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A Novel GMR-Based Eddy Current Testing Platform

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Abstract

Detection and quantitative evaluation of deep defects in multi-layered structures is an essential task. Since electromagnetic sensor based on GMR effect is sensitive to the magnitude of the magnetic field, the GMR based EC probe can perform better than the conventional probe for low-frequency applications, i.e., when detecting defects deep buried in multilayered structures. A novel GMR-based eddy current testing platform for testing deep defects in multilayered conductive structures is presented. Firstly, the overall scheme and structure block diagram of the novel GMR-based eddy current testing platform are put forward. Then the paper focuses on analyzing and expounding the GMR effect and the key technique of design and development of GMR-based eddy current testing probe. Afterwards each function module and running process of hardware system and software system are introduced. It is able to fulfill the task of scanning inspection of deep defect in multilayered conductive structures.

Keywords: *nondestructive evaluation; eddy current testing; giant magneto resistive sensor; hardware system; LabVIEW*

1. Introduction

The traditional eddy current testing (ECT) instrument adopts the method of impedance plane analysis, and the obtained detecting signal pattern is impedance plane diagram. According to the calibration curve of signal's amplitude and phase which is corresponding to the length and depth of defect, the operator will achieve the estimated value of defect in test piece. Some shortcomings such as high cost of hardware, high power consumption, difficult debugging, complicated measurement, inaccurate testing results, etc, go with the traditional instrument [1].

The GMR-based novel eddy current testing platform adopts the method of field analysis and measures the magnitude of magnetic field directly, so that to increase the sensitivity and spatial resolution of sensors when detecting the defect in deep layers [2-4]. The platform is a set of measuring system with combination of hardware and software which is designed for sake of realizing quick, non-destructive and complete measurement of the defects deeply embedded in multilayered conductive structure. This system is able to achieve the automatic detection of multilayered conductive structure and to trigger an auto-alarm. It adopts the modular design so as to transform itself into a hand-held instrument further, and to realize the detection of in-service work piece with multilayered conductive structure.

This paper mainly introduces the hardware and software system of the testing platform, its main contents are:

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(1) Overall scheme of the testing platform;
(2) GMR ECT probe and its development;
(3) Hardware system;
(4) Software system.

2. Overall Scheme of the System

Specifically the detection object and task of this testing platform is: scanning inspection of deep defects in multilayered conductive structure. In order to realize the above functions the experiment platform of eddy current testing is demanded for the following characteristics:

(1) Adjustable frequency: The detecting frequency that is continuously adjustable ranges from 10Hz through 10 KHz. It's able to detect the defects deeply embedded in multilayered conductive structure where the depth is more than 5 mm by using low frequency eddy current;

(2) Continuously adjustable detecting power: It requires enough energy to get eddy current permeate the multilayered structure and reach the lower plate;

(3) Replaceable probe: The probe is composed of exciting coil and GMR magnetic sensors, and it's compatible with most existing probes;

(4) Overrun alarm: It is equipped with alarm system in case of omitting defects and the alarm covers all over the screen. It's able to be configured by demands and setup audio/video. When the signal of defect is within the effective alarm region, the preset warning will be on display in time;

(5) Adjustable gain: The linear gain ranges from 0 through 60dB, and independent X and Y gain adjustment;

(6) Various filtering ways: Lowpass filter and various digital filtering techniques;

(7) Multichannel detection: Adopt 2 frequencies, 4 channels and orthogonal decomposition output;

(8) Antijamming capability: Few zero-drift, and strong diamagnetic, anti-seismic capacity;

(9) Data processing and display by PC: Store the setting-up of instrument and the report records of former detection history, so that to substantially increase the traceability of signal;

(10) Instant balance: Press the button to restore balance immediately without waiting.

Operating environment: Temperature ranges from 15℃ through 45℃.

Consequently, our research group develops the corresponding ECT experiment platform which consists of the following components:

(1) Excitation signal source;
(2) GMR probe;
(3) The adjustment module and acquisition module of signal;
(4) The upper computer software based on LabVIEW platform;
(5) Scanning mechanism.

