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DEVELOPMENT OF MAGNETIC IMAGING SYSTEM FOR SHAPE IDENTIFICATION BASED ON GMR SENSOR ARRAY

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BY
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DEVELOPMENT OF GIANT MAGNETO RESISTANCE SENSOR FOR MAGNETIC IMAGING SYSTEM

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Non-Destructive Evaluation (NDE) is one of the most common methodologies used in the industries. This method is proposed to examine the properties of ferromagnetic materials. NDE technique carries the ability to perform shapes evaluation of ferrous objects without permanently altering its characteristics. The NDE technique used in this study for shapes evaluation is based on the magnetization characteristics of ferrous metal specimens. In NDT industries measurement time is a key feature. Therefore, using a single small sized Giant Magneto Resistance (GMR) sensor element to scan an object in a fine grid is in most cases not practicable. Alternatively, a sensor array housing several tens of simultaneously operating elements is more reasonable. In this study, it presents the performance study of an array lining up 21 pieces of GMR sensor developed for evaluating shapes of ferrous metal specimens.

This thesis is made up of few chapters elaborating the development of Giant Magneto Resistance Sensor for Magnetic Imaging (GMR-mi) System. It is developed to do

assessment for ferrous metal specimen`s shapes evaluation. Focusing only on ferrous metal specimens which are SS400 mild steel iron specimens with various shapes, the prototype of GMR-mi system confirmed the ability to do the evaluation. Magnetic images produced as the result of the shapes evaluation after following the development steps of building the prototype of GMR-mi system. Few components development, started with Signals Sensing Unit (SSU) started off the measurement sensing the magnetic flux perturbation in the system. Next, Signals Acquisition Units (SAU) continues with the transferring the captured data for later processed at Signals Processing Unit (SPU). These developments steps giving out a brief flow on how the development of GMR-mi system is function.

Magnetic imaging system developed with NDE characteristics by fully utilized Magnetic Flux Leakage Testing (MFLT) principle. It is performed on the surface of target ferrous metal specimens. Target specimen is navigates underneath the sensing measurement area with magnetic field supplied by the induction coil. Induction coils create the magnetic field environment with supplied an amount of specific current *I,* thus making magnetic flux present between the thickness evaluation gap *g.* perturbation of magnetic flux density will occurred when it is in contact with a present of ferrous metal specimens.

Finally, the prototype of Giant Magneto Resistance Sensor Magnetic Imaging System is developed. Performance parameters of Giant Magneto Resistance Sensor Magnetic Imaging System are listed which are current *I*, induction coils number of turn *n* and thickness of evaluation gap *g*. In addition, all the experimental results have been studied and presented in this thesis. Firstly, it explains the ability of the system in visualizing the shapes of ferrous metal specimens with magnetic images. Next, all results presented showing the capability of this system in visualizing the shapes of ferrous metal specimens from the actual ferrous objects are having the same capabilities as other magnetic imaging technique. Last but not least, the effect of perpendicular gap towards accuracy of Giant Magneto Resistance Sensor Magnetic Imaging System for ferrous metal specimen is studied. According to the brief studies and assessment of all the magnetic images, the optimized perpendicular thickness of evaluation gap *g* is 7mm.

Summing up, Giant Magneto Resistance Sensor Magnetic Imaging System is capable to evaluate the shapes of ferrous metal specimens.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Master Sains

PEMBANGUNAN SISTEM PENGIMEJAN MAGNETIK UNTUK MENGENALPASTI BENTUK SPESIMEN DENGAN MENGGUNAKAN ARRAY SENSOR PERINTANG GIANT MAGNETO

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Penilaian Tanpa Kemusnahan (NDE) merupakan salah satu cara metodologi yang sering digunakan didalam industri. Metod ini dilakukan untuk mengkaji sesetengah sifat bahan feromagnetik. Teknik NDE mampu melakukan pemeriksaan bentuk bahan feromagnetik tanpa mengubah bentuk asal serta tidak merosakkan cirri-ciri asalnya. Didalam kajian ini, teknik NDE diguna pakai untuk melakukan pemeriksaan bentuk berdasarkan sifat magnetik sesuatu bahan itu. Masa pemeriksaan amat penting ketika ujian NDT dilakukan. Oleh itu, penggunaan sensor *Giant Magneto Resistance* (GMR) bersaiz kecil yang digunakan secara bersendirian adalah tidak praktikal. Secara alternatifnya, array sensor yang disusun secara berselang-seli didalam jumlah yang tertentu diperkenalkan kerana ia lebih munasabah. Didalam kajian ini, ia menerangkan berkenaan dua puluh satu biji sensor GMR yang telah disusun secara array untuk melakukan pemeriksaan bentuk bahan besi fero.

