SYSTEM FOR LEVEL CONTROL IN A CONICAL TANK

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Abstract: In an industry, control systems are widely used for process improvement. Thus, it is very common to use tank level control, hence, identifying this demand, in order to further the studies on control systems with strong nonlinearity, this work deals with the development of a simulator involving a two-tank system, where the upper tank is conical. Then, for this project, a Root Locus controller was developed, responsible for two subsystems which implemented the continuous control of level of the conical tank by varying the pump speed and the position of the main valve. Thus, the characteristic equation of the subsystems for simulation was obtained and the efficiency of the PID compensator system was demonstrated when correcting the errors in the controlled variable.

Keywords: root locus, PID Compensator, nonlinear system, continuous control.

SISTEMA PARA CONTROLE DE NÍVEL EM TANQUE CÔNICO

Resumo: Na indústria, sistemas de controle são muito utilizados para o aprimoramento de processos. Assim, é muito comum o controle de nível e, a fim de aprofundar os estudos sobre sistemas de controle com forte não-linearidade, este trabalho trata do desenvolvimento de um simulador envolvendo um sistema de dois tanques, onde o tanque superior é cônico. Logo, para o projeto, foi desenvolvido um controlador via Lugar das Raízes, responsável por três subsistemas os quais implementaram o controle contínuo de nível do tanque cônico por meio da variação de velocidade da bomba e da posição da válvula principal. Isto posto, foi obtida a equação característica dos subsistemas para simulação e demonstrada a eficiência do sistema compensador PID ao corrigir os erros na variável controlada.

Palavras-chave: lugar das raízes, Compensador PID, sistema não-linear, controle contínuo.

1. INTRODUCTION

In industry, it is very common to use control systems due to the need for precision and process improvement. Therefore, in systems there are several components that are subject to disturbances that can cause equipment to operates in undesired regions, which leads to deviation from the main characteristics of a product and undesired results. In this way, the application of control and automation technologies in processes is advantageous, as it can increase the level of quality, minimize reprocessing time, and increase the reliability of the systems [1].

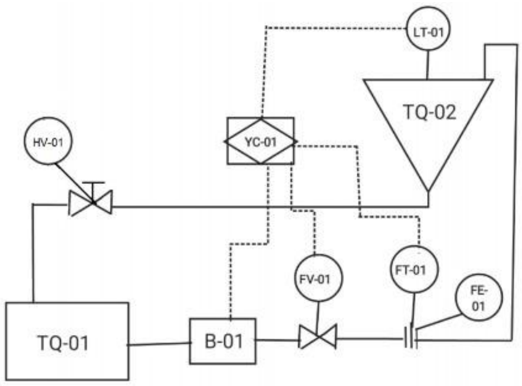
For the appropriate design of controllers there are several control methods such as Ziegler-Nichols and Root Locus. The former suggests tuning PID controllers based on the experimental response to a step or based on the value of kp that results in marginal stability, when only a proportional control action is used. On the other hand, the Root Locus method is a graphical technique that allows visualizing how the poles of a closed loop system vary when changing the gain value.

In this context, tank level control is a basic problem in process industries. Commonly, liquids are required to be pumped, stored in tanks, and then pumped to another tank. Often the liquid will be processed by chemical treatment or blending, but always the fluid level in the tanks must be controlled. In this scenario, in order to further the studies on control systems with strong nonlinearity, this work deals with the development of a simulator involving a two-tank system, where the upper tank is conical.

2. METHODOLOGY

The system consists of two tanks (TQ-02 with a conical shape and TQ-01 with any shape), a pump motor (B-01), a hand valve (HV-01) and a flow control valve (FV-01). In addition there is a level transmiter (LT-01) installed in the TQ-02 tank and a flow transmiter (FT-01) installed in the piping between the B-01 pump and the TQ-02 tank. These sensors send information to a controller (YC-01), which will be responsible for controlling the entire system (Figure 1).

Figure 1. The system diagram.



This project aims to implement 2 control systems:

- **Control System I:** Implementation of continuous level control in TQ-02, keeping the position of FV-01 constant and regulating the speed of B-01;

- **Control System II:** Implementation of continuous level control in TQ-02, keeping the speed of B-01 constant and regulating the position of FV-01;

For all 2 systems, the manual valve HV-01 was considered to be 100% open, allowing all the liquid that reaches it to pass through, so that it can be disregarded from the system. Pressure drops for both valves and the piping were disregarded. Tank TQ-01 was considered as just a liquid reservoir, large enough for pump B-01 not to operate dry. Thus, this tank was also disregarded in obtaining the mathematical models of the system.

