QFT CONTROL APPLIED TO A DRIVE BY WIRE (DBW) SYSTEM

Fabio Delatore [(a)], **Fabrizio Leonardi** [(b)], **Alexsander T. Carvalho** [(c)], **Carlos A. Morioka** [(d)]

[(b)] Centro Universitario da FEI – Sao Bernardo do Campo/SP
[(a), (c), (d)] FATEC Santo Andre – Santo Andre/SP

[(a)] fabio.delatore@gmail.com, [(b)] fabrizio@fei.edu.br, [(c)] tressino@gmail.com, [(d)] carlos.morioka@uol.com.br

ABSTRACT

Tradionally, the throttle valve positioning was performed mechanically by means of a steel cable. Nowadays at the embedded system stage, an electromechanical system named as *Drive by Wire* (DBW) substitutes the direct positioning. The DBW is controlled by the vehicle *Engine Control Unit* (ECU) and is responsible to adjust the mass air flow delivered to the engine and to control the idle engine rotation. The throttle valve control is somehow a challenging task because of nonlinear phenomena caused by the spring and the gearbox. The present work aims to design a robust parametric control for a DBW system, using a plant model identified numerically at different operations points. The results show that the controller is able to deal with the nonlinear phenomena providing a reasonable performance with no steady state error and a consistent setting time.

Keywords: QFT control, Throttle Valve, Engine Control, Drive-by-Wire.

1. INTRODUCTION

Traditionally and for many years, the union between the gas pedal (car accelerator) and the throttle valve was performed mechanically by means of a steel cable, in order to perform the opening/closing procedure of the valve (Deur *et al.* 2005). This valve is responsible to control the air supply to the vehicle engine, keeping the desired engine rotation and torque according with the driver request, by using the gas pedal. Another important item presented on this system, is the engine idle rotation actuator, which is responsible to keep the engine in a specific rotation when there is no driver´s request on the gas pedal (Morioka *et al.* 2011).

With the advent of the electronic embedded systems, mainly on the engine management systems (represented by the electronic fuel injection), the throttle control system was modified and incorporating some others components, such as a potentiometer responsible to inform the valve position (named as *Throttle Position Sensor* – TPS) and a DC motor, responsible to open/close the valve in a combination with a gearbox (Deur *et al.* 2005). This new system is named as *Drive by Wire* – DBW and it is nowadays responsible to adjust the mass air flow delivered to the engine in a similar way of the mechanical system with the steel cable did (Tilli *et al.* 2000).

The DBW is an important evolution on the automotive management systems. Including the DC motor, it not only eliminated the steel cable to perform the opening/closing task, but it also allows eliminate the idle engine actuator. The DBW has two important tasks on the engine management. It is responsible to control the engine rotation at idle and also to supply the engine with the exact air quantity (Tilli *et al.* 2000).

A simplified structure of the DBW system it is shown in the Figure 1. Figure 2 brings a Volkswagen EA-111 engine throttle valve which contains the TPS sensor and the DC motor. Note that the system input is the gas pedal position and the system output is the TPS sensor.

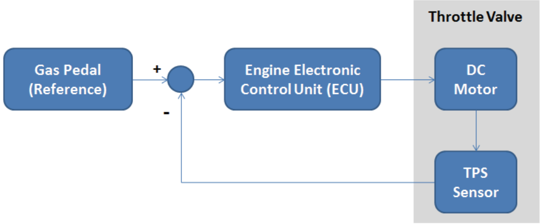

Figure 1: DBW system block diagram.

Figure 2: Volkswagen EA-111 throttle valve (Author).

The throttle valve is one of the most important actuators presents on the moderns' cars engines. As mentioned before, it involves a DC motor which drives the throttle plate through a gearbox unit, and the opening angle is measured by means of a potentiometer integrated into the gearbox. This gearbox has two mechanical stops that define the valve opening range, which is approximately 90º. In case of a failure associated to the DC motor, the valve plate is repositioned into the home position (0º) by a spring mechanism (Reichhartinger and Horn, 2009).

