A PC-Based Real-Time Hall Probe Automatic Measurement System for Magnetic Fields

C. S. Hwang, F. Y. Lin, and P. K. Tseng

***Abstract*—A real-time, Hall-probe automatic measurement system was developed at the Synchrotron Radiation Research Center (SRRC) for the magnetic field measurement of the "C"-type rectangular combined function bending magnet, multipole magnets, and the insertion device magnets. The sampling rate on the x–y–z table with dynamic moving speed of 15 cm/s can be up to 200 samples/s, and the precision is within ±0.01%. A PC is used as a system controller which connects instrument function cards with instruments via the PC bus and an IEEE-488 interface card. An inexpensive, stable within ±15 ppm current source is produced to supply a high-stability constant current for the Hall probe; a temperature controller maintains the Hall probe temperature within ±0.2 °C. The system's software has been divided into different modules that can be connected into a network global data base. System testing has shown that the magnetic field measurement accuracy of this system is better than ±25 ppm in the static measurement.**

I. Introduction

A MODERN Hall probe automatic measurement and analysis system fulfills the newly developed concept for the special mapping trajectory [1] and the harmonic field analysis [1]. A PC is the main control unit. A PC with a motor control card, counter card, and IEEE-488 interface card controls the instruments, monitors the system, and performs the data acquisition.

The system's preliminary design goal was to set up a multipurpose automatic system [2]–[4] for measuring the magnetic field of the SRRC storage ring magnets. It also can be used to measure the insertion device magnet and test the stability and accuracy of other instruments. A Hall probe device is used to measure magnetic field distribution. The Hall probe device was designed to match our magnet pole dimensions and field accuracy requirements. For this Hall probe, a highly stable constant current source and a temperature controller must be used to avoid temperature and current excitation fluctuations. A commercially available Group 3 Hall probe is calibrated with a function of field strength and temperature.

The software of this system was written in "C" language and was developed under MS-DOS. It has been organized in a number of modules. Those modules can be connected into a global data base via a network so that the program can be easily modified in the future. The system's expansion capability makes it useful in various applications. The system's software is divided into four major parts:

1) device installation;
2) stepping motor driver;
3) data acquisition;
4) analysis process.

Each major part contains several subprograms to expand its capability.

The x–y–z stage is the heart of this system, which can be driven by the control system to move the Hall probe through the PC bus. Simultaneously, the position and magnetic field data can be saved to the data base for on-line/off-line analysis. The exact position of the three-dimensional movable x–y–z stage can be read from the optical linear scale whose resolution is 1 μm. The position, angle error and the orthogonal error between the axes of the x–y–z stage were kept within 0.03 mm, 4 and 12 arsec, respectively. Preserving system accuracy requires special attention to avoid Hall probe vibration and reduce the signal noise by the electric shielding of the signal wire.

II. Automatic Measurement System

The Hall probe is mounted on the x–y–z stage to map the magnetic field distribution. Completing the magnetic field measurement normally takes a considerable amount of time. Consequently, manpower can be saved and human errors can be prevented through automation [5]–[7]. The hardware and software details are discussed below.

A. Hardware Description

The main controller and analysis unit for this automatic measurement system is a PC-compatible 486. The computer has an IEEE-488 interface card which connects with the 15 measuring instruments. The hardware includes the main controller unit, various measuring instruments, the movable three-axes stage and the Hall probe device. Fig. 1 shows the block diagram.

1) Main Controller Unit: The PC controls either the moving platform or data acquisition. Installed in the PC are: one stepping motor control card (PCL-839) for controlling the three axes of the x–y–z stage, the two end limit switches of the three axes, and one 24-bit digital counter card (ENC-9266) for reading the position of the three axes. The counter card counts the signals from the optical scales. The total count number is equal to the number of PR (preset requests) and the

