Pressure Surge Reduction for a Cold Gas Attitude Control System using a Novel Valve Design and Charging Procedure

By Sangwoon Jeon,1) Jihun Kim,1) Joonyun Kim,2) Jungho Lee1) and Youngsung Ko3)

1) Launcher Stage Engineering Team, Korea Aerospace Research Institute, Daejeon, Korea
2) Launcher Electronics Team, Korea Aerospace Research Institute, Daejeon, Korea
3) Aerospace Engineering Department, Chungnam National University, Daejeon, Korea

(Received June 28th, 2013)

Key Words: Reaction Control System, High-pressure Propellant, Pressure Surge, Anti-surge Solenoid Valve, Charging Procedure

1. Introduction

Propulsion systems used in launch vehicles and satellites store high-pressure propellants in tanks, and maintain the operating pressure through pyro- or latch valves to control attitude according to flight scenarios. The surge pressure in the solenoid valve of a thruster is usually 20% higher than the normal pressure.1) This induces a surge condition which increases the supply pressure of the system, resulting in higher operating pressure. This higher operating pressure increases the system weight as follows. Usually, hydrazine thruster systems employ serial protection orifices2) to reduce the water hammer (surge), as it may result in a catastrophic explosion due to adiabatic compression.3) Ariane uses a bypass orifice for its 400 N thruster system to mitigate the surge. Either method requires additional parts (e.g., orifices) to resolve the surge problem. The other factor contributing to the weight increase is the solenoid valve. Solenoid valves generally stop functioning when they encounter a high surge pressure because the force due to the surge pressure becomes higher than the valve’s maximum suction force. Therefore, solenoid valves are designed for the maximum surge pressure. However, operation under a higher pressure requires more coils in the solenoid valve or more electric current. Thus, designing such propulsion systems for surge conditions results in extra weight due to additional and/or larger components.

The purpose of this paper is to describe two design tactics for mitigation of pressure surge for the reaction control system (RCS) of the Korea space launch vehicle-I (KSLV-I).

2. RCS Configuration

The RCS, which comprises pneumatic and control parts is to be installed on the KSLV-I upper stage. The pneumatic part comprises two bottles for storage of nitrogen gas, thrusters for reaction force generation, a regulator for regulated pressure generation, a pneumatic connector for connection with the first stage, a latch valve for flow control, a vent valve for drainage of propellant, a check valve, a relief valve and a tube part for the connector with all pneumatic components. The control part comprises a thruster control unit which controls the valves and monitors the system and cables for connection of all electrical valves.4)

3. Anti-Surge Solenoid Valve

A general schematic of solenoid valves is shown in Fig. 1. The suction force of the solenoid valve should be designed to be greater than the resultant force due to the pressure on the valve seat and the spring. Generally, a design margin is allowed for operation under a pressure higher than normal. An advantage of a solenoid valve with an O-ring is that it has a low leakage rate. However, when high force is encountered, such as during a surge, the valve seat may get stuck in the O-ring. Therefore, the valve seat should be designed to prevent this.

The conventional design for the O-ring setup is a valve without a groove, as shown in Fig. 2. A disadvantage of this design is that when it experiences momentary pressure 20% higher than the normal operating pressure, the valve seat may get stuck to the lower poppet assembly. To resolve this problem, a groove is made on the upper surface of the lower poppet assembly. The pressure is the force per unit area

Fig. 1. Schematic diagram of the solenoid valve.
applied in a direction perpendicular to the surface of an object. Thus, pressure force is reduced by the smaller surface area. This groove transfers the surge pressure to the lower part, and the downward force from the upper part is reduced. As a result, the solenoid valve can function even with a low suction force (approximately 15% down). Test results show that 33% of conventional solenoid valves function under normal pressure and get stuck at surge pressure. However, with the novel solenoid valve, every valve functions under both operation pressure and surge pressure.

In the RCS of the KSLV-I, thrusters with the anti-surge solenoid valve are adopted. These thrusters show no performance degradation during many component tests and system tests. Moreover, the RCS thrusters operate successfully under flight conditions, and their function and performance satisfy the system requirements of the KSLV-I. 5,6

4. Charging Procedure

There is always a pressure change $\Delta p$ associated with the rapid velocity change $\Delta V$ across a pressure. The relationship between pressure change and rapid velocity from the basic physics of linear momentum yields the well-known Joukowsky equation

$$\Delta p = \rho a \Delta V$$

where $\rho$ is the mass density and $a$ is the sonic velocity of the pressure wave in the fluid medium in the conduit. 7 If the pressure of the system decreases, a drop in the pressure surge will occur.

A typical pressure regulator automatically reduces a higher inlet pressure to a steady lower downstream pressure regardless of changing flow rate and/or varying inlet pressure. An increase in the downstream pressure of the regulator before latch valve operation will decrease the pressure surge.

The tanks of the RCS are charged on the flight test day. We can control the regulator downstream pressure with the pressure-operated latch valve open until the regulator downstream pressure reaches 300 psia. During this time, the charging flow rate is 0.3 g/s without pressure surge. When the regulator downstream pressure reaches 300 psia, the latch valve is closed. Then, the RCS bottles are charged with the operating pressure (220 bar). Before lift-off, the latch valve is open, and at this time, pressure surge occurs. With this method, pressure surge can be reduced by 66%. Figure 3 shows the charging history of the RCS.

5. Conclusions

The present study proposed a solenoid valve with a groove on the upper surface of the lower poppet and a charging procedure to reduce the occurrence of pressure surge. The grooved solenoid valve minimized the impact of the surge pressure, and an increased suction force was not required even under surge conditions. Moreover, this anti-surge thruster was successfully operated under a pressure surge condition, as verified through component level tests and system level tests. The charging procedure was a simple method to reduce pressure surge. No additional weight to minimize pressure surge was necessary with the proposed method.

The effectiveness of the proposed tactics was verified through two flight tests results. 5,6 The proposed methods can be usefully applied in launch vehicles in the aerospace industry.

References

1) Adler, S., Warshavsky, A. and Peretz, A.: Low-cost Cold-gas Reaction Control System for Slohsat FLEVO Small Satellite, J. Spacecraft Rocket, 42, 2 (2005), pp. 345–351.
2) Yang, A.-S. and Kuo, T.-C.: Design Analysis of a Satellite Hydrazine Propulsion System, J. Propul. Power, 18, 2 (2002), pp. 270–279.
3) AIAA: Fire, Explosion, Compatibility, and Safety Hazards of Hypergols-hydrazine, SP-084-1999, 1999.
4) Jeon, S.-W. and Jung, S.: Hardware in the Loop Simulation for the Reaction Control System using PWM-based Limit Cycle Analysis, IEEE Trans. Control Syst. Technol., 20, 2 (2012), pp. 538–545.
5) Cho, G.-R.: KSLV-I 3rd Flight Test Report, Korea Aerospace Research Institute, 2013, pp. 680–699.
6) Cho, G.-R.: KSLV-I 1st Flight Test Report, Korea Aerospace Research Institute, 2009, pp. 563–574.
7) Sciamarella, D. and Artana, G.: A Water Hammer Analysis of Pressure and Flow in the Voice Production System, Speech Commun., 51 (2009), pp. 344–351.