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A CURRENT VISION

A new approach to signals and dynamic systems

Un nuevo enfoque de señales y sistemas dinámicos

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Abstract

This document based on the concept of Dynamic Systems presents a compilation of singular signals and their applications for Control and Identification. The following paper moves away from the usual presentation of the topic -strictly mathematical- to bring it closer to the Systems Dynamics approach, which implies showing the signals importance in the development of operational character with the direct and inverse Laplace transform and the transfer functions calculation, as well as in the solution of models established by Ordinary Differential Equations

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with constant coefficients, particularly in first and second order Dynamic Systems stimuli-response that appear in Identification processes.

Keywords: Applications, Control, Dynamic Systems, Identification, Operations, Singular signals.

Resumen

Este documento a partir del concepto de Sistemas Dinámicos presenta una recopilación de las señales singulares y sus aplicaciones para el Control e Identificación. El presente artículo se aleja de la presentación usual del tema –estrictamente matemático- para acercarlo al enfoque de la Dinámica de Sistemas que implica mostrar la importancia de las señales en el desarrollo de carácter operativo con la transformada de Laplace directa e inversa y el cálculo de funciones de transferencia, así como en la solución de modelos establecidos por Ecuaciones Diferenciales Ordinarias con coeficientes constantes, particularmente en estímulo-respuesta de Sistemas Dinámicos de primer y segundo orden que aparecen en procesos de Identificación.

Palabras clave: Aplicaciones, Control, Sistemas Dinámicos, Identificación, Operaciones, Señales singulares.

1. Introduction

The word dynamic refers, in essence, to the non-static; in the case of Dynamic Systems, then, it is possible to define as systems those that have related elements to each other in such a way that a change in one of them affects the set of all the others, therefore there are diverse behaviors, states or forms of response in time. These systems can be modeled in order to have a mathematical approach or a comprehensible and simplified description of the phenomenon that concrete reality cannot exhibit. In that sense, non-static physical systems are an example of a dynamic system [1-2]

In Dynamic Systems the input, output and internal response variables are time signals (for continuous time systems) or time sequences (for discrete time systems) [3], [4], [1], [5]. The signals, thanks to their presence in diverse natural sources, and being physical phenomena the ones that generate them, must be widely known and if necessary manipulated. This gives reason to the need to understand their behavior, operativity, and superposition -among others of the so called singular signals- so that the field of the analogous Control and the analysis of systems is really understood [3], [4], [6]–[27].

For this reason, in the researches that are made about how to teach correctly the signals theory and what subjects are essential so that the level of its comprehension is complete, the signals theory and its applications becomes important [28]–[41]. In this sense, the signal applications in Dynamic Systems and Control range from their use in the definition of Laplace's direct and inverse transform, to the practical concept of Identification of Dynamic Systems. In general, the signals are used in these fields in all mathematical or experimental analysis [4], [1], [6], [7], [20], [42]–[50].

Given the above, the success of a good signal theory analysis is based on understanding certain signals and their properties. Consequently, the objective of this paper is to show a practical compilation of signals, their operations and applications in Dynamic Systems. It is expected that this approach will solidify the signal knowledge in continuous time, its operations, as well as some applications in Dynamic Systems and Control.

This paper is organized as follows: In section 2 the signal relevance in Dynamic Systems is shown; in section 3 the signal operations are observed, as well as some examples of composite signals; in section 4 the model conceptualization is done and some examples of the application of the model theory in Dynamic Systems and Control are shown.

2. Signal relevance in Dynamic Systems

2.1 Typical Signals Relevance in Dynamic Systems

The actual system excitations are almost always varied and strictly random signals. However, the engineer analyzes and designs based on simple signals -such as Senoids-, [3], [8], [11], [16], [18], [20], [22]–[24], [51]–[53].