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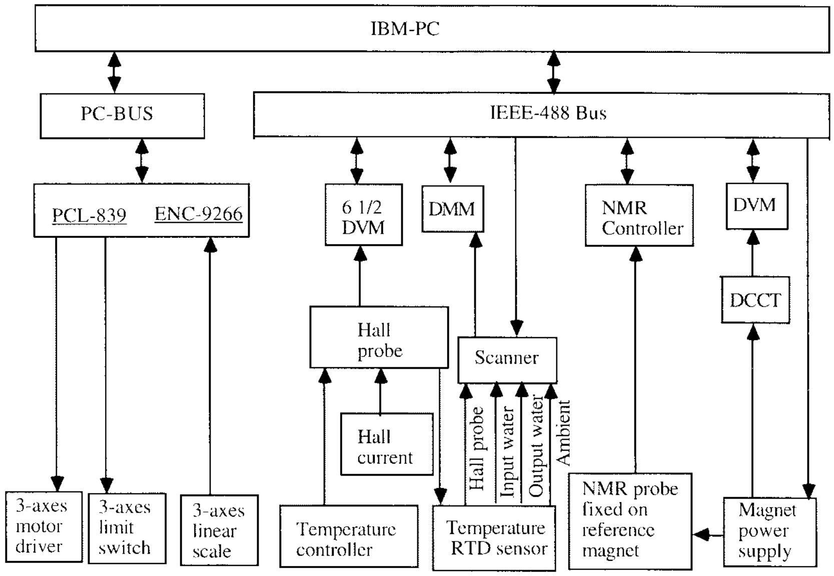


Fig. 1. Schematic functional block diagram of the hardware configuration for the real-time automatic magnetic field measurement system.

comparator in the counter card will send an interrupt request (IRQ4) to perform the interrupt service routine (ISR). This will trigger every instrument device to latch the result in its buffer and then save to the PC. The limit switches of the x–y–z stage can transmit the high-low 5 or 0 V signal to the control card so as to halt the x–y–z stage motor.

2) Three Axes of x–y–z Stage: The accuracy requirement of the accelerator magnet must be within $\pm 1 \times 10^{-4}$. The precision for the position of the three axes can be estimated. Reference [8] shows the position accuracy must be within $\pm$0.025 mm in the transverse direction mapping range of $\pm$50 mm. The total stroke range of the three axes is $200 \times 60 \times 30$ cm^3.

The errors of pitch, yaw, and roll are rather sensitive to the Hall probe and subsequently create an extra error of the position, angle and the planar Hall effect [9], [10]. All of the position and angle errors of the stage are measured using one HP 5528A laser interferometer. Those errors introduce an enlarged error on the extended location of the Hall probe. The accuracy at the location of the Hall probe being 1.2 m away from the stage is within $\pm$0.02 mm and 4 arsec [7]. The orthogonal error between the three axes is within 12 arsec [7]. Hence, based on the accuracy requirement of the magnet tolerance, the accuracy of this x–y–z stage is adequate for the field mapping and analysis.

3) The Hall Probe Device and Its Temperature Control: The SBV 613 Hall plate[1] is temperature controlled [1], [9], [10] and connected to a constant current source. This constant current source must be very stable. The electrical block diagram is shown in Fig. 2. This high circuit performance depends on voltage regulator LM7815 and LM7812, the reference voltage LM399H (whose stability is 3 ppm/°C) and the resistor R (whose stability is 10 ppm/°C). The operational preamplifier is OP 177. This constant current source has a long-term stability

