Modern methods of improvement of efficiency and trustworthiness of flaw-detection eddy-current automated online testinh of high-volume metal products.

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Abstract

Sever technical requirements are imposed on the flaw detection equipment in the process of on-line testing of rolled products and tubes. That is why, in addition to commonly used testing methods, electromagnetic methods (i.e. eddy current and magnetic) are widely used in the process of metal products fabrication. Most widely are used the flaw detectors with encircling eddy current transducers (ECT). Continuously increasing quality requirements towards testing procedures and equipment explain necessity to develop new examination methods and instruments.

In the paper will be presented two methods on enhancement of signal-to-noise ratio ($K=U_{defect}/U_{noise}$) as well new design of combined transducer (encircling type exciting winding and rotating measuring winding of attached type) providing reliable detection of long longitudinal defects. The coefficient K increase is achieved due to use of special shape metal screen (used for tubes diameters 100÷220mm) or additional noise suppression channel. As a signal source for the last one used is an additional differential pair of measuring winding with dia. D_{noise} bigger than one of the basic winding used for defect evaluation ($\varnothing D_{noise} >> \varnothing D_{defect.}$). Signals generated by noise on both windings are aligned and subtracted on summator while signals from defects induced only in basic winding are separated for further processing. In discussed case the defects can be revealed for SNR – $K<<1$.

Discussed is the technique of eddy-current and magnetic testing methods combination for systems with attached type transducers. Moving tube is magnetized through by transverse constant magnetic field. Magnetic leakage field over defects is measured by means of Hall sensors set. Revealed defects are classified as surface (signals from ECT and Hall sensors) and internal ones (signals only from Hall sensors).

Developed industrial eddy-current flaw detectors VD-41P and VMD-30N (combines eddy-current and magnetic methods) passed practical trails at leading pipe-mills in Russia, Ukraine, Moldova, Kazakhstan. The examination reliability reaches 93-95% in comparison with previous level of 70-80%.

Key words: eddy-current flaw detector, encircling transducers, on-line inspection, noise-to-signal ratio, examination reliability

Introduction

When inspecting pipes and rolled metal in flaw-line production, severe requirements are set for the flaw detection equipment. It should be highly efficient (~100÷200 items/hour), operate in severe conditions (at temperatures 5÷50^{0}C, high humidity, high dust level, dirtiness of pipe surface, the presence of cinder), evaluate defects automatically, etc. That is why in flaw-line production the electromagnetic testing methods (eddy current and magnetic) are widely applied together with other methods. The flaw detectors with encircling ECT are more often applied. They are used to inspect 95% of thin wire (diameter 0.05÷3 mm); up to 80% of electric-welded pipes (diameter 10÷114 mm) in flaw-line of arc welding sets; great volume of hot-rolled and cold-rolled pipes and rolled metal (diameter up to 100 mm); 95% of pipes and rolled metal of a nonround shape (square, rectangular, hexagous shape). Along with the high operational characteristics, the eddy-current flaw detectors with encircling ECT have a number of significant disadvantages. They feature the sensitivity to such dangerous defects as corrosion in metal particularly in the cases when the internal side of a pipe is corroded and the wall thickness is 6÷10 mm especially when corrosion has no clear borders. Low sensitivity is the feature of encircling differential ECT (whereas absolute ECT are inefficient due to low reliability of indications), as well as longitudinal defects with smooth lead-in zones become problematic. The sensitivity of encircling ECT decreases with the increase in diameter of tested objects (more than 100 mm). The well-known disadvantage of eddy-current flaw detectors is also high interference between testing results and structural and mechanical noise from metal discontinuities (internal local stress). Such noise rises when inspecting pipes and rolled metal made from high-tensile alloy-treated ferromagnetic steels. The noise is also high enough when testing objects are made from stainless steel alloys. The noise from structural discontinuities decreases signal-to-noise ratio very much. If s/n ratio is less than two, the inspection becomes unreliable and the results should be admitted negative. To reduce the noise from structural discontinuities when testing objects made from ferromagnetic steels, the longitudinal magnetization of pipes (or rolled metal) by constant magnetic field is commonly used. For this purpose, differential measuring coils and frequency filtering of information signals are used[1]. In a number of cases, however, for “noisy” pipes (that appear in flaw-line production at random), the s/n ratio becomes lower than two and the testing results become unacceptable. The disturbance that is strong enough is impulse noise appearing in the measuring channel of a encircling ECT when a moving pipe hits a roller table. It is not always possible to exclude this hitting by mechanical centering. Such noise is very close to signals from defects by the frequency spectrum. That is why the development of new techniques assigned to eliminate the above disadvantages of eddy-current flaw detectors with encircling ECT is a burning task. A number of such techniques is described below.