Laporan tesis ini terdiri daripada beberapa bahagian menerangkan serba sedikit pembinaan Sistem Pengimejan Magnetik bersama Sensor Perintang Giant Magneto (GMR-mi). System ini dibangunkan untuk melakukan pemeriksaan bentuk spesimen besi fero. Kajian dilakukan menggunakan sampel spesimen besi SS400 dengan pelbagai bentuk dan prototaip ini telah dibuktikan mampu melakukan pemeriksaan bentuk besi fero. Imej magnetic dihasilkan keputusan dari melakukan pemeriksaan setelah melalui beberapa proses pembinaan prototaip sistem GMR-mi. Ia dimulakan dengan Unit Kesan Signal (SSU) mengesan kehadiran perubahan fluk magnetik didalam sistem. Seterusnya, Unit Penyimpanan Signal (SAU) akan memindahkan data terkumpul kepada Unit Pemprosesan Signal (SPU) untuk penghasilan imej magnetik. Langkah-langkah ini menerangkan aliran ringkas mengenai sistem GMR-mi.

Sistem pengimejan magnetic dengan ciri-ciri NDE ini sepenuhnya mengaplikasikan prinsip Ujian Kebocoran Fluk Magnetik (MFLT). Pemeriksaan yang dijalankan hanya dilakukan diatas permukaan spesimen besi fero. Spesimen target digerakkan dibawah kawasan pemeriksaan sensor dengan kehadiran medan magnet disekitarnya. Wayar induksi digunakan untuk menghasilkan kawasan medan magnet dan ia dibekalkan dengan sesuatu nilai arus, I seterusnya menghasilkan fluk magnetic diantara sensor dan spesimen besi fero g. Suatu gangguan densiti fluk magnet akan terjadi apabila ia bertindak balas dengan kehadiran spesimen besi fero.

Akhirnya, prototaip Sistem Pengimejan Magnetik bersama Sensor Perintang Giant Magneto telah dihasilkan. Parameter keupayaan sistem ini telah disenaraikan iaitu arus, I, jumlah gulungan wayar induksi *n*, dan ketebalan ruang pemeriksaan *g*. Tambahan pula, keputusan ujian telah dikaji dan disertakn didalam laporan tesis ini. Pertama, ia menerangkan keupayaan sistem dalam melakukan kajian bentuk spesimen besi fero. Seterusnya, ia membuktikan hasil pemeriksaan dan kajian yang dilakukan terhadap imej magnetic yang dihasilkan sama seperti hasil imej megnetik berdasarkan teknik-teknik yang lain. Lagi, kesan ruang sejajar terhadap ketepatan sistem GMR-mi untuk melakukan pemeriksaan bentuk spesimen besi fero juga dilakukan. Berdasarkan kajian ini, ketebalan ruang sejajar terhadap ketepatan sistem GMR-mi adalah 7mm.

Secara keseluruhan, Sistem Pengimbas Imej Magnetik bersama Sensor Perintang Giant Magneto ini mampu melakukan pemeriksaan dan kajian bentuk spesimen besi kajian.

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DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institutions.

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LIST OF ABBREVIATION AND SYMBOLS

μ_o	Magnetic permeability
1D	1 dimensional
2D	2 dimensional
3D	3 dimensional
B	Magnetic field density
dA	Vector of the magnitude of differential element A
dl	Vector direction of current flow
DOE	Design of experiment
ECPT	Eddy Current Pulsed Thermography
ECT	Eddy Current testing
GMR	Giant Magneto Resistance
GMR-mi system	Giant Magneto Resistance Sensor for magnetic imaging system
H	Magnetic field intensity/ strength
I	Current (Ampere)
I_e	Closed loop current flowing through wire
ILI	In line inspection
K_m	Relative permeability of magnetic material
MFL	Magnetic Flux Leakage

