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# An Automatic System Measuring Electromagnetic Parameters for Oil Field Pipes

Jiming Yin<sup>1</sup>  
J. Pineda de Gyves  
Mi Lu<sup>2</sup>

Department of Electrical Engineering  
Texas A&M University  
College Station, TX 77843  
U.S.A.

**Abstract**— The fault detection and diagnosis of oil field pipes are very important to the petroleum companies. As is known, the fault of steel products can be detected based on the eddy current technique. The depth of a defect on an oil field pipe will determine the change in amplitude and phase of the detect signal. However, this signal is also affected by electromagnetic parameters in the vicinity of the fault. It is impossible, therefore, to accurately interpret the severity of the fault from a detect signal, without the knowledge of electromagnetic parameters.

A system which can automatically measure electromagnetic parameters of oil field pipes has been developed, so that the correct interpretation of pipe defect can be provided. An electronic emulator was built for differentiating the permeability of pipes accurately. The electronic emulator takes the signal from the transmission circuit, and converts it to the compensation signal with a certain amplitude and phase shift according to the pre-settings. The combined received signal and compensation signal are conditioned and compared with the transmitting signal to give the expanded phase shift signal at the output. To stand the rigorous working condition in the underground pipes, the system is made capable of working at high temperature. Also taken into account is the variation of the internal diameter and the wall thickness of casing pipes, which affect the measurement of electromagnetic parameters. Therefore, the system can provide the high sensitivity electromagnetic parameters for interpreting various types of defects in oil field pipes.

## I. INTRODUCTION

It is known that eddy current techniques can be applied to flaw detection for steel products. The amplitude of a flaw signal is related to the depth of a defect. However, it is also affected by electromagnetic parameters, such as conductivity and permeability, in the vicinity of the flaw. Therefore, the accurate interpretation of the severity of defects heavily relies on the information of electromagnetic parameters provided. For an oil field casing pipe being inspected, such information should be made available at any portion of the pipe. All these make the downhole inspection of oil field casing pipes a very difficult task.

Since the electromagnetic parameters of steel pipes, es-

pecially the values of permeability, vary from point to point within a pipe, and the instrument cannot be kept steady in a downhole inspection environment, it is impossible to provide the information for a whole string of pipe using the traditional *sample checking* method [1]. On the other side, the phase difference caused by different permeability of pipes is too small to distinguish, and one cannot expect to read the variation of parameters within pipes by the *strait phase angle* method [2].

A new approach with adjustable phase angle was adopted for electromagnetic parameter measuring. Similar to the remote field eddy current coil arrangement [3], a very long transmitter coil was used to generate homogeneous AC magnetic fields inside the casing pipe, and a short receiver coil is placed in a short distance from the transmitter coil. The generated homogeneous AC magnetic fields provide the measurement environment for a whole string of casing pipes during a downhole inspection, and the electromagnetic parameters were obtained either from the amplitude of a received signal or from the phase difference between the transmitting wave and received signal. An electronic emulator has been developed for differentiating the permeability of pipes accurately. It can convert the received signal to the compensation signal. The combined received signal and compensation signal are conditioned and compared with the transmitting signal to obtain the expanded phase shift signal.

For the same size of casing pipes, even though the outside diameters (OD) are the same, the internal diameter (ID) and the wall thickness (WT) are different from each other. Besides, the collapse resistance or yield strength varies significantly. An electronic circuit has been installed to automatically and continuously adjust the measured value in accordance with the ID value of the pipe.

The rest of the paper is organized as follows. The electromagnetic parameter measuring system is introduced in section 2. The experimental results are presented in section 3. Section 4 gives the summary and the related work.

## II. DESIGN OF THE ELECTROMAGNETIC PARAMETERS MEASURING SYSTEM

The design of a system for measuring electromagnetic parameters of oil field pipes is presented below. It can be

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expected that better readings and more accurate measurement to be acquired by the designed system.

#### A. Background of the system

Similar to the remote field eddy current coil arrangement [2], a very long transmitter coil was adopted for generating a homogeneous AC magnetic fields in a pipe, and a short receiver coil was placed in a short distance from the transmitter coil for measuring the electromagnetic parameters.

