Enhancement of Technical Parameters of Eddy-Current Flaw Detectors Designed for Lengthy Metal Products On-Line Examination

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Abstract. Developed are methods of improvement of signal-to-noise ratio of eddy-current flaw detectors with encircling transducers used in the process of automated inspection of tubes and rolled products. The positive results obtained due to suppression of noise generated due to metals structure and mechanical inhomogeneities; caused by impacts of produced tube and rolls of carry-over table and increase of sensitivity towards long flaws with smooth lead-in areas are discussed. To solve the task used are additional test coils, metal screens and combined transducers of special design.

Introduction

In electromagnetic flaw detection the main disturbing the examination process parameters are the structural and mechanical (due to internal local stresses) noises generated by metal inhomogeneity. Such noises are considerably increasing when examination of tubes fabricated of high-strength ferromagnetic steel alloys is performed. They also are rather high during testing of items made of stainless steels (nonferromagnetic types). Noises caused by structural nonuniformity strongly reduce value of signal-to-noise ratio (SNR). If SNR becomes less than 2 the testing results cannot be treated as valuable and considered as unacceptable. It is known that simultaneously with increase of tested tube diameter the SNR parameter of encircling transducers is reducing; this phenomena becomes even more evident when examined tubes diameter is above 80-100mm.

To suppress noise from structural nonuniformity in the process of ferromagnetic steel items testing usually implemented is technique of tube longitudinal magnetization by means of magnetostatic field or used are differential transducers or frequency filtration of informative signals [1]. Still, in some cases, when during production the pack of “noisy” tubes appear (and in working environment this is a random process) the RNS can happen to be less than 2, hence the results of testing will be below allowance norms. That is why the development of new methods of reduction and suppression of noise caused by structural nonuniformity is of great importance [2]. Below a number of such methods is presented.

1. Obtained results

1.1 First method

The method is based on use of encircling eddy-current transducer (ECT) with angle asymmetry of electromagnetic field. The asymmetry is achieved due to use of special screen with four notches that are spaced apart along the transducer length. The design scheme of such ECT is presented in Fig. 1.

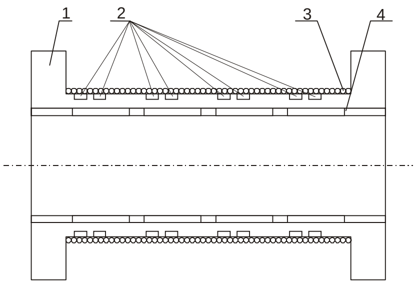


Fig. 1. Design of encircling ECT with asymmetric field created due to presence of special screen.

The ECT comprises the exciting winding 3, four pairs of differential measuring windings 2 and screen 4. The screen design is demonstrated in Fig. 2. It presents cupper or aluminum piping with four notches displaced relative to each other along angle coordinate on 90°. The notches are spaced apart along the transducer length and placed in the areas where pairs of differential windings mounted. In such a manner four sources of electromagnetic field interacting with four tested areas of examined object are created.

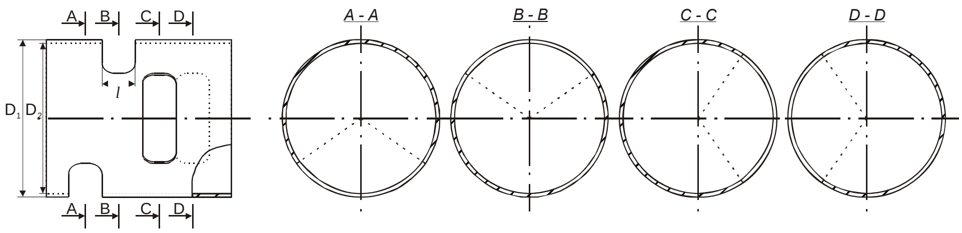


Fig. 2. Screen design.

Such scheme provides covering of the perimeter of the object with improved examination locality.