Nonlinear phenomena like stick–slip friction, gear backlash, and discontinuities, mainly caused by the spring mechanism, render the control of this mechatronic system a challenging task (Reichhartinger and Horn, 2009). This fact is documented by a number of publications dedicated to the modeling, identification, and control of electronic throttle devices (Corno *et al.* 2011; Reichhartinger and Horn 2009; Deur *et al.* 2005; Tilli *et al.* 2000; Poggio *et al.*1997).

The authors Gharib *et al.* (2010) proposed to use the QFT technique to design a controller of the engine at idle speed. They used a phenomenological model that relates the inputs, throttle angle and load torque, with the outputs, manifold pressure and engine speed. The model was linearized and they used the second order transfer function from the throttle angle to the motor speed for the robust design. The gain and the damping coefficient were used as uncertainties, but there is no further discussion of this choice. In that paper, the authors considered that the throttle angle is given, i.e., do not take into account the dynamic between the pedal and the throttle valve. This present article addresses the problem of dynamics of this loop between the pedal and the throttle valve, and therefore can be viewed as an internal control loop of the system described by Gharib *et al.* (2010).

The throttle dynamics is highly nonlinear and its performance affects the response of the engine speed control system. As pointed out before, the throttle valve dynamics affects directly the engine rotation. It must be point out that the knowledge of the dynamics of the throttle valve control system is important during the engine calibration process. On this process, different engine operating regimes are evaluated for different temperature and atmospheric pressure. With the DBW system, the valve opening with a correct pre-determined dynamic contributes to the driving comfort.

This work proposes the usage of a QFT controller to be applied on a throttle valve in order to impose an adequate throttle dynamic and robustness to the DBW system.

2. METHODOLOGY

The present work aims to design a robust control system for a DBW system using a plant model identified numerically by applying several steps on a VW EA-111 throttle valve. Different from some works founded on the scientific literature (i.e. Poggio *et al.* 1997) which presents the throttle modeling, this work intends to identify an approximated model by applying several step signals on an open loop structure. Analyzing the parameters variation of the model obtained, the Quantitative Feedback Theory design is used to develop a robust controller to the DBW system with a desired dynamic.

2.1. Robustness

The modeling errors are translated into uncertainty of the plant transfer function. The dynamic model of the plant considered in this work includes three uncertain parameters.

The stability margins (gain and phase) are often used to evaluate the tolerance of the system to modeling errors of the gain and phase of the transfer function. However, in fact, they are fragile to reveal the degree of robustness of the system, because even systems with high stability margins may have its corresponding Nyquist diagram near to the critical point -1+0*j* and therefore are not robust (Da Cruz 1996). The example of Figure 3 illustrates how even high gain and phase margins are unable to represent the robustness of the system.

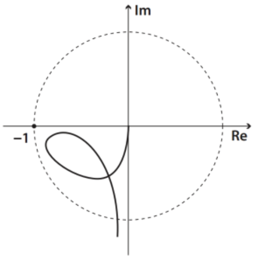

Figure 3: Robustness *x* Stability Margins.

Note that the values of the stability margins are approximately 90° for the phase margin and infinite for the gain margin. These values suggest that the system tolerates large modeling errors, and so has high robustness. Note that due to the apparent vicinity of the curve to point -1+0*j*, a small change in the plant model may cause a change in the number of encirclements of the critical point, causing the system to lose stability.

The uncertainty of a model can be classified as structured and unstructured. The unstructured uncertainties are usually associated to the parts not modeled of the plant and are frequency dependent. Note that normally the neglected characteristics are of high frequency dynamics. The parametric uncertainties are associated to structured uncertainties such as the uncertainties in the model of this paper. The common used techniques for the case of parametric uncertainties are the µ-synthesis and QFT (Houpis 1999).

To characterize the unstructured modeling errors, one may define the multiplicative error representing the relative difference between all the real plants and the nominal plant model in relation to this nominal model. For the design purpose the modeling errors are evaluated by means of the absolute value of a frequency dependent upper limit of the errors. Note that since unstructured modeling error are evaluated without phase information, there is an inherent conservatism associated to the obtained controllers in the sense that the loop gain is higher than minimum needed for the case where the phase information has been taken into account.