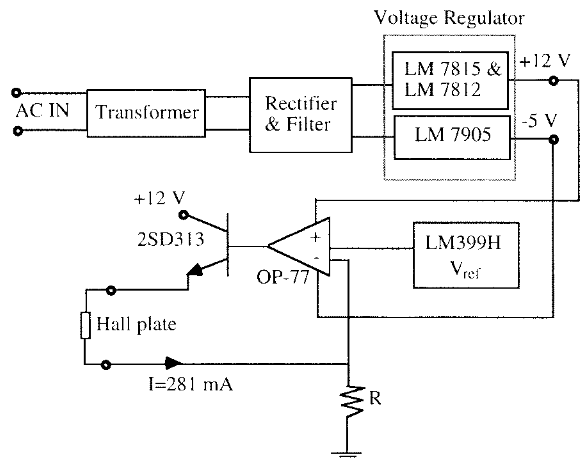


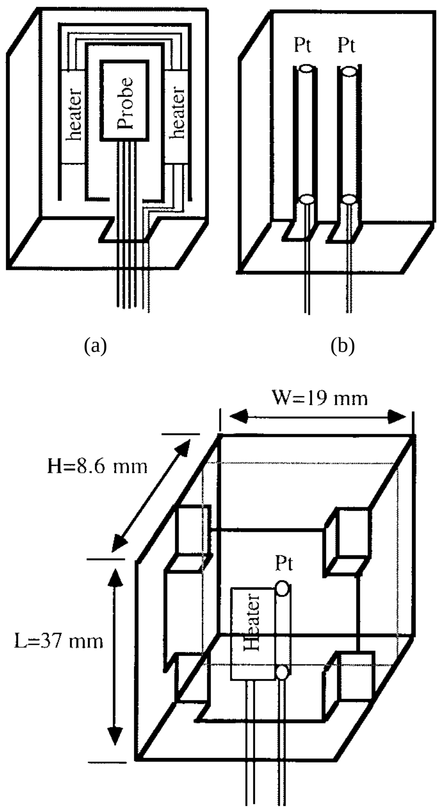
Fig. 2. Electrical circuit diagram of the Hall current source device.

better than $\pm$15 ppm at an ambient temperature change of 3 °C. The short term stability is within $\pm$2 ppm.

The Hall plate is mounted in a temperature-controlled copper box. This copper box is mounted at the end of the aluminum probe (Fig. 3). The Hall probe's center is denoted by a paper target (the resolution is 25 μm). The induced Hall voltage is measured here by a 6 1/2 digital voltmeter (HP 3478A).

The temperature is controlled on the outside of the box and inside. The outside controller consists of a thin heater chip attached to the aluminum block [Fig. 3(c)]. This heater chip is a nonmagnetic resistor capable of preventing interaction from occurring with the magnetic field. A platinum resistor is placed on the heater chip to control the outside temperature. The heater inside the copper box controls the inner temperature of the Hall plate. The material of the inside layer is copper in light of its efficient thermal conductivity [Fig. 3(a) and (b)]. Consequently, the temperature balance point can be reached in a short time period. This prevents large temperature

[1] InAs SBV 613 is a product of the SIEMENS Company (Germany).



(c)

Fig. 3. Geometrical structure of the Hall plate and temperature controller: (a) lower copper of the inside layer for Hall probe and inside heater, (b) upper copper of the inside layer for platinum resistors, and (c) aluminum box of the outside layer for outside heater and platinum resistor.

differences from occurring between the Hall plate and the control temperature. The heater chip arrangement of these two resistors must be symmetrical to reduce the magnetic field variation which is caused by the heater current. Two platinum resistors which is near the Hall plate were mounted on the back side: one measures its temperature, and the other controls the temperature. Fig. 4 shows the block diagram of the temperature control circuit. $V_{\rm in}$ controls the inside temperature, and $V_{\rm out}$ controls the temperature of the enclosure. Two temperature controllers are situated in the control circuit, i.e., one for the inner layer ($V_{\rm in}$) and the other for the outside layer ($V_{\rm out}$). An ambient temperature compensation is also made available for the outside layer. Two adjustable resistors, R_3 and R_4, can change the slope of the output power to set an optimum point for the temperature control. Adjustable resistors R_1 and R_2 can be used to optimize the temperature compensation condition. The Hall plate temperature variation was measured with an ambient temperature change of 1 °C and a magnetic field change from −0.003 to 1.24 T, going in either direction. The automatic measurement system was also used to measure temperature variations. It is shown in Fig. 5 that the Hall plate temperature can be maintained within (38.72 ± 0.2) °C. However, the maximum temperature variation on the fixed magnetic field is about 0.1 °C. The larger Hall probe temperature fluctuation is caused by the change of magnetoresistance.

