HEWLETT-PACKARD JOURNAL

MARCH 1967

A Computer for Instrumentation Systems

Problems of interconnection, programming, and environment arise in the design of systems containing both computers and instruments. They are solved in advance by this new integrated-circuit computer.

DIGITAL COMPUTERS AND LABORATORY INSTRUMENTS ordinarily make strange bedfellows. They not only have difficulty making contact with each other and working together, but most computers don't even feel comfortable in the unsympathetic everyday world in which instruments live.

In recent years, however, a growing need has arisen for a computer that can work efficiently in instrumentation systems. These systems are becoming more numerous and more complex. Many of them would not be feasible without the data processing and flexible control that a computer can provide.*

Because the need for an instrumentation computer was not being filled by others, *-hp-* decided to go ahead and build one, feeling that a computer to work with instruments could probably be built best by an instrumentation manufacturer. Our new computer is an integrated-circuit machine which has the computing power and special capabilities needed to work well in instrumen-

* See p. 11 for descriptions of some of these systems.

PRINTED IN U.S.A.

tation systems. It does away with three discouraging problems that have plagued systems designers in the past:

—the interface problem, or how to connect the instruments with the computer so that efficient data communication can take place

—the software problem, or how to program the computer efficiently, using programming systems that were not designed with instruments in mind

—the environmental problem, or how to keep the computer working in the unfriendly environments in which instruments operate.

A closer look at these problems and at how the instrumentation computer eliminates them will be the best introduction to the new machine and what it can do for the systems designer.

Convenient Computer/Instrument Interfaces . . .

Laboratory instruments are unfamiliar input/output devices for most computers. Seldom is there any ready-made, convenient means for connecting an instrument to a computer; it usually takes an expensive, custom-designed interface. This is true even of some common computer input/output devices. For example, if a computer is not specifically designed to work with a magnetic tape unit, and many are not, it may take several thousand dollars worth of engineering talent and equipment, plus several months, to produce an interface that will allow the computer and a tape unit to work together. If a number of instruments have to be interfaced, or if the system configuration has to be changed, the user's problems are multiplied many times, of course.

. . . Provided by Flexible Input/Output System

The new instrumentation computer is different; it has an extremely flexible input/output system which greatly simplifies interfacing to a large number of instruments. Within the main frame of the basic computer is a box which accepts up to 16 plug-in interface cards (Fig. 1). Most instruments and input/output devices can be interfaced to the computer with one card each; a few require two cards. Accessory modules raise the maximum number of interface cards to 48.

Cover

To get this striking effect for our March cover, photographer Hal Smith placed his lights underneath one of the plug-in logic boards from the new *-hp-* Model 2116A Instrumentation Computer. Component density on these boards is quite high for two-sided (not multi-layer) boards — about 200 integrated-circuit flatpacks per square foot. Each flatpack is the equivalent of 50 to 100 discrete components.

Eventually, there will be plug-in interface cards for all *-hp-* instruments which either provide a digital output or can be programmed.* At present, cards have been designed for more than 20 instruments, including counters, nuclear scalers, electronic thermometers, digital voltmeters, ac/ohms converters, data amplifiers, and input scanners. Interface cards have also been designed for most kinds of input/output devices, such as magnetic tape recorders, teletypewriters, paper tape readers and punches, and dataphones. Interfaces for printers and card readers and punches are under development.

Efficient Programming . . .

Programming systems, or 'software' in computer jargon, which have not been designed to work with instruments can be made to do so only reluctantly and inefficiently. The inability of previously available software to cope with instruments is never more obvious than when the computer and its instruments have to exchange data or control signals.

* Instruments which provide analog outputs can be interfaced with the computer via a digital voltmeter or an analog-to-digital converter. Instruments which require analog programming can be interfaced via a digital-to-analog converter.

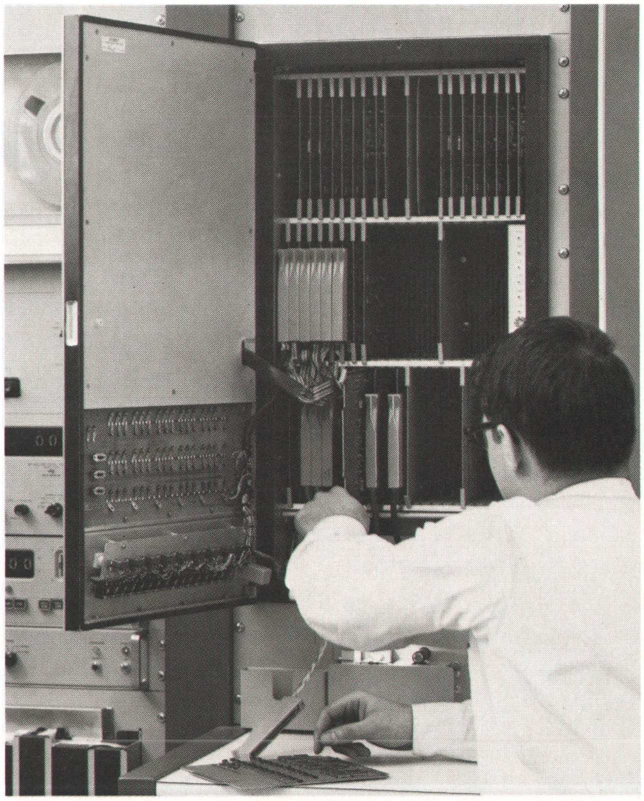


Fig. 1. *Operator of new -hp- 2116A Computer changes one of the plug-in interface cards which make it easy to connect the computer with laboratory instruments and other input/output devices. This and other features of the new machine greatly simplify the task of augmenting an instrumentation system with a general-purpose computer.*

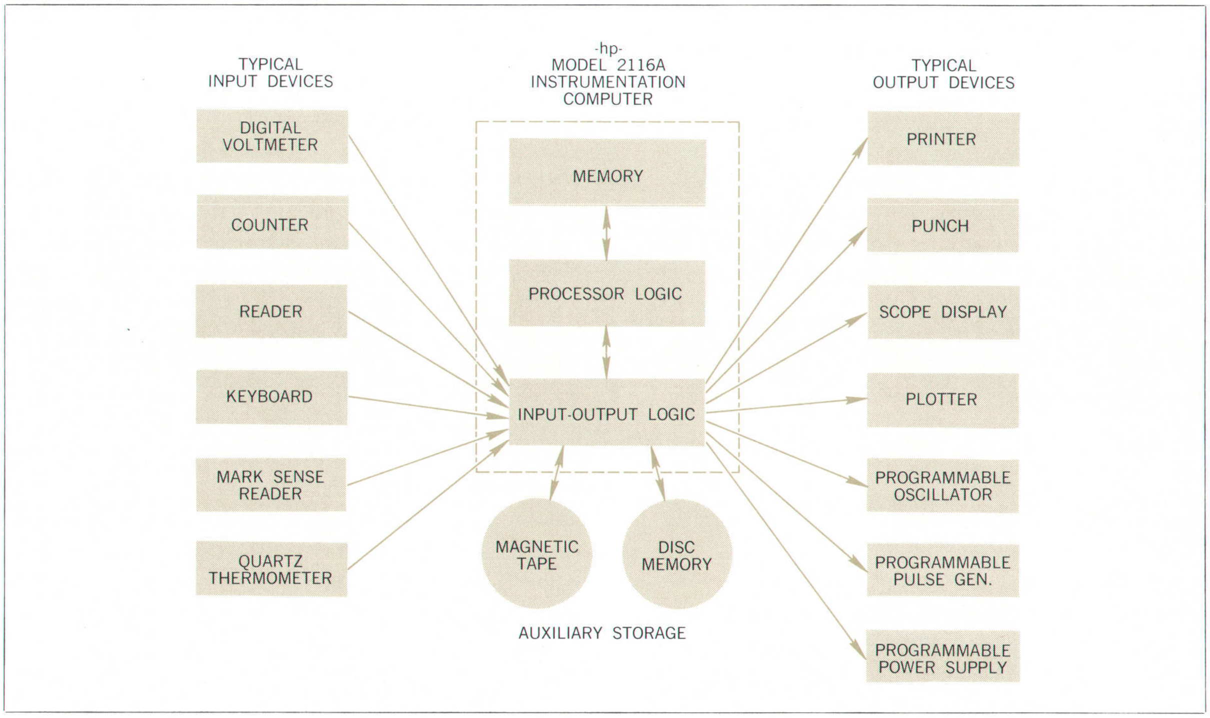


Fig. 2. *Some of the input/output devices that can be connected to –hp– 2116A Computer by means of plug-in cards. More are listed in text.*

Typically, computers in instrumentation systems process data in real time — as soon as it is acquired — rather than at some later time. The computer is 'on line' continually, processing data according to the program prepared by the user. When an instrument is ready to transmit data to the computer, the computer must interrupt its regular program, determine which instrument is requesting service, and load the new data into the proper place in the memory. Although this seems simple enough, it is not. Unless the computer has been designed to work with instruments, it takes a surprisingly long time for the computer to scan all of the instruments and find the one which has the data to transmit. This time can usually be put to better use. What's more, someone — a programmer — has to write the programs which tell the computer how to talk to each instrument. Data formats and codes often differ from instrument to instrument, so programs for different instruments may have to be quite different. In fact, the software problem may outweigh the interface problem when a system is being assembled or changed.

. . . Provided by Multi-Channel Interrupt System . . .

To allow all of its instruments to be serviced rapidly and in real time, the instrumentation computer has a multi-channel priority interrupt system. 'Multi-channel' is the key word here. The priority of each instrument is determined by the slot occupied by its interface card, and each slot, or channel, is assigned a different location in the computer's memory. When one or more instruments signal the computer that they are ready to transmit data, the computer does not have to scan the instruments in order of their priorities to find out which one has produced the interrupt. While other machines may require a millisecond or more just to determine which instrument is requesting service, the instrumentation computer locates the highest-priority interrupting instrument and its service subroutine in a few microseconds, transfers the data, and goes on to the next-lower-priority instrument. When all instruments requesting service have been serviced, the computer returns to its regular program, having spent a minimum of time away from it. Alternatively, interrupt signals from one or more instruments can be inhibited by the computer, or the computer can signal an instrument to make a measurement.

For those special occasions when even a few microseconds can't be spared, the new computer will soon have direct memory data channels. One of these direct channels can be assigned under program control to any input/output channel, permitting data to be transferred directly to memory without going through the normal channels (i.e., through one of the two accumulator registers). The maximum data transfer rate for a direct memory channel is 600,000 16-bit words per second, whereas the maximum rate for normal channels is about 60,000 words per second.

. . . and Compatible Software

Software for the instrumentation computer has been designed to make full use of the flexibility of the input/output (I/O) hardware. A modular control system allows programs to be written without concern for the specific operating requirements of individual I/O devices, and a 'software configurator' is furnished which allows the user to modify his control system easily to fit different I/O hardware configurations. Systems can be upgraded (say by switching from a low-speed to a high-speed tape punch) without changing the program. In other words, programming of the instrumentation computer is very nearly independent of the I/O devices used.