For the case of structured modeling errors one way to represent the errors is by means of the frequency response for each transfer function of the real plants, called templates. This frequency response is usually represented in the Nichols chart because it allows evaluating the magnitude and phase in the same plot, and also allows determining directly the values of gain and phase margins.

2.2. Quantitative Feedback Theory (QFT) Design

The QFT design (Quantitative Feedback Theory) is a technique in the frequency domain in the Nichols chart. As pointed by Borghesani (1993) and Yaniv (1999), the first step of design procedure is the determination of templates generated by the parameters uncertainties. A template is defined as the collection of uncertain plant frequency response functions at a given frequency. However, for the design, only the bounds of those templates are important.

Performance specification imposes barriers to the loop gain in the Nichols chart, and these templates should be above barriers in the specified frequency range. Margins of stability or robustness associated to the maximum resonance peak of the closed loop, imposes barriers around (0, -180º) in the Nichols chart.

The region around this point must be reshaped so that the boundary of all the templates does not violate this region. The design starts by selecting a point on the border of the template as the nominal plant and then, based on this point, the curve around (0,-180°) should be reshaped so that, when the nominal point does not violate the new curve, all points of the template are outside the original curve.

Then, the problem of finding a controller that meets the requirements of robust performance and stability should be done, for example, by trial and error, adding poles and zeros to the controller transfer function.

3. EXPERIMENTAL RESULTS

3.1. Overview of the DBW experimental system

The DBW experimental system developed on this work is presented on Figure 4, including some electronic circuits, the throttle valve and the gas pedal (car accelerator).

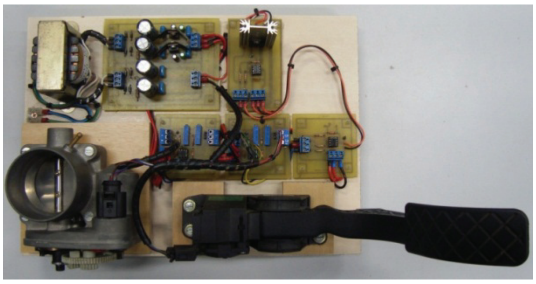

Figure 4: Overview of the experimental system.

The DBW system set point is defined by the gas pedal (desired angle) and the output is the throttle valve angle, measured by the TPS sensor. The gas pedal and the TPS sensor signals are conditioned into a 0-10 Volts output range, turning the plate position totally closed or totally opened, respectively, through the PWM driver (Morioka *et al*. (2011).

Figure 5 shows the connections between the DBW experimental system and the Advantech PCI 1718 DAQ board installed on a PC computer, operating at 30kHz sampling frequency.

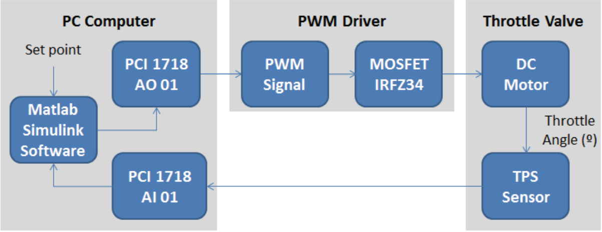

Figure 5: Experimental system and DAQ connections.

3.2. Plant model

In order to reveal the system dynamics it was performed several step tests with different amplitudes in open loop through the PWM. The typical dynamic obtained is presented by Figure 6.

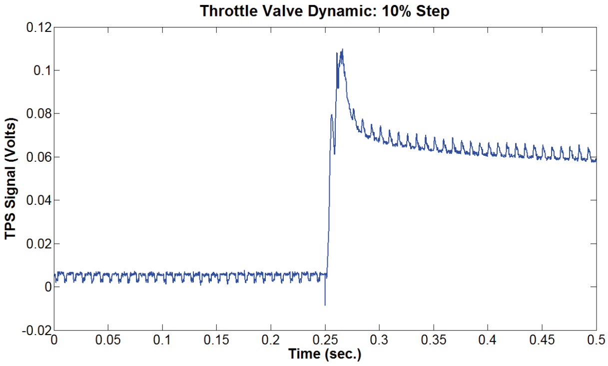

Figure 6: Throttle valve typical dynamic.

