SCI DEFINITIONS OF TERMS AND METHODS OF MEASUREMENT FOR GENERAL-PURPOSE ANALOG COMPUTERS TO BE PUBLISHED

In recent years it has become increasingly obvious that there are considerable ambiguities in some of the terms which are commonly used in specifying components and performance criteria of analog computers. In an effort to bring some uniformity to this area, Hans F. Meissinger, Chairman of the Western Simulation Council, appointed a committee to decide upon a set of standard definitions of terms used in specifying analog computers. This committee was appointed at a meeting of the Steering Committee of the Western Simulation Council at Norair, Division of Northrop Aircraft, on November 10, 1960. The committee is composed of the following people:

J. E. Sherman, Lockheed Missiles & Space Company
W. N. McLean, North American Aviation
J. E. Reich, Space Technology Laboratories, Inc.
W. Comley, Douglas Aircraft Company
R. D. Blosser, Autonetics

The primary goal of the committee is to define certain terms commonly used in specifying analog computers. In order to define some of these terms, it is necessary to describe the methods by which certain measurements should be made. Therefore, the definitions are divided into two parts entitled: (1) Definitions of Terms Used to Specify Analog Computers and (2) Measurement Procedures.

Some of the ambiguities which led to the establishment of the committee are: "Accuracy" as applied to analog computers, the definition of an electronic multiplier, etc.

One often hears of an analog computer having an "accuracy of 0.01%". This is obviously an erroneous statement. In truth, the statement should read that the computer has "an error of less than 0.01%", or the computer has "an accuracy of 99.999%". Ignoring the semantics for a moment, it has long been the practice of the industry to claim "an accuracy of 0.02%" for electronic multipliers. When it comes time to measure the performance of the component in question, it develops that the interpretation put upon this figure by the manufacturers is 0.02% of full scale (± 100 volts) and then is interpreted by them as being ± 40 millivolts. The reasoning they use in arriving at this conclusion is that it is possible for the peak-to-peak value of the signal-to-be 200 volts, and then they say that 0.02% of 200 volts is 40 millivolts. However, the point that they choose to suppress is that the term ± 40 millivolts is really 80 millivolts peak-to-peak, which is in truth 0.04% of the peak-to-peak signal value. Further these specifications apply to the multiplier only when the inputs are essentially stationary. There is no convenient or commonly accepted method of specifying the dynamic performance of the multiplier.

The term "electronic multiplier" is, at times, not clear. Does it merely require inputs of X and Y from any source? Or does it require inputs of both plus and minus X and plus and minus Y, all from low-impedance sources? Can the output be fed directly to a low-impedance termination, or must it be terminated in a high impedance? It is clear there may be a difference of five amplifiers between the two cases.

It was in an effort to clarify these and like situations that the Western Simulation Council Committee on Uniform Specifications for Analog
Multiple variable problems like the ones bothering our friend involve generating a great many independent trial solutions. The combination of GPS high-speed operation, with memory capability, logic-controlled iteration and time-sharing of computer units gives most reliable results. Operating on a compressed timescale of 3000 to 1, the GPS Computer System performs in one-tenth of a second a problem which in real time computation would require five minutes. A wide variety of problems, new to the analog computing art, can now be solved by the GPS Multiple Timescale Analog Computer with speeds and dynamic accuracy unmatched by any other analog computing system available today. Write for Technical Information.
Computer Performance was formed. The definitions proposed by the Committee have been discussed with technical representatives from the following manufacturers of analog-computing equipment:

- Applied Dynamics Inc.
- Beckman/Berkeley Division
- Computer Systems, Inc.
- Electronic Associates, Inc.
- Reeves Instrument Company

The set of definitions is not complete. There are a number of terms which have not yet been defined. The terms which have been defined are those generally associated with the description and performance of the following analog computing components:

- Arbitrary Electronic Function
- Generators
- Electronic Multipliers
- Summing Amplifiers
- Servo Multipliers
- Electronic Resolvers
- Electronic Sinusoid Generators

Yet to be defined by a similar set of terms are the following components:

- Power Supplies
- Time-History Recorders
- X-Y Plotting Boards
- Digital Voltmeters
- Random Noise Generators
- Relays
- Monitoring Devices
- Computing Consoles
- Potentiometers

Also to be defined are terms concerned with the following types of computation:

- Repetitive-Operation Computation
- Iterative Computation

and such specialized terms as:

- Algebraic Loop Gain
- Stability Margin

Work is continuing on the definitions and the methods of measurement. As this Newsletter goes to press, arrangements are being made to publish the results of the work already accomplished in future Newsletters in installments, beginning with the October issue of Instruiments and Control Systems. As more results are written up by the Western Simulation Council Committee, and other committees who have joined in the effort, we plan to publish them as additional installments. We hope that all people concerned with analog computers will follow this series and give us feedback by way of letters of comment and criticism. Only in this way can we eliminate the double-talk and be sure that we understand each other.

ANALOG VERSUS DIGITAL PANEL

At the invitation of Bill Gunning your Ed organized and moderated a panel discussion sponsored by the Orange County Chapter of the Professional Group on Electronic Computers of the IRE. We met at the Chrysler Training Center in Anaheim, California on the evening of June 28th to "Critically Compare Simulation Techniques" by considering the question: If you were to start from scratch today to equip a laboratory for the simulation of aerospace systems—and there were no budgetary limitations other than justification of the need—what kind of computers would you buy?

Considering this happy—and highly hypothetical—circumstance were:

- Dr. Walter Bauer (Informatics, Inc.)
- Dr. Edward DeLand (The Rand Corporation)
- Mr. William Farrand (Autonetics)
- Dr. Gerhard Hollander (Hollander Associates)
- Dr. Harold Skramstad (Naval Ordnance Laboratory)

Needless to say, nothing was settled for sure. However, some "interesting" remarks were made, some of which I offer here for readers' consideration. They are out of context, and possibly distorted. They might therefore sound more controversial than they were meant to. I hope so, because I would like to hear some reader back-talk.

Bauer: The real reason it (an early plan for combined simulation) was a flop was because there was no real need for analog-to-digital conversion. There are very few problems where you need the dynamic range of the analog and, in the same problem, the precise measurements of the digital.

Why analog-digital systems at all? I only see analog-digital systems where a guy has 400 amplifiers and wants to modernize, so he brings in a digital computer.

Digital computing is like counting on your fingers. Analog is like counting on your toes—with your socks on!

The problem of re-entry is the only one that looks as if it might call for the combined.

DeLand: I think you have never run an analog computer. Differential equations should be taught with an analog computer in the classroom; there's nothing like the analog for parameter-searching (don't call it knob-tiddling!)

I don't believe you should invent a machine to do just certain things. You should have the machine and then look around for applications. Now if you had the combined system—analog and digital linked together—and if you had had men there to sit and think, they would have come up with applications.

Skramstad: There are problems which are dynamic and really require the speed of the analog. The digital has flexibility, but there are many types of problems that it doesn't do efficiently. We need combinations of small cheap digital with the analog; the large digital computer is not needed.

I believe there is not enough communication between the digital and analog. I agree with DeLand that an analog computer should be in every school where differential equations are taught.

Farrand: "The General-Purpose Digital Computer can do anything." But the price you pay in some cases is rather extreme. The future of the GP is in housekeeping and bookkeeping.

Hollander: Analog, digital,
Large or small;
If they do my job
I like them all!

This ditty, attributed to Dick Hamming, represents my viewpoint that the potential computers must be evaluated on the basis of performance per unit cost; meaning performance useful to this job, and the total cost attributable to the use of the computer. Initial programming is cheaper for analog computers, but digital computers can be switched from one job to another on a second's notice.

Gary cited a series of trade-off factors between analog, DDA, and whole-number digital that his Fullerton firm had recently developed. Gary pointed particularly to the MIT pulsed-analog computers as a new direction for simulation.