Programs for the new computer can be written in either of two programming languages, FORTRAN or assembly language. The computer comes equipped with a FORTRAN compiler which operates in the basic memory of 4096 16-bit words. The compiler is a program which converts any program written in ASA Basic FORTRAN — a universally accepted programming language — to the binary machine language that the computer understands. Actually, the new computer's FORTRAN is an augmented version of ASA Basic FORTRAN, allowing more flexibility in programming.

Assembly language, the other programming system, is a symbolic language which is closely related to the computer's hardware. The assembler, a program which converts assembly language programs to binary machine language, also operates in the basic 4096-word core memory.

The example below illustrates the two programming languages.

An interesting fact not shown in the example is that the instrumentation computer's FORTRAN compiler can produce an assembly-language listing of a FORTRAN program at the same time that it translates the program to machine language. This unusual capability makes it easy for a programmer to write part of a program in FORTRAN and part in assembly language, and then combine the two parts. It is often most efficient to write part of a program for the specially-designed instrumentation computer in assembly language, which is more closely related to the design of the machine than is FORTRAN, a machine-independent language.

The new computer's modular basic control system includes the following software modules:

—a relocating loader, which loads, combines, and initiates the execution of programs or parts of programs prepared by the FORTRAN compiler and the assembler.

—an I/O control, a general I/O device control program

—I/O drivers, which control specific I/O devices.

Programming the Instrumentation Computer: An example

PROBLEM: Read magnitude and phase, then convert to rectangular coordinates.

Programmer writes this or this

FORTRAN program: Written by programmer and punched on paper tape for computer input.

```
READ (10) R
READ (11) THETA
Y=R*SIN (THETA)
X=R*COS (THETA)
```

FORTRAN compiler: Supplied with computer on paper tape. Loaded into memory, it causes computer to convert input program written in FORTRAN to machine language.

Assembly language program: Written by programmer and punched on paper tape for computer input.

```
LIA    10
JSB    CONV
STA    R
LIA    11
JSB    CONV
STA    THETA
JSB    SIN
LDB    R
JSB    MPY
STA    Y
LDA    THETA
JSB    COS
LDB    R
JSB    MPY
STA    X
```

Assembler: Supplied with computer on paper tape. Loaded into memory, it causes computer to convert input program written in assembly language to machine language.

```
1 0 0 0 0 1 1 1 0 1 0 0 1 0 0 0
0 0 0 1 1 1 0 0 0 0 0 1 0 0 0 0
0 1 1 1 0 1 0 0 1 0 0 0 0 0 0 0
    •       •       •
    •       •       •
    •       •       •
```

Machine language program: Punched on paper tape by computer operating under control of assembler or FORTRAN compiler. Loaded into memory to cause computer to operate on data to solve problem.

Two other software packages provided with the basic control system are:

—a 'prepare control system' program, used to combine or modify the elements of the basic control system.

—debugging routines.

Other software elements which have been designed for the instrumentation computer include hardware diagnostic programs for troubleshooting, a symbolic editor program which makes it easy to edit or change any program, and a library of subroutines for various mathematical operations. All of this software is provided on punched paper tape. All of it works in the computer's basic memory of 4096 16-bit words, although the memory can be expanded to 16,384 words if desired and the software will take full advantage of the additional memory.

Environment Not a Problem

Unfriendly environments in which instruments must commonly work are no problem for the instrumentation computer. Unlike most computers, it will not balk at temperatures ranging from 0°C to 55°C, line voltage varying ±10%, line frequency varying between 50 and 70 Hz, and humidity up to 95%. The computer needs no air conditioning in order to operate in such environments. It can also function normally under conditions of electromagnetic interference and vibration that would seriously hamper most computers.

What It Can Do

Some general categories of problems which can be solved easily by the new computer and an appropriate combination of standard *–hp–* instruments are:

1. **Data reduction problems,** in which a large number of data points are taken, but only a few answers are required. A computer can perform mathematical operations, such as integration and convolution, thereby greatly reducing the amount of data requiring human analysis later on. Time savings are possible too, because the computer can be on line, processing data while measurements are being made.

2. **Data transformation and report preparation.** Frequently the data produced by an instrument is not in the best form for the user. The computer can perform operations such as curve-fitting and linearization, and then present the data graphically, or in other required forms.

3. **Problems which require fast results** for feedback during a test. When feedback is available, the amount of data taken can often be reduced substantially by not taking redundant data. The computer can decide on the basis of previous data what new measurements should be made, and then direct the proper instruments to make the measurements.

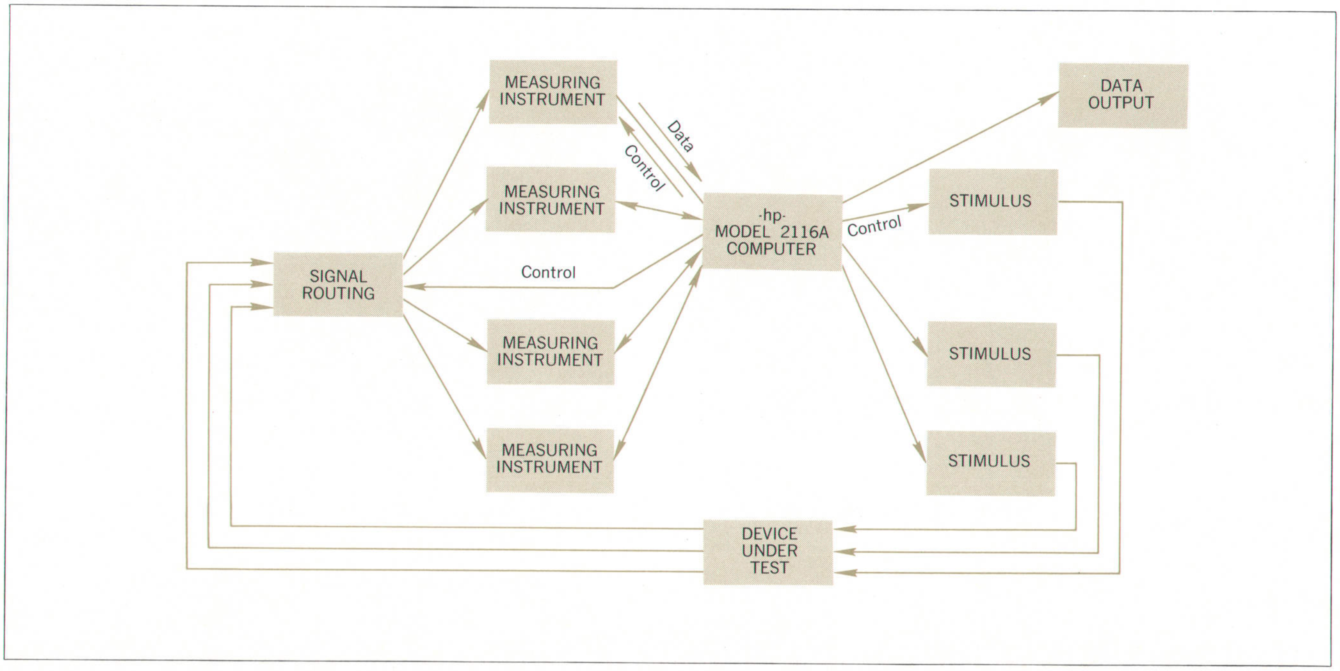


Fig. 3. *Typical application for –hp– 2116A Computer is controlling detailed tests of transistors, printed circuit cards, or other devices, then presenting processed data in any required form.*

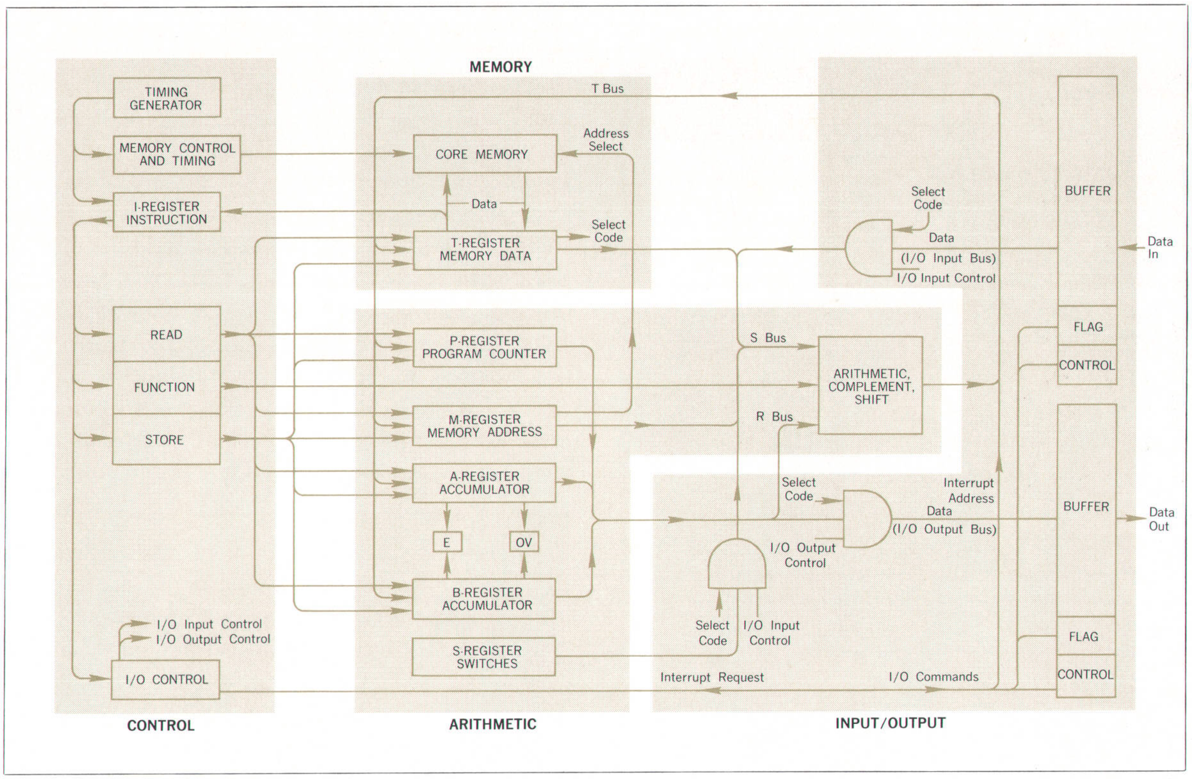


Fig. 4. *Block diagram of –hp– 2116A Computer.*

4. **System and process control.** The computer can receive data from instruments which are monitoring a system or process, operate on this data, and make adjustments to the process in order to optimize its performance. Computer control is automatic and continuous, and the computer program can be changed easily when necessary.

5. **Automatic testing.** The computer can cause a device under test to be stimulated, monitor its response, and reduce the results to any desired form (Fig. 3). It can perform complex tests quickly and automatically, and can even keep records of test results for statistical analysis.

Instrumentation computers have been integrated into several different systems to perform these and other kinds of tasks. Descriptions of four of these systems can be found on page 11.

What's Inside

So far, I've tried to describe the new computer from the point of view of a designer of instrumentation systems, emphasizing how this computer differs from others, why it differs, and what it will do for the systems designer. Now, I'd like to take you inside the machine for a closer look at certain aspects of its design.

Fig. 4 is a block diagram of the instrumentation computer, showing its four major sections, which are:

1. an arithmetic section
2. a memory
3. a control unit
4. an input/output (I/O) system.

