A Flexible Digital PID Controller for an Internal Combustion Engine Testing System

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Abstract. *The Environmental Studies Laboratory (LEA) of the Mechanical Engineering Department of the University of Brasilia has an internal combustion engine testing system based on a hydraulic dynamometer and an analog electronic PID controller (proportional-integral-derivative controller). The purpose of the testing system is to detect characteristics of engines that use a variety of fuels such as diesel, propane or biofuel. In order to adequately characterize the engines, there are two testing classes: testing with selected speed and testing with selected torque.*

In this study, a new digital PID controller system was implemented by using a microcontroller of the 8051 family, interconnected with a PC via serial interface. The new control system was developed for speed control, where the user can choose the PID controller's parameters using a software system running on a PC. In this case, the system is able to maintain the selected speed even though the engine is throttled. The control of the hydraulic dynamometer is made possible by a DC-servo-motor with position feedback, which is implemented with a potentiometer. The PID controller reads the position and speed sensors and relays the proper control signals to the servomotor.

In this approach the controller's parameters can be changed even in real time by the user, implementing a flexible system useful for the testing and the characterization of a wide variety of internal combustion engines.

Although the system composed by the tested engine and the dynamometer is not linear, this work shows that a proportional-derivative controller (PD controller) provides the best results. This conclusion could be obtained given the great flexibility of the implemented system.

***Keywords**: PID Controller, Microcontroller, Internal-Combustion-Engine.*

1. Introduction

The testing system for internal combustion machines of the LEA (Environmental Studies Laboratory) has a hydraulic dynamometer, which is used to determine power consumption and engine torque. The current testing system is used to detect characteristics of the engines that use a variety of fuels such as diesel, propane or biofuel. The system is basically composed of an analog electronic PID controller and a hydraulic dynamometer, which is coupled to a servomotor. In this case the charge of the engine can be modified through the water flux variation. The current system is completely analog and should be replaced by a new digital one.

The old system offers the user the possibility to execute testing for both constant speed and constant torque. In this case it is more important to test the engine for constant speed. The testing system implements an analog PID controller, which must maintain the speed constant. The user specifies the speed reference and the controller maintains it constant even if the engine is throttled.

Proportional-integral-derivative (PID) controllers are still widely used in the process industry and according with Ho *et al* (2001) the state of process control systems in 1989 conducted by the Japan Electric Measuring Instrument Manufacturer's Association, more than 90% of the control loops were of the proportional-integral-derivative (PID) type.

Despite the amount of researches done on tuning PID controllers, many PID controllers are poorly tuned in practice (Grassi *et al*, 2001; Wang *et al*, 1999). This may be due to the fact that most methods are derived for particular processes and situations and then applied in a satisfactory manner only within restricted areas. Moreover, the common experience is that there isn't assurance about which method should be chosen to provide good parameter values to obtain a good control (Wang *et al*, 1999).

Many formulas have been derived to tune the PID controller for single-input/single-output (SISO) systems. Among the well-known formulas are the Ziegler-Nichols rule, the Cohen-Coon method, IAE, ATAE, and internal model control (Wang *et al*, 1999). Among them, the internal model control (IMC) formula is very well known. The IMC-PID formula is attractive to industrial users because it has only one tuning parameter, which is related to the closed-loop time constant. This makes it easy and convenient to tune the PID controller to meet specified time domain performance (Ho *et al*, 2001).

Despite the chosen tuning PID methodology it is very important to have a flexible software-hardware control system available in order to test the parameter obtained through a given tuning method. This is even more important in complex control processes, such as those evolving non-linearity aspects.

In this study, a new digital PID controller system was implemented by using a microcontroller of the 8051 family, interconnected with a PC via serial interface. The new control system was developed for speed control, where the user can choose the PID controller's parameters using a software system running on a PC. In this case, the system is capable of maintaining the selected speed even though the engine is throttled up/down and/or the load is varied. There is a DC-servomotor with position feedback, which is implemented through a potentiometer. The servomotor operates the hydraulic dynamometer. The PID controller reads the position and speed sensors and relays the proper control signals to the servomotor.

