Time-Domain Measurements in Electromagnetics

Edited by

Edmund K. Miller

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TIME-DOMAIN MEASUREMENTS IN ELECTROMAGNETICS

This book is dedicated to my parents, Edmund W. and Viola L. Miller, who saw me through my BS degree; to my wife, Patricia A. Denn Miller, who helped make the PhD degree a reality; and to my children, Kerry A. and Mark C. Miller, who made it all worthwhile.

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Preface

The technology of making time-domain electromagnetic measurements continues to evolve as better sources, sensors, and instrumentation become available. Progressing from the radars of the 1940s with bandwidths of a few percent; to early TDR and EMP test systems of the 1960s with bandwidths of 2:1, or so; to the short-pulse hardware used today with bandwidths that can exceed 10:1—throughout all this development, there has occurred a steady improvement in time-domain technology. This improvement has accompanied an increasing variety of applications that benefit from or require wide-bandwidth systems. These include radar-target identification from short-pulse signatures, lightning and EMP analysis and protection, inverse and nondestructive evaluation, radiation and interference in high-speed digital systems, and various measurement applications ranging from basic studies to meeting routine data needs.

Although the technical literature exhibits a growing attention to time-domain technology, there does not yet exist a dedicated reference source that provides a comprehensive overview of the area. Were this source to be developed, it could contribute significantly to accelerating the development and exploitation of this important technology. The primary purpose of this book is to provide such a source by collecting together in one place an overview of the state-of-the-art in EM time-domain measurements. It is intended as a resource for those working in the area and as an introductory reference for the larger community of potential users. We are especially interested in seeing time-domain techniques, both experimental and computational, become more widely taught at the college level than is now the case. Thus, we stress the physical insight such techniques provide, as well as the relatively small expense of setting up a basic time-domain laboratory.

The specific idea for this book came about from my being invited to organize a special session of Commission A (Metrology) of the International Scientific Radio Union (URSI) at the 1982 United States National Meeting in Boulder, CO. The invitation was extended by Dr. Helmut Hellwig, then Commission A chairman, who felt that holding topical special sessions of the Commission dealing with various topics in measurement technology could contribute to the Commission's focus on metrology. Since my interest in computational and experimental time-domain electromagnetics extends back to the late 60s, I readily accepted, as the time seemed especially appropriate for a review of this important and fascinating area.

Special sessions at professional-society meetings are typically organized in one of two general ways, or some combination thereof. Perhaps the more common, simpler approach is to announce in the meeting's call for papers that certain topics will receive special attention, with the sessions then organized to accord with the papers submitted. As the other alternative, a specific outline is developed and presentations are identified so that some desired theme can be developed or a set of viewpoints presented. The latter approach was used for the Commission A session organized for the 1982 meeting, whose final title was "Time-Domain Measurements."

After discussion of these matters with various colleagues at Lawrence Livermore National Laboratory (H. C. Cabayan, K. F. Casey, R. J. Lytle, and A. J. Poggio), it was concluded that the overall topic of the special session could best be treated by subdividing it into the four basic areas of (1) background, benefits, and opportunities; (2) measurement technology; (3) applications; and (4) signal processing. These subjects form the main sections of this book, with the addition of an appendix dealing with design considerations and the hardware selection involved in setting up a time-domain range.

Although the session was developed for the sole purpose of providing a review of electromagnetics time-domain technology at the URSI meeting, response to the presentations was so positive that a book organized along similar lines seemed worthwhile considering. Consequently, I prepared a prospectus and outline, which Van Nostrand soon agreed to publish as an edited book, the results of which appear here.

The first section on background, benefits, and opportunities contains three chapters, which address, in turn, (1) historical development and motivations, (2) current status and future directions, and (3) instructional opportunities offered by time-domain measurements in electromagnetics. Chapter 1 by Dr. G. F. Ross, one of the pioneers of time-domain electromagnetics, sets the tone for the rest of the book. It does this by establishing the rationale for looking at EM phenomena in the time domain from the viewpoints of physical insight and efficiency of characterization. Dr. Ross demonstrates how representing equivalent information in the time domain differs from its frequency-domain counterpart and illustrates the benefits of time-domain analysis through the use of numerous examples. In Chap. 2 by Dr. N. S. Nahman, another long-time contributor to time-domain technology, the present status and future directions of time-domain measurements are reviewed. He summarizes information collected from numerous sources in text descriptions and tables and provides an extensive bibliography. This section concludes with a discussion of the instructional opportunities afforded by time-domain measurements by Dr. S. M. Riad in Chap. 3. Professor Riad describes three approaches that might be used to obtain transient information for linear problems and illustrates their attributes for the specific problem of deriving the impulse response of an RC network.

