

59: Introduction to the Dynamic Regime of Measurement Systems

Peter H. Sydenham

GSEC Pty Ltd, Adelaide, South Australia

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1 INTRODUCTION TO THE DYNAMIC REGIME OF MEASUREMENT SYSTEMS PERFORMANCE

The dynamic regime of an instrument stage is generally a more complex aspect to characterize and test than the stage's static performance. To fully understand the behavior during the dynamic state, it is necessary to allow additionally for the transient solution of the transfer characteristic when forced by an input function, a factor that is not important in understanding the steady state and static regime behaviors.

Dynamic behavior of systems has been well explained at the theoretical level if the performance remains linear during the dynamic state. It has been shown that the energy relationships of electrical, mechanical, thermal, and fluid regimes can each be characterized by the same mathematical description and that a system containing a cascaded chain of a mixture of these, as is typical of instrument systems, can be studied in a coherent manner by the use of such mathematical techniques. This body of knowledge and technique lies in the field

of the dynamics of systems. (This is not to be confused with a subject area called *Systems Dynamics*, SD, that is somewhat different to that being described here.) It has progressively grown from isolated, unconnected explanations of the analogous situations existing mainly in electrical, mechanical, and acoustical areas, into one cohesive systematic approach to the study of the dynamics of linear physical systems.

The approach has been widened considerably (see Klirs, 1972), to take in philosophical concepts, such as are found in social systems, this broader assembly of knowledge usually being referred to as *general systems theory*. General systems theory certainly has application and potential in some instrument systems, but most designers and users of instruments will find that the more confined and mathematically rigorous assembly of technique and knowledge (systems dynamics) will be that found to be usefully applicable in practical realization and understanding of measuring systems. The use of the word systems is extremely common and carries numerous connotations ranging from a totally general concept to the quite specific use that is based in mathematical explanation.

As indicators of the part that is useful to measuring instrument dynamic studies the reader is referred to some classic texts that sorted out this field well. Karnopp and Rosenberg (1975), MacFarlane (1964), Paynter (1961), Shearer, Murphy and Richardson (1967), and Zahed and Desoer (1963) for general expositions, and to Coughanowr and Koppel (1965), Fitzgerald and Kingsley (1961), Koenig and Blackwell (1961), and Olson (1943) for more specific uses in areas of chemical plant, electrical machines, electromechanical devices, and the so-called analogies,

respectively. Other more recent works of the engineering systems kind are Franklin (1997), Hsu and Hse (1996), Nise (2000), Oppenheim *et al.* (1996).

Several authors have extracted, from the total systems knowledge contained in such works, the much smaller part that is needed by measuring systems interests, presenting this as chapters in their works. Such accounts are to be found in Beckwith and Buck (1969), Doebelin (2003), and Neubert (1976).

Notable foundation papers have also been published that further condense the information for measurement systems application (see Bosman, 1978; Finkelstein and Watts, 1978). Finally, many control-theory-based works are of relevance.

There exists, therefore, a considerable quantity of well-organized knowledge about the physical behavior that may be encountered in measurement systems studies. When response is linear it is possible to make use of mathematical models to obtain a very workable understanding of the dynamic behavior. If it is nonlinear, however, then the situation is not so well catered for because no such widespread and generally applicable mathematical foundation has been forthcoming in truly formal description terms. In practice, however, designers and users of instruments can find considerable value in assuming linearity, if only for a limited range of operation. For this reason, it is important to know how to recognize whether a system functions in a linear manner and which techniques apply in such cases. Further, it is often up to the designer to choose methods and, thus, it is recommended that consideration be given to the use of those modules that do respond in a linear manner for their operation can be modeled precisely using long hand math or modeling tools.

The purpose of this article is not to expound the mathematical modeling and design of transducers in a concise and rigorous manner, but to present the commonly seen characteristics of linear dynamic systems that will be encountered so that they can be recognized and operated upon by using a fundamental approach that is based on knowledge of their characteristics, *see Article 19, Dynamic Behavior of Closed-loop Systems, Volume 1*. It also provides the basic descriptive terminology needed in specification of response characteristics.

