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Quasi-tomographic ultrasonic inspection of tubes

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Abstract

Results obtained from the ultrasonic inspection of tubes and other parts may not be satisfactory due to insufficient sensitivity and the inability to characterize and size a flaw (i.e. determine shape and orientation). Alternatively, tomography, the most accurate and reliable method of inspection, is a very complicated process, and ultrasonic tomographs are not commercially available. It is therefore worthwhile to develop a "quasi-tomographic" approach for parts examination, which could significantly improve inspection capabilities by using only a few simple techniques. For example, to realize a "quasi-tomographic" method, one can employ a few transducers positioned differently in order to insonify a flaw from a variety of angles and directions. The combined image obtained will not only allow detecting the flaw, but also determining — at least approximately — its shape and orientation, as well as providing an estimate of flaw width and depth.

1. Introduction

Ultrasonic Testing (UT) of different tubes is a commonly used inspection method. Various techniques are employed for tube examination in order to detect, characterize and size different flaws, laminations, pores, inclusions, inhomogeneities, etc. However, sometimes the results of the inspection are not satisfactory due to insufficient sensitivity and/or inability to characterize and size the flaw (i.e. determine flaw shape). Typically the pulse-echo (PE) and pitch-catch (PC) techniques are used for tube testing to detect, characterize and size flaws located within the tube wall, on the inside diameter (ID) or outside diameter (OD). (Sometimes terms ID and OD are used in context of inside and outside surfaces, respectively). Normal beam (NB) longitudinal waves and angle beam shear waves propagated in circumferential and axial directions are commonly employed. Each technique has its advantages and deficiencies. Nevertheless, pretty often it is still very difficult to characterize the flaw and size it. Only tomographic method, as the most accurate and reliable one, allows solving this problem. Such a method assumes insonification of each area of the tested object from different points and at various angles; in other words, it allows "seeing" each area of the object simultaneously from different points of view. But unfortunately, tomography is a very complicated and expensive technique, it is still on the development stage only, and the commercial UT tomographs are not available. Therefore it is worthwhile to develop something like "quasi-tomographic" approach for UT testing, which could significantly improve the inspection capability by employing only a few rather simple tomographic techniques.

2. General "quasi-tomographic" approach

During last twenty years there has been considerable interest in ultrasonic computed tomography, because of its very significant potential abilities. For example, UT tomographic method may generate cross-sectional images (tomograms) of internal structure of the test object accurately depicting distributions of four different material properties (acoustic impedance, ultrasound speed, density, and attenuation coefficient), thus providing high resolution 2D and 3D images. The ultrasonic tomography is based on the insonification of each area of the testing object by ultrasonic waves from different points and at various angles and also on the reception of the transmitted, reflected, refracted and scattered ultrasonic pulses in different points and at various angles too. In particular, the reflection tomogram, depicting acoustic impedance distribution, is of interest for the NDE community, because most industrial parts, unlike medical objects, allow only one-side access.

At present various techniques and probes are employed for tube testing to detect, characterize and size different flaws (1-4): NB and angle transducers, longitudinal and shear waves, PE and PC methods, etc. These or similar techniques (with necessary changes, of course) can be used for flaw detection, characterization and sizing in different objects. Of course, every technique has advantages and disadvantages.

We assume that tube is filled with water, and all transducers are positioned inside the tube. Different techniques and probes used for tube inspection allow "seeing" the flaw from various directions: e.g. NB PE ID focused probe gives the possibility "to look" at the flaw from the ID direction in the reflected longitudinal waves, angle PE and PC probes allow "seeing" flaw almost from the OD direction in the reflected shear waves, and so on. However, some flaws (e.g. tight cracks, small scratches, weak inhomogeneities, and so on) can be easily missed. It happens, first of all, because typically positions of all probes in the probe module are fixed, and therefore tube areas cannot be insonified at different angles. And secondly, images obtained by using different transducers and methods are not combined together. To improve performance of the system, the probe module, where transducer angles could vary, should be applied. Then different images should be somehow interposed or combined. As a result, one will get something like a rather simple "quasi-tomographic" method (5), which allows detecting, characterizing and sizing even the small flaws; and this will significantly improve sensitivity, resolution, and reliability of the inspection.

3. "Quasi-tomographic" techniques

3.1. Variable angle shear wave two-skip PC technique at large incident angle

Schematic of the shear wave two-skip PC technique for tube inspection (1-4) is presented in Fig. 1.