The second section on measurement technology describes the basic hardware needed to implement a time-domain range and contains four chapters that deal with (4) fast pulsers, (5) sensors and radiators, (6) instrumentation, and (7) the validation and calibration of a representative time-domain range. Dr. J. R. Andrews surveys subnanosecond, fast-pulse generators in Chap. 4, ranging from the low-energy extreme of milli-Joule transistorized pulsers to the high-energy extreme of mega-Joule linear accelerators. Dr. Andrews provides a figure of merit for comparing pulsers in terms of the time-rate-of-change of the output voltage, with values, in V/nsec, ranging from ~ 1 for transistor pulse generators to several thousand for spark gaps and linear accelerators. In Chap. 5, Dr. M. Kanda covers the kinds of radiators and sensors that are needed to produce and measure impulsive fields. Dr. Kanda provides both mathematical and physical explanations for how impulsively excited antennas behave when used as transmitters or receivers and presents extensive results from analysis and measurement. The instrumentation required to complete the measurement system is discussed in Chap. 6 by Dr. G. D. Sower and Mr. J. R. Pressley. They describe the various kinds of hardware that might be used for this purpose, ranging from film-based recording systems to electronic transient digitizers. To conclude the section on measurement technology, Drs. R. M. Bevensee and E. K. Miller demonstrate how all of the various components are brought together in developing a working time-domain range. In particular, they describe the Electromagnetic Transient Facility at Lawrence Livermore National Laboratory, the procedures employed for its calibration and validation, and various applications for which it has been used.

In the third section are a variety of examples of time-domain applications in electromagnetics. The four chapters included here deal with (8) EMP measurement techniques, (9) applications of a subsurface, transient radar, (10) the time-domain measurement of components and materials, and (11) the measurement of lightning waveforms. Drs. J. P. Castillo and L. Marin present an introduction to making EMP measurements in Chap. 8. They discuss the simulators (radiators), instrumentation, and data-acquisition and processing systems employed in EMP applications; they also explain how EMP simulation needs provided the impetus for much of the development that has occurred in short-pulse technology in electromagnetics. The intriguing area of near subsurface exploration using a transient radar is covered in Chap. 9 by Drs. J. D. Young and L. Peters. They consider requirements unique to this kind of application, including pulse propagation in a lossy, dispersive medium that typifies most real grounds and comment on the data-processing needs for this particular application. In Chap. 10, the use of time-domain measurement techniques to characterize both components and materials is explored by Dr. H. M. Cronson. He demonstrates the advantages and limitations of using short-pulse data to obtain wide-band information in closed systems. The concluding applications discussion in Chapter 11 by Drs.

E. F. Vance and J. Nanovitz covers the real-world problem of measuring lightning-induced phenomena. They examine the almost unique requirements of measuring lightning waveforms and present current capabilities and representative results in this particular area.

The text proper concludes with two chapters on some signal-processing issues. The general problem of processing transient signals is discussed in Chap. 12 by Drs. J. V. Candy, D. B. Harris, and D. M. Goodman, who provide an overview of the techniques presently being used. The closely related, but more specialized, topic of electromagnetic parameter estimation from transient waveforms is treated in Chap. 13 by Drs. D. G. Dudley and D. M. Goodman. The message conveyed by both chapters is that for fuller realization of the benefits of time-domain measurements, it is mandatory to give appropriate attention to processing the waveforms involved. Failure to do so may result in available information not being extracted from the data, or, even worse, incorrect answers being obtained.

Closing out the book, an appendix by Dr. J. A. Landt summarizes the issues involved in selecting hardware and designing a time-domain range. This discussion reviews the various tradeoffs and design choices to be kept in mind in the design process. Dr. Landt includes performance specifications and price information and provides a nominal design for a time-domain range.