The GMR-based novel eddy current testing platform is shown in Figure 1. This novel ECT device adopts GMR magnetic sensors and it has high degree of automation, high detection precision.

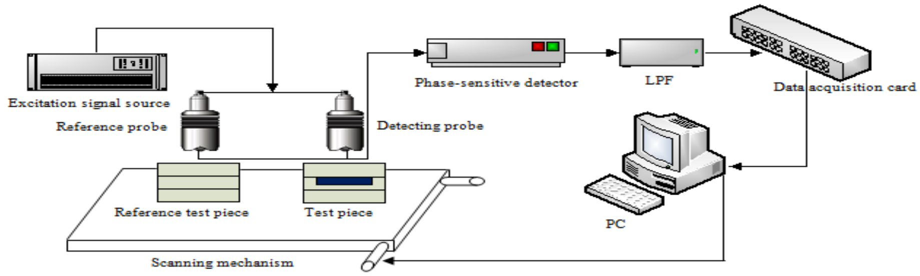


Figure 1. GMR-based Novel Eddy Current Testing Platform

3. The Design of Eddy Current Probe using GMR Magnetic Field Sensors

Coils are usually applied as detecting probe in conventional eddy current testing, and the major drawbacks are requiring to low the excitation frequency (low frequency) or to increase the diameter of detecting coil (large probe) when detecting the relatively deep defects, which could lead to decreasing the detection sensitivity to very low and increasing the distortion of local detecting signal and omitting the defect with smaller dimension than the diameter of detecting coil. In recent years, the electromagnetic field methods of ECT using advanced magnetic sensors have been being paid increasingly attention. Magnetic field sensors, such as Hall sensors, Anisotropic Magneto Resistance (AMR), Giant Magneto Resistance (GMR) and Superconducting Quantum Interference Device (SQUID), have been successfully applied to detect the micro crack deeply embedded in multilayered conductive structure. Under the circumstances of low frequency, the probe with magnetic field sensors has better performance than the conventional one, which is because the magnetic field sensors are only sensitive to the magnitude of the field; while to inductive probe, its output voltage varies in proportion to the change rate of the magnetic field, therefore its sensitivity decreases in cases of low frequency [5, 6].

Among the magnetic field sensors above, SQUID has extremely high sensitivity, but due to its complicated structure, bulky volume and high price, it's usually used in medical and research of magnetic material field at present; AMR sensors have characteristics of relatively high sensitivity and quick response, whereas they can only measure a small range of magnetic field and have poor antijamming capability; Hall sensors cost low and have very wide applications, but they have relatively low sensitivity, large offsets and low temperature stability; while GMR sensors not only have high sensitivity, superior temperature stability, but also have relatively low cost, strong antijamming capability and large measureable range of field, so the GMR sensor is one of the best performance-price-ratio types among the numerous magnetic induction sensors so far [7-10]. The comparison of performance and price of different types of magnetic field sensors is shown in Table 1 and Table 2.

Table 1. Comparison of Different Types of Magnetic Field Sensors

	GMR	Hall	AMR
dimension	small	small	big
signal level	high	low	medium
sensitivity	high	low	high
temperature stability	high	low	medium
power consumption	low	low	high
cost	low	low	high

Table 2. Comparison of Different Types of Magnetic Field Sensors

Type	Measureable range of magnetic field (103/(4π)) 10^{-8} 10^{-4} 10^{-0} 10^{4} 10^{8}	Price (yuan)
SQUID		10,000～1,000,000
FLUXGATE		1,000～100,000
AMR		10～10,000
HALL		10～100
GMR		10～1,000

3.1. The Selection and Characterization of GMR Magnetic Field Sensors

American NVE Corporation is the first enterprise to transfer GMR technology into sensor products [10]. The corporation produced the first analog sensor in 1995, and developed multiple series of analog and digital sensors afterwards. And the material of sensors is Ni/Fe/Co/Cu multilayered membrane material. Within from 10% through 70% of sensor's full range, the sensor provides linear output of 98% degree, great GMR effect (13%~16%), superior temperature stability (<0.14%/℃), wide operating temperature range (±150℃), large measureable range of magnetic field (0~±300Gauss).

