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BIBLIOGRAPHY AND SUMMARY OF METHODS RELATED TO THE ERROR ANALYSIS OF HYBRID COMPUTERS

By Thomas M. White, Jr.

Prepared for
George C. Marshall Space Flight Center
Huntsville, Alabama

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Introduction

A general approach to error analysis for any kind of computing (or problem solving) equipment is very difficult, if not impossible, to achieve.

Most straight-forward approaches result in equations for the error which are an order of magnitude more complicated than the original equations. Much work, whoever, has been done toward specialized error analysis for analog computers and sampled-data systems. Since the field of hybrid computation has developed rapidly only in the last several years, less work has been done in this area. It is the purpose of this note to summarize, or at least list, the methods (some which have been used solely with analog computers, some which have been used solely with sampled-data systems and some which have been used with hybrid computer systems) most likely to lead to useful results in error analyses of hybrid computers.

In addition to the errors caused by non-ideal passive elements, finite gain amplifiers, drift in amplifiers, offset, phase shift, and improper setting of coefficients associated with analog computers the hybrid computer has errors caused by the digital section as well. Among the errors contributed by the digital section are errors due to quantization, truncation, sampling interval, sampling time, and time delay.

An ideal error analysis would be short, tractable, and accurate. It must, furthermore, answer many questions about the system being analyzed. Some typical questions are:

1. What effect does the deviation in the value of one or more elements have on the static and dynamic error of the system?
2. What is the effect of the discrete data on the static and dynamic error of the system?
3. How should analog and digital sections be chosen for use together so that the static and dynamic error of the hybrid system satisfies certain error requirements?
4. What effect does noise have on the static and dynamic error of the system?

The following sections give current methods of attacking the error problems present in analog computers, sampled-data systems, and hybrid computers.

Error Analysis of Analog Computers

A good survey of methods developed for error analysis of analog computers is given by chapter 3 of Tomovic and Karplus*. A similar chapter appears in Eterman[1**]. A brief description of some of the most widely used methods is presented in this note. Details are available from the references cited.

A general approach to error analysis of analog computation has been developed by Miller and Murray[7]. Their method of analysis applies when a computer is solving a system of linear or nonlinear differential equations of the form

$$F_i(\dot{x}_1, \ldots, \dot{x}_n, x_1, \ldots, x_n, t) = 0, \quad i = 1, \ldots, n. \tag{1}$$

The system (1) is realized on the machine in the form

$$G_i(\dot{x}_1, \ldots, \dot{x}_n, x_1, \ldots, x_n, t, \alpha_1, \ldots, \alpha_M, \beta_1, \ldots, \beta_M, \gamma_1, \ldots, \gamma_p) = 0,$$

$$i = 1, \ldots, n. \tag{2}$$

The α, β, and γ values account for perturbation errors in the system components. The α and β values do not change the order of the system but the γ values do. The solution of system (2) has the general form

$$x_i = x_i(t, \alpha_1, \ldots, \alpha_N, \beta_1, \ldots, \beta_M, \gamma_1, \ldots, \gamma_p) \tag{3}$$

Since the solution (3) depends analytically on the α, β, and γ values, the solution can be expanded in a power series where partial derivatives of x_i with respect to α, β, and γ appear in the expansion. These partial derivatives are termed sensitivity coefficients and calculation or measurement of these sensitivity coefficients allows the errors in the solution to be expressed by means of Taylor-series expansions. The partial derivatives may be calculated by solving a linear system of differential equations whose homogeneous part is derived from the original equations. The partial derivatives may be measured by means of an experimental approach. They can also be obtained from the computer solution of the system of differential equations derived from the original equations.

