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IMPLEMENTATION OF A PID CONTROL SYSTEM FOR THE SPEED OF A HYDRAULIC DYNAMOMETER USED IN THE CHARACTERIZATION OF INTERNAL COMBUSTION ENGINES

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Abstract. *This paper presents the design and implementation of a PID controller for the speed control of a hydraulic dynamometer in a combustion engine. The constants of the controller were determined using the Ziegler-Nichols tuning methodology. The speed control of the hydraulic dynamometer is carried out by varying the volumetric flow of the working fluid (water) with a control valve, which represents the engine load. The hydraulic dynamometer has an encoder and load cell sensors used to obtain the main operational characteristics of the motor (torque, power and speed). Robustness tests were carried out in the controller applying disturbances in the manipulated variable to compare the different responses obtained for each P, PI and PID controller. The results indicate that by applying a PI control strategy, it can be achieving a stable state error of 0.2% and a stabilization time of 30 seconds.*

Keywords: *PID Control, Ziegler-Nichols, Hydraulic dynamometer, combustion motor characteristics.*

1. INTRODUCTION

In a globalized world the advancement of technology and process optimization make companies of automotive industry committed to the study of new components in order to improve the performance of their equipment and processes, achieving a sustainable development. However, despite the clean energy solutions trends the Internal Combustion Engines (ICE) remain as the most commonly used equipment in the industry. This causes an increase in competition in the various engine designs, in which manufacturers are forced to develop new projects to optimize their devices and thus obtain better efficiency.

In ICE research, it is important to have suitable instruments that allow to obtain their characteristic curves for study their behavior and these curves present the engine power, torque and speed. Based on these properties it is possible to performed an eventual failures diagnose in the equipment (Montilla et al., 2007). In this sense, dynamometers are used to extract these parameters and trace the ICE characterization curves. There are different types of dynamometers such as electric, friction and hydraulic dynamometer (Guerrero Amaya, 2008). In the hydraulic dynamometer, the shaft of the internal combustion engine is coupled to the dynamometer by means of a pulley-belt transmission system. In this way, when the working fluid circulates inside the dynamometer chamber (Fig. 1), load is generated due to the momentum and turbulent friction effects, then the sensors measuring the parameters of the engine, resulting in the characteristic curve of the ICE. The behavior of the motor depends on the amount of the load, this means that in the case of a minimum load the motor will have a relatively high speed and low torque. On the other hand, if a high load is applied, the engine speed will decrease however it will deliver a higher torque (Ariza and Vanegas, 2013; Gil and Rincón, 2014).

In the characteristic curves of the ICE the most sensible parameter is the engine speed, therefore the power and torque graphs are related to this parameter. For this reason, a control strategy must be intended to control the speed through the manipulation of the flow of water that circulates inside the dynamometer (load) (Calderón Giraldo, 2012).

Nowadays it is possible to find in the open literature many control strategies for SISO (Single Input - Single Output) systems, from the classic PID to the most complex, adaptive and intelligent methods (Mohammadzaheri, Chen and Grainger, 2012). However, according to Somwanshi et al., (2019), PID control is still highly used in this kind of application due to its robustness, versatility, low computational cost and its massive applicability in industrial equipment. For this reason, in this work a PID controller for the speed control of a hydraulic dynamometer was designed and applied in a combustion engine. The control strategy is based on a classic structure PID, optimizing the process by keeping the system working at the optimum point designated by the designer (Chaves, 2016). To achieve this target, the PID controller is first calculated and tuned through the Ziegler-Nichols reaction curve criteria, then the controller is implemented in the LabVIEW® software, to obtain the characteristic curves of the internal combustion engine by performing the variation in the load to control speed in the ICE.

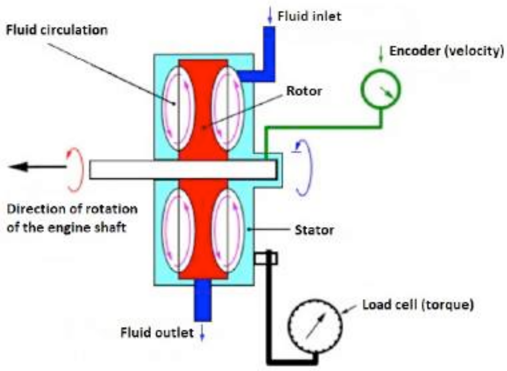


Figure 1. Schematic detail of the hydraulic dynamometer.