2.1. Control System I

For Control System I, it is desired to control the liquid level in tank TQ-02 by adjusting the speed of pump B-01 and keeping the position of valve FV-01 fixed. This way, it will be assumed that this valve is 100 % open, allowing the passage of all the flow pumped by B-01.

The transfer function relating the height of the liquid in the tank to its inlet flow rate, after linearization (1), was obtained in [2].

$$\frac{\widehat{H_2}(s)}{\widehat{Q_v}(s)} = \frac{1}{s\frac{\pi R^2 \bar{h}^2}{H^2} + \frac{k_v}{2\sqrt{\bar{h}}}} \quad (1)$$

Where $\widehat{H_2}$ is the liquid height, $\widehat{Q_v}$ is the tank inlet flow, H is the total height of the conical tank, R is the tank radius, $\bar{h}$ is the linearization point and k_v is the tank constant.

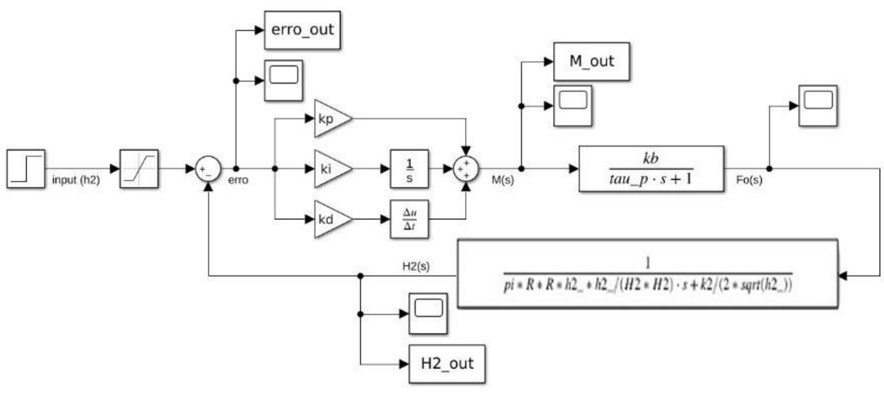
Applying the Laplace Transform, we find the transfer function of the pump (2), where $\widehat{F_o}(s) = \widehat{Q_v}(s)$. τ_p is the time constant of the pump, and k_b an assigned gain.

$$\frac{\widehat{F_o}(s)}{\widehat{M}(s)} = \frac{k_b}{s\tau_p + 1} \quad (2)$$

Where $\widehat{F_o}$ is the pump output flow rate, $\widehat{M}$ is the pump speed, k_b is the pump gain and τ_p is the time constant.

To perform this level control, a PID type controller was used, which was received as an error signal the difference between the desired liquid height and that obtained by the LT-01 level sensor, thus generating the *m(t)* signal that corresponds to the pump speed. This system was assembled in MATLAB Simulink, in order to perform simulations about its operation, and can be seen in Figure 2.

Figure 2. Control System I in Simulink.



The design of the PID controller was based on the Root Locus Method. For the conical tank, it was considered a radius $\mathrm{R} = 0.7\ \mathrm{m}$ and a height $\mathrm{H} = 1.4\ \mathrm{m}$, and for the pump a time constant $\tau_p = 3s$, besides a unitary gain k_b. The mathematical model of the conical tank was linearized at $\bar{h} = 0.7\mathrm{m}$. As requirements for the control design, a damping coefficient $\zeta = 0.6$, an accommodation time $t_s = 2s$, for the 2% criterion, and a zero error in the steady state were chosen. The compensator constants $K_p, K_i\ and\ K_d$ were obtained using an algorithm. [3]

2.2. Control System II

For Control System II, the pump speed should remain constant, so that the position of valve FV-01 controls the liquid level in the reservoir. Thus, the flow f_o out of pump B-01 will also be constant.

The Equation (3), represents the linearized behavior of the valve according to its opening position [2]. Through the Laplace transform, it is possible to obtain the transfer function (4).

