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Design of a temperature control system for an egg incubator

Diseño de un sistema de control de temperatura para una incubadora de huevos

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In general, an egg incubator is used to increase the productivity of poultry egg incubation. This tool develops a set of important variables that influence the incubation process for successful hatching, one of these variables is temperature. In order to increase the percentage of hatchability of the system, it is necessary to be able to guarantee temperature stability. This article will address the problem of temperature control in a hen egg incubator, which is key to obtaining baby chicks in optimal conditions. Using the PID control system, the aim is to provide a solution to the temperature variation that occurs in the incubation process. Thus, the purpose of this article is to design a temperature control system based on mathematical calculations using experimental data.

Keywords: Control, eggs, incubator, PID, stability, temperature

En general, una incubadora de huevos se utiliza para aumentar la productividad de la incubación de huevos de aves de corral. Esta herramienta desarrolla un conjunto de variables importantes que influyen en el proceso de incubación para una eclosión exitosa, una de estas variables es la temperatura. Para elevar el porcentaje de incubabilidad del sistema, este requiere poder garantizar una estabilidad en la temperatura. En este artículo se abordará el problema del control de la temperatura en una incubadora de huevos de gallina, que es clave para la obtención de pollos bebé en óptimas condiciones. Utilizando el sistema de control PID se busca aportar una solución a la variación de temperatura que se presenta en el proceso de incubación. Así pues, la finalidad de este artículo es diseñar un sistema de control de temperatura a partir de cálculos matemáticos tomando como base datos experimentales.

Palabras clave: Control, estabilidad, huevos, incubadora, PID, temperatura

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Introduction

The birth and development of the proportional-integral-derivative controller (PID) date back to the period from 1920 to 1940 in the last century, in response to the insistent demands of industrial automation before, during, and particularly after World War II (Han, 2010). In other words, this control system arose from the need to simplify manual control and reduce the errors that occurred in the various industrial processes. Its role in the explosive growth in the post-war manufacturing industry is unmistakable; its mastery is evident even today in several sectors of the entire industry.

The PID controller is widely used in many control applications because of its simplicity and effectiveness (Zhigang Wang & Lu, 2017). Due to this feature, we can say that this is the bread and butter of automatic control. The PID controller is used for a wide range of problems: process control, motor drives, magnetic and optical memories, automotive, flight control, instrumentation, temperature control, etc. (Åström & Hägglund, 2010). These problems can be translated into keeping the variables of a process as close as possible to specified values and keeping the variables of a process within a range (F. Martínez & Acero, 2020).

PID controllers are tools used to exercise control over variables in a process in a system to bring it to a working point, known as a *set point* (Zhenlong Wu & Wang, 2016). To reach this set point, the controller must respond or act quickly to system dynamics, eliminating errors and increasing system stability, resulting in improved performance.

A PID controller is implemented in closed-loop systems thus having a single input (reference variable) and a single output configuration (controlled variable) (Utama & Hari, 2017). The controller must keep the output or response of the system at the set point. When this does not happen and the controller keeps the system output in a range close to the setpoint, errors are introduced in the system response which is corrected by the feedback (Ogata, 1998). Feedback is the comparison between the setpoint which is expected to be the value of the system response and the actual value of the process variable. The loop created by the feedback ensures control over the system by causing the error in the response to be corrected each time the controlled variable is compared to the reference variable until finally the error in the output disappears. As this comparison exists, the process variable will be conditioned by the response of the system. The feedback from the controller is of great importance since it creates the desired behavior in the system resulting in stability.

In a control system, the controller is a device or mechanism that compares the desired output or setpoint of a system with the actual output, and adjusts the input or control signal to the system in order to bring the output closer to the setpoint. This process is known as feedback control.

The feedback from the controller is important because it helps to ensure that the system operates as intended and achieves the desired behavior. Without feedback, the controller would have no way of knowing if the system is performing as desired, and the system may become unstable or drift away from the desired behavior. By continuously comparing the output with the setpoint and adjusting the control signal as needed, the feedback from the controller helps to maintain stability and achieve the desired behavior of the system.