2. METHODOLOGY

2.1 Speed Control System for Hydraulic Dynamometer.

Figure 2a depict the test bench for characterization of ICE by controlling the velocity in the hydraulic dynamometer. The test bench is composed by: 1) Internal combustion engine: diesel type reference LISTER LT1, with a rotation speed of 3600 RPM and power of 7.5 HP; 2) Hydraulic dynamometer: manufactured by the company Dising Industrial in stainless steel, with absorption capacity of up to 100 HP, designed with flat radial blades (Fig. 2b) in order to work bidirectionally, that is to say that the load is generated regardless of the direction of rotation of the internal combustion engine; 3) Encoder sensor, used to measure the engine revolutions of the LINE SEIKI brand, reference CB 100 HC and a resolution of 100 pulses per revolution; 4) Strain gauge, MAVIN brand monoblock type, with a maximum capacity of 40 kg, this device is used to measure the force exerted by the engine when applying the load, these units of force are converted to torque by a conversion factor taking into account the distance of the arm of the hydraulic dynamometer; 5) Fluid reservoir; 6) Centrifugal pump, reference EVANS, with power of 1 HP, with rotation speed 3500 RPM, with a maximum flow of 215 L/min; 7) Power supply; 8) Control valve, DANFOSS brand reference EV260B 6B-20B, with a pipe diameter ¾ inch and an internal resistance of 250; 9) Flowmeter, FS300A with a frequency output of 0 to 200 Hz and pipe diameter of ¾ inch used to measure the volumetric flow of fluid circulating through the dynamometer.

(a) (b)

Figure 2. a) Test bench for internal combustion engines. b) Interior detail of the housing. Dising Industrial. Font: (Estupiñan and Franco, 2014)

Figure 3 shows the P&ID diagram for speed control of the hydraulic dynamometer, which shows the different sensors connected to the test bench. In this diagram the speed control in the internal combustion engine is carried out through the manipulation of the volumetric flow that circulates through the hydraulic dynamometer (load), while the measurements of the torque and flow variables are executed.

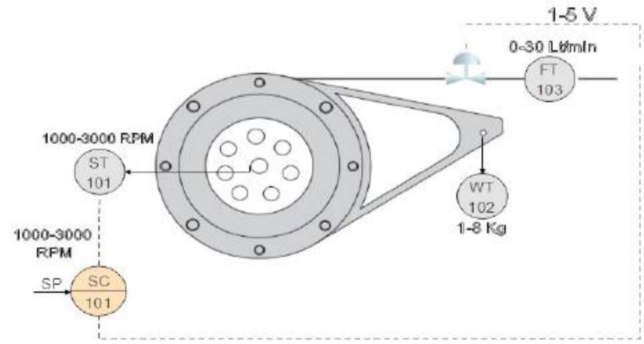


Figure 3. P&ID diagram of the speed control system used for the hydraulic dynamometer.

The function of each element in the speed control loop is explained as follows: Speed transducer (ST), this device, represented by an encoder sensor, is used to measure motor rpm; Speed controller (SC), the controller was programmed in the LABVIEW software and implemented in the test bench with the NI 6009 card of the NATIONAL INSTRUMENTS, on this card the data acquisition, monitoring, process control and saving are carried out of data from the different types of sensors in the test bench. The control has the function of sending an analog signal in voltage of 1 to 5 volts, which will be converted from 4 to 20 MA by the internal resistance of the control valve; Strain gauge (WT) this sensor is used in the test bench to measure engine torque; Volumetric flow transmitter (FT), this sensor is used to measure the flow rate through the dynamometer; and Control valve, this device is used to manipulate the volumetric flow that circulates through the hydraulic dynamometer. Tab. 1 shows the errors by the manufacturer for each sensor.

