Analog/hybrid—What it was, what it is, what it may be

by ARTHUR I. RUBIN

Electronic Associates, Inc.
Princeton, New Jersey

THE ZEROTH GENERATION

Introduction

The history of the analog computer goes back to antiquity, where tax maps were first reported being used for assessments and surveying. However, I shall confine this paper to the analog computer as it evolved from World War II to the present time. For those interested in the history of the analog computer, from antiquity to World War II, I refer the reader to an excellent introductory article by J. Roedel, Reference 1. The "Palimpsest" in which Roedel's history of the analog computing art is included is in itself an excellent history of analog computers in the early days dating from World War II to about 1954. From page 4 of the Palimpsest, I would like to show a diagram of computing devices as visualized by George Philbrick for an article in Industrial Laboratories in May, 1952. Of interest to us in this diagram on the analog side, is the separation, at the bottom, between *fast* and *slow analog* which I will discuss shortly. We will also note the presence of *hybrid* at the very top, and this article was written in 1952! Of course, Mr. Philbrick's "hybrid" was reserved for the use of the analog computer first to obtain a ball-park idea of a solution, then followed by a separate digital solution to obtain a more accurate answer to the same problem. I am certain that very few people thought of this as being hybrid computation at the time. However, consider this definition in the light of later work reported by Mark Connelly (Reference 2) in his use of a "skeleton" representation of a problem on the analog in conjunction with a more accurate representation of the problem on the digital.

It is interesting to observe the basic operations as defined by Roedel in Reference 1. This is shown in Figure 2. Note that the early practitioners of the analog art considered differentiation to be a basic linear element for the fast speed computers and did not show potentiometers, since the latter must have been taken for granted. Furthermore, an arbitrary function generator was also not shown. Apparently, that device, which is necessary to make analog computation capable of solving any problem, was developed later or was considered an oddball, along with the comparator (which is really represented by the dry friction element, provided that the output of the dry friction element is