The Hall probe accuracy depends on the stability of the Hall current and the Hall plate temperature. The Hall probe stability is tested by comparison with the NMR probe measurement in the same reference magnetic field over long and short periods of time. Fig. 6 shows the NMR readings with respect to Hall probe voltage readings as a function of time. A (1.18 ± 0.0002) T magnetic field of the reference magnet was maintained during the testing period, which is typically one month. The magnetic field of the NMR reading, if considered here, is the standard field, and the calibration curve should be a very narrow straight line; however, these fluctuations are actually inside a certain band width. This width represents the Hall probe measurement error and is an indicator of the long-term stability. The stability is observed over a one-month time period to be better than ±25 ppm. Over a short time period, the ripple is within ±5 ppm. Therefore, the results of Fig. 6 revealed that the accuracy of this Hall probe system is about ±25 ppm for long-term measurement.

4) Calibration and Monitor Device: An NMR Teslameter (Metrolab model PT 3020) was utilized to perform the reference magnetic field measurement. The field strength readings were taken from seven sections of both the NMR and Hall voltage. Calibrating the Hall voltage with respect to the magnetic field required taking the tenth-order polynomial fit of each section. Those calibration functions were programmed into the software. The calibration accuracy was found to be approximately ±0.05 G. The NMR was also used to monitor the field deviation which occurs during the field measurement. The magnetic excitation current was also monitored at the same time by the dc current transformer (DCCT) which was connected to the HP 3478A 6 1/2 digital voltmeter. A Keithley model 705 scanner and a Keithley model 196 digital multimeter (DMM) were used to record the temperature of the Hall plate, ambient, input and output cooling water, and the magnet using a platinum resistor for the sensor.

B. Software Description

The measurement system operates in real time. The system's behavior can be observed on the PC display by the operator. Modifications can be made if deemed necessary. The program has been written in the "C" language. The executable program occupies 220 kB of RAM. This system is logically divided into four modules (see Fig. 7).

1) Device Installation: This part can pre-establish connections and presets of instruments for specified parameters. The communication can be tested as well.

2) Stepping Motor Driver: This part is used to control the stepping motor drive which includes the direction, speed, distance, and step size. The position of the x–y–z stage can be read from the optical linear scale. The signals coming from the linear scales can be decoded simultaneously to correct the position error to less than ±10 μm. This correction can take place at any calculated position for the entire distance at any time. This part can be operated independently on the execution sequential loop.

3) Data Acquisition: This part is the heart of this system. The functions can be divided into parameter settings,

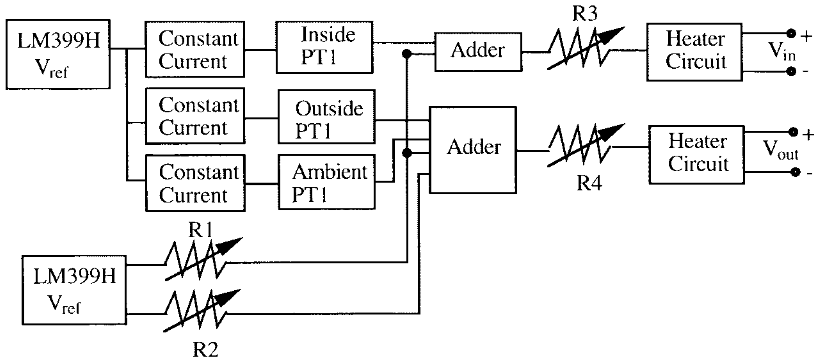


Fig. 4. Electrical circuit diagram of the Hall generator temperature controller.

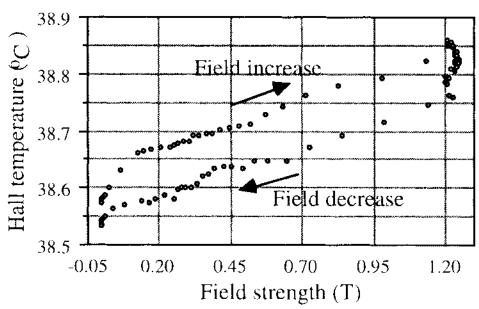


Fig. 5. Hall plate temperature variation during a magnetic field change of 1.2 T, going in both directions and at an ambient temperature change of 1 °C.