Arithmetic operations and temporary storage of data and instructions are accomplished in the nine internal registers indicated in Fig. 4. Eight of these are flip-flop (integrated circuit) registers. The ninth is a row of toggle switches for manual data entry. The contents of all but one of the flip-flop registers are available to the programmer, and are displayed on the front panel.

The A and B registers, called accumulators, execute and hold the results of the arithmetic and logical operations called for by programmed instructions. These registers operate independently, giving the programmer considerable freedom in program design. (Many small com-

Spring Joint Computer Conference

Hewlett-Packard's new 2116A Computer will be at the Spring Joint Computer Conference in Atlantic City, New Jersey, April 18–20, 1967, operating with a variety of instruments and peripheral devices. Stop in and see us at booths E7–E11.

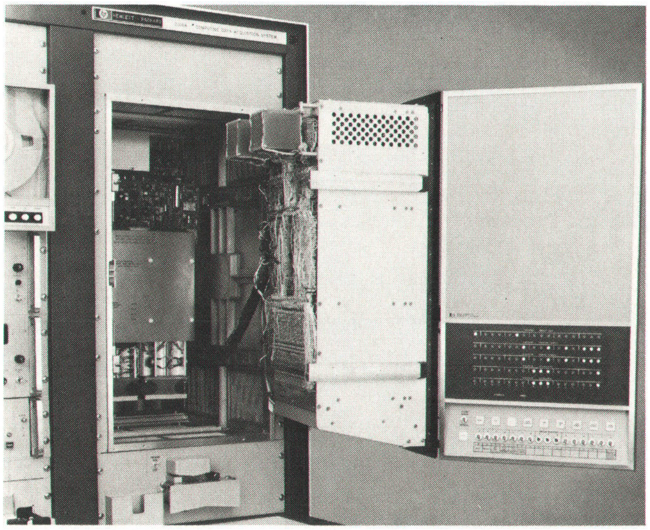


Fig. 5. *All elements of –hp– 2116A Computer are accessible from front of cabinet. Memory modules (the two cube-shaped objects protruding from top of backplane) can be changed in five minutes. Computer is fully enclosed for bench use, weighs only 230 lbs. (10.4 kg) and stands 31½ inches high (782.4 mm). It can be rack mounted.*

puters have only one accumulator; others have two, but they are not independent.) These two registers can be addressed by any memory reference instruction as memory locations 00000 and 00001, thus permitting inter-register operations, such as 'add (B) to (A), 'compare (B) with (A),' etc., using a single-word instruction.

In addition to the nine internal registers, there is an input/output buffer register for each instrument or device connected to the computer. These I/O buffers are located on the plug-in interface cards. Each interface card also contains a flag flip-flop, which is set by the external device to indicate that it is ready to transmit data, and a control flip-flop, which is set by the computer to inhibit or request data transfer, or to cause the external device to do whatever it is supposed to do.

Memory

The instrumentation computer has a coincident-current core memory system capable of storing 4096 16-bit words. A second 4096-word memory module can be installed within the computer main frame (Fig. 5), and external modules can be added to expand the memory capacity to 16,384 words. Another memory option is a seventeenth bit in each word, to be used for parity checking (error detection). Cycle time of the memory, the time required to read and write one word, is 1.6 microseconds.

Cores used in the memory have low temperature coefficients, and are also temperature compensated in order to meet the wide environmental specifications necessary for operation in instrumentation systems. Lithium core material is used because of its insensitivity to temperature variations.

The memory is organized into 'pages' of 1024 words each. One page is designated the 'base' page. There is only one base page, regardless of how many 4096-word memory modules there are. A one-word program instruction stored on one page can order the computer to do something with any other word stored on either the same page or the base page, but not with words stored on the other pages. Words stored on the other pages have to be called out, or 'addressed,' indirectly, using more than one word. Thus it is always possible to address 2048 words (two pages) directly. This is an unusually large direct-addressing capability for this size of computer, and it makes for more efficient, faster-running programs.

Instruction Repertoire

Choosing a set of instructions is the most critical decision in the design of any computer. The computer will be wired to respond to whatever instructions are chosen, and it will respond only to these instructions. If a machine is easy to program, if it carries out programs efficiently, it is because the instructions have been well designed. A look at the instruction repertoire, therefore, will tell a knowledgeable person more about a computer than anything else.

There are 68 basic instructions in the instrumentation computer's repertoire. Fourteen are memory reference instructions, which are used when information is to be obtained from the memory or stored there, forty-one are register reference instructions, used to alter or test the contents of the registers, and the last thirteen are input/output instructions.

Diagrams showing the 68 instructions and how they are coded into 16-bit words are presented on page 9. There isn't space in this article to discuss all of the instructions in detail, but the diagrams shouldn't be difficult to understand, especially if you know something about computers. Notice that each instruction has a three-letter symbol (mnemonic) which is used in writing assembly-language programs.

Of major significance in the design of the instructions is the manner in which several register reference instructions can be combined into a single 16-bit word. The in-

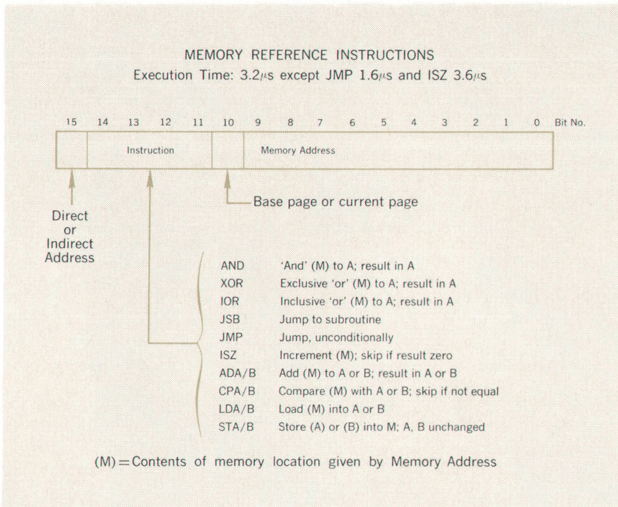
CORRECTION

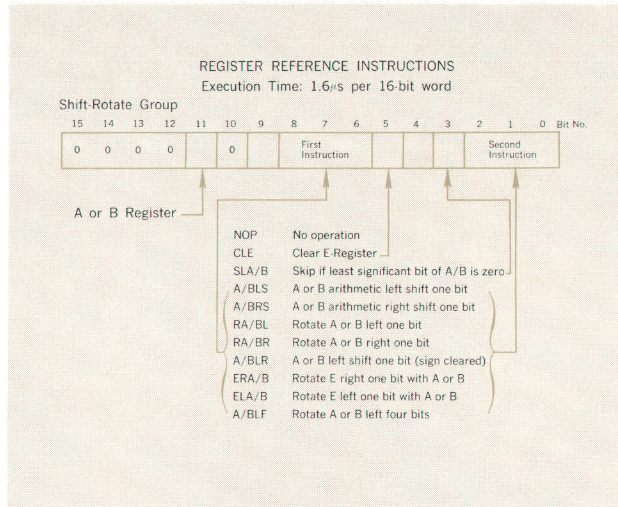
In the article 'S-parameter Techniques for Faster, More Accurate Network Design,' Feb., 1967, two equations in the table on pages 23 and 24 contained incorrect signs. The correct equations are

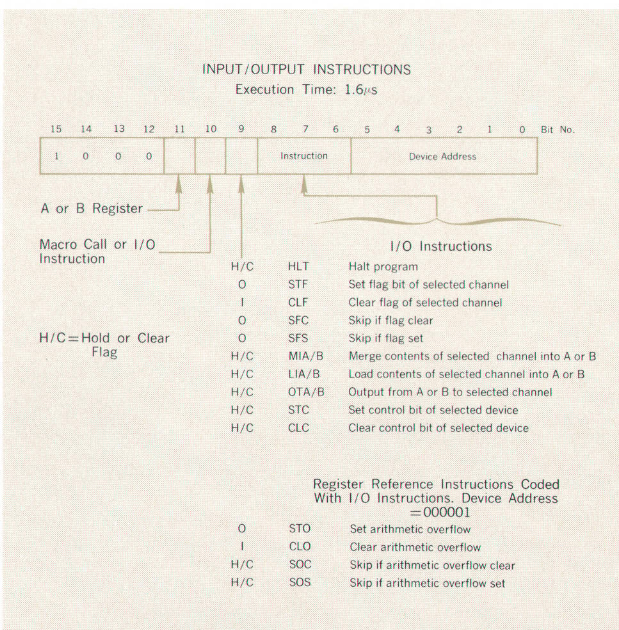
$$s_{11} = \frac{(1 - y_{11})(1 + y_{22}) + y_{12}y_{21}}{(1 + y_{11})(1 + y_{22}) - y_{12}y_{21}}$$

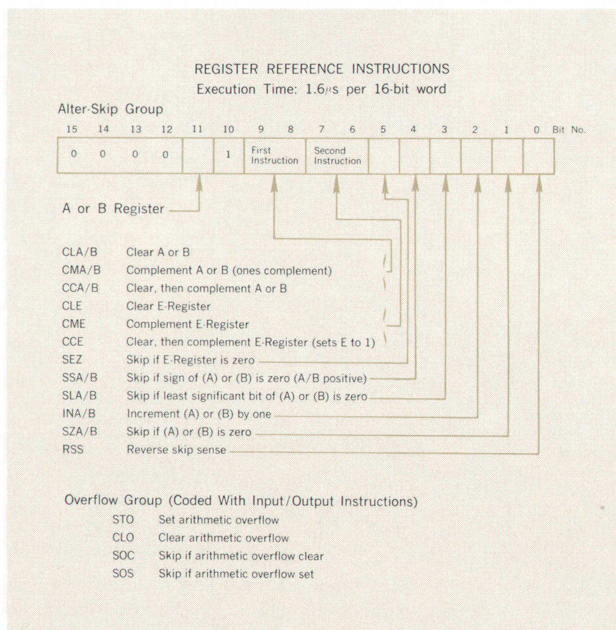
$$s_{22} = \frac{(1 + y_{11})(1 - y_{22}) + y_{12}y_{21}}{(1 + y_{11})(1 + y_{22}) - y_{12}y_{21}}$$

-hp- Model 2116A
Instrumentation Computer Instruction Repertoire and Coding









structions in each word are executed in time sequence, reading from left to right in the diagrams above, and it takes only one memory cycle, 1.6 microseconds, to execute all of the instructions in a word. This powerful capability of combining instructions makes the instrumentation computer's repertoire equivalent to over 1000 useful one-word, one-cycle instructions. It lets the programmer write extremely compact, efficient programs.

Several of the individual instructions are tailor-made for instrumentation work. For example, one of the 'shift-rotate' group of register reference instructions is ALF (or BLF), which causes the word in the A (or B) register to be shifted four places to the left in one memory cycle. This operation is needed often when translating data from the binary-coded-decimal format favored by instrument designers to the straight binary format used by the computer.

If this instruction (ALF) is written twice in a row, it will fit twice into one 16-bit word and will cause the computer to exchange the most significant 8 bits of a word with the least significant 8 bits in only one memory cycle. This operation is needed in changing from 16-bit words to the 8-bit characters used by teletype or punched-tape units, and vice versa. To be able to do it in one memory cycle instead of eight represents quite a lot of time saved.