MFLT	Magnetic Flux Leakage Testing
MRI	Magnetic Resonance Imaging
NDE	Non Destructive Evaluation
NDT	Non Destructive Testing
$\dot{r}$	Vector unit in the direction of r
SAU	Signals Acquisition Units
SPU	Signals Processing Units
SSU	Signals Sensing Units
USB	Universal Serial Bus
UT	Ultrasonic Testing
UWB	Ultra-Wideband
Φ_m	Magnetic flux

CHAPTER 1

INTRODUCTION

1.1 Background

The non-destructive evaluation (NDE) is a field of study which is concerning about the development of measurement technologies and any analysis techniques related for the quantitative characterization of materials, tissues and structures by noninvasive means without causing any damage to it (D. S. Benitez et al. 2009). To probe interior microstructure and characterize subsurface features, radiographic, ultrasonic, electromagnetic, thermo-graphic, and optic methods are employed. Some of the applications are in non-invasive medical diagnosis, intelligent robotics, security screening, and on-line manufacturing process control, other than that which are traditional NDE areas of flaw detection, structural health monitoring, and materials characterization.

For example, NDE is often employed to evaluate the performances and quality of steel water pipe and steel cables embedded underneath walls or floors (D. S. Benitez et al. 2009). This techniques employed electromagnetic method for flaw detection. Besides that, it is also regarding the health hazards free environment to its operator which makes additional advantages to it (L. J. Yang et al. 2009).

The main contribution of this research is the development of the prototype of metal shapes evaluation for ferromagnetic materials. In field application, this enables the system to be used in detecting shapes of the ferrous objects with small in sizes of the devices and it is portable. The performance study of the prototype system provides useful guidelines for future enhancement of the system to perform surface evaluation on ferromagnetic materials.

1.2 Problem Statement

Currently there are only few prototype devices to visualize the shapes of ferromagnetic materials (J. W. Jun et al.). Evaluation of ferromagnetic metal is based on identifying the edges of metal or any discontinuity surface (Edward C. and Palmer S.). These prototype devices are huge in size and are not portable. The massive size of these prototype devices prohibits their deployment for field applications for shapes evaluation on ferromagnetic materials. Therefore, the prototype device with relatively small size and portable are more practical for field application of surface evaluation on ferromagnetic materials.

Developing a small size device in carrying out the metal shape evaluation affected a certain problems. The most important impact of using small size devices are highly time consuming. This is because less area of detection as the device is small. A proper design of Giant Magneto Resistance (GMR) sensor arrangement build before carrying out the evaluation is essential in order to make sure less time consuming. An array of GMR sensors could be introduced instead of using a single sensor. It is not only less time consuming, in addition it could increase the sensitivity within the evaluation area. By using array of sensors instead of using single sensors could increase the sensitivity with less time consuming.

Prior to the relatively small size and portable device for complex shapes evaluation, it requires an initial prototype device which is able to detect the magnetic flux distribution and visualize the simple shapes of ferromagnetic materials. Multiple improvements could be done which ultimately enables the prototype device to perform complex shapes evaluation on ferromagnetic materials.

With the above mentioned reason, it serves as the motivation to develop a prototype device which is able to perform shape evaluation on ferrous objects that are portable and small in sizes. The prototype device for shapes evaluation of ferrous object is known as Giant Magneto Resistance with magnetic imaging (GMR-mi) system. It is a system comprised of magnetic induction coil, GMR sensor array, data acquisition card, LabVIEW Software and computer with signal array processing application software.

Based on the previous studies, N. Misron et al., a prototype of magnetic imaging system for shape evaluation was build. This device function with a permanent magnet works as the magnetic source supplier. The disadvantages of using permanent magnet are it is stronger than induction coil and has fixed magnetic strength. Stronger magnetic field will result in disturbing the evaluation as the metal specimen could stick onto the magnet when the metal is near to the permanent magnet. Besides, induction coil has the ability to vary its strength according to the power supply. Indeed, induction coil is cheaper than a permanent magnet (Y. N. Cao et al.,)which this will add a huge value to the design.

