

Compensation Force CFD Analysis of Pressure Regulating Valve Applied in FMU of Engine and System Controls

2011-01-2641

Published
10/18/2011William W. Ni, Steven Heitz, Daniel Bartholme and Michael Cass
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doi:[10.4271/2011-01-2641](https://doi.org/10.4271/2011-01-2641)

ABSTRACT

A pressure regulating valve is a type of flow control device that is a combination of a control orifice and a flow compensator. The compensator orifice modulates its opening to regulate the flow rate at a constant pressure drop across the control orifice. The objective of this paper is an experimental and numerical analysis of flow compensation forces on pressure regulating valve applied on aircraft engine and control systems in a Fuel Metering Unit (FMU). The CFD analysis was applied to analyze and evaluate the various flow rates and patterns and thus estimate the pressure regulating control valve flow compensation force and characteristic curve. The CFD model is used to validate the dynamic behavior of the pressure regulating valve to bypass the fuel flow from a high pressure gear pump and to compensate burn flow of the metering valve. The model can then be used to evaluate and improve the design and operation of the valve for specific operations.

INTRODUCTION

In an engine control system, the control valve performs a special task, controlling the flow of fluids so that a process variable such as fluid pressure, fluid flow rate or temperature can be controlled. In addition to controlling the flow, a control valve may be used to shut off the flow and may be defined as a valve with a powered actuator that responds to an external signal. This signal usually comes from a controller. The controller and valve together form a basic control loop. The control valve is seldom fully open or closed but is generally in an intermediate position controlling the flow of fluid through the valve. In the dynamic service condition, the valve must withstand erosive effects of the flowing fluid (ex: cavitation etc..) while maintaining an

accurate position to maintain the process variable. In the engine system loop, the pressure regulating spool valve performance and sizing is generally stated in terms of envelope of inlet characteristics and required discharge characteristics.

Regulating valves, a kind of control valve, are used in engine fuel systems as variable restrictions to accomplish changes in flow or pressure as required for proper system operation. The regulation is required to provide a continuously variable flow restriction between shutoff and maximum flow and pass the maximum required flow rate with minimal pressure drop. The regulating valves are generally classified either as a balancing type, which include butterfly and spool valves, or an unbalanced type which included poppet, plug and gate valves. In the engine control system, the most popular regulating valves are spool valves in which flow is to be modulated in order to meet the engine required burn flow. The control spool valve dynamic performance is critical to the overall performance of the engine and control system. Proper control of a system is based on the consistent operation of all valves within the system. Without consistent valve operation, the system becomes unpredictable. While this may not be applicable to all systems, it is necessary that valve performance be known to an engine system designer.

The pressure regulating valve performance is dependant on the presence of flow reaction forces which act on the spool. These forces from the fluid pressure and spring load can result in the necessary unbalance which drive the spool and in some cases have been directly linked to valve and circuit instabilities and cavitation erosion in the system recirculation downstream piping. As such, the valve force balance analysis has concentrated on ways to reduce or compensate for flow forces. The classic work proved to be introductory valve

design that can be found in text books [1,2,3]. The transient flow force estimation on the pilot stage of a hydraulic valve was studied by M. Borghi, M. Milani, and R. Paoluzzi [4]. K Krishnaswamy and P.Li [5] and Q. Yuan and P Li [6] who studied the unstable valve in the electrohydraulic valves for control and steady flow force. R. Amirante, G. Vescovo, and A. Lippolis [7] applied CFD to study flow force analysis of an open center hydraulic direction control valve sliding spool. M. Borghi, M. Milani, and F. Paltrinieri performed CFD analysis on the influence of notch shape and number on proportional direction control valve. R Yang [9-10] also utilized the CFD tool to predict hydraulic valve flow forces. D. Wu, R. Burton, G. Schoenau [11] studied the pressure compensation flow control valve with defined flow gain transfer function and flow-pressure coefficient transfer function. All of their researchers were very similar to our study, but not in the pressure compensation combined with flow metering valve control applied in a FMU.