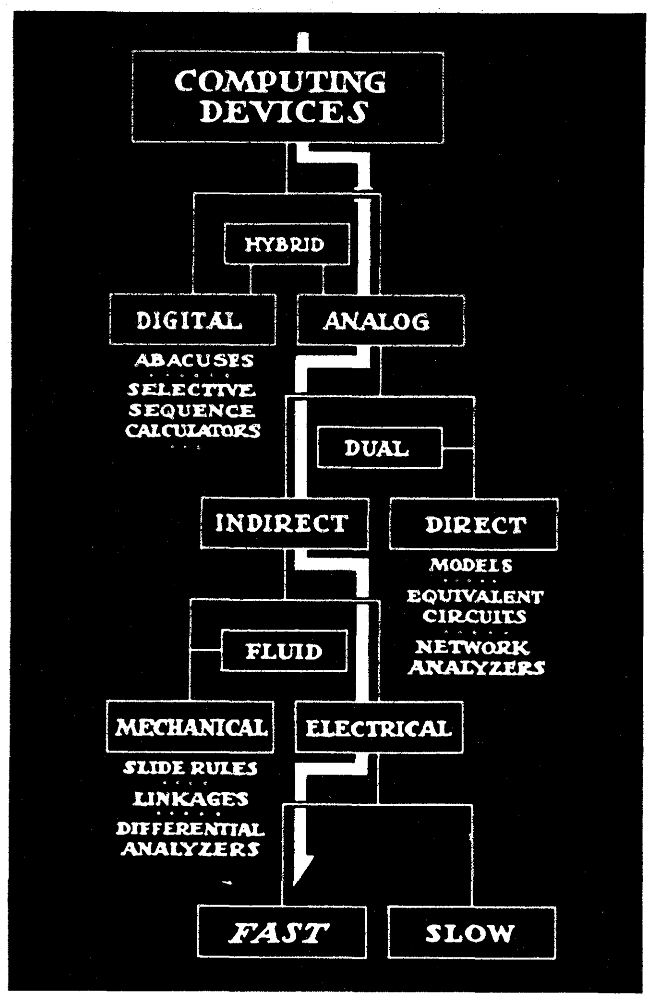

Figure 1—Structure of computing devices as visualized in 1952

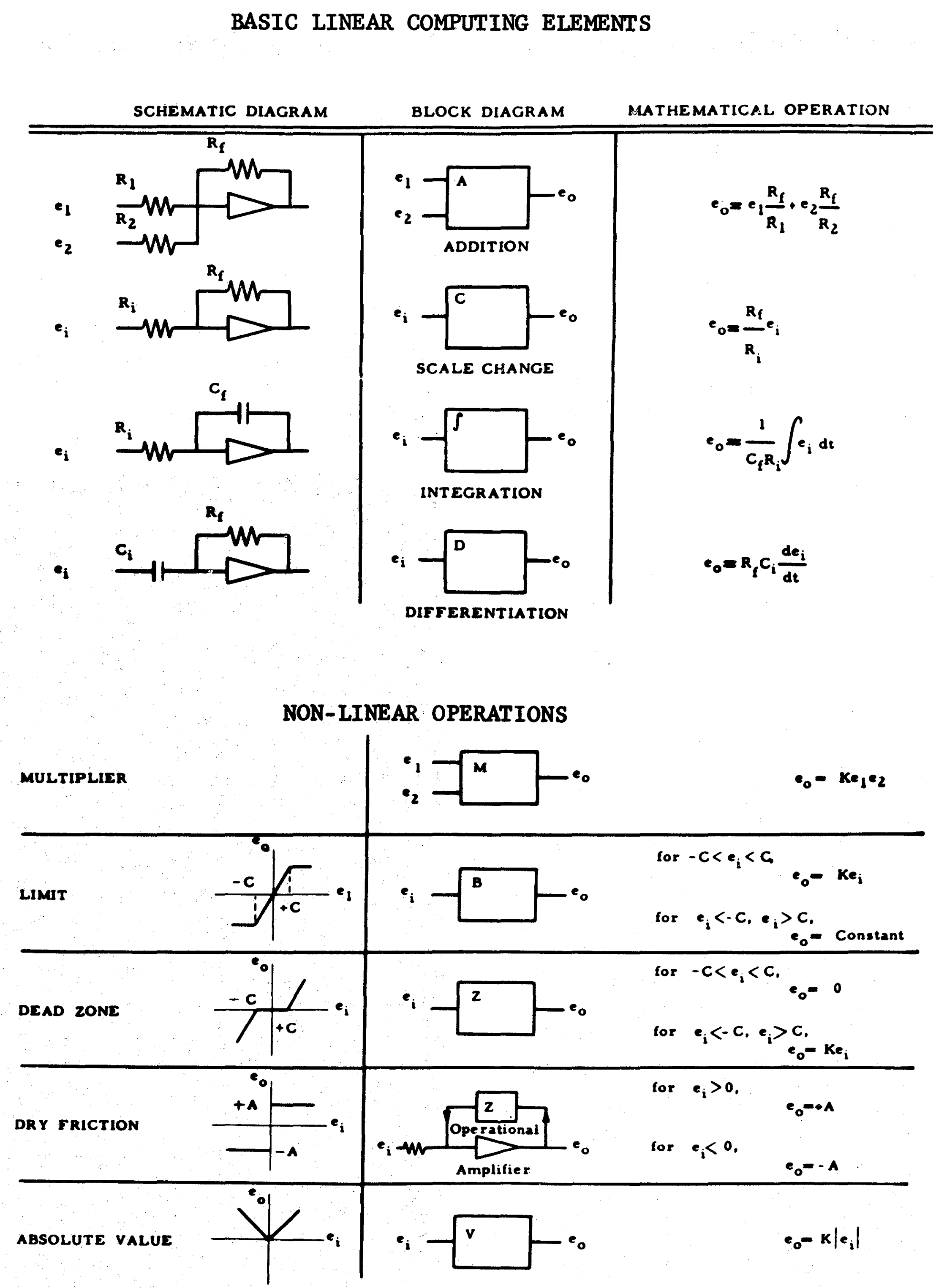

Figure 2—Basic linear and non-linear analog operation and components

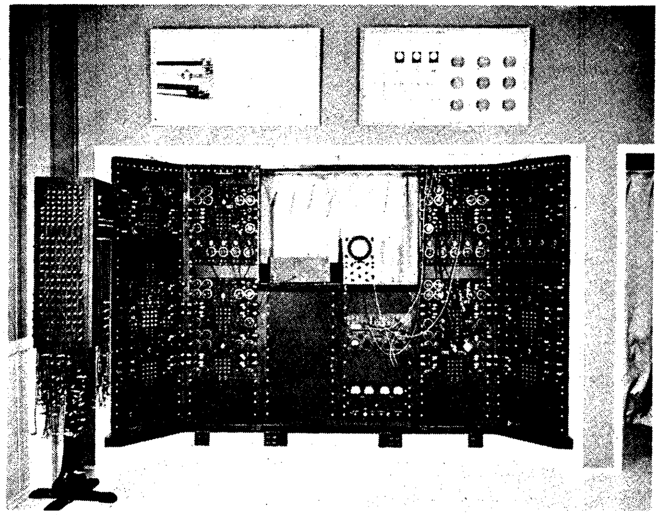

Figure 3—Pullman-Standard Car Manufacturing Company's analog computer installation

used to drive a switch or a gate connected to some other computing element). There was a great deal of emphasis in those days on the solution of linear differential equations, obviously because those required the simplest computing components. Perhaps also, because one could obtain check solutions to such equations with pencil and paper, and computers, being relatively new, could not yet be trusted.

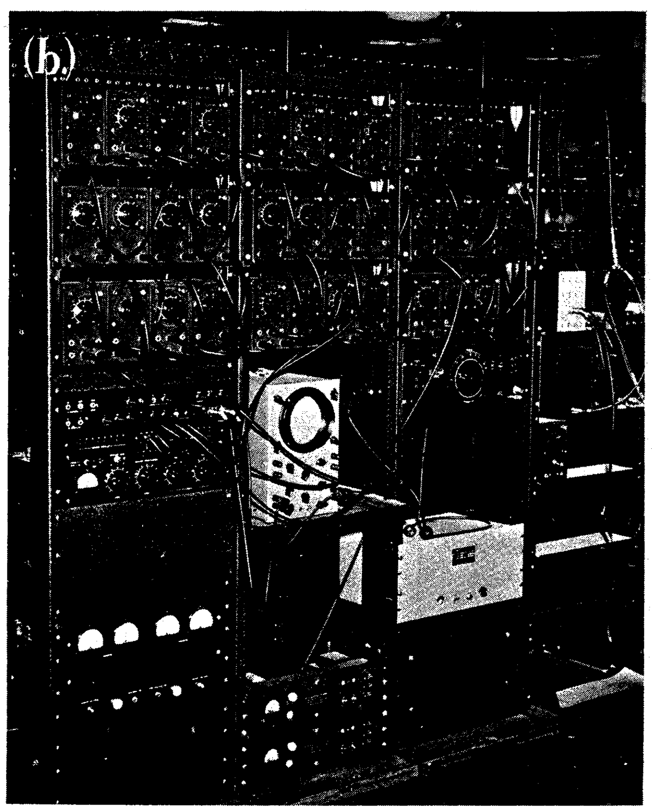

Figure 4—Computing equipment in a typical rack assembly

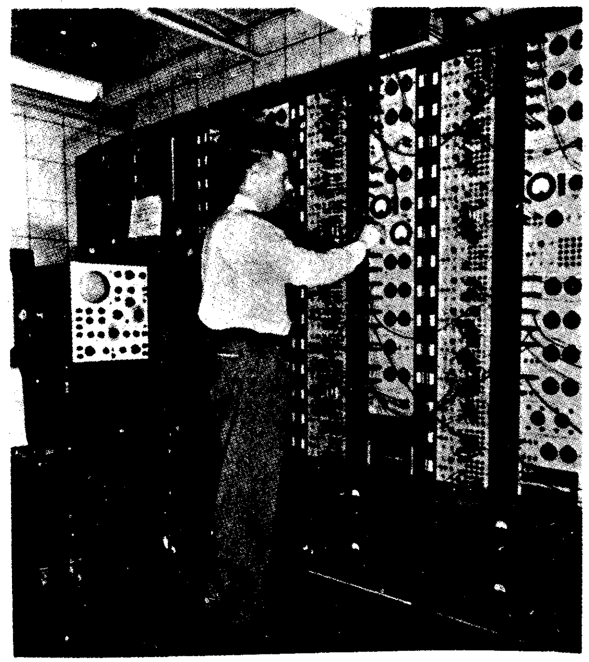

Figure 5—Boeing analog computer, courtesy of Boeing Airplane Co.

Hardware

The major manufacturers during this initial period were the Boeing Company which made the BEAC computer, the Berkeley Scientific Computing Company which made the EASE computer (Berkeley subsequently became part of Beckman Instruments), the Goodyear Aircraft Company which made the GEDA, the IDA computer with which I am not familiar at all, the George A. Philbrick Research Company which made the GAP/R computer, and finally, there was the Reeves Instrument Company which made the REAC computer. Some pictures of these early analog computers are shown in Figures 3 through 8. Figure 3 shows a GAP/R installation while Figure 4 shows a close-up of how those computing components were interconnected. You will note an absence of a patchboard. Can you imagine checking this one out today?