The AA-series magnetic field sensors from NVE have the characteristics of superior temperature stability, high sensitivity, low power consumption and miniaturization. Figure 2 shows the detection threshold of each magnetic field sensor under different frequency band which is given by National Bureau of Standards (NBS), of which the AA-series magnetic field sensors from NVE are based on GMR effect and the sensors from Honeywell are based on AMR effect; it's clear to find out the performance of AA-series magnetic field sensors from NVE is generally better than the sensors based on AMR effect. We choose the AA002-2 GMR sensors by comprehensive consideration of cost and technical parameters of chips, and the structure is shown in Figure 3. The sensor deposits on the silicon substrate and its dimension is 0.44×3.37mm. It's easy to know magnetoresistance characteristics of this type of sensors according to its symmetrical single-pole response (see Figure 4.).

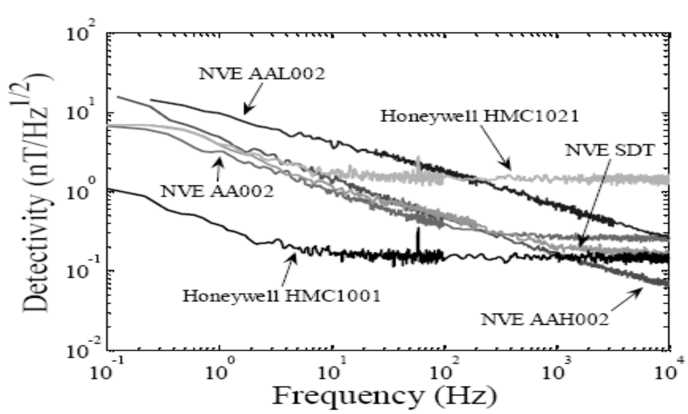


Figure 2. Detection Thresholds of Several Commercial Magnetic Field Sensors

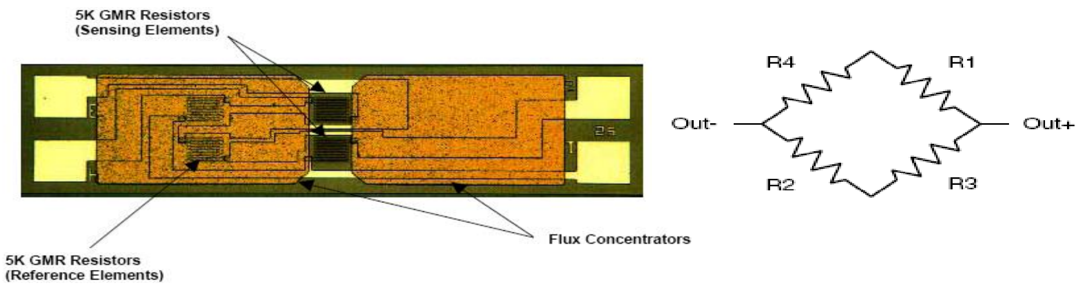


Figure 3. Photomicrograph and Structure of NVE-AA002 Magnetic Field Sensor

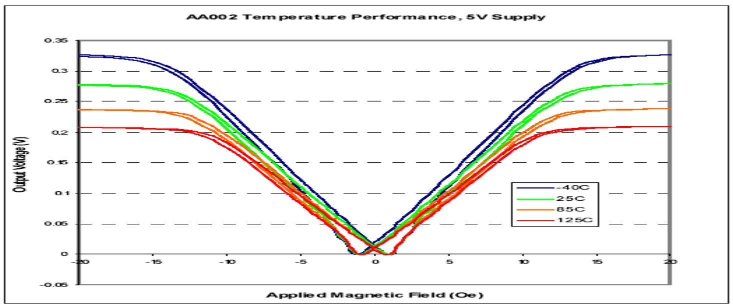


Figure 4. Response Characteristics of NVE-AA002 GMR Sensor Chip

In the figure, the hysteresis effect makes the magnetoresistance characteristics have double values near the origin. Generally speaking, the hysteresis influences the shape of rectified signal, to a sinusoidal magnetic field, bringing in high-frequency harmonics into the output. Since the signal is low pass filtered to extract its mean value, the harmonics don’t appear in the output. The origin distortion of sensor has small influence to the mean value as well, but the linear relation between the amplitude of excitation magnetic field and the DC output will not change. So the operating frequency of excitation field should be chosen within the range of making the sensor response linearly.

