Flaw shape reconstruction – an experimental approach

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***Abstract* – Flaws can be classified as acceptable and unacceptable flaws. As a result of nondestructive testing, one takes de decision Admit/Reject regarding the tested product related to some acceptability criteria. In order to take the right decision, one should know the shape and the dimension of the flaw. On the other hand, the flaws considered to be acceptable, develop in time, such that they can become unacceptable. In this case, the knowledge of the shape and dimension of the flaw allows determining the product time life. For interior flaw shape reconstruction the best procedure is the use of difference static magnetic field. We have a stationary magnetic field problem, but we face the problem given by the nonlinear media. This paper presents the results of the experimental work for control specimen with and without flaw.**

***Keywords:* flaw shape reconstruction, magnetic field, nondestructive testing.**

I. INTRODUCTION

The researches in nondestructive testing are oriented in two main directions [1]: flaw detection and flaw reconstruction. If flaw detection is a relatively simple problem, flaw reconstruction is an ill-posed electromagnetic inverse problem that requires a huge amount of direct problems to be solved. The use of eddy currents for interior flaw shape reconstruction in ferromagnetic pieces has a big disadvantage: due to the big permeability, the magnetic field depth is very small, so only surface flaws can be detected.

For interior flaw shape reconstruction the best procedure is the use of difference static magnetic field [2]. We have a stationary magnetic field problem, but we face the problem given by the nonlinear media.

For interior flaw shape reconstruction, the proposed solution for the above problems is to follow the steps [3]:

1. The use of magnetic field theory for ferromagnetic materials for a rapid and precise determination of the electromagnetic field.
2. The use of magnetic field theory for nonlinearity treatment of ferromagnetic bodies (fixed point polarization method, over-relaxed).
3. Aged flaw reconstruction from ferromagnetic pieces.
4. Ferromagnetic pieces flaw shape reconstruction.
5. Interior flaw shape reconstruction from ferromagnetic pipes by elaboration of efficient algorithms for flaw shape search.

The results were validated by experimental researches.

II. EXPERIMENTS ON A CONTROL SPECIMEN WITH AND WITHOUT FLAW

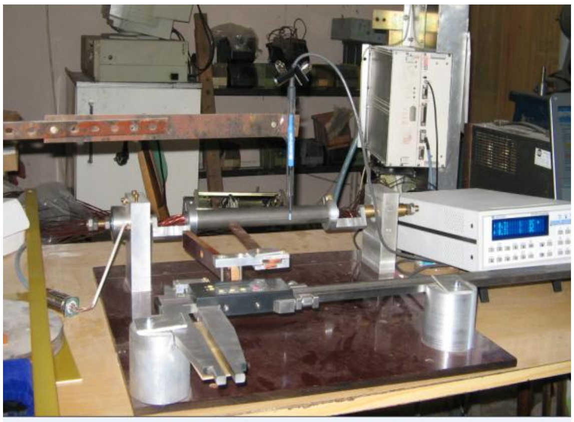


Fig.1 Magnetic induction measuring system

Technical details of the experiment:

The experiment took place in the research laboratory from ICPE SA, Bucharest, on a *stainless magnetic pipe* (a), inside which we artificially produced a *flaw* (b). The values of the magnetic induction have been measured using the *magnetic induction measurement system* (c) in the in the neighbourhood of the pipe with and without flaw (Fig. 1).

a) the stainless magnetic pipe:
- inner diameter: 28 mm;
- outer diameter: 25 mm;

b) the flaw: - has been produced along the pipe such that:

- shape: rectangular;
- depth: 0.5 mm – variable because it decreases at distance;
- width: 0.5 mm;
- length: sufficiently big such that plane parallel model can be admitted;

c) the measuring system consists of:
- calibre – used to precisely place at a given position the Hall probe;
- solver – used to precisely place at a given angle the Hall probe;
- DC source: 20A/30V;
- to read the normal component of the magnetic induction we used:
  - Lakeshore DSP Gaussmeter Model 455 with transversal Hall Probe HMFT-3E03-VF (Fig. 2, Fig. 3);
  - laptop – for automatic data acquisition and processing.