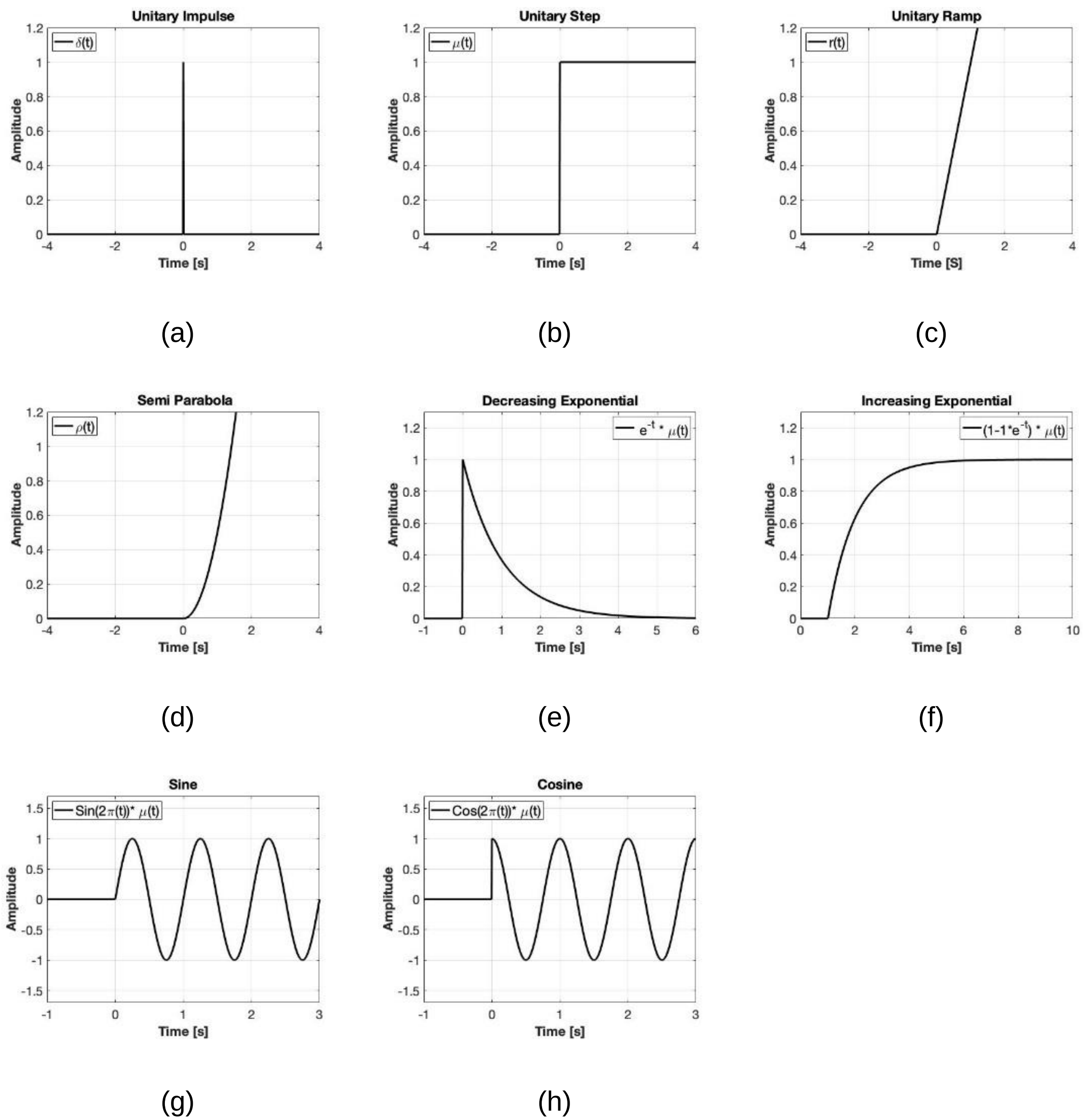
In the proposed direction, periodic signals are relevant to steady state studies in systems. For example, Fourier analysis can be used to obtain the frequency response to periodic and non-periodic signals by Fourier series and integral resource – when the function period tends to infinity. In other cases, the form of a sudden or gradual change in excitation that produces effects on the response is of interest; these considerations motivate interest in the so-called Singular Signals [3], [15], [16], [18], [22], [51], [54], [55].

2.2. Signal

A signal is a physical magnitude that may or may not give information on its own, coming from a generally physical or digital source. In the first case they are normally transformed to electrical signals through transducers [8], [10], [12], [16], [22], [30], [32], [40], [46], [51], [56]–[59]. The signals, in their most basic form, are classified according to the variable on which they depend (time, space, temperature, among others) [8], [10], [12], [16], [22], [30], [32], [40], [46], [51], [56]–[59]. In discrete signals they only have values in a discrete number of points [8], [10], [12], [16], [18], [30], [32], [40], [51], [54], [56]–[58], [60]–[62]. These signals come in general from analog-to-digital converters; or their equivalents: the signal continuous discretization [3], [24], [34], [52],

[57]. In this context the efficient compression and handling of the theory behind the signals is fundamental for both industrial and academic applications: [9], [19], [46], [51], [52], [56], [59], [60], [63].

Figure 1. (a) Unitary Impulse, (b) Unitary Step, (c) Unitary Ramp, (d) Semi-Parabola, (e) Decreasing Exponential, (f) Increasing Exponential, (g) Sine, (h) Cosine.



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2.3. Singular Signals

The main role in non-periodic impulse type signals is played by the so-called singular signals: composed by the unitary step and its derivatives and integrals [9], [13], [14], [21], [22].

2.3.1. Unitary Step

It is a signal that is usually employed in the physical systems operation due to its state characteristics in low and then in high. In addition to being useful in Control system response tests, it simplifies the transfer signal characterization of a dynamic system. It is defined as follows:

$$\mu(t) = \begin{cases} 0 \ when \ \ t < 0 \\ 1 \ when \ \ t \geq 0 \end{cases} \tag{1}$$

See figure 1 (b).

The graph shows a continuous signal except at *t=0*; it is important because it characterizes every signal "that has an ignition or start". See Figure 1 (b). This can be a useful tool for testing and defining other signals. For example, the unitary step signal is operated with other signals to select a certain part of the signal.

2.3.2. Unitary Ramp

The first integral of the unitary step results in a signal called the unitary ramp described by:

$$r(t) = \int_{-\infty}^{t} \mu(t)dt = t\,\mu(t) = \begin{cases} 0 \ when \ t < 0 \\ t \ when \ t \geq 0 \end{cases} \tag{2}$$

The graphical representation will allow you to observe its behavior better. See Figure 1 (c).