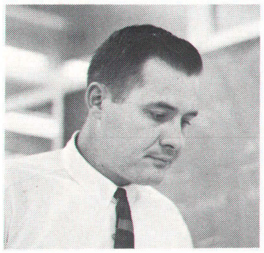
Acknowledgments

So many people have contributed to the design of the instrumentation computer that it would be impossible to list them all individually. I am most grateful for the dedication and the creative efforts of all my colleagues in the following groups:

Group	Leaders
Logic Design	*Edward R. Holland and Eugene R. Stinson*
Memory	*Robert L. Gray and Joseph Olkowski, Jr.*
Input/Output	*Richard C. Reyna*
Mechanical Design	*Tor Larsen*
Programming	*Roy L. Clay*
Applications	*John Koudela, Jr.*

I also wish to acknowledge the valuable consulting services of Samuel N. Irwin, and the support of Henry A. Doust, Jr.'s engineering services group, Joseph B. Dixon's prototype shop, and Norman A. Day, Jr.'s layout group.

—Kay B. Magleby



Kay B. Magleby

Kay Magleby received his BS degree from the University of Utah in 1957, and his MS and PhD degrees from Stanford University in 1960 and 1964, respectively. He came to *–hp–* in 1958 and became the first *–hp–* engineer to work on sampling oscilloscopes. He subsequently served as project leader for the development of several sampling-oscilloscope plug-ins. Then, after moving from the oscilloscope division to the advanced research and development group, he contributed to the 8405A Vector Voltmeter project and to research projects in digital techniques, eventually starting the 2116A Computer project. In 1965, he transferred to the *–hp–* Dymec Division as head of the computer development group.

Kay holds several patents in sampling and digital instrumentation. He is active in the IEEE Instrumentation and Measurements Group and is a member of Phi Kappa Phi, Tau Beta Pi, Sigma Xi, and Eta Kappa Nu. He has a wife and three children, and enjoys skiing and woodworking.

SPECIFICATIONS
–hp– Model 2116A COMPUTER

TYPE

General-purpose digital computer, with input/output system and modular software organized for flexible application in on-line instrumentation systems.

MEMORY

TYPE. Magnetic core.

SIZE: 4096 16-bit words. Expandable to 8192 words (in main frame) with plug-in 4096-word module and associated cards, Option M4. Maximum memory size 16,384 words. (Parity bit included in standard stack for use with Option M2, Memory Parity Check.)

ADDRESSING: Memory is organized in 1024-word pages, 2048 words directly addressable.

SPEED: 1.6 microsecond cycle time.

LOADER PROTECTION: Last 64 locations of memory reserved for Basic Binary Loader. Front panel switch, in 'Protect' position, prevents alteration of contents of these locations.

MEMORY PARITY CHECK (Option M2): Permits parity checking within memory. Consists of one plug-in card for each 4K of memory.

MEMORY TEST (Option M3): Enables memory to be tested independently of program control. Consists of one plug-in card.

ARITHMETIC Parallel, binary, fixed point, two's complement.

SPEED

Add	3.2 μs
Subtract	4.8 μs
Multiply	130 μs
Divide	200 μs
Floating point add	375 μs
Floating point subtract	375 μs
Floating point multiply	750 μs
Floating point divide	1.1 ms

(Above are subroutine operations except for Add. Times shown are approximate.)

REGISTERS

Eight internal hardware (flip-flop) registers and Switch register. Contents of all registers except Instruction and Switch register displayed by front panel lamps.

A-REGISTER. Accumulator, input/output. (16 bits.)

B-REGISTER: Accumulator, input/output. (16 bits.)

E-REGISTER: Extend register, links A and B register; indicates carry from A or B register. (1 bit.)

OV-REGISTER: Overflow register, indicates overflow from A or B register. (1 bit.)

T-REGISTER: Transfer register, temporarily holds data transferred in or out of memory. (16 bits.)

P-REGISTER: Program counter. (15 bits.)

M-REGISTER: Memory address register, holds address of next memory location to be accessed. (15 bits.)

I-REGISTER: Instruction register, decodes Memory Reference instructions, holds indicators for zero/current page and direct/indirect addressing. (6 bits, 10-15.)

S-REGISTER: Toggle switches on front panel for manual data entry. Contents of register indicated by switch positions. (16 bits.)

INSTRUCTIONS

68 basic, one-word instructions, in three types:

Memory Reference	(2-cycle)	14
Register Reference	(1-cycle)	41
Input/Output	(1-cycle)	13

Register Reference instructions are micro-operations, can be combined to form over 1000 one-word, single-cycle instructions.

INPUT/OUTPUT

NUMBER OF CHANNELS: 48, 16-bit parallel interrupting channels, with priority control, utilized through plug-in I/O interface cards (1 per channel). 44 channels available for I/O devices; 4 channels reserved for processor options.

MAIN FRAME CAPACITY: 16 channels for I/O devices. Power for interface cards provided from internal supply. (Peripherals draw power directly from 115/230v line.)

INTERRUPT RESPONSE: Servicing of interrupt request (execution of first useful instruction) begins within 3 μs with one I/O channel in use, or within 7 μs for highest priority channel in multiple-channel system.

DATA FORM

PUNCHED TAPE: ASCII. Parity not used, 8th level always punched. (1-inch tape.)

MAGNETIC TAPE: IBM-compatible, 7-channel NRZI. (½-inch tape).

SOFTWARE

Software (punched tape) available consists of:
Compiler, ASA Basic FORTRAN (Extended)
Assembler
Symbolic Editor
Basic Control System
I/O Device Handling Routines
Cross-reference Symbol Table Generator
Hardware Diagnostics
Basic Control System is modular, includes configurator (Prepare Control System) to permit adaptation by user to different I/O arrangements. Also includes Debugging Routines.)

PRICES: 2116A Computer (4096-word memory, no I/O options) $22,000
Memory parity check. Option M2, $1000
Memory test, Option M3, $420
8192-word memory (basic 4K plus 4K additional), Option M4, $8000
I/O Options, $1000 to $15,000

MANUFACTURING DIVISION: *–hp–*-Dymec Division
395 Page Mill Road
Palo Alto, California 94306

Successful Instrument-Computer Marriages

Instrumentation computers are designed to be easy to incorporate into any system which contains electronic, chemical, or medical instruments. Here are four remarkably varied examples of how these computers are being used.

Fig. 1. *Computing data acquisition system can be used in a variety of scientific and industrial applications, including jet engine testing (see Fig. 2).*

Computing Data Acquisition System

Data acquisition systems are the simplest type of instrumentation system. An elementary data acquisition system converts data from a number of inputs to a form suitable for printing by an output recorder. In more complex systems, some processing of the raw data is done, and the operation of the system may be controlled to some extent by the data.

Because it can easily carry out complex programs, and because its programs can be changed easily, an instrumentation computer in a data acquisition system makes control of the system extremely flexible. It also provides rapid, local data processing, thereby eliminating the loss of time inherent in remote data processing.

A typical computing data acquisition system is shown in Fig. 1. Such systems are used, for example, in testing jet engines: the analog inputs are physical parameters such as pressure, temperature, fuel flow, and engine speed, and the computer outputs are operating parameters such as efficiency and power. The computer not only provides immediate results to help the operator set up the test, but also controls some portions of the test, thereby making the checkout more automatic.

Fig. 2 is a block diagram of the system of Fig. 1, illustrating its use in jet engine testing. Surprisingly, this computing system costs little more than a less flexible

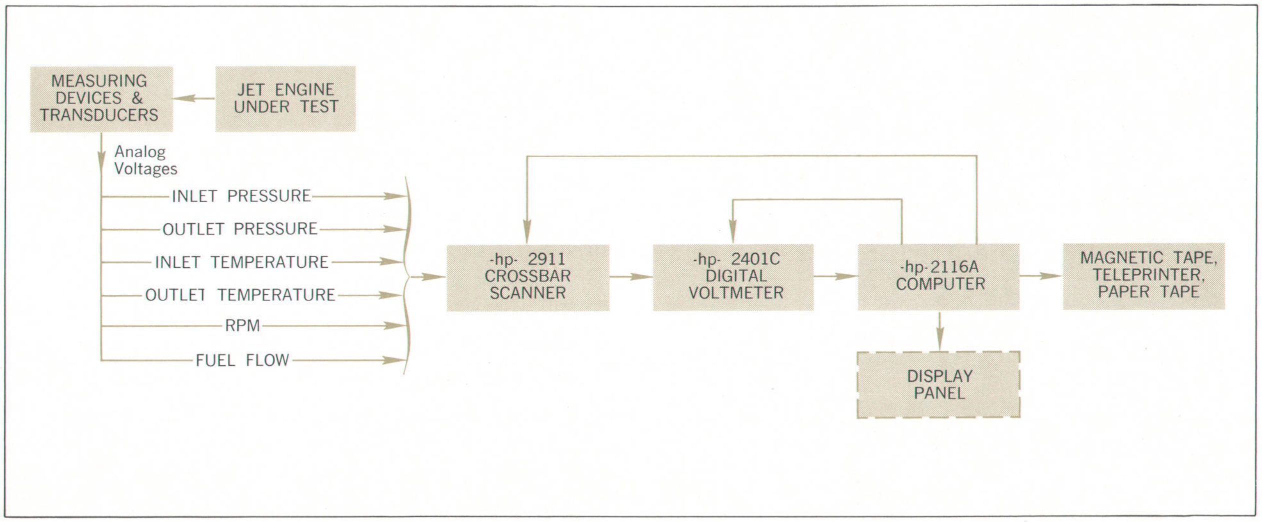


Fig. 2. *Block diagram of computing data acquisition system used for testing jet engines. Computer calculates engine efficiency, power, and other performance data.*

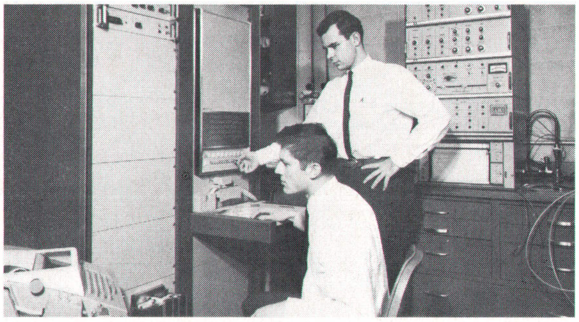


Fig. 3. *–hp– 2116A Computer speeds gas chromatography by analyzing outputs of several chromatographs (one is visible at right), freeing chemist to do less tedious tasks.*

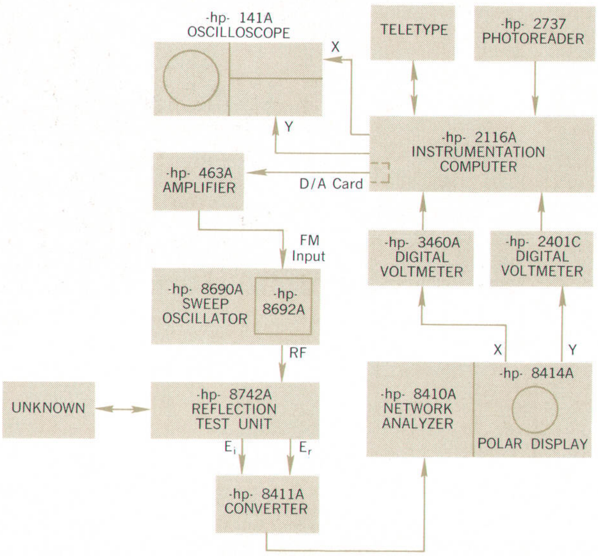


Fig. 4. *Block diagram of microwave impedance-measuring system including instrumentation computer. Computer controls test instruments, refines measurements, and presents results in several forms.*

