Automated Eddy Current System for Flaw Detection and Sizing during In-service Stainless Steel Tube Inspection

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Abstract. Automated eddy current computerized system CRAB for detection and identification of cracks situated on different sides of stainless steel tubes are presented. Presented system provide next feathers:
- The automated 4-channel 2-frequency eddy current testing with special 4-probe scanner;
- The detection of like crack flaw on inner side of 15 mm thick tube with 50 % of wall thickness depth sensitivity;
- The crack identification by displacement on outer or inner tube size and orientation;
- The detected crack depth (in % of wall thickness) and length estimation.

Introduction

The demand of safe equipment exploitation in chemical industry explains the important role of in-service nondestructive inspection. The detection and sizing of different side flaws in thick wall tubes during in-service is one of the most actual and complicated NDT problem. For some kind of stainless tubes the ultrasonic method is not applicable for flaw detection due very high structural noise and anisotropic behavior. In some cases the special developed transmitter receiver phased array probe were used to obtain better signal to noise ratio [1]. For eddy current method application with outer surface probe scanning the good penetration depth must be achieved for the detection of the flaws situated on the inner tube surface. The next possible problem is the necessity to suppress the influence on eddy current probe signal the material structural inhomogeneity.

The task of quantitative automated detection of cracks situated on inner and outer surface of secondary reforming furnace tubes was stated and solved. The tubes are 15 mm thick and have 102,0 mm in diameter and were produced from 40X25H20 stainless steel by centrifugal casting process. The next requirement to developed eddy current system is the possibility to identify and separate cracks on inner and outer tube surface and estimate their depth in percent of tube wall thickness. All obtained testing results must be documented and stored for further analyzing.

Eddy Current Probe Investigation

For stated task solving it is needed to use the low frequency eddy current probes with very high penetration enough to provide good sensitivity to subsurface flaws on the distance (residual depth) 7-8 mm from outer surface. However, accordingly with noise limited depth of penetration concept even good penetration is not only one factor needed to receive good eddy current probe signal response from deeply deposited flaw [2,3]. As mentioned above the important difficulty for eddy current method application is very high structural noise due large grain size of tested material. To minimize this noise the low frequency multidifferential Leotest MDF 3301 type eddy current probe was developed [3-6]. The developed probe has 33 mm in diameter and work in operational frequency range from 50 Hz to 10 kHz. The spatial filtering features of eddy current probe are connected with electromagnetic field integration in probe coils and are dependant from the probe coils dimensions. So, the ferrite core and coil sizes of developed probe were selected to minimize structural noise connected with large grain size of material.

