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EXPLORING IN AEROSPACE ROCKETRY
16. ELEMENTS OF COMPUTERS

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Presented to Lewis Aerospace Explorers
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1966-67

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16. ELEMENTS OF COMPUTERS

Robert L. Miller*

Aids to computation are quite old, and evidence of them can be found in ancient history. The earliest aids were the fingers. Then groups of small objects such as pebbles were used loosely. Eventually, beads were strung on wires fixed in a frame; this became known as the abacus.

The abacus most likely originated in the Tigris-Euphrates valley and its use traveled both east and west along the routes of the caravans. Elaboration of the instrument and later development of the techniques of its manipulation made it applicable to multiplication, division, and even to the extraction of square and cube roots, as well as to addition and subtraction for which the instrument was probably originally intended. The abacus, despite its ancient origin, is still in use by the Oriental peoples.

After the invention of the abacus, 5000 years elapsed before the next computational aid was developed. During this time, gears and printers were used in the design of clocks. These machine elements paved the way for the development of calculating machinery.

Chapter 15 considered the techniques for measuring the physical quantities associated with testing rockets. Some of these physical quantities (thrust, pressure, and temperature) are converted to electrical signals by transducers such as strain gages and thermocouples. In order to solve equations with a computer whose inputs are introduced automatically, it is necessary to have each of the elements of the equation in the form required by the input to the computer, such as voltage. At this point, therefore, it becomes important to select the computer. This will be determined by the computations that need to be made, the accuracies required, and the form that the answers will take after the computations are made. An examination of the characteristics of the two basic types of computers, analog and digital, will reveal which would best fit the computing requirements of rocket testing.

ANALOG COMPUTER

In 1617, John Napier, following his invention of logarithms, published an account of his numbering rods, known as Napier's bones. Various forms of the bones appeared, some approaching the beginning of mechanical computation. Following the acceptance of

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logarithms, Oughtred (1630) developed the slide rule, and it received wide recognition by scientists before 1700. Everard (1755), Mannheim (1850), and others continued to improve it. Useful in solving simple problems which require an accuracy of only three or four significant figures, the slide rule is probably the ancestor of all those calculating devices whose operation is based on an analogy between numbers and physical magnitudes. Many such analogy devices, such as the planimeter, the integraph, and the differential analyzer have since been constructed. All analogy devices like the slide rule are limited to the accuracy of a physical measurement.

Many of the problems encountered in rocket testing are time dependent. Pressures and temperatures vary rapidly with time and so, therefore, does performance. This is particularly true in the startup and shutdown phases of operation. Any instabilities that occur are also time related. For computations that are performed on time-dependent measurements to be useful they must either be made at very short time intervals or must be continuous.

The analog computer can perform continuous calculations in either expanded, real, or compressed time.

Chapter 15 gave the method by which a typical rocket performance equation can be solved in terms of measured quantities:

$$I_{sp} = \frac{F}{\dot{W}} = \frac{F}{\rho_F \dot{V}_F + \rho_O \dot{V}_O} \tag{1}$$

where

I_{sp} specific impulse

F thrust, measured by a load cell

ρ_F fuel density

$\dot{V}_F$ volume flow rate of fuel (e.g., gal/min)

ρ_O oxidizer density

$\dot{V}_O$ volume flow rate of oxidizer

All of these variables can be measured directly during a test with the exception of the densities. The density of a liquid is essentially proportional to temperature and can be represented by

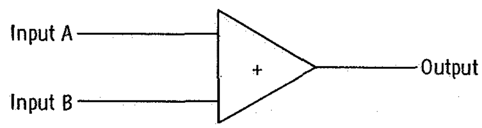
$$\rho = kT \tag{2}$$

where k is a constant, and T is the temperature of the liquid, which can be measured. Equation (1) now becomes

$$I_{sp} = \frac{F}{kT_F\dot{V}_F + kT_O\dot{V}_O} \tag{3}$$

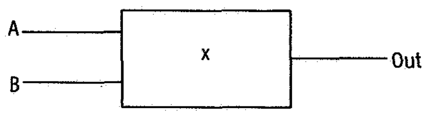
Measuring the temperature and volume flow rate of both the fuel and oxidizer, along with the thrust, enables calculation of the specific impulse I_{sp}.

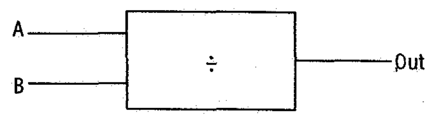
The analog computer is ideal for this problem because it can compute continuously in real time using several variables. The computer contains components which perform the basic arithmetic functions of addition, subtraction, multiplication, and division. The inputs and outputs of these components are voltages. A summing amplifier has two inputs and one output:



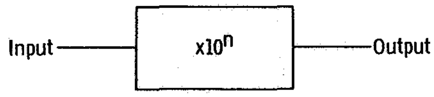
If a signal of 2 volts is received at input A and 3 volts at input B, the summing amplifier produces an output of 5 volts.