In this approach the user can change the controller's parameters even in real time, implementing a flexible system useful for both testing and characterizing of a wide variety of internal combustion engines. This characteristic is very important since the whole testing system has non-linearity characteristics. Given the great flexibility of the implemented system it was possible to determine the best configuration of the controller for the current application.

This paper is divided as follows: section 2 describes the current engine testing system. Section 3 presents basic concepts in PID controller. Section 4 presents the main characteristics of the current testing system. Section 5 shows the implementation of the controller in software. Section 6 describes the results obtained with the new control system. Finally, section 7 is the conclusion.

2. The system for testing engines

The testing system for internal combustion machines has the following functional parts:

a) Engine under testing;
b) an hydraulic dynamometer;
c) a DC servomotor to drive the dynamometer;
d) a tachometer to measure motor speed;
e) Strain-gage-based system for measuring motor torque;
f) an analog controller board.

The control of the hydraulic dynamometer is made possible through 25 volts DC-servo-motor with position feedback. This electric motor permits to control the water flux through the hydraulic dynamometer. Therefore, the load applied to the engine increases or decreases depending of the flux variation. The water flux is controlled by a butterfly valve coupled to the servomotor axle. The load variation allows the implementation of the speed control of the engine. In this case it is possible to obtain a given speed whenever the engine is throttled.

Figure 1 shows the servomotor and butterfly system (Schenck Measuring Mechanical Dynamics, 2005), which has a security lock that prevents the motor from rotating completely.

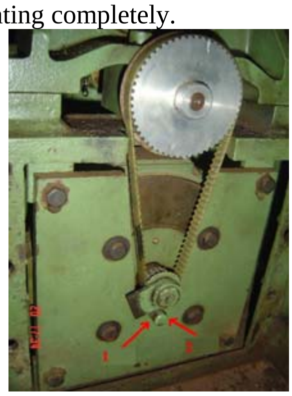


Figure 1. Servomotor and butterfly valve with lock

The servomotor has a potentiometer that produces a voltage signal output depending on its axle position. This analog signal provides feedback information in order to implement the control system. Along with the servo position feedback, the system has an analog tachometer, which measures the speed of the motor under testing and a strain-gage to measure the load applied by the dynamometer.

The PID controller reads the position feedback (potentiometer signal) and tachometer and relays the proper control signals to the servomotor. The analog system offers the user the possibility to execute both the testing for constant speed and constant torque.

3. The PID controller equations

The controller has the structure showed in figure 2 (Ogata, 2003). Basically, the user set the speed reference input (Ref (s)) and the current speed signal is obtained through the feedback loop. The servomotor position feedback is only used to set the initial state of the control process (see section 4.2).

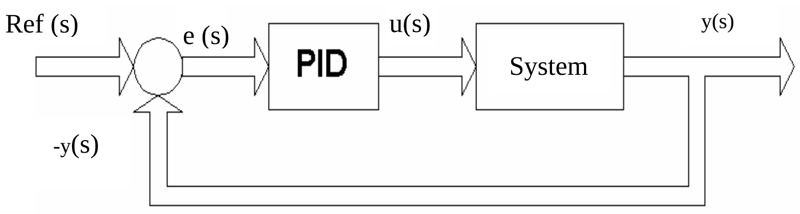


Figure 2. Basic control structure

In general a PID controller has the equation:

$$G_c(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d s \qquad (1)$$

where K_P, K_I and K_D are the proportional, integral and derivative parameter of the controller, and *U(s)* and *E(s)* are the control and error signals respectively. The tuning objective is to determine the PID parameter so that the controller achieves high and consistent performance for a general class of internal combustion engines. In order to obtain the digital implementation of the controller a discrete approximation of the derivate and integral is used. In the derivate case the backward rectangular rule is used, while the forward rectangular integration is used for the integral one (Franklin *et al*, 1997; Phillips *et al*, 1995). The PID discrete controller in the Z-domain is showed in equation 2.

