DESIGN AND CONSTRUCTION OF MAGNETIC FLUX LEAKAGE INSPECTION SYSTEM FOR FERROMAGNETIC MATERIAL

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ABSTRACT

The purpose of this study is to develop a magnetic flux leakage inspection system for ferromagnetic materials. It features a newly designed scanner, together with its signal processing circuit and software. Strong permanent magnet discs (1Tesla) are used to establish a magnetic flux in the material to be inspected. When there is no defect, the uniform flux remains in the plate. In contrast, flux leakage occurs outside the plate when there is a local defect due to corrosion or erosion. Hall effect sensor which can detect this flux leakage is placed between the poles of the magnet and generate an electric signal proportional to the magnetic leakage flux. Defects causing a leakage flux exceeding an adjustable predetermined threshold are detected and can be recorded. The amount of leakage flux is dependent on depth, width, breadth of the defects, and also the lift-off sensor and the plate thickness. The developed system enables fast scanning of ferromagnetic plate with qualitative results, with optimum speed 0.2-0.7ms^{-1}. Its sensitivity is 0.2$V(mT)^{-1}$ and it is able to resolve to defects as close as 1mm apart. From the output signal displayed on the computer, the location and the severity of defects can be determined.

ABSTRAK

Penyelidikan ini bertujuan untuk membina sebuah sistem pengesan kebocoran fluks magnetik bagi ujian bahan feromagnetik. Sistem ini meliputi rekabentuk pengimbasan termaju dan pemprosesan isyarat dalam bentuk elektronick dan juga perisian. Cakera magnet kekal yang kuat (1 Tesla) telah digunakan untuk mengaruhkan bahan feromagnet yang hendak diuji. Flux di dalam bahan feromagnet akan kekal seragam sekiranya tiada kecacatan. Sebaliknya, kebocoran fluks berlaku disebabkan terdapatnya kecacatan yang diakibatkan oleh pengaratan atau penghakisan. Magnetometer kesan Hall diletakkan di antara dua muka cakera magnet dan satu isyarat elektrik yang berkadaran dengan kebocoran fluks akan terjana. Kecacatan yang melebihi sesuatu had akan dikesan and direkod. Kebocoran fluks amoun didapati bergantung kepada kedalaman kecacatan, lebar, panjang dan juga bezantara pengimbas dengan permukaan bahan diuji, serta ketebalan bahan. Sistem yang dibina membolehkan pengimbasan yang pantas (halaju optimum dalam julat 0.2-0.7ms^{-1}. Kesensitifan sistem adalah 0.2V(mT)$^{-1}$ dan ia dapat juga membezakan dua kecacatan yang ditempatkan sedekat 1mm. Daripada isyarat keluaran yang dipaparkan pada komputer, kedudukan and keadaan tentang kecacatan dapat ditentukan.

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LIST OF SYMBOLS

A	-	Cross sectional area (m^2)
V_{cm}	-	Common mode gain
A_v	-	Voltage gain
B	-	Magnetic flux density
d	-	Depth
dB	-	Desibel
dt	-	Time interval
dz	-	Change in distance
dS	-	Differential area
D	-	Electric charge density
E_{H}	-	Hall electric field
E	-	Charge of electron
F	-	Force
f_c	-	Cut-off frequency
H	-	Magnetic flux intensity
I	-	Current (A)
L	-	Length (m)
M	-	Magnetisation vector
N	-	Number of turns
n	-	Free carrier density
Q	-	Electric charge
R	-	Resistance
r	-	Radius
r_1	-	Displacement vector
t	-	Thickness
P	-	Magnetic pole of strength
PT	-	Plate thickness
R_H	-	Hall coefficient

T	-	Temperature
V	-	Voltage
V_{OQ}	-	Output quiescent voltage
V_{in}	-	Input voltage
V_{out}	-	Output voltage
Φ	-	Flux
μ_r	-	Relative permeability
χ_m	-	Magnetic susceptibility
υ	-	Velocity of electricity

