Journal of Applied Sciences

ISSN 1812-5654

ANSInet
an open access publisher
http://ansinet.com

Journal of Applied Sciences 5 (4): 781-786, 2005
ISSN 1812-5654

Simulation, Testing and Sensitivity Analysis of Fuel Pressure Regulator for MPFI Paykan 1600 cc Engine

S.S. Mohtasebi, A. Keyhani and M. Rahimi
Department of Power and Machinery, University of Tehran, Iran

Abstract: In this study, the fuel pressure regulator for MPFI PAYKAN 1600 cc engine which is a diaphragm operated valve has been simulated, analyzed and tested. The fuel pressure regulator is usually mounted on the fuel rail to maintain a constant relative pressure (3.5 bar) between the fuel injector and the air intake manifold. The regulator is first described and analyzed based on its functionality. Then, the mathematical equations of various sections of the regulator are presented. After that and based on those equations, the mathematical model of whole system is derived. This model is solved and analyzed using MATLAB engineering software. The good agreement between simulation and experiment results provided confidence to use the mathematical model to find out the steady state and transient responses of the regulator at different operating conditions. Finally, to make the regulator less sensitive to parameter variations, the sensitivity analysis is also done.

Key words: Pressure regulator, PAYKAN 1600 cc engine, mathematical model, simulation, sensitivity analysis

INTRODUCTION

Obtaining a mathematical model of a physical system is a complicated task due to the expectation from the model in analysis as well as assessment of the system behaviour.

The analysis of hydraulic and pneumatic system elements in order to determine their components sensitivity is carried out either through simplified linear or complicated non linear models. This is for the researchers to get knowledge of the elements behaviour with respect to their roles and functionality. In other words, the purpose of modelling, determines the degree of its complication[1,2].

The sensitivity analysis of the fuel pressure regulator is mainly followed to achieve the following goals:

- Analysis of the valve components sensitivities from the view point of manufacturing, to obtain the accuracy and also the tolerances of components.
- To know the system identification in order to understand it and to prescribe advices to improve and optimize its performance.

System operation and description: The fuel section of a Multi Point Fuel Injection (MPFI) system includes; fuel pump, filter, fuel rail, tank, injectors and pressure regulator. This system is used to maintain required fuel flow for each cylinder through its injectors; the time and period of injections being controlled by an Electronic Control Unit (ECU).

The fuel pressure regulator (Fig. 1) is a diaphragm flat seat valve which is used to maintain a constant differential pressure between the fuel rail and air intake manifold. In other words, the fuel pressure in fuel rail is always 350±6 KPa more than air manifold pressure and in this case, the variation of air intake pressure does not have any significant effect on fuel flow rate of injectors[3].

Fig. 1: Fuel pressure regulator assembly

There are two chambers in the regulator separated by a diaphragm; the fuel chamber and the air chamber. The fuel chamber which is located in the lower part of Fig. 2, which contains an inlet tube, a valve and an outlet tube. The air chamber contains a spring and a reference pressure port which is connected to the intake manifold. A valve body and a retainer are located at the center of the diaphragm to hold the spring. When the engine is off, the spring due to its preload force, pushes down the valve

Correponding Author: Seyed Saeid Mohtasebi, Associate Professor, #91, Farabi Alley, Safa East, Imam Hossein Square, Tehran 17138, Iran Tel: 0098 912 1066902 Fax: 0098261 2808138 Email: mohtaseb@ut.ac.ir