1. Technique for noise reduction from structural and mechanical discontinuities in metal[2]

The technique is based on different dependences between signal and noise as well as a defect of radial direction. Electromagnetic scattering field from defect is mainly concentrated near the defect zone approximately 1-2mm under pipe surface. The scattering field around the defect is concentrated in a narrow zone, and field force curves feature significant slope. When the distance to the pipe increases, the defect field spreads out, i.e. the field force distributes smoother along the scanning direction. The field force distribution from structural discontinuities along the scanning direction at 5÷10 mm above the pipe surface changes insignificantly. When differentiated by scanning directions via differential measuring coils, the signals amplitude will depend on the field dissipation shape at the measuring distance. The lower the field gradient is, the lower the output signal is. Fig. 1 shows an ECT design where a number of techniques employed to enhance technical characteristics of eddy-current flaw detectors with encircling ECTs.

An ECT consists of an excitation coil 1 and three measuring differential coils 2, 3, and 4. A tested object is a pipe with a defect of an open-ended type with the diameter – D_{∂}. Coil 2 has the diameter D_1 (η_1 – space factor), and coil 3 with D_2 and η_2, thereat $D_1 < D_2$; $\eta_1 > \eta_2$. The signals are differentiated by the long axis of the pipe.

Figure 1.b shows the graph of scattering field force distribution versus defect H_ρ along the coordinate ρ (cylindrical coordinate system). The growth of Z, besides H_ρ fall, is shown to change the curves shape of $H_\rho = f(\rho)$ (become smoother).

The lower derivative of function $\frac{dH}{d\rho}$ is, the smoother the function $H_\rho = f(\rho)$ is. Therefore, differential couples of measuring coils are located correspondingly from the pipe surface (diameterD_1 and D_2), the defect signal in the upper coil being significantly attenuated. The experiments show that the shapes of signals from structural discontinuities at 3÷8 mm above the surface change a little. That is why, if to make the noise signals equal in measuring channels of both coils (by means of the amplification gain adjustment of the upper coil channel), then substrate two signals by an adder circuit, at the output we will have a defect signal, and noise signals will be suppressed at high extent.

