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THE LAWRENCE BERKELEY LABORATORY
GENERAL PURPOSE MAGNETIC MEASUREMENT
DATA ACQUISITION SYSTEM

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Abstract - The Lawrence Berkeley Laboratory (LBL) Magnetic Measurements
Engineering (MME) Group has developed a Real-Time Data Acquisition System
(DAS) for magnetic measurements. The design objective was for a system
that was versatile, "portable," modular, expandable, maintainable, quickly
and easily reconfigurable both in hardware and software, and inexpensive.
All objectives except the last were attained. An LSI 11/23 microcomputer
is interfaced to a clock-calendar, printer, CRT control terminals, plotter
with hard copy, floppy and hard disks, GPIB, and CAMAC buses. Off-the-shelf
hardware and software have been used where possible. Operational capabili-
ties include: (1) measurement of high permeability materials, (2) harmonic
error analysis of (a) superconducting dipoles and (b) rare earth cobalt
(REC) and conventional quadrupole magnets, and (3) 0.1% accuracy x-y mapping
with Hall probes. Results are typically presented in both tabular and
graphical form during measurements. Only minutes are required to switch
from one measurement capability to another. Brief descriptions of the DAS
capabilities, some of the special instrumentation developed to implement
these capabilities, and some planned developments are given.

I - INTRODUCTION

The MME DAS was developed to meet LBL requirements for magnetic measurements,
requirements which are both varied and unpredictable. Often, our two-man group is
not informed of the specifications for a measurement until shortly before the
results are needed. We have been asked to make an harmonic analysis of a quadru-
pole on the same day we were scheduled to make permeability measurements. Although
it would be more convenient for us to make all of our magnetic measurements in one
of our three limited-purpose MME laboratories, the power structure at LBL has dis-
couraged us from moving structures such as the Bevatron accelerator. Therefore, most of our measurements are made in assembly shops, existing beam lines, or interiors of existing accelerators. Accuracy requirements vary from 100% to 1 part in $10^6$. A wide variety of measurement techniques and instrumentation is needed to meet customer requirements. Although the MME DAS general design was defined in our minds several years ago, its evolution has been determined by the immediate needs of projects and the realities of available funds.

II-THE SYSTEM

Figure 1 is a block diagram of a mapping system representative of the present state of our hardware.

Computer

Primary interfacing of the LSI 11/23 microcomputer is accomplished on the DEC Q-BUS. Attached to the Q-BUS are 160 kwords of RAM, a Digital Pathways Clock Calendar, a DSD 440 dual double-density floppy disk system, a DEC RL02 10-Mbyte hard disk, a Standard Engineering Co. CAMAC interface, a National Instruments GPIB interface, and two DEC DLV11-J 4-channel RS 232 interfaces. Connected to the DLV11-J's are a DEC LA-120 printing terminal (used primarily as a printer), a Tektronix 4051

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Fig. 1. Block diagram of the LBL MME DAS configuration for tuning and mapping the LBL/SSRL/EXXON wiggler magnet.
graphics minicomputer (for plotting) with a Tektronix 4631 Hard Copy Unit, a DEC VT-100 CRT terminal, and two Zenith Z-19 CRT terminals. During a measurement, a single CRT terminal, used as a control terminal, presents status information to the operator. The other CRT terminals are used under the TSX PLUS time-share operating system for system development.

CAMAC Digital Bus

The CAMAC bus is typically used for digital I/O. Shown interfaced in Figure 1 are two stepping motor controllers, two 4-channel up-down counters, and a MME optical encoder interface. Mechanical stage position is recorded by up-down counters monitoring optical encoders mounted on lead screws. By this means, stage positions are determined independently from the position command. This independent determination has been extremely helpful in debugging our mechanical stages.

Other implementations of the measurement system use CAMAC modules that control power supplies, monitor the LBL/CERN NMR magnetometer, monitor/control the MME Precision Programmable Bipolar V/f converter /1/ (LBL Engr. Drawing No. 16V120) and the MME very low noise Programmable Search Coil Switching Module (LBL Engr. Drawing No. 16V121).

Analog GPIB Bus

Interfaced to the GPIB Bus is a Hewlett Packard Model 3455A 6-1/2 digit DVM, which is multiplexed by means of a Hewlett Packard Model 3495A Scanner. This combination monitors the outputs of power supply shunts, Hall effect gaussmeters, thermocouples, thermistors, and analog integrators. (Not shown is an ICS Model 4880 Instrument Coupler, used to interface the logic bins used in harmonic error analysis of magnets, and a Hewlett Packard Model 3437A High Speed 3-1/2 digit DVM.) To date, all high precision/resolution analog data have been acquired on the GPIB Bus.