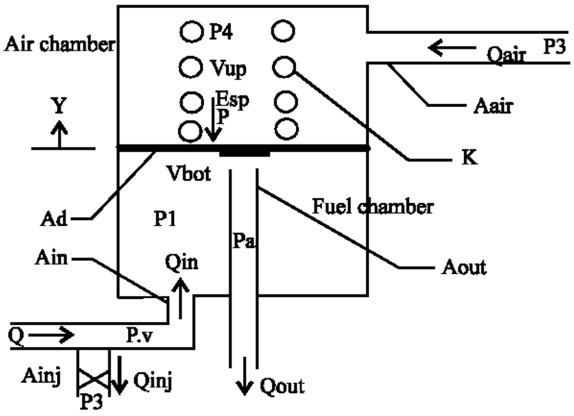

Fig. 2: Schematic diagram of fuel pressure regulator model

body to close the valve so as to seal the fuel. During operation, the fuel rail pressure and thus the regulator inlet pressure may build up to overcome the spring preload force and open the valve. The minimum pressure to open up the valve is called the cracking point or the cracking pressure. The cracking point of this regulator is 350±6 KPa.

Mathematical model description: Schematic diagrams of the fuel pressure regulator are shown in Fig. 2 and 3, the equations describing the different parts of the system are presented in the following sections[4]:

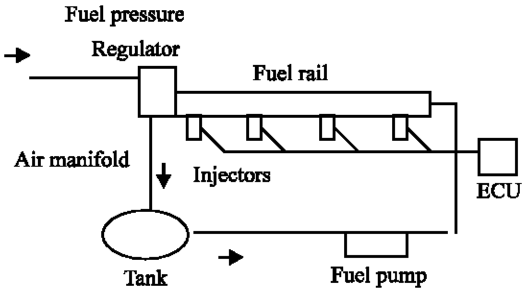

Fig. 3: The schematic of a MPFI

Motion equation: Forces acting on the diaphragm during a transient process are mainly due to the pressure difference across the diaphragm, the spring and its preload force and the inertia forces required to accelerate the diaphragm. Damping forces can be neglected as compared to the spring and pressure forces. The motion equation for the diaphragm is given by:

$$P_1\,(A_d - A_{out}) + P_a A_{out} - F_{sp} - KY - P_4 A_d = M\ddot{Y} \qquad (1)$$

Flow equations

Fuel delivery to regulator: The fuel flow delivered from fuel pump to the regulator is given by:

$$Q_{in} = cd_{in} A_{in} \sqrt{2\,(P - P_1)/\,\rho_g} \qquad (2)$$

Bypass flow: The excess flow returned to the tank is given by:

$$Q_{out} = cd_{out} \pi DY \sqrt{2\,(P_1 - P_a)/\,\rho_g} \qquad (3)$$

where, Y is the diaphragm displacement.

Air flow to air chamber:

$$Q_{air} = cd_{air} A_{air} \operatorname{sgn}(P_3 - P_4) \sqrt{2|P_3 - P_4|/\,\rho_a} \qquad (4)$$

The term $\operatorname{sgn}(P_3 - P_4)$ is used to indicate the air flow in both directions during the transient process.

Injectors flow:

$$Q_{inj} = cd_{inj} A_{inj} \sqrt{2\,(P - P_3)/\,\rho_g} \qquad (5)$$

Continuity equations: Pressure P of fuel rail volume is a function of the volume included between the pump outlet and regulator inlet (fuel rail volume), the effective bulk modulus of elasticity of the fuel (β) and the net influx of fuel to the volume:

$$\frac{dP}{dt} = \frac{\beta_{fuel}}{V} \,(Q - Q_{in} - Q_{inj}) \qquad (6)$$

Diaphragm fuel chamber volume: Variation of fuel pressure in bottom side of diaphragm, has an important role in regulator operation. This variation is given by:

$$\frac{dP_1}{dt} = \frac{\beta_{fuel}}{V_{bot}} \,(Q_{in} - Q_{out} - A_d \frac{dY}{dt}) \qquad (7)$$

where, A_d is the diaphragm effective area.