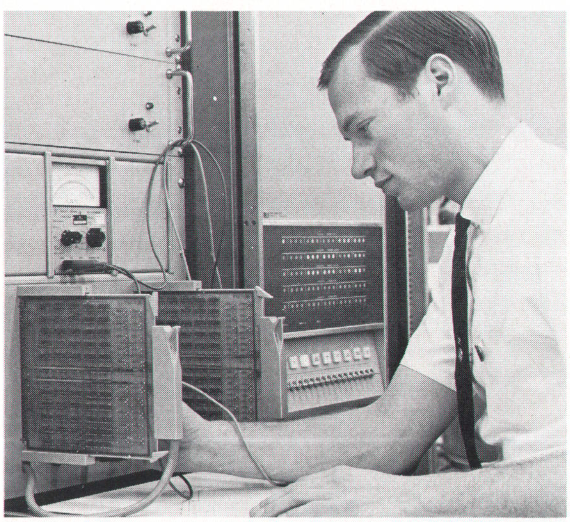


Fig. 5. *–hp– 2116A Computer pretests logic cards for other –hp– 2116A Computers. Tests take only minutes per card, would take months without computer. Computer also keeps statistics for quality control.*

noncomputing system capable of performing some, but not all, of the same tasks.

Gas Chromatograph System

A gas chromatograph is a versatile chemical instrument which provides an analytical chemist with information about the composition of an unknown sample of material. However, it takes a considerable amount of interpretation and analysis to extract this information from the output of the chromatograph, and analytical chemists who do this type of work spend a large portion of their time on data reduction. An instrumentation computer in a chromatograph system can not only free the chemist from time-consuming data reduction, but because it can analyze the outputs of many instruments, it can also greatly increase the number of samples that a chemist can test in a day. Fig. 3 shows part of a developmental system in which an instrumentation computer will be used to analyze the outputs of up to 36 gas chromatographs.

Microwave Impedance-Measuring System

A block diagram of an impedance-measuring system including an instrumentation computer and a network analyzer (Hewlett-Packard Journal, Feb., 1967) is shown in Fig. 4. This system measures the reflection coefficient of an unknown device as a function of frequency, then calculates impedance, admittance, standing wave ratio, return loss, and mismatch loss. Residual errors in the system are measured with a calibrating short in place of the unknown, and the computer automatically subtracts these errors from the measurements. The refined results are stored in the computer memory and displayed on the oscilloscope. The network analyzer provides a Smith Chart display of the raw data.

Logic Module Test System

Final testing of a complex system (e.g., a computer) can be greatly simplified by pre-testing the modules or cards that make up the system. However, manual testing of logic modules can be extremely expensive and time consuming, because there are so many inputs and outputs to be checked. A computer makes pre-testing practical, because it can automatically stimulate the modules and monitor their responses. A complete test of a module with 16 inputs would require 2^{16}, or 64,000, different tests. At one minute per test, it would take a technician six months to test one module. An instrumentation computer can do it in less than one minute. The computer can also keep statistics on the tests for quality control.

Logic modules for *–hp–* instrumentation computers are tested by the computer system illustrated in Fig. 5. The response of the module under test is compared with that of a reference circuit and the operator is alerted if the test device's response is not within specified limits. ■

A Wideband Analog Frequency Meter and FM Discriminator

PARADOXICALLY, one of the most often overlooked methods of frequency measurement — the pulse discriminator — happens to be one of the most versatile. This apparent contradiction may now have been resolved by the development of a new analog frequency meter and FM pulse discriminator by the -hp- Frequency and Time Division. The new instrument extends the sizeable potential of the pulse discriminator principle to frequencies where it was not available before, and provides a means for making certain frequency measurements with greater convenience, speed, accuracy, and economy. It promises to be an excellent solution to the problem of how to measure the instantaneous frequencies of bursts, sweeps, frequency modulated signals, and phase modulated signals. Surprisingly, it may even be more accurate than digital instruments for measuring average frequencies below about 1 kHz.

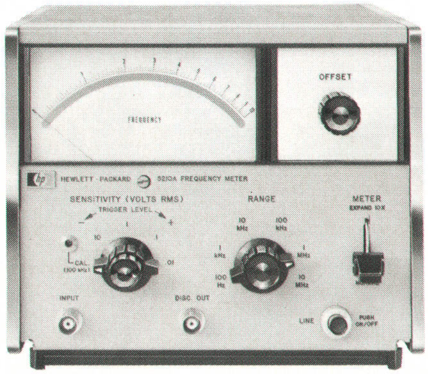


Fig. 1. *New -hp- Model 5210A Frequency Meter and FM Discriminator directly measures frequencies between 3 Hz and 10 MHz. Special log-linear meter scale can be read accurately within ± 1% of reading. Discriminator output is useful for measurements of instantaneous frequencies of FM signals, measurements that are impossible for most other frequency measuring devices.*

A precision, all solid-state, analog instrument, the new frequency meter measures frequencies between 3 Hz and 10 MHz, nearly seven times the measurement range of older instruments of the same type. It has four kinds of frequency readout: a taut-band indicating meter which is accurate within ±1% of reading, a discriminator output, and outputs for potentiometer-type and galvanometer-type recorders.

Probably the most important of the four outputs is the discriminator output, which provides a pulse train which has an average voltage proportional to the instantaneous frequency of the input signal. Both the input bandwidth (10 MHz) and the output bandwidth (1 MHz) of the discriminator greatly exceed those of previous instruments of this type. Furthermore, these added capabilities are readily accessible. An accessory set of plug-in low-pass filters makes it possible to remove the carrier-frequency components from the discriminator output so that the modulation can be recovered. With the filters, the new instrument is extremely useful in conjunction with an oscilloscope, wave analyzer, or voltmeter for measuring swept frequencies, bursts, FM, FM noise, phase noise (see p. 18), and mechanical flutter and wow.

Besides measuring frequencies directly up to 10 MHz, the new meter/discriminator can also be used to analyze high-frequency FM signals such as chirp radar signals, telemetry signals, and so on. The high-frequency signal can be heterodyned down to less than 10 MHz, or if the frequency deviation is large, the signal to be measured can be divided down in frequency to less than 10 MHz.

Principle of Operation and Operating Characteristics

The pulse-discriminator circuit uses an RC time constant as a standard of frequency to yield an analog output for a frequency input. Fig. 2(a) shows a typical input signal with frequency modulation. This signal triggers a pulse circuit, which generates a train of identical pulses. Each pulse has a duration shorter than the period of the highest frequency input for the range used, and an area which is constant and independent of repetition rate, supply voltages, and environmental conditions. Using the latest fast components, and taking advantage of the superior switching characteristics of transistors, the circuit can produce such a pulse with up to a 10 MHz input frequency, essentially independent of line frequency or voltage. The pulse train is shown schematically in Fig. 2(b). The average value of the pulse train is directly proportional to the duty cycle and to the input frequency.

If the input frequency varies the duty cycle of the pulse will vary and the average value will then represent the

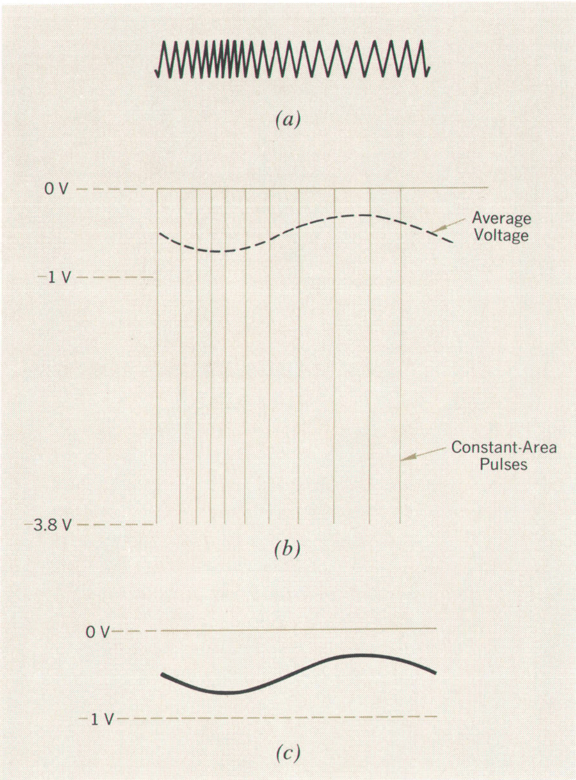


Fig. 2. *Waveforms illustrating pulse discriminator principle used in new analog frequency meter/FM discriminator. (a) Frequency modulated input waveform. (b) Constant-area pulses generated by frequency meter, one for every two input cycles. (c) Modulating signal, recovered by filtering discriminator output to remove pulses. Average discriminator output voltage is 0 V for dc input, −1 V for input frequency equal to full scale on meter.*

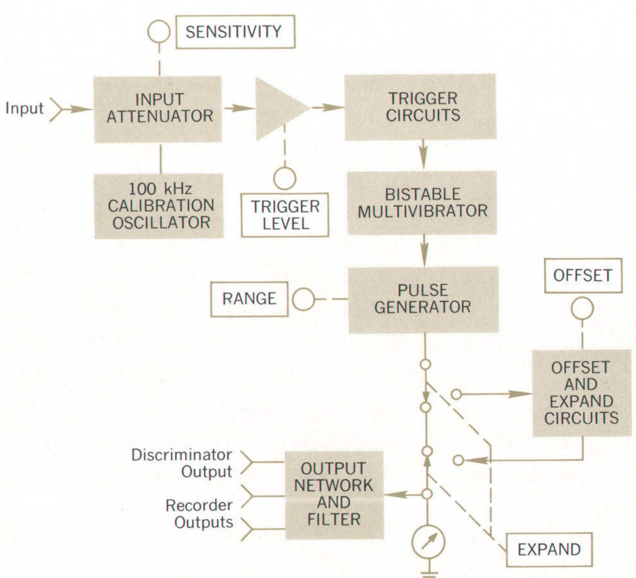


Fig. 3. *Block diagram of Model 5210A Frequency Meter. Internal calibrator, accurate within ± 0.01%, makes meter calibration independent of power-line frequency.*

frequency modulation contained in the input signal as shown in Fig. 2(b) and 2(c). By using a low-pass filter in the discriminator output the carrier pulses can be smoothed and the modulation recovered. Modulation components whose frequencies are as high as 25% of the carrier frequency can be measured. This limit is a theoretical one imposed by the modulation-theory requirement of at least 2 carrier cycles per modulation cycle for full recovery of the modulation information. A divide-by-two circuit (a bistable multivibrator) in the discriminator raises this to 4 carrier cycles/modulation cycle, setting the upper limit on the modulating frequency at 25% of the carrier frequency. Another limit on the highest modulating frequency that can be recovered is the 1 MHz 3-dB bandwidth of the discriminator output. This is a practical limit imposed by stray capacitance.