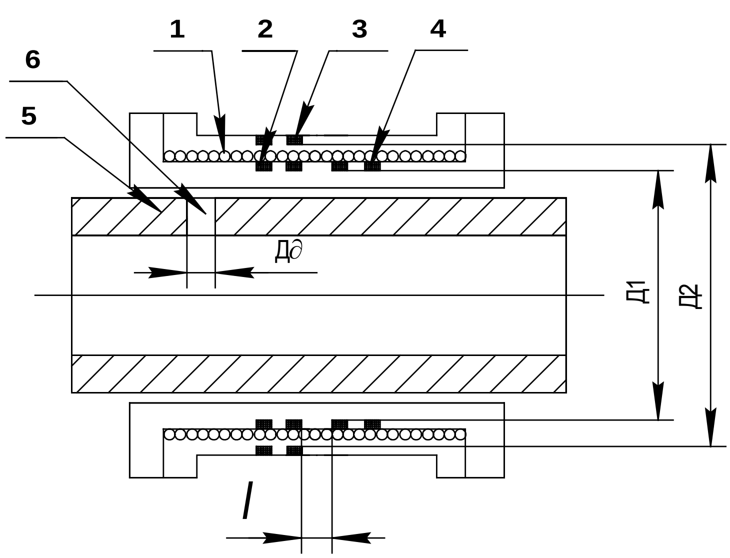


Fig 1.a Design of encircling ECT added by differential coil

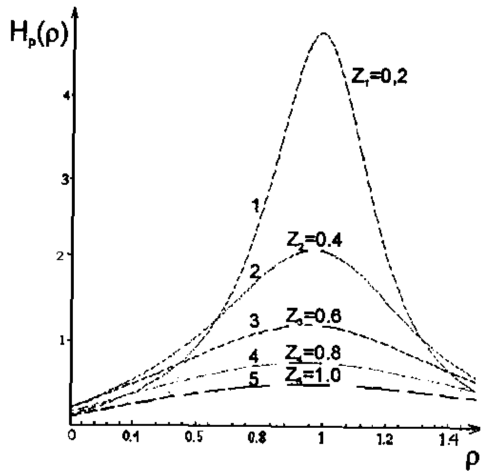


Fig 1.b Distribution of H along coordinate for various values Z

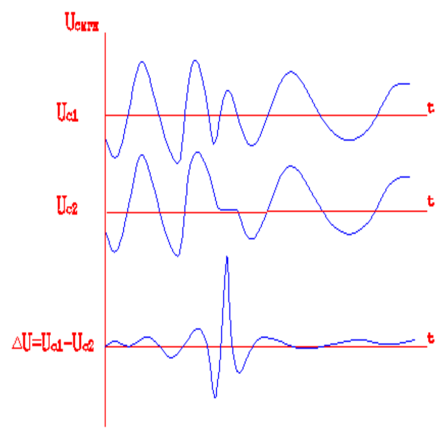


Fig 1.c

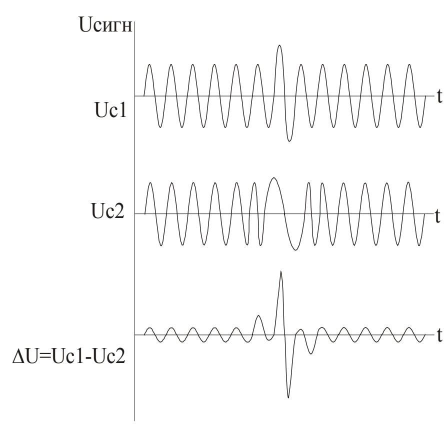


Fig 1.d

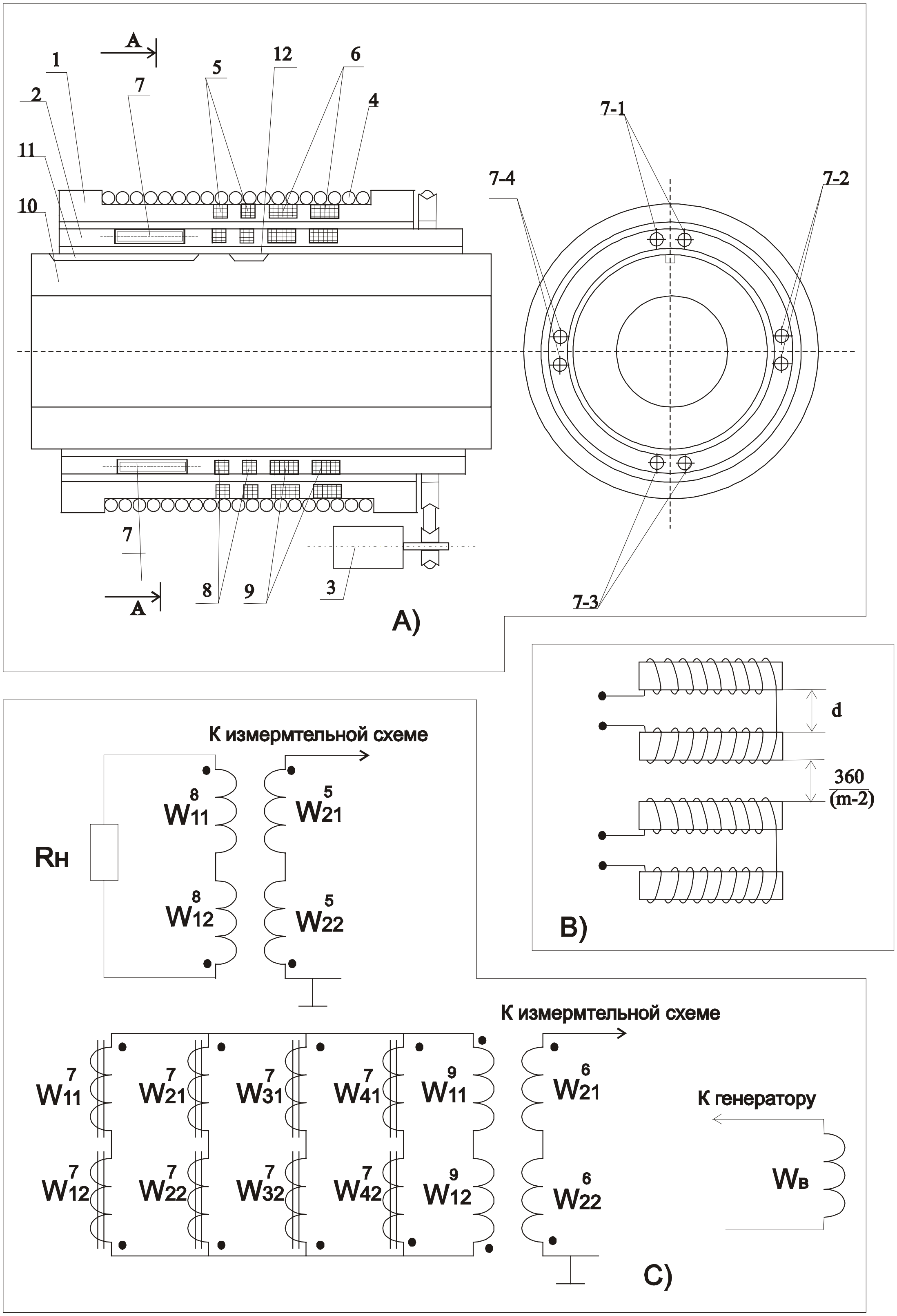


Fig 1.e Scheme of placement and connection of encircling transducer of combined type

Fig. 1. New design of encircling ECTs

2. Technique for the reliability enhancement in detection of axial defects

The technique is directed to the leap of sensitivity to longitudinal defects with smooth lead-in zones. The classical differential encircling ECT is scarcely capable to detect such defects. The use of an absolute measuring coil is inefficient due to low reliability of testing (high influence of noise from structural discontinuities in metal and cross movement of an object). The use of a combined ECT appears to be more effective[3]. The design of such transducers is shown in Fig. 1.e.