3.2 Layout of Cylindrical GMR Eddy Current Probe

The major components of eddy current probe are: A relatively large cylindrical coil is taken as excitation coil, and place a GMR sensor on the axis. The parameters of excitation coil are shown in Table 3 and the overall structure of the probe is shown in Figure 5.

Table 3. Parameters of Excitation Coil

number of turns (N)	330
inside radius (r1)	3.0m
outside radius (r2)	5.11mm
length (l2-l1)	20.7mm
coil inductance (L0)	1.02mH
coil resistance (R0)	19.84om
diameter of wire (d)	0.15mm

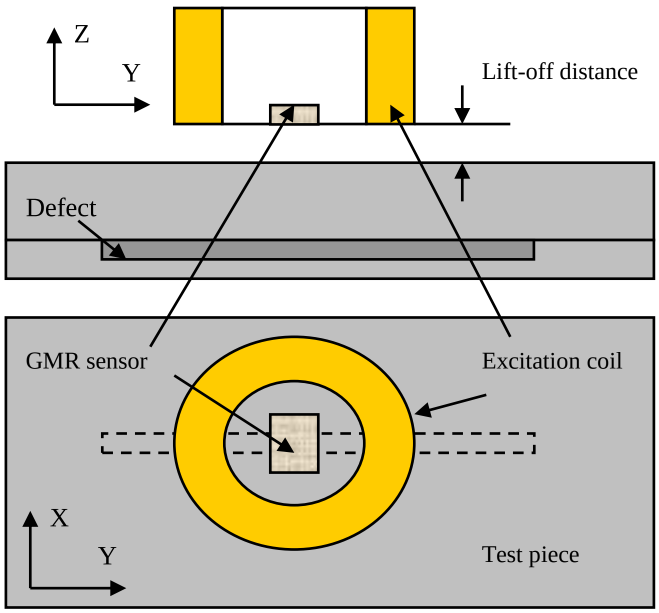


Figure 5. The Structure of GMR-based ECT Probe

The GMR sensor is composed of four thin resistors in a Wheatstone bridge configuration, of which the two resistors of four are magnetically shielded and act as dummy resistors. The sensing axis of GMR probe is coplanar with the surface of test piece, and the excitation magnetic on coil axis which is perpendicular to the sensing axis of GMR thin film has no influence to the sensor. Being placed above the test piece without defect, the sensor will have no output because of the circular symmetry of the induced eddy current; when the defects do present, the output signal of the sensor is engendered only if the perturbation in the eddy current path happens.

4. The Hardware System of the GMR-based Novel Eddy Current Testing Platform

A multi-frequency ECT instrument can be regarded as a “combination” consists of two or more single frequency instruments. The structure block diagram of the hardware system of GMR-based novel eddy current testing platform is shown in Figure 6 which is composed of the following main function units:

(1) DC power module: Provide respective 9V, 12V, -12V, 15V, -15V DC voltage and value of maximum current is up to 500mA. At the same time, inhibits the power supply ripple below millivolt level in order to avoid the interference to detecting signal from the noise of power supply.

(2) Excitation and reference signal module: The excitation and reference signal source is engendered by DDS integrated chip controlled by microprocessor. After filtering high harmonic components through LPF and then get rid of the sc component; amplify the amplitude of ac component through preamplification circuit first and then amplify the power, which can generate quad-way orthogonal sinusoidal ac signal as the excitation signal of detecting probe and reference signal of phase-sensitive detector circuit. The frequency of generated signal is adjustable from 10Hz through 10 KHz, and the phase error of the orthogonal signal is no more than 0.2 degree.