LIST OF ABBREVIATIONS

ASTM	-	American Society for Testing and Materials
BS	-	British Standard
DC	-	Direct current
LED	-	Light Emitting Diode
MFL	-	Magnetic Flux Leakage
MPI	-	Magnetic Particle Inspection
NDE	-	Non-destructive Evaluation
NDI	-	Non-destructive Inspection
NDT	-	Non-destructive Testing
NSR	-	Noise-to-signal ratio
PC	-	Personal computer
UT	-	Ultrasonic Testing
VCO	-	Voltage Controlled Oscillator

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CHAPTER I

INTRODUCTION

1.1 Foreword

Non-destructive testing (NDT) is a testing method without destroying the products and/or structures. It will provide information on the material quality but does not alter or damage the material under test. Materials and manufactured products are often tested prior to delivery to the user to ensure the quality and expectations of the customers. It is essential that any test made on a product intended for future use does not in anyway impair its properties and performance. Increasingly, NDT is used as an economic tool in predictive maintenance approach of plant operators. This allows lifetime extension based on planned replacement or repair of deteriorated components. This tendency demands full surface coverage rather than the usual spot inspection of plant components. Moreover, it often requires in-service inspection of most of these components. This challenge is met by recent developments in NDT. Any technique used to test under these conditions is called a non-destructive method (Blitz, 1991). In this chapter, an overview about the NDT, background of the study, the objectives of research, and the scopes of research would be discussed briefly.

Instruments working in factories, automobiles, railroads, airplanes, structures, plants, petroleum tanks, gas tanks will have to undergo inspection and to check whether there is a defect. For any defects detected, an estimate on the propagation rate of the defects in terms of their shapes, dimensions and working stress on the defects must be stated. NDT contributes very much to estimate the life span of industrial products. Thus, regular inspection is very important for confirming the safety of industrial products. Through regular inspection, we can check the situations of defect propagation when we know the location where the defect exists.

For this purpose, routine inspection is needed to monitor the corrosion growth and corrective action will be taken whenever necessary. For a safer environment for industrial operation, there is also a scheduled inspection to check for the containers of liquid such as oil, petrol and gas for hazardous leakage in order to prevent the whole plant from ceasing its operation. Thus, this scheduled inspection is necessary in order to avoid any further loss if there is any unexpected factory shut down.

The focus on an inspection is to detect a flaw or a defect. According to Japanese Industrial Standard (JIS) Z2300 "Terminology of NDT", a flaw is defined as discontinuity judging from the results obtained by NDT. However, a defect is defined as a flaw rejected because of exceeding the judging standard prescribed in the specification or the standard.

NDT should not be confused with non-destructive inspection (NDI). NDT is a means to examine whether there is a flaw in objects (the smaller ones are ICs and the larger ones are oil tanks, aircrafts and large oil tankers), of which their sizes and inner structures we cannot see through without scratching, decomposing and/or destroying the objects. NDT does not depend on the kinds of materials, parts and structures, etc. It includes visual testing, radiographic testing, ultrasonic testing, magnetic testing, liquid penetrant testing, eddy current testing, etc. However, NDI includes the judgement whether it is safe when we continue to use the objects, whether it is necessary to repair them or whether it is necessary to renew the parts using the results obtained by NDT. Simply speaking, we decide whether the objects are good, good under some conditions or not good through NDI.

NDT can be performed on metals and non-metals and the method of testing used depends on factors such as the type of material and its dimensions, the environment, the positions of interest within the structure of component under examination, that is, whether internal or surface defects are sought, and the suitability for data acquisition and processing. Often the first stage in the examination of a component is visual inspection. Examination by the naked eye will not reveal much other than relatively large defects which break through the surface. The effectiveness of visual inspection can be increased through the use of visual aids such as microscope or optical scope (Hull and John, 1988).