The transducer consists of the stator and rotor hubs. The rotor hub 2 is moved by an electric engine 3. The stator hub carries the excitation coil 4 and two couples of differential measuring coils 5 and 6. The rotor hub carries two differential couples of coils 8 and 9 of a encircling type and four couples of laid-on differential coils 7-1, 7-2, 7-3, 7-4. These coils are winded around the longitudinal ferrite rods and are placed into the coupled longitudinal grooves, with the distance between them being equal to the diameter of the ferrite rod *d*. Fig. 1.e shows four couples of laid-on coils, but the number of them can be 8, 16 depending on the testing speed and the length of a minimal defect to be detected.

The differential couples of encircling measuring coils 5 and 6, 8 and 9 are correspondingly winded around the stator and rotor hubs. They form rotating transformers and serve as signal transmitters from the rotor hub to the stator one. The laid-on coils 7 help to detect longitudinal defects including the ones with smooth lead-in zones. Short defects are detected by the encircling coils 8. A part of defects are detected by the coils of both types, e.g. long cracks with sharp boundaries along the pipe axis.

3. Technique for impulse noise tuning-out

This technique considerably enhances the testing reliability with the use of encircling ECT and is intended to reduce impulse noise appearing when a tested object (e.g. a pipe) hits the rollers of a processing table. Such impulses appear in the measuring coils of ECT and cannot be reduces by the conventional methods of frequency filtration. The offered method employs the use of a encircling transducer manufactured with an additional couple of differential measuring coils that are shifted along the longitudinal pipe axis by distance l (Fig. 1.a – design of a encircling ECT added by differential coil 4).

The signals from this coil are processed by an additional measuring channel similar to the basic one. In this case the impulse noise appears in both coils simultaneously but the information signals appear sequentially: firstly, in the first coils couple, then in the second one with the time delay $\Delta t = l / v$, where v – longitudinal speed of the object movement. The time delay is calculated by the microprocessor on the basis of the input data l and v.

The signals appeared in both channels simultaneously are considered spurious. The criterion for the signal from defect is the impulse from the second measuring channel in Δt time after the one in the first channel. The tuning-out algorithm runs under the software.

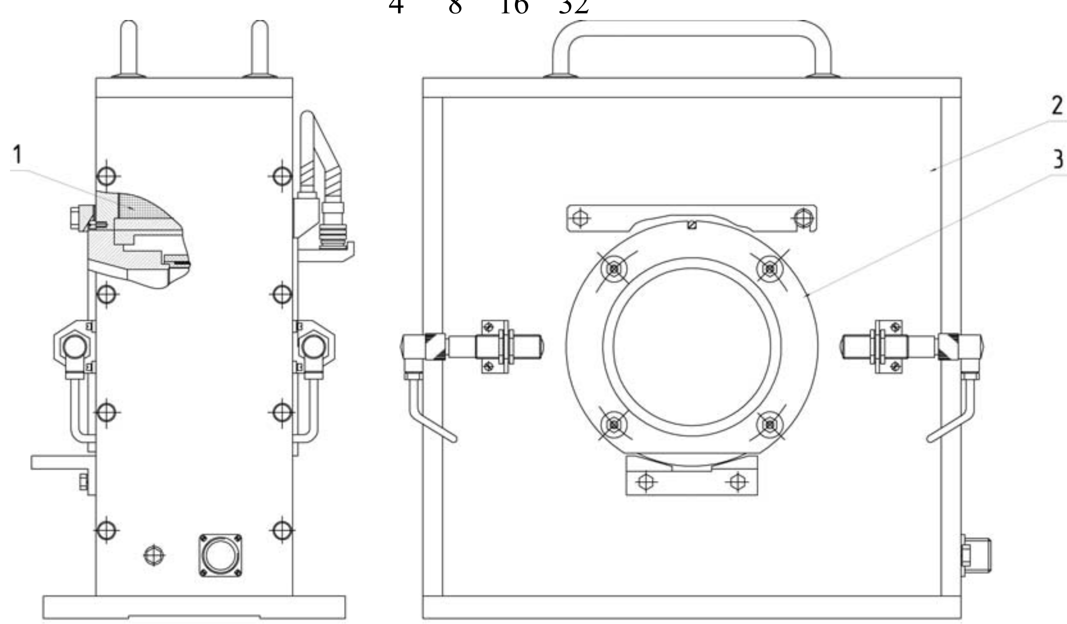
4. Technique for the division between surface and internal defects

The technique rests upon the joint use of eddy-current and magnetic testing methods for pipes with the use of laid-on ECT and Hall transducers.