Note how *r(t)* can be expressed as *tμ(t)* ; that is, the specific slope line multiplied by the unit step in this case starting at *t=0*. See Figure 1 (c)..

2.3.3. Semi-Parabola

Applying double integral to the unitary step signal results in the signal in time called semi-parabola, which is described by the following equation:

$$\rho(t) = \int_{-\infty}^{t} r(t)dx = \int_{-\infty}^{t} t\mu(t)dt = \begin{cases} \left(\frac{1}{2}\right)t^2 & when\ \ t \geq 0 \\ 0 & \text{when}\ \ t < 0 \end{cases} \tag{3}$$

Based on the above equation, the semiparabolic signal can be described as follows:

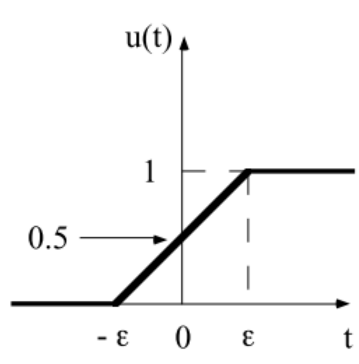
$$\rho(t) = \left(\frac{1}{2}\right) t\, r(t) = \left(\frac{1}{2}\right) t^2 \mu(t) \tag{4}$$

For a better signal visualization, see figure 1 (d).

2.3.4. Unitary Impulse

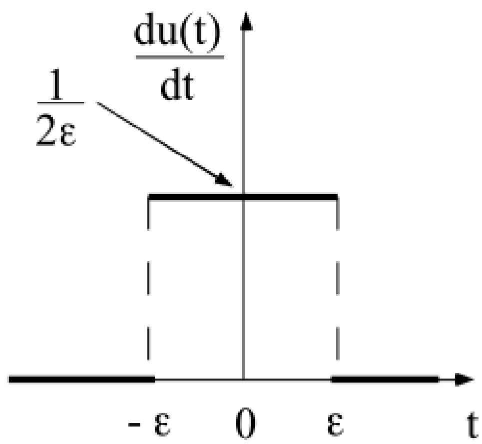
In order to obtain the unitary impulse signal, referring to the first derivative of the unitary step, a linear approximation to the step signal is defined. The approximation is expressed in terms of a parameter (*ε*) that can be made as close to 0 as desired, figure 2.

Figure 2. Unitary step representation on a time scale tending to 0 [27].



In the unitary step derivative, in the generalized distributional sense, the length tends to 0 and the amplitude tends to ∞ In addition, the area between the signal and the abscissa axis remains constant when ε tends to 0, figure 3.

Figure 3. Unitary step drift representation [27].



The derivative is the unitary impulse signal (Dirac delta) bearing in mind that ε tends to 0:

$$\delta(t) = \lim_{\varepsilon \to 0} \frac{du}{dt} \tag{5}$$

After obtaining the mathematical representation of what the signal would be, the signal behavior in time is noted in Figure 1 (a).

2.4. Non-Singular Signals, Exponential Signal

In what is called dynamic analysis, exponential signals that start and sometimes end in finite times are of interest. It will be increasing exponentials if it include a term e^{at} with $a > 0$ and decreasing if it include e^{-at} with $a > 0$. See Figure 1 (e), (f).

The decreasing exponentials are characterized by:

- Initiation time and initial value.
- Time constant.
- The asymptote in other cases, the completion time.

Its general representation is presented as follows:

$$f(t) = \left[B + Ae^{\frac{-(t-t_0)}{\tau}}\right] * \mu(t - t_0) \qquad (6)$$

Where B refers to the asymptote of the signal, B+A to the initial signal value and τ time constant of the exponential signal. See Figure 1 (e), (f).

2.4.1. Sine Signal

The sinusoidal signal constitutes the periodic signal of importance in the study of systems since, for example, for Fourier analysis any periodic signal can be reduced to an overlapping of sinuses and cosines.

The sinusoidal signal is characterized by:

- Magnitude (A)
- Frecuency (ω)
- Phase (φ)

The period of a sinusoidal signal is the distance between two successive and equal signal peaks:

$$T = 2\pi/\omega \tag{7}$$

2.4.2. Cosine Signal

The cosine signals mathematical representation is, in general, in Dynamic Systems as follows:

$$f(t) = [A\cos(\omega t + \varphi)] * \mu(t) \tag{8}$$

For a better understanding of the behavior see Figure 1 (h).

2.4.3. Sine Signal

The sine signals mathematical representation is, in general, in Dynamic Systems as follows:

$$f(t) = [A\,\mathrm{Sin}(\omega t + \varphi)].\,\mu(t) \tag{9}$$

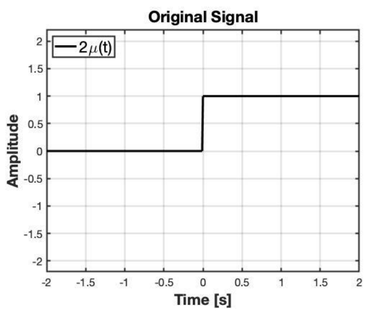
The signal is shown simply and clearly in Figure 1 (g).