Diaphragm air chamber volume: The pressure in the upper volume of diaphragm is described by:

$$\frac{dP_4}{dt} = \frac{\beta_{air}}{V_{up}} \,(Q_{air} + A_d \frac{dY}{dt}) \qquad (8)$$

To solve the non linear differential equations and obtaining the transient response, one of MATLAB toolbox, SIMULINK was used. MATLAB which stands for MATRIX LABORATORY, is a high quality programming software for numerical computations and visualization. It integrates numerical analysis, matrix computation and signal processing[5]. The toolbox SIMULINK has different types of integration algorithm such as third and fifth order Runge-Kutta, Euler, Gear and Adams and other[6]. In this research for numerical integration, Gear and Adams algorithm was used.

Experimental validation of model: To validate the mathematical model and for further investigation a test prototype was built and installed on a test bench as shown in Fig. 4. The air manifold pressure and also fuel rail pressure (fuel delivery to regulator) were measured by diaphragm type pressure transducers. The fuel flow delivered to regulator, bypass flow and injector flow were measured by three turbine flowmeters. A data acquisition system was used to record the signals during experiments.

Figure 5-7 compare the simulated and experimental transient responses of the system to different step inputs of air manifold pressures. In Fig. 5, the step input of manifold pressure is 0.8 bar (absolute). As seen, the response is overdamped and the settling time is about 0.45 S. The steady state results in both simulation and experiment are 3.3 bar gauge pressure (P_{abs}= 4.3 bar) and thus the differential pressure between fuel rail pressure and air manifold pressure is kept constant (i.e. 4.3-0.8=3.5 bar).

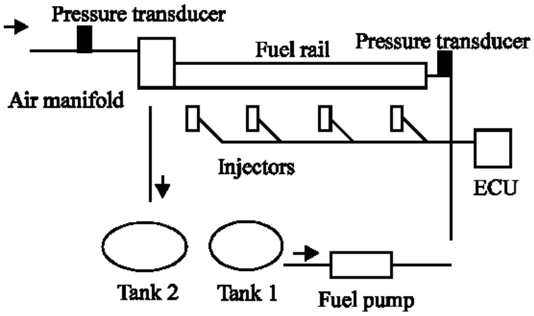

Fig. 4: Schematic diagram of the experimental set-up

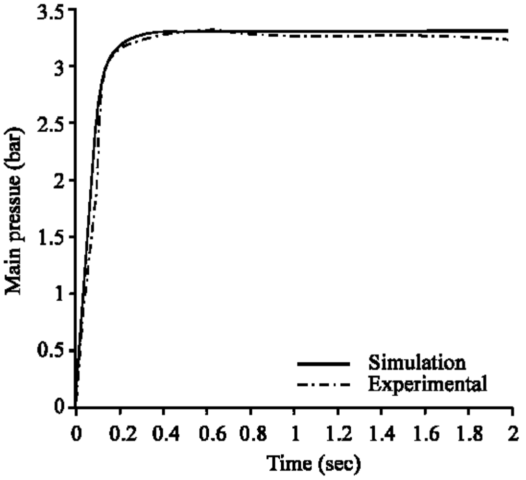

Fig. 5: Comparison of experimental and simulation results for the fuel rail pressure (P_3=0.8 Bar)

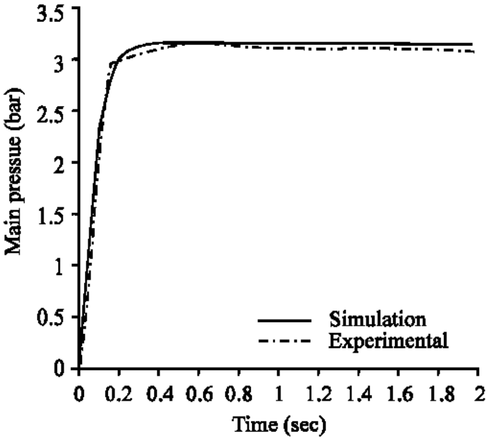

Fig. 6: Comparison of experimental and simulation results for the fuel rail pressure (P_3=0.6 Bar)