Other components are multipliers and dividers:

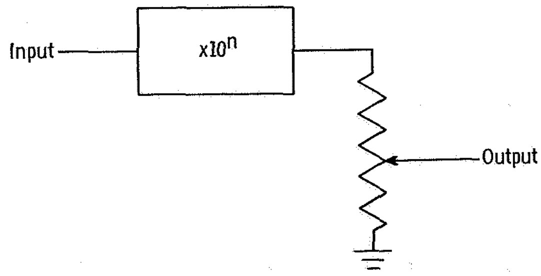




Another basic component is an amplifier which multiplies by a power of 10:



Multiplication by a constant other than a power of 10 can be accomplished by adding a potentiometer to the preceding component:



The effect of the potentiometer is to multiply by a number less than 1.

Equation (3) can be solved by interconnecting these basic components as instructed by the equation and introducing the signals directly from the transducers on the rocket. Note that all signals are multiplied by 1000 to make them large enough to be resolved by the computer (fig. 16-1).

$$I_{sp} = \frac{F}{kT_F\dot{V}_F + kT_O\dot{V}_O}$$

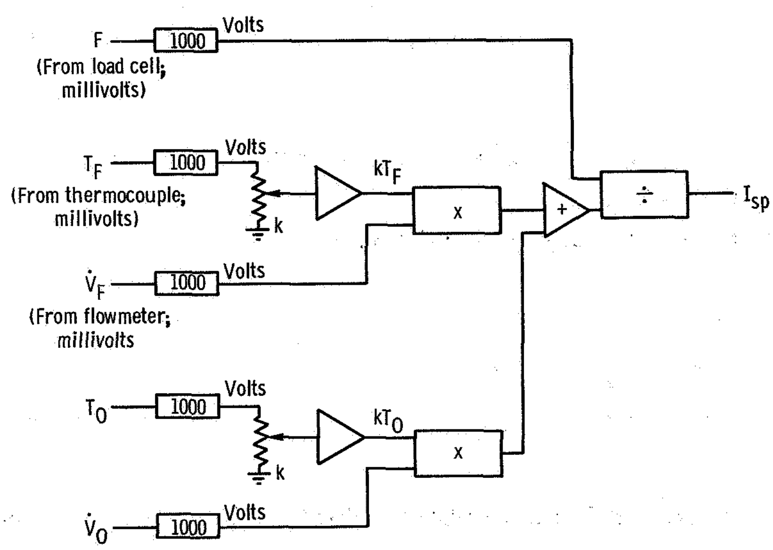


Figure 16-1. - Analog setup for specific impulse calculation.

The answer to the computation is a voltage representing the specific impulse as a function of time. This could be read from a voltmeter, but the usual method of presentation is an oscilloscope or graphical plotter. If the plotter is adjusted to compensate for the electrical characteristics of the transducers, the amplification of the voltages through each stage of the computer, and the sensitivity of the plotter, specific impulse can be read directly in seconds.

The analog computer has many other components which perform mathematical functions more complex than generating voltage proportional to time. They are used in the electrical simulation of physical problems; for example, they enable the engineer to investigate mechanical motion without having the mechanical device present.

DIGITAL COMPUTER

The digital computer differs from the analog in the fact that internally it operates with digits, rather than with voltages proportional to the numbers.

The electronic digital computer evolved from the mechanical adding machine and in many respects still maintains some of its basic characteristics. Like the adding machine, its input must be in the form of digits. Unfortunately, it cannot use the decimal digit system efficiently because of the many symbols used for each digit. The computer

TABLE 16-I. - BINARY NUMBERS AND THEIR DECIMAL EQUIVALENTS UP TO 49

Decimal		Binary					Decimal		Binary					
Decimal weight							Decimal weight							
10	1	16	8	4	2	1	10	1	32	16	8	4	2	1
	0					0	2	5		1	1	0	0	1
	1					1	2	6		1	1	0	1	0
	2				1	0	2	7		1	1	0	1	1
	3				1	1	2	8		1	1	1	0	0
	4			1	0	0	2	9		1	1	1	0	1
	5			1	0	1	3	0		1	1	1	1	0
	6			1	1	0	3	1		1	1	1	1	1
	7			1	1	1	3	2	1	0	0	0	0	0
	8		1	0	0	0	3	3	1	0	0	0	0	1
	9		1	0	0	1	3	4	1	0	0	0	1	0
1	0		1	0	1	0	3	5	1	0	0	0	1	1
1	1		1	0	1	1	3	6	1	0	0	1	0	0
1	2		1	1	0	0	3	7	1	0	0	1	0	1
1	3		1	1	0	1	3	8	1	0	0	1	1	0
1	4		1	1	1	0	3	9	1	0	0	1	1	1
1	5		1	1	1	1	4	0	1	0	1	0	0	0
1	6	1	0	0	0	0	4	1	1	0	1	0	0	1
1	7	1	0	0	0	1	4	2	1	0	1	0	1	0
1	8	1	0	0	1	0	4	3	1	0	1	0	1	1
1	9	1	0	0	1	1	4	4	1	0	1	1	0	0
2	0	1	0	1	0	0	4	5	1	0	1	1	0	1
2	1	1	0	1	0	1	4	6	1	0	1	1	1	0
2	2	1	0	1	1	0	4	7	1	0	1	1	1	1
2	3	1	0	1	1	1	4	8	1	1	0	0	0	0
2	4	1	1	0	0	0	4	9	1	1	0	0	0	1

