

Use of Transfer Functions to Investigate the Robustness of an In-Tank Fuel Delivery system

Zehgham Shah
Jaguar Landrover

Hashim Ali Malik, Felician Campean, Bill Seale and Pete Olley
University of Bradford

Copyright © 2008 SAE International

ABSTRACT

This paper presents an investigation into the functional robustness of an in-tank fuel delivery system (FDS) used in a saddle type fuel tank application for a high performance petrol engine. Robust design tools were used to identify the noise factors that affect the performance of the in-tank FDS. A transfer function relating the system's response to key control and noise factors was developed using a combination of theoretical modeling based on fluid mechanics and component level experimentation. The transfer function was validated with data from system level testing. A sensitivity study using the transfer function was conducted to validate the performance of the system against key noise factors.

INTRODUCTION

The fundamental principle of robust design is to maximize the quality of a product by minimizing the effects of variation in the critical design and manufacturing parameters without necessarily eliminating the causes. (Phadke, 1989).

In this paper a structured methodology for robust design is illustrated through an investigation into the robustness of an in-tank fuel delivery system. A Fuel Delivery System (FDS) can be divided into three sub-systems: in-tank, under-body and under-bonnet as shown in Figure 1. The design of the in-tank system varies significantly depending upon the tank shape and size, and the packaging of surrounding components whereas the design of the under-body and under-bonnet FDS components is generic in most vehicles.

This increase in structural complexity leads to an increased functional risk of field failures, which potentially can have a catastrophic effect. Also, although the part price of individual components in the in-tank FDS is low, any repairs would be very expensive as the

fuel tank would be replaced rather than repaired. Therefore the reliability and functional robustness of the in-tank system is critical to the design of the FDS.

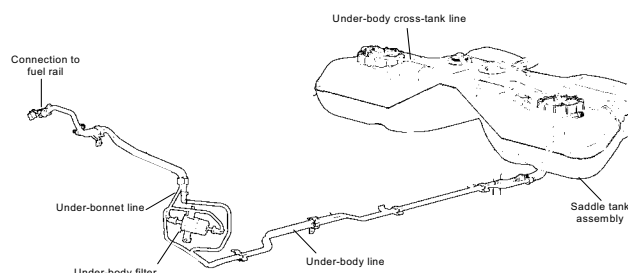


Figure 1. Schematic of a Fuel Delivery System Showing a Saddle Type Fuel Tank [Shah, 2004]

The objective of this paper is to present an investigation into the functional robustness of an in-tank fuel delivery system. The study starts with a functional assessment through application of robustness tools to identify factors that affect the functional performance, followed by the development of analytical transfer functions based on a combination of theoretical modeling and experimentation, to study and validate the functional performance.

FUNCTIONAL ASSESSMENT OF THE IN-TANK FUEL DELIVERY SYSTEM

A schematic of the in tank system investigated in this study is presented in Figure 2. The fuel tank has two separate compartments, illustrated in Figure 2. The active compartment contains a fuel delivery module (FDM) and the passive compartment contains a jet pump module (JPM), which are connected by the transfer lines. The FDM includes a variable speed rotary vane type pump that supplies fuel into the system. A manifold

distributes the fuel to the injection rail and also supplies the JPM with fuel in order that fuel may be entrained and returned from the passive side to the active side of the tank. This circulation process of fuel is enabled through the internal crossover lines, one being the feed hose from the FDM to the JPM, and the other being the return hose from the JPM to the FDM. There is an additional jet pump located on the FDM to entrain fuel into the FDM. Fuel can also flow into the FDM through the FDM flapper valve.

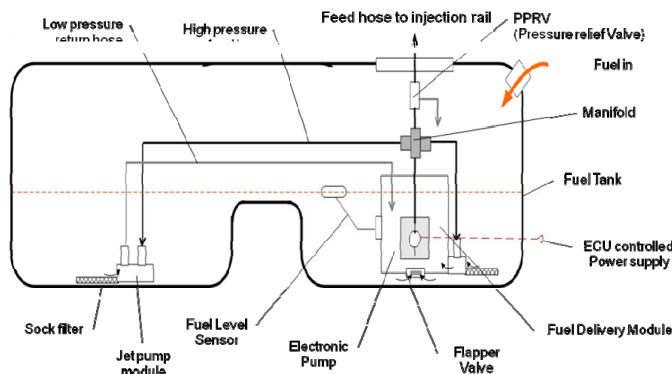


Figure 2. Schematic of in-tank system

The function of the in-tank FDS can be more easily depicted from the boundary diagram presented in Figure 3. The three main routes of the FDS through which fuel is distributed are controlled by the manifold to three key areas; FDM jet pump, JPM, and out from the tank to the fuel rail.