This article will show the steps to develop a suitable temperature control system for an egg incubator using PID controllers.

Problem formulation

The process of incubating hen eggs is an artificial process that simulates the natural conditions of a hen to allow the embryo to develop and reach the chick's hatch. In this process, the temperature is one of the most important factors, since small variations in temperature can be fatal for many embryos. Because of this, the interior of the incubator should provide a constant temperature of 37.5°C.

From this arises the following question How to develop a temperature control system for an egg incubator to maintain a constant temperature, and how to achieve this using the PID control system?

To solve this issue we must take into account aspects such as heat transfer in the egg, which happens when there is a difference in temperature between two regions. Where it is worth noting that the egg allows heat exchange between the interior and exterior of the egg, becoming the means of heat transfer.

Like any material, heat transfer can occur in eggs in three ways. First, conduction, this heat transfer occurs between regions or media that are in contact with each other, from the hottest to the coldest areas. The rate of heat transfer by conduction depends on the temperature difference and the thermal conductivity of these areas (C. Martínez & Josmell, 2015). Therefore, in the egg, heat is transferred by conduction from the embryo to the eggshell, whenever their temperatures are different.

Second, convection occurs when there is heat transfer by air currents and when a body loses heat by conduction (Sharawi, 2013). In that sense, when eggs lose heat by conduction, the air around the eggshell is heated and rises, moving the cooler air near the eggshell to replace the warm air, generating convection currents, which help remove heat from the egg.

Thirdly, radiation, this heat transfer occurs from the surface of a warm body to another one whose temperature is different by emitting heat waves that propagate through the air (Zhigang Wang & Lu, 2017). According to this thermodynamic principle, the loss or gain of heat in an egg by radiation depends on the difference in temperature between the egg surface and the incubation environment. This means that the best way to ensure the right temperature for incubating the egg is through heat transfer by radiation.

So, with the egg at the correct temperature, the biological process of incubation begins and the embryo starts to grow, then the correct temperature range must be maintained throughout the entire incubation period to achieve a higher rate of hatchability.

Consequently, we can say that the incubation temperature affects the thermoregulatory capacity, hormone levels, and growth rate of the brood. Therefore, the key is to model the temperature of the system properly to achieve the correct temperature in the incubator.

Objective

Design a control system for a hen egg incubator using the PID control system.

Methods

As indicated above, the main objective of this article is the design and development of a temperature control system. To carry out the design, three stages were established in the methodology, which are:

1. Plant system.
2. PID control system.
3. Mathematical models.

Plant system

First, the incubator was built with a closed box made of expanded polystyrene and inside it, a resistor, a temperature sensor, and a fan were placed to guarantee the movement of the hot air inside.

Second, a transient response test was performed by feeding the resistance and measuring the temperature behavior concerning time. From these measurements, a table was made with the data obtained, as shown in Table 1.

Third, we plot the transient response where we get an exponential waveform as shown in Fig. 1.

Fourth, the set point of the egg incubator is set at 37.5°C.

PID control system

Initially, you should know that a PID controller or regulator is a device that allows you to control a closed-loop system so that it reaches the desired output state (Shafiudin & Kholis, 2018). In our case, this controller will allow us to set a constant output temperature of 37.5°C.

Table 1

Transient response values of the egg incubator

Time [m]	Temperature[°C]
0.0	19
2	38.7
4	43.3
6	45.2
7	45.8
10	49.6
13.5	52.6
17.0	56.1
23.5	59.6
30.0	63.1
39.0	64.9
40.0	65.6
50.0	66.4
60.0	67.5
70.0	68.2
80.0	68.4
90.0	68.4
100.0	68.5

As shown in Fig. 2 the PID has three components, which are added together to give the output of the controller. Each one fulfills a certain function and improves a certain part of the response (Ogata, 1998). These functions are:

1. It uses the feedback to reject the disturbances.
2. Eliminates stationary error with integral action.
3. Anticipate the future with derivative action.