In the June issue of your Newsletter we promised that we would give
New instrumentation system capabilities are available to systems designers and laboratory engineers in EAI's fully transistorized digital voltmeters and system accessories. Solid-state reliability, six-month guaranteed stability, high speed and complete system provisions make EAI Series 5000 and 5001 DVM's ideal for the most critical applications. □ EAI Series 5000 and 5001 Digital Voltmeters are completely solid-state with 0.01% plus 1 digit absolute accuracy, six months stability, 10 milliseconds maximum reading time, buffer storage with BCD and decimal outputs and full-time input impedance to 1000 megohms. □ Series 5500 AC-DC Converter is a completely solid-state operational amplifier type providing 0.05% accuracy with 150 milliseconds maximum settling time. □ Series 5700 Input Scanner utilizes highly reliable cross-bar switching for scanning up to 30 points per second.

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ELECTRONIC ASSOCIATES, INC. Long Branch, New Jersey

CIRCLE 119 ON READER-SERVICE CARD
THE APPLICATION OF ELECTRONIC ANALOG COMPUTERS TO THE SOLUTION OF NONLINEAR DIFFERENTIAL EQUATIONS

Prof. C. P. ATKINSON, University of California

Among the specially valuable applications of an electronic analog computer is its use as the physical analog of the mathematical process of integration. The simple integrating amplifier can perform processes of continuous summation that still defy the wiles of our mathematicians for exact solutions.

I have been concerned for the past few years with the application of this aspect of the analog computer to that group of ordinary differential equations classified as nonlinear ordinary differential equations.

In recent years, the increase in diversity and accuracy of those computer components necessary for handling nonlinear problems has made the simulation of the nonlinear problem not only simple and gratifying but a continual source of joy and amazement.

As a first example of the solution of a nonlinear differential equation let us take the simple pendulum in oscillation about a fixed point of support, and solve the problem for large angles—that is, do not linearize the problem to the standard harmonic motion equation, but retain the nonlinear term. The differential equation is:

\[ \dot{\theta} + \left( -\frac{g}{l} \right) \sin \theta = 0 \]

All we need to do is to integrate:

\[ \theta = -\left( -\frac{g}{l} \right) \int \sin \theta \, dt \]

From which we get:

\[ \theta = -\int \sin \theta \, dt \]

We must remember that

\[ f \sin \theta \, dt \neq \cos \theta \]

This problem shows all of the weak points of the simple integrator, which integrates only with respect to time. For the problem discussed we must generate

\[ \cos \theta = -\int \sin \theta \, d\theta \]

and

\[ \sin \theta = \int \cos \theta \, d\theta \]

The process is called generalized integration to distinguish it from ordinary integration with respect to time. The techniques for generating the sine of the dependent variable are based on the following integrations:

\[ \int q \, dq = \int q \left( \frac{dq}{dt} \right) dt \]

If we have available the \( \dot{q} \) term, and a multiplier to obtain the product \( q \times \dot{q} \), we could use the circuit of Fig. 1 to obtain the term \( \int q \, dq \), which equals \( q^2/2 \).

The integral for this case could just as well have been gotten from a multiplier that gave \( q \times q \), or \( q^2 \), but the generation of the sine is not possible with a multiplier alone.

Let us consider the equation

\[ \dot{\theta} + K \sin \theta = 0 \]

The circuit for solving this equation (that is, to find \( K \sin \theta \), starting with \( \dot{\theta} \)) is shown in Fig. 2, with signs ignored.

Editor's note:

Another approach is shown in Fig. 3. This method may be limited by the swing of the function generator (generally \( \pm 180^\circ \)).

The important lessons learned are that:

1. Generalized integration can be accomplished if the appropriate voltages are available.
2. Initial conditions are of extreme importance.
3. Variable period is characteristic of a system (such as a pendulum) when the amplitudes do not allow linearization.

Another type of problem to be considered is

\[ q + q^n = 0 \]

The equation can be solved with as few as seven multipliers for \( n = 65 \).

The free vibrations of the system mentioned have well-known analytical solutions of exact form. When we introduce forcing terms or damping terms then only approximate solutions are available, and certain standard methods have been used for them. In such cases the analog computer is an excellent tool for the solution of these problems.

We have recently been investigat-
How much does a full-fledged 0.01% analog computer cost these days?