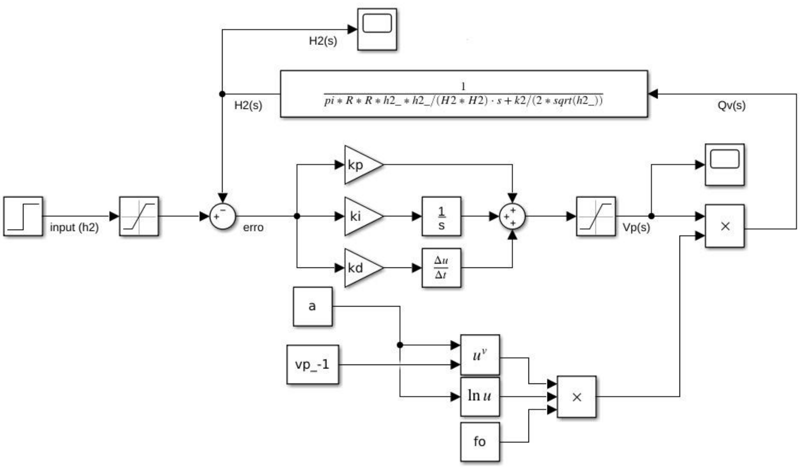
$$\widehat{Q_v} = \alpha^{\overline{v_p}-1} \ln \alpha\, f_o \widehat{v_p} \tag{3}$$

$$\frac{\widehat{Q_v}(s)}{\widehat{V_p}(s)} = \alpha^{\overline{v_p}-1} \ln \alpha\, f_o \tag{4}$$

Where α is the valve constant, f_o is the pump output flow rate, $\widehat{v_p}$ and $\widehat{V_p}$ is the valve opening percentage and $\widehat{Q_v}$ is the tank inlet flow

As in System I, a PID controller will be used, whose error signal is the difference between the desired liquid height and the height read by the level sensor. However, the signal generated this time will be $v_p(t)$, which will pass through a limiter, ensuring that this signal remains between 0 and 1, being the opening percentage of the control valve. The system built in Simulink can be seen in Figure 3.

Figure 3. Control System II in Simulink.



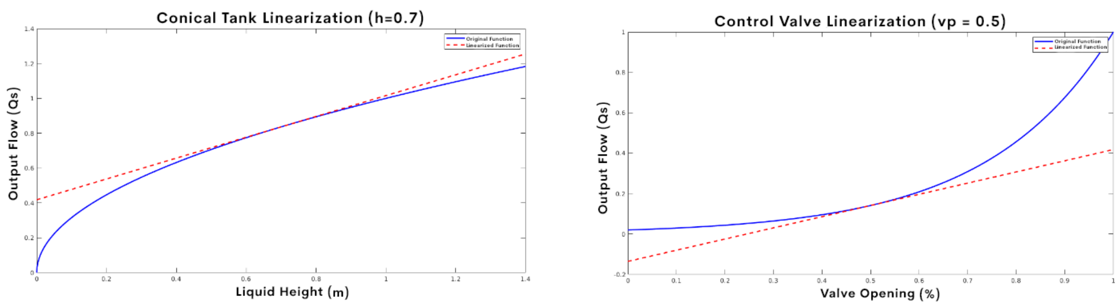
The control of the PID compensator occurred in the same way as in System I, through an algorithm that was developed. For this case, due to the presence of only one pole in the system transfer function, it was necessary to choose a root for the PI controller of -10. The nominal pump flow rate chosen was $f_o = 2L/s$, and the valve coefficient $\alpha = 50$. The valve was linearized at $v_p = 0.5$.

3. RESULTS AND DISCUSSION

3.1. System Linearization

The Figures 4.a and 4.b show, in graphical form, the real and linearized mathematical models for the conical tank and the control valve, respectively. For the conical tank, the linearization point chosen was $\bar{h} = 0.7m$, so that the region around it is approximately equal when comparing the linear function with the original one. The control should therefore operate around this region. Likewise, the linearization point chosen for the control valve was $\overline{v_p} = 0.5$, or 50% opening.

Figure 4. System Linearization.