Note the telephone jack panels on the Reeves computer and note also that the Berkeley and the Goodyear computers are the first ones with patch panels. These figures date from about 1952 or 1953. EAI, which was just beginning to build analog computers, does not even show. The typical size of computers in those days ranged from about 20 amplifiers up to 80

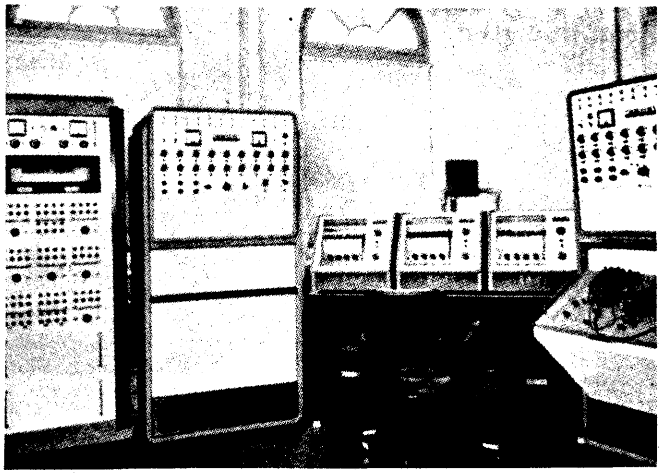

Figure 6—Goodyear GEDA computer installation, courtesy of Goodyear Aircraft Company, Akron, Ohio

amplifiers, which was considered to be fairly large. One manager, in fact, was proud of the fact that he could expand his 80 amplifier installation to 160 without requiring any additional wiring. The accuracy of the components was of the order of one percent (and that applied to resistors and capacitors as well as to the electrical components). Overall solution accuracies on what was then considered medium size non-linear problems was of the order of five percent. One final point of interest is that several of these manufacturers, mainly Boeing, Goodyear, and Reeves were primarily aerospace/defense manufacturers who saw the obvious need for such devices in the design of their own equipment, whether it was airplanes, electronic gear such as radars, or control systems. Philbrick, on the other hand, and possibly also the Berkeley Company, concentrated from the very beginning on the process control applications.

Applications

The 2nd page of the table of contents of the Palimpsest is reproduced here in Figure 9 and shows the wide variety of applications that were actively investigated in the early 1950's. You will note in particular the beginnings of an analytical attack on our environmental problems in the papers on the freezing and thawing of soils as well as flood routing. The analog equipment, especially that which did not have patch panels was generally purchased for a particular problem or problem type. For example, the Pullman Car Company would buy one for solving their "transportation equipment design" problem. An aircraft manufacturer would buy a computer to study the control system of a particular airplane. There was an almost complete lack of user conveniences leading to the ridiculous situation of being able to obtain a complete, single solution to a complex set of differential equations in 5 milliseconds, but having to wait several days, at least, to change to another problem, due to the lack of a patch panel and other amenities, such as a readout system. This type of inaccessibility (to the "next"

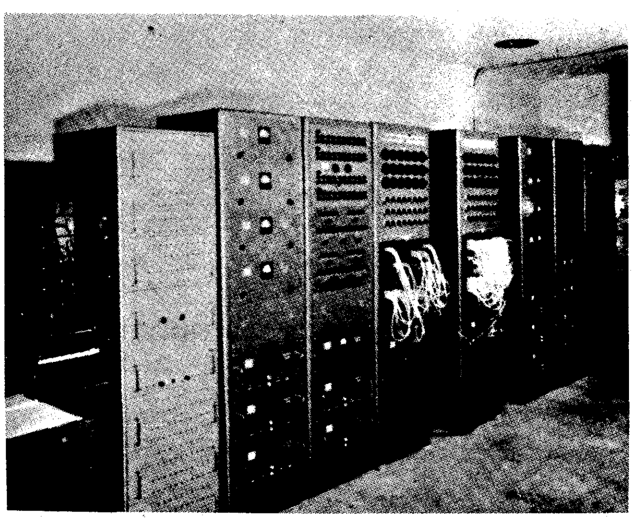

Figure 7—Berkeley EASE computer, courtesy of J. B. RAE, Los Angeles

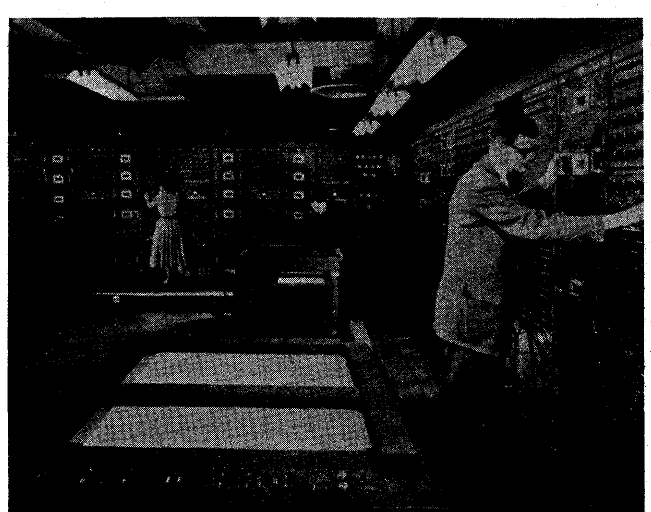

Figure 8—Reeves computer installation, courtesy Reeves Instrument Company

problem) has been at the root core of the ailment in the analog field and has given the analog computer the reputation of being "inflexible." This ailment is still with us, albeit to a much smaller extent, and a cure is visible on the horizon, as we shall see later. For further information on techniques and methods that were expounded in the early years of analog computation, the reader is referred to References 3, 4 and 5. This by and large represents the first generation analog; however, since I seem to have too many generations, as we shall see later, I will term this the heroic age, or the zeroth generation. This generation coexisted with the heroic age digitals, such as the ENIAC, EDVAC, the ORDVAC, MANIAC, and the UNIVAC.

THE FIRST GENERATION

The next generation, here termed the first, more or less coincided with the arrival of EAI on the scene, with its establishment of the firm need for a patch panel and an integrated set-up and readout console as part and parcel of the analog computer. In other words, human factors entered into the picture, also, this generation saw the arrival of the .01 percent component, such as resistors and capacitors, which allowed linear problems to be solved more accurately than the solutions could be displayed on a strip chart recorder, X–Y plotter, or oscilloscope. The credit for this shift in emphasis on more accuracy and more user conveniences must go to the manufacturers who went against the ideas of some of the then old line users, who kept pointing to the problems that were being solved and observing that much of the input data was unknown perhaps even within a factor of two of the correct value. These old time analysts recognized that there was no need for obtaining very accurate solutions to such problems. However, they overlooked the crutch available to the insecure analyst if he can get a repeatable, accurate answer even though the model is not exact. This analyst then has fewer questions from his management, because when he goes back for reruns, he gets the same old answer to compare with at the same time, the solutions for the new set of parameter values. Thus, he and management both think they understand the problem.

(Aside—I learned this trick early in the game. In order to convince my management and customers as to the validity or correctness of a set-up to a problem, I always went back to a "standard" solution, if a check solution was not available. And if the standard or check didn't repeat, then I would hopefully "tune-up" the equipment to produce a "replica" of the check solution. In some cases, I must confess, I may have "de-tuned" the equipment to produce the so-called "check".)