(3) Power amplification module: Provide exciting current for the probe that can reach to 400mA and without self-excitation.

(4) Probe module: Including excitation coil, GMR magnetic field sensor and the relevant circuit. The excitation coil induces eddy current in test piece and the GMR sensors detect the magnetic field signal generated by eddy current.

(5) Detecting signal adjustment and phase-sensitive detector module: Hereinto, the balancing circuit of probe will eliminate the dc signal in detecting probe and balance the ac voltage output in static state in order to make the value of static ac signal to be zero, to make most of the dynamic range of amplification circuit and to increase the SNR; the signal amplification circuit amplifies the output signal of detecting probe from the milli-volt level to the range from -10V through 10V and with no presence of phase error nor self-excitation in process of signal amplification; the phase-sensitive detector circuit uses dual-way orthogonal reference signals to decompose the amplified detecting signal and get the so-called decomposition signal of magnetic field.

(6) Data acquisition module: The adopted data acquisition card is the DAQ Pad-6015 type from NI Corporation with sampling rate of 200KS/s, resolution of 16bit, supporting 16-way analog input and dual-way analog output, data communication with PC through USB Bus. Collect the signal with the A/D acquisition card and put it into PC, and conduct inversion calculation after preprocessing the signal in PC.

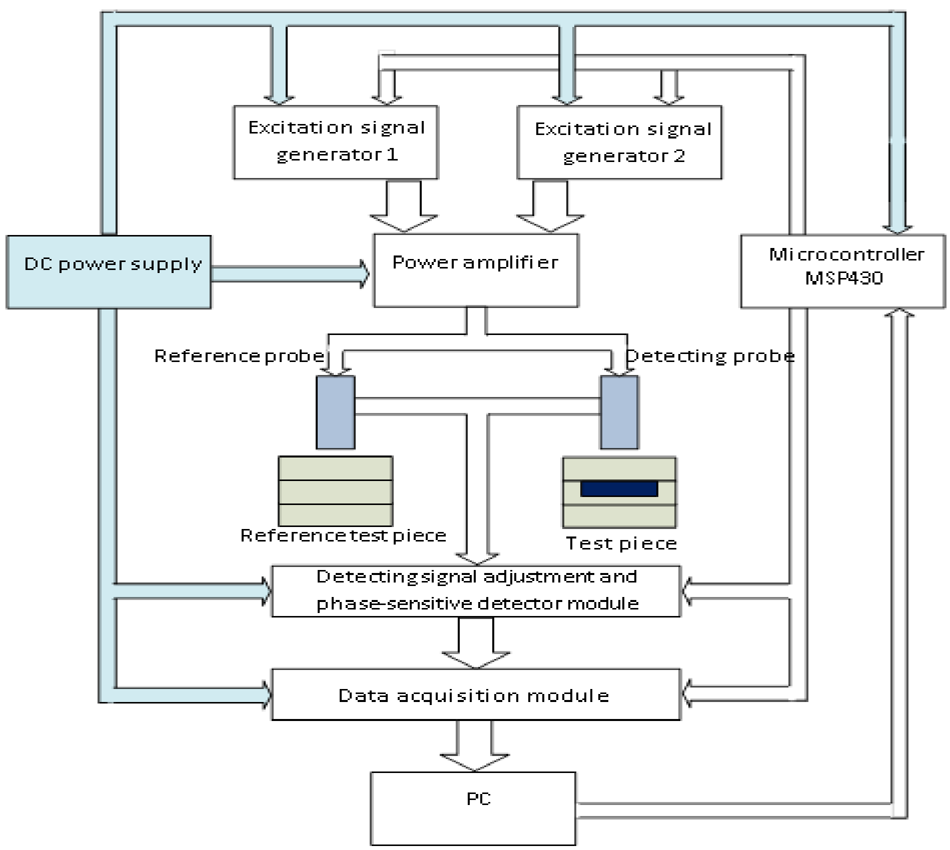


Figure 6. Structure Block Diagram of the Hardware System of GMR-based Novel Eddy Current Testing Platform

(7) Control module: Use the MSP430 as the core of control to accomplish the jobs such as programmable gain, automatic zero setting, data acquisition, communication with upper computer, *etc*. The functions of programmable gain and automatic zero setting are controlled by buttons; when the detection begins or in need, the staff starts the programmable gain or automatic zero setting by pressing the corresponding button. The data acquisition and communication with upper computer are part of a whole, and the orders of frequency collection, order acquisition, *etc*., are given by upper computer, after receiving the orders the single chip microcomputer (SCM) sets the corresponding parameters and starts collecting and uploading data to upper computer.