Here's Donner's answer: less than $50,000. This buys a full 100 amplifier Donner 3200 with 0.01% computing components, broadband, stable amplifiers, and an ample supply of non-linear equipment and accessories.

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That makes the 3200 the lowest priced 0.01% computer on the market. The reason? The latest manufacturing techniques and big lot production.

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One final point. Since its introduction last fall, the 3200 has gained wide acceptance in this country and abroad. You will be buying a thoroughly proven computer.

Donner has technical literature which tends to prove the wild claims made here. Please write to Mr. David Taskett.
ing nonlinear systems of two degrees of freedom; for such systems there have been found in general no exact solutions, even for free vibrations. Our investigations of these systems by the analog computer revealed some rather interesting phenomena and yielded a group of these equations with exact solutions. For example, we looked at the system

\[
\begin{align*}
\dot{x}_1 &= -a_1 x_1 - a_2 x_2^3 - \left( A_1 (x_1 - x_0) + A_2 (x_1 - x_0)^2 \right) \\
\dot{x}_2 &= -b_1 x_1 - b_2 x_2^3 - \left( A_3 (x_1 - x_0) + A_4 (x_1 - x_0)^2 \right)
\end{align*}
\]

and asked the question, "Are there systems of this type which can oscillate according to the restriction \( x_1 = C x_2 \) where \( C \) is a constant?"

Such a restriction would yield solutions similar to the in-phase and out-of-phase modes of linear systems. There was no attempt to linearize the systems but only to require the so-called modal restraint. When the modal equation is substituted into these equations, a polynomial in \( C \) can be found which will answer the question as to whether a modal constant can be found for any set of parameters of the equations. For a certain class of systems, such modal constants can be found. One class is the symmetric system of the type

\[
\begin{align*}
\dot{x}_1 &= -a_1 x_1 - a_2 x_2^3 - \left( A_1 (x_1 - x_0) + A_2 (x_1 - x_0)^2 \right) \\
\dot{x}_2 &= -a_1 x_2 - a_2 x_2^3 + \left( A_3 (x_1 - x_0) + A_4 (x_1 - x_0)^2 \right)
\end{align*}
\]

For this type of system, the modal constant of \( x_1 = C x_2 \) is \( C = \pm 1 \), suggesting the in-phase and out-of-phase relations. Actually there exist for some systems more than two constants which satisfy the modal restraint.

The important thing about the fact of the existence of a modal constant is that the original differential equations are uncoupled similar to the technique of generalized coordinates in linear systems, and the pair of differential equations reduce to two single-degree-of-freedom equations (in the symmetric case, identical equation if \( C = \pm 1 \)) which can usually be solved by quadratures.

It was at this point that the analog simulation of the original pair of coupled differential equations was attempted to confirm the existence of the modal oscillations.

The computer solutions showed that modal oscillations were possible (that is, the solutions would stay in mode) for certain amplitudes in some systems, but for different amplitudes the modal oscillations could not be maintained. This fact of the computer discovery of unstable modes led to the analytic investigation of the stability of the modes. One approach to the stability of the modes is by a rotation of the axes in the \( x_2 \) vs \( x_1 \) plane to the axes \( x \) and \( y \) with the development of a pair of equations:

Mathieu:

\[
\begin{align*}
\ddot{x} &= x (K_1 + K_2^2) \\
\ddot{y} &= K_3 y + K_4 y^3 + \cdots + \frac{x^3}{a^2}
\end{align*}
\]

Duffing:

\[
\begin{align*}
\ddot{x} &= x (K_1 + K_2 x^2) \\
\ddot{y} &= K_3 y + K_4 y^3 + \cdots + \frac{x^3}{a^2}
\end{align*}
\]

The \( y \) direction represents modal oscillations and the \( x \) direction represents cross-modal or out-of-phase oscillations.