A simplified schematic diagram of a FMU with an engine burn flow Metering Valve (MV) and a Pressure Regulating Valve (PRV) is shown in Figure 1 where HP is the high pressure engine driven positive displacement pump, normally an external gear pump. The engine burn flow rate Q2 is variably dependant to the flight envelope, ex take-off, climb, cruise, and descent etc. and a non-linear function of engine speed. The HP positive displacement pump which delivers the fuel flow Q1 is a linear function of engine speed. The figure 2 shows a typical engine fuel consumption flow rate Q2 and positive displacement pump delivery flow rate Q1 vs the engine speed. The aircraft fuel system is subjected to the continuous operating procedure of the flight conditions. The take-off and climb time segments are typically rolled in the high fuel flow rate operation regime when compared to the cruise portion of a typical mission. During the flight envelope, the PRV works to bypass the maximum inlet flow Qb and pressure available P1 under the control band versus other system variables. This pressure regulator discharge pressure differential P1 - Pd verse flow rate Qb is shown in Figure 3.

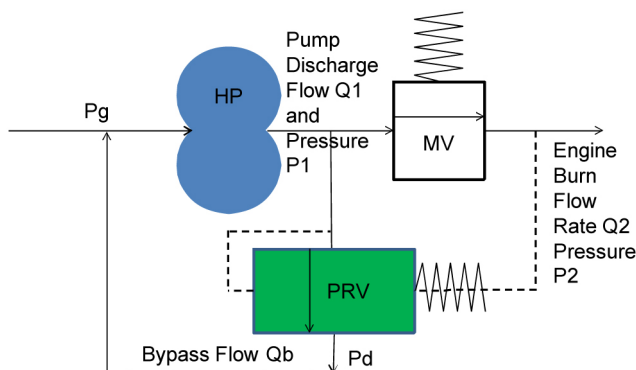


Figure 1. Schematic diagram of engine fuel control

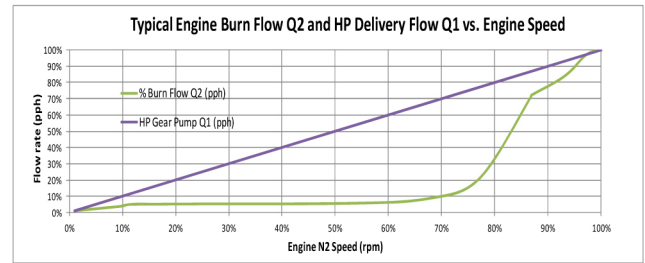


Figure 2. Typical engine burn flow rate and gear pump delivery flow vs. speed

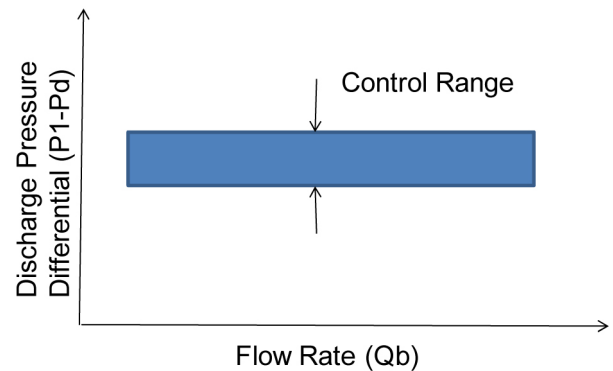


Figure 3. Pressure regulating valve discharge pressure vs flow rate.

CONTROL VALVE GENERAL FLOW EQUATION VS. GEOMETRY

In this paper studying application of engine control technology conducted on a flow regulating valve as shown in Figure 4, it was established that the u-notch with radius tap machined into the inlet land of the PRV spool as shown in circle of Figure 4 to reduce the flow dividing error, and it was deduced that the main contribution to this error was flow force. The PRV spool is immersed in the fuel and the fuel around the spool forces it to move. The motion is bidirectional, along the axial direction of the valve, and the force is determined based on the spool position, calculating a force balance on the solid face of the spool. The usual PRV sizing is based on the flow coefficient C_v calculation that is made for required flow rate and related pressure drop in control valve as shown in Equation 1. The flow coefficient C_v is based on the relationship between the pressure drop and the flow rate in the control valve, where the complete turbulent flow following power law flow coefficient C_v is the proportional constant.