In Fig. 3 presented are curves of distribution of longitudinal H_z component of variable magnetic field along the angle coordinate φ. The curves 1, 2 & 3 are drawn for values of sector angle $\varphi_T = \frac{\pi}{6};\frac{\pi}{4};\frac{\pi}{3}$. The curves $H_z = f(z)$ are shown in Fig. 4. The curves 1, 2, 3 present results obtained for notch width z^* = 0.9; 0.5; 0.4 mm correspondingly. From figures 5 & 6 it is clear, that the electromagnetic field is mostly concentrated within the area of notch (approximately 80%), therefore the localization of the examination when using the screen is determined by the sizes of an arc-like notches. If its sector angle is equal to $\varphi_S = \frac{\pi}{2}$, i.e. four times less than the inspected object perimeter ($\varphi_T = 2\pi$), so also noise level will be reduced four times. If the signal generated by defect is kept approximately the same then the signal-to-noise ratio will increase approximately in 2.5÷3 times.

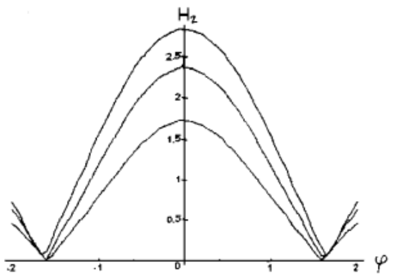


Fig. 3. The curves of H_z distribution along angle coordinate **φ**

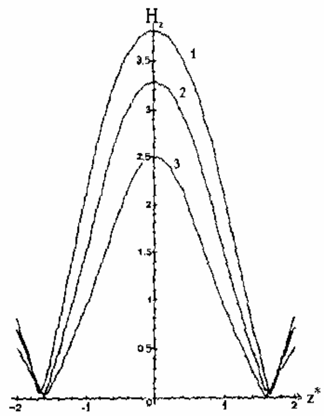


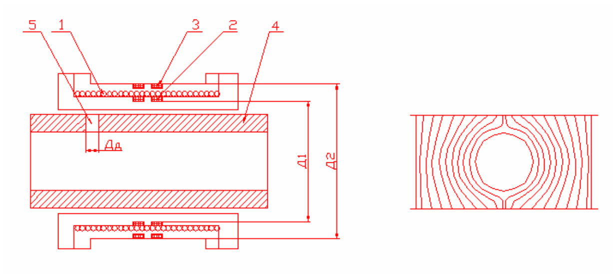
Fig. 4. The curves of H_z distribution depending on the notch width Z

1.2 Second method

This methods is based on the fact that depending on the distance between defective area of the examined tube and measuring winding of the encircling ECT the signal generated by defect and noise signal are distributed along the scanning directions but along different curves: the shape of noise signal practically does not change while the signal from the defect varies significantly. With increase of the distance from the defect, its field becomes less local, i.e. the distribution of the field intensity along the direction of scanning is presented by more smooth curves. After differentiation of such signals their amplitude drops strongly. That is why, if for informative signals measurement to use two pairs of differential measuring encircling windings with different radius, in the windings with smaller diameter will be induced the signals from defect and noise, while in the winding with bigger radius mostly will be induced the signal from noise while signals from defect will be attenuated several times. After subtraction of signals on the output, it is possible to select signals from defects and suppress noise signals. The verification of this statement was carried out with the help of artificial defect fabricated in accordance with relevant international standards ISO, DIN, API and Russian standards (GOSTs) that are traditionally used for normalization of sensitivity threshold level of flaw detectors with encircling ECT. For such a defect usually used are drilled holes of various diameter and depth depending on the diameter of tubes or rods. For the tube, the drilled depth is determined by the wall thickness and hole is a through-drilled type. For the rods, the drilled depth is usually 0.5 – 1.0 mm.

In Fig. 5a presented is the model of encircling ECT with two pairs of differentiating measuring windings. The examined object is a tube with artificial defect in the form of through-drilled hole of certain diameter D_d. The winding #2 for defects detection has diameter D_1 (space factor η_1); the winding #3 for noise signals suppression – diameter D_2 (space factor η_2). At the same time, $D_1 < D_2$ and $\eta_1 > \eta_2$. The signals differentiation by the measuring windings is performed along the tube longitudinal axis.