Other features of the book include comprehensive references at the end of every chapter (more than 400 entries in all), which provide an excellent resource base for more detailed information about the subjects treated. Finally, a keyword and abbreviation list should help the reader decipher the specialized and sometimes cryptic terminology employed in the text for the sake of conciseness.

I would like to acknowledge the cooperation of the chapter authors cited here for their hard work and persistence in seeing this project through to its conclusion. It has been a pleasure to work with them. I also want to express my appreciation to Rose O'Brien and Jan Grimm of LLNL, who provided expert and enthusiastic secretarial help during the course of this endeavor. Finally, the contributions of Barbara Sokolowski, also of LLNL, were above and beyond the call of duty in her dedicated typing of the entire manuscript.

EDMUND K. MILLER

Contents

1
Early Developments and Motivations for Time-Domain Analysis and Application

Gerald F. Ross, Ph.D

Anro Engineering Consultants, Inc.

1.0 INTRODUCTION

Although the use of the time domain for analysis and synthesis became prominent with the corresponding advances in the development of short pulse hardware and instrumentation, one may ask what the motivation is for using the time domain or, for that matter, any other domain for the analysis and synthesis of lumped and distributed networks. In classical analysis, we know that a linear, time-invariant system can be described uniquely by its impulse response, $h(t)$. And, from the impulse response, we can find the amplitude spectrum, $A(\omega)$, and the phase function, $\phi(\omega)$, by a Fourier transformation as follows:

$$F(\omega) = A(\omega)e^{-j\phi(\omega)} \overset{\mathbf{F}}{\leftrightarrow} h(t) \tag{1-1}$$

But we may also describe a network in the complex domain, $p = \sigma + j\omega$, by a Laplace transform, or in the domain, $Z = e^{+pT,}$ where poles and zeros in the complex plane fall within the unit circle (T is a sampling constant). Other representations, of course, are also possible and useful.

As engineers, we seek simply the domain that presents a mathematical solution most compactly: a domain where the response of a network in time, or its real or complex spectrum, can readily be defined. The use of such a domain, almost as a by-product, provides insight for system behavior.

As an example, consider a high Q series or parallel resonant circuit. The duration of the impulse response of such a circuit may exist over most of the time domain, but in the frequency domain, it is well contained over a narrow bandwidth. The time domain would be the wrong domain in which to describe the behavior of the network or to measure its properties; the network can be readily described, however, in the frequency domain.

In a stable, sample-data system where a closed-form solution for the system function exists, the Laplace transform consists of an infinitely denumerable number of poles and zeros that are periodic in the left hand plane. By describing the system in the $Z = e^{+pT}$ plane, the periodic poles and zeros all coalesce and map as a finite number of points within the unit circle.[1] Clearly, the complex Z plane provides the most convenient domain to represent the properties of the networks.

In certain very wideband networks (for example, a length of TEM mode line), the time-domain representation is the obvious choice. The impulse response is simply a delayed impulse. We cannot generate or realize a perfect impulse, but we can generate a short pulse, one whose duration is much shorter than the duration of the impulse response. Recent advances in pulse technology using tunnel diodes permit the generation of pulses as short as 20 picoseconds for diagnostic purposes, and recent developments in sampling oscilloscope technology permit one to display these pulses.[2] The capability of generating and displaying pulses of such short duration leads to many interesting system applications, as will be described in later sections of this chapter.

In Sec. 1.1, direct time-domain techniques, both theoretical and experimental, are described. In Sec. 1.2, these techniques are applied to the analysis of microwave networks, antennas, target scattering, and material diagnostics. Some system applications that developed directly from the analytical tools are described in Sec. 1.3, and a brief summary is presented in Sec. 1.4.

1.1 ANALYSIS IN THE TIME DOMAIN

Theoretical Formulation

As indicated in the introduction, when the response of a network or system is well contained in the time domain (i.e., time-limited), analysis in the time domain is most appropriate.