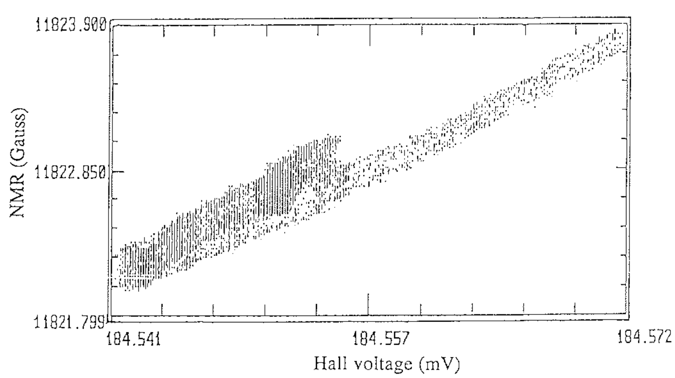


Fig. 6. Over a one-month period, the long-term stability of the Hall probe with respect to NMR measurement results in the same magnetic field at an ambient temperature variation of 5 °C. This figure was a hard copy from the real-time monitor of this measurement system.

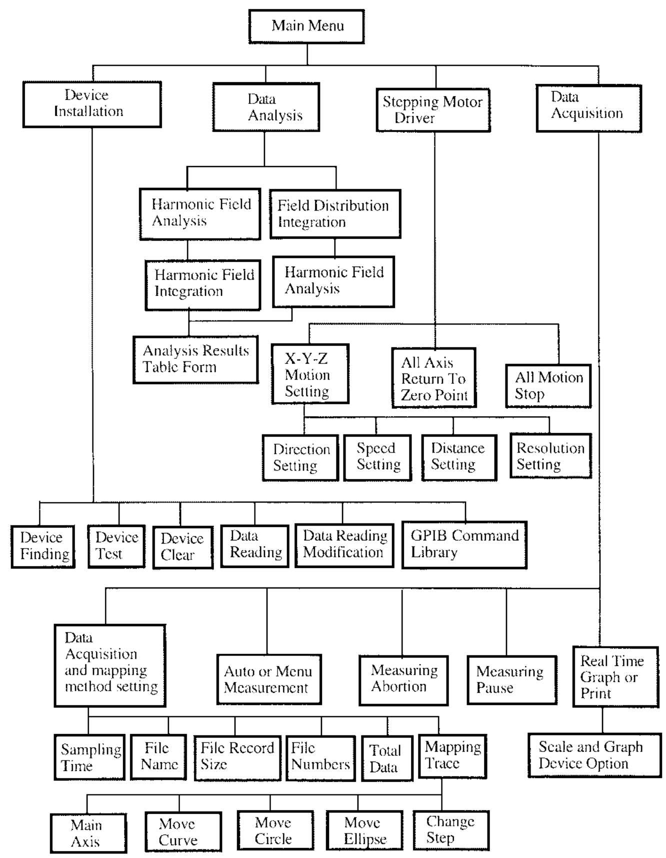


Fig. 7. Schematic functional block diagram of the software configuration for the real-time automatic magnetic field measurement system.

measurement process control, measurement trajectory, monitor graph display, and printer control. The trajectory can be moved on a curve, ellipse, or circle for various kinds of magnets; in addition, the main axis can be selected by choice. The results can be observed on-line to facilitate the user in sorting out, analyzing the data of the magnetic field distribution and performing diagnostics. The density of the interval spacing in the measurement depends on the field deviation and can be altered in order to save time. This system can either be operated in automatic or in menu mode. The device option for graph or print and the scale can be changed on-line. After completing the measurement, the identifier of the test, along with its related information, can be saved in an automatic step.