(8) Scanning mechanism: The height of probe lift-off can be freely adjusted, and the probe which can be random loading and unloading is able to take step motion equidistantly on metal surface. The scanning device adopted by this system is composed of the GT-series motion controller, servo motor, servo motor driver, etc, which are from Googol, and communicates with PC through PCI interface. After installing the communication driver of motion controller, we can operate the platform through the XY platform controlling software provided from Googol.

In work state, the signal generating circuit for excitation signal and reference signal produces the excitation signal and the signal flows into the probe after being power amplified; the excitation coil in probe induces eddy current in test piece and the GMR magnetic field sensor receives the magnetic field signal and generates the corresponding voltage signal; the voltage signal enters the amplification circuit after being balanced, and then it is decomposed by phase-sensitive detector circuit and so that the decomposition signal of magnetic field is obtained; after the decomposition signal is A/D converted, it is put into PC and preprocessed; then conduct the inversion calculation and confirm the parameters of the deep defect in multilayered conductive structure; display and output the variation of detecting voltage and the parameters of defect to be tested.

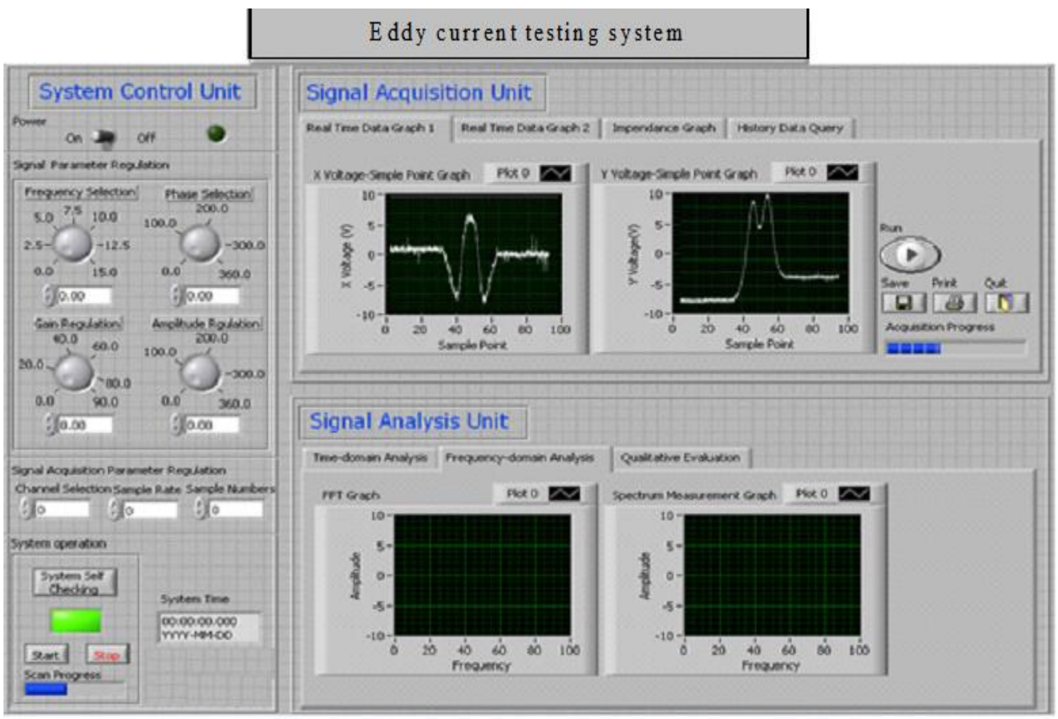
5. The Software System of the GMR-based Novel Eddy Current Testing Platform