The current winding #1 creates variable electromagnetic field, the vector-potential of which and hence the vector of eddy current in isotropic media has only A_φ and I_φ components. Electromagnetic field generated in the area of defect presence is formed due to redistribution of initial eddy currents I_φ that bend around the defect both sides (see Fig. 5b).



a) b)

Fig. 5. The model of the encircling eddy-current transducer with two differential pairs of measuring windings and examined item in the form of trough-drilled hole

The accurate solution of the task of the distribution of electromagnetic field in cylinder with round through type hole though is possible but is very difficult. If to take into account only dependence of the filed parameters from the distance ρ (Fig. 5a) the defect can be presented in the form of current lay of given radius $R_S \approx 1.5 \div 2R_d$, where R_d – the defect radius.

Then in cylindrical coordinates ρ, φ, Z adhere with the defect coordinates the strength of magnetic component of field generated by the defect is described by the formula:

$$H_\rho = \frac{I}{2\pi\rho}\frac{Z}{\sqrt{(R_S+\rho)^2+Z^2}}\left[\frac{R_S{}^2+\rho^2+Z^2}{(R_S-\rho)^2}E(k)-K(k)\right] \qquad (1),$$

where *E(k)* and *K(k)* – full elliptic co-ordinates; $k^2 = \frac{4R_S\rho}{(R_S+\rho)^2+Z^2}$.

If to introduce the relative values $\rho^* = \frac{\rho}{R_S}, Z^* = \frac{Z}{R_S}$, than (1) may be presented as follows:

$$H_\rho = \frac{I}{2\pi\rho^*}\frac{Z}{\sqrt{(1+\rho^*)^2+(Z^*)^2}}\left[\frac{1+(\rho^*)^2+(Z^*)^2}{(1-\rho^*)^2+(Z^*)^2}E(k)-K(k)\right] \qquad (2)$$

In Fig. 6 the curves of distribution of H_ρ along coordinate ρ for various values of Z are presented. The curves drawn based on H_ρ calculations with the help of (1) and use of Maple5 software package.

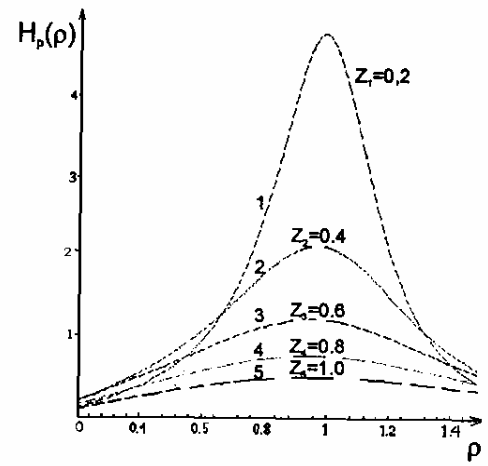


Fig. 6. The curves of Hρ distribution along coordinate ρ for various values of Z.

From Fig. 6 it is evident that simultaneously with Z increase besides decrease of value H_ρ the change of curves $H_\rho = f(\rho)$ shape happens (the curves become more smooth). For value Z_1 the distribution is presented by curve 1, for Z_2 – curve 3. The value of the derivative $\frac{dH}{d\rho}$ will be as less as more smooth is the function $H_\rho = f(\rho)$.

That is why in case when the pairs of differential measuring windings will be spaced out at the required distance, for example Z_2 and Z_4, the signal generated by the defect and present in upper winding will be essentially attenuated. As experiments showed the shape of noise signals will vary insignificantly with the growth of ρ. That is why it is possible to separate out the signal generated by defect and suppress noise if to adjust the gain factor of measuring circuit of upper winding in such a manner that noise signals in both channels will be equal and after that to subtract these signals with the help of differential amplifier.

This method helps to suppress noise and to increase RNS value proportionally to the noise level. This technique is of special practical use in terms of poor tube and rode magnetization that sometimes happen on-site when for examination of items used is longitudinal constant magnetic field. The poor magnetization reveals itself by noise with shape close to sine. It seems the phenomena can be explained by periodical loads applied to metal in the process of rolled metal cogging. In these cases the RNS on the measuring scheme output is much less than 1. Proposed method makes it possible to increase the RNS by order.

1.3 Third method

The technique discussed in this paragraph provides system high sensitivity towards long defects with smooth lead-in areas. The classical differential encircling ECTs practically do not reveal such defects. The use of well known ECT with absolute measuring winding is low efficient due to low value of RNS. This statement is especially correct when to talk about detection of longitudinal flaws with relatively small depth (about 10% of tube wall thickness). In Fig. 7 presented is the layout of windings in combined ECT as well as scheme of their connection to measuring channels.