works much better using the binary system in which only two different symbols are used for each digit. This corresponds to a circuit which is either conducting or not conducting, a relay that either is energized or is not energized, or a card with a hole punched or not punched. The binary digit is called a "bit," and the two possible states of this bit are represented by the symbols 0 and 1.

Since humans use the decimal system, it is necessary to convert from decimal to binary when using computers. Table 16-I shows the relation between binary numbers and their decimal equivalents up to 49.

The problem now arises of compatibility between the output of the measuring devices, or transducers, and the digital computer. The transducer output is continuous in millivolts, while the digital computer must have binary digits. To solve this problem an analog-to-digital (A-D) converter is used between the transducer and computer. This device, upon command, will convert a millivolt signal at its input into bits. The number of bits basically limits the resolution or accuracy of the measurement. Devices in use presently have 12 or 13 bits and attain a resolution of 1/4096. At each command, the millivolt input is converted into a 13-bit number.

Another problem arises because the digital computer can only accept one binary number or transducer output at a time; the problem is the need for sequentially connecting the transducer outputs to the A-D converter. A device known as a scanner, or multiplexer, is used for this sequencing. Shown in figure 16-2 are the components of a data system used to switch the analog signals from several transducers into an analog-to-digital converter for entry into a digital computer.

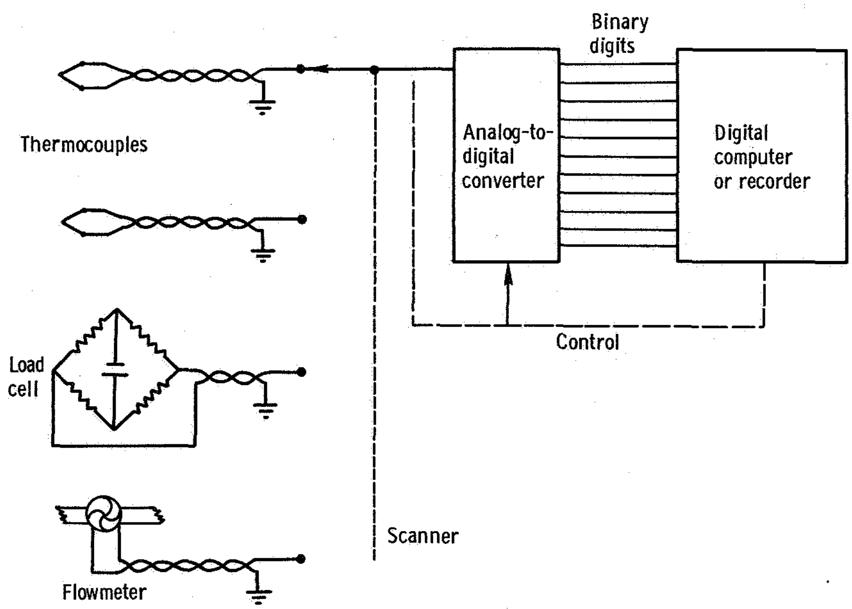


Figure 16-2. - Typical data system.

The scanner and analog-to-digital converter, along with the controls, are usually built into a data system which may or may not be connected directly to the computer. If it is not, the bits are recorded by the data system on either magnetic or paper tape for later entry into the computer.

Once the transducer signals have been sequentially converted to digital form, what happens inside a basic digital computer is block diagrammed in figure 16-3.

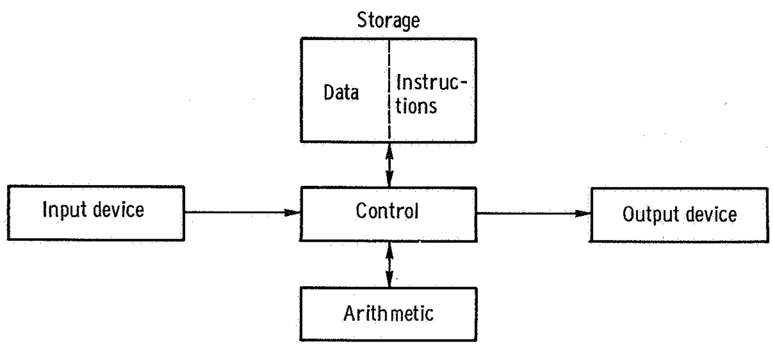


Figure 16-3. - Basic digital computer.