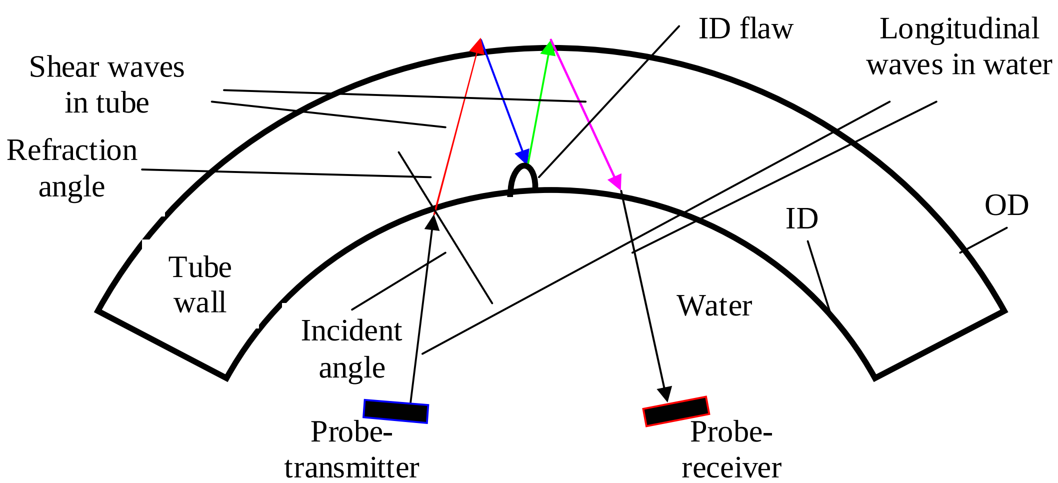

Figure 1. Schematic of the circumferential shear wave PC technique for tube inspection.

This technique allows detecting, characterizing (to some extent), and sometimes even sizing the ID and OD flaws. Flaw is flagged, first of all, as the signal amplitude drop relative to the signal typically reflected from the tube OD and ID. This is because a typical PC signal is partially blocked by flaw. Secondly, another peak of the PC response may appear due to the signal reflected directly from the flaw. Fig. 1 shows that PC transducers are located at such angles and in such positions that after entering the tube and refraction at the interface water/tube the acoustic beam performs (see color lines) two full skips within the tube wall between the ID and OD before going out of the tube. Using this technique, one can “see” the flaw in reflected shear waves almost from the OD direction.

In all Figures presented lower (except Fig.10) the scans were performed on $90^0/60^0$ ID axial V-notch 0.5mm deep with tip radius 0.2mm, see Fig. 2. The unusual shape of notch in Fig. 2 was chosen in order to demonstrate the abilities of “quasi-tomographic” method to characterize the complicated flaw (i.e. determine its shape, position and orientation) and measure its dimensions.

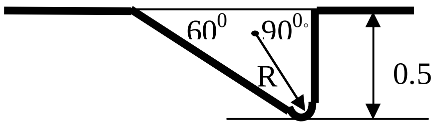

Figure 2. Cross-section of $90^0/60^0$ ID axial notch 0.5mm deep with tip radius 0.2mm.

Typical circumferential two-skip PC B-scan of this notch is presented in Fig. 3. This scan was performed using computerized scanning rig with rotary and three axial motions, Winspect software for data acquisition, SONIX STR-81G card, and UTEX UT-340 pulser-receiver. The tested tube (ID=103mm, wall thickness WT=4mm) filled with water, was positioned on the rotary table, and transducers were located inside it.