The upper computer software adopts the LabVIEW from NI as development platform. The LabVIEW is a development environment based on graphical programming language, it constitute the program by establishing and connecting the icons, at the same time it is able to call the programs written in other languages through dynamic link library (DLL); it has good extensibility, and the modularized program written in this language not only owns a nice user interface and seems simple and intuitive but also is easy to comprehend, adjust and maintain. LabVIEW is an open development environment and it's able to connect the acquisition card from NI; it contains rich subprograms of data acquisition, signal analysis and control, therefore it is able to conveniently complete the acquisition, analysis and display of ECT signal [11-12].

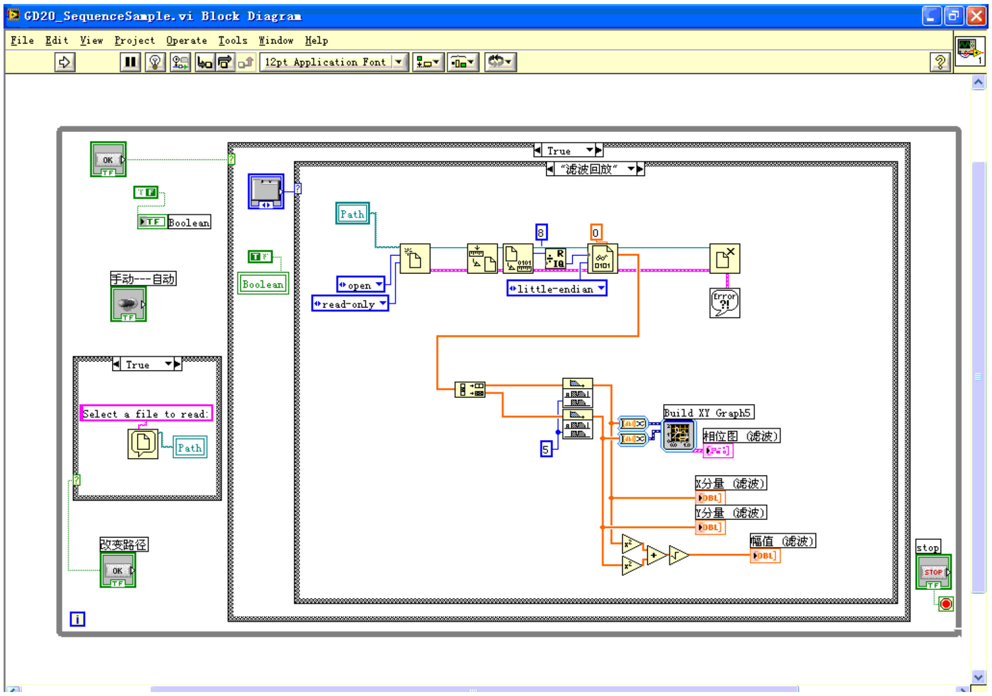
LabVIEW program is called Virtual Instruments (VI) program, and it mainly consists of three parts, that is, ①The panel: It has graphical user interface and is used to set the controlling parameters and to display the output results; ②The Diagram Programme: It is written in graphical programming language and equivalent to the source code of traditional programming language; ③The Icon/Terminal: It can transform the VI into a SubVI, that is a VI subprogram, and then it can be called like a subprogram in other VI. The developed upper computer software in this paper is shown in Figure 7.

The overall structure of upper computer software is shown in the flow charts (see Figure 8.). Choose the needed function module which is independent of each other after entering the software and it's convenient for the upgrading and maintenance of entire system in this way.

