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Study, design and manufacture eddy current probes for industry applications

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Abstract: This study is based on the studying, designing and manufacturing of eddy current probes for industry applications. The main tasks of this study include:
+ Describes the overview and classification of eddy current probes (which can be classified into three categories based on the mode of operation: absolute eddy current probe, differential eddy current probe and reflect eddy current probe).
+ Describes the three methods of probe designing and manufacturing (including experimental, analytical and numerical designs).
+ Describes the designing and manufacturing of eddy current probes for industry applications, which based on experimental and analytical methods.
Based on this study, we have successfully manufactured some current probes (including absolute eddy current probe, differential eddy current probe and reflect eddy current probe) for surface and tube inspections.

Keywords: *NDT - Non-Destructive Testing; ECT- Eddy Current Testing.*

I. INTRODUCTION

In thermal power plants and petrochemical power plants, we use a lot of pipelines compare to other equipment. Those pipeline systems always have to work in extreme conditions which contain high temperature gas or liquid, sometime contain toxic chemical which damages the pipe material. So the quality inspection of the pipelines is very critical in order to maintain the normal operation function of the pipeline system. Especially in Vietnam, where the climatic conditions are very harsh and greatly affect the operations of pipeline system, the pipe quality inspection is become more critical issues.

NDT (Non-Destructive Testing) Method plays an important role in the processes of checking product qualities. Together with the developments of sciences, electronics sciences and information technology, nowadays, NDT techniques has archived huge developments which satisfy the growing requirements for material inconsistency test in power plants industry, petrochemical plants, aviation, construction, metal industry, machine construction technology…

NDT has various types of method, include: Ultrasound Testing (UT), Radiographic Testing (RT), Permeability Testing (PT), Magnetic Powder Testing (MT) and Eddy Current Testing (ECT). Each method has its own advantages and disadvantages. To conduct a test, operators can choose either one NDT method or a combination of several NDT methods; depend on different requirements and circumstances. And among them, ECT is one of the key and the most used NDT technique.

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ECT method can be flexibly used for testing and detecting surface cracks, assessing corrosion, measuring coating thickness or measuring the conductivity of conductive objects.

ECT method overview [1], [3]:

If we put an alternating current through an induction coil near a conductive material, inside the material will appear an induction current called Eddy Current.

If we put the alternating current through an induction coil in parallel to the surface of the conductor, the Eddy Current i_c will run parallel to the conductor surface.

If we put the alternating current through an induction coil in perpendicular to the surface of the conductor, the Eddy Current i_c will run perpendicularly to the conductor surface.

So in short, the Eddy currents will be appeared in parallel curves in the induction coils. If there is a crack in the conductor which perpendicular to the eddy currents, clearly the crack will affect the eddy currents appear in the conductor. This is the important basis of the Eddy current method.

When the Eddy current i_c is altered, a variation of magnetic field H_c will be recorded. Measuring those variations will help us detect defects in the conductor. Standard ECT equipment will include probe (the coils) part, AC power suppliers, data acquisition & data exhibition parts [5]. Depend on the development of science and technology; the technical requirements of those parts are constantly improved.

The equipment for eddy current inspection is not many in category. In contrary, eddy current probes are very diverse in structure and variety in category. The probes are usually damaged, unstable and have exceptional characteristics based on each specific test types. Sooner or later, each facility using ECT devices has to be able to design and manufacture eddy current probes of their own.

Worldwide, ECT device manufacturers always design and manufacture thousands of different probe types in order to meet various common problems (Standard probes) and Custom-made probes for customers.

For example, OPLYMPUS [6] has 10.000 standard probe types and custom-made types.

The subject of this study is to understand the structure of existing ECT probe types on the world, select and build some eddy current probes for general implementation and some specific probes for specific and diversity requirements of Vietnam's industry.

The content of this article includes the following sessions: Overview study of the eddy current probe types, Research internal structure, characteristics, connections and pair between probes and servers; design and manufacture prototype probes; paired prototype probes with servers and perform measurement on test subjects

II. CONTENTS

A. Eddy Current probes overview

Probes classification will be based on different criteria (based on frequency, intended use, mode of operation or structure) [1], [3]

Probes classification based on mode of operation will have 04 categories: Absolute electronic Eddy current probe, Different Electronic Eddy current probe, Reflex Electronic Eddy current probe, and Array electronic eddy current probe [2]

Absolute electronic eddy current probe: Created from a single coil or equivalent. The resistance or the induction current in the coil of this probe type is directly measured (measure the absolute values of those two quantities). This is the simplest and most widely used, as shown in figure 1 below.