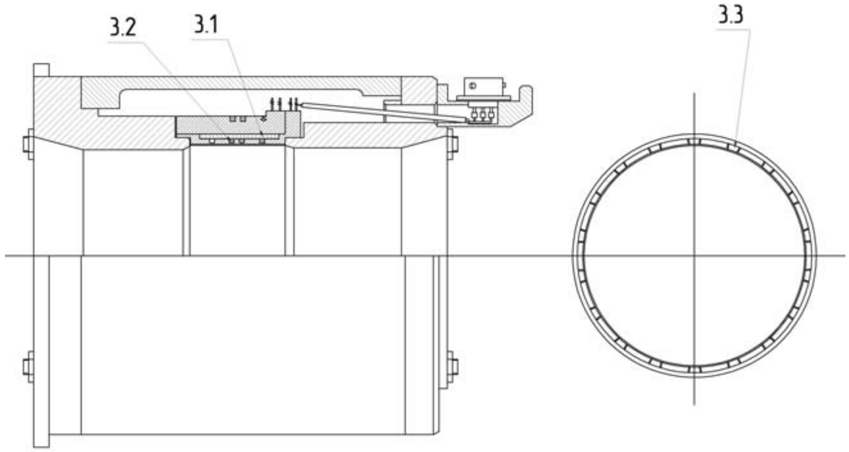
A progressively moving pipe is magnetized by cross magnetic field. The set of laid-on transducers is placed above the pipe. Two types of transducers – eddy-current and variable inductance transducers (Hall transducers) – make up the set. They pick up constant magnetic field above defects that is formed when a pipe is magnetized in cross direction. The field of eddy-currents (f=300Hz) is used to detect surface defects (penetration of the field – 1.5-2 mm). The constant cross magnetic field detects both surface and internal defects. Signals that appear simultaneously in variable inductance and eddy-current transducers are formed by surface defects; signals of variable inductance transducers only are formed by internal defects located mainly on the internal side of a pipe wall. The operating principle of defects division is programmable in industrial equipment.

5. Technique for joint use of alternating and constant electromagnetic field

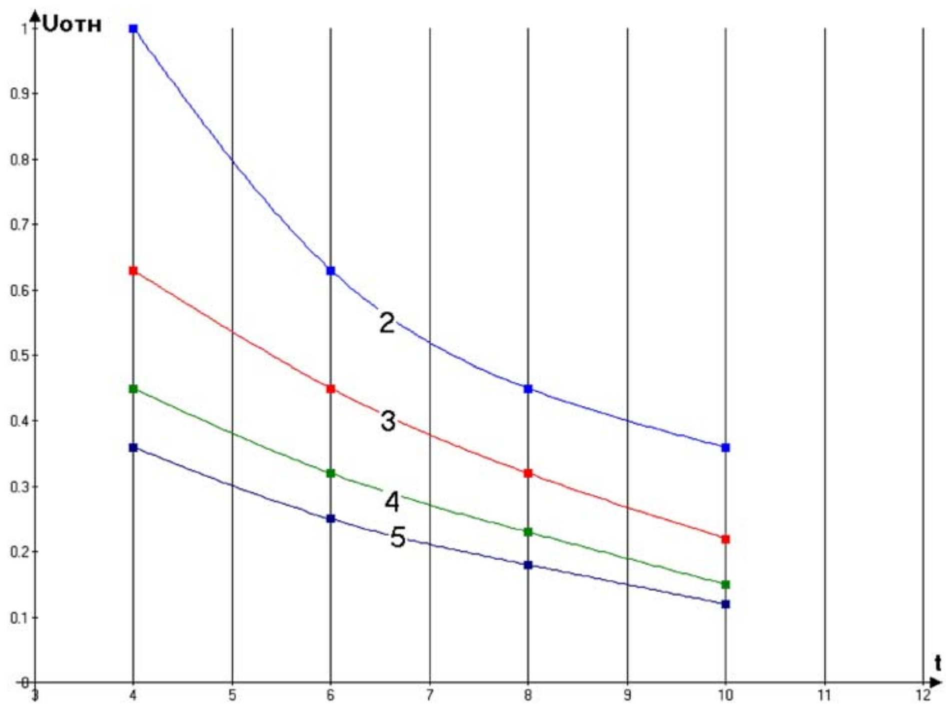
In eddy-current flaw detectors with encircling ECTs, a tested object is magnetized by constant longitudinal magnetic field up to the state close to the magnetic saturation of a ferromagnet (B~1Tesla), that reduces noise from both structural and mechanical stresses in ferromagnetic material. This field can be used for thickness measurement of pipes and detection of corrosion on both the external and internal surfaces by means of it.For this purpose a classical eddy-current flaw detector should be additionally supplied with a set of Hall transducers located by the perimeter of a encircling ECT and a multichannel circuit to measure longitudinal component of magnetic force H_z. Depending on the minimal size (by an angle coordinate) of corrosion area to be detected, the number of Hall transducers and the corresponding number of channels can be equal to 4, 8, 16, 32 with the size of corrosion area along the perimeter of ECT, namely: $\frac{\pi D}{4};\frac{\pi D}{8};\frac{\pi D}{16};\frac{\pi D}{32}$, where D – diameter of tested pipe.



a. Design of the transducers units of the flaw detector with a simultaneous measurement of pipe wall thickness.



b. Design of the measuring unit



c. Design of the transducers unit of the flaw detector with a simultaneous measurement of pipe wall thickness

Fig. 2. Design of the transducers units of the flaw detector with a simultaneous measurement of pipe wall thickness.