$$G_c(z) = \frac{U(z)}{E(z)} = K_p + \frac{K_i T z}{(z-1)} + K_d \frac{(z-1)}{Tz} \qquad (2)$$

The general difference equation that represents the PID controller is obtained adding the three terms (it is used *x(KT) = x(K)*):

$$\begin{aligned} u(K) &= K_p e(K) + K_i[u(K-1) + Te(K)] + (K_d/T)[e(K) - e(K-1)] \\ u(K) &= [K_p + K_i T + (K_d/T)]e(K) + K_d T e(K-1) + K_i u(K-1) \end{aligned} \qquad (3)$$

The equation 3 can be implemented in a digital computer such as a microcontroller. Additionally, it is possible to implement a PI or PD controller by making the appropriate gain equal to zero.

4. The Implementation of the control system

The new control system consists of a computer (PC) that is used to develop and run the system as a supervisory, the microcontroller kit (CW552 KIT, 2005) based on the 80552 microcontroller (which implements the controller and has a Digital-Analog converter system based on Pulse Wide Modulation -PWM) and the power driver (a full-bridge H was used). Figure 3 depicts the functional structure of the new system.

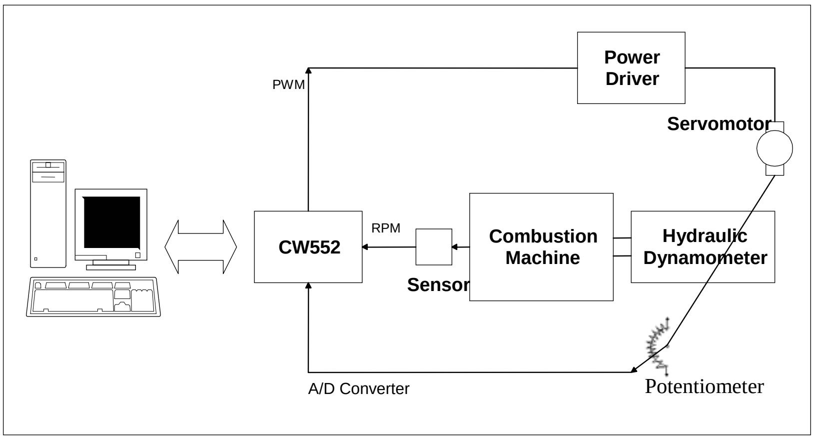


Figure 3: The new system structure

4.1 The microcontroller kit

The microcontroller 80552 is a 8051 family microprocessor system with several added subsystems such as two counters/timers, serial communication interface, external interruption, and PWM (Pulse Width Modulation) outputs. This microcontroller was developed for real time applications such as instrumentation, process control, and automotive industry, among others. Besides the classical 8051 instructions the 80552 has specific ones for implementing special functions for interruption and data acquisition, which are suitable for real time applications. Other specific new characteristics of this microcontroller include (CW552 KIT, 2005):

a) Three 16 bits counters/timers.
b) Serial communication interface (asynchronous).
c) Analog-Digital (AD) converter.
d) Digital-Analog converter system based on Pulse Wide Modulation (PWM).
e) *I2C* communication interface.
f) Watchdog system.

4.2 The feedback signals used in the new system

Two feedback signals are used for the controller. The first one is the position signal, which also represents the load applied by the dynamometer. This signal is implemented through the potentiometer coupled with the servomotor. The position of the butterfly valve is read via the microcontroller's analog to digital converter (AD-converter).

The second signal is the engine speed, which is implemented by an optical sensor. This optical sensor replaced the original tachometer of the analog system. In this case a device composed of a Light Emitter Diode (LED) and a phototransistor was used, producing a TTL compatible output signal, and at every engine shaft rotation a pulse is created. Figure 4 shows the signal generated by an engine speed of 2100-rpm.