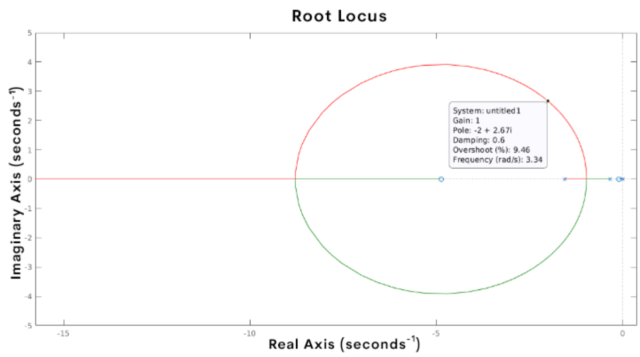


a) Conical Tank Linearization. b) Control valve Linearization

3.2. Control System I

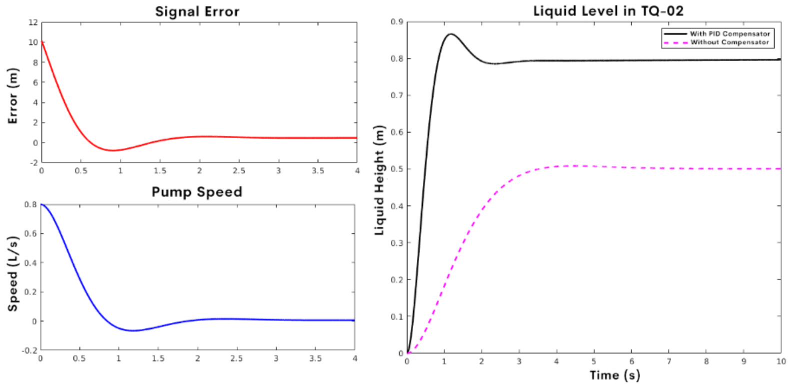
Figure 7 shows the Root Locus plot for Control System I. Note that the projected pole of interest $s_1 = -2 + 2.67j$ as well as its conjugate s_2 lie on the Root Locus map, as desired. The values found for the constants for this first system were $k_p = 12.68$, $k_i = 1.24 \; and \; k_d = 2.55$.

Figure 5. Root Locus Control System I.



To analyze the operation of the designed PID controller, a reference was injected into the system input of 0.8 m by applying a step signal. Initially the response of the system without the designed controller was observed. The graphs on the left of the figure 8 show the error signals $e(t)$, which represents the difference between the *setpoint* and the height value read by the sensor, and motor speed $m(t)$.

Figure 6. Graphs of Control System I.

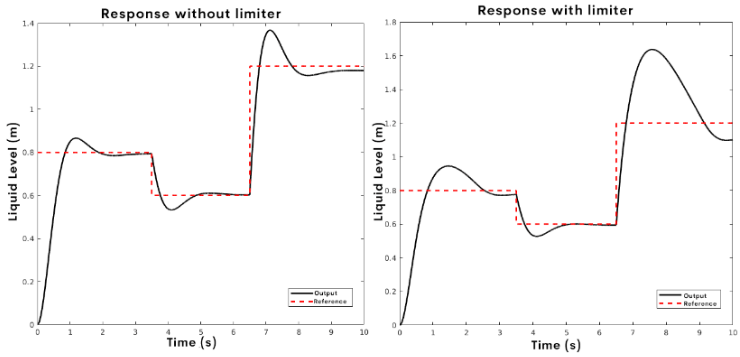


When analyzing the graph on the right, which represents the output signal, it is clear the difference that the designed compensator makes in the system. For the signal with compensator, the maximum point occurred at $h = 0.8661\,m$ (a maximum overshoot of 8.27%), and it also has a zero error on a steady state and an accommodation time of approximately $2s$, as designed.

Note that there is a time interval in which the $m(t)$ signal assumes a negative value, which would indicate a pump running in the opposite direction, removing liquid from the TQ-02 tank. To avoid this, a new Limiter has been inserted in the output of the PID compensator, in order to limit the pump's speed signal to a minimum of 0, preventing it from operating in the opposite direction. This, however, should interfere with both the maximum overshoot and the system accommodation time.

To observe the response of the system to a variation in the reference, step signals were added to its input, making the reference vary from 0.8 m to 0.6 m and 1.2 m, respectively. In the image 7, the graph on the right corresponds to the system with the pump speed limiter, and the difference in the maximum overshoot of the system and in its settling time is clear.

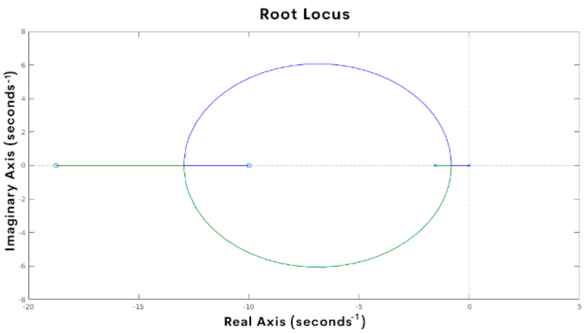
Figure 7. System I response to reference variation.