Software

The RT-11 operating system was designed by DEC for real-time applications. Programming is done in FORTRAN IV. Software libraries utilized include: Tektronix PLOT 10 (TCS) for plotting, DEC Laboratory Subroutines, DEC Scientific Subroutines, OMNEX Sub-Device Package to partition the RL02 hard disk to floppy-disk-size sections, S&H Computer TSX PLUS time-sharing system for program development, Standard Engineering Co. CAMAC library, and the National Instruments GPIB library. We are in the process of implementing a Data Base Management System (SIMILE) which will be used for: controlling the inventory of our loan instruments, monitoring the status of our projects, and maintaining our records.

Our software systems usually include: operator prompting with verification of typed-in parameters, real-time plotting of data that facilitate the detection of drifts or extraneous data points, immediate storage of all raw data, monitoring the status of the measurement on the CRT control terminal, and the immediate printout of the measurement parameters. Although some selected data reduction may occur in real time, extensive data analysis and expanded scale plotting are accomplished by post-processing programs, which we usually run immediately after each measurement data set.

A major reduction in system costs occurred when we switched from flow charting to structured programming /2/ and structure diagrams. Short structured programs are written that are primarily only calls to subroutines or groups of short subroutines. Short subroutines are easier to debug and often have wide utility. Structured programming has significantly reduced the effort necessary to design, maintain, and modify complex data acquisition systems.
III - APPLICATIONS

Mapping

Figure 1 is the block diagram of the system used to tune and map the LBL/SSRL/EXXON wiggler /3-5/. SC 2 and SC 3 are long search coils which are positioned by hand to measure field integrals needed to tune the wiggler. The computer is programmed to prompt the operators in a sequence of actions that move the coils and acquire and process the raw data. SC 1 (one wiggler period long) and three orthogonally mounted Hall probes are on a moving stage. A map with a grid of 3 X-positions and 2201 Z-positions consists of a collection of 50,000 numbers and requires 4 1/2 hours. The raw data are plotted in real time. Post-processing programs curve fit in the vicinity of the peaks determining peak magnitude and positions for the 57-pole wiggler. Other post-processing programs make expanded scale plots of the fields measured. The wiggler magnet is reported in Reference 3. Our magnetic measurements for tuning and operating the hybrid wiggler are reported at this conference in Reference 4. Figure 2 is a post-processed plot that is representative of the real-time plotting of a map of a section of the interior of the 88-Inch Cyclotron at LBL. The objective of the measurements was to determine if the electrostatic deflector used to withdraw the beam from the accelerator could be replaced by a magnetic deflector. Four Hall probes mapped four separate, overlapping regions—CN, CS, IN, and IS, which are portrayed in the top portion of the plot. The three lower plots are expanded scale plots of a fixed position Hall probe, an NMR magnetometer, and the power-supply shunt voltage. Easily discernible is a 0.1% downward drift of the fixed Hall probe gaussmeter system due to a rather large temperature rise during the measurement. Temperature was monitored by the DAS throughout the measurement allowing correction for this drift. Also discernible are several points where the NMR magnetometer was not locked onto the field. Real-time plots such as this allow us to scan thousands of data points for discrepancies and drifts while the measurement is proceeding.

Harmonic Error Analysis of Dipole and Quadrupole Magnets

Error harmonics and the fundamental signal are measured using search-coil arrays rotating slowly on a symmetry axis of the magnet. A single search coil detects the fundamental signal during the first cycle of rotation. The search-coil arrays are

--- 88° XMAP --0717A1.DAT -- 17-JUL-82 -- 09:05:51 -- 3156, AMPS --
REFBEAM=16B 04+1 TRNCLS=ONI MAGCH=IN; ENTR=EXIT=CENT.; SHIMS=IN
MAP No. 10

--- PLOT POST PROCESSED -- 21-JUL-82 -- 13:25:13 ---

Fig. 2. Example of real-time plotting (reproduced with plot post-processing program). Approximately 10,000 numbers are displayed.
reconfigured to buck the fundamental and lower harmonics during the second rotational cycle, allowing the measurement of higher harmonics with excellent resolution. Data are first drift-corrected, then harmonic analysis is done using the Fast Fourier Transform Technique.