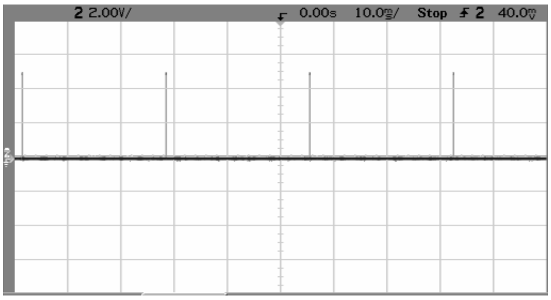


Figure 4. Output signal from optical sensor

5. The implementation of the controller in software

The program was implemented in C language and its modular structure is showed in figure 5.

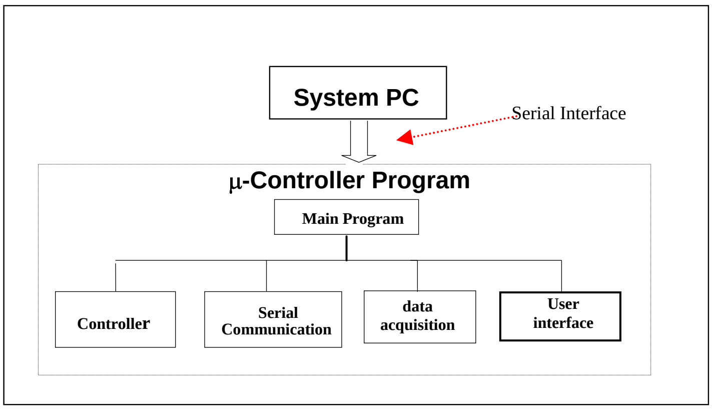


Figure 5. Modular structure for the implementation of the controller

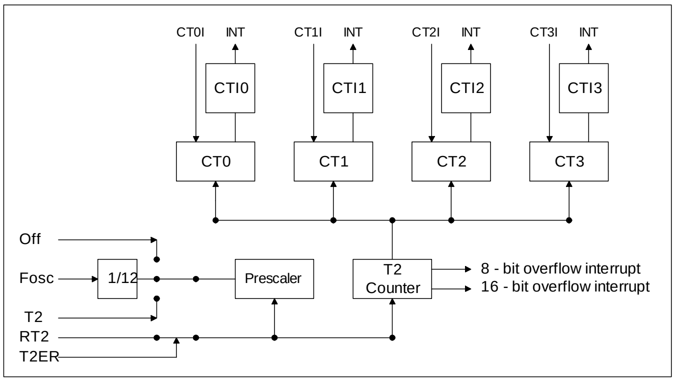
The system PC works as supervisory system where the user receives information from the microcontroller. The user can also send data via serial interface in order to configure the control system, which was totally implemented in the microcontroller. The controller module was implemented through a special function (see section 5.2). The communication between PC and microcontroller (serial communication module) was implemented via serial interface using special functions. In the microcontroller the communication was implemented using poling technique, and its serial port is read all the time by the interface-function in order to receive or send data.

The data-acquisition module for speed signal manipulation was implemented in a function, which uses a special timer configuration of the 80552 microcontroller (see section 5.1).

The user interface module implements the necessaries functions to show in the display of the microcontroller the information about the speed reference, the current speed and the state of the servomotor's potentiometer.

5.1 The routine for speed signal processing

In order to process the speed signal a function was implemented taking into account special features of the microcontroller. In this case a TTL compatible signal coming from the speed sensor brings information about the rotation of the engine. The signal has two periods per rotation given that the disk, where the sensor is coupled, has two symmetric holes. In order to determine the speed it is only necessary to calculate the time between the two rising edges of the sensor signal. To accomplish this, the timer 2 (*T2*) of the microcontroller (also called *capture*) was used. Figure 6.a shows the functional structure of the timer 2.




```
void cap_CT3_Timer2(void)
{
 1      p = CTH3;
 2      p = p << 8;
 3      p = p + CTL3;
 4      CTI3 = 0;
 5      RT2 = 1;
 6      RT2 = 0
}
```

(a) (b)

Figure 6. (a): Functional structure of the Timer 2. (b): Basic routine for the Timer 2 interruption

In this application a counter frequency equal to the kit's oscillator frequency (f_{osc} = 11592000 Hz) was chosen. This frequency is divided by 12, resulting in a new frequency of 921600 Hz (a period of 1.085 μs). Therefore, timer T2 is incremented by a value equal to one period, at every moment. A 16-bit register is connected to the timer, more specifically CT3. This register is charged with the current value of the timer. The flag CT3I, which is located in the TM2IR register, is used to require an interruption to the timer. On the other hand, the same flags are related to the input pin P13 (one pin of the microcontroller's P1 bidirectional port).