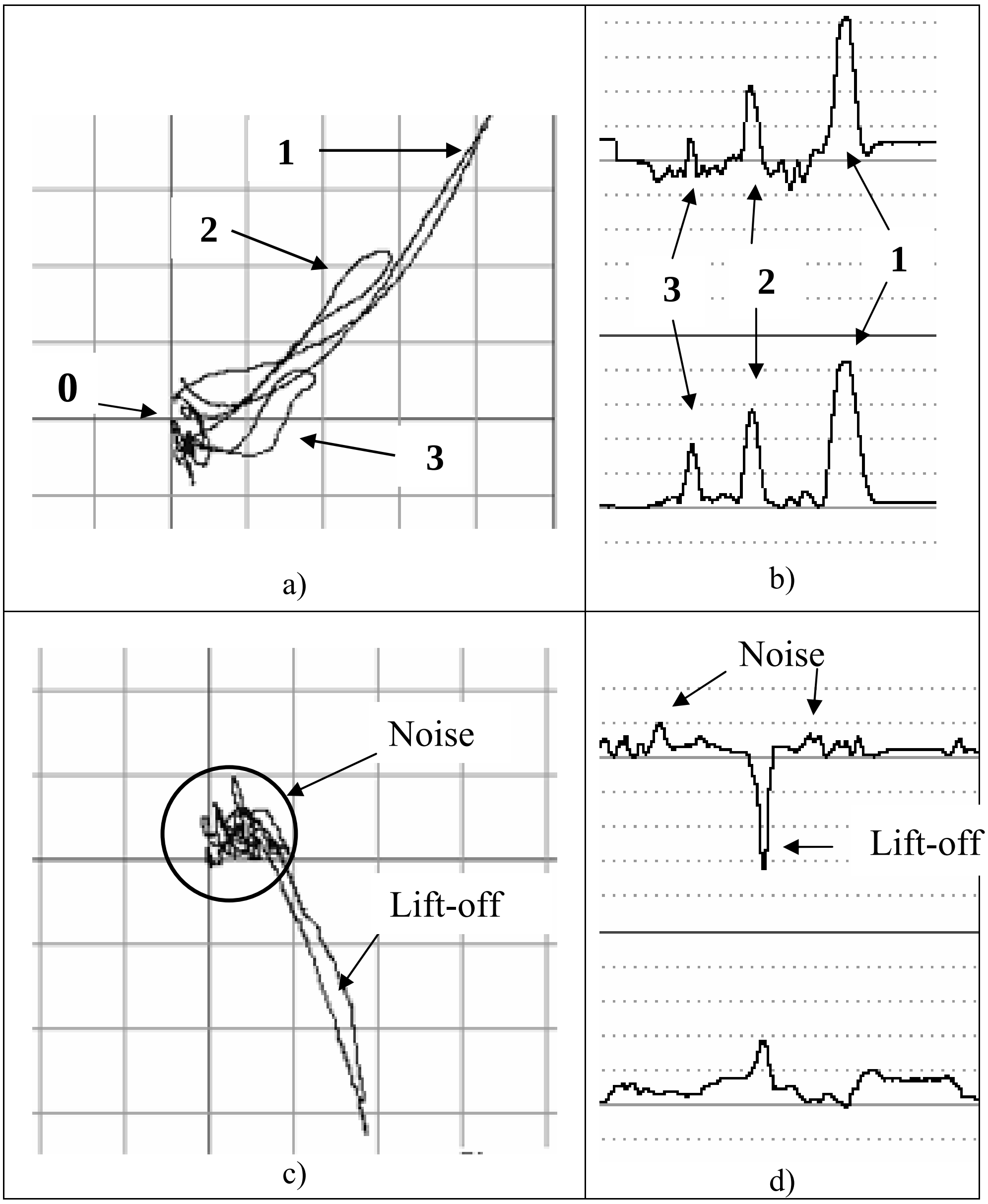

Figure 1. The Leotest 3301 eddy current probe responses obtained for slot with depth of underlying 7,5 mm (**1** on **a** and **b**); 6,0 (**2** on **a** and **b**) and 5,0 (**3** on **a** and **b**) and structural noise and lift-off in complex plane (**a, c**) and in time sweep mode (**b, d**).

The Leotest MDF 3301 eddy current probe sensitivity to subsurface flaws in stainless tube and noise signal responses were investigated with computerized eddy current card EDDYMAX produced by Test Maschinen Technik (Schwarmstedt, Germany). The investigations were carried out on operational frequency 1,5 kHz in which the investigated eddy current probe have the best sensitivity to flaws on inner tube surface. The specimen was produced from the tube fragment in which artificial like crack slots with depth 7,5 mm, 9,0 mm and 10,0 mm were produced by 0,8 mm milling cutter. So, when this specimen was tested from outer tube surface the residual depths of underlying for produced slots were 7,5 mm; 6,0 mm and 5,0 mm (50 %, 40 % and 33,3 % of tube thickness correspondently).

On figures 1-a and 1-b the signal responses from three subsurface slots in complex plane (left) and real and imaginary signal components in time sweep mode are presented. On figure 1-c and figure 1-d the corresponding structural noise signals and lift-off signals are presented. The structural noise was obtained by the without flaw tube part scanning. Structural noise can be observed in complex plane to be marked by circle (figure 1-c) or in time sweep mode (figure 1-d). Lift-off signal was obtained by the probe lifting under the tested tube surface on the distance 3-4 mm. All signal responses on figure 1 were obtained with the same sensitivity for better comparison. From flaw signal responses comparison we can see that signal to noise ratio obtained for the subsurface slot with 7,5 depth of underlying (50 % of tube thickness) and structural noise is more then 6 dB.