Using the information collected by the data acquisition system, several curves have been plotted. The observation of these curves, allow one to elect the transfer function

$$F(s) = K\frac{as+1}{bs+1}, \tag{3.1}$$

as a candidate to represent the plant. Although the amplitude and time constant are not the same for all plots, the shape pattern was approximately the same for all tests. The constants K, a and b were obtained by a numerical identification procedure through the least square method (LSM). The range obtained with these analyses represents the plant uncertainties and are shown on the Table 3.1.

Table 3.1. Range of the model parameters.

Model Parameters	**Range**	
	Minimum	**Maximum**
K	0.05	0.09
a	0.12	0.20
b	0.07	0.15

3.3. QFT controller design

As a performance specification, it is desired that the control system output tracks a reference signal with an error below 10% at least up to 0.1 rad/s in the presence of simultaneous parametric uncertainty in the range represented on the Table 3.1.

Based on the plant frequency response with nominal parameters, it was elected the 0.1, 5, 10 and 100 rad/s as the working frequencies for the QFT design. In the sequence, 64 plants have been chosen by the simultaneous variation of the 3 parameters within the specified range, generating the templates presented by Figure 7.

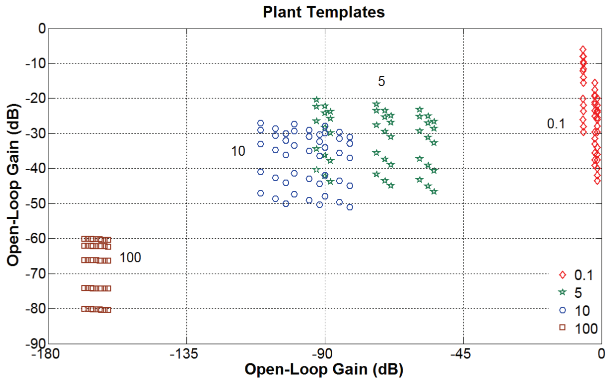

Figure 7: Templates for 0.1, 5, 10 and 100 rad/s.

The choice of the QFT controller structure and its parameters is usually done by trials (Yaniv 1999). However, there are several controllers that do not violate these specific stability bounds in the Nichols chart. To help with this choice, we also used the Root Locus plot. Note that the model plant has a pole and a zero relatively far away from the imaginary axis, making it impossible to achieve the closed loop time constant near to 1s, which is a typical value for this application. To solve this issue, it was chosen a controller with a zero relatively close to the imaginary axis and a pole at the origin, providing also null steady state error, thus resulting in a controller with a PI structure.

In the last step on the QFT design, a stability margin of 1.05 dB was defined and this bound was reshaped by the templates (see Figure 8). The resulting controller is presented by Equation 3.2.

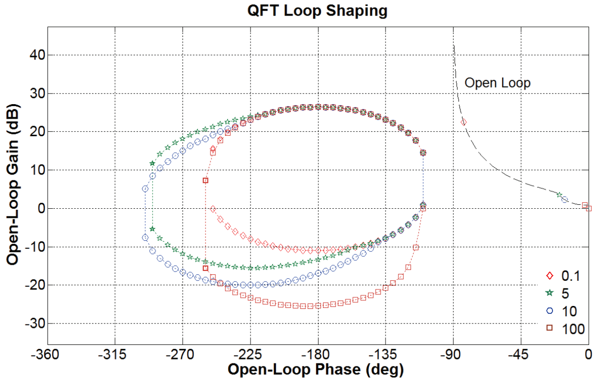

Figure 8: QFT loop shaping.

$$G(s) = 2.2\frac{15s+1}{s}. \tag{3.2}$$

3.4. Time domain performance

The experimental structure used to check the controller performance is the same one presented by Figure 5. The Matlab/Simulink software was used to implement the closed loop, including the controller.