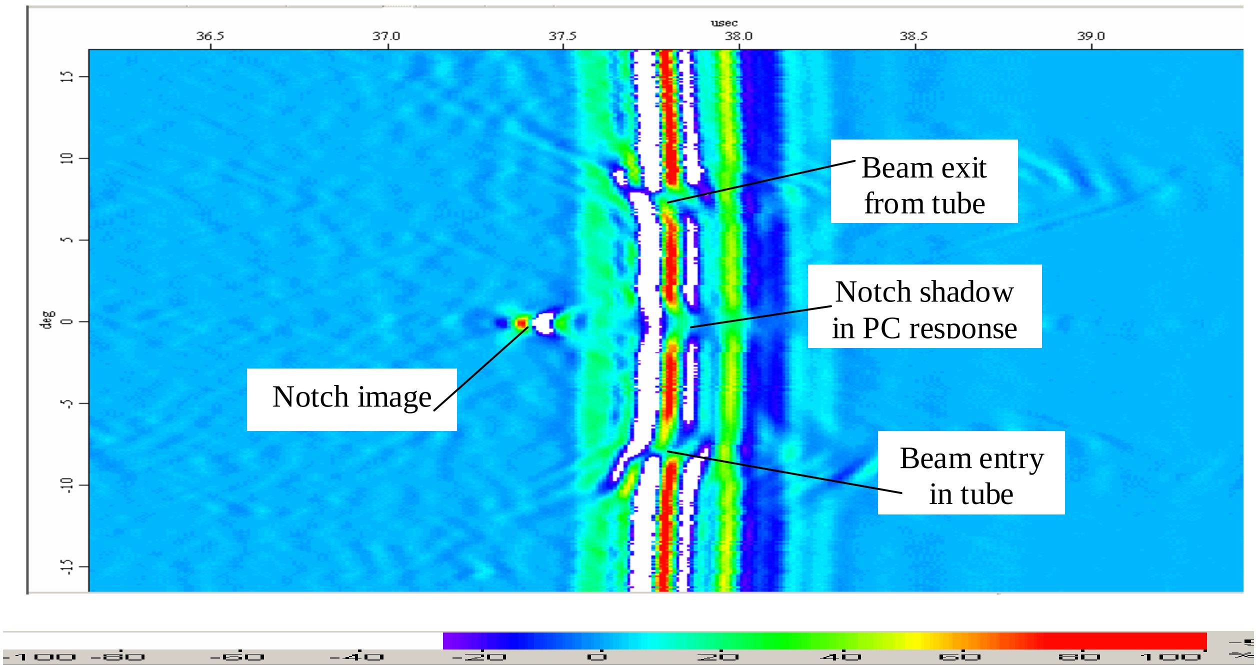

Figure 3. Circumferential shear wave 2D two-skip PC B-scan of $90^0/60^0$ ID axial notch 0.5mm deep with tip radius 0.2mm. Probes: focal length FL=33mm, center frequency f=20MHz, aperture diameter D=9.5mm, water-path WP=20.6mm, and incident angle $\alpha=25^0$.

The beam is interrupted by the flaw three times: as it enters and exits the tube, and at the one-skip position. One can see from Fig. 3, that using PC two-skip technique it is possible to detect notch and estimate its width (dimension of notch image in circumferential vertical direction) and depth (difference between UT pulse time-of-flight in radial horizontal direction for notch response and main PC response). However, the shape and orientation of the notch cannot be determined.

In order to characterize the flaw, one should have an ability to "see" it at different angles. The two-skip PC technique used at various incident angles allows "looking" at the flaw from different directions. Changing transducers orientation angles and distance between them one can control the incoming beam incident angle, the refraction angle, the acoustic beam trajectory within the tube and the angle, at which beam impinges the flaw (i.e. flaw observation angle). Moreover, it is much better to use not a standard spherically focused probe, but special transducer with logarithmic acoustic lens (5), which has a stretched focal zone, i.e. creates a narrow weakly diverging acoustic beam. Such a probe provides high sensitivity and good lateral resolution within a large insonification range.

Special variable angle probe module was used to perform the required scans. This module allows changing the orientation (angle position) of each transducer and distance between them. This module was employed to perform the PC scans at various incident angles. Note that only shear waves were used for testing, since they have smaller wavelength and therefore provide higher resolution than longitudinal waves. Because of this, all incident angles were greater than the first critical angle for water/tube interface. The best result, presented in Fig. 4, was obtained at large incident angle $\alpha=34^0$.