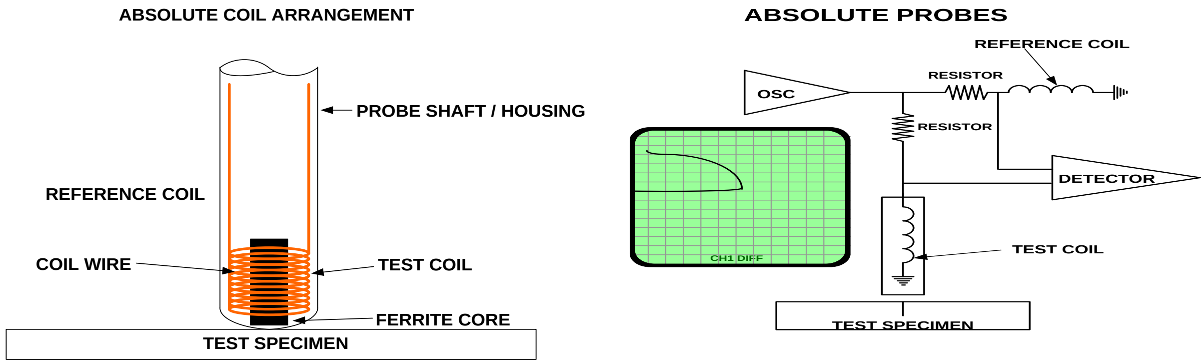


Fig. 1. Absolute probes

Different electronic Eddy current probe: Created from two or more coils which are electrical arranged to be in opposition to each other. The measurement will be the subtraction of the two outputs from each coils; this arrangement minimizes effects which act on both coils simultaneously (e.g. material variations, temperature). Signals which affect the coils differently are enhanced. The different variable electronic eddy current probe is used to detect changes in the test material. It can remove noise and other undesirable characteristics. This probe type is more sensible to the changes in material properties than the absolute probe. Meanwhile, the lift-off changes and the vibration of the probe will be affected due to none simultaneously occurrences on both coils. As shown in figure 2 below:

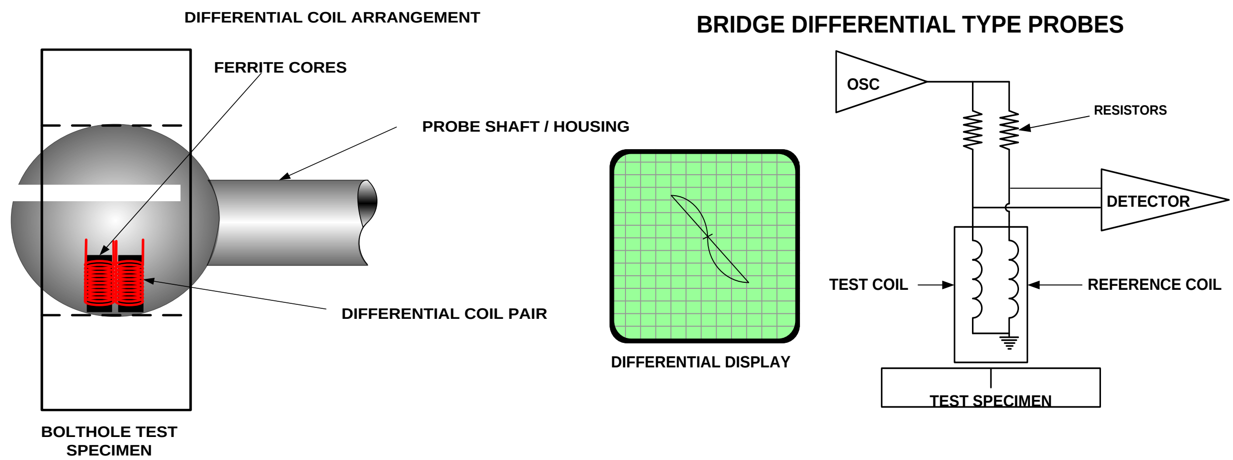


Fig. 2. Different probes

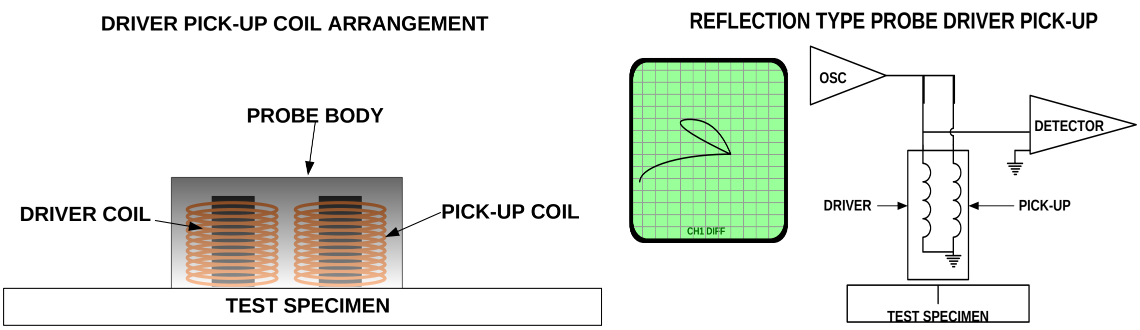


Fig. 3. Reflex probes

Reflex electronic eddy current probes: Created from two coils: Driver coil and Pick-up coil. Normally the Trigger coil will have bigger diameter and be outside of the pick-up coil, as shown in figure 3

Array electronic eddy current probe: For the efficiency in use, we classify this as a different type of probe, but essentially this probe type use the two previous types of operations, which is absolute or different, or a combination of both types depend on the coils connection as in pairs or in common management circuits or in separate management circuits.

B. Connect probes to server[5]

Connection bridges

Due to the small signal from the coils is usually mixed with the driver noise, so the most efficient method for retrieving the signal is by using bridge circuits.

Absolute probe connection

Absolute probe has only one coil, with two outputs will be connected as follow:

Nortec500 equipment [7] has Female BCN J2-1 and J2-2 connectors. We connect both outputs of the coil to a Male BNC, and connect to these J2-1 and J2-2 connectors on Nortec 500.

Locator equipment [8] *has* Female Lemo 7 holes on the device. In order to use Absolute probe with Locator equipment, we have to connect two outputs of the absolute probe to Male Lemo 7 pins as following: Pair pin 1,2 and 4 to the 1st output, pair pin 3 to the 2nd output and to an 200Ω to pin 5.

EddyMax equipment [9] *has* Female 9 pins 9 – pole sub –D, so we have to use Male 9-pole sub –D connected to the probe as shown in figure 4 below:

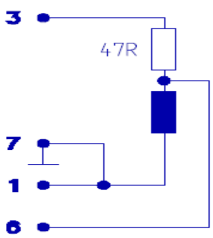


Fig. 4. Absolute probe connection

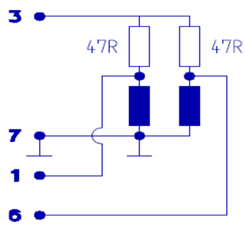


Fig. 5. Different probe connection

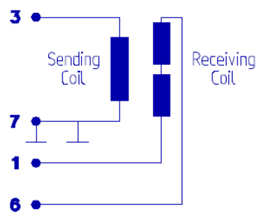


Fig. 6. Reflex probe connection

Different probe connection

Different probe has two symmetric coils, connection has three outputs: + different line, - different line and a neutral line.

Nortec *500 equipment* has Female Lemo 16 holes (J1-11 – different, J1-2 + different, J1-3 for driver and J1-1 for GND on the equipment). Therefore we use a Male Lemo 16 pins connector for connection as following: The coil's + different line to J1-2 of Male Lemo 16 pins, and to 200Ω Resistance to J1-3 of Male Lemo 16 pins; The coil's – different line to J1-11 of Male Lemo 16 pins and to 200Ω Resistance to J1-3 of Male Lemo 16 pins; The mutual line of the probe to J1-1 of Male Lemo 16 pins.