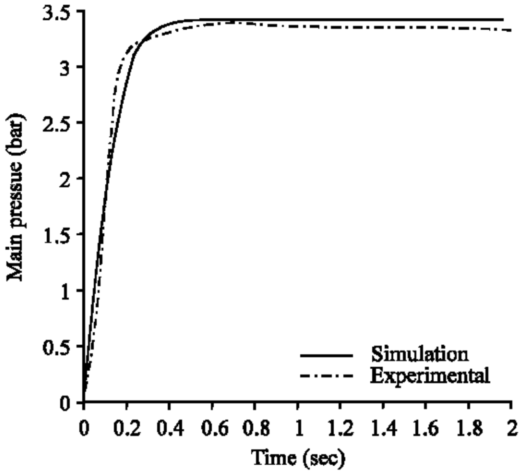

Fig. 7: Comparison of experimental and simulation results for the fuel rail pressure (P_3=0.9 Bar)

In Fig. 6 and 7, the air manifold pressures are 0.6 and 0.9 bar (absolute), respectively. In both cases, the responses are overdamped and the settling times are 0.6 and 0.65 S, respectively. As seen, the differential pressures are almost 3.5 bar.

The results show that the mathematical model accurately predicts the test results and the differential pressure remains almost constant over variation of air manifold pressure. Some visible discrepancies between simulation and experiments can be due to the inaccuracies in estimation of the fuel modulus of elasticity and flow coefficients, in the volume of various chambers within the regulator. In general, the model predicts the steady state and transient behaviors of the system quite accurately and could be used for design optimization and sensitivity analysis.

Simulation of dynamic response: Figure 8 shows the pressure variation of fuel chamber of diaphragm during transient state. This chamber has an important role in regulator operation. Actually, time to fill the chamber and then increasing the pressure and moving the diaphragm affect the response of the system. The steady state value is 4.4 bar (abs) and the settling time is about 0.61 S.

Figure 9 shows the diaphragm deflection transient. The diaphragm moves up due to air manifold pressure (vacuum) as well as fuel pressure and then moves down to reach its steady state value of 0.034 mm. In this case, there is a continuous flow through the bypass orifice (A_{out}) to tank. The flow is constant until the engine speed or its load changes.