Additionally, when the three components of the PID work in the right proportion, we can achieve the expected behavior (Widhiada et al., 2019).

Mathematically, a PID controller has the following formulation:

$$output(t) = K_p e(t) + K_i \int e(t)\, dt + K_d \frac{de(t)}{dt} \qquad (1)$$

Where, K_p is the proportional gain, K_i is the integral time constant and K_d is the derivative time constant.

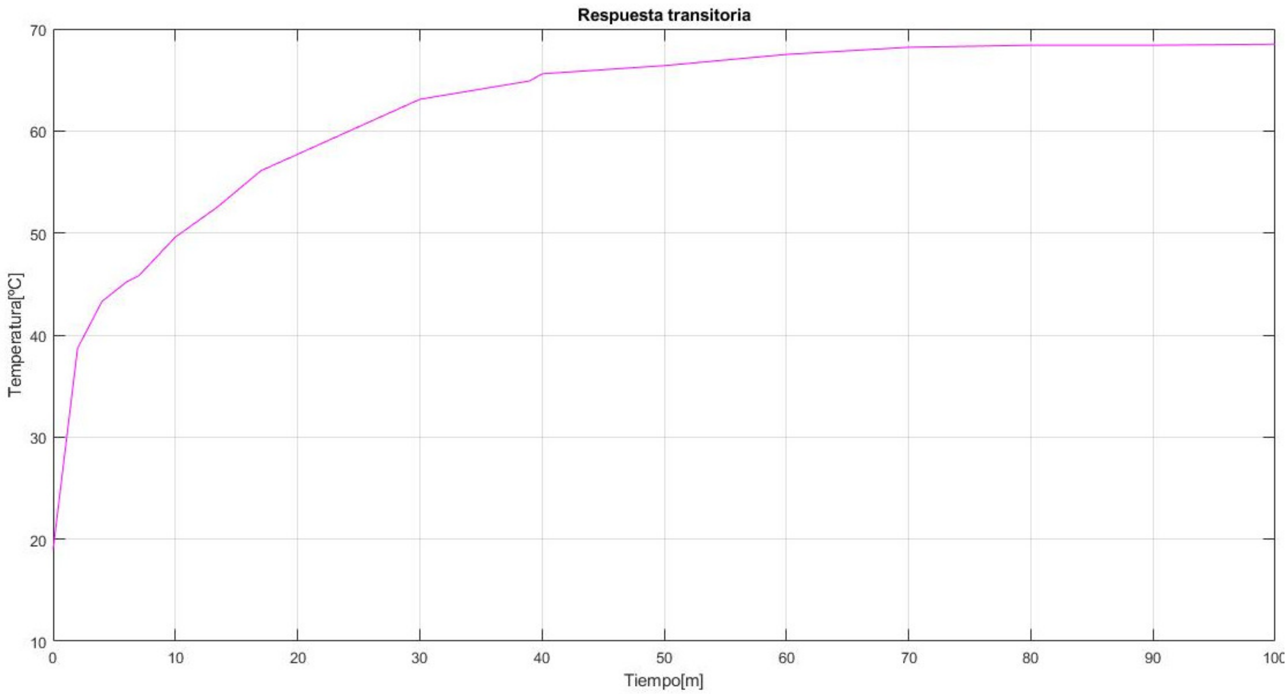
As seen in Eq. (1) each component of the PID is independent of the others, in the sense that each calculates an output of what "for it" should do to obtain the proper response.

That is, the sensor will collect the temperature values obtained indoors, and they will be read by the PID controller and compared at all times to the target temperature which has a value of 37.5°C.