Table 1. Manufacturer error for each sensor used on the test bank.

Reference	Sensor type	Error
FS300A	Flow meter	3% (1L/min a 10L/min)
CB 100 HC	Encoder sensor	100 PPR
Mavin C3	Load cell	20 mV/V ± 10%

2.2 PID controller tuning

Currently, there are different methods to obtain the coefficients of a classic PID controller. One of the most common techniques to obtain such coefficients are the Ziegler-Nichols tuning methods, such methods are: Oscillation method, reaction curve method and Cohen-Coon reaction curve method (Bansal Hari et al., 2012; Hernandez Mendoza et al., 2012). For each method, there is a specific procedure and a series of restrictions that, depending on the design conditions, must be chosen which is the most appropriate. For this case it was implemented the Ziegler-Nichols reaction curve method. This method consists in applying an excite signal to the entrance of the plant in open loop (Fig. 4) and record the response data of the process reaction curve.

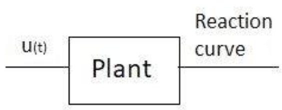
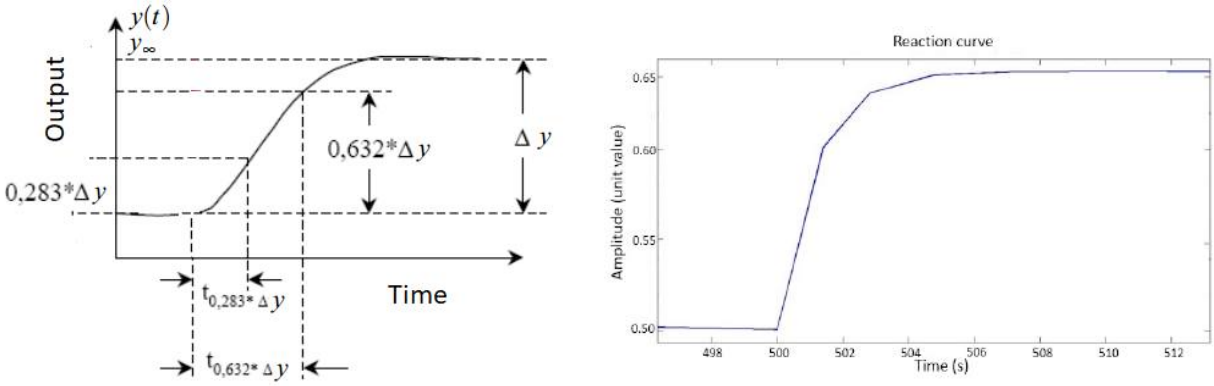


Figure 4. Open loop plant.

To obtain the reaction curve, initially the plant must be in open loop, modifying the manipulated variable "u (t)" of the system (volumetric flow of water inside dynamometer). Once the reference point is established, a step change must be applied to the manipulated variable u (t), this change must be between 10 and 20% of the nominal value. Then, the response generated by the plant is recorded by the DAQ system. In the Figs. 5a and 5b it is shown the theoretical reaction curve and the reaction curve obtained by exciting the plant with a 20% of the manipulated variable u (t) of its reference value in this work.



(a) (b)

Figure 5. Reaction curve of an open loop plant: a) Theoretical curve and b) Obtained curve

All the parameters shown in Fig. 6a are estimated from the reaction curve found in the Fig. 6b, and the characteristic equation of the system is determined as follows:

$$G_o(S) = \frac{k_0 * e^{-S*t_0}}{\tau * S + 1} \quad \tau > 0 \tag{1}$$

According to Ogata (2010), the values of the static gain (K_0), the time constant (τ) and delay time (t0), can be calculated by the Eqs. (2) to (4).

$$K_0 = \frac{y_\infty - y_0}{u_\infty - u_0} \tag{2}$$

$$\tau = 1.5(t_{0,632*\Delta y} - t_{0,283*\Delta y}) \tag{3}$$

$$t_0 = t_{0,632*\Delta y} - \tau \tag{4}$$

Thus, the static gain, time count and delay time of the process were, -2.5763, 0.45 and 0.79, respectively. In Eq. (5) the mathematical model of the plant resulting of the Ziegler-Nichols reaction curve method is presented.

$$G_o(S) = \frac{-2.5763 * e^{-S*(0.79)}}{0.45 * S + 1} \tag{5}$$

The parameters of the PID control and the transfer function of the controller were determined according to Tab. 2.