3. Signals basic operations in continuous time

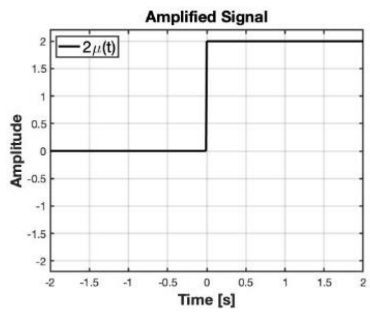
3.1. Signal Basic Operations

An important element in the signal study are the basic operations that can be applied to a signal. Here are some of the basic operations. Each one of these implies a modification of the signal variables: either time or amplitude, [3], [8], [9], [16], [18], [19], [24].

Figure 4. (a) Original Signal, (b) Amplified Signal, (c) Inverted Signal, (d) Attenuated Signal, (e) Forward Displaced Signal, (f) Backward Displaced Signal, (g) Scaled Step Signal, (h) Reflected Signal.



(a)



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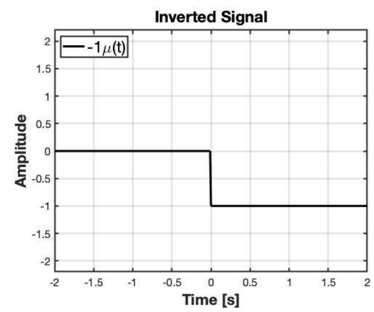

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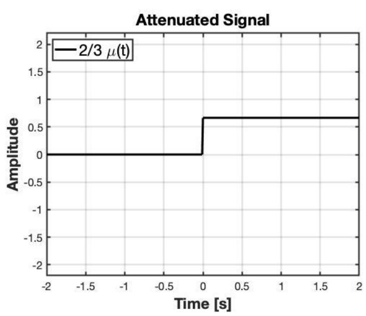

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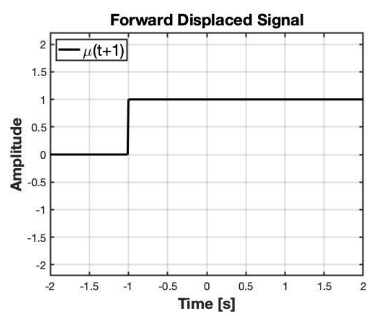
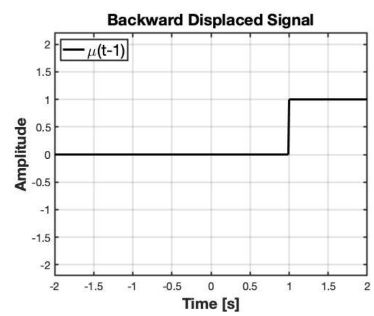
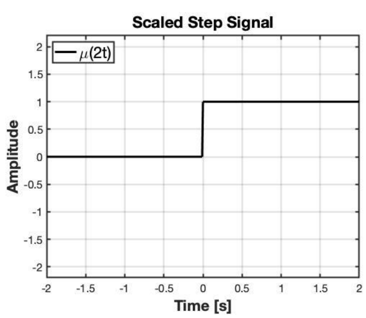


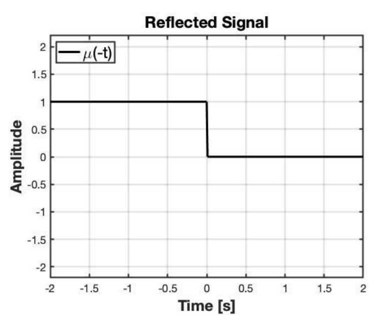
(e)



(f)



(g)



(h)

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3.1.1. Amplification

The first operation is amplification, this operation maps the input signal $x(t)$ to the output signal $f(t)$ which is the result of a modification in the original signal amplitude as well:

$$f(t) = ax(t) \tag{10}$$

Where a is the amplification constant, this constant is greater than 1, for a better representation see Figure 4 (a) and Figure 4 (b) being the signal resulting from the amplification twice of the original signal [9], [16], [17], [26].

3.1.2. Inversion

Inversion is an operation that reflects or inverts the signal with respect to the x-axis or maps the input signal $x(t)$ to the output signal $f(t)$ that is the result of an inversion of the original signal as follows:

$$f(t) = -x(t) \tag{11}$$

To more clearly identify the behavior, see Figure 4 (c) with the signal resulting from the inversion in Figure 4 (a) [26], [27].

3.1.3. Attenuation

The attenuation is an operation in which the input signal is $x(t)$ and an output signal$f(t)$ that is the result of a modification in the amplitude of the original signal reducing it in magnitude or attenuating it, the operation is represented by (12) where a is the attenuation constant and in addition $0 < a < 1$, as an example it can be seen Figure 4 (d) that has $\frac{2}{3}$ of amplitude with respect to the original signal of Figure 4 (a). [3], [36], [51], [64].

3.1.4. Discplacement over time

This is the transformation of a signal, mapping the input signal $x\ (t)$ to the output signal $f\ (t)$ as specified by:

$$y\ (t)\ =\ x\ (t\ - t_0) \tag{12}$$

Where t_0 is the displacement constant, the output signal $y\ (t)$ is formed by replacing t with $t\ - t_0$ in the input signal in other words this operation shifts the signal (left or right) along the time axis. If t_0 is positive, $y\ (t)$ is the input signal shifted to the right with respect to $x\ (t)$ that is, delayed in time, see Figure 4 (f). If t_0 is negative, $y\ (t)$ moves to the left with respect to $x\ (t)$ that is, advanced in time, see Figure 4 (e) [9], [16], [19]–[21], [23], [24], [26].