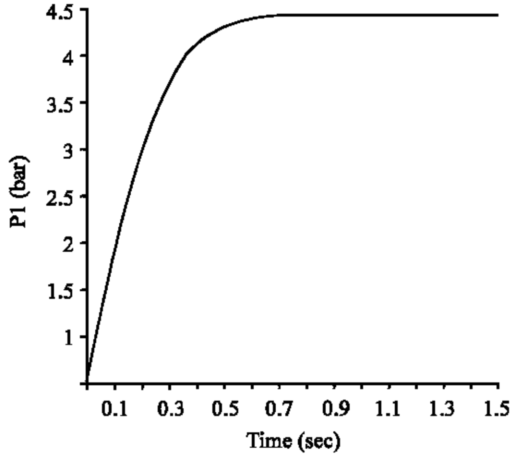

Fig. 8: Transient response of fuel chamber pressure

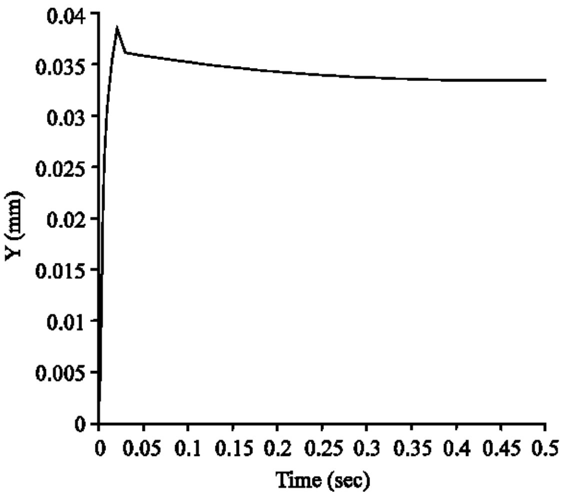

Fig. 9: Transient response of diaphragm deflection

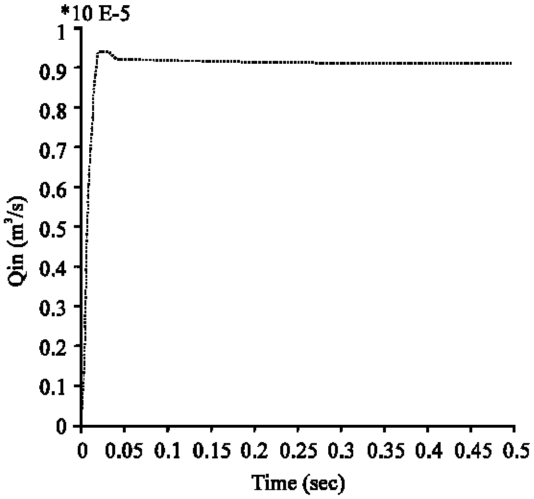

Fig. 10: Transient response of total flow to regulator

Figure 10 shows the inlet fuel flow to regulator. As seen, by opening the diaphragm orifice, more fuel flows to regulator. However, by its closing, the fuel flow reduces. The steady state value of input flow is about 9 cm^3/S.

Sensitivity analysis: Sensitivity considerations are important since the behaviour of a control system varies with the changes in the component values or system parameters[7]. These changes can be caused by temperature, pressure, wear, contamination or other environmental factors. Systems must be built so that the expected changes do not degrade its performance beyond some specified limits. A sensitivity analysis can yield the percent of change in a specification, as a function of change in a system parameter. One of the designer's goal, then, is to build a system with minimum sensitivity over an expected range of the environmental changes. Finally, to apply the sensitivity analysis, the definition of sensitivity has to be formulated as follows[8].

$$S_{F:P} = \lim_{\Delta P \to 0} \frac{\text{Fraction change in the function, F}}{\text{Fractional change in the parameter, P}}$$

$$= \lim_{\Delta P \to 0} \frac{\Delta F/F}{\Delta P/P} = \lim_{\Delta P \to 0} \frac{P\Delta F}{F\Delta P} = \frac{P}{F}\frac{\delta F}{\delta P} \qquad (9)$$

For the pressure regulator, five design parameters are considered as subjects to change: regulator inlet flow area, A_{in}, the spring preload force, Fsp, spring constant, K, diaphragm effective area, A_d and regulator outlet flow area, A_{out}.

Now it is desired to calculate the variation of the fuel rail pressure with respect to these parameters, i.e:

$$\frac{dP}{dAin}, \frac{dP}{dF}, \frac{dP}{dK}, \frac{dP}{dAd}, \frac{dP}{dAo}.$$

To do this, first of all, from the steady state mathematical model, it is necessary to eliminate the state variables (Y, P1 and P4) except fuel rail pressure (P). This gives a single expression which contains only the state variable P[3]. To calculate the sensitivity of fuel rail pressure (P) to each parameter, the sensitivity equation is used. For example, to calculate the sensitivity of P with respect to spring constant K, using Eq. 9, we have:

$$S_{P.K}=\frac{K}{P}.\frac{dP}{dK} \qquad (10)$$

The same procedure is used to calculate the sensitivity of P to other parameters.

A program is written in MATLAB domain to calculate the sensitivity equations according to the nominal design parameters. The results are plotted in the sensitivity histogram of Fig. 11.