In the PID block diagram, it is observed how the sensor will collect the temperature values obtained inside the plant,

Figure 1

Egg Hatchery transient response graph.



and these will be read by the microcontroller and compared with the target temperature. The transfer function of the PID controller is:

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s \tag{2}$$

Mathematical model

Analyzing the behavior of the transient response curve of the egg incubator, we can say that it has the behavior of a first order system, where the form of its response will be represented by Eq. (3):

$$y(t) = K - Ke^{(-\frac{t}{\tau})} + C \tag{3}$$

Where the initial values are known:

$$t = 0, \quad C = 19 \tag{4}$$

The final condition of the data curve obtained in the laboratory is acquired.

$$t = \infty, \quad y(\infty) = 68.5 \tag{5}$$

Knowing the final and initial condition, the value of K can be calculated:

$$K = 68.5 - 19$$

$$K = 49.5$$

The equation of the system would be as follows:

$$y(t) = 49.5 - 49.5e^{(-\frac{t}{\tau})} + 19 \tag{6}$$

Now the value of τ will be calculated, for this, a linear regression of the function is performed.

$$T(t) = 0.7329t + 20.23 \tag{7}$$

The variable t is cleared:

$$0.7329t = T(t) - 20.23$$

$$t = \frac{T(t) - 20.23}{0.7329} \tag{8}$$

The 63% of the final value of the system function must then be calculated.

$$T = 63\%(68.5)$$

$$T = 31.18$$

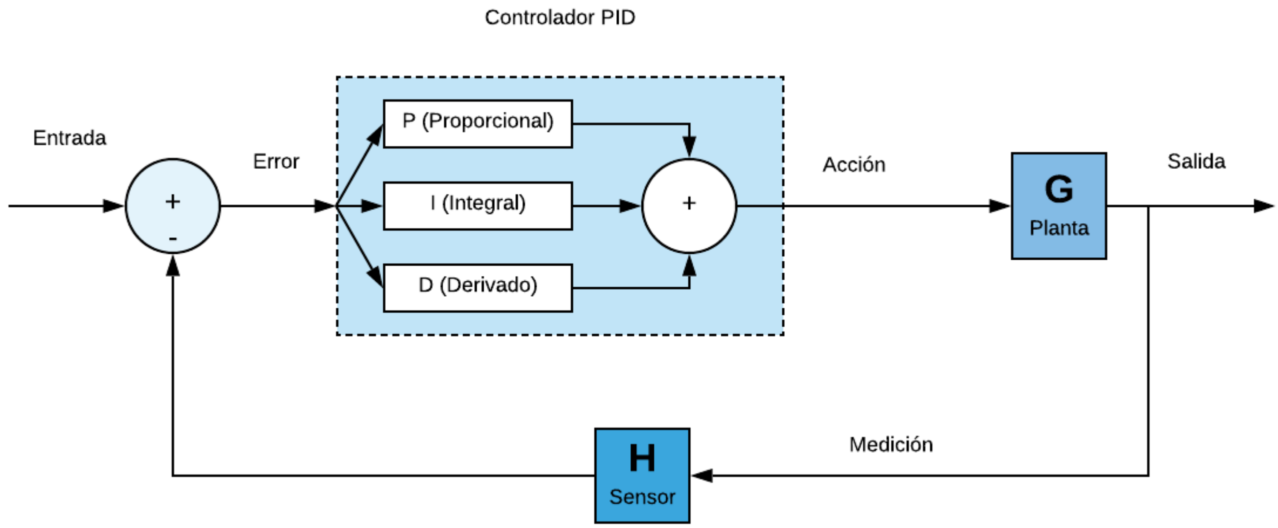
Now the value of τ is obtained:

$$t = 14.940$$

$$\tau \approx 14.940$$

Figure 2

Block diagram of the closed-loop system.



$$y(t) = 49.5 - 49.5e^{(-\frac{t}{14.940})} + 19 \tag{9}$$

$$y(t) = 68.5 - 49.5e^{(-\frac{t}{14.940})} \tag{10}$$

In Fig. 3 a comparison of the curve of the data obtained in the laboratory and the shape of the assumed response can be seen showing that both have a similar shape.