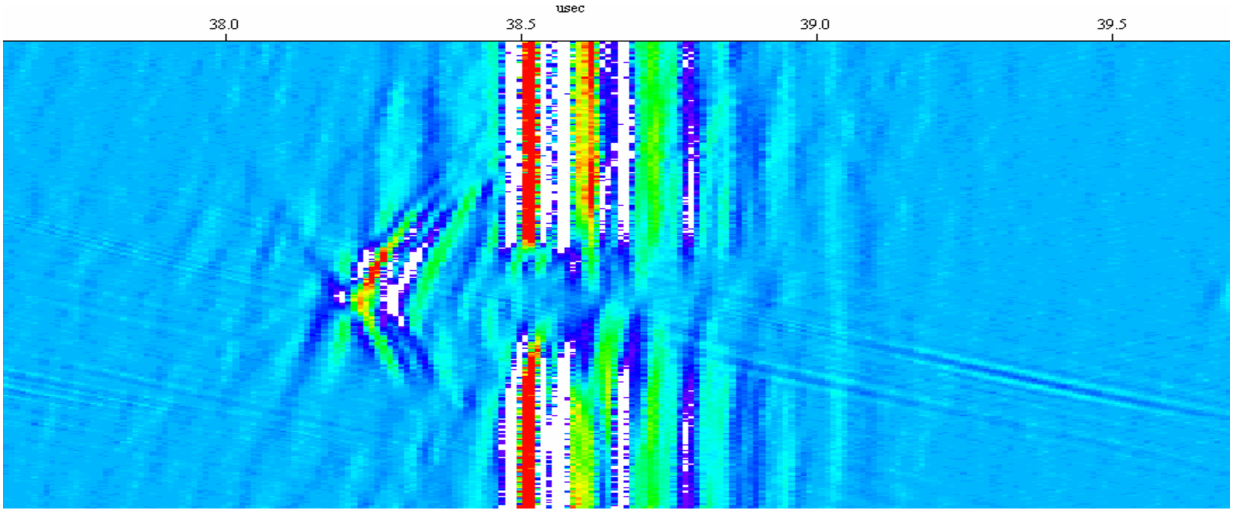

Figure 4. Circumferential shear wave 2D two-skip PC B-scan of $90^0/60^0$ ID axial V-notch 0.5mm deep with tip radius 0.2mm at large incident angle $\alpha=34^0$. Probes: f=20MHz, D=9.5mm, stretched focal zone FZ=20-50mm. Color scale is shown in Fig.3.

Fig. 4 clearly demonstrates that shear wave two-skip PC technique at large incident angle allows not only detecting notch and estimating its width and depth, but also determining to some extent the shape and orientation of the notch (e.g. asymmetric profile of notch in Fig. 2). Of course, only approximately the notch shape, shown in Fig. 2, can be "reconstructed" using Fig. 4 image. However, one should remember that so far it was only one technique, which has been used for flaw characterization and sizing. Information obtained by using other methods (see below sections 3.2-3.4), will significantly help to determine flaw shape, orientation and dimensions.

3.2. Variable angle one-skip PE technique at small incident angle

Schematic of circumferential one-skip PE technique is presented in Fig. 5.

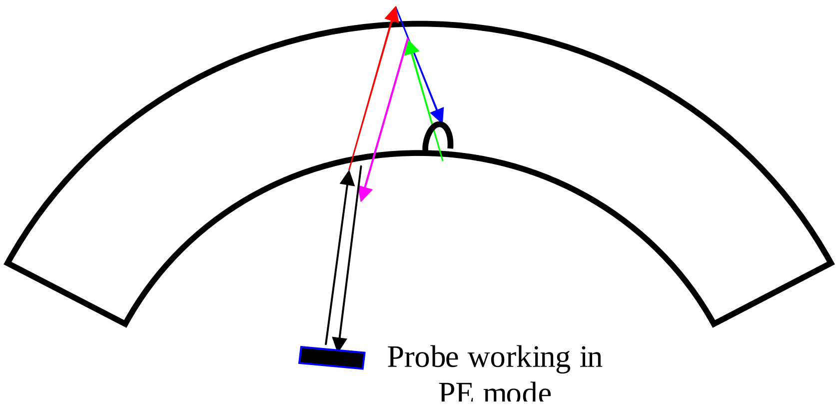

Figure 5. Schematic of circumferential one-skip PE technique.

This technique is very sensitive to flaw detection. Flaws (even the small ones) clearly appear on the B- and C-images as the reflected responses with significant peak amplitude. Using such a technique one can “see” the flaw in reflected waves almost from the OD direction. In order to characterize and size the flaw, one should have an ability to “see” it at the different angles. The variable angle probe module with one transducer working in circumferential PE mode was used to perform the required scans. The best result was obtained at small incident angle $\alpha=3^0$. Circumferential PE B-scan of $90^0/60^0$ ID axial V-notch 0.5mm wide and 0.5mm deep with tip radius 0.2mm is presented in Fig. 6. Using this technique at small incident angles (about ~3-4^0) it is possible to detect the flaw, approximately determine its shape and orientation (e.g. asymmetric profile of the notch), and estimate its size. Since tube dimensions and probe position inside it are known, one can calculate the notch depth and width using Fig. 6 image and applying the geometrical acoustics method.