Due to small dimensions and simple design, Hall transducers can easily by arranged within an additional round notch of a encircling ECT that neither makes the ECT design more complicated nor declines the operational reliability of transducers set. Fig. 2 shows the transducer set design added by a Hall transducer set.

The configuration comprises a solenoid 1 with a magnet core 2, replaceable measuring unit 3 with a set of coils of a encircling type: excitation coil – 3.1, differential measuring coil – 3.2. In the additional round notch, the set of Hall transducers is located. Fig. 2.c shows the graphic chart – Hall transducer pickup signal versus pipe wall thickness.

6. Discussion

Detection of corrosion on external and internal sides of pipes by eddy-current flaw detectors with encircling ECTs gives a positive result when using longitudinal constant magnetic field not only to reduce the noise from structural discontinuities in metal but also to measure pipe wall thickness with the use of the additional multi-channel circuit that measures the longitudinal component of constant electromagnetic field strength H_z. The dependences between the output signal from Hall transducer and the pipe wall thickness $U_c=f(t)$ shown in Fig. 2.c are non-linear and call for the use of the linearization method. Due to the smooth curves – $U_c=f(t)$, the piecewise linearization method is the most effective one. This method was realized to have 4-5 pieces in good supply. The measurement accuracy ranges 5-7% from measured pipe wall thickness.

The noise factor when measuring pipe wall thickness is cross movement into the transducers unit due to changes in the air gap *h* between the Hall transducer and the pipe. When employing a mechanical stabilization way of pipe spatial position by double pressure rollers at the input and output points of the transducer unit, we manage to keep *h* changes within ±0.5 mm. This leads to the increase in measurement accuracy by 10%. Such value of the error provides sufficient accuracy when detecting corrosion.

The noise reduction technique gives better results due to the added channel when noise level is high. Fig.s 1.c and 1.d show experimental oscillograms where the defect signal is separated from structural discontinuities. Fig. 1.c shows the case when the noise signal is higher than the defect signal (small-sized tubing with the diameter 33 mm, wall thickness 5.5 mm, 32G2 steel grade and an artificial flaw of 2.2 mm in diameter). The signal-to-noise ratio is less than one in this case. After the spatial filtration, the s/n ratio becomes greater by an order of magnitude. With a better s/n ratio (Fig. 1.d) (defect signal is 20% stronger than noise signal), the spatial filtration enhances s/n ratio by 2-3 times.

The use of the combined ECT provides the detection of longitudinal defects with smooth lead-in zones with 90-95% reliability due to the laid-on rotating coil that scans the field from defect in the direction of abrupt change in field strength (perpendicular to the longitudinal pipe axis).

The described techniques were used when designing the VD-41P industrial eddy-current flaw detector. It has been employed at pipe factories of Russia, Ukraine, Byelorussia, Kazakhstan, passed the trials that proved the efficiency of the above techniques. The testing reliability was increased from 80-85% up to 90-96%.The pipe testing with the joint use of the magnetic (cross magnetization) and eddy-current methods is realized in the VMD-30N flaw detector[4].

Conclusions

The developed techniques for the improvement of technical characteristics of eddy-current flaw detectors with encircling differential transducers allow us to:

(1) Enhance s/n ratio by more than an order of magnitude separating signals from defects when initial s/n ratio is less than one. The method of spatial filtering is more effective when noise level is high;
(2) Provide the detection of longitudinal defects with smooth lead-in zones with 90-95% reliability due to the application of the combined eddy-current ECT with the laid-on rotating differential coils;
(3) Remove impulse noise of any amplitude appearing in the measuring channels of flaw detectors when a pipe hits rollers of a processing table due to the added measuring differential coil shifted along the ECT axis by Δl.
(4) Provide corrosion detection on both the external and internal surfaces of pipes by means of pipe wall measurement by longitudinal constant magnetic field commonly used in eddy-current flaw detectors for noise reduction from structural discontinuities in metal;

References

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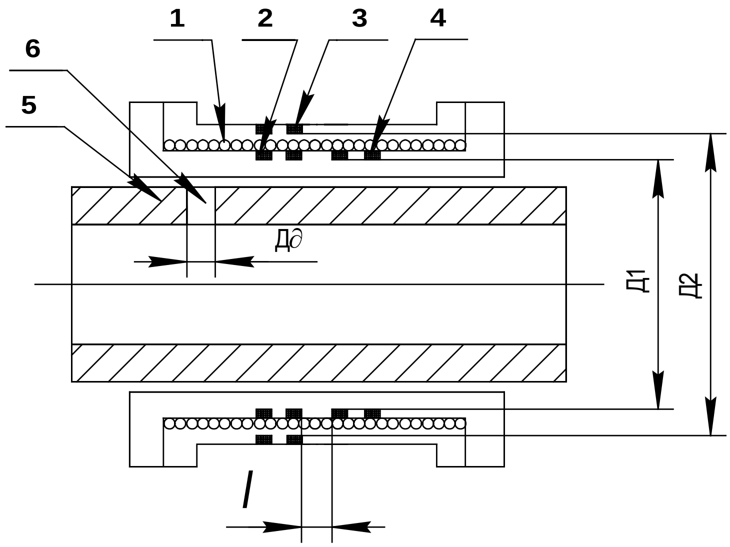