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* Tomovic and Karplus, "High Speed Analog Computers," John Wiley, 1962

**Superscripts refer to Bibliography reference numbers.

When the system is restricted to be linear the error analysis becomes more straightforward and easier to handle. Many authors have used a Laplace transform approach which transfers the analysis of the linear system from the time domain to the complex-frequency domain. The characteristic equation of an n^{th} order differential equation can be expressed as

$$\sum_{i=o}^{n} a_i S^i = 0. \tag{4}$$

If the coefficients of equation (4) are perturbed a small amount, a new equation of the same form is obtained. The roots of the new equation are shifted with respect to the roots of the original equation. The root shifts can be determined by methods proposed by Macnee,[5] Marsocci,[6] Miura and Nagata,[8] and others. Probably the most sophisticated analysis of this type is that due to Miura and Nagata.[8]

Work by Nelson[10] is also of interest. The approach refers primarily to Miller and Murray;[7] sensitivities are defined; and root shifts are considered.

Error Analysis of Sampled-Data Systems

Extensive literature is available on the analysis of sampled-data systems but only a limited amount is available on the error analysis problem. It is impossible to summarize and perhaps even to identify all the work which might be of future use in the analysis of hybrid systems. Summaries of some of the various approaches follow.

Kuo[4] proposes the use of state transition flow graphs for analysis. The state transition flow graph of a continuous-data system is defined as the analog computer simulation flow graph of the system with initial conditions applied at corresponding nodes of the state variables as input signals. The state transition flow graph of a discrete-data system is similar but it contains arithmetic operations portraying digital programming. The two state transition flow graphs are combined for a system with discrete and continuous data. In the actual mathematical analysis Z transform theory is used.

Errors introduced by sampling and quantization are discussed by Nelson,[10] Katzenelson,[3] Widrow,[12] Turtle,[11] and others. The paper by Nelson[10] develops the mechanics of error in a digital differential analyzer and he applies the result of this development to rectangular and trapezoidal integration. The W transform is proposed for use in general analysis and several examples are included showing how the errors cause a shift in the roots of the characteristic equation.

The work by Katzenelson[3] evaluates the mean-square error, caused by sampling and quantization at the output of a linear network which contains a single quantizer.

Widrow[12] presents a statistical description of the quantization process. Several examples of closed loop systems containing quantizers in various locations are shown and an error analysis is included.

A statistical analysis of round-off error and a detailed discussion of truncation error is presented in the work by Turtle.[11] Analytical simplicity is obtained by representing an integrator by a transform so that block diagram algebra applies. Generation of an exponential is used as an example. The error bounds determined through analysis of the increasing exponential serve as error bounds for a large class of linear problems.

Synthesis procedures for sampled-data systems and the use of Z transforms are subjects covered by numerous authors, many of whom are included in the bibliography.

<u>Error Analysis of Hybrid Computers</u>

Since hybrid computers combine analog and digital systems, the errors of the overall system come from the errors inherent in each individual system but complications arise because of interaction between the systems. The methods of analysis applicable to analog and digital systems individually do not generally apply without modification to the hybrid computer although there is reason to expect modified forms of the methods could apply.

Very few papers in the literature deal directly with the effects of digital computation when it is used as part of a closed loop hybrid system. A promising article in this area is "Effects of Digital Execution Time in a Hybrid Computer" by Miura and Iwata.[9] This analysis is based on approximating the transfer function of the digital computer section by a function of the form

$$D(s) = Ae^{-(\tau + \frac{T}{2})s} \tag{5}$$

where τ represents a time delay due to digital computing time and T is the sampling period. This transfer function, when expanded in a power series, is used in conjunction with the characteristic equation of an ideal analog computer representation to derive a new characteristic equation which includes the effect of the digital system. The root shift of the hybrid system with respect to the ideal analog system is a measure of the error due to the digital section.

In summary, the survey of the literature indicates that the best approaches to error analysis of hybrid computers are probably:

1) The use of sensitivity coefficients based on a modification of the method of Miller and Murray; and

2) The use of root shifting techniques in linear problems or problems which can be linearized.

In both approaches approximations for transfer functions of different components will be useful and the use of a variety of mathematical tools such as Z transforms will be helpful.

Bibliography

The following references are separated into three categories:

I. References most directly concerned with error analysis of hybrid computers:

II. References of general interest as far as computers are concerned but of average interest as far as error analysis is concerned; and

III. References somewhat related to the problem but not to be considered as essential reading.

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