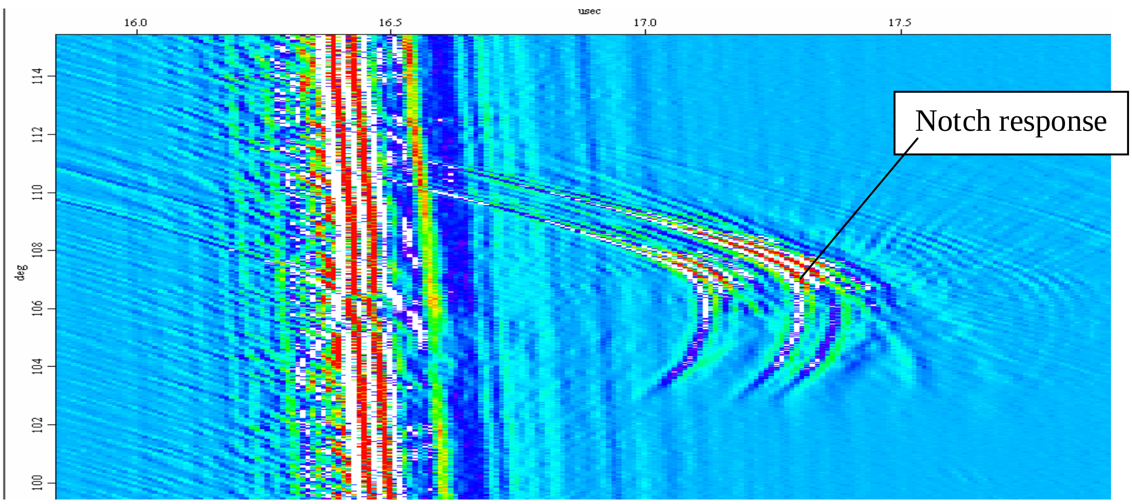

Figure 6. Circumferential 2D PE B-scan of $90^0/60^0$ ID axial V-notch 0.5mm deep with tip radius 0.2mm at small incident angle 3^0. Probe: FZ=20-50mm, f=20MHz, D=9.5mm. Color scale is shown in Fig.3.

3.3. Variable angle shear wave one-skip PC technique

Schematic of shear wave one-skip PC technique for tube inspection is presented in Fig. 7.

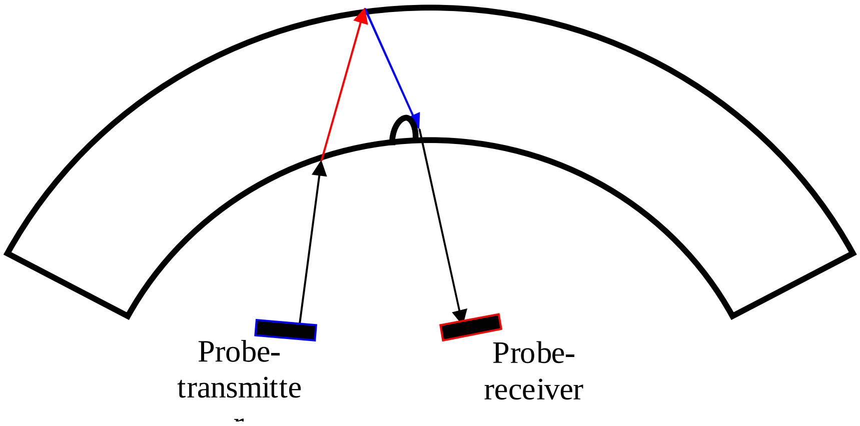

Figure 7. Schematic of circumferential one-skip shear wave PC technique.

This technique allows detecting, characterizing, and sometimes sizing the ID and OD flaws. The flaw is flagged, first of all, as the signal amplitude drop relative to the signal typically reflected from the tube OD and ID. This is because the PC signal is partially blocked and reflected from the flaw. Secondly, another peak of the PC response appears due to the signal transmitted directly through the flaw. Fig. 7 shows that PC transducers are located at such angles and in such positions that after entering the tube and refraction at the interface water/tube, the acoustic beam performs (see color lines) one skip within the tube wall between the ID and OD before going out of the tube. Using this technique one can "see" the flaw in transmitted waves almost from the OD direction.

The one-skip PC technique performed at various incident angles allows "looking" at the flaw from different directions. The best result was obtained at incident angle $\alpha=23^0$. Typical circumferential one-skip PC B-scan of $90^0/60^0$ ID axial V-notch 0.5mm wide and 0.5mm deep with tip radius 0.2mm is presented in Fig. 8. The beam is interrupted by the flaw two times: as it enters and exits the tube. One can see from Fig. 8, that using PC one-skip technique it is possible to detect notch and evaluate its width and depth; even the asymmetric shape and orientation of the notch can be estimated.