1.3 Objectives of Research

This study is focusing on the development and performances of the prototype of Giant Magneto Resistance sensor with magnetic imaging (GMR-mi) system for shapes evaluation of ferrous objects. The objectives of this study are to;

- Built the lay-out of the circuit and design of the prototype system

- Develop a prototype of GMR-mi system for shapes evaluation of ferrous objects.
- Evaluate the performances of the prototype device for shapes evaluation of ferrous objects.

1.4 Scope of Work

Giant magneto resistance sensor with magnetic imaging (GMR-mi) system is proposed to detect the shape of ferrous magnetic metal specimens. This proposed research is apprehensive in the development and performance study of the prototype of GMR-mi system. This research consists of three major phases. The first phase focused on defining the development methodologies for prototype of GMR-mi system. The development of GMR-mi system consists of three main modules including the signals sensing unit (SSU), signals acquisition unit (SAU) and signals processing unit (SPU). The first module encompassed the design SSU by linearly integrating 21 GMR sensors into the 1-D GMR sensor array bounded with magnetic induction coil. The second module encompassed the design of SAU comprised of data acquisition card and LabVIEW software for data collection. Lastly, the third module encompassed the implementation of signal array processing algorithm into the GMR sensor array processing application software.

The second phase focused on the design-of-experiments (DOE) to evaluate the performance of GMR-mi system in the shapes evaluation of various ferrous objects. This encompassed the shapes evaluation of actual ferrous objects. In addition, the DOE to evaluate the effect perpendicular gap towards the accuracy of GMR-mi system in shapes evaluation of various ferrous objects is performed. The third phase focused on the analysis of experimental results from the DOE and future improvement to the prototype GMR-mi system. This includes plotting the magnetic images of various ferrous objects for shapes evaluation at different perpendicular gaps. In addition, the observation from the experimental results is explicitly explained.

1.5 Thesis Contribution

In this dissertation, it introduces a magnetic imaging system purposely for the ferrous metal shape evaluation. Industries are distinguished with massive machines capable in carrying out magnetic evaluation. For instances the Magnetic Resonance Imaging (MRI) device for medical imaging technique of anatomy images generated and pulse induction security metal detector. These devices could be easily found in hospital, airports and some attraction places. There is something in common between these two devices which they use strong magnetic fields to generate images based on the target specimens. Where as in this study it constraint only in the usage of small and low magnetic field. A prototype of magnetic imaging system is build with low magnetic usage.

Besides, a new technique is introduced in delivering out a more consistent processed image. It is the data averaging method. Data averaging method calibrates data obtained based on signal captured. The system is made up of few sensors in an array system. All sensors are closely located next to each other in other to maximize the sensing area capability. Even though these sensors are close enough, but relatively a few tiny lines could be noticed between the sensors. Data averaging method is introduced to eliminate these tiny lines between the sensors. Through this, a clearer processed imagecould be produced from the evaluation system.

1.6 Thesis Outlines

Generally, the first chapter of this thesis is presenting the overview of NDE techniques used in ferromagnetic surface evaluation and explaining the problem statement related on recent available NDE devices. As an intro, it initiates the research to develop the magnetic imaging system for shapes evaluation of ferrous objects with the development of its prototype. Explicitly, this chapter presents the list of objectives and also explained regarding the scope of research that has to be carried out to be met the outcome of the research. Thesis outline is presented in the end of this chapter.

Second chapter presents the literature review allied to the research to develop the prototype of GMR-mi system for the shapes evaluation of different ferrous objects. The extent for literature review encompassed the magnetic circuit and magnetic vector quantities outline, GMR effects sensor overview as well as embedded device design outline. A part from this, the literature studies are also done on allied research of at present existing non-destructive evaluation method for ferromagnetic surface evaluation and signal array processing method. These literature studies are very significant references in the research and development of the prototype of GMR-mi system.

All research methodology defined for research and development of the prototype of GMR-mi system is explained in chapter three. It started with an explicitly explanations regarding the overall principle operation of magnetic imaging system. Adding up, this chapter also presents the methodologies used in developing the SSU, SAU and SPU which built the magnetic imaging system. Indeed, the series of DOE is presented. The DOE is intended for the performance understanding of magnetic imaging system in the shapes evaluation of ferrous objects.