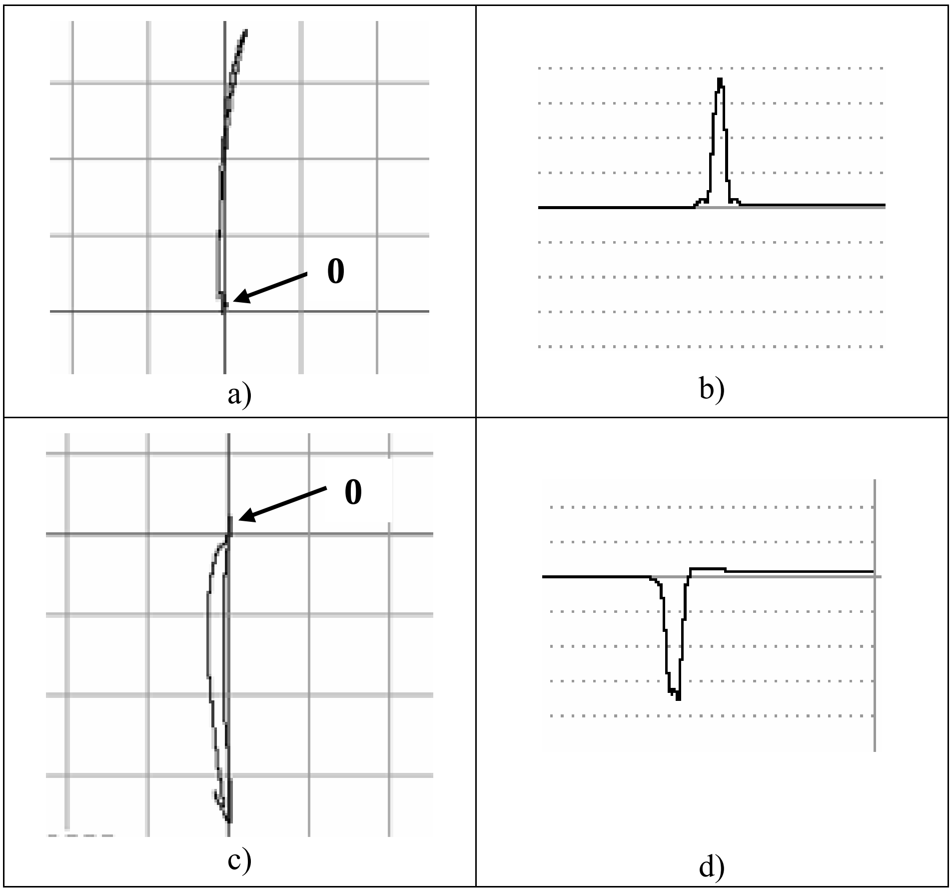

Figure 2. Leotest MDF 3301 eddy current probe signal responses obtained for longitudinal outer surface slots (**a, b**) and for transverse outer surface slots **(c, d**).

On figure 2 the signal responses obtained from surface slots with different orientation relatively to the tube axis are presented. Signal responses were obtained on operational frequency 7,5 kHz with sensitivity level 18 dB less then signal responses on figure 1. On figure 2-a and figure 2-b the signal responses in complex plane and in time sweep mode correspondently from longitudinal slots with depth 5,0 mm are presented. On figure 2-c and figure 2-d the signal responses obtained for transverse slots are presented.

The large lift-off signal on figure can be explained by multidifferential probe orientation relatively to cylindrical tube surface. The multidifferential eddy current probe has good lift-off suppression only in case of plane surface of tested object. When the probe was oriented relatively to cylindrical surface to have best sensitivity to longitudinal slots, the condition of lift-off signal suppression are not violated. But from figure 1 we can see that the possibility to separate the flaw signal responses and lift-off signals can be realized by the difference in signal directions (phase angles) on complex plane. From other side the lift-off signal suppression can be achieved by lift-off stabilization during the scanning procedure.

