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

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

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
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"
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".)

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.
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 transistorization of analog components. The first transistorized 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 square quarter 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 Astrodatal, 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.

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 7000 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!

### 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 transistorization 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.

<table>
<thead>
<tr>
<th>Year</th>
<th>Typical Computer</th>
<th>Description</th>
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<tbody>
<tr>
<td>1962</td>
<td>231R (EAI)</td>
<td>Continued</td>
</tr>
<tr>
<td>1964</td>
<td>231RV (EAI)</td>
<td>Beckman</td>
</tr>
<tr>
<td>1966</td>
<td>CL-5000</td>
<td>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.</td>
</tr>
<tr>
<td>1968</td>
<td>ADI-4</td>
<td>Present EAI - Various</td>
</tr>
<tr>
<td>1969</td>
<td>EAI 8800</td>
<td>Digital pots for microsecond (electronic gate) setup - or millisecond (read relay setup), large scale use of NMAs 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.</td>
</tr>
<tr>
<td>1970</td>
<td>EAI 680</td>
<td>Card set DFGs reprogrammed from a standard IBM card.</td>
</tr>
</tbody>
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Figure 12—History of analog computer evolution since 1951
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
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 ad-
vantage 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 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 adapt-0r-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.

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