4) Data Analysis: The analysis equation depends on the field characteristic constrain equation [11]. It is solved by the Laplace's equation in a two-dimensional plane. The integrated fundamental and harmonic field strength at each midplane position can be obtained by the 1-D or 2-D nonlinear least square fitting method. Each multipole field strength can be normalized at the location of the field range which is selectable. The harmonic field strength, orientation angle, phase angle, and the multipole field normalization results are summarized and sorted in table form. This table also displays the center offset of the longitudinal and transverse axes between the mechanical magnet center and the magnetic field center. The fundamental

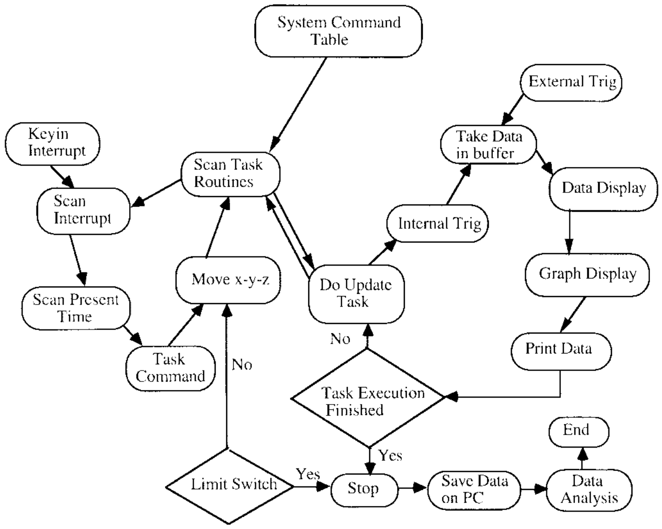


Fig. 8. Command execution sequential architecture of the measurement process.

and higher multipole field distributions are recorded and displayed as a function of the longitudinal axis.

III. System Sequential Architecture

A C-language-based modularized design approach is employed here. A multilevel command tree structure is implemented with key interrupts capable of providing an on-line menu or auto interactive environment. The system's operations can be divided into foreground and background status. This system, when not having received an external interrupt, (e.g., from the keyboard interrupt signal) performs the background operation which is an infinite loop. An external interrupt signal temporarily changes the state to foreground operation with the moment data that has been obtained. Interrupts may also be caused by the three axes limit switch signals or the "stop" function key.

Fig. 8 shows the software architecture. The consecutive scan task routines are infinite task loops which include the "present time scan," "interrupt scan," and three axes "moving scan." The execution time of one cycle of the background infinite operation loop is about 1.5 ms on the PC486-DX66. The data acquisition speed of this system is about 5 ms per one instrument for the static measurement. This speed depends on the instrument performance. The measurement time of the dynamic measurement with the external trig is not limited by the execution time of the background infinite operation loop. The measurement time is limited by the data transit time of the IEEE-488 bus and what accuracy we need in the measurement duration. If the task routine is completed, the updates are implemented. The updated task is also an infinite loop. The functions of "take data," "data display," "raw data graph display," "print data," and "scan execution" are part of the loop.

IV. Discussion

This system was constructed as a set of modules. These modules can also be readily used in other practical applications. Further, extra corrections are necessary. The time needed to measure the magnet is significantly reduced. This automatic magnetic field measurement system not only saves the manpower required to perform the measurements, but also permits an untrained operator to perform complex measurements within a short time. This measurement system, with its reliable mechanical parts as well as control by a versatile real-time system, efficiently produces precise mapping results automatically.

The Hall probe automatic mapping system can be operated to dynamically measure different kinds of magnets and also to take a fly measurement for insertion device magnets. This feature is particularly relevant for the prototype magnets, since it can detect those defects quickly, thereby permitting improvements. Besides dipole, quadrupole, sextupole, and insertion device magnetic field measurement, the system's different probes can be used to perform the accuracy testing for any kind of instrument.

In this work, we have used this system for point-to-point measurements of a homogeneous or gradient field. The results were shown in [1], and the accuracy of this system testing on the harmonic field analysis is maintained within $\pm 0.01\%$.

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