Locator equipment has Female Lemo 7 holes on the device. In order to use different probe with Locator equipment, we have to connect the probe outputs to Male Lemo 7 pins as following: Pair pin 1,4 to the mutual line of the probe, pin 3 to +different line and to 200Ω Resistance to pin 5, pin 2 to –different line and to 200Ω to pin 5;

EddyMax equipment has Female 9 pins 9 – pole sub –D, so we have to use Male 9-pole sub –D connected to the probe as shown in figure 5.

Reflex probe connection

Reflex probe connection has two independent coils, coaxially cover each other, with external driver coil and internal pick-up coil. Normally both coils have the same direction and parameters. Outputs include: signal output, driver output, and a mutual line – ground.

Nortec 500 equipment has Female Lemo 16 holes (J1-11 – different, J1-2 + different, J1-3 for driver and J1-1 for GND on the equipment). Therefore we use a Male Lemo 16 pins connector for connection as following: Signal output to J1-2 of Male Lemo 16 pins; Driver output to J1-3 of Male Lemo 16 pins; Mutual line to J1-1 and J1-11 of Male Lemo 16 pins.

Locator equipment has Female Lemo 7 holes on the device. In order to use different probe with Locator equipment, we have to connect the probe outputs to Male Lemo 7 pins as following: Pins 1,2,4 to the mutual line, pin 3 to the signal output, pin 5 to the driver output;

EddyMax equipment has Female 9 pins 9 – pole sub –D, so we have to use Male 9-pole sub –D connected to the probe as shown in figure 6

C. Design and manufacture Eddy current probes

General concept of design for electronic eddy current probes [2]

Electronic Eddy Current probes based solely on quite simple principles, consisted of one or more coils in optional configurations. Design parameters includes: the shape of coils, cross-sectional area, coil size, coil configuration and power suppliers. Those parameters will be varied based on specific requirements and applications. In particular, electronic eddy current probes can have diameter size from 2,5mm to more than 300mm, cross-section can be square, circle or oval, with magnetic core or non-magnetic core, shielding or non-shielding.

The probe design will be based on the following basic parameters: Inductance, Resistance, Distribution of Magnetic Field in space, the response of the coils to the gradual changes in material; Lift-off characteristics; the response of the coils to cracks, holes or the inconsistency.

There are 03 methods to design eddy current probes: experimental design, analysis design and digital design.

In fact, a probe can be designed by experiment, then can be analyzed or digitalized to calculate the various parameters of the probe. In detail, we start with a theory analysis design (Exact or approximate expression) based on actual requirements. And then after the manufacturing a prototype, we evaluate it empirically. Repeat these processes until the requirements achived, if necessary.

Design Eddy current probes by Experimental Method

Experimental method is not a process that can be defined in documents, but may evolve from the need to modify an existing system, to adapt it to the changing needs of a particular test. It may also arise from a fortunate (or unfortunate) accident or it may be a response to the lack of any better method of design. The need for experimental design has its roots in our inability to solve Maxwell equations in realistic test geometries. Though Eddy current techniques and its probes have developed a lot, but the classic experimental design method is still be effective in many cases. Multiple widely used probes are still related to this method. The process of assisting the probe cannot be done without these experimental methods.

Design Eddy current probes by Analysis method

This design method includes: 1/ calculate the impedance of the coils with identified size and requirements or 2/ given the impedance of the coils, figure out the actual size of the probe, not all of the probe's parameters can be independently designed.

Firstly we need the detailed design of an air-core for one or more coils probe, then detailed design for magnetic core, shielding…

Analysis calculation

Based on the initial requirements and conditions: (Location of the surface crack, crack depth is 1mm, test material is Aluminum σ = 15 MS/m.)

Select the corresponding parameters of the probe such as diameter d, L value of coils (ferrite core type, numbers of coils, coils diameter…), frequency, cable length…

Probe Resistor calculation

The impedance coils consist of real part and complex part

$$Z = R + JwL \quad (1)$$

The real part is the Resistor of the coils

$$R = \rho l/a = \pi\rho dN/a \quad (2)$$

In general, when the coil get close to the conductor, the real part of the impedance will be added by the eddy current loss effect in conductor.

The simple formula for the real part of impedance can only be used with air-core probe, which cannot be used for magnetic core or conductive core, as well as aired-core closed to magnetic objects or conductive objects.