The presented ECT consists of two bushes: stator 1 and rotor 2 ones. Rotor bush is rotated by motor 3. On the stator bush placed are exciting 4 and two pairs 5 & 6 of differential coils. On the rotor bush placed are two differential winding pairs of encircling type (8 & 9) and four pairs of surface differential windings 7-1; 7-2; 7-3 and 7-4. This windings are coiled on longitudinal ferrite cores and placed on dual grooves axes which are oriented along transducer axis (see Fig. 7b). The distance between grooves is d, where d is ferrite core diameter. The angle displacement between two neighboring longitudinal groove pairs is $\varphi = \frac{360}{m}$. When m=4, $\varphi = 90^0$ exciting winding W_{exc} is connected to AC generator. Surface pairs of measuring windings $W_{11}^7; W_{12}^7; W_{21}^7; W_{22}^7; W_{31}^7; W_{32}^7; W_{41}^7; W_{42}^7$ are connected in parallel and further connected to encircling differential pair of measuring windings $W_{11}^9; W_{12}^9$. While windings $W_{11}^9; W_{12}^9$ and $W_{21}^6; W_{22}^6$ form rotating transformers and provide signals (generated by surface windings) transfer to measuring circuitry. The second pair of rotating transformer is formed by encircling windings $W_{11}^8; W_{12}^8; W_{21}^5; W_{22}^5$. Here the signals are formed in rotor measuring winding $W_{11}^8; W_{12}^8$ and transferred to stator winding $W_{21}^5; W_{22}^5$. To increase the transfer constant the rotor measuring winding 8 is connected to resistor load R_{load}. Tested item (tube) 10 with long 11 and short 12 defects is moved with set forward speed V. Eddy currents induced in the tube are redistributed in defective areas, i.e. flowing around the defects, as an area with infinitely large resistance. The signals induced in measuring windings transferred to stator to be processed in measuring channels.