The configuration of timer T2 is implemented by the CTCON register. Moreover, the capture mode characteristics of the signal such as falling or rising sensitive edges or falling-and-rising sensitive edges can be configured using the special CTCON register. In this case, a rising edge sensitive mode was chosen using the P13 input pin (related to the CT3I flag).

Figure 6.b shows the routine code that captures the data signal coming from the speed sensor (which was written in C language). The counter value is acquired in two registers (CTH3 and CTL3 for the most significant byte and the least significant byte respectively). The CTH3 value is stored in *p* variable (see line 1). An 8 bit shift-left operation is done before reading the CTL3 register (line 2 and 3) in order to store the CTL3 value.

In addition to the above, it is necessary to clear the two registers before initiating a new count. To accomplish this, one rising edge signal is applied to the RT2 special bit, which is allocated in the CTCON register (see lines 5 and 6).

Afterward, the captured value is multiplied by 921600 in order to obtain real frequency, and this value is multiplied in turn by 60 to obtain the rotation value in RPM.

5.2 The control signal calculus for this application

The transfer function of a PID controller in the frequency domain is obtained using the Zero-Order-Hold to calculate the appropriated discrete model ($G_c(z)$), starting with the classical model (see equation 4).

$$G_C(s) = K_P\left(1 + \frac{1}{T_i.s} + Td.s\right) \quad (4)$$

To accomplish this, one pole is added in *–a*. Therefore, the following equation is obtained

$$\frac{G(s)}{s} = \frac{KpTd}{s+a} + \frac{Kp}{s(s+a)} + \frac{Kp}{Ti}\frac{1}{s^2(s+a)}$$
$$G(z) = \left(\frac{z-1}{z}\right)Z\left\{\frac{G(s)}{s}\right\} = KpTd\,\frac{z-1}{z-e^{-aT}} + \frac{Kp}{a}\frac{1-e^{-aT}}{a-e^{-aT}} + \quad (5)$$
$$+\frac{Kp}{a^2Ti}\frac{(aT-1+e^{-aT})z + (1-e^{-aT} - aTe^{-aT})}{(z-1)(z-e^{-aT})} = \frac{U(z)}{E(z)}$$

where T is the sample time.

The difference equation version of the control signal is the following:

$$u(k) = c0.u(k-1) - c1.u(k-2) + c2.e(k) + c3.e(k-1) + c4.e(k-2) \quad (6)$$

where

$$c0 = 1 + e^{-aT}$$
$$c1 = e^{-aT}$$
$$c2 = KpTd \quad (7)$$
$$c3 = \frac{Kp}{a}(1-e^{-aT}) - 2KpTd + \frac{Kp}{a^2Ti}(aT - 1 + e^{-aT})$$
$$c4 = \frac{Kp}{a^2Ti}(1-e^{-aT} - aTe^{-aT}) + KpTd - \frac{Kp}{a}(1-e^{-aT})$$

Given that the term e^{-aT} can be neglected for one pole in $-a$ = -10, a new equation is obtained

$$u(k) = u(k-1) + c0.e(k) + c1.e(k-1) + c2.e(k-2) \quad (8)$$

where

$$c0 = KpTd$$
$$c1 = \frac{Kp}{10} - 2KpTd + \frac{Kp}{100Ti}(10.T - 1) \quad (9)$$
$$c2 = \frac{Kp}{100Ti} + KpTd - \frac{Kp}{10}$$

The error signal is calculated by

$$e(K) = ref - y(k) \quad (10)$$

6. Results

Figure 7 shows the results obtained using the first Ziegler-Nichols method (0gata, 2003). In this case the engine was started with maximum charge and with an initial speed of 1000 RPM. Afterwards, the butterfly valve was closed in order to apply a step input function to the system. In this case, it can be observed that the time constant (*T)* is approximately equal to 1.5 seconds. A chronometer measured the delay time due to the fact that the response was close to a line and it was not possible to plot the step input jointly with the response. In several experiments the delay constant (*L*) was approximately 2 seconds. Test results are showed in table 1 and these clearly describe a non-linear system (see also figure 7).