The net resistor will be consistent but will need to be added by the loss in the probe core and the test component. These losses can be estimated by calculation. In fact, losses in ferrite toroids are very difficult to valuate, except for special format (for example: cup-shaped torus). So then manufactures usually provide those empirical values in tables or schema.

Probe Reactance calculation

The inductance of a circular long plate will be determined as follow:

$$L = (4\pi A/ \ell) \times 10^{-7} \quad (3)$$

In probes consist of many coils, the calculation of inductance is more complicated because of the mutual inductance. In this case we do not solve the general problem but the commonly case of two coils probe only. The mutual inductance can be calculated as follow [3]

$$M_{12} = (N_1N_2)f\sqrt{r_1r_2} \quad (4)$$

Therefore, the total inductance of both coils will be affected by the mutual inductance, depend on the coils connection. The total induction will be added if the connection is convenient, or will be subtracted if the connection is reverse.

$$L = L_1 + L_2 \pm M_{12} \quad (5)$$

The same calculation can also be applied to more coils, by calculate the mutual inductance between each pair of coils individually.

Complex Eddy current probe design: The probe design is the simplest configuration with air-core coils, and doesn't consider other aspects of the test such as: the effects of the test conductor, effects of the discontinuities, the differences of the probe configurations for magnetic subject or conductive subjects. Those designs are not realistic and practical, because the probes only make sense when it's operated in the actual conductive or magnetic environment.

The introduction of magnetic or conductive core into the probe has two difficulties: 1/ the loss in core and other conductive material under the magnetic field of the probe need to be calculated and 2/the frequency dependency of the probe. The calculation of the loss inside the conductor is difficult but critical to estimate the impedance of the probe. The calculation of the probe resistor is also complicated unless the magnetic field lines are simple.

Those are significant limitations when applying existing formulas into complex eddy current probe design.

Eddy current probe design by digital method

Digital methods was first used to design Eddy current probe by Dodd in 1970, to integrate and stimulate the expression related to the driver and pick-up coils for the probe parameters.

The probe reaction was calculated from exact physical interactions within electromagnetic fields. The inconsistencies, material properties, coil parameters…are used as parts of the stimulation, also with some assumptions were included (such as linearity, two-dimensional, symmetric…). The irregular shape of probes was also modeled, such as oval type, contours and three dimensional modeling, which is very expensive.

In short, using digital method to design eddy current probe is idealistic, but require a deep understanding about physic and a modern, expensive computational system (includes both hardware and software)

Design steps using empirical and analysis methods

Use a probe from a prestige manufacturer to survey its parameters, characteristics and interior structure. Capture images of applying those probes connected with servers on standard cracks, record those data as initial experiment data.

Analysis and calculation step: Based on the initial conditions and requirements, select the probe parameters such as coil diameter d, L values of coils (Ferrite core type, number of coils, thread diameter), frequency, cable lengths. Noted the frequency should be selected under resonance frequency 0,8 f_r.

The following physical characteristics must be noted during the calculation:

Distribution of eddy current depth in test subject; the standard depth δ when eddy current density at surface reach 0.37 and phase shift 57.3 degree.

Standard depth equation:

$$\delta = 1/\sqrt{\pi\sigma\mu f} = 503/\sqrt{\sigma\mu f} \qquad (6)$$

which σ is the conductivity, μ is the relative permeability, f is frequency of the probe

and Phase shift equation:

$$\Psi\ (\text{rad.}) = -P/\delta \qquad (7)$$

which P is the depth, δ is the standard depth

Magnetic field distribution around the eddy current probe coil:

Normally there is a strong magnetic field at a distance of 1/10 the coils diameter, in which the measurement calculation and defects sensitivity is the best, for example: if the coils diameter d = 5mm, the most sensitive crack depth will be 0.5mm. At a distance of 1/3 the coils diameter, the magnetic field is only 50% of the maximum. At a distance of the coils diameter, the magnetic field is only 10% of the maximum.

Select ferrite core with relative permeability μ_r = 300; The core has bar shape, with d from 1,5 mm to 20mm, length from 1mm to 5mm.