Fourth chapter focused on the analysis of experimental results and discussions of the magnetic imaging system in shapes evaluation of ferrous objects. This encompassed the illustration of magnetic images for various ferrous objects. The shapes of various ferrous objects are able to be identified through the magnetic images. In addition, the effect of perpendicular gap towards the accuracy of magnetic imaging system in shapes evaluation of ferrous objects is presented and discussed.

Indeed, chapter five concludes the outcome of proposed study. In this chapter, it concludes the study and development of GMR-mi system for the shapes evaluation of ferrous objects. The conclusions are achieved based on the proposed research methodology presented experimental results from chapter four. Besides, some of future work is explained in this chapter for a better improvement of GMR-mi system device.

REFERENCES

A.Gasparics, G.Vertesy, T.Farkas and J.Szollosy, Magnetic Imaging in Non-destructive Testing. (2010). *2nd International Conference on Mechanical and Electrical Technology (ICMET) 2010*. pp. 47 – 49.

A.J.C.Bik. (2004). *The Software Vectorization Handbook – Applying Multimedia Extension for Maximum Performance*, Hillsboro: Intel Press, pp. 204 – 213.

A.Jander, C.Smith and R.Schneider, Magnetoresistive Sensors for Nondestructive Evaluation. (2005) *10th SPIE International Symposium, Nondestructive Evaluation for Health Monitoring and Diagnostics*.

A.S.Sedra and K.C.Smith. (2003). *Microelectronic Circuits 5th Edition*, New York: Oxford University Press, pp. 484 – 1039.

Baibich, M., Broto, J., Fert, A., Nguyen Van Dau, F., Petroff, F., Eitenne, P., Cruezet, G.; Friederich, A.; Chazelas, J. (1988) Giant magnetoresistance of (001)Fe/(001)Cr magnetic superlattices . *Phys. Rev. Lett*. 66, 2472–2475.

Bickerstaff R., Vaughn M. (2002). Review of Sensor Technologies for In-Line Inspection for Natural Gas Pipelines. *Sandia National.* pp. 1-10.

Bakonyi, I. Péter, L. (2010). Electrodeposited multilayer films with giant magnetoresistance (GMR): Progress and problems. *Prog. Mater. Sci*. 55. 107–245.

Binasch, G., Grünberg, G., Saurenbach, F., Zinn, W. (1989). Enhanced magnetoresistance in layered magnetic structures with antiferromagnetic interlayer exchange. *Phys. Rev. B* 1989, 57, pp 4828–4830.

C.Walls. (2006). *Embedded Software: The Works*, Burlington: Elsevier Inc., pp. 1 – 90.

Cacciola, M., Megali, G., Pallicanó, D., Morabito, F.C. (2011). A GMR-ECT based embedded solution for applications on PCB inspections. *Sens. Actuators A: Phys*. 167, pp. 25–33.

Christides, C., Panagiotopoulos, I., Niarchos, D., Jones, G. (2003). Fast magnetic field mapping of permanent magnets with GMR bridge and hall-probe sensors. Sens. Actuators A: Phys. 106, pp. 243–245.

.

D.Martinez-Nieto, M.McDonnell, P.Carlston, K.Reynolds and V.Santos. (2009). Digital Signal Processing on Intel Architecture, *Intel Technology Journal*, Vol. 13, No. 1. pp. 122 – 145.

D.S.Benitez, S.Quek, P.Gaydecki and V.Torres. (2009). A 1-D Solid-State Sensor BasedArray System for Magnetic Field Imaging of Steel Reinforcing Bars Embedded Within Reinforced Concrete, *IEEE Transactions on Instruments and Measurement*, Vol. 58, No. 9. pp. 3335 – 3340.

Daughton, J.M. (1999). GMR applications. J. Magn. Mater. 192, pp. 334–342.

Dogaru, T., Smith, S.T. (2001). Giant magnetoresistance-based eddy-current sensor. IEEE Trans. Magn. 37, pp.3831–3838.

Dolabdjian, C.P., Perez, L., de Haan, V.O., de Jong, P.A. (2006). Performance of magnetic pulsed-eddy -current system using h igh dynamic and high linearity improved giant magneto resistance magnetometer. IEEE Sens. J. 6, pp. 1511–1517.