2 FORCING FUNCTIONS

To see how a stage performs to various kinds of changing input signals, it is forced into its transient state by one or more external inputs. These are termed *forcing input* or *excitation functions*. They may be applied to the intentional input of the stage or cause transient behavior by entering, as

influence quantities, through numerous other unintentional ports. In reality the true two-port, four-terminal, instrument stage can rarely be realized for virtually all designs are influenced to some extent by unwanted noise perturbations entering through many mechanisms.

When considering the dynamic response that might arise for a stage it is, therefore, necessary to first decide the ports through which a forcing function signal might enter. This decided, the next step is to assess which kind of forcing function is relevant and apply this to the real physical device, or to its correct mathematical model expressed in the state-variable or transfer function form. Alternatively, it might be simulated in a digital computer. When the transfer function model is used, the product of the Laplace transform of the forcing function and the transfer function can be solved to provide the transient dynamic behavior in a reasonably simple manner, *see Article 19, Dynamic Behavior of Closed-loop Systems, Volume 1*. This method is dealt with in detail numerous electrical engineering and systems texts. Here are presented some typical forcing functions that might be used to test or study an instrument stage.

Certain types of forcing function lend themselves to analytical solution being easy to apply to the Laplace method of response evaluation. They are also simple to procure as practical test signals that, although not perfect, come close enough to the mathematical ideal. For these reasons, testing and evaluation of systems tends to attempt first to make use of one or more of several basic forcing functions.

These functions (see Figure 1) are the discontinuous unit step and the unit impulse, the ramp plus the continuous sine wave. They are described elsewhere and, therefore they do not need further theoretical expansion here.

These functions are easy to produce and apply in practice, but it must be recognized that they may not provide an adequate simulation of the real forcing signals existing. This point is not always made clear in the general treatment of the dynamics of common linear systems stages.

When such simplifications are not adequate, other more suitable ones must be applied. If they can be transformed with the Laplace transform expression, and if the product with the transfer function can be arranged so that a solution into time-variant terms is obtained, then a theoretical study can be made. In many cases, however, this is not possible within bounds of realistic adequacy, and alternative methods of study must be employed if no way can be seen to simplify satisfactorily the forcing transfer function. Simulation using a computer-based tool often provides the means to a solution.

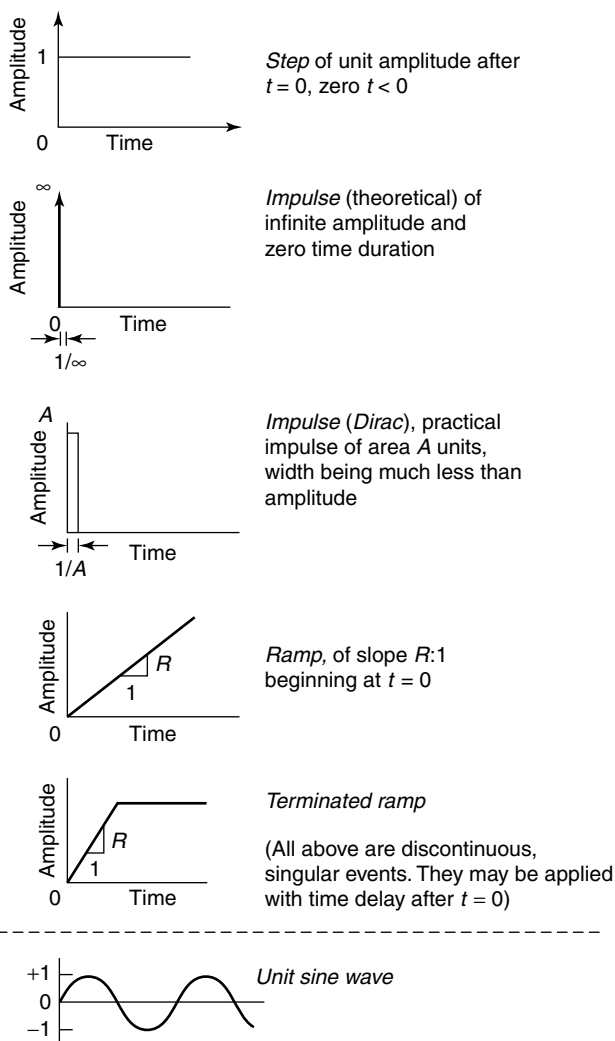


Figure 1. Typical forcing functions used in testing and study of the dynamic response of systems.