A homogeneous magnetic fields was generated by the long transmitter coil with an air core. It can cover the large area of a pipe, without being disturbed by the jiggling of the sonde when it travels in the pipe.

The exciting frequency of the transmitter is specially chosen for the receiver so that the receiver is not sensitive to the thickness of the pipe wall, but only reflects the variation of electromagnetic parameters.

A flaw signal is affected by electromagnetic parameters including the conductivity and permeability. However, it is not necessary to know the values of conductivity and permeability separately, since in most cases the conductivity is a constant. For correcting the affection of electromagnetic parameters on flaw signals, it is sufficient to know the variation of the permeability for different grades of pipes about which our system can provide information.

Either the amplitude or the phase of received signals can provide information on electromagnetic parameters on casing pipes. Since the phase is less sensitive to noises, it is chosen for parameters measurement. The phase of the received signal is compared with the transmitting signal and a phase reading is given after the comparison. A circuit to process such signal is shown in Fig. 1 in a block diagram form.

#### B. Expansion of the phase separation angle

Let  $A_1$  and  $A_2$  be the amplitudes of the received signals from pipe 1 and pipe 2, and  $\theta_1$  and  $\theta_2$  their phase angles with respect to the transmitting signal. As shown in Fig. 2, the signal can be expressed in the following phasor form:

$$\begin{aligned} R_1 &= A_1 e^{j\theta_1} \\ R_2 &= A_2 e^{j\theta_2}. \end{aligned}$$

The phase separation angle ( $\phi$ ) between  $R_1$  and  $R_2$  can be determined by

$$\phi = \theta_1 - \theta_2.$$

The phase separation angle for different grades of oil field pipes is very small in general. For example, a phase separation angle of 6 degrees out of 360-degree base can be found for the H40 pipes and P110 pipes in 7-inch OD casings. Such kind of phase separation angle is too small to differentiate pipe grades. It should be expanded before used to measure parameters.

An emulator has been incorporated into our system to generate a compensating signal. The block diagram is shown in

Fig. 3. Let the compensated signal have the following form:

$$R_c = A_c e^{j\theta_c}.$$

When  $R_1$  and  $R_2$  are compensated by  $R_c$  respectively, the compensated waveforms  $R_{c1}$  and  $R_{c2}$  will be

$$\begin{aligned} R_{c1} &= A_{c1} e^{j\theta_{c1}} \\ R_{c2} &= A_{c2} e^{j\theta_{c2}}, \end{aligned}$$

where  $\theta_{c1}$  and  $\theta_{c2}$  are the phase angles with respect to the transmitting signals, and  $A_{c1}$  and  $A_{c2}$  are the amplitudes of the compensated signals.

Now the phase separation angle for  $R_{c1}$  and  $R_{c2}$  becomes

$$\phi_c = \theta_{c1} - \theta_{c2}.$$

The nice point is that depending on the location of intercepting points  $P_1$  and  $P_2$  in Fig. 4,  $\phi_c$  can be adjusted larger than  $\phi$  or smaller than it.

Since  $R_{c1}$  can be obtained from the combination of  $R_1$  with  $R_c$ , we have

$$R_{c1} = A_1 e^{j\theta_1} + A_c e^{j\theta_c} = A_{c1} e^{j\theta_{c1}}.$$

Similarly,  $R_{c2}$  can be obtained by combining  $R_2$  with  $R_c$ , and

$$R_{c2} = A_2 e^{j\theta_2} + A_c e^{j\theta_c} = A_{c2} e^{j\theta_{c2}}.$$

The phase angles  $\theta_{c1}$  and  $\theta_{c2}$  are decided by

$$\begin{aligned} \theta_{c1} &= \arctan \frac{F_1}{F_2} \\ \theta_{c2} &= \arctan \frac{F_3}{F_4} \end{aligned}$$

with

$$\begin{aligned} F_1 &= A_1 \sin \theta_1 + A_c \sin \theta_c \\ F_2 &= A_1 \cos \theta_1 + A_c \cos \theta_c \\ F_3 &= A_2 \sin \theta_2 + A_c \sin \theta_c \\ F_4 &= A_2 \cos \theta_2 + A_c \cos \theta_c. \end{aligned}$$