Edwards, C.; Palmer, S. (1986). The magnetic leakage field of surface-breaking cracks. J. Phys. D: Appl. Phys. 19, 657–673

F.T.Ulaby. (2004). *Fundamentals of Applied Electromagnetism*. Upper Saddle River: Prentice Hall.

F.Thiel, O.Kosch and F.Seifert. (2010). Ultra-Wideband Sensors for Improved Magnetic Resonance Imaging, Cardiovascular Monitoring and Tumour Diagnostics, *Sensors*, Vol. 10. pp. 10778 – 10802.

Foerster, F. (1986). New findings in the field of non-destructive magnetic leakage field inspection. NDT Int. 19, 3–14.

G.S.Park and E.S.Park. (2002). Improvement of the Sensor System in Magnetic Flux Leakage-Type Nondestructive Testing (NDT), *IEEE Transactions on Magnetics*, Vol. 38, No. 2, Part 1. pp. 1277 – 1280.

G. Rieger, K. Ludwig, J. hauch and W. Clemens. (2011). GMR sensors for contactless position detection, *Sensors and Actuators*. pp. 7-11.

H.Grüger. (2003). Array of Miniaturized Fluxgate Sensors for Non-destructive Testing Applications, *Sensors and Actuators A*, Vol. 106, pp. 326 – 328.

H.Ming. (2009). Hardware Design of Signal Processing Based on DSP, *International Conference on Communication Software and Networks (ICCSN*. pp. 834 – 837.

I.Mohammad and H.Huang. (2010). Monitoring Fatigue Crack Growth and Opening Using Antenna Sensors, *Smart Materials & Structures, IOP Science*, Issue 19. pp. 1 – 9.

J.Allen. (1985). Computer Architecture for Digital Signal Processing, *Proceedings of the IEEE*, Vol. 73, No. 5. pp. 852 – 873.

J.Catsoulis. (2005). *Designing Embedded Hardware 2nd Edition*, Sebastopol: O'Reiley, pp. 110 – 159.

J.Freden. (2010). *Handbook of Modern Sensors 4th Edition*, New York: Springer Science + Business Media LLC, pp. 103 – 105.

J.L.Axelson. (2005). *USB Complete 3rd Edition – Everything You Need to Develop Custom USB Peripherals*, Madison: Lakeview Research LLC, pp. 1 – 84.

J.N.Barkdull and S.C.Douglas. (1996). General-purpose microprocessor performance for DSP applications, *Record of the Thirtieth Asilomar Conference on Signals, Systems and Computer 1996*, pp. 912 – 916.

J.S.Hwang, J.M.Kim and J.Y.Lee,. (2009). Magnetic Images of Surface Crack on Heated Specimen using an Array-type Magnetic Camera with High Spatial Resolution, *IEEE*

Conference on Instrumentation and Measurement Technology (I2MTC) 2009, 5 – 7. pp. 1546 – 1551.

J.S.Hwang, J.Y.Lee and S.J.Kwon, (2009). The Application of a Differential-type Hall Sensors Array to the Nondestructive Testing of Express Train Wheels, *NDT & E International*, Vol. 42, pp. 34 – 41.

J.W.Jun, J.S.Hwang and J.Y.Lee, (2007). Quantitative Nondestructive Evaluation of the Crack on the Austenite Stainless Steel Using the Induced Eddy Current and the Hall Sensor Array, *Conference Proceedings of IEEE Instrumentation and Measurement Technology (IMTC) 2007*, pp. 1 – 6.

J.W.Jun, M.K.Choi , J.Y.Lee, J.W.Seo and K.S.Shin, (2011). Nondestructive Testing of Express Train Wheel Using the Linearly Integrated Hall Sensors Array on a Curved Surface, *NDT & E International*, Vol. 44,pp. 449 – 455.

J.W.Nilsson and S.A.Riedel. (2001). *Electric Circuits 6th Edition*, Upper Saddle River: Prentice Hall, pp. 65 – 87.

J.Y.Lee, J.S.Hwang, J.W.Jun and S.H.Choi, (2008). Nondestructive Testing and Crack Evaluation of Ferromagnetic Material by using the Linearly Integrated Hall Sensor Array, *Journal of Mechanical Science & Technology*, Vol. 22, No. 12, pp. 2310 – 2317.