Table 1 – Results to the first Ziegler-Nichols test

Controller Type	Kp	Ti	Td
P	0,75	inf	0
PI	0,75	6,667	0
PID	0,75	4	1

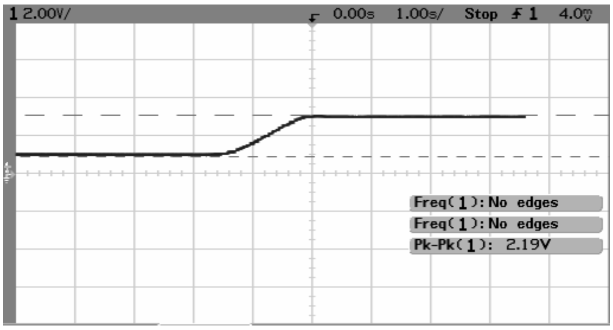
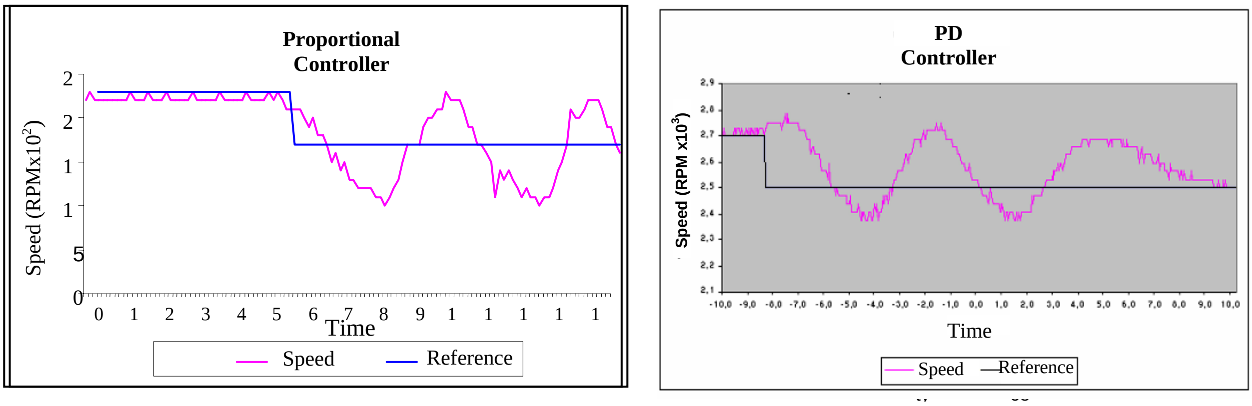