Using well-established physical principles, a number of non-visual inspection systems have been developed. The following paragraphs will give an overview about the developments and evaluation of modern NDT technique and their applications. The Low And High Energy RTR (Real Time Radiography) is used to detect corrosion under insulation. A low energy (<70kV) X-ray beam tangentially illuminates the "horizon" of the pipe. Radiation is detected by an image intensifier, upon which metal loss particularly the corrosion product causes a "shadow". The RTR system can be safely man-operated and used in a continuous mode moving on a "skate-board". Such a system needs a robot for remote manipulation due to the high radiation levels. Some of these systems are developed for use on the North Slope of Alaska with extremely long lengths of thermally insulated pipe work.

Over the past ten years, several attempts have been made, and with some success to apply low frequency eddy currents to establish the presence and severity of corrosion under lagging. The most promising attempt named INCOTEST pulsed eddy current system to measure wall thickness of thermally insulated components. A considerable market demand exists despite the fact that the technique will not (and cannot) detect very localized corrosion. The battery-powered system is not dynamic, and requires several seconds for each measurement; at present, a crew can achieve 1000 measuring points per day (Stalenhoef and Raad, 1997).

Corrosion detection at locations with limited access gives rise to many inspection problems in daily practice. Hidden corrosion at inaccessible locations such as pipes on sleepers or supports, insulated pipe work, tank floor annular plates, riser pipes at clamp locations, nozzle reinforcement plates and complex joints is sometimes only found with great difficulty or in a late stage when damage is already done. At present it often requires costly measures to shut down and open or lift the component for access. A new ultrasonic pulse echo method (LORUS-Long Range Ultrasonic System) has been optimized for inspection over considerable distance (typically one meter) which can overcome most of the access problem. The technique utilizes optimized bulk wave transducers with a dedicated data recording system (Hoppenbrouwers, 1997).

Contrary to LORUS, Creeping Headware Inspection Method (CHIME) is especially developed to detect and qualify hidden corrosion of pipes on sleepers or corrosion at risers clamp areas. It requires access at two opposite places to locate the transmitter and receiver probe. Results are presented as B-scan images which require considerable skill to interpret. However, both LORUS and CHIME, not matured yet, are in their validation stage, and possibilities and restriction are not fully known at present.

A Time Of Flight Diffraction (TOFD) system makes use of a hand-held "bicycle" with two ultrasonic probes and position encoder. In one day about 40m of welds can be inspected. It is a rather new ultrasonic method suitable for fast weld defect detection but also for sizing.

All these NDT methods co-exist and depending on the application, may either be used singly or in conjunction with one another. There are some overlaps between the various test methods but they are complementary to one another. The fact that, for example, ultrasonic testing can reveal both internal and surface flaws does not necessarily mean that it will be the best method for all inspection applications. Usually, a combination of two or even more methods may be required for the complete inspection of an object. The methods most commonly used are ultrasonic testing, X-ray radiography, eddy current testing, magnetic particle inspection and dye-penetrant application. These methods receive the greatest amount of attention from national and international standards organizations as they attract regular training courses in practical applications and certificates of proficiency in them are awarded by recognized bodies to proven skilled operators. Each NDT method has its advantages and disadvantages. Hence, it is necessary to select the appropriate NDT method, which is just the method for its use. Much will depend upon the type of flaw present, the shape, the size and the property of the component to be examined. The introduction of any inspection system incurs cost but the effective use of suitable inspection techniques will give rise to very considerable financial savings.

The methods of testing the object under examination may already be specified but, when a choice of technique is permitted, the testing should be carefully planned with regard to safety, economics and efficiency. Whatever methods are used, even when pre-specified, the test object should first be thoroughly inspected as far as possible by eye, perhaps with the aid of a magnifying glass, and by touch. Many cases have occurred in which the use of valuable equipment and time have been wasted in locating flaws which could easily have been seen with the unaided eye in the first instance.

This work will bring to the alternative of the inspection of the carbon steel plate that is usually being the material of storage tank floors. The storage tanks, for instance, are used to fill in the crude oil and distilled petroleum such as diesel, petrol and kerosene. The size of these tanks is usually huge and is exposed to high risk of corrosion since their location is always near the seaside. The corrosion will then grow to form more severe defect.