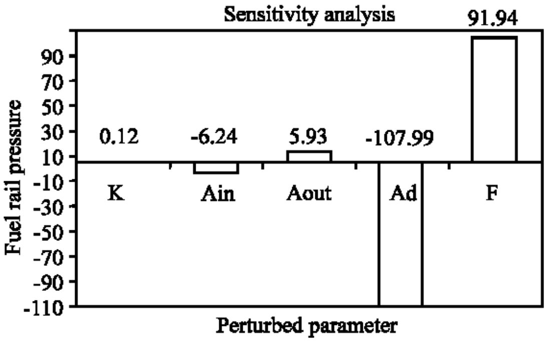

Fig. 11: Sensitivity histogram

As it is shown in the Fig. 11, the fuel rail pressure has the maximum sensitivity to the diaphragm effective area. The negative sign indicates that by increasing the area, pressure P decreases.

A change in the spring pre load force setting has also a significant impact on the sensitivity. This means that the thermal expansion of the diaphragm air chamber can effectively change the pressure P.

Finally, Fig. 11 shows that P has low sensitivity to inlet and outlet flow area of regulator (A_{in}, A_{out}) and no sensitivity to spring constant K.

Now, it is possible to calculate the components tolerances of the system considering the nominal air manifold pressure of 80 kPa and fuel rail pressure of 430±6 kPa[9]. For example if the diaphragm effective area decreases 10% (from nominal value of 3.46 to 3.11 cm^2),

$$dP=(-1.08)\,\frac{(3.11-3.46)}{3.46}\,430=-46.44\text{ kPa}$$

then the variation of P is equal to:

This means that 10% change in Ad produces 46.44 kPa change in P, though the permissible change is just±6 kPa[9]. Now if Ad changes 1.2% (i.e. from 3.46 to 3.42 cm^2), then dP is equal to:

$$dP=(-1.08)\,\frac{(3.42-3.46)}{3.46}\,430=-5.37\text{ kPa}$$

which is acceptable. Thus the tolerance of diaphragm effective diameter is equal to ±0.1 mm. Following this procedure, the tolerances of input flow diameter and outlet flow diameter are ±0.3 and ±0.5 mm, respectively.

CONCLUSION

The fuel pressure regulator for multi point fuel injection in Paykan 1600 cc engine was presented and investigated. Then, the mathematical model for transient process was first developed and used for computer simulation. Next, experiments were performed in order to validate the model. It was proved that the model accurately predicted the test results and therefore, it could be used for sensitivity analysis. The analysis shows that the system is more sensitive to spring preload force as well as diaphragm effective area. However, it is less sensitive to inlet and outlet flow area and finally no sensitivity to spring constant.

ACKNOWLEDGMENTS

The authors would like to thank the Research Deputy, Tehran University and SAPCO (Supplier of Automotive Parts Company) for providing technical assistance and finical support.

REFERENCES

1. Shin, Y.C., 1991. Static and dynamic characteristics of a two stage pilot relief valve. ASME J. Dynamic Systems, Measurement and Control, 133: 280-288.
2. Handroos, H. M. and M.J. Vilenius, 1992. The influence of semi-empirical control valve model parameter accuracy on simulated hydraulic system response. ASME J. Dynamic Systems, Measurement and Control, 114: 707-713.
3. Rahimi, M., 2002. Analysis and simulation of fuel pressure regulator. M.Sc. Thesis, Tehran University, Sept. 2002.
4. Mohtasebi, S.S. and H. Hong, 1999. Low cost electronically controlled fuel metering system for small gas turbine engines. SAE Transactions, J. Engines, 108: 766-774.

5. Anonymous, 1992. Matlab Users Guide, The MATH Works Incorporation.
6. Anonymous, 1993. Simulink Users Guide, The MATH Works Incorporation.
7. Vilenius, M. J., 1983. The application of sensitivity analysis to electrohydraulic position control servos. ASME J. Dynamic System, Measurement and Control, 105: 77-82.
8. Nise, N.S., 1992. Control System Engineering. The Benjamin/Cummings Publishing Company Incorporation, 1992.
9. SAGEM-11RV001 DATA SHEET, 2000.