The Laplace transform is then applied to both the input and output in order to know the transfer function.

$$Y(s) = \frac{137}{2s} + \frac{-99}{2(s + \frac{50}{747})} \tag{11}$$

$$Y(s) = \frac{14193s + 3425}{s(747s + 50)} \tag{12}$$

Where its input is a unitary step.

$$u(t) = 1$$

$$U(s) = \frac{1}{s}$$

$$G(S) = \frac{Y(S)}{U(S)} = \frac{14193s + 3425}{747s + 50} \tag{13}$$

$$G(S) = \frac{19(s + 241.316 * 10 - 3)}{s + 66.9344 * 10 - 3} \tag{14}$$

Stability analysis

To determine the stability of the system from its transfer function, the roots of the polynomial of the denominator of the function must be determined and consider whether or not any of these are positive.

$$G(S) = \frac{19(s + 241.316 * 10 - 3)}{s + 66.9344 * 10 - 3} \tag{15}$$

Initially, the values of the coefficients of the denominator of Eq. (15) should be reviewed. Here it is observed that all the coefficients are positive, then, it can be said that the system is stable.

$$P(S) = s + 66.9344 * 10 - 3$$

Analyzing Eq. (15) it can be said that the function has a pole and a zero with the following values (Fig. 4):

$$z = -0.2413$$

$$p = -0.0669$$

Examining the graph in the s-plane it can be confirmed that the pole and zero values are located in the stable zone (Fig. 5). The root locus graph is a graphical representation of the locations of the roots (or zeros) of the closed-loop transfer function of a control system as a function of a design parameter. It is a useful tool for understanding the stability of the system and for designing control systems to meet specific performance requirements. The root locus graph can be used to determine the stability of the system by examining the location of the roots in the complex plane. Roots that are located in the right-half plane (RHP) correspond to unstable

Figure 3

Comparison of the assumed model and curve of the laboratory data.