The remarkable feature of multidifferential eddy current probe to separate the slots by their orientation can be explained from the figure 2. We can see the signal responses obtained from longitudinal and transverse slots are differed with 180 degrees by the direction and different signal response polarity in time sweep mode.

Due good eddy current penetration and noise suppression the developed probes can detect inner 7,5 mm cracks (50% of wall thickness) in 15 mm thick tubes with good signal to noise ratio.

Automated Eddy Current System Development

The obtained results are used in the specialized automated eddy current system “CRAB” created and produced by Ukrainian firm “Promprylad” [7]. The developed eddy current system provides computerized 4-channel 2-frequency stainless steel tube in-service testing and consists of scanner with control card, industrial computer and four identical eddy current cards with four probes. The control card is able to form from 1 to 6 control signals (with current to 1A) and to receive 4 signals from executive mechanisms. Control card receive and process the signals from angle movement sensor also. Each eddy current card generate the needed waveform of excitation signal for be primary coils loading and the output signal processing. All eddy current cards have next parameters:

1. The voltage of generator output — 8 B
2. The maximal generator current — 100 mA
3. Operational frequency range — 100 Hz – 1 MHz
4. The gain factor — 20 – 86 dB
5. The ADC capacity — 12

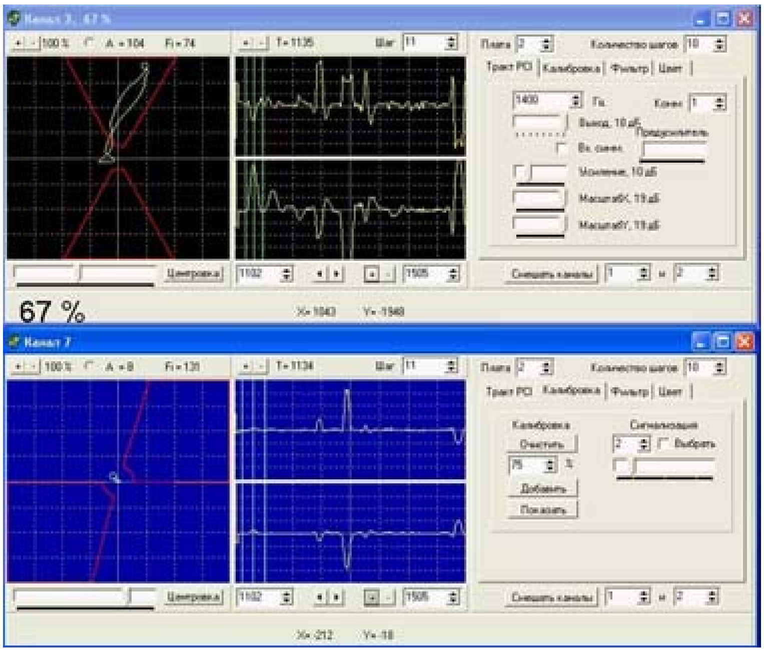

Figure 3. Computer display interface for one eddy current card.

Each eddy current card process signals from one eddy current probe on two operational frequencies - 1,5 and 5,0 kHz. It is needed to provide the possibility to identify the detected cracks by the displacement on inner or outer surface of tested tube. The computer display interface for each card eddy current signal response observing and testing parameters controlling is presented in figure 1.

The eddy current system CRAB has possibility to indicate changes of eddy current probe signal vector in complex plane or components of signal in time sweep mode (see figure 3). For automatic flaw alarm each channel can be provided from 1 to 4 alarm zones by amplitude and phase. There is possibility to build the developed view of selected tube sector surface or tube surface for inner (ID) or outer (OD) defects.

In testing mode it is possible to observe signal responses from four eddy current probes cards on 2 operational frequencies simultaneously (see figure 4).