MODELLING of PHYSICAL PROCESSES 146
The Electro-Analogue .... J. M. L. Janssen and L. Ensing 147
Discontinuous Low-Frequency Delay Line with Continuously Variable Delay .... J. M. L. Janssen 162
Bucket-Brigade Time Delay .... G. A. Philbrick 163
Solving Process-Control Problems by Analog Computer .... R. J. Medkeff and H. Matthews 164
ELECTRONIC ANALOG METHODS in DETAIL 167
Precision in High-speed Electronic Differential Analyzers .... H. Bell, Jr., and V. C. Rideout 168
Analog Computer Solution of a Nonlinear Differential Equation .... H. G. Markey and V. C. Rideout 177
The Study of Oscillator Circuits by Analog Computer Methods .... H. Chang, R. C. Lathrop, and V. C. Rideout 184
A Differential-Analyzer Study of Certain Nonlinearly Damped Servomechanisms .... R. C. Caldwell and V. C. Rideout 193
Application of an Analog Computer to Design Problems for Transportation Equipment .... J. Roedel 199
ANALOG STUDIES of ELECTRIC POWER SYSTEM TRANSIENTS 216
Surge and Water Hammer Problems .... H. M. Paynter 217
Methods and Results from MIT Studies in Unsteady Flow .... H. M. Paynter 224
The Analog in Governor Design .... H. M. Paynter 228
Tie Line Power & Frequency Control .... H. M. Paynter 229
Electronic Computer for Resolution of Steady — State Stability Problems and Particularly for Automatic Control Studies .... I. Obradovic 233
How to Select Governor Parameters with Analog Computers .... E. C. Koenig and W. C. Shultz 237
COMPUTER TECHNIQUES in HYDROLOGY 239
Flood Routing by Admittances .... H. M. Paynter 240
ANALOG SOLUTION of THERMAL PROBLEMS 246
Freezing and Thawing of Soils .... H. P. Aldrich, Jr., and H. M. Paynter 247
The Analogue Computer and Automatic Control Applications .... R. J. Bibbero 261
Process Regulation with Analogue Control .... R. J. Bibbero 264
Continuous Electric Representation of Nonlinear Functions of n-Variables .... G. A. Philbrick 266

First printing 1955
Second printing 1958
Third printing 1960
Fourth printing 1965

Figure 9—A portion of the table of contents of the Palimpsest

Conveniences such as a digital volt meter readout of amplifiers and all other components via push-button selectors, servo set pots as well as experiments with quarter-square multipliers and time division multipliers were introduced. The second phase lasted roughly from 1955 to 1960 and saw the rise of EAI from the position of young upstart to that of the major supplier of analog computing equipment. While EAI was rising, the period saw several companies such as Boeing, Goodyear, IDA (or perhaps Mid-Century) drop out of the industry. After these defections from the ranks of the manufacturers, the field of slow speed analogs was split amongst EAI, Berkeley, which by this time had become merged with Beckman, and Reeves Instruments. The high speed analog now had two manufacturers, the old Philbrick Co. and a newcomer to the high speed camp, the GPS Company. This period saw the 31R and the 131R and to lesser extent, the Reeves' C400 gain wide distribution.

1958 NATIONAL SIMULATION CONFERENCE

Clymer, "Operational Analog Simulation of the Viration and Flutter of a Rectangular Multicellular Structure"

Powell, "Distributed Parameter Vibration With Structural Damping and Noise Excitation"

Ladd and Wolf, "A Non-Real-Time Simulation of SAGE Tracking and BOMARC Guidance"

Miller and Enger, "Liquid Transfer and Storage System Simulation by Active Element Computers"

Azgapetian, "Some Aircraft Problems Simulated by Means of Z-forms"

Boxer, "Z-forms, and the Digital Simulation of Dynamics"

Nemerever, "A New Technique in System Performance Evaluation"

Gilbert, "Linear System Approximation by Differential Analyzer Simulation of Orthonormal Approximating Functions"

Brammer, "Solutions of Convolution Integrals by Analog Computers"

Rideout, "Some Applications of a High-Speed Analog Correlator"

Rawdin, "A Time Multiplexing Technique"

Heffron and Bristow, "A Method for Helicopter Rotor Performance Simulation"

Bush and Orlando, "A Perturbation Technique for Analog Computers"

1958 NATIONAL SIMULATION CONFERENCE, continued

Ehlers, "Standard Simulation Circuits"

Gilbert, "The Design of Position and Velocity Servos for Multiplying and Function Generation"

Sinker, "The Card Programmed Diode Function Generator"

Shen, "Multiplier Circuits Utilizing Squaring Property of a Triangular Wave"

Pfeiffer, "A Four Quadrant Multiplier Using Triangular Waves, Diodes, Resistors, and Operational Amplifiers"

Ehlers, "General Purpose DC Analog Computer with Transistor Circuitry"

Pritsker, Buskirk, and Wetherbee, "Simulation to Obtain Systems Measure of Air-Duel Environment"

Billinghurst and Single, "Extending the bandwidth of Precision Analog Systems"

Bekey and Whittier, "Generalized Integration on the Analog Computer"

Bruns, and Wilcher, "Transistorized Relay Amplifier"

Neshyba and Coffman, "Airborne Radar-Beacon Traffic Simulator"

Munson and Rubin, Optimization by Random Search on the Analog Computer"

Schwarm, "Computer Systems for Jet Transport Simulators"

1958 NATIONAL SIMULATION CONFERENCE, continued

Morrison, "APPR-1 Simulator Description"

Meilander and Hellman, "A Technique for Absolute Measurement of Analog Computer Capacitors"

Gerlough, "A Comparison of Techniques for Simulating the Flow of Discrete Objects"

Figure 10—1958 National Simulation Conference

The end of the period saw the introduction of the 231R computer, (See Figure 13) a machine which was to see much service in the '60s.

Applications

The applications of this era (the end of the first generation) perhaps are best described by scanning the list of titles of papers that were presented at the 1958 Fall National Simulation Council Conference (Figure 10). From the list of titles it is clear that the aerospace/defense industry dominated applications, but there were a significant number of papers reporting new mathematical techniques and even applications of digital computers to the field of simulation. New hardware circuits such as the card programmed diode function generator and a quarter square multiplier were first described. Also included were descriptions of a much later transistorized analog, a computer optimization study by analog computers, as well as discrete event simulation by digital computers.

THE SECOND GENERATION

The next generation which I must here call the second, lasted roughly from 1960 to 1965. The size of the analog computer at the upper end was getting physically larger and larger, which by virtue of the vacuum created at the small end led to the design of a small desk-top computer, which was the logical outgrowth of the transitorization of analog components. The first transitorized computers were of the small desk-top type and had a voltage range of plus or minus 10 volts. They coexisted with their big brothers, the 100 volt vacuum tube computer, during this period. Another hardware innovation saw the combining of heretofore separate *fast* and so called *slow* analog into a single machine. This occurred in both the desk-top machines as well as the large 100 volt machines. This latter turn of events, was brought about by the introduction and the widespread use of quarter square multipliers, replacing the old slow servo and time division multipliers. At the same time, manufacturers introduced the fixed diode type of function generator for such analytical functions as sines and cosines of angles and exponential functions. The above developments, in conjunction with the introduction of solid state highspeed switching made the high speed and the low speed analog in a single computer a practical reality.

Two new companies were formed during this period that proved to be significant factors throughout the '60s. These were Comcor, Inc., which subsequently merged with Astrodata, and Applied Dynamics, Inc., which subsequently merged with Reliance Electric. These companies helped to fill the partial vacuum created by the withdrawal of GEDA from the field during the second generation and the subsequent rise and fall of several other companies. During the same period (1960 to 1965), the Reeves Instruments Company, which had been in the business of manufacturing analog computers from the very beginning, more or less indicated that it was finished with this activity.