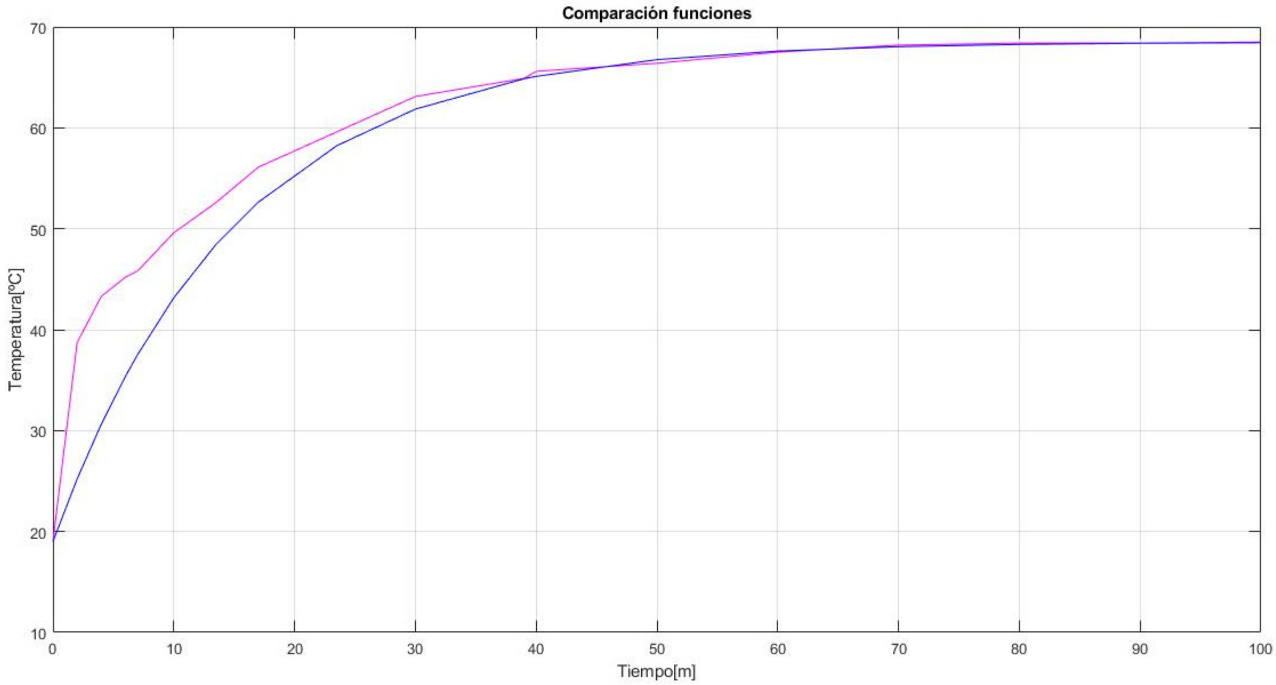


Figure 4

Location of poles and zeros of the transfer function.

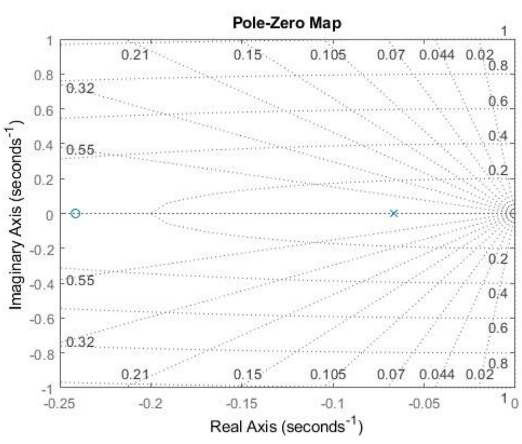
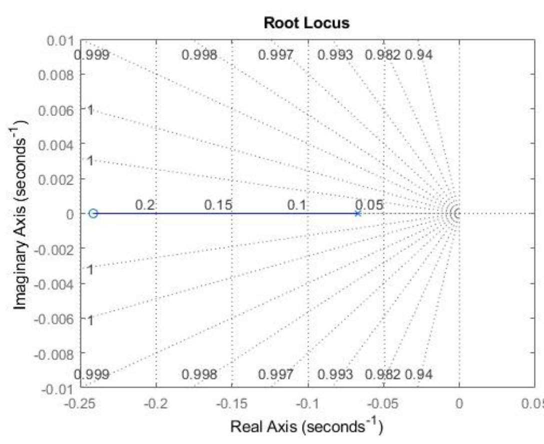


Figure 5

System Root Locus.



poles, while roots that are located in the left-half plane (LHP) correspond to stable poles.

Using the transfer function of the system and with the help of MATLAB, the K_p, K_i and K_d constants of the PID controller were calculated.

$$K_p = 0.015$$

$$K_i = 0.032$$

Where the transfer function of the controller is taken:

$$G_c(s) = 0.015 + \frac{0.032}{s}$$

Results

Although mathematically it is possible to select any gain value for the PID controller, in real life this is not the case;

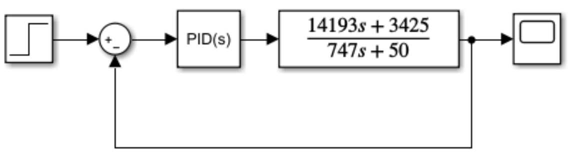
Figure 6

Code in MATLAB.

```
%Calculo de constantes PID
num=[14193 3425];
den=[747 50];
H=tf(num,den)
pidtool %Herramienta para el cálculo
        %de las constantes K_p,K_i y K_d
```

Figure 7

Block algebra graph.



on the contrary, there are limits of all kinds. The root locus graph can be used to predict the response of the system to a disturbance based on the location of the roots. For example, a system with roots that are closer to the imaginary axis will have a faster response to a disturbance than a system with roots that are farther from the axis.

Therefore, in order to verify that the design is physically feasible, the Simulink tool of the Matlab software was used to perform a set of tests to prove the correct operation of the PID controller with the constants previously found with the pidtool of the same software as shown in Fig. 6.

Having obtained the transfer function of the plant and the controller, we will replace the data in the closed-loop block diagram in the Simulink program, as shown in Fig. 7 to obtain the response curve.