Changing ranges on the discriminator is merely a matter of changing RC time constants to change the pulse duty cycle. Because it is possible to obtain RC time constants with excellent stability, the accuracy of the discriminator output current can be held to 0.2% in most cases.

Fig. 3 is a simplified block diagram of the frequency meter. The instrument has a constant-impedance MOSFET input amplifier which gives it a wide dynamic range and a high (1 MΩ) input impedance. Sensitivity is adjustable from 10 mV rms to 10 V rms. An internal, 100 kHz crystal calibrator, accurate within 0.01%, is included, freeing the accuracy of the instrument from dependence on the power line frequency and giving a high degree of repeatability to readings. The TRIGGER LEVEL control can be used to set the discriminator to trigger precisely at the zero-crossings of the input signal, in order to make accurate measurements of incidental FM on AM input signals.

FM Measurements

Before discussing the more conventional type of frequency measurement where the long-term average of the unknown is equal to its instantaneous value, it is best to look at frequency measurements in which the unknown is varied from its average value and it is the variations that are of interest. This is an area of frequency measurement that the new meter is ideally suited for. The discriminator output characteristic is a linear relation with 0 volts out (average) for 0 frequency and —1 volt out (average) for a frequency equal to the range setting. Compared to other frequency-to-voltage converters that have their 0 outputs at some nonzero center frequency value, the advantages of the pulse discriminator are obvious: the circuit need not be tuned for various input frequencies, and the deviation bandwidth is large (equal to the carrier frequency). In addition, the linearity of the pulse discriminator (see Fig. 4) is quite good, being better than .025% over most of its range. Notice in Fig. 4 that the discriminator is usable out to 12 MHz.

These very linear, wide-band characteristics result in a measuring instrument which yields an accurate output that is easily interpreted and used. An important advantage of the pulse discriminator is that its transfer characteristic is constant and independent of input frequency, making the instrument convenient to use in measuring characteristics of FM systems such as modulation index, distortion, and frequency response.

To filter out the carrier-frequency components from the pulse discriminator circuit so that the modulation can be recovered at the discriminator output, an accessory set of low-pass filters has been designed. Any upper cutoff frequency between 100 Hz and 1 MHz can be obtained with these filters. The filters have a 24 dB per octave (80 dB/decade) attenuation characteristic in the stop band, and their pass band characteristic may be made either flat amplitude (Butterworth) or flat delay (Bessel). Figs. 5 and 6 show the frequency-versus-amplitude and step response of these filters, demonstrating the superiority of the flat amplitude filter for spectral measurements and the flat delay filter for time domain measurements.

As an example of the use of the filters, assume that the maximum modulation frequency on an 80 kHz carrier is 8 kHz, and that the frequency deviation is ±15 kHz. To recover the modulating signal, an output filter with a 10 kHz cutoff would be suitable. The lowest-frequency component that needs to be filtered out is at half the carrier frequency, which in this case is 40 kHz, and the attenuation of the filter at this frequency (53 dB) yields a carrier ripple of approximately 3.3 mV peak. This is a 2.2% ripple on the information we wish to observe. On an rms meter this would result in less than 1.1% error, and on an oscilloscope the remaining ripple would be of little significance. Taking another example of the use of these filters, consider a 1 MHz carrier with very small deviations. Some quick calculations would show that a 200 kHz filter would reduce the 500 kHz carrier component in the discriminator output to 30 mV peak. With this sort of carrier ripple an *-hp-* wave analyzer could be used to measure rms deviations as small as 3 or 4 Hz at modulation frequencies up to 200 kHz, or 20% of the carrier frequency. With proper care, deviations as small as one part in 10^6 or —120 dB can be measured.

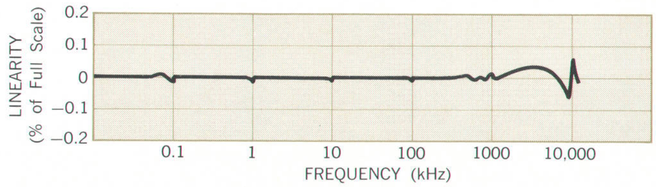


Fig. 4. *Average discriminator output of analog frequency meter is linear function of frequency within ± 0.025% below 100 kHz, ± 0.05% on 1 MHz range, and ± 0.1% on 10 MHz range. Measured deviations from linearity for typical production instrument are shown. Instrument is usable to 12 MHz.*

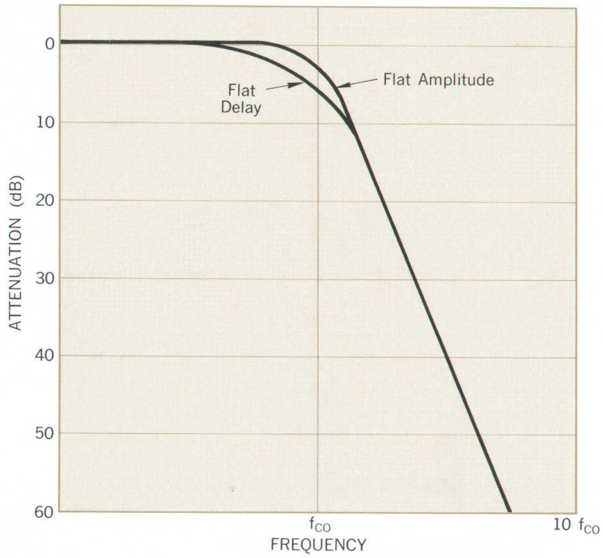


Fig. 5. *Frequency response of accessory plug-in filters for analog frequency meter discriminator output can be either flat-amplitude (Butterworth) or flat delay (Bessel). Attenuation slope in stop band is 24 dB/octave. Cutoff frequency f_{co} is adjustable between 100 Hz and 1 MHz.*

Swept Frequencies

Two examples of frequencies whose instantaneous values differ from their average value, and for which measurements by counter techniques are extremely difficult or impossible, are short bursts and swept frequencies. While in some of the more extreme examples that could be examined it is difficult to define what is meant by 'frequency,' for many signals of this type significant measurements can be made using the new frequency meter/discriminator and the accessory filter set.

One limitation on the accuracy with which a rapidly changing frequency can be measured using a pulse discriminator is the ripple due to the carrier components on the output. The effect of ripple on the discriminator output may be seen in Fig. 7. In this case a 10 kHz filter was used to smooth the output from a 0 to 100 kHz linear sweep. In Fig. 7, the polarity of the discriminator output is inverted, so the output is shown positive instead of negative. For the first few cycles, where the discriminator output is still below the filter cutoff, the ripple is quite large compared to the average output. However, at 0.6 V (60 kHz) the ripple is at most 4% peak-to-peak and at 1 V (100 kHz) it is about 0.5% peak-to-peak. (These values can easily be predicted before a measurement is to be made, because the filter performance is in

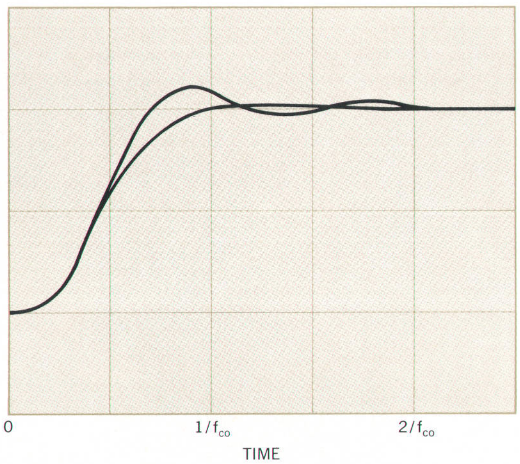


Fig. 6. *Step responses of flat amplitude and flat delay low-pass filters. Flat amplitude filter has better frequency response (Fig. 5) but more overshoot in step response.*

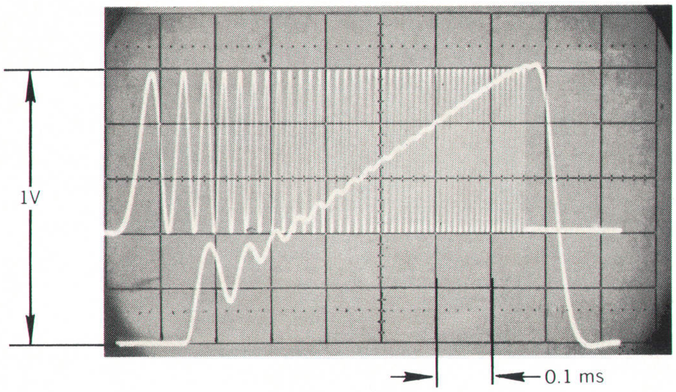


Fig. 7. *Double-exposure oscillogram showing input (top) and discriminator output of new frequency meter with accessory 10-kHz flat delay filter installed in discriminator output circuit. Input is a 0-to-100-kHz linear sweep. Lower filter cutoff requency, say 1 kHz, would eliminate ripple, but would increase output fall time and time delay between input and output.*

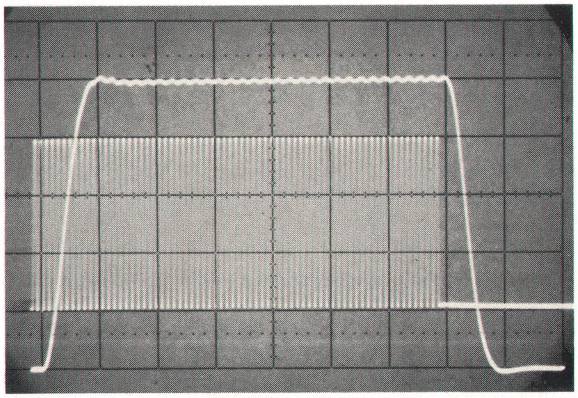


Fig. 8. *Double exposure oscillogram showing 100-kHz burst input and discriminator output of frequency meter with 10 kHz output filter. Unfiltered ripple in discriminator output is only 0.6% after first few cycles.*

close agreement with theory.) The utility of the new meter in making measurements of this type can be seen in Fig. 7. The last two cycles of the sweep do not yield the proper increase in frequency, but level off at 100 kHz because of modulator saturation. The error of about 1.5% shows up clearly in the analog signal provided by the discriminator.

Excessive ripple in the discriminator output can be reduced, of course, by using a low-pass filter with a lower cutoff frequency. However, the lower the cutoff frequency, the greater is the time delay between input and output and the slower is the fall time of the output.

Another application is suggested by the foregoing discussion and oscillograms: the meter/discriminator can be used as a frequency-to-voltage converter in sweep frequency measurements and display systems, eliminating the need for accurate sweep generators which are hard to obtain with the accuracy and linearity of the pulse discriminator.