In process of eddy current testing of deep defect in multilayered conductive structure, the frequency, phase, amplitude and gain of excitation signal need to be set up in the first place, and then set the sampling frequency and the length of each packet during continuous sampling process; the parameters and orders are transmitted to MSP430 SCM performing control task through serial communication module, where the SCM lies in eddy current instrument. In actual testing, the collected signal is divided into dual-way; one way of the signal is displayed in real time, when one packet is full, the display will update once; the other way of signal is stored onto hard drive as files. During the signal analyzing, the analysis and playback of signal can be realized in different scales (time domain, frequency domain). Furthermore, in order to make the other software convenient for analyzing the data, the function that transform the binary format of acquisition signal into character format is realized as well. Signal analysis is relatively complicated and its realization needs the help of other analyzing software, which will be solved a step further in the follow-up work.



(a)



(b)

Figure 7. ECT Software System: (a) Panel; (b) Block Diagram Pnel

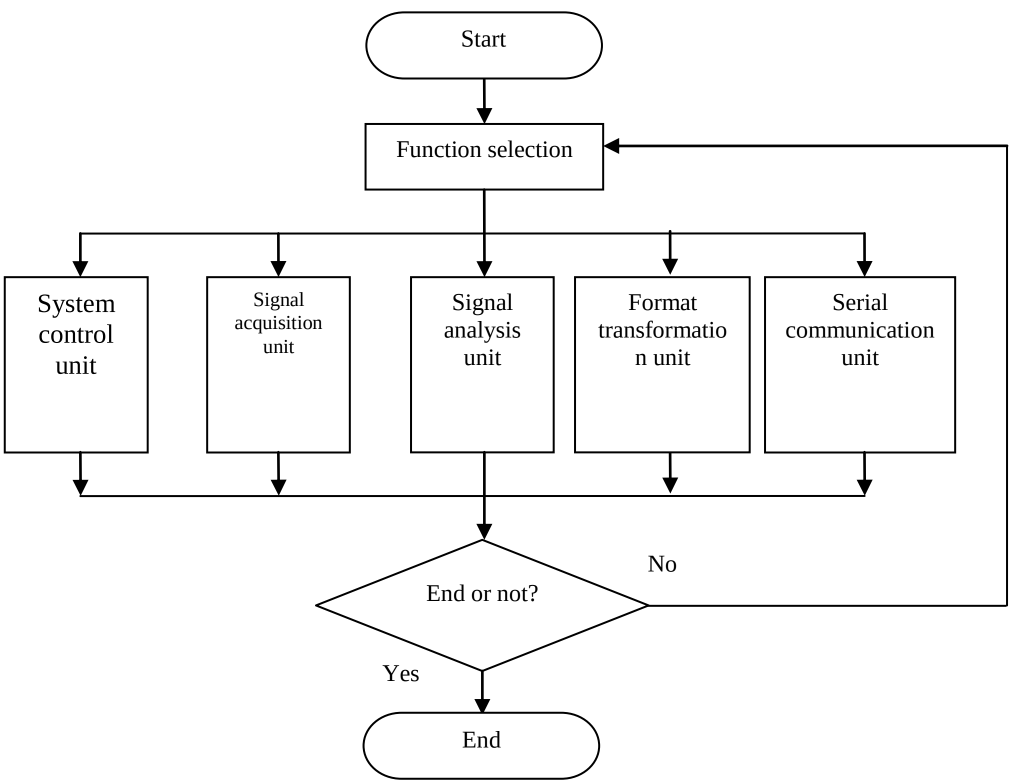


Figure 8. Flow Charts of Software System

6. Conclusions

This paper introduces the GMR-based novel eddy current testing platform which is researched and developed by our research group. It puts forward the overall scheme and structure block diagram first of all, and next focuses on expounding the GMR effect and the development of GMR ECT probe. Afterwards it introduces each function module and running process of both hardware and software system of the testing platform. Due to adopt the idea of modular design, the novel eddy current testing platform has the advantages of compact structure, convenient use and maintenance, high sensitivity and resolution, fast scanning speed, etc, as a consequence it is able to fulfill the task of scanning inspection of deep defect in multilayered conductive structure well.

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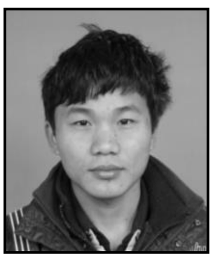

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