For previous practice, periodic visual inspection had been used to locate and assess top surface corrosion whereas a combination of random ultrasonic checks and the removal of coupons from the floor have been used to assess underfloor corrosion. However, these traditional methods have not always proved to be reliable in detecting potential product leakage sites (Horner, 1991).

Nowadays, liquid penetrant inspection is an important industrial method and it can be used to indicate the presence of defects such as cracks, laminations and laps of surface porosity in a wide variety of components. However, its obvious major limitation is that it can detect surface-breaking defects only. Sub-surface defects require additional inspection methods. Other factors inhibiting the effectiveness of liquid penetrant inspection are surface roughness and material porosity. The latter, in particular, can produce false indications, since each pore will register as a potential defect (Hull and John, 1988).

Comparing to the other NDT methods of specimen magnetisation, magnetic particle testing relies on the existence of leakage fields, which are set up around defects when the test specimen is magnetised internally by a very large direct current. The main disadvantages of this method are: (a) The need for providing a very high current in order to magnetize the material, and (b) the qualitative nature of the results do not allow the method to be used as an effective in-line control tool (McMaster, 1986). When large components are to be inspected, extremely large currents are required and care will be needed to avoid localized heating and surface burning at the points of electrical contact. The indications observed in magnetic particle testing may be readily visible but, frequently, considerable reliance must be placed on the skill and experience of the operator for the correct interpretation of the significance of indications.

Eddy current testing devices eliminate both of the above disadvantages by using externally induced eddy current reaction fields to give an indication of the presence of defects. However, the eddy current pick-up coil is constrained/forced to move in relatively simple paths, which limits the method to the detection of defects in specimens having smooth continuous surfaces, unless automatic gain control (a mean of correcting for sensitivity changes caused by probe-to-part spacing) is used. For instance, the detection of corner defects on billets is difficult, because the coil moves in a path parallel to the flat face of the billet. Another disadvantage occurs because the high frequency eddy currents remain close to the surface of the billet, preventing the detection of deep subsurface flaws. These comments apply in part to the magnetic reaction analyzer, which uses a Hall plate as the detection device in place of the conventional eddy current pick-up coil. (McMaster, 1986) Furthermore, in order to test highly permeable (magnetic) alloys such as carbon steel, due to the high permeability of carbon steel, eddy current penetration is severely limited, and the detection of subsurface and far surface defects are not detectable with that method.

Magnetography is essentially an extension of magnetic particle testing. Present magnetographic methods of defect detection, although still in the developmental stage, require a large direct current to set up the leakage fields around surface defects, which are then recorded on magnetic tape. The output information is qualitative rather than quantitative. The major advantage of the magnetographic method, at the present time, is that corner defects on billets are now detectable, because the physical properties of the magnetic tape allow it to be formed to the surface of the billet. One disadvantage that arise due to the intimate contact, which must be maintained between the magnetic tape and the test specimen, resulting in excessive/too much tape wear.

Radiography, although it is a very useful non-destructive test method, it possesses some relatively unattractive features. It tends to be an expensive technique, compared to other non-destructive test methods. Besides, the use of radiography and related processes must be strictly controlled because exposure of humans to radiation could lead to body tissue damage.

Recently, the coverage and reliability of in-service inspection techniques has improved through the introduction of Magnetic Flux Leakage techniques (MFL) (Saunderson and Kear, 1991). It is only in the last ten years that this inspection technique had been applied to aboveground storage tank floors, in an attempt to provide a reliable indication of the overall floor condition within an economical time-frame (Amos, 1996).

MFL inspection of low-alloy carbon steel components is attractive while, contrary to ultrasound inspection, no coupling is needed between the sensor system and the object. Unlike the magnetic particle inspection (MPI) technique, MFL is fast and reliable to detect local corrosion (Amos, 2001). On the other hand, the MPI method has two disadvantages as discussed earlier, which are, the need for providing a very high current in order to magnetize the material, and the qualitative nature of the results does not allow the method to be used as an effective in-line control tool (Lord and Oswald, 1972). Also, by using the ultrasonic system, the conventional approach for inspection was to make manual ultrasonic defect detection on a grid of points typically 1ft apart. This could take up to 2 weeks for a large tank and is very ineffective in detecting pitting corrosion. It is time-consuming and laborious.