3.1.5. Escalation

Another type of signal transformation is called time scale, the time scale maps the input signal *x (t)* to the output signal *y(t)* modifying its representation in time can be compressing or expanding the signal along the time axis [16], [18], [21], [24], [26].

The scaling operation can be mathematically represented as:

$$y\ (t)\ =\ x\ (at) \tag{13}$$

Where a is the scaling constant, then if $a > 1$ compresses the signal, and if $a < 1$ expands the signal in time [16], [18], [21], [24], [26]. See Figure 4 (g).

3.1.6. Reflection

The reflection of a signal also known as time inversion maps the input signal $x\ (t)$ to the output signal $y\ (t)$ that can be described as follows:

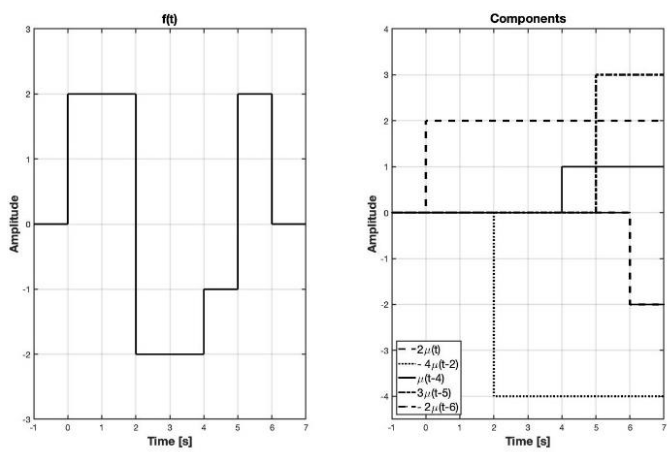
$$y(t) = x(-t) \tag{14}$$

Basically the output signal $y(t)$ is formed replacing t with $-t$ in the input signal $x(t)$ which would indicate the signal inversion or the reflection in the domain axis in the case of signals in time. [8], [16]–[20], [23], [24], [26], [27]. See Figure 4 (h).

3.2. Signal Composition and Operations

In this section, some operation examples between step, ramp, sinusoidal and exponential signals will be dealt with, which will facilitate the application understanding of diverse operations with different continuous time signals.

Figure 5. Sample signal 1.



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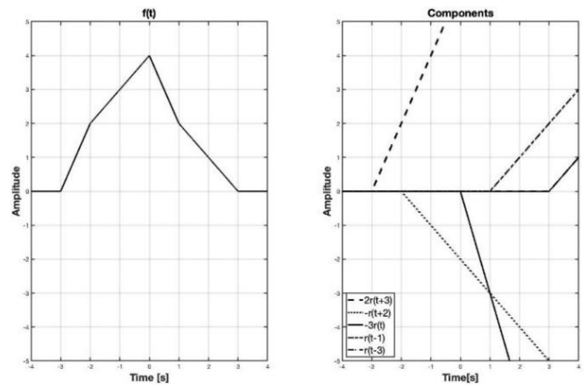
Where the signal is described, in terms of the unitary step, by:

$$f(t) = 2\mu(t) - 4\mu(t-2) + \mu(t-4) + 3\mu(t-5) - 2\mu(t-6) \tag{15}$$

Figure 5 is a clear example of a composite signal and the use of signal operations, in this case unitary step signals. Figure 5 shows both the resulting signal and its components, which in this case are all unitary steps shifted in time, amplified, inverted or with different transformations applied to a single signal.

Figure 6. Sample signal 2.



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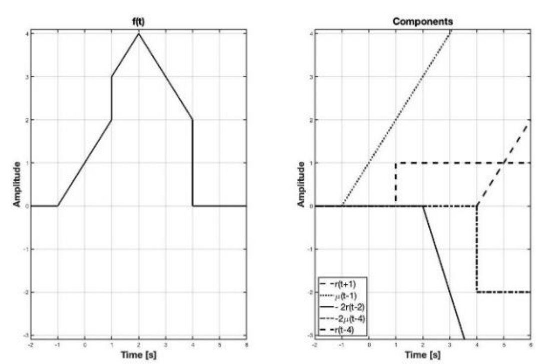
Representing the signal:

$$f(t) = 2r(t+3) - r(t+2) - 3r(t) + r(t-1) + r(t-3) \tag{16}$$

It can be seen in Figure 6 a signal that is a sum of ramp signals with different transformations, the signal has five components that are observed in more detail on the right side of Figure 6.

Figure 7. Sample signal 3.