3.3. Control System II

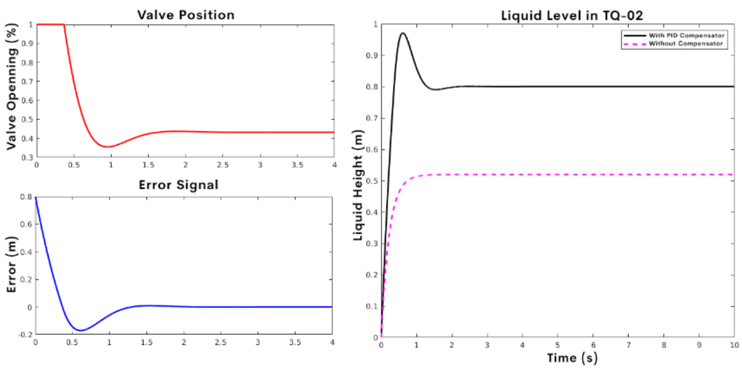
The analysis of the operation of the designed PID controller took place in the same way as in System I. The graph of the Root Locus can be seen in figure 8. The values of the constants found for the PID parameters were: $k_p = 1.90$, $k_i = 8.27 \; and \; k_d = 0.05$.

Figure 8. Root Locus Control System II.



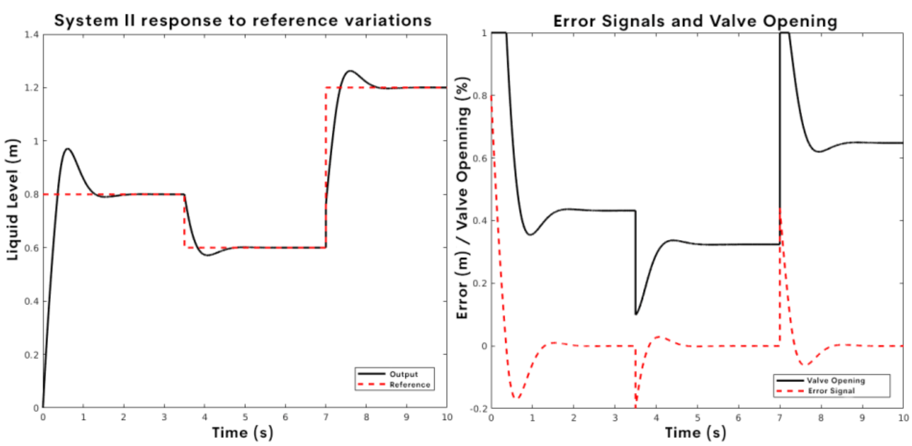
By analyzing the graph on the right of the figure 9, one can again notice the importance of the PID compensator. The peak output signal for a reference of 0.8 m was 0.9709, representing an overshoot of 21.4%, higher than expected. This is due, in part, to the approximations due to the linearization of the system, as well as the saturation required in the signal $v_p(t)$, since being a percentage value, it must always be between 0 and 1.

Figure 9. Graphs of Control System II.



This saturation can be seen in the graphs on the left of the Figure: when the error signal is high, the $v_p(t)$ signal saturates at its upper limit, in order to release a higher liquid flow, to correct the error; when this error becomes lower, the control valve position signal also decreases, leaving the saturation region. Note, however, that the settling time is as expected. The figure 10 brings the graphs of the system signals by variations in the reference signals, and it can be seen that the values found for k_p, k_i and k_d met the project well.

Figure 10. System II response to reference variation.



4. CONCLUSION

Given the objective of the project of a controller capable of correcting errors present in the controlled variable, in relation to reference and disturbances in a system with two coupled tanks, one of them being conical, it was necessary the controller sizing via root locus. Furthermore, the control project was divided into two subsystems which implemented the continuous control of level in the conical tank by varying the pump speed and the position of the main valve.

For the design of the Root Locus PID controller, the selected conical tank has a radius of 0.7 m and a height of 1.4 m and it was considered that the valve FV-01 is fully open. This system was assembled in MATLAB Simulink software, in order to perform simulations about each subsystem. Thus, through graphical analysis, it was verified the clear difference that the controller made in the subsystems, presenting the null error in the permanent regime and accommodation times as designed. Hence, the objective, for the process in question, was completed. At last, as a suggestion for future work, it is possible to associate the block diagrams with a supervisory system, which would be easy to manipulate.

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