$$Q = C_v \times A \times \sqrt{\frac{2\Delta P}{\rho}}$$

Eq. - (1)



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Where:

Q = Fluid flow rate

C_v = Valve flow coefficient

A = Valve window area

ΔP = Pressure drop

ρ = Density

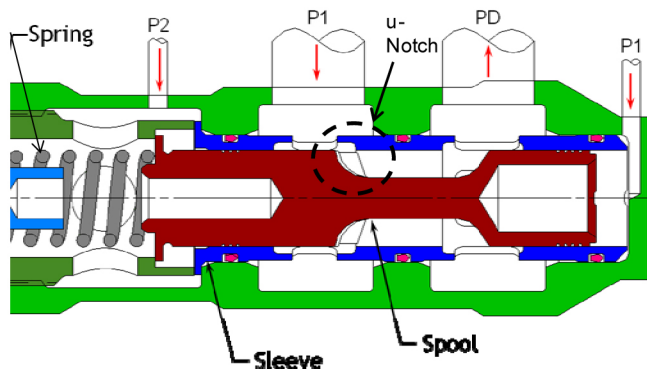


Figure 4. Pressure regulating valve Section view

The figure 4 spool diameter is 16.497 mm, mass 86 mg, and spring stiffness 10.5 kN/m. The PRV flow rate is modulated by the constant pressure differential from the circuits P1 and P2 from metering valve; therefore its dynamic performance is critical to the overall performance of the circuit. Fundamental to this performance is the presence of flow reaction forces which act on the spool. These forces can result in the necessary use of the metering valve (MV) pressures (P1 and P2) to drive the spool and in some cases have been directly linked to valve and circuit instabilities. As such, this CFD analysis has concentrated on ways to reduce or compensate for flow forces and describe the fluid mechanics associated with the steady state flow forces as it provides a detailed structure of the flow through the valve, and to identify the flow mechanism whereby flow forces are analyzed by the size of the u-notch with a radius tap on the inlet land of the spool.

If the pressure differential across the PRV orifice can be kept constant, then the flow through the orifice will be independent of the pressure in the circuit supplied. The pressure compensated flow regulator valve shown in Figure 4 is a means of achieving a constant pressure differential across orifice.

FLOW FORCE ON SPOOL VALVE: STEADY STATE FLOW FORCE COMPENSATION

In the engine start-up mode, the PRV spool is closed to begin the pumping pressure at a fixed pressure hydraulic force (P1-P2) from MV which is sustained by EHSV to inject fuel into the engine nozzles. Continuous MV flow requires a stable pressure, which, in turn, requires matching the fuel flow rate and pressure to the engine burn flow demand until the HP pump delivers a flow rate in excess of the system requirement. After that, the spool moves a small stroke, and initial motion is provoked by the upstream dynamic pressure field of HP positive displacement pump which generates pressure ripple, viscosity forces around the spool, and balance of the elastic force of the spring.

For the theoretical case, the influence of the inlet and outlet connections on the internal flow field of PRV is the inlet characteristics variations with the spool opening. The PRV fluid flow force on a spool valve due to flow entering a valve chamber is shown in Figure 5. When the fluid flows through the valve there will be induced forces acting on the valve. By Newton's law, the fluid jet force has an equal and opposite reaction force which revolves into two components in lateral and axial directions. The lateral component tends to push the valve spool sideways against the sleeve and cause potential sticking. The axial force is not compensated and acts in a direction to close the valve port, as may be seen by a comparison of the pressure distribution on faces A and B as shown in Figure 5. In detail, the attention is mainly not only focused on the description of the inlet coefficient and on the jet angle variation but also the spool compensation balancing force. The total force over the spool is calculated as sum of the pressure force, viscosity damping force, spring force, and the spool momentum force as shown in Equation (2). These forces are normally calculated using a mathematical formulation of Newton's second law suitable for application to a controlled volume.

$$F_{Total} = F_{pressure} + F_{damping} + F_{spring} + F_{momentum}$$

Eq - (2)