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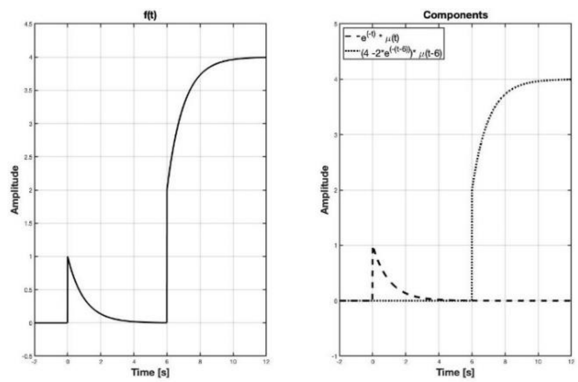
Being the graphic representation of:

$$f(t) = r(t+1) + \mu(t-1) - 2r(t-2) - 2\mu(t-4) + r(t-4) \tag{17}$$

Figure 7 allows to see a signal composed by signals both step and ramp, it is important to notice that the signals are operated between them point to point, the signal can be obtained analytically by means of analysis of its components and the behavior in time.

Figure 8. Sample signal 4.



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The signal is described by the equation: (18):

$$f(t) = e^{-t}\mu(t) + \left(4 - 2e^{-(t-6)}\right)\mu(t-6) \tag{18}$$

The exponential signals are the most important in the topic of Dynamic and Control Systems due to their characteristics in time, since in certain cases they allow us to see how certain systems behave. In this case Figure 8 shows a signal that has as components exponential signals, these are generally expressed with a multiplied step since these signals like any other must have a defined beginning in time, in Figure 8 is seen both a growing exponential signal and a decreasing giving as a result a signal with a particular shape.

4. Model concept and applications

The model is an object that tries to define a phenomenon, a process or in its defect a physical system; it is a tool that helps a person to answer questions related to the system's behavior. Generally the models are meant to serve as a solution or support to the solution of a specific problem which has motivated the development of the same model [1], [2].

Models can be built using three characteristic phases:

- Conceptualization: It is based on having a basic and intuitive perspective as well as understanding of a real-world phenomenon.

- Model formulation: This is where the elements obtained in the conceptualization phase are represented with a formal language.

- Model evaluation: It consists of carrying out a validation and analysis of the model, resulting in its acceptance or not according to the acceptability criteria.

4.1. First Order Systems Analysis

- Conceptualization:

It is known that a system that behaves like a first-order system has an exponential response when its input signal or stimulus is a unitary step signal. The typical form of the transfer signal of a first order system is:

$$G(s) = G_0 \frac{e^{-T_d s}}{1 + Ts} \tag{19}$$

- Model formulation:

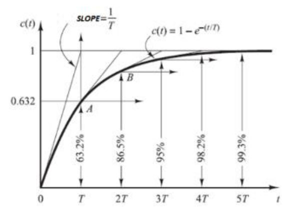
If this system is stimulated with a step signal, a typical time response is obtained.

$$y(t) = G_0\left(1 - e^{\frac{t-T_d}{T}}\right)\mu(t - T_d) \quad (20)$$

- Model evaluation:

Where G_0 is the System gain, T_d is dead time and T is the system time constant, if this system is stimulated with a step signal it gets, figure 9.

Figure 9. First order system step response [4].



As it can be seen, the response is a growing exponential signal that originates in 0 and stabilizes in 1. Based on this behavior, characteristics such as the time constant, the signal $c(t)$ that describes the response, the amplitude in which the system stabilizes and the stabilization time can be calculated depending on the criterion taken, which can be between $3T$ and $5T$.

4.2. Second Order Systems Analysis

- Conceptualization:

The second order systems have a behavior that is expressed through a composition of exponential signals, sinusoidal and unitary steps so it can be characterized from its signal form, the typical transfer signal of this system is:

$$G(s) = \frac{K_A * \omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{21}$$

- Model formulation:

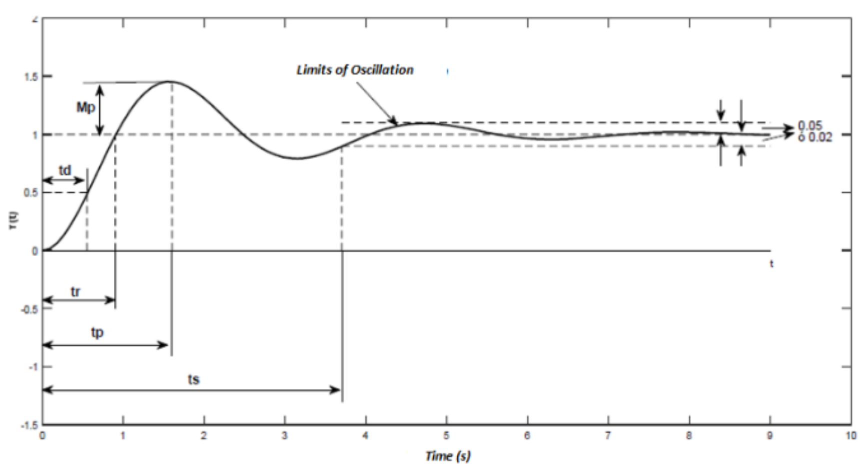
If the system is stimulated with a step signal the time response is represented by:

$$Y(t) = K_A \left\{1 - e^{-\zeta\omega_n t}\left[\cos\left(\omega_n\sqrt{1-\zeta^2}t\right) + \frac{\zeta}{\sqrt{1-\zeta^2}}\sin(\omega_n\sqrt{1-\zeta^2}t)\right]\right\}\mu(t) \tag{22}$$

- Model evaluation:

Where K_A is the System gain, ζ is damping factor, ω_n is the natural frequency of the system, $Y(t)$ is time response and $G(s)$ is the typical transfer signal of a second order system, graphically it can be seen with a unitary step input and having $0 < \zeta < 1$ (sub damped system), figure 10:

Figure 10. Response to the second order sub damped system step, [4].