The correlation of the numbers of coils and L values for different ferrite cores will be recorded. With the diameter of copper coils is 0.1mm, L, meter, multilayer with length less than 1.5mm. Table I below is an example:

Table I. The correlation of the coil number and L value for ferrite core which has core diameter 1,5mm

Number of coils	L values	Number of coils	L values	Number of coils	L values
7	0,3µH	27	9,6µH	47	27,7µH
8	0,4	28	10,4	48	28,8
9	0,7	29	11	49	29,7
10	1,3	30	11,6	50	32,3
11	1,7	31	12,3	51	33,4
12	1,9	32	13,2	52	34,6
13	2,3	33	14,0	53	36,2
14	2,8	34	14,9	54	38,3
15	3,0	35	15,8	55	38,6
16	3,3	36	16,9	56	39,7
17	3,7	37	17,9	57	40,3
18	4,2	38	18,7	58	41,8
19	4,7	39	19,4	59	42,9
20	5,1	40	20,4	60	45,7
21	5,6	41	21,3	61	46
22	6,4	42	22,5	62	47,8
23	6,8	43	23,6	63	49,1
24	7,3	44	24,5	64	
25	7,9	45	25,6	65	
26	8,5	46	26,7	66	

Table II. The correlation between L value and Frequency

Frequency	L value
From 500 KHz to 4 MHz	5,6µH
From 150 KHz to 1 MHz	22µH
From 35 KHz to 250 KHz	82µH
From 7 KHz to 60 kHz	390µH
From 2 KHz to 15 kHz	1000µH

According to the references, the correlation between L value of the probe with Frequency (Trigger pulse) as shown in table II.

Based on the above information, we can design a specific probe to handle specific problem in a specific range of basic probe characteristics, followed by manufacturing prototype probe and evaluating results.

Optional selection for each optimal characteristic, after multiple loops of operations, we have obtained the final results.

Design and manufacture Absolute Eddy current probe for detecting surface crack

Crack location: about 1mm in depth, on the surface of an aluminum test subject with σ = 15 MS/m.

Standard frequency to penetrate 1mm is:

from $\delta = 50\sqrt{\frac{\rho}{f\mu}}$ therefor $f = \frac{\rho \times 50^2}{\mu\delta^2}$ $= \frac{6{,}6 \times 50^2}{1 \times 0{,}1^2} \approx 1{,}5$ MHz;

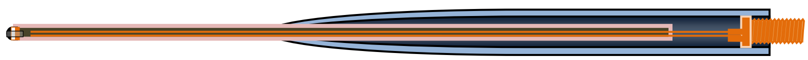
According to table 2, L ≈ 10 µH;

If the probe and cable parasitic capacitors is about 100 nF, then the resonance frequency is:

$$f_r = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{10 \times 10^{-6} 10^{-7}}} = 10 \text{ MHz}$$

is higher than the probe operational frequency, which decreased the possibility of self-exciting.

For sensitive measurements at the surface using absolute probe, we choose the probe diameter of 2mm to 3mm. According to table 1 for ferrite core with relative permeability of $\mu_r = 300$, d = 1,5mm, ℓ = 1,5mm, copper wire φ = 0,1mm, we found the approximate number of coils is about 30 circles, wrapped in 6 layers, each layer has 5 circles. Details as shown in Figure 7.


a


b

Fig. 7. Absolute eddy current probe modeling stimulation (a) and our product (b)

Prototype manufacturing, data measurement and result evaluation processes is performed by *Nortec 500* on *SPO 1141 standard test subject* of OLYMPUS with cracks 0.25mm, 0.5mm and 1mm. Review and selection of the best optimal parameters is performed in multiple loops to obtain the final result. Details as shown in figure 9.

Design and manufacture Different Eddy current probe for detecting surface crack

Crack location: about 1mm in depth, on the surface of an aluminum test subjects with σ = 15 MS/m.

a

b

Fig. 8. Different eddy current probe modeling stimulation (a) and our product (b)

The procedures are the same as Absolute Eddy current probe. Noted that different eddy current probe is consisted two different coils which paralleled in axis II, V shaped or D shaped. Those coils must be absolutely identical. After semi-empirical processes and multiple loops of operation, the probe optimal results are obtained. The results obtained when examined cracks using a prototype Different Eddy Current Probe is shown on figure 10.

