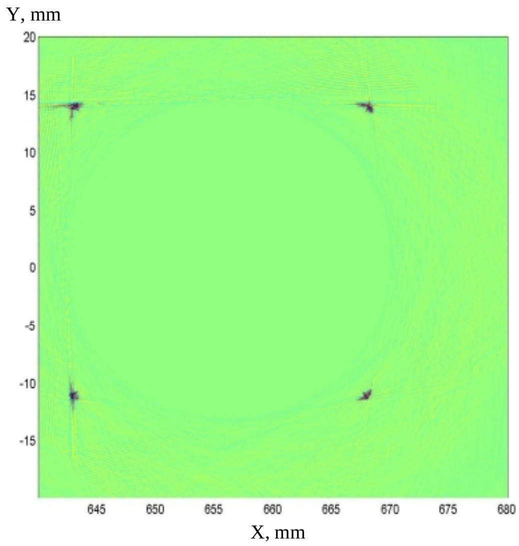


Figure 8: The reconstructed image of the rectangular bar obtained only from the edge wave signals. The four points correspond to position of edges

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