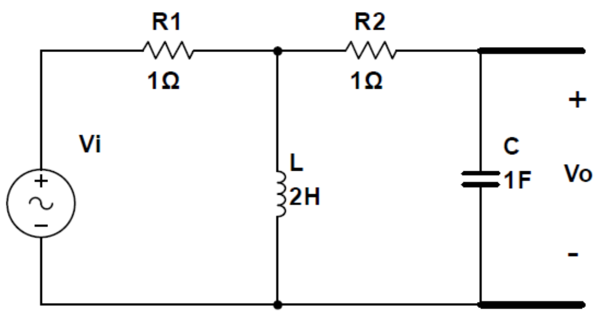


It can be seen that the signal response is a signal used to calculate important characteristic values in second order systems as maximum on impulse (M_P), stabilization time (t_s), peak time (t_P), delay time (t_d) and rise time (t_r).

4.3. Response time calculation of a system

- Conceptualization:

Figure 11. Electrical System Example.



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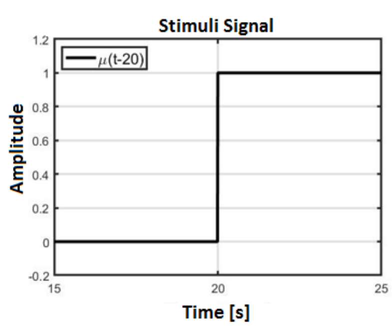
Based on the circuit in Figure 11, the analysis is performed, and the time response of this electrical system is found. To start the necessary calculations, the initial conditions are as follows:

$Vc(0) = 0\,,\qquad i_l(0) = 1A,\qquad V_i = \mu(t-20)$

Figure 12. Stimuli signal $\boldsymbol{Vi(t) = \mu(t-20)}$.



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- Model formulation:

Analyzing the circuit in Figure 12, the following differential equations are obtained:

$$\frac{di_L}{dt} = \frac{(Vc\ R1 - i_L R1\ R2 + Vi\ R2)}{(R1 + R2)L} \tag{23}$$

$$\frac{dVc}{dt} = \frac{(-Vc - i_L R1 + Vi)}{(R1 + R2)C} \tag{24}$$

Performing the relevant calculations using the differential equations obtained, it was found that the answer in the system time is:

$$Vo(t) = Vc(t) =$$

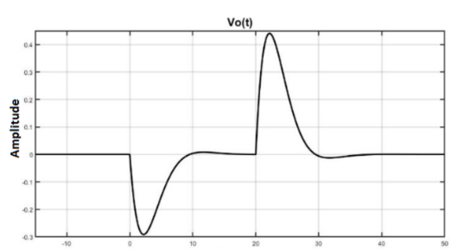
$$\{\frac{8}{2 * \sqrt{7}} e^{\frac{-3(t-20)}{8}} \sin\left(\frac{\sqrt{7}}{8}(t-20)\right)\mu(t-20)\} - e^{\frac{-3(t)}{8}} \sin\left(\frac{\sqrt{7}}{8}(t)\right)\mu(t) \tag{25}$$

- Model evaluation:

It is observed that the response in time is a signal composed of exponential signals, sinusoidal and unitary steps, hence the importance of theory knowledge of signals in continuous time to be able to analyze this type of system responses, figure 13.

Graphically $Vo(t)$ gives:

Figure 13. System output.



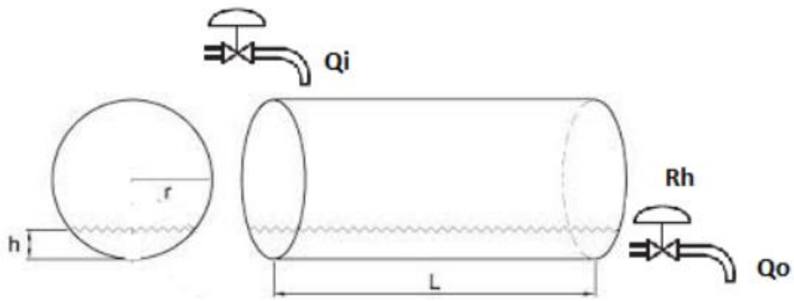
Source: own.

4.4. Identification

The systems identification deals with the estimation of models of dynamic systems from the data obtained in the analysis of the system, below is an example of application:

- Conceptualization

Figure 14. Cylindrical tank hydraulic system (laid).



Source: own.