The second generation equipment brought to fruition the concept of patchable, parallel, digital logic as an integral part of the analog computer. At the same time, it should be noted that the first conference on the use of combined analog and digital computers in a single problem simultaneously, (the first conference on essentially hybrid applications) was held in 1960, Reference 12, which is why I chose 1960 as a key date for the second generation.

Hybrid computation evolved along several different paths. In one path a "stand-alone digital," was placed next to a "stand-alone analog" with communication between the two allowed via logic lines, control lines, an AD (analog to digital) converter with a multiplexer, and several D/A (digital to analog) converters. Along another path a "logic computer" was developed by Electronic Associates which consisted of a number of parallel, patchable circulating (memory) delay lines, "and" gates, "or" gates, flipflops, four bit registers, shift registers, and one shots (mono-stables) to the point where, if a programmer were clever enough, he could devise and patch together his own special purpose digital computer. The logic computer ultimately got reduced to a reasonably small, manageable complement of logic functions (see Figure 14) on later analog computers and became fully integrated with the analog computer instead of being a separate device.

Index : Volume 4

Permuted Titles

[redacted]

Analog Computer Potentiometers, Digital Computer Control of, *W. J. Chandler* and *R. B. McGhee*.....Jan. 14
Counter-Current Crystallization Process, Analog Simulation of a, *W. L. Godfrey* and *R. D. Benham*.....Jan. 26
Differential Equations, The DES-1, A New Digital Computer for Solving, *L. Levine*.....Apr. 264
Digital Differential Analyzer and its Application as a Hybrid Computing System Element, The Parallel, *O. A. Reichardt, M. W. Hoyt,* and *W. T. Lee*.....Feb. 104
Digital Simulation of a Hybrid Computer, MADBLOC ... a Program for, *V. C. Rideout* and *L. Tavernini*.....Jan 21
Hybrid Computer, MADBLOC ... a Program for Digital Simulation of a, *V. C. Rideout* and *L. Tavernini*.....Jan 21
Hybrid Computation, A Discussion of Beckman's Approach to, *R. E. Lord* and *R. A. Nesbit*.....June 372
Hybrid Computing System Element, The Parallel Digital Differential Analyzer and its Application as a, *O. A. Reichardt, M. W. Hoyt, and W. T. Lee*..Feb. 104
Hybrid Signal Processor, A Parallel/Sequential, Stored Program, *J. D. Grandine* and *T. G. Hagan*..Jan. 35
Laguerre Functions, Function Generation on an Analog Computer Using Generalized, *C. H. Burgin*.Mar. 152
Measuring Statistics from Quantized Data, Hybrid Computer Techniques for, *G. A. Korn*.....Apr. 229
Nonstationary Random Processes, Generation of, *R. E. Bryan*.....Jan. 42
Numerical Method for Simulation, A New, *M. Fowler*.....May 324
Pontryagin's Maximum Principle to Solve One-Dimensional Optimization Problems, with and without Constraints, on an Iterative Analog Computer, Using, *H. L. Steinmetz*.....June 382
Pseudo-Random Noise, Fxperiments Using, *R. L. Hampton*.....Apr. 246
Punched-Card Programmer, MACON: MAtrix CONnector, *L. J. Kamm*.....May 332
Random Processes, Generation of Nonstationary, *R. E. Bryan*.....Jan. 42
River Kitakami, Flood Simulator for the, *K. Otoba, K. Shibatani,* and *H. Kuwata*.....Feb. 86
Simulation, A New Numerical Method for, *M. E. Fowler*.....May 324
Simulation of a Chemical Feeder System, Analysis and, *J. C. Vogt*.....Apr. 256
Simulation of a Spinning Rigid Body, Quaternion Parameters in the, *E. E. L. Mitchell* and *A. E. Rogers*.....June 390
State Variable Techniques in Analog Computer Programming, Application of, *J. L. Hammond, Jr.*..May 316
Statistics from Quantized Data, Hybrid-Computer Techniques for Measuring, *G. A. Korn*.....Apr. 229

[redacted]

Equipotential Lines of a Potential Field, Plotting the, *W. R. Lym*.....Feb. 81
Forty-Step Quantizer, *H. Marks* and *C. M. Callison*..May 307
Hysteresis, Use of Logical Elements to Simulate, *C. W. Schulte*.....June 364
Imperfect Differentiator, A Note on the Simulation of the, *A. Bridgeman*.....Jan. 10
Multiplier, A Four-Quadrant, *W. H. Alliston*.....Jan. 9
Reticle Evaluation Studies, A Method for Generating Simulated Targets Used in, *M. D. Camp*.....Apr. 223
Sample-and-Hold Circuit, High Sensitivity, *C. C. Willems*.....Mar. 140

[redacted]

APACHE, *R. D. Brennan* and *R. N. Linebarger*.....Mar. 142
Let's face it, *R. D. Brennan* and *R. N. Linebarger*....Apr. 226
PACTOLUS Program for Simulation of Antenna Servos, Use of the, *N. B. Kurek*.....June 365

[redacted]

Analog Data Processing with a Hybrid Computer, *W. G. McClintock*.....June 369

[redacted]

Analog Oriented Input Language, A Compiler with an, *M. L. Stein, J. Rose,* and *D. B. Parker*.....Mar. 159
Human Interaction in Small Groups, Computer Simulation of, *J. T. Gullahorn* and *J. E. Gullahorn*..Jan. 50
Input Language, A Compiler with an Analog Oriented, *M. L. Stein, J. Rose,* and *D. B. Parker*....Mar. 159
Learning Control Systems, A Computer Simulated On-Line Experiment in, *J. D. Hill, G. J. McMurtry,* and *K. S. Fu*.....Feb. 117
Noise Generator, A Hybrid Analog-Digital Pseudo-Random, *R. L. T. Hampton*.....Mar. 179
Parameter Optimizer for ASTRAC II, A Hybrid Analog-Digital, *B. A. Mitchell, Jr.*.....June 399
Partial Differential Operators, A New Method of Analyzing the Truncation Error in the Finite Representation Difference of, *R. Vichnevetsky*....Mar. 190
Pseudo-Random Noise Generator, A Hybrid Analog-Digital, *R. L. T. Hampton*.....Mar. 179
Transistors in Current-Analog Computing, *B. P. Kerfoot*.....May 339
Truncation Error in the Finite Representation Difference of Partial Differential Operators, A New Method of Analyzing the, *R. Vichnevetsky*.....Mar. 190

SIMULATION

Figure 11—Index to Vol. 4 SIMULATION, June, 1965

The largest analog computing consoles had upwards of 200 amplifiers in them. One example is the Applied Dynamics 256 (Figure 15) which had 256 amplifiers. There was a movement towards more "committed" amplifiers such as the class 0 type quarter square multiplier with many of the largest, most sophisticated users trending towards the class 0 resolver as well. This meant the computer was easier to use, but it became more expensive.