3 APPLICATION OF FORCING FUNCTIONS

A step or impulse will excite a system into its dynamic transient response as might a sudden change of demand in a control loop, or a sudden change in a measurand as exists when an indicating voltmeter is first connected to a live circuit. Many physical systems, however, cannot provide such rapidly changing signals. Mechanical and thermal systems often cannot supply a rate of rise that is great enough to be regarded as a step because of the presence of significant storage of energy within the components. For example, attempting to square-wave modulate the dimensions of a piezoelectric crystal at relatively high frequency will produce quasi-sinusoidal output response, not a square wave – the crystal acts as a filter. Similarly, it is not possible to

provide a perfect step function to a pressure sensor to obtain its step response. Faster acting systems, such as found in the electronic and optical disciplines, can supply rapid changes.

When the response to a slow-to-rise input signal is needed, the use of the step or impulse function may provide misleading information. A ramp function is more applicable in such cases. Many of the published systematized transient behavior descriptions have not included this particular forcing function, the solutions usually presented being for impulse, step, and sine wave inputs. Sinusoidal excitation can, however, sometimes be used to approximate ramp responses.

The unit impulse function represents the input provided by a sudden shock in a mechanical system – it might be due to slackness in a drive link taking up. In electronic systems, it represents such events as a high-voltage pulse generated by lightning or the switching surges from a nonzero crossing controlled silicon controlled rectifier. In practice, a pseudoimpulsive function, called the *Dirac* or *delta function*, is used instead of the true impulse. As will be seen, the transient solutions of typical linear systems to impulse and step functions are somewhat similar in transient shape.

The third most commonly used input function is the sine wave (or cosine wave, which is the same function, phase-shifted in time). This acts to excite a system in a continuous cyclic manner forcing it to be excited in both the transient and steady state when the sine wave is initially applied, the former dying away to leave the latter as the solution most usually discussed.

In practice, systems are often likely to be disturbed by a continuous complex input waveform. As complex waveforms can be broken down, by Fourier techniques, into a set of sine waves of different frequencies, amplitudes, and phases, the use of sine waves of the correct amplitude and frequency enables the system to be studied one component at a time. Sine wave response is also called *frequency response*, see **Article 27, Signals in the Frequency Domain, Volume 1; Article 28, Signals in the Time Domain, Volume 1; and Article 29, Relationship Between Signals in the Time and Frequency Domain, Volume 1.**

The concept that a complex continuous waveform can be so resolved into separate components rests on the assumption that the system is linear and that superposition applies. Nonlinear systems can behave quite differently to complex signals, creating, for instance, harmonics of lower frequency than those existing in the original signal.

It is often considerably easier, and more reliable to obtain the transient response of a system by practical testing than it would be to develop a mathematical model. This is one of the reasons why the data sheets of instrument products

often include graphical statements of transient response. Further, a detail about forcing functions can be found in chapters of classical control texts such as Atkinson (1972), Coughanowr and Koppel (1965), and Shearer, Murphy and Richardson (1967).

RELATED ARTICLES

Article 18, Nature and Scope of Closed-loop Systems, Volume 1; Article 19, Dynamic Behavior of Closed-loop Systems, Volume 1; Article 27, Signals in the Frequency Domain, Volume 1; Article 28, Signals in the Time Domain, Volume 1; Article 29, Relationship Between Signals in the Time and Frequency Domain, Volume 1; Article 30, Statistical Signal Representations, Volume 1.

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