J.Z.Chen, L.Li and B.G.Xu, (2008). Magnetic Flux Leakage Testing Method for Well Casing Based on Gaussian Kernel RBF Neural Network, *International Conference on Advanced Computer Theory and Engineering (ICACTE) 2008*, pp. 228 – 231.

K.Miya, (2002). Recent Advancement of Electromagnetic Nondestructive Inspection Technology in Japan, *IEEE Transactions on Magnetics*, Vol. 38, No. 2, pp. 321 – 326.

Kataoka, Y. Murayama, S. Wakiwaka, H. Shinoura , O. (2001). Application of GMR line sensor to detect the magnetic flux distribution for nondestructive testing. Int. J. Appl. Electromagn. Mech. 15, 47–52.

Kim, J. Yang, G. Udpa, L. Udpa , S. (2010). Classification of pulsed eddy current GMR data on aircraft structures. NDT&E Int. 43, 141–144.

Kreutzbruck, M. Allweins, K. Strackbein, C. Bernau, H. (2009). Inverse algorithm for electromagnetic wire inspection based on GMR-Sensor arrays. Int. J. Appl. Electromagn. Mech. 30, 299–308.

L.J.Yang, G.Liu, G.G.Zhang and S.W.Gao, (2009). Sensor Development and Application on The Oil-gas Pipeline Magnetic Flux Leakage Detection, *9th International Conference on Electronic Measurement and Instruments (ICEMI) 2009*, 16 – 19, pp. 2876 – 2878.

L.M.Li, S.L.Huang, P.Zheng and K.Shi, (2002). Evaluation of Surface Crack Using Magnetic Flux Leakage Testing, *Journal of Material Science & Technology*, Vol. 18, No. 4, pp. 319 – 321.

L.T.Huang and G.J.Li, (2008). A Reconfigurable System for Digital Signal Processing, Systems, Signals and Devices, *9th International Conference on Signal Processing (ICSP) 2008*, pp. 439 – 442.

M.Dolle and M.Schlett, (1995). A Cost-effective RISC/DSP Microprocessor for Embedded Systems, *Micro, IEEE*, Vol. 15, No. 5, pp. 32 – 40.

M.Domeika. (2008). *Software Development for Embedded Multi-core Systems – A Practical Guide Using Embedded Intel Architecture*, Burlington: Elsevier Inc., pp. 1 – 88.

M.Li and G.Hayward, (2011). Ultrasound Nondestructive Evaluation (NDE) Imaging with Transducer Array and Adaptive Processing, *Sensors*, Vol. 12, pp. 42 – 54.

Matthias Pelkner, Andreas Neubauer, Verena Reimund, Marc Kreutzbruck and Andreas Schütze. (2013). Routes for GMR-Sensor Design in Non-Destructive Testing. Sens. Actuators A: Phys. 2013, vol 203, pp: 335-340

N. Misron, N Wei Shin, Suhaidi S. M. H. Marhaban and N. Farzilah M. (2011). A Mobile Ferromagnetic Shape Detection Sensor Using a Hall Sensor Array and Magnetic Imaging, *Sensors 2011*, pp 10474-10489.

N.Misron, A.Norrimah, R.Wagiran, R.M.Sidek, N.Mariun and H.Wakiwaka, (2008). Consideration of Theoretical Equation for Output Voltage of Linear Displacement Sensor Using Meander Coil and Pattern Guide**,** *Sensors and Actuators A*, Vol. 147, 2008, pp. 470 – 473.

N.Wei Shin. (2006). *Development of Wire Rope Sensor*, Bachelor of Engineering Thesis, Universiti Putra Malaysia.

P.D.Dimitropoulos and J.N.Avaritsiotis, (2003). A 2-D Ferrous Object Imaging Technique Based On Magnetic Field Sensor Arrays, *Sensors and Actuators A*, Vol. 106, pp. 336 – 339

P.G.Donato, J.Ure˜na, M.Mazo, C.D.Marziani and A.Ochoa, (2006). Design and Signal Processing of a Magnetic Sensor Array for Train Wheel Detection, *Sensors and Actuators A*, Vol. 132, pp. 516 – 525

Pelkner, M.; Neubauer, A.; Blome, M.; Reimund, V.; Thomas, H.-M.; Kreutzbruck, M. (2011). Flux leakage measurements for defect characterization using NDT adapted GMR sensors. In Studies in Applied Electromagnetics and Mechanics; IOP Press: Fairfax, VA, USA, pp. 217–224.