Table 2. PID controller parameters according to the method of the Ziegler Nichols reaction curve. (Ziegler and Nichols, 1942)

Controller type	Parameters	Controller structure
P	$kp = \frac{\tau}{k_0 * t_0}$	$G_c(s) = K_p(1 + \frac{1}{T_i S} + T_d S)$
PI	$kp = \frac{0,9*\tau}{k_0 * t_0}$, $T_i = 3*t_0$	
PID	$kp = \frac{1,2*\tau}{k_0 * t_0}$; $T_i = 2*t_0$, $T_d = 0,5*t_0$	

The estimated parameters of the PID controllers were assessed using the Integral Absolute Error criterion (IAE), which represents is the area between the process variable (speed) curve and the set point, and is calculated as follows:

$$IAE = \int_{0}^{\infty} \left| e(t) \right| dt \tag{6}$$

In Table 3 are summarized the calculated constants of each controller and its respective IAE. According to their IAE, the best performance is related to the controller PI. This will be checked latter through experimental test.

Table 3. Constants of the best performance PID controllers

	Constants			Stabilization Time	Error
Controller	KP	TI	TD	(TS)	IAE
P	-5	--	--	44.35	-23.09
PI	-2	0.2	--	30,2	0.01
PID	-0.26	1.58	0.2	32.5	2.57

2.3 Hydraulic Dynamometer Speed Controller in the LabVIEW® Software.

With the results that were obtained from the tuning of the controller by the Ziegler-Nichols method, it was introduced the driver for best response obtained in the LABVIEW. The data was acquired with the NI 6009 card in which it was connected to the encoder sensor to perform the speed measurement, strain gauge to perform the torque measurement and finally the power that is the product of torque and speed. The characteristic curves were built using these data. Figure 6 depicts the front panel of monitoring of the test bench and the programming in the LabVIEW® software.

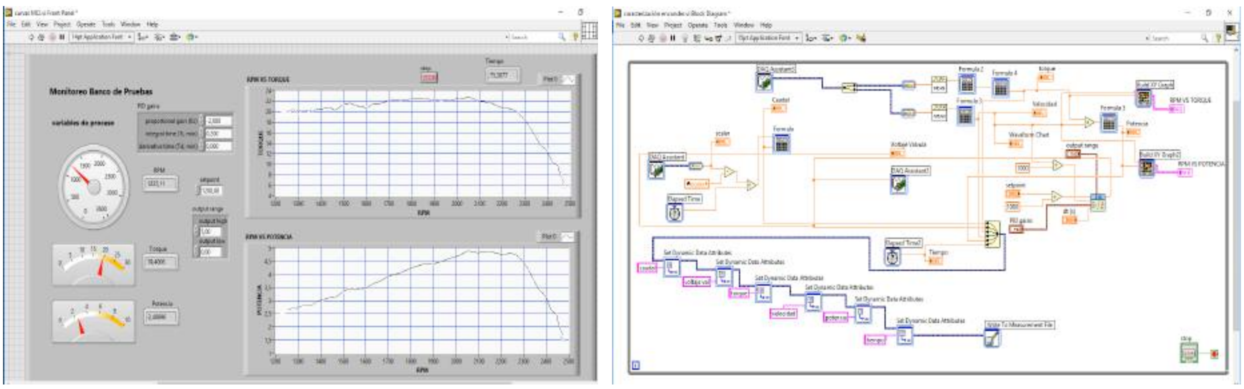
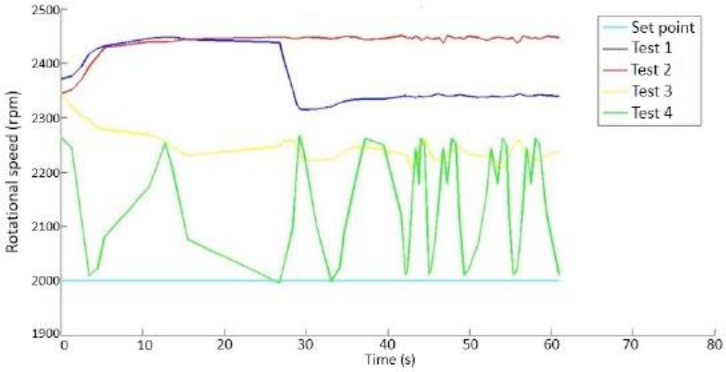