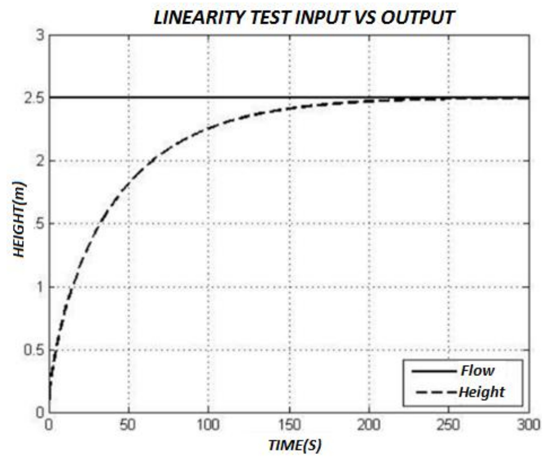
The system to be identified is a non-linear hydraulic system. See Figure 14. In the first instance, a series of experiments are carried out to determine the system's linearity at different points of operation. To do this, the plant is stimulated with step type signals and the gain and time constant of the system is determined.

In view of the above, 5 different unit steps have been chosen for the input signal, which have an amplitude of:

- 0.5 Volts
- 1.5 Volts
- 2.5 Volts
- 3.5 Volts

- 4.5 Volts

Figure 15. Input vs output.



Source: own.

Figure 15 shows the system's response to an input signal with a 2.5V step.

In the experiment carried out, the following experimental data was obtained.

Table 1. Experimental Data.

Input	Gain(K)	Time Constant (τ(s))
Step 0.5	1	22
Step 1.5	1	33
Step 2.5	1	40
Step 3.5	1	44
Step 4.5	1	46

Source: own.

Once the previous procedure is done, the mathematical models are calculated based on the one which describes the behavior of the system when it is stimulated with the different step signals. Afterwards, its validation is done, and the approximation percentage is compared with the experimental data. First order models have been chosen for continuous time, TABLE II, where the parameters obtained during the validation process of the models can be visualized.

- Model formulation:

Table 2. First Order Models Validation Data.

G(S) \ Input	**0.5**	**1.5**	**2.5**	**3.5**	**4.5**
$\frac{0.99322}{1+22.182s}$	91.92%	71.83%	61.34%	57.1%	57.68%
$\frac{0.98736}{1+34.918s}$	73.32%	93.12%	88.15%	84.74%	85.06%
$\frac{0.98719}{1+41.377s}$	65.05%	87.96%	94.2%	93.78%	93.19%
$\frac{0.9936}{1+45.243s}$	62.5%	84.92%	92.94%	95.39%	94.84%
$\frac{1.0097}{1+47.287s}$	63.98%	85.23%	91.75%	93.24%	96.45%

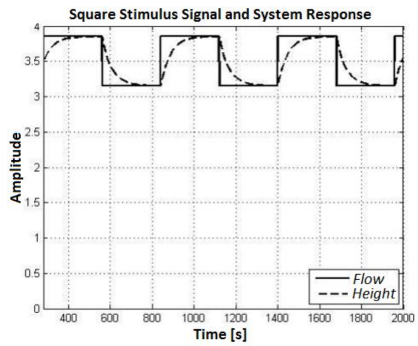
Source: own.

- Model evaluation:

In this way it is observed how the signals are used for the systems stimuli, and from the response that the system has, make an approximation of its transfer signal. In the previous case the test was made with five different steps and based on the results, the models that can represent this system are generated and in what percentage of approximation they are found.

In addition to the step signal, it is possible to make use of more elaborated signals. The typical ones in the Identification process are the step by step, square and pseudo random signals for the same process in Figure 16 the answer in the case of having an input of square type is the following one:

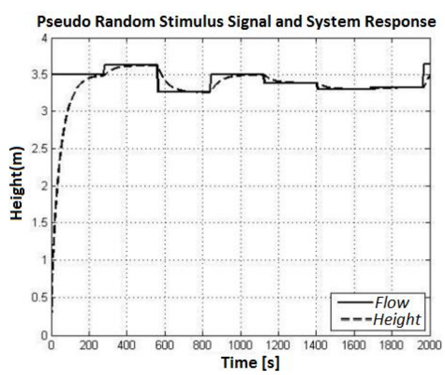
Figure 16. Square stimulus signal and system response.



Source: own.

If the system is stimulated with a pseudo-random signal, it is obtained that:

Figure 17. Pseudo random stimulus signal and system response.



Source: own.

The input signals used in Identification can change depending on the system to be identified, also in some cases the typical Identification signals will not work efficiently and a signal design will have to be done to evaluate all the operation points of the system to have a better identification of the system [7], [45], [47]–[50], [65].

5. Conclusions

Signal theory is a fundamental element in the field of system dynamics as it allows the understanding of the system's behavior in time, describing them and characterizing them in a rational and analytical way.

Signal operations make it possible to look beyond signal theory and find feasible uses of signals in the field of system dynamics, understanding the application of both basic operations and the very composition and use of compound signals in branches of dynamics analysis such as the systems identification.

Through what has been developed, the signal application in mathematical and experimental analysis of modeling, Control and Identification of Dynamic Systems is evident, as well as its importance in improving the understanding of how they behave in time.

The paper allows the reader to become familiar with the theory of signals, to show the typical signals used such as singular, exponential, and sinusoidal signals, also is observed signal operations, examples of operations and composite signals by various basic signals. Finally, it simplifies the signal use in some of the applications of Dynamic Systems and control systems.

In this paper, the concept of the central model is evident in the analysis of dynamic systems, since the model allows to unravel characteristics and helps to understand the system's behavior over time making use of three phases of model construction.

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