The convolution integral is used in linear systems analysis to find the response, $r(t)$, of a system to an excitation, $f(t)$, knowing its impulse response, $h(t)$. The most general form of the convolution integral is given by the following[3]:

$$\begin{aligned} r(t) &= \int_{-\infty}^{+\infty} h(x)f(t - x)dx \\ &= \int_{-\infty}^{+\infty} f(x)h(t - x)dx \end{aligned} \tag{1-2}$$

where x is a dummy variable. Here, the upper and lower limits on the integral x are $+\infty$ and $-\infty$, respectively. Often, however, neither the function $h(x)$ nor

$f(x)$ exists over the entire space, $-\infty < x < \infty$, and it is appropriate to modify the limits on Eq. 1-2. The choice of the integration interval (i.e., the choice of upper and lower limits) often is not obvious. In the paragraphs that follow, the limits on the integral will be given for the most functions $h(t)$ and $f(t)$. The method involves the novel use of the step function.[4]

The step function method. Assume it is required to convolve the two functions, $h(t)$ and $f(t)$, shown in Fig. 1-1, where $h(t)$ exists for all positive time, t (abbreviated $\forall_{t+}$), and $f(t)$ exists for negative time, $\forall_{t-}$, but is time limited for t positive (abbreviated tl_{t+}). The existence of these signals in the time domain can be conveniently described by the use of step functions. For example, the functions $h(t)$ and $f(t)$ shown in Fig. 1-1 may be described as

$$\begin{aligned} h(t) &= 0 \qquad t < 0 \\ h(t) & \qquad\quad t > 0 \end{aligned} \tag{1-3a}$$

$$\begin{aligned} f(t) &= 0 \qquad t > T \\ f(t) & \qquad\quad -\infty < t < T \end{aligned} \tag{1-3b}$$

or more compactly as

$$\begin{aligned} h &= h(t) \times U(t) \\ f &= f(t) \times U(T - t) \end{aligned} \tag{1-4}$$

where

$$\begin{aligned} U(t) &= 0,\ t < 0 \\ U(t) &= 1,\ t > 0 \end{aligned}$$

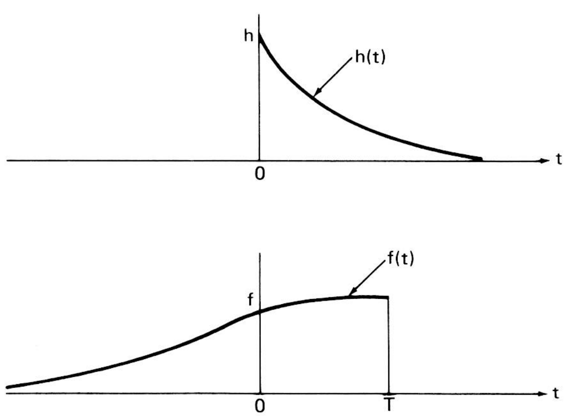

Fig. 1-1. Functions $h(t)$ and $f(t)$.

To find $h(t) * f(t)$, or the convolution of $h(t)$ with $f(t)$, one substitutes Eq. 1-4 into Eq. 1-2 and obtains

$$\begin{aligned} r(t) &= \int_{-\infty}^{+\infty} [h(x)U(x)][f(t - x) \cdot U(x + T - t)]dx \\ &= \int_{-\infty}^{+\infty} h(x)f(t - x)\frac{U(x)}{2} \cdot 2U(x + T - t)dx \end{aligned} \tag{1-5}$$

where x and $(t - x)$ have been substituted for t in the expressions for $h(t)$ and $f(t)$, respectively.

The bracketed term in the integrand of Eq. 1-5 can be used to determine the specific limits on the integral. This term is shown in Fig. 1-2. When the constant, $t - T$, is greater than zero (i.e., with respect to the variable of integration x), the value of the integrand (determined by the product of the two displaced step functions) is zero $\forall x < t - T$, as shown in Fig. 1-2.