The applications of analog during the period 1960–1965 are more difficult to characterize since by this time the well known industry-wide Spring and Fall Joint Computer Conferences, which are sponsored by AFIPS, had replaced the old National Simulation Conferences. To help plug the information on applications gap, a significant event occurred during the second generation, which was the launching and the publication of the new journal SIMULATION by Simulation Councils, Inc., under the editorship of John McLeod. The index of articles published in Volume 4 (June, 1965) is shown in Figure 11, as an example of the type of applications that were being done on these bigger, better and more powerful systems. It may be remarked in passing that even during this second generation period, indeed throughout the history of the analog, the analog has been used very much as it was originally used *when there was no patchboard on the analog console.* This method of use consists of committing the analog to a single problem, of very high priority, and tieing it up full time doing the same job over and over and over again, as exemplified by the typical hardware or man-in-the-loop simulator. Very often when the project that required the simulator was completed or nowadays we would say cancelled, there was no further use or need for the analog computer, since no one else had been able to get at the machine during the "fat" days. Those analysts who had short duration, small problems, which can be considered to be ideal candidates for the analog computer, especially during the development or the "model" stage of the problem, were forced to go against their own wishes to the, by then, widely available large, fast, digital computer of the 7090 class. These small, repetitive, studies went to digital *not* because the machine was fast, *not* because the digital was cheaper, *not* because it was better, *not* because it was more accurate, *but* simply because it was available!

Year	Typical Computer	
1951	C100 (Reeves)	20 amplifier computer; servo multipliers introduction of removable patchboard.
1954	31R (EAI)	20 amplifier computer, expandable to 60; more accurate servo multipliers; integrated slaving system; .01% capacitors; .01% resistors, both temperature controlled.
1956	131R (EAI) C400 (Reeves)	Integrated readout; human engineered for faster, easier programmer use; electronic time division multipliers; mechanical digital voltmeter; tube diode function generators.
1959	231R (EAI)	100 amplifier computer; modular concept patchboard; significant improvements in amplifier bandwidths providing faster response and switching times; compressed time capability (some jobs can be run as fast as 10:1 real time instead of all at real time); faster potentiometer readout; electronic digital voltmeter; solid state diodes in function generator; repetitive operation capability.
1962	Improved 231R (EAI)	More accurate 1/4 square multiplier; electronic sinusoidal generator; point storage via transistor circuit; card-set function generators; Mark 200

Year	Typical Computer	
1962	231R (EAI) continued	recorder now compatible with accuracy and repeatability of computer. More useful bandwidth.
1964	231RV (EAI Beckman	Electronic mode control of integrators, time-scale selection (6 decades) via push buttons, more accurate multipliers and sinusoid generators. Digital logic control capability - for the first time analog has a full 10KC bandwidth in all components, Variable breakpoint and polarity, card-programmed function generators. This allows instant set-up of DFGs (takes only one hour to turn around a problem). (Mostly pot settings time.)
1966	Ci-5000 ADI-4 EAI 8800 EAI 680	Fully transistorized, more accurate, more reliable analog computer - all gates (reset, hold, operate, are electronic) bandwidth up to and beyond 100 KC, reliability estimated as 60,000 hours MTBF for amplifiers vs. 5,000 hours measured on 231R-V. Computers can have 300-400 amplifiers in one console. Analog directly controllable by small digital computer. Easy mating with digital for hybrid computation. Self-contained patchboard - digital logic (much, much larger than in 231R-V). Card-set DFGs programmable from a standard IBM card.

Year	Typical Computer	
1968 to Present	ADI - Various EAI - Various	Digital pots for microsecond (electronic gate) setup - or millisecond (reed relay setup), large scale use of MDACs in hybrid interface, software developed for automatic setup and checkout of hybrid analog computers. Direct digital/analog function generator (more accurate than card set diode function generator) completely controllable from digital computer.

Figure 12—History of analog computer evolution since 1951

THE THIRD GENERATION

The third generation has shown itself to be in existence from roughly 1965 to the present time, 1970. The major hardware characteristic of this generation is the complete transitorization of the analog computer, for both the large scale 100 volt machine and the small scale 10 volt machine. A new scale machine evolved in between these two extremes, called the medium scale. A major hardware feature is the integral design of digital logic as part and parcel of most analog consoles,

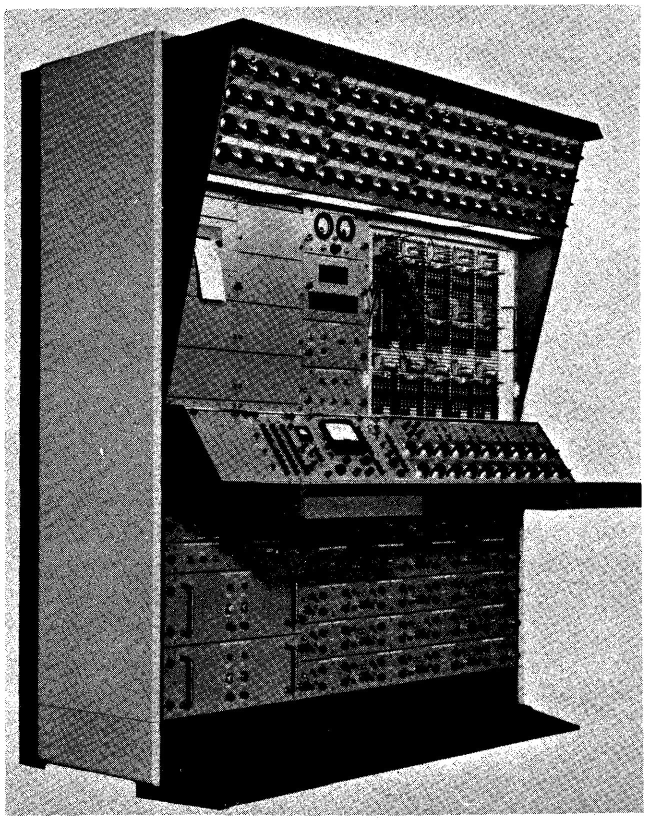

Figure 13—231*R* computer, courtesy Electronic Associates, Inc.

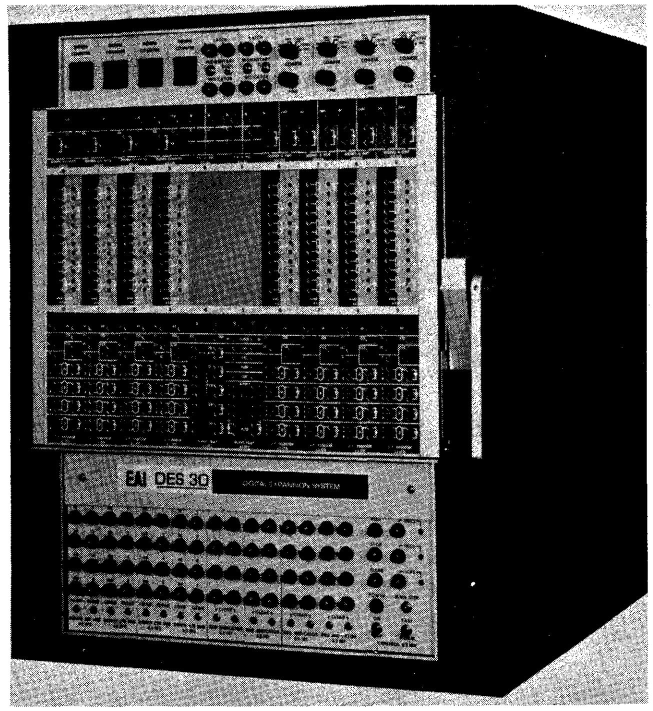

Figure 14—Digital expansion system by EAI (allows parallel patchable digital logic expansion to 10 volt systems, in a self-contained desk top frame