We immediately plot the drift-corrected raw data and a semilog bar graph of the error harmonic ratios. A table of the error harmonic ratios and their phases relative to the fundamental is printed. For a quadrupole magnet, the measurements, data processing, and output described above require about 90 seconds.

We have developed a post-processing program for "fixing" permanent magnet rare earth cobalt (REC) quadrupoles /6-8/. The shims required to "zero" selected harmonics are calculated. An REC quad can be measured, shimmed, and remeasured within an half hour.

Several specialized electronic modules have been developed for harmonic analysis systems. The MME very low noise Programmable Search Coil Switching Module feeds signals to the MME Precision Programmable Bipolar V/f converter, which in turn feeds a latchable up-down counter in an LBL logic bin. The combination of the V/f converter and up-down counter functions as a digital integrator. While the "digital integrator" continues to count, the contents of the counter are periodically latched and sent to the computer by pulses from an optical encoder mounted on the shafts of the search-coil arrays, i.e., data are collected "on the fly."

Permeability Measurements

Because the conceptual design for a permeameter suggested by Dr. Klaus Halbach in 1978 used a technique for determining magnetic intensity that is unique among permeameters described in the literature, we have suggested that the measurement technique and the D.C. permeameter be named after Halbach /9/.

A cylindrical sample is "sandwiched" between the pole tips of an electromagnet. The "B-coil" surrounds the central portion of the sample in the usual manner. Magnetic intensity, H, is determined from a separate measurement of magnetic induction, B, using the following unique technique. A 0.080-inch-diameter axial Hall probe measures B in a small (0.100-inch-diameter) hole located on the symmetry axis of the sample. $H_{\text{air}} = B_{\text{air}}/\mu_0$ and, because the tangential component of H is continuous at any boundary, $H_{\text{sample}}$ is determined. The magnetomotive force is provided by a bipolar power supply. The DAS controls the sequencing of the magnetomotive force and the measurements of quantities for determining B and H.

One advantage of the Halbach permeameter over permeameters described in the literature is that the B-coil may be removed from the sample and placed in a "zero" field reference. This makes it possible to measure flux linkage absolutely, rather than measuring only changes in flux linkage. A second advantage is ease of measuring magnetic properties at very high magnetizing intensities. Whereas permeameters without iron return paths may be limited to magnetizing intensities up to 1000 Oe, our first implementation, using a 30-year-old convection-cooled magnet, enabled us to measure up to 8000 Oe.

The timetable for automating the Halbach permeameter illustrates the versatility of the DAS. We were preparing to measure the harmonic content of a superconducting dipole in September 1981 when E. Hoyer asked us to make permeability measurements of vanadium permendur at higher magnetizing intensities than were available on commercial charts. In less than two months, the system was operational and preliminary results had been obtained.

IV - DISCUSSION

In November 1979, we envisioned a data acquisition system that encompassed a major portion of anticipated measurements. We have implemented many of the capabilities we originally anticipated. In May 1980, our initial DAS configuration was a quadru-
pole harmonic analysis system /10/. In October 1981, we automated a permeameter for measuring permeability at magnetic intensities above those reported in the literature. In October 1981, we made harmonic analysis measurements of a superconducting dipole magnet /11/. In July 1982, we implemented a 2-dimensional mapping system with a position precision of 0.01 mm /12/. In January 1983, we reconfigured the mapping capability to measure three orthogonal components of magnetic induction on the 2-m length of the LBL/SSRL/EXXON 57-pole REClvanadium permendur wiggler.

Although none of the implementations of the DAS discussed above were inexpensive for its first application, subsequent applications of implementations have been very competitive. Software, a major cost, is being reduced as we create a larger library of transportable subroutines. The mechanical hardware for the two mapping systems was very expensive, about $30,000 each. The conceptual design of a versatile and reconfigurable 3-axis, 3-component mapping system has just been funded. Components for a 3-axis, laser interferometry position measurement system have been ordered. Air bearings are being considered for moving surfaces. Position determination by laser interferometry should allow the use of inexpensive mechanical positioning hardware. We also intend to automate MME floating-wire analog measurement techniques and to interface and update other magnetic measurement instruments developed at LBL.

The versatility and reconfigurability of the LBL Magnetic Measurements Data Acquisition System have brought demands for its services that have exceeded expectations.

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