Figure 7. Step function response of the system

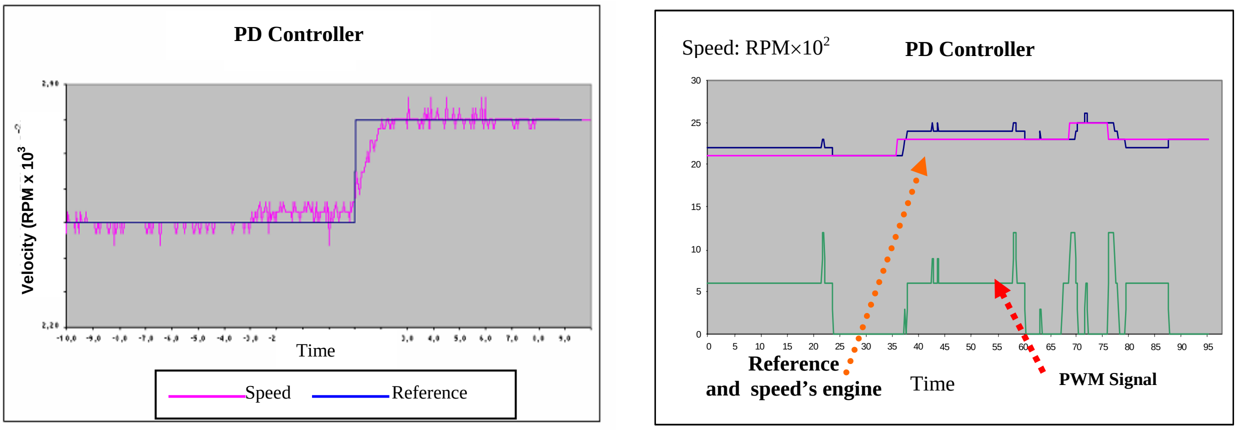
The results obtained through the Ziegler-Nichols test were not satisfactory. In this case the methodology for tuning the controller consisted of implementing a Proportional-Controller (P-Controller) in order to obtain a first proportional parameter. The best result was obtained with K_p equal to 5. Figure 8.a shows the step response for an initial 2300 RPM input reference that is changed suddenly to 1700 RPM, and the result is similar to an underdamped step response.



(a) (b)

Figure 8. (a): Step function response for P controller. (b): Step function response for PD controller

Given these results it was observed the necessity to add a derivative parameter (T_d) in order to decrease the oscillation. Figure 8.b shows the step response of the PD controller using K_p = 3 and T_d = 1, where it was possible to obtain a control for varying the input reference from 2700 RPM to 2500 RMP.



(a) (b)

Figure 9. (a) Step function response increasing the reference. (b) PWM signal behavior for PD Controller.

Note that after 8 seconds the system was stable and the overshoot was approximately 10%. Using the same parameters a step function varying from 2500 RPM to 2800 RPM was applied (see figure 9.a). In this case the controller's response was satisfactory with a short overshoot and a delay time (L) of approximately 2 seconds. Note that this delay time is very similar to the one obtained through the Ziegler-Nichols test (approximately 2 seconds).

Figure 9.b shows the controller's PWM signal response where it can be observed the variations of this signal depending of the current speed of the engine.

In all experiments the input reference variations were done in real time using the supervisory system, which was implemented in the PC.

7. Conclusions

This paper described a new implementation of the internal combustion engines testing system of the Environmental Studies Laboratory (LEA) of the Mechanical Engineering Department of the University of Brasilia. The new system is, basically, a digital PID controller system that was implemented by using a microcontroller of the 8051 family, interconnected with a PC via serial interface. The new control system was developed for speed control, where the user can choose the PID controller's parameters and also change them (even in real time) using a software system running on a PC.

Given that the new system is highly flexible it was possible to tune the initial parameters firstly achieved using the Ziegler-Nichols test. Results for the P and PD controllers analyzing the step function response were achieved. These results showed that the best results were obtained using a PD controller. In this case it was observed that the step response is better when increasing the reference point than decreasing the same. This can be explained due to some phenomena in the hydraulic dynamometer such as cavitation, the water flow, among others. In the water flow case is clear that the physics of the water flow going into the dynamometer is different of the same involved in the flow going out. This explains the fact that the controller responds better when the reference is incremented (see figures 8.b and 9.a). In this implementation, it was not necessary to implement the integral part of the controller (T_i parameter) due to the fact that the PD controller accomplished the reference value without error.

Future works will be focused on improving the current implementation and using new digital techniques such as Reconfigurable Architectures based in **F**ield **P**rogrammable **G**ate **A**rrays (FPGAs). These devices provide the possibility of hardware reconfiguration by software means. This characteristic transforms them into very flexible devices for the implementation of different hardware architectures. Such flexibility opens a wide range of architectural alternatives to implement control and/or automation solutions directly in hardware instead of software using microcontrollers (Muller-Glaser, 2004; Becker, 2003).

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