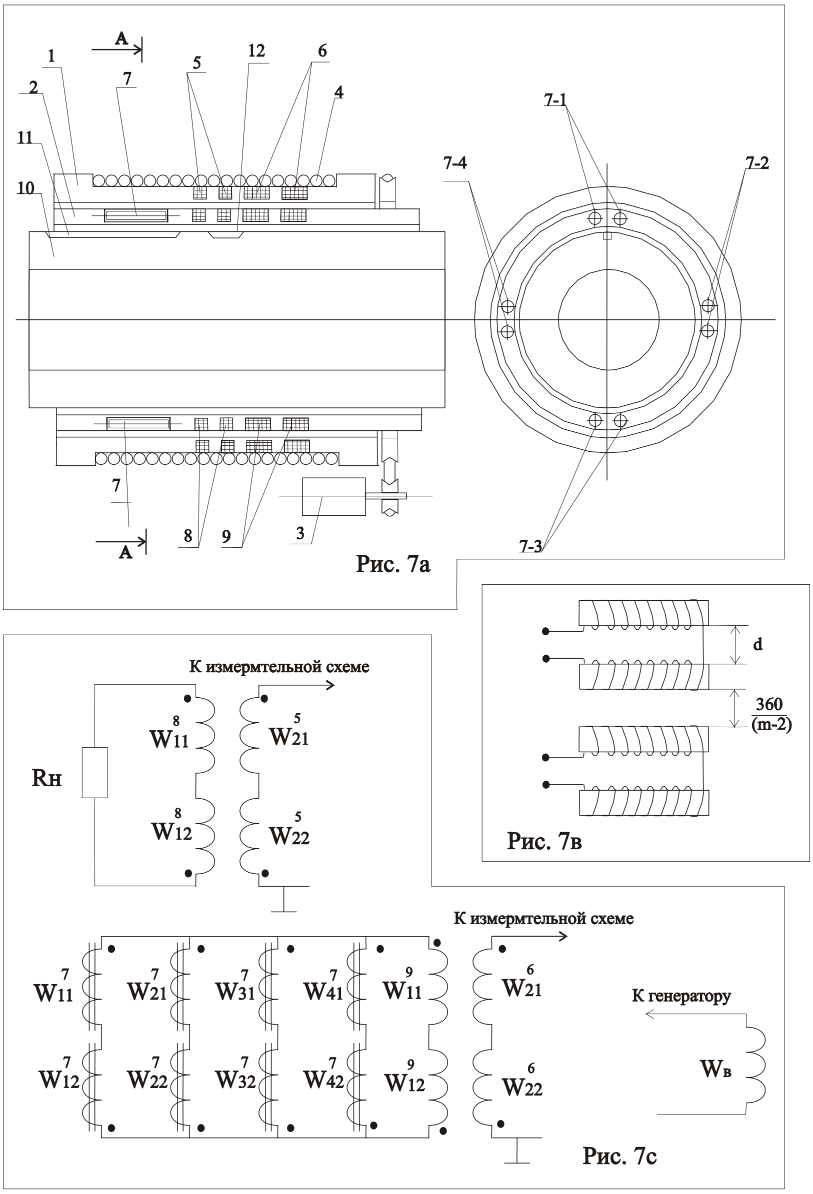


Fig. 7. Layout of windings in combined ECT and scheme of their connection to measuring channels.

In this case the long defect will induce in measuring windings 8 practically zero signal as along the axis of scanning the field value practically does not change.

At the same time in the direction of rotation the change of field from long defect is strong enough (has large gradient) and due to this the rotating surface transducers will induce signal with level enough for further processing. Ferrite cores considerably increase the sensitivity. This improvement also is explained by location of cores inside exciting core close to current turns. Short defects at rather high forward velocity V can be missed by surface transducers, but in this case they will be detected by windings 5 of encircling type.

1.4 Forth method

This technique of enhancement of the examination reliability in case of encircling ECT use is based on suppression of the pulse disturbances caused by impacts between examined item (for example, tube) and carry-over table' rollers (such pulses occur due to impact between examined item (for example, tube) and transportation roll table' rollers). The generated in the ECT measuring windings pulses cannot be suppressed by methods of standard frequency filtration. The proposed idea is as follows: the encircling ECT is fabricated with additional pair of measuring windings displaced along longitudinal axis of ECT at fixed distance L (in case when the block has four pairs of measuring windings see Fig. 1 – the outer windings (2) are used). The output signals from second additional pair are processed by additional measuring channel which parameters are similar to those of main one. In this case the pulse disturbance signals occur practically simultaneously in both windings while informative signals occur sequentially: at first – in the first (relative to longitudinal motion of the tube) measuring winding pair and then in the second one with the time delay $\Delta t = L/V$, where L – the distance between windings, V – velocity of forward motion of examined item. The delay time is calculated by microprocessor based on actual values of parameters L and V.

2. Discussion of results

The method of disturbances suppression by means of introduction of additional channel is as more efficient as higher is the noises level. When the SNR is less than 1 the use of this method increases its value by order. In Fig. 8 presented are experimental oscillograms of signals from defects selection on the background of structural heterogeneity. In Fig. 8a presented the case when noise level exceeds level of signal from defect (examination of the oil-well tubing fabricated from steel 32G2, ∅ 33mm; wall thickness 5.5mm with artificial defect ∅ 2.2mm). The value of the SNR increased more than by order. In Fig. 8b presented is the case when noise level is below the level of the signal from defect by several tens of percent. The increase of SNR in this case is approx. 2-3 times.

In Fig. 8 presented oscillograms obtained with the help of experimental installation developed for testing of tubes with diameters 42; 73; 114 & 146mm with the help of encircling ECTs of two types:

- ❖ Encircling pair differential measuring windings;
- ❖ Encircling transducer with screen.

The curves were obtained for space factor $h \approx 0.8$. The sizes of arc-like notch: sector angle $\varphi_n = \pi/2$; notch width $l_n = 12$ mm.