small and large, which has certainly made pure analog computation, if we include this digital logic, more powerful than it has ever been. Another hardware feature is the complete flexibility of the multi-time scale integration capability of the analog, wherein one can have a choice of fast, slow or in-between speeds of solution as well as the flexibility of using any integrating capacitor as an integrator gain. The most versatile machines have a choice of 6 capacitors, giving the programmer a five-decade range of integrator gains or time scales. Examples of this class of computer are the Applied Dynamics AD/4 (Figure 16), the Electronic Associates, Inc. 8800 (Figure 17) and the Comcor Ci-5000 (Figure 18). Note the two patchboards in each, one for digital logic, and one for analog components.

This period also saw a more intimate tie-in of the analog computer with a digital computer due to the development of such true hybrid devices as the MDAC (multiplying D/A) and the "digital attenuator" or "digital potentiometer." So widely accepted has the hybrid aspect of analog computation become that it appears that close to half of the larger consoles that are being sold at the present time are going into hybrid systems. This in turn has led to the need, and the development of software specifically designed to aid the hybrid programmer and operator. The large systems have grown larger and larger and now are truly prodigious, consisting of 300, 400, even 500 amplifiers in a

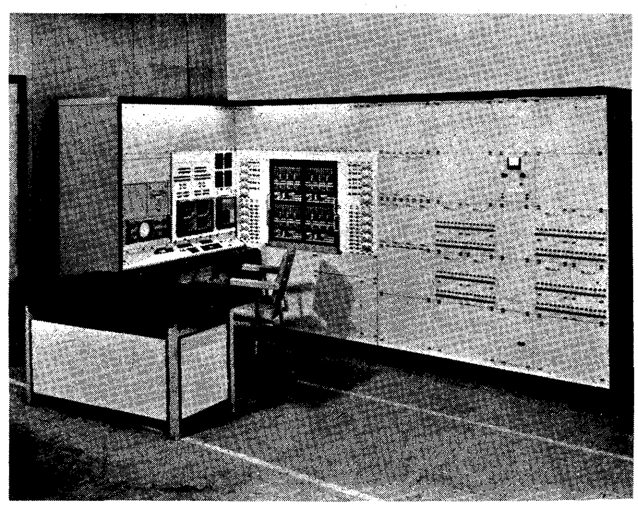

Figure 15—Applied Dynamics large scale 256 amplifier computer

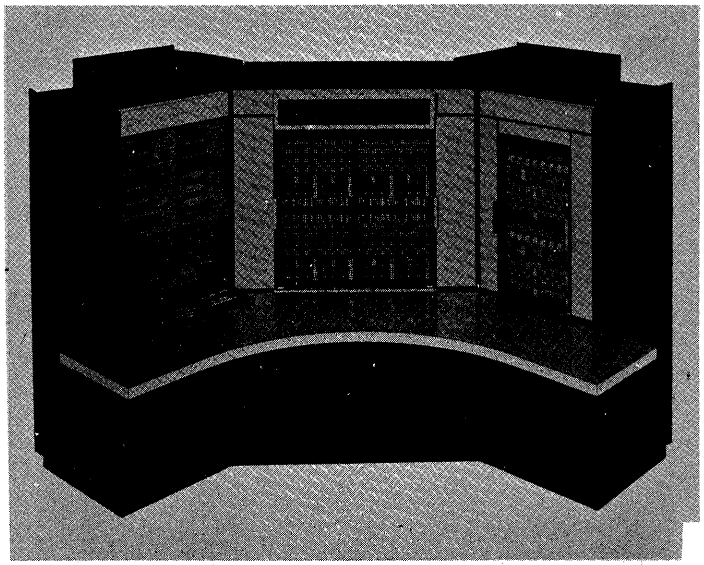

Figure 16—Applied Dynamics AD/4 analog computer

single console. At the low end of the scale, the 10 volt desk-top computers have grown larger and larger until they are no longer desk-top and now are fully grown consoles consisting of several hundred amplifiers, as exemplified by the EAI 680 computer shown in Figure 19.

The solid state revolution, which only overtook analog in the third generation has led to the concept of the class 0 type component or "blackbox" use of the analog components to help minimize patching and to make it easier for the more casual user of the machine to program, patch, and obtain solutions by himself. Another reason for this trend is that the solid state amplifiers are obviously less costly and more reliable than their vacuum tube predecessors. Analog speeds of solution which could be too fast to be absorbed by humans, or recorded by devices, even back in the early 50's, are even faster. Present day bandwidth ranges from a minimum of 100 KHz to over 1 MHz. Some of the other important equipment improvements are quarter square multiplier accuracy of close to 0.01 percent and arbitrary function generation performed by a true hybrid device, the digitally controlled function generator (DCFG), which eliminates spurious drifts, non-repeatability, and difficulty in setup of the old diode function generator. These, together with the new digital potentiometer, a good hybrid interface with good software, and a well integrated system design, make it theoretically possible to setup and checkout an analog computer in a few *seconds.*

Some persons have been known to state the opinion that an analog computer of today is not much different than one of 10 years ago. A reading of this paper should dispel such a notion. To make clear the advances that have been made in the analog field, from post World War II to the present time, I have summarized in Figure 12 the major hardware improvements by year of general availability showing the typical computers incorporating the named improvements. It is obvious that these improvements have come at more frequent intervals than analog computer generations as I have defined them, and shows that major improvements have come along in the analog field at an average spacing of about 2½ years. This interval of time is, interestingly enough, approximately equal to the half-life of a "generation" of analog computers. This fact might lead to the conclusion that one generation of computers cannot survive (or absorb) two sets of major hardware improvements, but that the manufacturers have been reasonably successful in extending the life of a generation of their computers through at least one significant hardware evolution. Perhaps it is the ability to extend the life of a "generation" of analog computers, because of the nature of the organization of analog computers (parallel building blocks) which has led to the inaccurate observation that "analog computers of today are not much different than they were 5 or 10 years ago."

ANALOG/HYBRID TODAY

We have now come to the point in analog/hybrid developments where not only do we have more raw computing speed than it is possible to take full advantage of, for solutions, but we also have more speed in terms of setup and checkout than we have customers

Figure 17—680 10V computer with display wing

who understand this type of computation. Or to put it another way, we've reached the stage in evolution where we can get a customer on, get his answers for him, and get him off, far faster than is justifiable based on the fact that we have a highly serial, slow input, mainly the input from a single man, to a very fast parallel console. We have almost reached the stage, as a matter of fact, where the slow recorders on the outputs from the analog are one of the limiting output factors. We've reached the point where we can make many, many solutions in a very short time. In other words, we are production oriented in terms of solution speed. At the same time, we have retained all of our man-machine interactive capabilities which everyone says is desirable in the engineering use of computers, but which obviously work *against* production. In fact, production capabilities are so great that I have estimated that for every hour of production running on our modern hybrid systems, the amount of post run data reduction of the results by a large fast, stand alone digital computer operating in a batch mode would be at least two and possibly as high as five hours depending on how much analysis is desired, or more realistically, how much the project can afford.