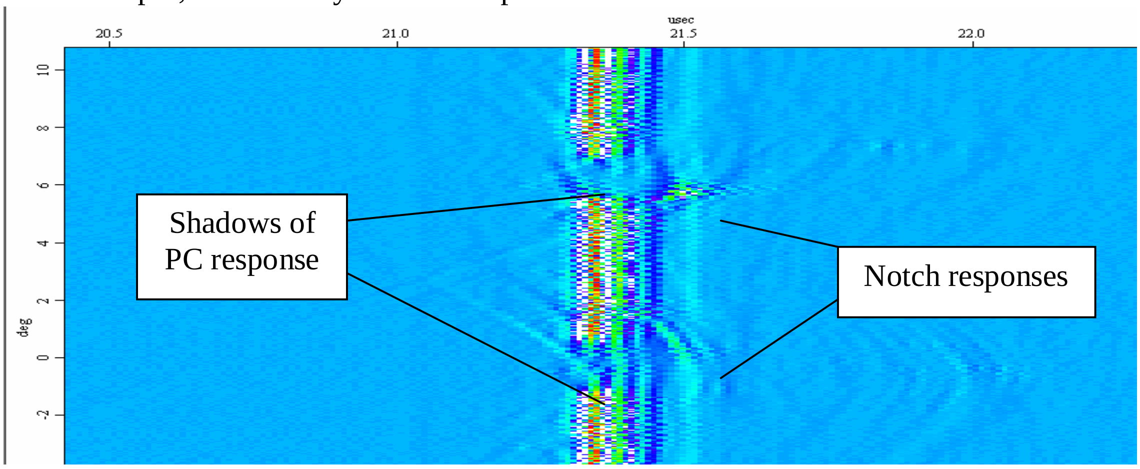

Figure 8. Circumferential shear wave 2D one-skip PC B-scan of $90^0/60^0$ ID axial V-notch 0.5mm deep with tip radius 0.2mm at incident angle $\alpha=23^0$. Probes: f=20MHz, D=9.5mm, stretched focal zone FZ=20-50mm. Color scale is shown in Fig.3.

3.4. Combination of images obtained by using different techniques and probes

Techniques described in sections 3.1-3.3 clearly demonstrate that ability to observe flaw in reflected and transmitted shear waves at different angles is very useful for flaw characterization and sizing. Of course, the other techniques, employing e.g. NB PE ID and OD focused probe, are extremely useful if one wants to determine flaw shape and orientation.

The ability to combine information, obtained by using different techniques and probes, and then reconstruct the flaw, is the main advantage of the classic tomographic method. To do it, special software should be developed. In order to realize the simplified “quasi-tomographic” technique, one can use some other simple method, which combines information from different transducers. One of the ideas is to connect simultaneously two probes (e.g. two circumferentially positioned transducers, clock-wise CW and counter-clock-wise CCW) to pulser-receiver working in the PE mode (5).

As a result, both transducers will simultaneously transmit UT signals and both will receive the responses. Each transducer will receive its own signals, reflected from the tube ID and OD, and also signals, transmitted by other probe and reflected from tube surfaces. Subsequently, three techniques will be realized simultaneously: CW PE, CCW PE, and PC. The obtained “combined” image will contain responses typical for these three techniques; in other words, it will look like three interposed images: CW PE, CCW PE, and PC. This “combined technique” can be performed as 3D or 2D scans at different incident angles and various probes positions. This method offers a very simple way to “combine” information.

Typical 2D circumferential B-scan of $90^0/60^0$ ID axial V-notch 0.5mm wide and 0.5mm deep with tip radius 0.2mm, performed at large incident angle $\alpha=30^0$, is presented in Fig. 9. This scan has CW, CCW, and two-skip PC responses in one image.