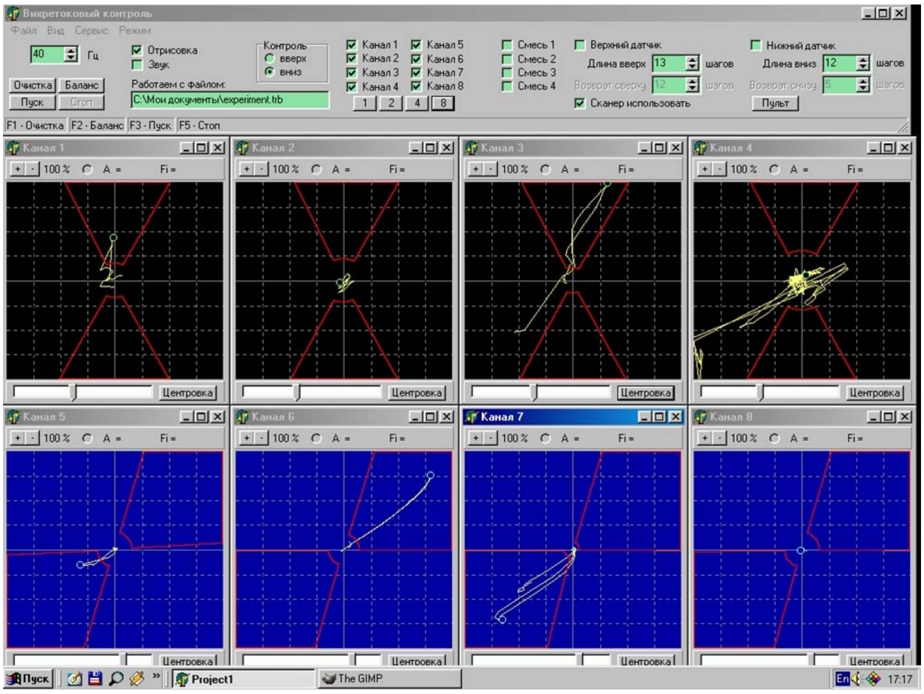

Figure 4. The signal responses obtained from 4 eddy current probes on 2 operational frequencies.

The systems software allows storing all data for further analyzing and documentation. During analyzing process the depth of detected crack is sized in per sent of tube thickness independently of their displacement.

The scanner system controls the simultaneous moving of four eddy current probes, each of which provides the evaluation of corresponding tube sector by zigzag trajectory. Each of eddy current probes has independent hinge suspension and move in circumference direction along sliding guides that are formed from two connected half-rings.

After the one tube part tube testing was completed the scanner system move to the next tube part. The scanner system holding on the tested tube and the displacement to the next zone was provide by two clamping platforms. Scanner system is moved and controlled with the application of compressed air by pneumatic mechanism. Such solution provides the noise increasing due the electrical motor absence in zone of eddy current probes location. The scanning speed in longitudinal direction is 1 m/min. The scanner construction provides the possibility to install it from cylindrical part of tube (not only from the tube end). Such construction allows the providing the testing of tube under repair.

A picture of installed on tested tube scanner system can be seen in figure 4.

Figure 5. Four probe automated scanner system installed on tested tube.

The test and sensitivity investigations of the automated system CRAB were carried out on samples made from real tube fragments with longitudinal and transverse like crack artificial flaws on outer and tube surface. From investigations the sensitivity limit in real condition was estimated as the 10 % for outer surface slots and 50 % for inner surface slots.

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Conclusions

- The automated eddy current system CRAB for in-service detection and identification of like crack flaws situated on different side of 15 mm thick stainless steel tubes was developed and presented.
- The sensitivity and eddy current probes penetration ability provide the safe detection of 7,5 mm deep cracks (50 % of wall thickness) situated on inner wall surface.
- The automated eddy current system CRAB also provides the next properties:
  - Automated 4-channel 2-frequency eddy current testing with special 4-probe scanner;
  - Crack identification by displacement on outer or inner tube size and orientation;
  - Detected crack depth (in % of wall thickness) and length estimation.

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