The analytic results of this study confirmed the computer findings of unstable modes, as is neatly shown in the following example:

\[
\begin{align*}
\ddot{x} &= x - \frac{1}{4} x^3 + \frac{1}{2} (x_1 - x_0) - \frac{1}{40} (x_1 - x_0)^3 \\
\ddot{x}_2 &= x_2 + \frac{1}{4} x^3 - \frac{1}{2} (x_1 - x_0) + \frac{1}{40} (x_1 - x_0)^3
\end{align*}
\]

where the out-of-phase mode is \( x_1 = -x_2 \).

The stability analysis yielded a Mathieu equation of the form

\[
x + x (\delta + \epsilon \cos \omega t) = 0
\]

with

\[
\delta = \frac{1}{40 a^2}, \quad \epsilon = -\frac{1}{16 \sqrt{a}} \left( \frac{A}{\omega} \right)^2, \quad \omega = \frac{1}{2} + \frac{1}{24} A^2
\]

When the \( \epsilon \) and \( \delta \) parameters are plotted on the Mathieu plane the lower stability characteristic was found to describe the stability of this particular mode (Fig. 4). Small amplitudes yield stable mode, larger amplitudes were unstable, and still larger amplitudes again became stable. Computer results are plotted in Fig. 5. These results showed an excellent correlation between the analytic and experimental results.

The problem yet remaining is to
The Pratt & Whitney RL-10 rocket engine was developed for NASA to power upper stages of Centaur and Saturn space vehicles. During the final stages of development, this engine was simulated on a Beckman EASE Analog Computer. As a result of discoveries in this simulation work, many refinements were implemented to greatly improve design and performance. This work was done at United Aircraft Research Laboratories in East Hartford, Connecticut, where accelerated research in aerophysics, electrical propulsion, advanced materials, plasma physics, and electromagnetics has been achieved through the use of these computers. Successful United Aircraft studies in such highly complex problems as aircraft and missile stability and control, guidance, maneuvering loads, and vibration have resulted in an acknowledged position of leadership in many of these fields.
describe the exact mechanism that produces this modal instability. It is suspected that these are due to irregularities in the potential surface, and certain cross-product terms which produce even harmonics that unbalance the system. Other factors, at this time, remain undefined.

Tom Connolly followed this talk with the observation that it is often overlooked that, in a nonlinear system, amplitude of the forcing function is of utmost importance.

Sam Giser of GPS pointed out that integration with respect to other than time can be accomplished with a "black box" that plugs into a computer. He wondered why this was not built by some company for general use.

R. Seferian indicated that he felt that the natural aversion of analog people to differentiation was ridiculous since he does it all the time. He then proposed a system for generating powers of a variable.

Prof. Atkinson indicated that the equipment used in this work was donated by the Berkeley Division of Beckman Instruments.

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**ANALOG TECHNIQUES**

**A NEW ANALOG-COMPUTER SETUP FOR SIMULATION OF STATIC AND COULOMB FRICTION**

Professor GRANINO A. KORN, University of Arizona

Guest Editor for September

Dry friction acting on a body capable of sliding in the x direction is represented commonly as a force (F_{friction}). If \( F_{applied} \) is the external force applied in the x direction, \( v \) the velocity of the sliding body, \( F_s \) the breakaway friction, and \( \epsilon \) is a small velocity (say 1/500 of the total velocity range), then

\[
F_{friction} = -F_{applied}, \quad \text{for } |F_{applied}| < F_s
\]

\[
F_{friction} = -F_s \cdot \text{sign}(F_{applied}), \quad \text{for } |v| < \epsilon
\]

\[
F_{friction} = -F_s \cdot \text{sign}(v), \quad \text{for } |v| \geq \epsilon
\]

With the body at rest \((v = 0)\), we have static friction which is equal and opposite to \( F_{applied} \) until the absolute value of \( F_{applied} \) exceeds the breakaway force \( F_s \).

As the body begins to slide \((v > \epsilon)\), where \( \epsilon \) is a small velocity, say 1/500 of the total velocity range), we have coulomb friction—i.e., a constant force of value \( F_s < F_a \) opposing the velocity.