The robustness of the system was tested by operating the valve with different opening angles. Varying the angle it modifies the gain, the pole and the zero position of the $F(s)$ (Equation 3.1), demonstrated by the parameters variation on Table 3.1

The three tests were performed during 14s by applying three different step signals, on t=5s: 11°, 15° and 20° valve opening. The throttle dynamic and the control effort were observed and compared with the desired amplitude defined by the step amplitude. The results obtained are shown by the Figures 9, 10 and 11.

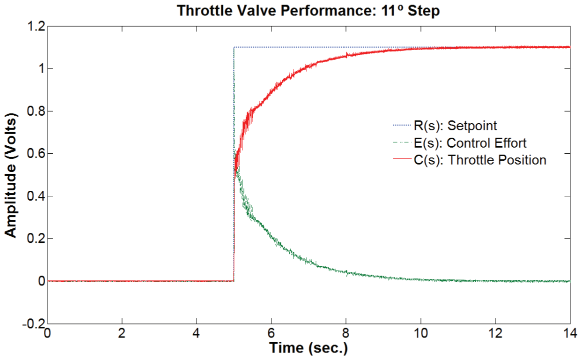

Figure 9: Performance for a 11° step variation.

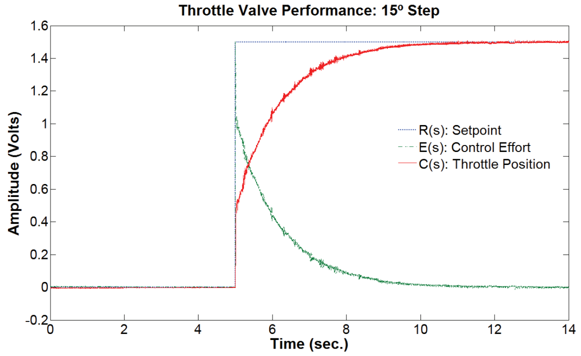

Figure 10: Performance for a 15° step variation.

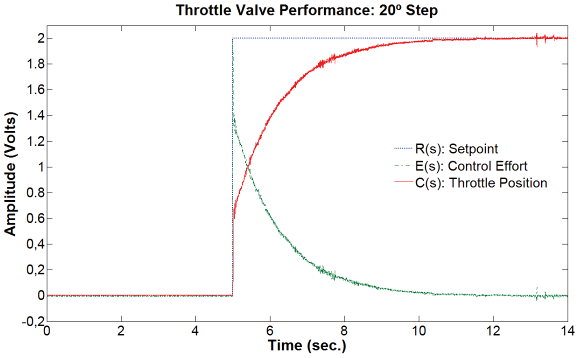

Figure 11: Performance for a 20° step variation.

Analyzing the results presented by the Figures 9, 10 and 11, it is easy to notice that the throttle position achieved the desired set point at the steady state and a reasonable setting time (approximately 0.8 seconds) was obtained on each individual test. The setting time could be modified by changing the controller gains in order to adapt the DBW system + controller to the engine dynamics, i.e. a 2.0L engine has a different dynamic and a demanded air supply of a 1.0L engine.

4. CONCLUSIONS

Due to the nonlinearities of the drive by wire systems, the phenomenological model is not trivial but also implies difficulties in the definition and design of the controller. Alternatively, this article discussed the modeling and experimental parametric robust control applied on the drive by wire system.

An open loop experimental investigation was used in order to provide the insights into the structure of the linear model. The non-linearities have been incorporated through a parametric variation over the three coefficients of the transfer function defined.

Only few robust control methods provide good tolerance to simultaneous variation of the plant parameters, so the robust technique chosen for the controller design was the Quantitative Feedback Theory. Through trial, typically on the QFT design, a PI controller was selected bases on its robustness observed on the Nichols chart and its performance on the real system.

The performance of the system observed on time domain confirmed what was expected by the robust design, since for a wide range of operating conditions, the performance of the system was high. The observed transient dynamic response can be roughly approximated by a 1st order dynamic with a less than 1 sec. time constant.

Our group intends to continue the studies, so we proposed to investigate the ability to adjust the time response for the DBW system in order to be used on different engines, which require different reactions of the DBW system due the different engine dynamics.

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