Figure 6. Front panel and screen of the test bench.

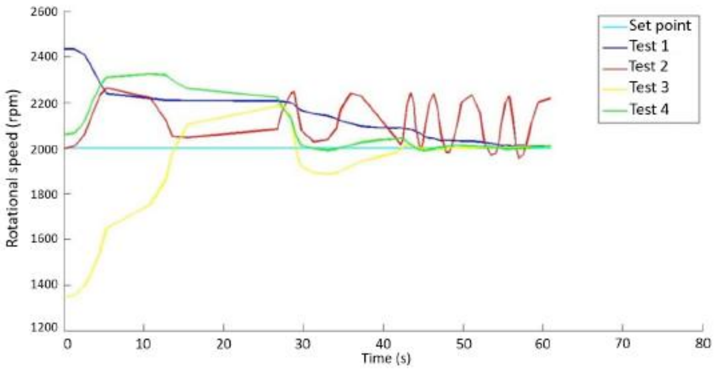
3. RESULTS

In order to evaluate the effects of applying an inadequate control strategy, there were performed different tests modifying the controller constants. In all the carried-out tests, the reference level for the speed was 2000 RPM. In this sense, Figs. 7, 8 and 9 show the results of a P, PI and PID controller respectively, with the control constants and the calculated error for each case, where is highlighted the optimal controller constants calculated.



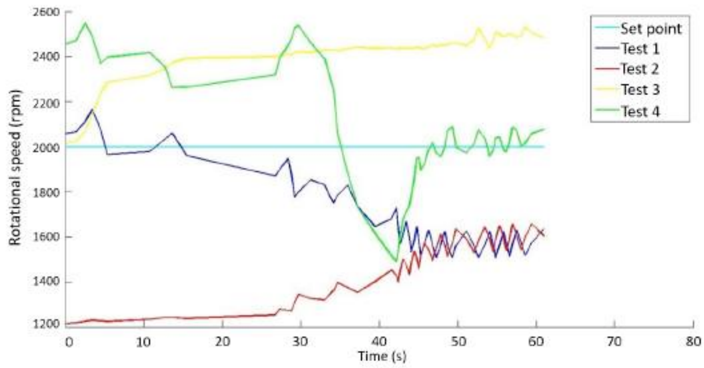
Test	Controller Type P	Error (%)
	KP	
1	-3	17
2	-0.22	22
3	-5	11
4	-8	Oscillatory

Figure 7. P controller constants and tests results.



Test	Controller Type PI		Error (%)
	KP	TI	
1	-3	0.26	0.5
2	-5	1.2	Oscillatory
3	-2	0.2	0.1
4	-2	0.1	0.2

Figure 8. PI controller constants and tests results.



Test	Controller Type PID			Error (%)
	KP	TI	TD	
1	-2	0.26	0.39	Oscillatory
2	-2	0.26	3	Oscillatory
3	-0.2	1.58	0.2	24.5
4	-4.2	0.2	0.1	Oscillatory

Figure 9. Controller constants and tests results.

The results obtained from the tests performed for each controller confirm that just the PI controller calculated from the reaction curve Ziegler-Nichols method, will be able to maintain the value of the dynamometer speed at the desirable level whit a minimum error. Thus, this is the controller that will be implemented herein after in the test bench to obtain the performance curves of the internal combustion engine under test.