Hence, the phase separation angle ( $\phi_c$ ) is

$$\phi_c = \theta_{c1} - \theta_{c2} = \arctan \frac{F_1}{F_2} - \arctan \frac{F_3}{F_4}.$$

Taking tangent on both sides, we have

$$\begin{aligned} \tan \phi_c &= \tan \left[ \arctan \frac{F_1}{F_2} - \arctan \frac{F_3}{F_4} \right] \\ &= \frac{F_1 F_4 - F_2 F_3}{F_2 F_4 + F_1 F_3}. \end{aligned}$$

That is,

$$\begin{aligned} \phi_c &= \arctan \frac{F_1 F_4 - F_2 F_3}{F_2 F_4 + F_1 F_3} \\ &= \arctan \frac{A_1 A_2 \sin(\theta_1 - \theta_2) + A_2 A_c \sin(\theta_c - \theta_2) + A_1 A_c \sin(\theta_1 - \theta_c)}{A_1 A_2 \cos(\theta_1 - \theta_2) + A_2 A_c \cos(\theta_c - \theta_2) + A_1 A_c \cos(\theta_1 - \theta_c) + A_c^2}. \end{aligned}$$

We can choose the appropriate values for  $A_c$  and  $\theta_c$  so that  $\phi_c$  can be made larger than  $\phi$ , with  $A_1$ ,  $A_2$ ,  $\theta_1$  and  $\theta_2$  being fixed values. The emulator in our system can generate a signal with wide range of amplitude and phase. The amplitude  $A_c$  can be larger or smaller than that of the transmitter signal and the phase  $\theta_c$  can be leading or lagging to that of the transmitting signal. The method of presetting  $A_c$  and  $\theta_c$  has been identified and used in our laboratory experiment.

### C. Adjustment in accordance with ID

The following facts are noticed which may result in the incorrect measurement of electromagnetic parameters. The size, grade and weight of the oil field pipes are classified by API (American Petroleum Institute). However, big variation of the internal diameters (ID) may exist even if the outside diameters (OD) of the pipes have the same classification. Besides, the collapse resistance or yield strength varies significantly. To assure the correctness of parameters measurement under such situation, an electronic circuit has to be installed to automatically and continuously adjust the measured value in accordance with the ID values of pipes. In our procedure, we assign a reference ID value first. During the system operation, an actual ID value would be obtained from an ID measuring instruments. Then, based on the reference ID and the measured ID, the system would generate a correcting factor. This factor would be used in the electromagnetic parameters measurement, adjusting the readings to a correct one. As a special case, the supply of the readings would be suspended if an ID variation beyond a given limit is detected in a portion of the pipe. Extra circuits were added to Fig. 3 to adjust the measured parameters and suspend the supply of wrong information. The modified circuit is shown in Fig. 5.

## III. EXPERIMENTAL RESULTS

A prototype of the system with housing based on 7-inch OD casing was constructed. The system was tested, and the results proved its performance satisfactory. The output of the system reads in phase voltage, which gives the electromagnetic parameters by measuring the phase shift of received signals and reporting it in terms of volts. 10 millivolts of phase voltage equal to 0.41 degrees of phase shift.

### A. Readings of the phase shift

Four 7-inch OD casings which had different values of ID were used for testing. The identification of them are 7-19, 7-15, 361278 and 360602, respectively. A sorter was used to provide relative permeability in the laboratory environment before the test. With its probe contacting a steel product, we can manually find the permeability value of a pipe at the contacting point, and that value would be used as a reference. The test was conducted with our system seating inside the pipe.

The measurement of the pipes with the wave compensating

circuit and without it are compared, and the test results are shown in Table 1. Also listed are the relative permeability of each pipe, so that each phase voltage obtained from a pipe is corresponding to a permeability value. One can see that the absolute phase voltage readings for the system with the wave compensating circuit are different from that without the wave compensating circuit. For the convenience of comparison, the data obtained with the compensating circuit is normalized to the readings from pipe 7-19 without the compensating circuit.