Camerini *et al.* (1992) pointed out the importance of developing this MFL inspection system. Fuel tanks are provided with small thickness bottom plates (6mm), which are in contact with the soil and, as a result, are subject to corrosion often provoking leaks and the resulting interruption of the equipment in non-scheduled periods. The non-destructive inspection of such plates has been a difficult problem, due not only to the wide area to be inspected but also to the inefficiency of conventionally used test – typically pointed hammers and ultrasound (Buhrow, 1984). In both cases, corroded points are located at random, which is a strong limitation, considering the vast areas to be inspected. When using automatic ultrasound measurement technique, sensitivity is reduced, as corrosion aggravates, mainly due to the shape of the pits, which are deficient reflectors of ultrasonic energy (Birring, 1986 and Sigh, 1985).

MFL method was developed by Röntgen Technische Dienst bv (RTD), a subsidiary company of Llyod. It provides the mentioned inspection services to big industries throughout the country. However, RTD does not sell the inspection system and charge a high price for each servicing. In this work, a MFL inspection system for ferromagnetic material has been developed to provide an alternative of steel plate inspection and to reduce the operational costs. This MFL inspection system is expected to become the pioneer project in Malaysia, to aim for lower cost and better quality service to serve the small and medium industries in future development. The developed MFL inspection system provides permanent records; the scanned parameters will be recorded and stored. For display, a computerised MFL inspection system for ferromagnetic material is being developed in a laboratory environment, as previous work employed the oscilloscope to inform the user of the existence of imperfections on the plate undergoing inspection (Camerini, 1992).

1.2 Objectives Of Research

There are several objectives need to be achieved in this research. The first objective is the design the MFL sensor circuitry. It is then followed by the design of MFL signal processing circuitry. Then, the next objective is to design a test rig used for inspection scanning. After that, a complete computerized MFL inspection system for ferromagnetic material need to be developed. Finally, a trial run is needed in order to verify the system. In order to achieve these objectives, activities as described in **Section 1.3** are carried out.

1.3 Scope of Research

Activities are carried out throughout the duration of this research consist in three phases, which were Phase A, Phase B and Phase C. In Phase A, a literature review about magnetic flux leakage inspection is done. After that, two different types of sensor are built, compared and evaluated. In Phase B, it involves the design and construction of the magnetic flux leakage sensor. Pre-amplifier, amplifier, filter and other signal conditioning circuitry are designed. Then, the test rig parameters are being adjusted in order to suit the response for steel inspection. During the last stage, which was Phase C, the whole computerised inspection system is developed. The system is tested with different types of defects and scanning parameters. It includes defect widths, defect depths, defect lengths, and also lift-off between the sensor and the sample. Besides that, scanning speed test, resolution test and sensitivity test are also been carried out.

5.3.3 The Essential of Sensor Arrays for Mapping

Once a defect has been detected and recorded, its location should be monitored on growth rate, and the results is better to be presented in a way which eases interpretation, e.g. mapping of results of floor inspection. Therefore, work in developing sensor arrays can be done to enable the MFL system to scan in a fine matrix over the defected area, and depth profile can be mapped. When it is done, colours can be used to enhance the results. Results also can be display to show the defect growth trend.

A significant development effort for MFL will continue at in-line inspection service companies, universities, and as part of storage tank floor company and government sponsored technology development programs. These efforts will undoubtedly lead to an enhanced understanding of the topics discussed herein and to continuing advances in the capabilities of commercial MFL in-line inspection tools. Through advances in technology, MFL will continue to be a beneficial tool that one can use as part of an overall integrity assurance program.

As a conclusion, a magnetic flux leakage inspection system for ferromagnetic material has been successfully designed and constructed. It is the first and the latest system in Malaysia uses the real time dynamic MFL scanning system using Hall effect sensor.

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