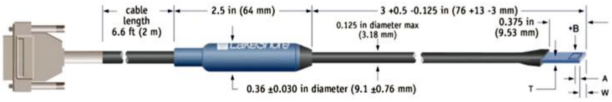
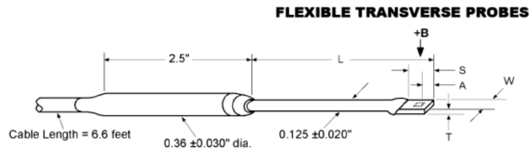


Fig. 2 Transversal Hall probe



This table is for L = 3 inches and S = 0.375 inch

Model No.	W	T	A	Active Area	Stem Material	Freq. Range	Type	Corrected Accuracy (% of Reading)	Operating Temp. Range	Temperature Coefficient (maximum)		Contain Temperature Sensor
										Zero	Calibration	
HMFT-3E03-VR*	0.135" max	0.025" max	0.125" ±0.005"	0.040" dia. approx.	Flexible Tubing	DC to 20 kHz	HSE	±0.20% to 30 kG ±0.25% 30–35 kG	0 °C to 75 °C	±0.09 G/°C	±0.015%/°C	Yes
HMFT-3E03-VF*						DC to 800 Hz	HST-4	±0.10% to 30 kG ±0.15% 30–35 kG		±0.13 G/°C	–0.005%/°C	
HMFT-2903-VJ	0.085" max	0.020" max	0.065" ±0.005"	0.030" dia. approx.		DC to 20 kHz	HSE	±0.50% to 35 kG		±0.09 G/°C	±0.015%/°C	
HMFT-2903-VH						DC to 800 Hz	HST-4	±0.25% to 35 kG		±0.13 G/°C	–0.005%/°C	

Fig. 3 Catalogue characteristics for transversal Hall probe

III. RESULTS

The measurements took place for the transversal Hall probe placed perpendicular on the coil's plane (Fig. 4).

Fig. 4 Hall probe placed perpendicular on the coil's plane

Fig. 5 B_n in the flaw area

The normal component of the magnetic induction is the useful component for the flaw detection, because, for the case without flaw this component is zero. The normal component of the magnetic induction was measured at the surface of the pipe in the flaw area, for different distances away from one end the pipe: 18 mm, 25mm, 30.5mm, 40mm and in the area without flaw, at distance 81mm (Fig. 5).

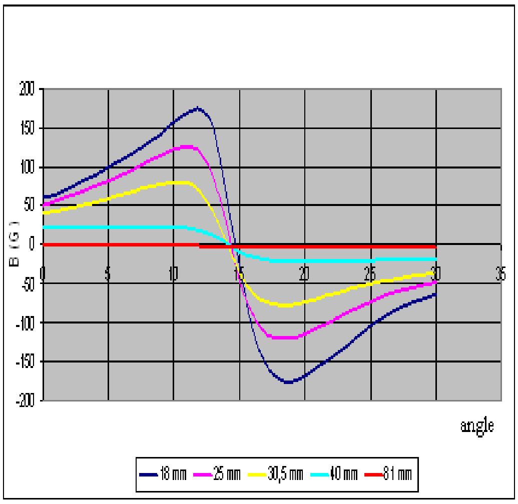


Fig. 5 B_n at different distances

The flaw shape reconstruction was done for a 416Stainless Steel pipe with inner flaw, which has the B-H characteristic presented in Fig. 6 [4].

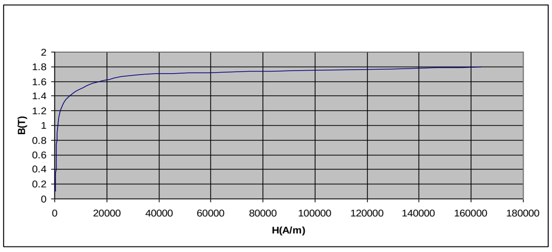


Fig 6 B-H characteristic

Two types of measurement took place during the experiment: firstly we measured the areas of the pipe without flaw; secondly the Hall probe was placed in different zones of the flaw. Through the coil (the number of turns = 31) was injected a current equals to 10A. The turns were place on one side of the measuring system.

We also studied how the measurement is influenced by the position of the turns. For example, if we split the turns symmetrically in the same plane, we noticed a small difference (1.2 G), which can be included in the measuring error.

We validated the measurements with the turns placed on one side of the measuring system (Fig.7).