The plotting of the normalized phase voltage versus the relative permeability readings from the sorter is shown in Fig. 6. One can see that without the wave compensating circuit, the difference between the phase voltage of pipe 7-19 and pipe 360602 is 0.12 volt, which is equivalent to 4.9 degrees out of a 360-degree base. With the wave compensating circuit included in the system, the phase difference of the two pipes is increased to 26.8 degree.

It may be confusing that some points are deviated from the ideal curve in Fig. 6. A possible cause to this is the incorrect measurement of the relative permeability from the sorter. The sorter provides permeability readings based on the result of some calculation with the assumption of constant conductivity, while the actual conductivity may change slightly. The situation can be improved if the calculation method is modified.

### B. Data Corrected with ID

Experiments were taken to verify the approach correcting the measured values in accordance with the ID of pipes. Five 7-inch OD casings were used, and the identification of the pipes were 7-19, 1230458, 7-15, 361278 and 360602, respectively. Also, their relative permeability were obtained from the sorter, and the test was conducted with the system seating inside the pipes.

The ID of pipe 7-19 was used as a reference ID. The original phase voltages and those corrected in accordance with pipe ID are listed in Table 2 along with different ID values. The data are also plotted in Fig. 7 for a clear view. It is obvious that the data corrected in accordance with pipe ID are closer to the ideal curve (indicated by the solid line), and can hence give a better representation of pipe electromagnetic parameters than the original measured values.

As in Fig. 6, some points are deviated from the expected curve in Fig. 7. It can be explained by the same reasons used to explain Fig. 6. In addition, one may feel confused that the phase voltage decreases with the increase of relative permeability in Fig. 6, while it increases with the increase of relative permeability in Fig. 7. The inconsistent presentation lies in the inverting amplifier in the correction circuit which changes the tendency of the curve. The data in Fig. 6 were obtained before the correction circuit, and those in Fig. 7 were obtained after that circuit.

Due to the rigorous working condition in the underground pipes, the emulator circuit is housed in a pressure housing and it is required to work at the temperature as high as 175°C.

assured.

#### IV. SUMMARY

A system which can automatically measure electromagnetic parameters of oil field pipes has been developed. In a homogeneous magnetic fields provided by a very long transmitter coil in a pipe, a continuous measurement of electromagnetic parameters could be taken for an entire string of pipes. An electronic emulator has been incorporated in the system for differentiating the permeability of pipes. In addition, electronic circuit has been installed in the system for adjusting parameter measurement in accordance with the ID of pipes. In this way, the better readings and more accurate measurement can be provided, and the high sensitivity to various types of defects and the possibility of properly monitoring the oil field pipes can be

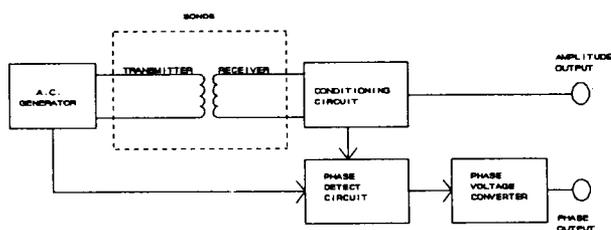


Fig. 1. Block diagram of the signal processing circuits

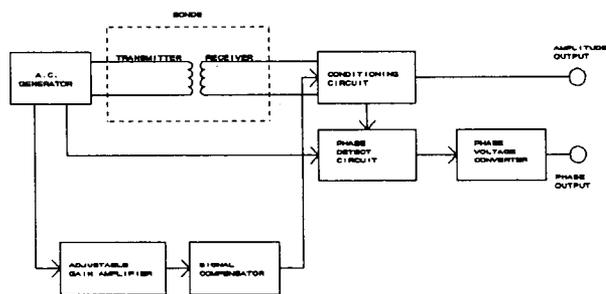


Fig. 3. Block diagram of the signal processor with a compensating circuit

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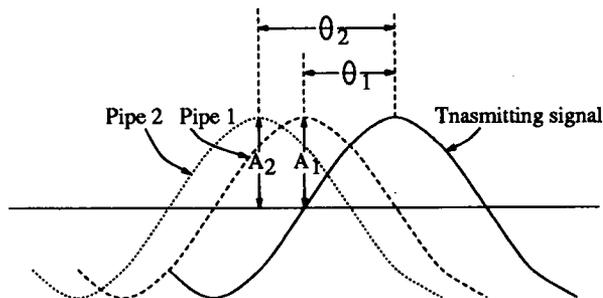