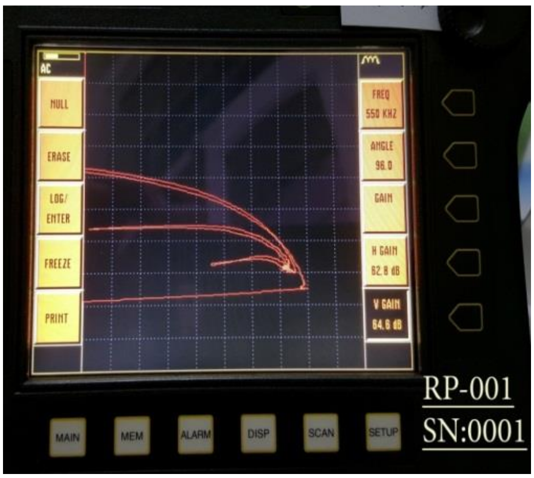


Fig. 9. Cracks image using absolute probe

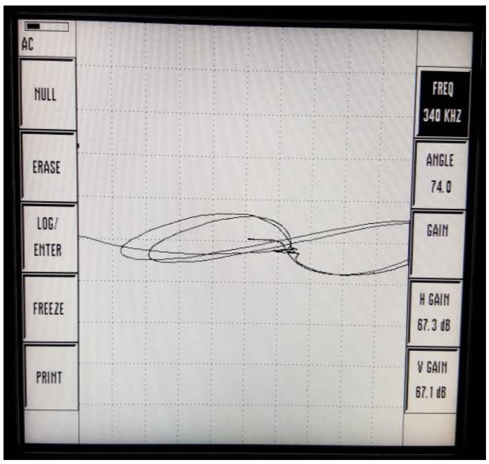


Fig. 10. Cracks image using different probe

Design and manufacture Absolute Eddy Current Probe for detecting pipe crack[4]

The design and manufacture of Absolute Eddy Current Probe was producted primarily based on the actual pipe samples with various defects. For example, our pipe samples are non-magnetic metal pipe, with inner diameter of 15mm, pipe thickness 1mm, and the pipe outer surface was crafted by defects with precisely size and depth

The probe manufacturing processes must meet the following conditions:

1. Coil technical conditions: Based on the theory, determine the exact L value to ensure the detection of cracks. In this case, the L value will be 100µH, 150µH, 200µH for non-magnetic subjects.

The coil outer diameter <15mm, inner diameter >12.5mm, thickness 1mm, coils gap about 1mm.

The probe design must comply with the following condition: coils diameter must be no less than 85% of the pipe inner diameter.

Due to large diameter of the coils and the number of coil round is small (about 80 rounds for 100µH, 90 rounds for 150µH and 100 rounds for 200µH), so the material used for coils can be Copper with d=0.14mm, air-core is good enough.

2. Machining details condition: The coils should be parallel wounded on a hard core. The coils cross-section must perpendicular to the length of the pipe. Center of the coils is the center of the pipe, and the null value on display screen must not change more than the smallest defect.

3. Other conditions: Other details in order to increase the stability in defect testing such as mounting screws with soft rubber material, probe and wire cover must be made from durable materials…

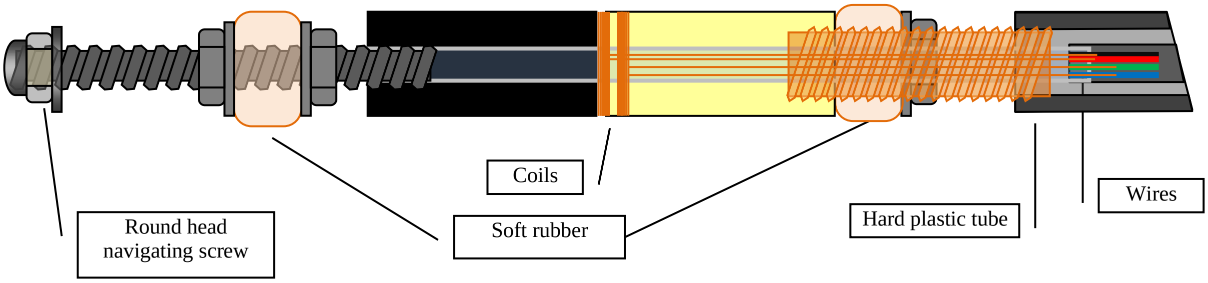
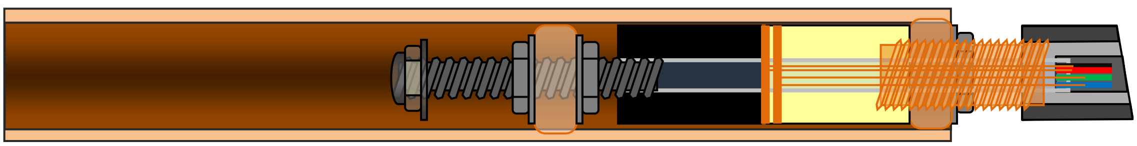