In order to assess the robustness of the PI controller, it was carried out a test by suddenly changing the system reference and observing the response of the controller. This test consists of a reference change, that is, let the system stabilize at 2000 rpm and then increasing or decreasing in the reference signal. When these changes are applying, the control system must respond to reach the new reference value. In this case, the reference was initially set at 2000 rpm and after the system attain the stability, the reference was changed to 1700 rpm and latter to 2300 rpm. The results of this test are shown in Fig. 10.

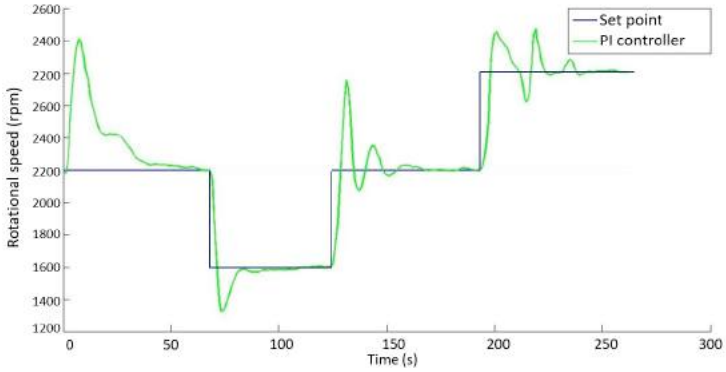


Figure 10. Robustness test of the selected controller.

In Figure 10 it was verified that the controller could reach the applied references presenting a stabilization time of 37.9 seconds and a maximum overshoot of 13.9%. Fig. 11 shows the response of the plant in real time when performed the robustness test.

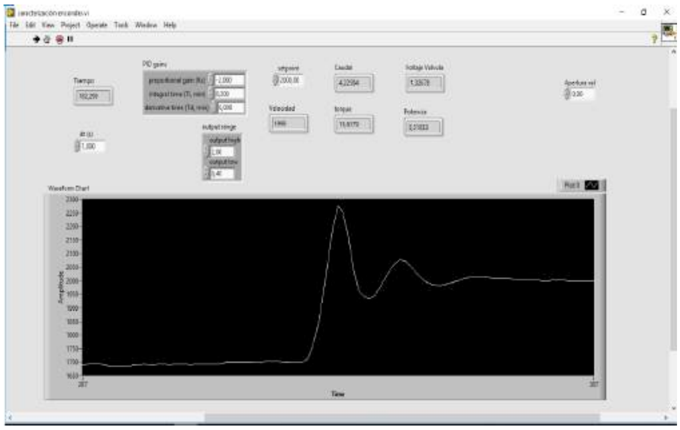


Figure 11. Real-time robustness test through LabVIEW software.

4. CONCLUSIONS

In this work, it was experimentally implemented a speed controller applied to a hydraulic dynamometer to obtain the characterization curves of an internal combustion engine. The PID controller was calculated and tuned using the Ziegler-Nichols methodology through the system reaction curve. Next, the main conclusions from the results obtained:

- It was found that the controller that best adapted to the process was the PI type, since it complied with the design parameters taking into account the following constants KP = -2, TI = 0.2, presenting a stable state error of 0.1% and a stabilization time 30 seconds.
- Robustness tests were implemented in the PI controller to observe its dynamic response for different disturbances, resulting in a stabilization time of 37.9 seconds and a maximum overshoot of 13.9%
- In the implementation of the controller, it is necessary do not change abruptly the refence values, in order to avoid disturbances caused by vibrations in the motor-dynamometer transmission system.
- When the tests were done on the internal combustion engine, it was observe that the control system responds in reverse since it presents a decrease in the manipulated variable due to an increase in the controlled variable, this is due to the increase in the volumetric flow that circulates through the dynamometer, therefore it generates a greater load and consequently the motor rotation decreases.
- The system presents a reverse behavior between the manipulated variable (volumetric flow of water) and the controlled variable (speed), it means that an increase in the volumetric flow that circulates through the dynamometer generates a higher load and consequently the motor rotation decreases.

5. ACKNOWLEDGEMENTS

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