Fig. 2. Location of two receiving signals

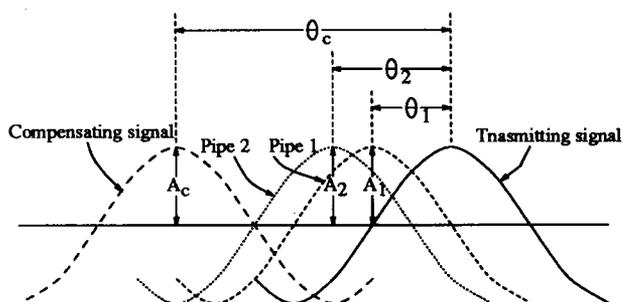


Fig. 4. Location of a compensating signal and two receiving signals

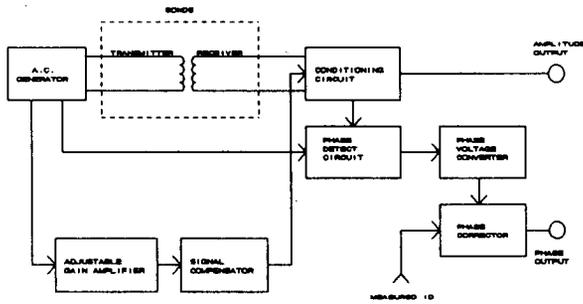


Fig. 5. Block diagram of the signal processor with a compensating circuit and a phase corrector

Pipe	Phase Voltage (without emulator) (volt)	Phase Voltage (with emulator) (volt)	Relative Permeability
7-19	6.882	6.882	62.0
7-15	6.846	6.766	76.0
361278	6.861	6.791	89.5
360602	6.763	6.227	151.0

Table 1. Phase voltages measured with and without the emulator.

Pipe	Original Phase Voltage (without emulator) (volt)	Corrected Phase Voltage (with emulator) (volt)	Internal Pipe Inside Diameter (inch)
7-19	4.907	4.907	6.221
1230458	5.272	5.077	6.453
7-15	5.186	5.046	6.391
361278	5.152	5.034	6.366
360602	5.452	5.404	6.276

Table 2. Original and corrected phase voltages.

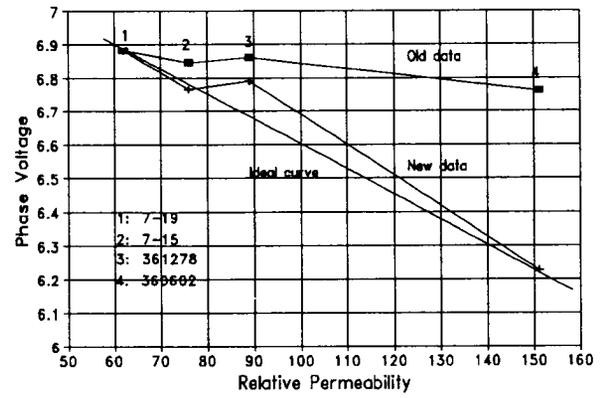


Fig. 6. Phase voltage with and without the emulator

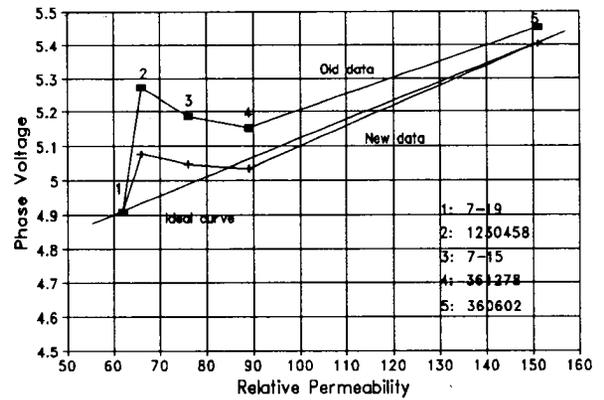


Fig. 7. Original and corrected phase voltage