Fig.11. Absolute Eddy current probe modeling stimulation for pipe testing

Design and manufacture Different Eddy Current Probe for detecting pipe crack

The processes and procedures of design and manufacture Different Eddy Current Probe for detecting pipe crack is the same as Absolute Eddy Current Probe for detecting pipe crack (Figure 12).



a

b

Fig. 12. Different Eddy current probemodeling stimulation for pipe testing (a) and our product (b)

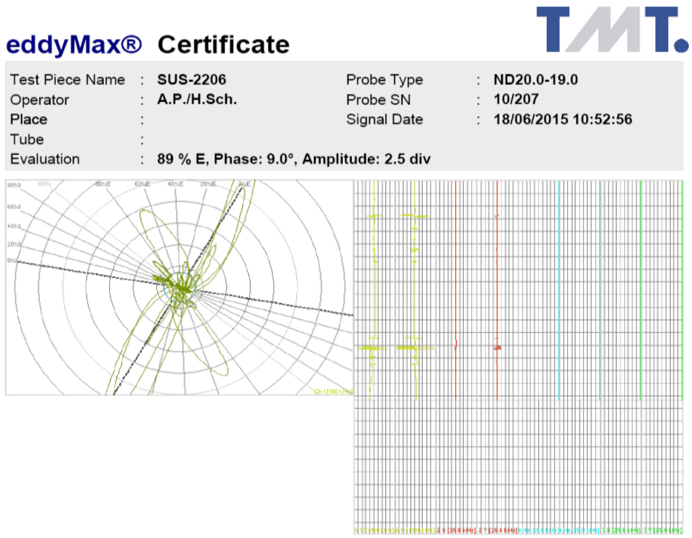


Fig. 13. Cracks signal obtained by Different Pipe Probe

However, the detailed processing of the coils in Different Probe requires strict conditions such as: exact value of both coils, which require a very precise and highly accurate processing, due to the great variability of L value on large diameter coil from 1 to more µH with just ¼ of the winding. The gap between two coils has to be uniform; the outer surface of the two coils must have the same height, and the rotation of the coils must also be considered.

The test results on a standard metal pipe performed by EddyMax equipment is shown on Figure 13.

We have manufactured some type of EC probes, they are shown in table III.

Table III. Table of our EC probe products

Item	Type of probes	Working length mm	Centre frequency KHz	Probe diameter mm	Probe connector
1	Unshielded detachable pencil absolute probes	25	1000	2	Lemo 2pin
2	Unshielded detachable pencil differential probes	25	1000	4	Lemo 5pin
3	Unshielded detachable surface absolute probes	50	600	4	Lemo 2pin
4	Unshielded detachable surface differential probes	50	600	8	Lemo 5pin
5	Unshielded attach pencil absolute probes	25	1000	2	BNC
6	Unshielded attach pencil differential probes	25	1000	4	Lemo 5pin
7	Unshielded attach surface absolute probes	50	600	4	Lemo 2pin
8	Unshielded attach surface differential probes	50	600	8	Lemo 5pin

9	Shielded detachable pencil absolute probes	25	1000	2	Lemo 2pin
10	Shielded detachable pencil differential probes	25	1000	4	Lemo 5pin
11	Shielded attach pencil absolute probes	25	1000	2	BNC
12	Shielded attach pencil differential probes	25	1000	4	Lemo 5pin
13	Attach ID absolute probes	50	100	14	Amphenol connector 4 pin
14	Attach ID differential probes	50	100	14	Amphenol connector 4 pin

III. CONCLUSION

We have studied the classification of eddy current probes; analyze the probes' structure and research dynamic characteristics of the probes. Therefore we have successfully designed and manufactured three types of probes for evaluating cracks on flat metal objects and industrial pipelines. We also built the procedures of probe manufacture in order to mass manufacture high quality probes equivalent to imported probes.

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