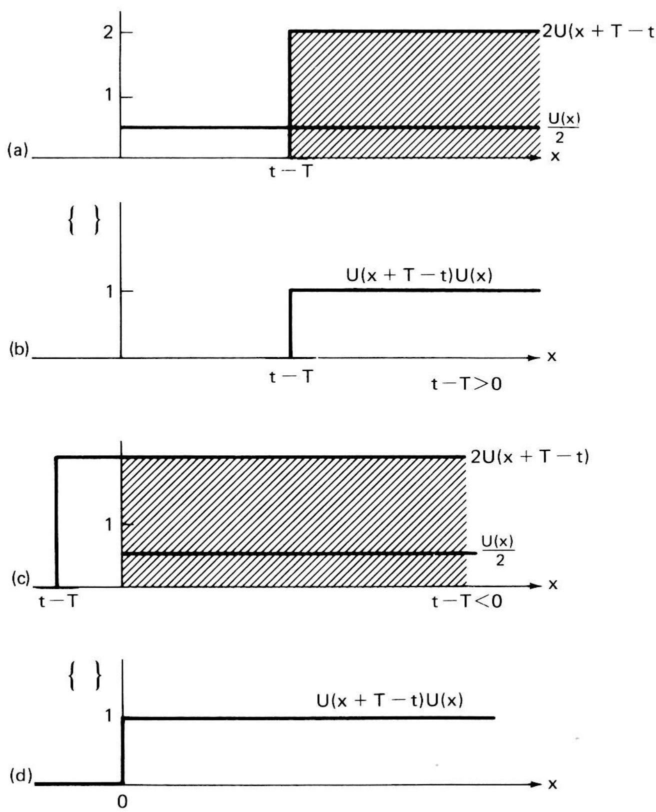

Fig. 1-2. The product of step functions.

When $t - T < 0$, the product of the two displaced step functions is zero $\forall x < 0$, as shown in Figs. 1-2(c) and 1-2(d). Thus,

$$r(t = \int_0^{\infty} h(x)f(t - x)dx \qquad \text{for } t - T < 0, \text{ or } \forall_{t < T} \qquad (1\text{-}6)$$

$$r(t) = \int_{t - T}^{\infty} h(x)f(t - x)dx \qquad \text{for } t - T > 0, \text{ or } \forall_{t > T} \qquad (1\text{-}7)$$

The integration indicated by Eq. 1-5 is with respect to the dummy variable x, and t and T are simply constants, as illustrated in Fig. 1-2. The limits on the integral are determined by assuming, alternately, that the constant is greater than or less than zero and then solving the inequality for t. The solution of t determines the region over which the answer, $r(t)$, is valid. A chart showing various combinations of possible functions, $h(t)$ and $f(t)$, is given in Fig. 1-3. The limits on the convolution integral of these combinations is presented in Table 1-1. In Fig. 1-3, some functions that are *tl* were selected, for convenience, to originate

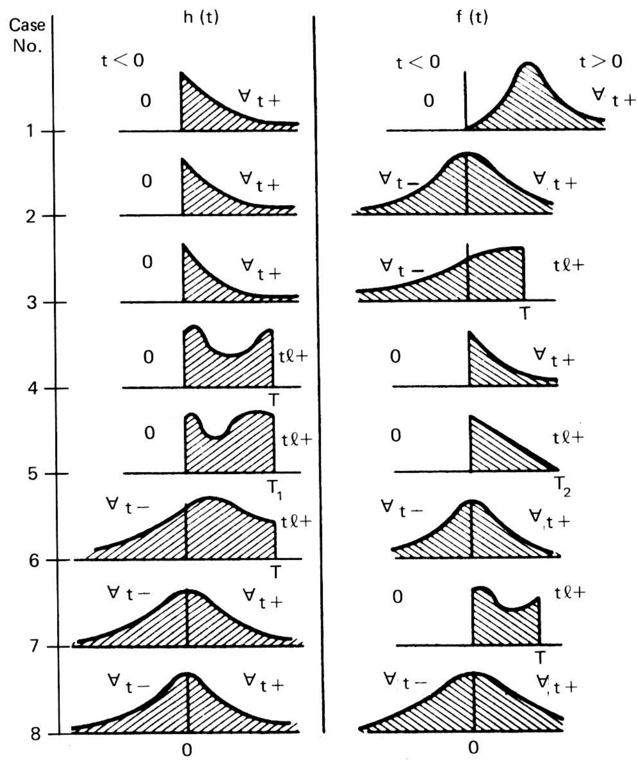

Fig. 1-3. Combinations of signals, $h(t)$ and $f(t)$.