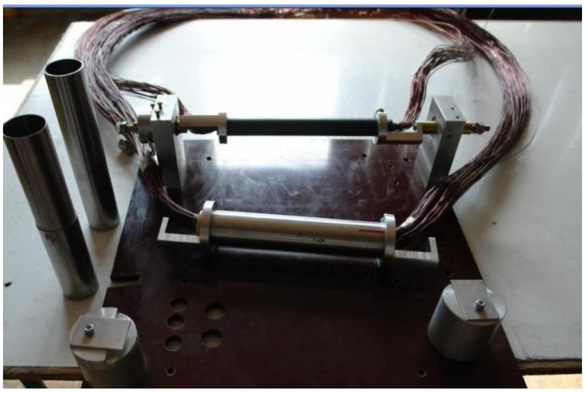


Fig. 7 The position of the turns

Taking into account the computing speed and the accuracy of the results, the most efficient methods used to solve the magnetic field problems are: Green function method and the hybrid FEM-BEM method, the non-linearity being treated by using the polarization method [5], [6]. Because the FEM-BEM procedure is difficult to be applied for multiply connected domains (e.g. pipes), the Green function method has been preferred for the data base construction. The results regarding the data basis can be also applied for the case when we use FEM-BEM procedure.

For simplification reasons, we model the pipe as in Fig. 8 and the mesh as in Fig. 9 and Fig. 10.

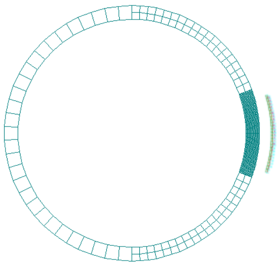


Fig. 8 Assembling the objects

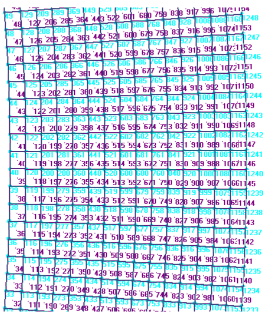


Fig. 9 Searching area – detail

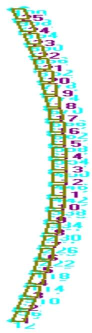


Fig. 10 Measuring points

We studied the case corresponding to the values of the normal component of the magnetic induction measured at 40 mm from the end of the stainless pipe (Table 1).

Table 1

Nr. crt.	Measured B_n
1.	0.002269
2.	0.002304
3.	0.002349
4.	0.002364
5.	0.002392
6.	0.002406
7.	0.002373
8.	0.002246
9.	0.002125
10.	0.001814
11.	0.001106
12.	0.000143
13.	-0.0009
14.	-0.00155
15.	-0.00191
16.	-0.00207
17.	-0.00212
18.	-0.00212
19.	-0.00213
20.	-0.00211
21.	-0.00209
22.	-0.00206
23.	-0.00204
24.	-0.00203
25.	-0.00201

For the values measured in the above table one obtains the first possible flaws represented by the occupied subdomains, in the increasing order of the error between to the computed and measured induction.

The obtained flaws are the result of mediating the first n possible flaws with weights equal to e^{-N^2} :

$$V = \frac{V_1 e^{-N_1^2} + V_2 e^{-N_2^2} + \dots\dots\dots\dots + V_n e^{-N_n^2}}{e^{-N_1^2} + e^{-N_2^2} + \dots\dots + e^{-N_n^2}} \qquad (1)$$

where the norm is computed by using the relation:

$$N = \sqrt{\sum_{1}^{n} \frac{(b_{calc} - b_{mas})^2}{n}} \qquad (2)$$

The graphical display of the flaw shape was done by using greyscale which reflects the more or less probable areas for the flaw to occupy the given subdomain.

For example, if the searching cell has 3 subdomains on the radial axis and 2 subdomains on the angular axis, then the number of subdomains is 6 and the total number of tested flaws is 109.

The subdomains occupied by the first 9 possible flaws are given in Fig. 11.
The first 9 possible flaws are:

38 117 39 118
37 116 38 117
39 118 40 119
36 1155 37 116
38 117 39 0
37 38 117 0
38 39 118 0
39 118 40 0
37 116 38 0

35	114	193	272	351
36	115	194	273	352
37	116	195	274	353
38	117	196	275	354
39	118	197	276	355
40	119	198	277	356
41	120	199	278	357
42	121	200	279	358
43	122	201	280	359

Fig. 11 Possible shape of the flaw - detail

IV. CONCLUSIONS

Flaw shape reconstruction by nondestructive testing is a very important and an actuality domain, but also a perspective one. The casuistry confirms that nondestructive testing is e very useful tool in the majority of the industrial processes, especially in the big energy consuming domains.

The experimental approach, dedicated to magnetic induction measurement in the neighbourhood of a stainless magnetic pipe with and without flaws, was used to validate the theoretical results developed in [3], [5], [6], [7] and it has as a result flaw shape reconstruction. Flaw shape reconstruction in ferromagnetic bodies is the objective of many nondestructive testing researches worldwide, with implications in very sensitive domains such as nuclear and military.

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