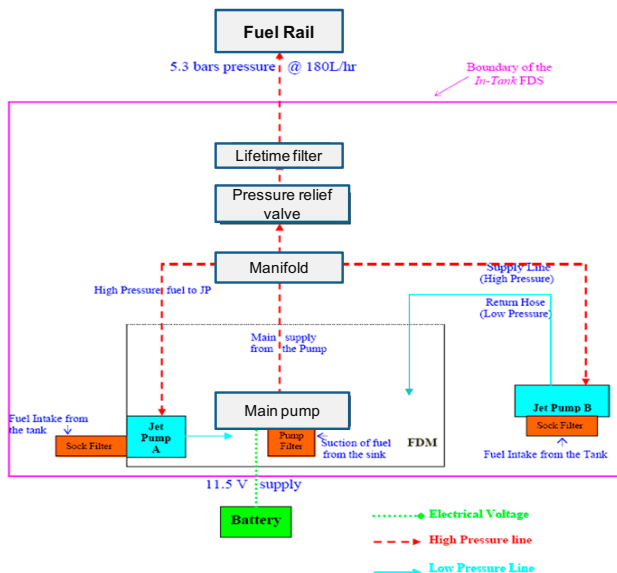


Figure 3. Boundary Diagram of the FDS

The jet pump located on the FDM body functions to entrain and deposit fuel from the active side into the FDM reservoir, so that positive fuel quantity is available inside the canister and hence FDM to be pumped by the electronic pump. The function of the JPM in the passive

side is to entrain and return fuel via the return crossover hose from the passive to the active side of the tank, thus under normal operation the JPM is always working to maintain the active side with positive fuel levels.

A Function Tree (Figure 4) is constructed that builds on the Boundary Diagram, explaining in more detail the way in which the functions of the FDS are achieved and identifying the system components delivering those functions.

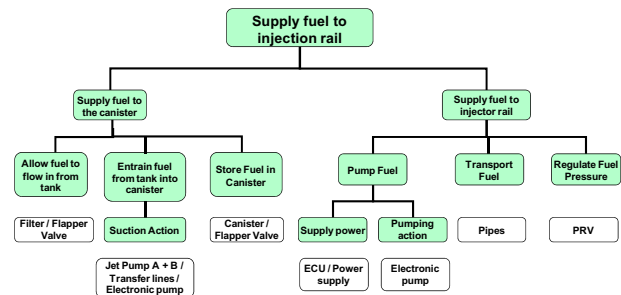


Figure 4. Function Tree Diagram

The inputs and responses required for and from the FDS are respectively shown in a Parameter diagram (Figure-5). A Parameter diagram also referred to as the P-diagram is described as a block diagram to graphically illustrate a manufacturing process or system to which robustness methodology is to be applied. (Phadke, 1989, Mistry, 2001, Webb, 2002). The functional and component level understanding achieved through Boundary Diagram Figure 3 and Functional Diagram Figure 4 helps in completing a P-Diagram for the FDS, shown in Figure 5.

The P-diagram also identifies the factors affecting and governing the system response, i.e. noise factors and control factors, which in this study are identified by researching the theory of fluid mechanics. The control factors and noise factors affecting the system response can be selected from the P-diagram and used to build an analytical model which will facilitate in characterizing the behavior of the system (Davis, 2004).

FDS TRANSFER FUNCTION DEVELOPMENT

Developing an analytical model or transfer function provides a means for understanding customer requirements and representing an overall product and process function (Matthew Hu and Kai Yang, 2005).

For the in-tank FDS, a transfer function which relates the system response i.e. pressure/flowrate at the injection rail, denoted by Y, to input variables (signal, control factors, and noise factors), collectively denoted X needs to be developed in order to assist with the functional robustness assessment. Information from the P-Diagram can be used to derive the transfer function denoted as $Y=f(X)$ through theoretical modeling.