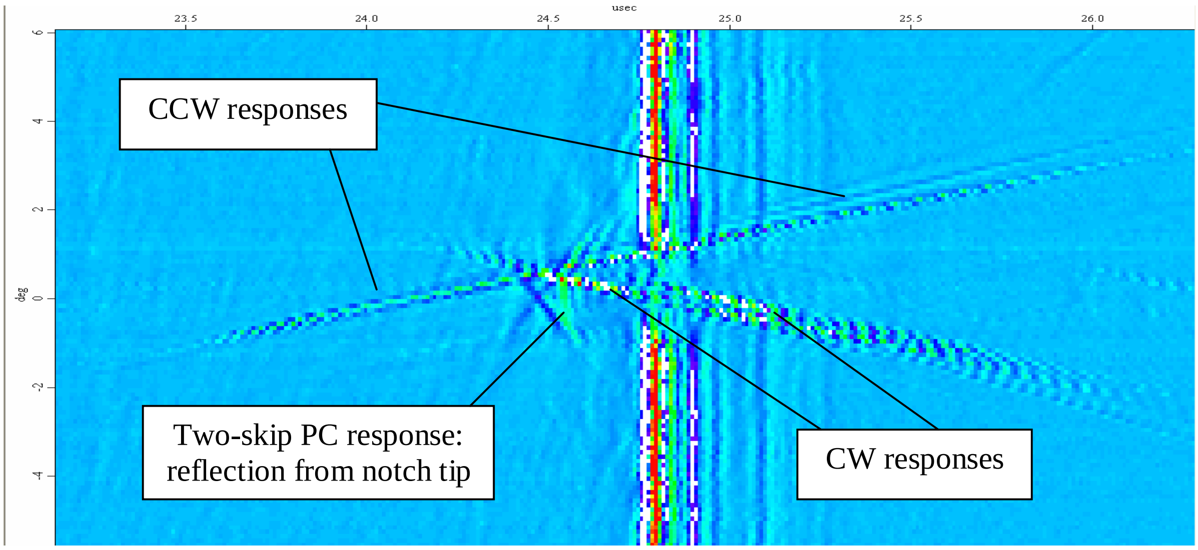

Figure 9. Circumferential shear wave 2D combined (CW + CCW + two-skip PC) B-scans of $90^0/60^0$ ID axial V-notch 0.5mm deep with tip radius 0.2mm at incident angle $\alpha=30^0$. Probes: FZ=20-50mm, f=20MHz, D=9.5mm, WP=8mm. Color scale is shown in Fig.3.

Fig. 9 clearly demonstrates that “combined” image allows obtaining significant information about flaw shape and orientation. Each single response in Fig. 9 is asymmetric, which means that notch tip is not in the middle of the notch. CW and CCW responses are oriented at different angles; it means that angles between notch and the tube ID are different at different sides of the notch. These two angles can be calculated using geometrical acoustics, knowing probes positions and incident angles, and measuring CW and CCW responses orientations. Moreover, notch tip reflection is rather strong (see PC response in Fig. 9); it means that radius of the notch tip is pretty large. For small tip radius (i.e. for "sharp" notch) this reflection would be weak. Preliminary experiments, performed on notches with various tip radii, confirmed that amplitude and length of the responses are proportional to notch tip radius. Therefore this method can probably be used for flaw tip radius estimation.

If not two but three probes (e.g. CW, CCW, and NB transducers) are hooked up in parallel to pulser-receiver working in the PE mode, then four techniques will be realized simultaneously: CW PE, CCW PE, PC, and NB. Typical 2D circumferential B-scan of rectangular ID axial symmetric notch 0.15mm wide and 0.076mm deep is presented in Fig. 10. This scan has NB, CW, CCW, and two-skip PC responses in one image.