Bursts

A measurement of a burst frequency is shown in Fig. 8. Here, the filter frequency is 10 kHz and the carrier is 100 kHz. The observed ripple is near the theoretical value of 0.6% peak. It is clear from this trace that the ripple is not the only limit on the measurement accuracy possible for a short group of input cycles. The rise time of the filter also represents a limit on the time required to make a measurement within a specified accuracy. Fig. 9 shows the number of cycles necessary to obtain a given accuracy, assuming a step change in frequency and an equal division between the error caused by ripple and that caused by filter settling time in a Bessel filter. The actual value may differ from Fig. 9 by —0 or +1 cycle due to the possible delay of the output by 1 cycle in the $\div$ 2 circuit. An example of a relatively crude measurement of frequency (±4% peak error resulting from ±2% peak ripple and ±2% error due to the filter output's having risen only to 98% of final value) is shown in Fig. 10 to illustrate the data given in Fig. 9. While it might be possible to measure one period of either the 100 kHz signal in Fig. 8 or the 60 kHz signal in Fig. 10 with a counter, it would be extremely difficult to obtain the cycle-by-cycle data shown here.

'Long-Term' Frequency Measurements

If the purpose of a measurement is to make an analog record of frequency and the accuracy required is less than 0.2% the new frequency meter is useful and is an economic solution to the problem at any frequency. But if the measurement frequency is below 1 kHz the analog frequency meter may actually be the most accurate solution to the problem, depending upon the constraints on the measurement.

The first assumption, and the principal one, in the following discussion is that the quantity that must be measured is frequency, and that period measurement information is less desirable. If we next assume that the gate time on a counter is 1 sec (i.e., that reasonably continuous data is required) then using a counter for the above measurement results in a ±1 cycle error. At 1 kHz the 0.2% recorder current output from the new meter is only one-half as accurate as the data from the counter, but below 500 Hz the recorder current from the new meter is actually more accurate than the data from the counter. If the data from the frequency measurement is to be used as part of a control system or recorded, as noted above, the major advantage of the analog meter is not so much the improved accuracy as it is the continuousness of the data coupled with its accuracy.

If the ultimate repository of the measured quantity is to be a human observer the analog current output must in turn be measured to a high accuracy to make use of the improved accuracy over counter techniques that is possible here. Calibrated offset is an optional feature of the new meter which makes accurate readings possible. During the calibration procedure a constant current is set equal to the full scale discriminator output. Then by

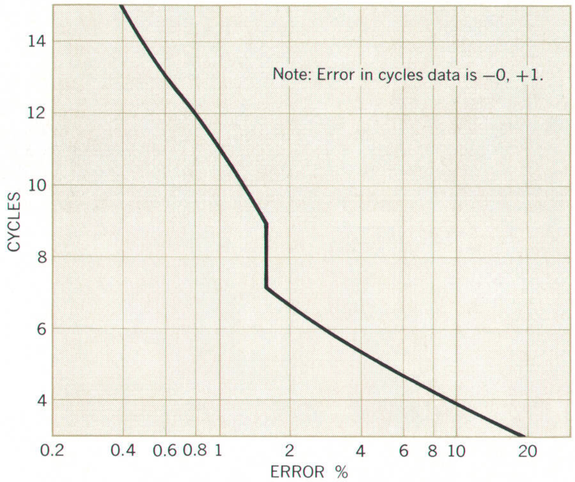


Fig. 9. *Number of cycles of burst needed to achieve a given maximum error in burst-frequency measurement at discriminator output of frequency meter.*

SPECIFICATIONS

-hp- MODEL 5210A FREQUENCY METER

FREQUENCY RANGE: 3 Hz to 10 MHz in six decade ranges from 100 Hz full scale to 10 MHz full scale. Log linear meter allows the discriminator current to be read to 1% of reading from 10% of full scale up.

EXPANDED SCALE: With a continuously adjustable OFFSET control, meter and recorder output display any 10% of full scale expanded to full scale.

INPUT VOLTAGE

Sensitivity: Maximum sensitivity of 10 mV rms from 20 Hz to 10 MHz, increasing to 200 mV at 3 Hz with four attenuator ranges of 0.01, 0.1, 1.0, and 10 V.

Overload: 20 V peak on 0.01 V range, 200 V peak on 0.1 V range, 500 V peak on higher ranges.

Input Impedance: 1 MΩ shunted by 30 pF; 10 MΩ shunted by 10 pF when used with -hp- 10003A 10:1 divider probe.

ACCURACY

Discriminator Output Current: 0.2% of reading below 1 MHz, 0.3% of reading on 10 MHz range.

Meter: 1% of reading from 10% of full scale to full scale.

Expanded Scale: 0.1% of full scale for differential frequency readings.

Calibration: Crystal calibration oscillator at 100 kHz accurate to ±0.01%.

Line Voltage and Frequency: Changes in line voltage of ±10% and frequency of 50–1000 Hz cause less than 0.05% change in output.

Temperature: Frequency reading changes less than 0.02%/°C 100 Hz to 1 MHz ranges, 0.04%/°C 10 MHz range from 0 to +55°C.

RECORDER OUTPUT

Level: Potentiometer outputs of 10 mV and 100 mV adjustable from 9 mV to 11 mV and 90 mV to 110 mV for full scale; galvanometer output 1 mA into 2 kΩ max. for full scale, adjustable ±10% for 1 kΩ to 2 kΩ loads.

Linearity: 0.025% of full scale 100 Hz to 100 kHz ranges; 0.05% of full scale 1 MHz range; 0.1% of full scale 10 MHz range.

Accuracy: Same as discriminator output current above.

Time Constant: Approximately 100 ms.

DISCRIMINATOR OUTPUT

Level: Adjustable 0.8 to 1.2 V for full scale.

Output Impedance: 1 kΩ constant.

Linearity: 0.025% of full scale 100 Hz to 100 kHz ranges; 0.05% of full scale 1 MHz range; 0.1% of full scale 10 MHz range.

Bandwidth: 3 dB down at greater than 1 MHz.

Residual FM Noise: rms line frequency components below 300 Hz are 100 dB below the 1 V full scale output. At other frequencies the rms noise deviations are at least 120 dB below the carrier frequency when the noise is measured in a 6 Hz bandwidth.

POWER REQUIREMENTS: 115 or 230 V ac ±10%, 50 to 1000 Hz at less than 12 W.

OPTION 01, CALIBRATED OFFSET

GENERAL: The calibrated offset provides for display of any of the 10 major divisions (six major divisions on 5210B) on a separate full meter scale (the EXPAND scale). This allows frequency measurements to be made with higher accuracy than is possible using the meter in the NORMAL mode.

ACCURACY: The 5210A accuracy specification is changed to the following:
±0.2% of full scale (range switch setting) for 100 Hz to 1 MHz ranges;
±0.3% of full scale (range switch setting) for the 10 MHz range.

TEMPERATURE: The accuracy specification is increased by 0.01%/°C of reading on the 100 Hz to 1MHz ranges and 0.03%/°C of reading on the 10 MHz range from 0°C to 55°C for departures from 25°C when zero and self-calibration adjustments are made at the ambient temperature.

DISCRIMINATOR OUTPUT: Same as above except for bandwidth: 3 dB down at greater than 750 kHz.

-hp- MODEL 5210B

GENERAL: Model 5210B frequency meter is identical in construction and circuitry to 5210A but is calibrated in r/min for greater convenience in tachometry applications. Option 01 and the -hp- 10531A Filter Kit are available for the 5210B. The specifications are equal to those of the 5210A on the 100 Hz to 100 kHz ranges.

SPEED RANGE: 6000; 60,000; 600,000; 6,000,000 (CAL position) r/min.

MAXIMUM RESOLUTION: 6 r/min.

10531A FILTER KIT

GENERAL: Consists of three plug-in low pass filters. Cutoff frequency is adjusted by changing four resistors in the filter circuit. These resistors are assembled on smaller boards that plug in on the filter boards.

FREQUENCY RANGE: The upper cutoff frequency can be adjusted from 100 Hz to 1 MHz, using three filter boards with ranges of 100Hz to 10 kHz, 10 kHz to 100 kHz, and 100 kHz to 1 MHz. The lower cutoff frequency will vary up to 10 Hz, depending on the external load resistance used with the filter.

CARRIER REJECTION: With the output filter the carrier and its harmonics are less than 30 mV rms total when the filter cutoff is less than 15% of the carrier frequency and drops to 1.0 mV maximum for filter cutoff frequency less than 5% of the carrier frequency.

OUTPUT IMPEDANCE: The nominal output impedance of the filter is 600Ω. However, matched loads are not required. The low frequency cutoff of the filter with a 100Ω load is less than 6 Hz and less than 3 Hz with a 1 kΩ load.

OUTPUT LEVEL: Zero to full scale deviations give 1 V open circuit at discriminator output.

TEMPERATURE: 0°C to +55°C.

ALL OTHER 5210 SPECIFICATIONS ARE NOT AFFECTED BY USE OF OUTPUT FILTER.

PRICES: 5210A, $575; Option 01, add $125. 5210B, $570. 10531A Filter Kit, $175.

MANUFACTURING DIVISION:
-hp- Frequency and Time Division
1501 Page Mill Road
Palo Alto, California 94304

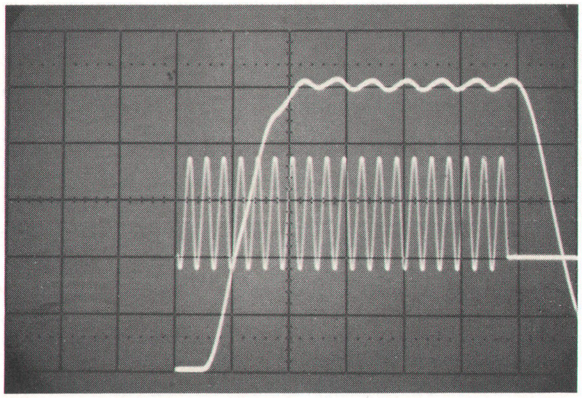


Fig. 10. *Oscillogram showing burst-frequency measurement to 4% accuracy. Number of cycles needed is 6.3, one more than that shown in Fig. 9 because of one-cycle delay in divide-by-two multivibrator.*

choosing a step on a precision current divider equal to 0.1, 0.2, etc. of the full scale current, the user can suppress the zero of the output to each of these points. The current remaining at the output is the difference between the calibrated offset current and the discriminator output. This current is expanded ten times and applied to the meter and outputs, resulting in a ten-fold increase in resolution. All errors in this circuit result in an absolute error of ±0.2% of full scale (0.3% on the 10 MHz range).

Before concluding the discussion of long-term frequency measurements a few comments on the new taut-band meter are in order. The meter is a specially developed movement with a log-linear characteristic. From 10% of full scale to full scale the meter movement is essentially logarithmic, and from 0 to 10% of full scale it is approximately linear. The advantage of the log function movement is its constant percent-of-reading error (in this case 1%). Compared to a 1%-of-full-scale movement, the log-linear movement has better accuracy and a wider dynamic range of operation. Linear movements typically have ranges in ratios of $\sqrt{10}$, but because the log-linear movement maintains its 1% accuracy over a full 10:1 range, there is no need for these additional ranges. In use this meter yields more realistic readings than a linear meter since its resolution is about equal to its accuracy, rather than exceeding the accuracy as it does in linear movements.