The application of hybrid equipment is still heavily oriented toward the aerospace-defense industry where most of the large systems are installed. The chemical process industries have maintained some interest in these systems over the years, but not at an increasing rate. The education field has interest in the small and medium size systems. Nuclear and power technology have shown signs of increasing awareness of the capability of hybrid systems for their highly complex

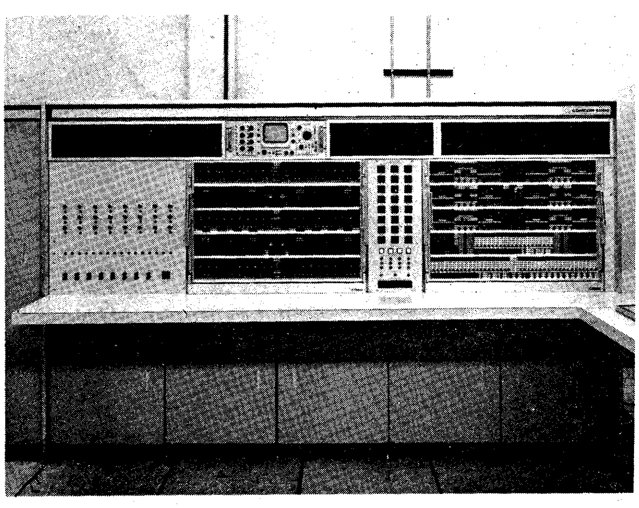

Figure 18—Comcor Ci-5000 analog computer

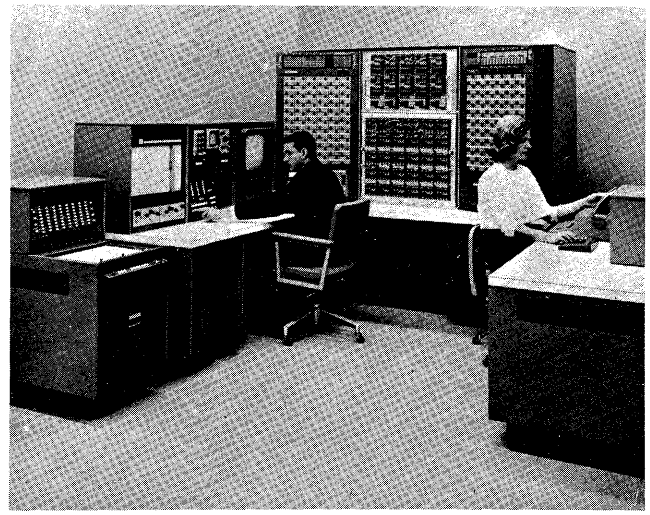

Figure 19—8800 100*V* transitorized computer with display wing

design, control, and training studies. Other popular applications are as an on-line testing device, such as measuring the amount of pollutants in an automobile engine exhaust (Reference 6); measuring the roundness of tires (Reference 7) in acting as an on-line predictor or adaptor-controller for a wide variety of processes (Reference 8), and for helping to control the quality of steel (Reference 9).

So what is the hybrid/analog system of today? It is a highly efficient fast production device when the user or man is not allowed to intervene and interfere with its operation. This is in direct contradiction to its other main feature, that is, its ease of man-machine communication which almost cries out for man's intervention. I would say that the analog/hybrid computer exhibits schizophrenic characteristics which may explain why not too many people understand it. It is almost impossible for a device to be responsive to man's intervention and at the same time to be highly productive. At least not the way the hybrid systems are configured today. It is this paradox that limits the expansion of the analog/hybrid field.

The analog hardware today is far more reliable than its early beginnings. The MTBF for a transistorized amplifier is somewhere between 30,000 hours and 60,000 hours. The high quality, chopperless amplifier, a recent development, brings us back, almost full circle to the point where we were with the very first analog amplifiers, that is, a chopperless, unstabilized amplifier with a virtually instantaneous overload recovery. This is a feature that all users will appreciate. However, it has taken 25 to 30 years, an electronic revolution, and 3 or 4 generations of computers to eliminate the drift and unreliability of the first unstabilized amplifiers, while retaining the desirable features of simplicity and quick overload recovery.

The future

The analog/hybrid computer could become more widespread in its use and acceptance by industry if it can eliminate its schizophrenia and solve its paradox. Hardware and software ideas have been mentioned for doing just this, such as an automatically patched analog computer (Reference 10), coupled with a high level language for programming the machine in user oriented language, such as APSE and APACHE, all of which is made highly accessible and productive with many interactive graphics terminals (Reference 11) controlled and hybridized by one of those next generation, fast, cheap, can-do-anything digital computers that I keep hearing about.

At the very least, it will continue to be used in those on-line experiments, those teaching-learning situations, those high frequency problems, that saturate large digitals, and by those specialists who are addicted to analog, as it has been used in the past.

REFERENCES

1 J ROEDEL
An introduction to analog computers
From A Palimpsest on the Electronic Analog Art ed by H M Paynter first printed by George A Philbrick Researchers Inc 1955 pp 27-47

2 M CONNELLY O FEDOROFF
A demonstration hybrid computer for real-time flight simulation
February 1965 Report ESL-FR-218 Contract AF 33(616)-8363 M I T Cambridge 39 Mass

3 Project Cyclone-Symposium I, Reeves Instrument Corp under contract with the Special Devices Center of the Department of the Navy March 1951

4 Project Cyclone—Symposium II Reeves Instrument Corp (Part II) under contract with the Special Devices Center of the Department of the Navy April 1952

5 Project Typhoon—Symposium III on Simulation and Computing Techniques Bureau of Aeronautics and US Naval Air Development Center October 1953

6 J P LANDAUER
Hybrid computer real-time data processing for engine testing
Electronic Associates Inc Market Development Report 17-70

7 J T MAGUIRE A J SCHNABOLK
Sorting out the tires
ELECTRONICS March 18 1968

8 P ADAMS A SCHOOLEY
Adaptive-predictive control of a batch reactor
EAI applications Reference Library #6.2.2/a

9 H J HENN J D SCHIMKETS T G JOHN
Development and operation of a refining control system for stainless steels
ASME Electric Furnace Conference Detroit Mich December 1969

10 G HANNAUER
Automatic patching for analog and hybrid computers
SIMULATION Vol 12 #5 May 1969 pp 219-232

11 R M HOWE R A MORAN
Time sharing of hybrid computers using electronic patching
Proc of 1970 Summer Computer Sim Conf Vol 1 pp 124-133

12 Proc of Combined Analog/Digital Computer Systems Symposium sponsored by SCi and General Electric Company December 1960 Available from SARE