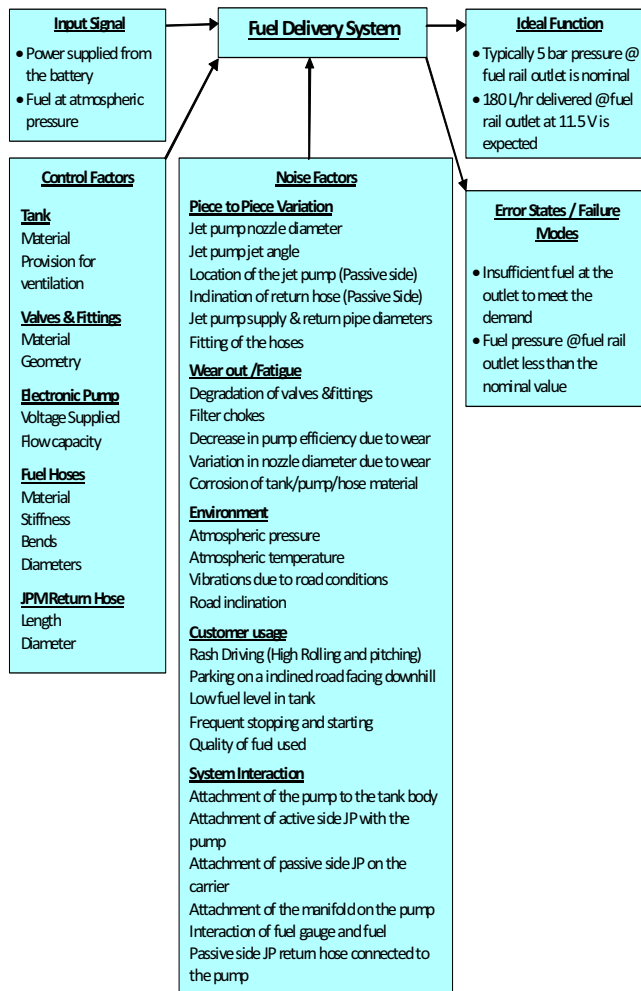


Figure 5. Parameter Diagram for FDS

For the high pressure side the response of interest for the in-tank FDS is the fuel flow / pressure at the fuel injection rail. The schematic in Figure 6 shows that the pressure output is a function of pressure input into the system from the fuel pump and the fuel pressure losses sustained through the in-tank FDS. In turn, the pressure output from the pump for given mechanical fuel properties is a function of the voltage supplied to the pump, assuming sufficient fuel is in the fuel delivery module (FDM).

The availability of fuel in the FDM relies on the jet pumps. In particular the jet pump located in the passive side has a critical function to supply fuel when due to slosh there is not enough fuel in the active side. This prompts to the need for a secondary transfer function for the low pressure side to model the output response from the jet pump module.

Control factors such as pump voltage, jet nozzle diameter and pipe diameters govern the pressure and flow of the FDS, and noise factors such as variation in these, and external environmental changes such as temperature affect the output response of the FDS.

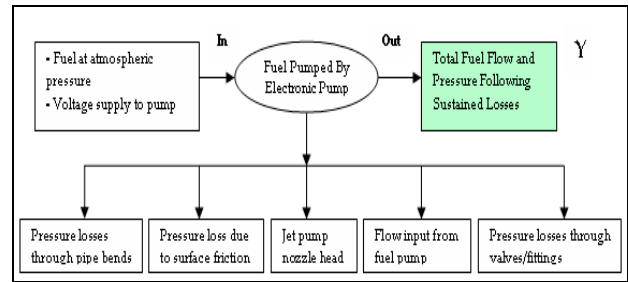


Figure 6. Schematic Representations of High Level Physics / Transfer Function of FDS

The transfer function for the high pressure side incorporates the response function for the pump giving the pressure output and the losses through the system.

Pressure (P) output from the electronic pump is a function of flow rate (Q) and the voltage (V), i.e.

$$P = f(Q, V) \quad \text{Equation 1}$$

The pressure (P) can be assumed to be quadratic in both 'Q' and 'V' variables (White, 2003). Thus, the transfer function for the fuel pump can be written as in Equation 2.

$$P = (a + bQ + cQ^2)(d + eV + fV^2) \quad \text{Equation 2}$$

The constants a, b, c, d, e and f in Equation 2 can be evaluated from experimental data relating P, Q and V. It is also known that any pressure change/loss (ΔP) through a component (such as pipe) is directly proportional to the squared flow rate (Q) (White, 2003).

$$\Delta P = \alpha Q^2 \quad \text{Equation 3}$$

where α = Loss co-efficient across a component. The diagram in Figure 7 shows the various flow paths in the system and indicates the loss coefficients (α) in every component.

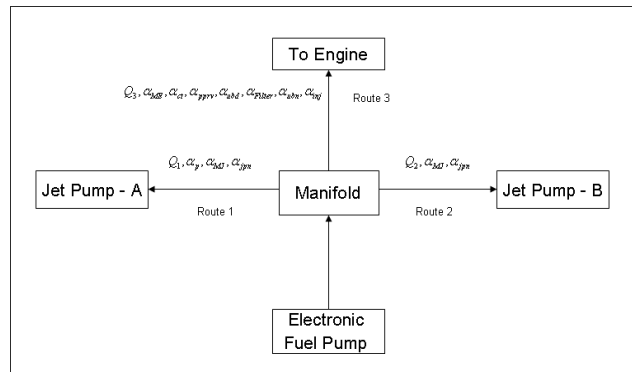


Figure 7. Flow Distributions through FDS and Energy Loss Coefficients through Each Component