A simple computer, for which the input device is a punched card reader and the output device is an electric typewriter, must receive two kinds of information in order to carry out a computation. It must have numbers or data to use in the computation and instructions concerning what to do with the data. Much as the analog computer was programmed step by step to perform a complex computation, so is the digital machine instructed in simple, sequential steps. For example, if told to add A+B the computer will do so.

Rather than rely on the input device to supply each of the numbers and instructions as they are required, these are placed in the block marked Storage (fig. 16-3). All of the numbers and instructions necessary to solve a complex problem are held in Storage in a known, orderly manner. Control takes data and instruction numbers from the input device and places them in Storage. When all data and instruction are in Storage, the problem is started. Control sends data to Arithmetic and controls the operation to be performed there according to the basic instruction of add, subtract, multiply, and divide. The answer is held in Arithmetic for the next instruction. The instructions necessary to solve a problem are sequentially extracted from Storage by Control. Control executes the instructions by transferring data from Storage to Arithmetic and back. This continues until the problem is solved, at which time the final answers are sent to the output device for printing.

The series of instructions necessary to solve $X = \frac{B + C}{D}$ begins after the data B, C, and D have been loaded in storage at locations much like slots in a file cabinet. Each slot, which can hold a number, has an address:

Address	Contents
1	B
2	C
3	D

The symbol 1 means the address 1, whereas the symbol (1) means the contents of address 1, or B. Similarly, A means the arithmetic section while (A) means the contents of that location.

The instructions necessary to solve for X would be as follows:

Instruction	Contents of A after operation
Send (1) to A	B
Add (2) to (A)	B + C
Divide (A) by (3)	$\frac{B + C}{D}$
Print (A)	Zero

Returning to the rocket problem, the equation for specific impulse is

$$I_{sp} = \frac{F}{k\dot{V}_F T_F + k\dot{V}_O T_O}$$

Assume that the data to solve this equation are loaded into the storage at the following locations:

Address	Contents
1	k
2	$\dot{V}_F$
3	T_F
4	$\dot{V}_O$
5	T_O
6	F
7	Empty

The instructions necessary to solve the equation would be as follows:

Instruction	Contents of A after operation
Send (1) to A	k
Multiply (2) by (A)	$k\dot{V}_F$
Multiply (3) by (A)	$k\dot{V}_F T_F$
Send (A) to 7	Zero
Send (1) to A	k
Multiply (4) by (A)	$k\dot{V}_O$
Multiply (5) by (A)	$k\dot{V}_O T_O$
Add (7) to (A)	$k\dot{V}_F T_F + k\dot{V}_O T_O$
Send (A) to 7	Zero
Send (6) to A	F
Divide (A) by (7)	$\dfrac{F}{k\dot{V}_F T_F + k\dot{V}_O T_O}$
Print (A)	Zero

In a typical situation the instructions necessary to carry out this computation would enter the computer on punched cards through a card reader similar to the one shown in figure 16-4. The data might come directly from an analog-to-digital converter in the

Figure 16-4. - Card reader-punch.

data system or from a magnetic tape recorded by the data system. Figure 16-5 shows magnetic tape units capable of reading or writing 80 000 bits per second.

The instructions, of course, are much more complex and there are many more measurements and computations than have been considered here. Together, the instructions are called the program for the test. Composing or writing the program for a test is a very complex job and is usually done by a mathematician.

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Figure 16-5. - Magnetic tape units.

Output from the computer may be listed in decimal form by a high speed line printer (fig. 16-6). This printer can print up to 2500 decimal digits per second.

If graphical output is a more desirable presentation, the plotter shown in figure 16-7 may be used. Its input is from a magnetic tape prepared by the computer.

Figure 16-6. - High-speed line printer.

Figure 16-7. - Graph plotter and magnetic tape unit.

SELECTION OF COMPUTER

Either the analog or digital computer can be used to perform a typical computation in the study of rocket performance. Each machine has characteristics which either make it desirable or limit its capabilities for a particular job.

In summary, the analog computer can operate in real time and provide immediate continuous plots of computed results. Accuracy is about 99 percent on the average, and about 10 variables can be handled simultaneously.

The digital computer generally does not operate in real time, but it can perform much more complex calculations than the analog. It also has the advantage of a stored program giving increased flexibility in computations to be performed. And finally, the number of variables is unlimited, while their individual accuracies are limited only by the number of bits representing the variable.

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