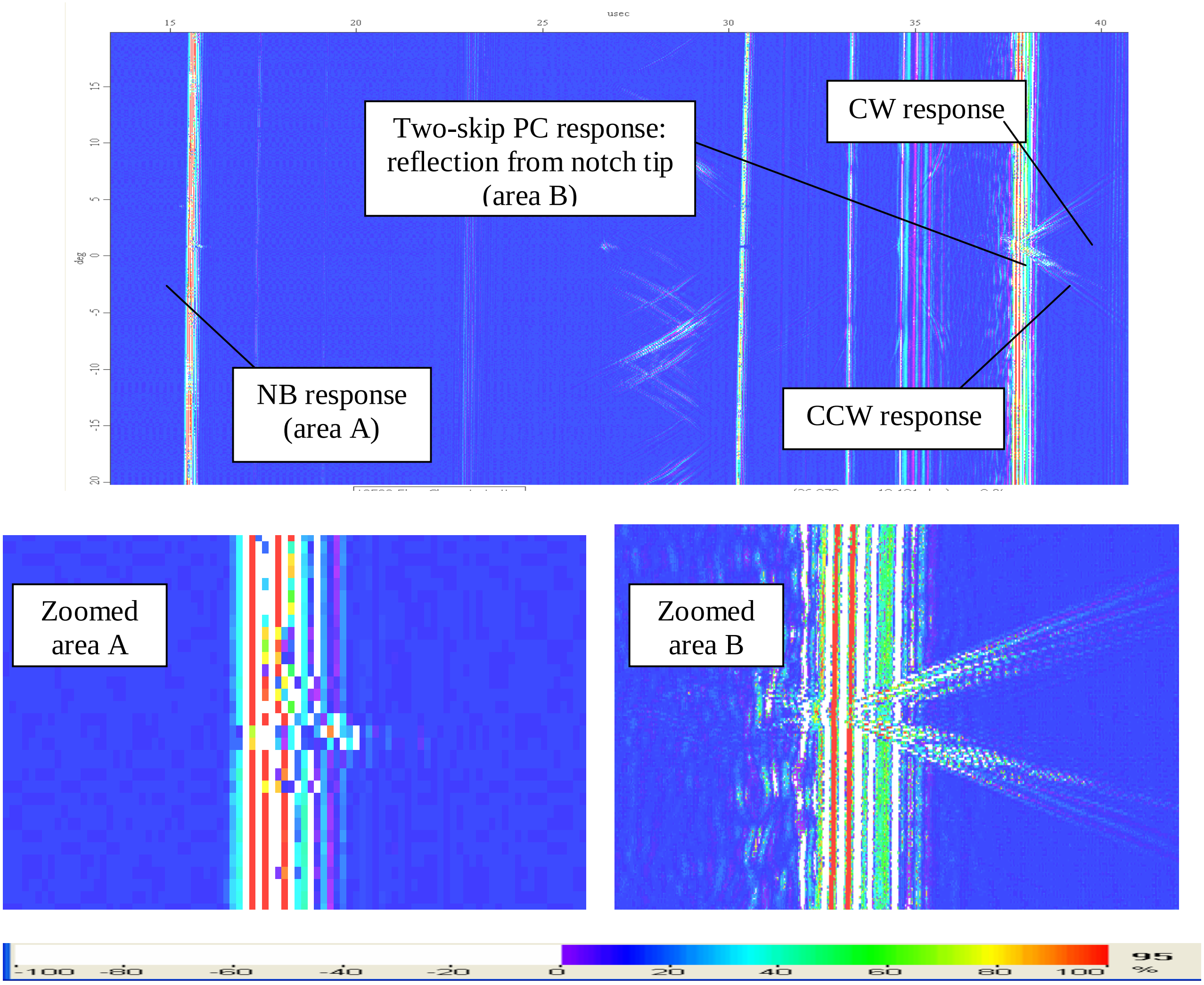

Figure 10. Circumferential 2D combined (NB + CW + CCW + two-skip PC) B-scans of ID axial symmetric notch 0.15mm wide and 0.076mm deep. CW and CCW probes: FL=33mm, f=10MHz, D=9.5mm, WP=21mm, $\alpha=25^0$. NB probe: FL=10mm, f=20MHz, D=6.35mm, WP=10mm.

Fig. 10 shows that responses from different probes can be easily distinguished and the obtained "combined" image presents significant information for flaw characterization and sizing.

4. Conclusions

- Sometimes results of the UT inspection of tubes are not satisfactory due to insufficient sensitivity, inability to characterize a flaw (i.e. determine its shape) or size a flaw. It is very difficult, even using various techniques, waves and transducers to determine defect shape and orientation, measure shallow flaw depth, detect cracks (particularly the tight ones), find areas with material morphology variations, and so on. Only tomographic method, as the most accurate and reliable one, allows solving all these problems. At the same time, the UT tomography is a very complicated and expensive technique, and it is now on the development stage only. That is why it is worthwhile to develop something like "quasi-tomographic" approach to tube examination, which could significantly improve the inspection capability by employing only some simple tomographic techniques.
- To realize "quasi-tomographic" technique, one should apply different methods, which allow "seeing" a flaw at various angles. In addition, images obtained by using different transducers and methods, should be combined.
- Shear wave one-skip and two-skip PC and PE techniques allow not only detecting the flaw and estimating its width and depth, but also determining to some extent the shape and orientation of the flaw.
- "Combined" image, containing NB, PE and PC responses, allows determining pretty accurately flaw shape and orientation and "reconstruct" the flaw.
- These or similar techniques can be used for flaw detection, characterization and sizing not only in tubes but in different objects.

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