It will be noted that analog-computer simulation of dry friction requires generation of a function of two variables, since \( F_{friction} \) depends on \( F_{applied} \) as well as on \( v \). Existing computer setups for this purpose are fairly complicated; McLeod has simulated both static and coulomb friction with the aid of operational amplifiers, while Zambino developed an all-electronic computer setup for approximate simulation of dry friction using seven amplifiers in addition to the integrator producing \(-v\). A simpler, and it is believed, more accurate analog-computer representation of dry friction is described here; only two amplifiers are required in addition to three diode-bridge limiters, which are available in many analog-computer patchbays.

Referring to Fig. 6, the phase inverter amplifier 1, and diode-bridge limiter 1 cancel the applied-force voltage by adding \(-F_{applied}\) to the input of integrator 2 as long as \( |v| < \epsilon \) and \( F_{applied} < F_s \). When \( F_{applied} \) exceeds \( F_s \), the bridge output is limited to \( F_s \) or \(-F_s\), and the resulting net integrator input can produce a velocity output in accordance with

\[
x = F_{applied} - F_s \cdot \text{sign}(F_{applied})\text{ sign}(v)
\]

where a body of unit mass is assumed for simplicity.

Amplifier 3 serves as a dead-space comparator whose output equals zero when feedback diode bridge 2 conducts (for \( |v| < \epsilon \)), but equals a sign function \( \text{sign}(v) \) for \( |v| \geq \epsilon \). The diode-bridge limiter 3 at the comparator output sets accurate limits of \( \pm a \), and also clips any comparator ringing. The comparator output is applied to amplifier 1 and drives the output of bridge 1 decisively into its limit \(-F_s \cdot \text{sign}(v)\) whenever \( |v| \geq \epsilon \). The required coulomb-friction force \(-F_s \cdot \text{sign}(v)\) is obtained by setting Pot 1 to \((F_s - F_o)/a\) to give \((F_s - F_o) \cdot \text{sign}(v)\); the \( F_s \cdot \text{sign}(v) \) component being necessary to cancel \(-F_o \cdot \text{sign}(v)\) from bridge limiter 1, to leave a net force acting on the body of \( F_{applied} - F_o \cdot \text{sign}(v) \) when \( |v| \geq \epsilon \).

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Reproduced from U. of Arizona Analog/Hybrid Computer Laboratory Memo. No. 43

![Fig. 6. Simulation of dry friction.](image-url)
ENGINEERS AND SCIENTISTS FOR ANALOG COMPUTING APPLICATION

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These are projects engineered by the technical employees at the Columbus Division of North American Aviation. Medium and long range research is being increasingly emphasized.

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FIG. 7. COMPUTER results obtained with circuit of Fig. 6.

Amplifier 4 is not part of the computer setup proper, but was added to display and record the total friction force.

Fig. 7 shows results obtained with the circuit of Fig. 6, using a standard 1-microfarad integrating capacitor; the transition between static and coulomb friction is clearly visible as the simulated body starts to move. A striking feature of the new circuit is the fact that, using sufficiently fast amplifiers (Philbrick K2-8A/K2-P), essentially similar results were obtained on a 1:1000 time scale, corresponding to repetitive-computer operation with a 0.001-microfarad integrating capacitor.

International Colloquium on Techniques of Analog and Numerical Calculation in Aeronautics

The Association Internationale pour le Calcul Analogique and other learned societies are organizing jointly at Liége, Belgium, from 9 to 12 September 1963, an International Colloquium on Modern Techniques of Calculation Applied to Aeronautics.

The program proposed by the Committee of Organization has been established provisionally as follows:

1. Aerodynamics
2. Structures
3. Dynamics
4. Servomechanisms
5. Navigation
6. Interpretation of the Results of Test Flights
7. The Flight Simulator (Behavior of the airplane, characteristics of the human pilot)

Papers at the colloquium may be presented in French, English, or German. The time for speaking allotted to authors of papers is limited to 20 minutes.

Persons who desire to attend the colloquium and authors of papers are asked to get in touch with the secretariat of the colloquium: Jean Florin, 50, avenue Franklin D. Roosevelt, Bruxelles 5, Belgium. They will be kept informed of details relative to the organization of the meeting.

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HE WENT THATAWAY!

Bob Gold to Hodges Space Systems Division, last June.