R.D.Fellman, R.T.Kaneshiro and K.Konstantinides, (1990). Design and Evaluation of an Architecture for a Digital Signal Processor for Instrumentation Applications, *IEEE Transactions on Acoustics, Speech and Signal Processing*, Vol. 38, No. 3, pp. 537 – 546.

R.Grimberg, L.Udpa, A.Savin, R.Steigmann, V.Palihovici and S.S.Udpa, (2006). 2D Eddy Current Sensor Array, *NDT & E International*, Vol. 39, pp. 264 – 271.

Reimund, V.; Blome, M.; Pelkner, M.; Kreutzbruck, M. (2011). Fast defect parameter estimation based on magnetic flux leakage measurements with GMR sensors. Int. J. Appl. Electromagn. Mech. 37, 199–205.

S.A.Morrison, J.S.Parks and K.S.Gugel, (2003). A High Performance Multipurpose DSP Architecture for Signal Processing Approach, *IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP) 2003*, pp. 601 – 604.

S.D.Choi, S.W.Kim, G.W.Kim, M.C.Ahn, M.S.Kim, D.G.Hwang and S.S.Lee, (2007). Development of Spatial Pulse Diagnostic Apparatus with Magnetic Sensor Array, *Journal of Magnetism and Magnetics Materials*, Vol. 310, pp. 983 – 985.

S.F.Barrett. (2010). *Embedded Systems Design with the Atmel AVR Microcontroller*, ed. Mitchell A. Thornton, San Rafael: Morgan & Claypool Publishers, pp. 17 – 41.

S.Liao, S.Devadas, K.Keutzer, S.Tjiang and A.Wang, (1995). Code Optimization Techniques for Embedded DSP Microprocessors, *32nd Conference on Design Automation (DAC) 1995*, pp. 599 – 604.

S.M.Kuo and B.H.Lee. (2001). *Real-time Digital Signal Processing*, West Sussex: John Wiley & Sons Ltd., pp. 1 – 18, 77 – 121.

S.Soloman. (2010). *Sensors Handbook 2nd Edition*, New York: McGraw-Hill Companies Inc, pp. 460 – 506.

T.Zahariadis, K.Pramataris, S.Voliotis and N.Zervos, (2003). Digital Signal Processing on a Fully Programmable Platform, Video/Image Processing and Multimedia Communications, *4th Conference of EURASIP 2003*, Vol. 1, pp. 257 – 263.

Sotoshi Y., Komkrit C., and Masayoshi M. (2006). Application of Giant Magneto Resistive Sensor for Nondestructive Evaluation, *IEEE Sensor.*

W.C.Kim, J.E.Kim and YY.Kim, (2009). Magnet Configuration Maximizing the Sensitivity and Linearity of a Magnetic Rotation Sensor, *Sensors and Actuators A*, Vol. 151, pp. 100 – 106.

X.L.Chen and T.H.Ding, (2007). Flexible Eddy Current Sensor Array for Proximity Sensing, *Sensors and Actuators A*, Vol. 135, pp. 126 – 130.

X.Li, L.Cheng, G.X.Qin, P.F.Feng and Z.Y.Huang, (2008). Steel pipeline Testing Using Magnetic Flux Leakage Method, *IEEE International Conference on Industrial Technology (ICIT) 2008*, pp. 1 – 4.

Yunlai Gao, Gun Yun Tian, Kongjin Li, Juan Ji, Ping Wang and Haitao Wang, 92015). Multiple Cracks detection and visualization using Magnetic flux leakage and Eddy current pulsed thermography, *Sensors and Actuators A: Physical*, pp. 269-281

Y.N.Cao, D.L.Zhang, C.Wang, Y.Gu and D.G.Xu, (2006). A Novel Electromagnetic Method for Local Defects Inspection of Wire Rope, *IEEE Region 10 Conference (TENCON) 2006*, pp. 1 – 4.