Acknowledgments

I wish to acknowledge the contribution of Gaylen T. Grover, who was responsible for the mechanical design and packaging of the new frequency meter/discriminator. Also noteworthy were the efforts of the precision components group of the *-hp-* Loveland Division, in particular those of Dale M. Jones and Woldemar Bartz, in developing the special meter movement. ■

—Peter R. Roth

Peter R. Roth

Before joining *-hp-* in January of 1965, Peter Roth was an engineering officer in the U. S. Coast Guard for three years. Assigned to the Coast Guard's electronics laboratory in Alexandria, Virginia, he worked on high-frequency communications and on Loran A and Loran C equipment design. At *-hp-*, Peter has been responsible for development of the 5210A Frequency Meter.

Peter received his BS and MS degrees in electrical engineering from Stanford University in 1959 and 1961. He is a member of IEEE and Tau Beta Pi.

Phase Noise and Phase Modulation Measurements with the Analog Frequency Meter

IN MAKING PHASE MEASUREMENTS on phase-modulation and phase-lock systems, it is frequently the case that the steady-state value of the phase is of little interest. This is nearly always true in PM systems, since the term 'modulation' means that the phase of the carrier is being varied and, hence, the time derivative of the phase, $\frac{d\theta}{dt}$, is not zero. In phase lock loops, the dynamic behavior of the system $\left(\frac{d\theta}{dt} \neq 0\right)$ is usually of more interest than the steady-state error of the loop.

When $\frac{d\theta}{dt}$ is not zero, there is a deviation of the carrier frequency from some nominal value, and this change in frequency can be measured using the FM discriminator output of the analog frequency meter described in the preceding article. This frequency information can readily be converted to phase information. In fact, the method described here for using the new instrument to obtain phase information has distinct advantages over conventional phase detectors. First, the method does not require coherent, phase-locked reference signals, which are frequently unobtainable anyway. Second, unlike balanced mixers and other devices of this type, phase measurements with the analog frequency meter/FM discriminator are linear, not just an approximation to a linear function for low phase deviations.

Obtaining Phase Information from the Discriminator Output

Consider a carrier with phase modulation or phase noise. This carrier can be described for most modulation signals both random and non-random as a Fourier series

$$S(t) = \cos\theta \quad (1)$$

where

$$\theta = 2\pi f_c t + \sum_{n=1}^{\infty} a_n \sin 2\pi f_n t + \sum_{n=1}^{\infty} b_n \cos 2\pi f_n t \quad (2)$$

The frequency of such a signal is

$$f(t) = \frac{1}{2\pi}\frac{d\theta}{dt} = f_c + \sum_{n=1}^{\infty} a_n f_n \cos 2\pi f_n t - \sum_{n=1}^{\infty} b_n f_n \sin 2\pi f_n t. \quad (3)$$

At the discriminator output of the analog frequency meter, the output voltage exclusive of carrier-frequency components, i.e., the output voltage with an appropriate low-pass filter installed, is

$$V_D(t) = -\frac{f(t)}{f_{FS}} \text{ volts} \quad (4)$$

where f_{FS} is the full-scale range factor in Hz/V (e.g., if the RANGE switch is set to 10 MHz, f_{FS} is 10 MHz/V, since $V_D = -1$ V for an input frequency equal to the range setting).

The discriminator output for a PM signal is then, from equations (3) and (4),

$$V_D(t) = \frac{f_c}{f_{FS}} + \sum_{n=1}^{\infty} \frac{a_n f_n}{f_{FS}} \cos 2\pi f_n t - \sum_{n=1}^{\infty} \frac{b_n f_n}{f_{FS}} \sin 2\pi f_n t \quad (5)$$

The dc term $\frac{f_c}{f_{FS}}$ represents the input carrier frequency.

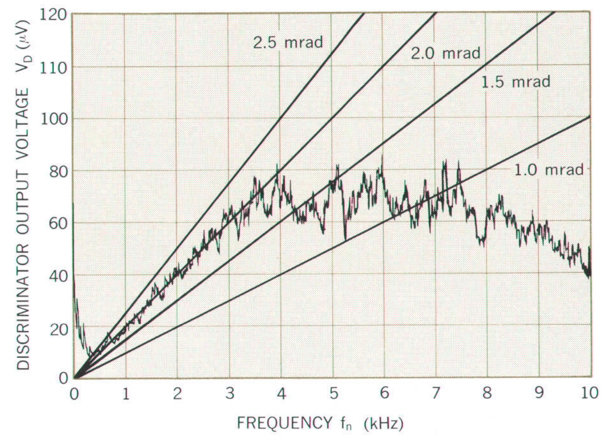


Fig. 1. *Model 5210A discriminator output voltage versus frequency, including lines of constant phase deviation. This kind of plot is useful for measuring phase modulation and phase noise. Setup was Fig. 2. See text for theory.*

The amplitude of any sinusoidal component (e.g., at frequency f_n) of the phase variation of the input carrier can be described as

$$\sqrt{a_n^2 + b_n^2} = \Delta\theta_n = \frac{f_{FS}}{f_n} V_{Dn} \text{ radians,} \quad (6)$$

where V_{Dn} is the amplitude of the component of the discriminator output voltage having frequency f_n.

The output voltage from the discriminator $V_D(t)$ can be processed in two ways to yield the value of phase deviation. First, it could be passed through a differentiator such as a high-pass filter whose response is f, i.e., a single pole RC filter in the stop band. The difficulty with this procedure is that the amplitude of the signal out of the filter soon falls below a level at which it is easily measured. A more satisfactory technique is to plot the discriminator output directly as a function of frequency and then to draw lines of constant phase deviation on the plot according to

$$V_{Dn} = \frac{\Delta\theta_n}{f_{FS}} \cdot f_n \quad (7)$$

An example of such a plot is shown in Fig. 1. As equation (7) shows, the amplitude of the discriminator output voltage at any frequency f_n is directly proportional to f_n as long as the phase deviation and the range factor are constant. Hence, in Fig. 1, which is a plot of V_{Dn} versus frequency, lines of constant phase deviation are straight lines radiating from the origin. The phase deviation at any frequency can be read directly from the plot, or V_{Dn} and f_n can be read from the plot and $\Delta\theta_n$ calculated using equations (6) and (7).

Fig. 1 is the result of a phase noise measurement on a 10-MHz carrier in a 1-GHz phase-lock loop. The setup is shown in Fig. 2. The measurement was made at 100 kHz by mixing the carrier with a 10.1 MHz stable carrier. Mixing does not affect the calibration of the system, since the component of the phase deviation of the carrier at frequency f_n is

$$\Delta\theta_n = \frac{\Delta f_n}{f_n},$$

where Δf_n is the component of the frequency deviation of the carrier at a modulation frequency f_n. Since neither Δf_n or f_n is changed by mixing, there is no correction to be made in the result if the measurement is made at 100 kHz instead of 10 MHz. In fact, using a lower range setting increases the sensitivity of the measurement, as the next section explains.

Sensitivity

Three types of noise limit the sensitivity of the method of phase noise and PM measurements just described.

1. Input noise. This may be either additive noise superimposed on the signal or noise added by the input amplifier of the frequency meter. Assuming that the noise is small compared to the signal, the frequency deviation of the signal caused by the noise component at frequency f_n is, after limiting,

$$\Delta f_n = f_n \cdot \frac{A_n}{A_s}$$

where A_n and A_s are the rms amplitudes of the noise component and signal, respectively. Notice that the effect of the noise is reduced by the factor $1/A_s$. Because of this reduction, input noise (especially that from the input amplifier) is usually negligible in comparison with other noise sources, although noise superimposed on the input signal may be significant if large enough.

2. Jitter in the pulse-discriminator trigger circuits. This type of phase noise is not a problem in the new instrument. Measurements have shown that this noise is completely masked by the other noise sources.

3. Output noise. This may be additive noise due to the output filters, or noise in whatever device is used to measure the discriminator output voltage. The plug-in output filters are active filters, and the noise generated by them is most noticeable at lower frequencies (1/f noise).

Fig. 3 gives typical limits on the sensitivity of the analog-frequency-meter method of measuring phase. These are the limits generally imposed by output filter noise. Additive noise supplied with the input signal can degrade this performance. Notice that the ultimate phase sensitivity (see equation 7) depends upon the range factor f_{FS} and may be improved by mixing the signal down to a lower frequency. For example the output phase-noise level on the 100 kHz range at a noise frequency of 1 kHz is 1.4×10^{-4} radians, whereas the same noise level on the 10 kHz range is only 1.4×10^{-6} radians. This technique of mixing down is limited by the requirement that the carrier frequency be several times the highest modulation frequency. Normally, the carrier frequency should not be mixed down so far that it is less than 10 times the highest modulation frequency to be measured. ■

—*Peter R. Roth*

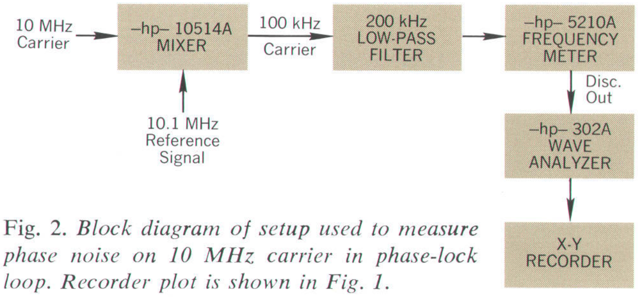


Fig. 2. *Block diagram of setup used to measure phase noise on 10 MHz carrier in phase-lock loop. Recorder plot is shown in Fig. 1.*

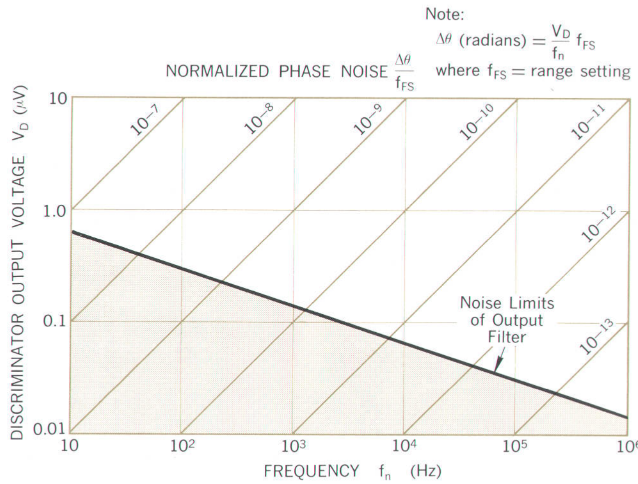


Fig. 3. *Typical noise levels on discriminator output of Model 5210A Frequency Meter. Noise, due principally to output low-pass filters, limits sensitivity of instrument in phase noise measurements. Measurements are accurate as long as V_D at each frequency is above noise level, i.e., in white area of graph. To find phase noise at frequency f_n, interpolate between light lines at point on heavy line corresponding to f_n. For example, $\Delta\theta$ (rms phase noise) for $f_n = 1$ kHz is $1.4 \times 10^{-10} \times f_{FS}$, where f_{FS} is setting of RANGE control.*

HEWLETT-PACKARD JOURNAL hp MARCH 1967 Volume 18 • Number 7

TECHNICAL INFORMATION FROM THE LABORATORIES OF THE HEWLETT-PACKARD COMPANY
PUBLISHED AT 1501 PAGE MILL ROAD, PALO ALTO, CALIFORNIA 94304
Editorial Staff: F. J. BURKHARD, R. P. DOLAN, L. D. SHERGALIS, R. H. SNYDER Art Director: R. A. ERICKSON