Fig 1.a Design of encircling ECT added by differential coil

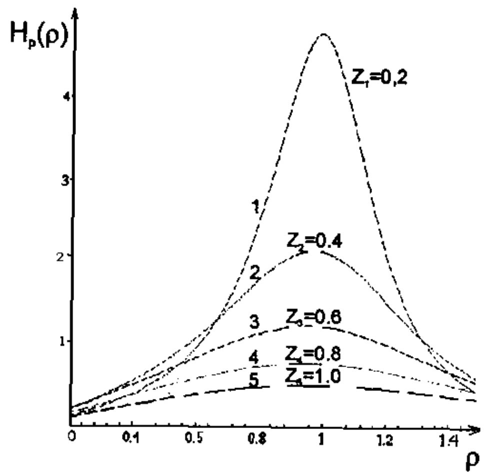


Fig 1.b Distribution of H along coordinate for various values Z

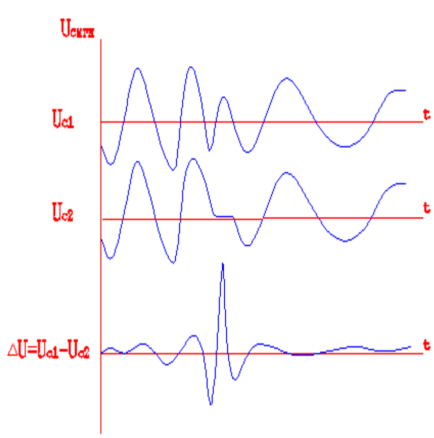


Fig 1.c

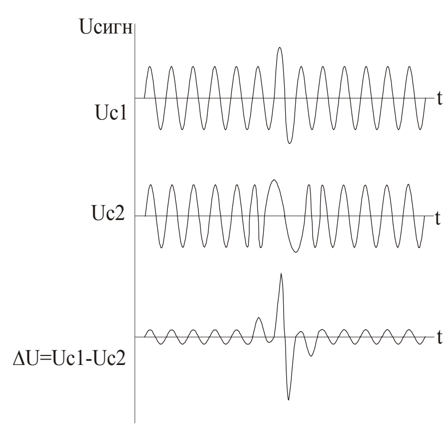


Fig 1.d

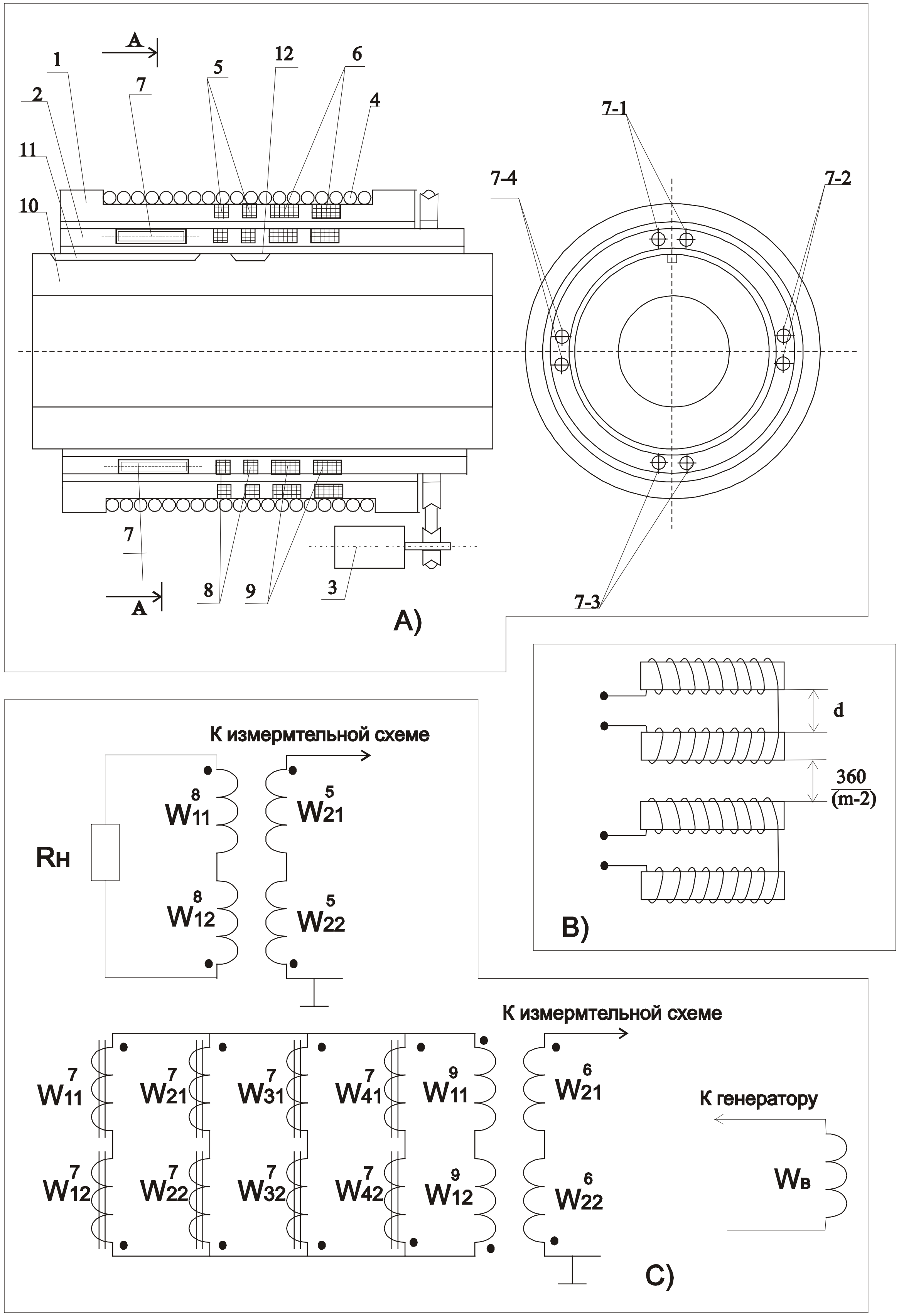
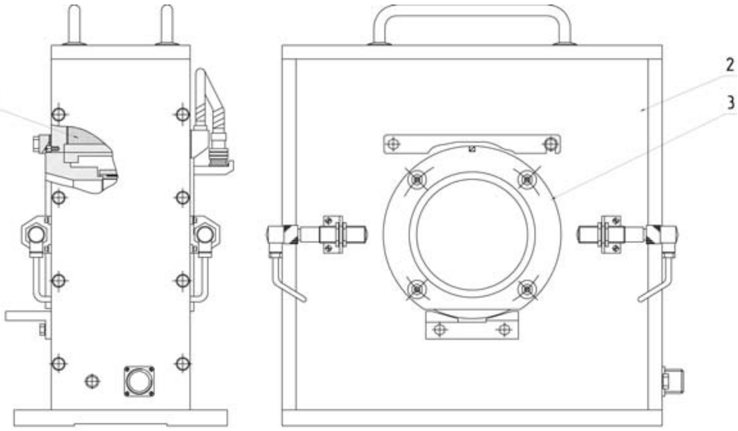
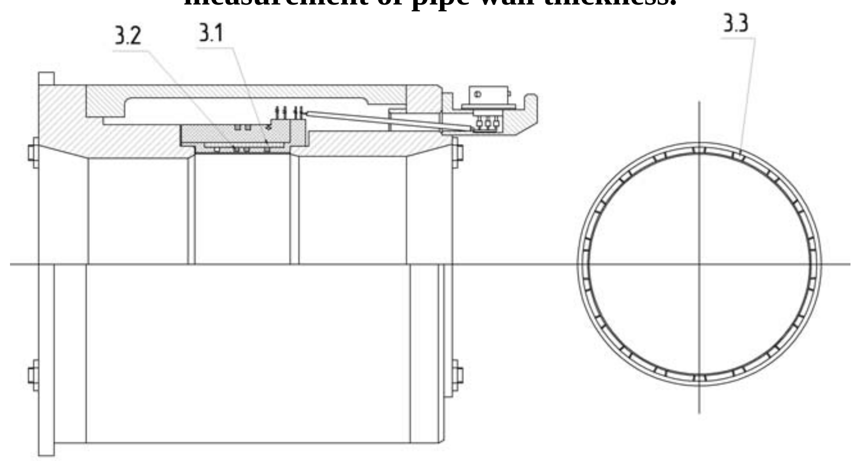


Fig 1.e Scheme of placement and connection of encircling transducer of combined type

Fig. 1. New design of encircling ECTs



a. Design of the transducers units of the flaw detector with a simultaneous measurement of pipe wall thickness.



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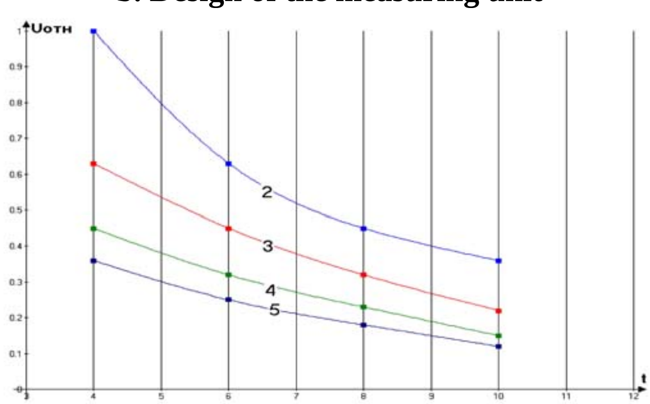

c. Design of the transducers unit of the flaw detector with a simultaneous measurement of pipe wall thickness

Fig. 2. Design of the transducers units of the flaw detector with a simultaneous measurement of pipe wall thickness.