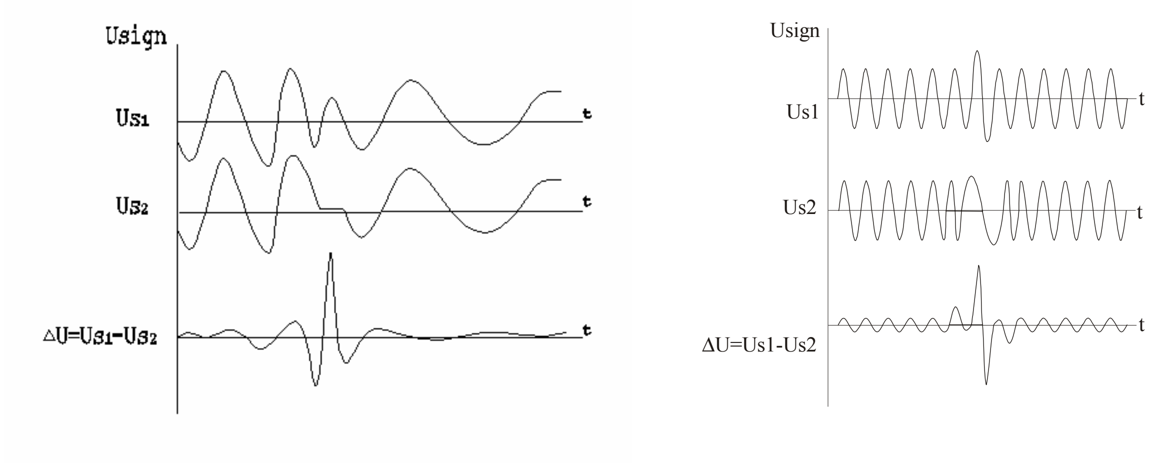


Fig. 8. Experimental oscillograms of signals from defects selection upon background with the help of technique of spatial filtration.

On the other hand from oscillograms shown in Fig. 9 it is clear that use of screen, depending on the tube diameter, helps to increase the SNR by 2-3 times. When standard (classical) encircling ECT is used the SNR decreases approx. 2-3 times when the tube diameter is increasing. For encircling ECTs with screen the SNR value is approximately equals to 2-3 for all diameters of tested tubes.

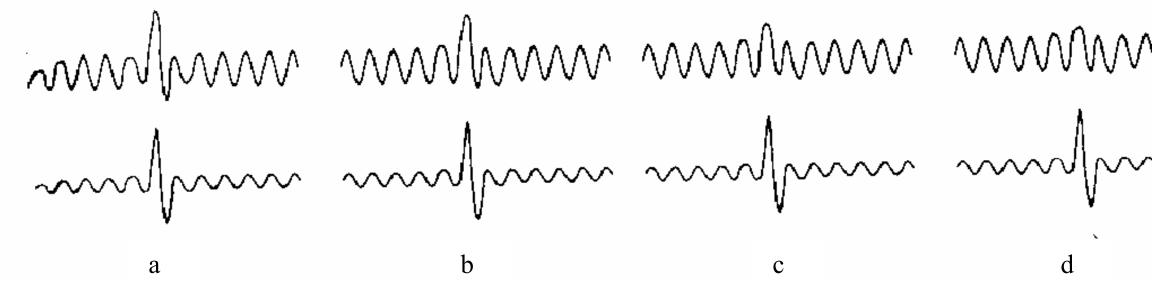


Fig. 9. Oscillograms of signals from defects registered during examination of tubes with diameters 42 (a); 73 (b); 114 (c) & 146 (d) mm.

Described methods are implemented in the developed industrial eddy-current flaw detector VD-41P [3]. The equipment introduced at the industrial facilities in Russia, Ukraine and Moldova. It passed long-term trails that proved efficiency of proposed methods for enhancement of the examination reliability. The examination reliability increased from 80-85% to 95-98%.

Conclusions

Developed methods of improvement of technical parameters of flaw detectors with encircling differential transducers provide:

- Approx. 2-3 times increase of the signal-to-noise ratio due to implementation of specially shaped metal screens forming the electromagnetic field transformers that cover the whole perimeter of examined cylindrical object and have four parallel field sources displaced relative to each other on 90° and at a set distance along longitudinal axis.
- Increase of the SNR approx. by order when testing items with increased noise generated by metal structural and mechanical nonuniformity due to introduction of additional pair of differential measuring windings remote from tested object to great distance. This make it possible to select signals from defects with amplitude level less than noise level.
- Reliable detection of long longitudinally oriented defects with smooth lead-in area due to implementation of combined ECT of special design.
- Suppression of pulse like disturbances of any level occurring in the measuring channels in case of tubes impact with rolls of carry-over table.

References

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