The simulations were performed with a unit step input, where an output in the form of a first-order system was obtained as shown in Fig. 8, which is the desired response.

Conclusion

In this article, we present a successful approach for designing and simulating a temperature control system for an egg incubator using a PID (proportional-integral-derivative) controller. We first obtained a data curve of the incubator's temperature over time, which allowed us to identify the system dynamics and model the system as a first-order process. Using this data, we were able to determine the process transfer function, which served as the basis for calculating the PID controller parameters. To optimize the control system's performance, we conducted simulations by varying the PID controller's parameters until we found a set that ensured stable temperature in the incubator. Our findings suggest that the efficiency of the incubation process depends on the effectiveness of the control scheme, which must provide stable and reliable control.

Overall, our results demonstrate that the use of a PID controller is an effective method for achieving temperature stability in an egg incubator. The successful simulation of the temperature control system using a PID controller suggests that this approach could be used in the design of other types of temperature control systems. The importance of temperature stability in the incubation process cannot be overstated, as it plays a critical role in the development and survival of the eggs. Therefore, the implementation of a reliable control scheme like the one presented in this article is crucial for ensuring the success of the incubation process. In conclusion, the development of a temperature control system using a PID controller, as described in this article, can significantly improve the efficiency and success of the incubation process in an egg incubator.

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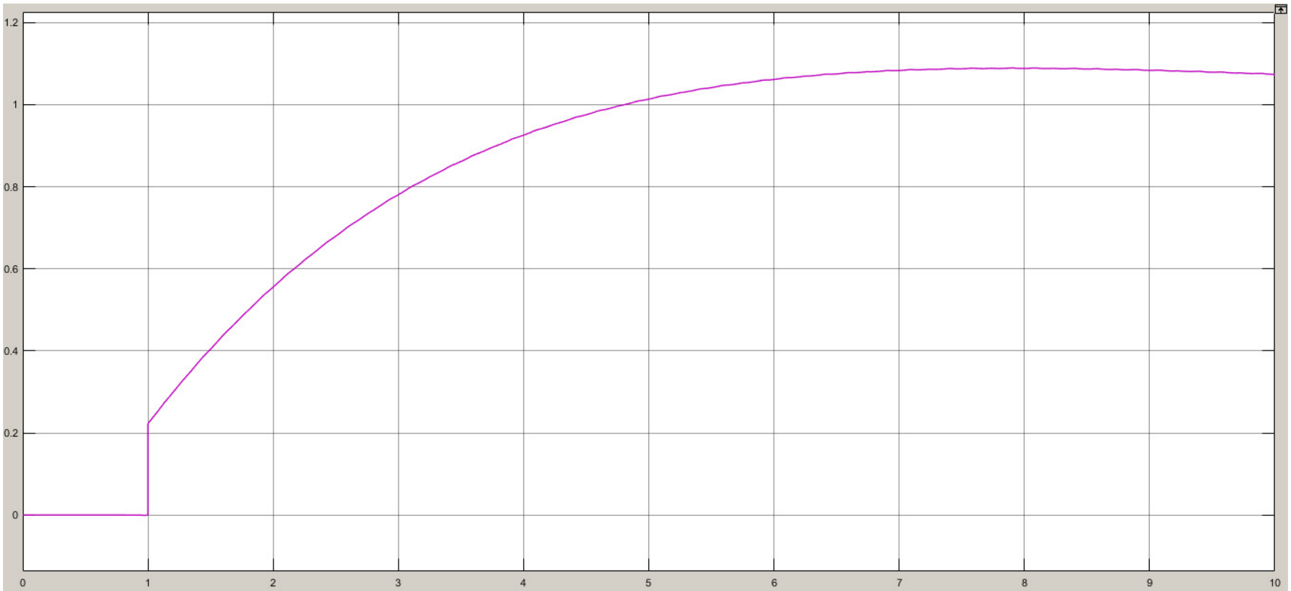
Figure 8

Response graph in Simulink.



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