Development of a Thrust Measurement System

S. Jeon, J. Kim, H. Choi

Abstract—KSLV-I(Korea Space Launch Vehicle-I) is designed as a launch vehicle to enter a 100 kg-class satellite to the LEO(Low Earth Orbit). Attitude angles of the upper-stage, including roll, pitch and yaw are controlled by the cold gas thruster system using nitrogen gas. The cold gas thruster is an actuator in the RCS(Reaction Control System). To design an attitude controller for the upper-stage, thrust measurement in vacuum condition is required. In this paper, the new thrust measurement system and calibration mechanism are developed and measurement errors and signal processing method are presented.

Keywords—cold gas thruster, launch vehicle, thrust measurement, calibration mechanism, signal processing

I. INTRODUCTION

KSLV-I is the first space launch vehicle of South Korea. KSLV-¬I is capable of launching a satellite weighting 100 kg into a low earth orbit. The first launch of KSLV¬-I is occurred in 2009 [1]. Launch vehicles require high accuracy of attitude control system. The RCS(Reaction Control System) is one of the common control system on-board launch vehicle for attitude and orbit control in vacuum condition. The RCS utilizes 22 N-class cold gas thrusters. The cold gas thruster has been developed as one of the thrusters used in the space [2-3].

The RCS consists of pneumatic part and control. The pneumatic part consists of two bottles for storage of nitrogen gas, four thrusters for reaction force generation, a regulator for regulated pressure generation, a pneumatic connector for connection with first stage, a latch valve for flow control, a vent valve for drainage of propellant, a check valve, a relief valve and tube part for connection with all pneumatic components. The configuration of RCS pneumatic part is shown in the Fig. 1.

To perform a precise attitude maneuver and analyze a flight test results of RCS, accurate knowledge of the thrust level becomes essential [4-6]. Since the RCS operates at high altitude, thrust measurement in vacuum is very important. Measuring the true direction and magnitude of the thruster force is very difficult on the ground. For testing thrusters, a highly accurate measurement system in vacuum is required. A general method for measuring thrust involves use of pendulums or rotating platforms that induce a displacement when impulse is applied [7-11].

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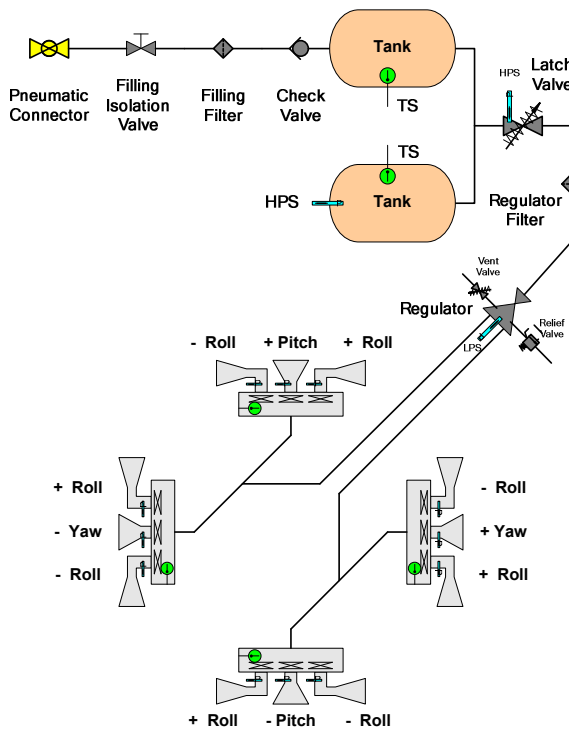
Fig. 1 Cold gas thruster system on-board KSLV-I

The thruster for KSLV-I has three nozzles: a middle nozzle for pitch or yaw control has a decline of 70 deg., and both end nozzles for roll control have a decline of 90 deg. [1].(see Fig. 2) Thrust is measured only two nozzles of the thruster since the two end nozzles are symmetrical.
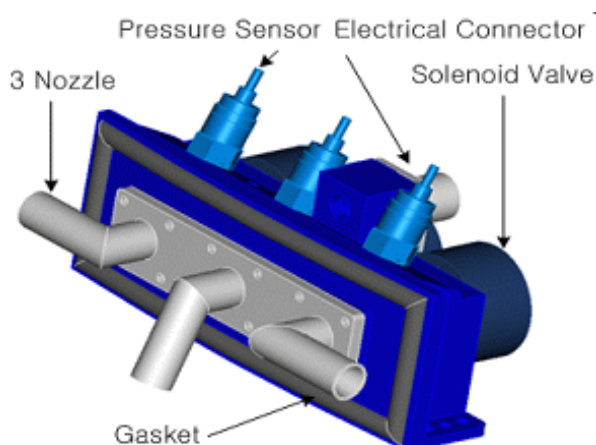

Fig. 2 Configuration of thruster

In this paper, a new thrust measurement system is developed and data acquisition system and calibration mechanism are developed for the thrust measurement system.

II. COMPOSITION OF THRUST MEASUREMENT SYSTEM

To perform a precise maneuver, the accurate measurement of the thrust level is essential. Thrust measurement in vacuum is an important factor for designing an accurate attitude controller

The system consists of a thruster, two regulators, a thrust stand, a vacuum chamber facility, a flow meter, a data acquisition system, a filter, and a nitrogen gas filling system.

A. Thruster

The thruster generates reaction force by exhausting cold gas through on-off operations by solenoid valves. The thruster consists of a nozzle part for thrust build-up, a solenoid valve part for valve on-off operations, a body part for gas flow and connections with other parts, and a connector part for electrical interface. The configuration and specification of the thruster for the KSLV-I is shown in Fig. 3 and listed in Table I.

The thruster has a conical nozzle with the throat diameter of 4 mm divergence cone angle of 15 deg. and is designed to produce about 26 N of thrust for a chamber pressure of around 1300 kPa. Thruster has three nozzles and they are designated as nozzle #1, nozzle #2, nozzle #3.(see Fig. 2) Nozzle #2 and nozzle #3 are evaluated in the current tests.

TABLE I
SPECIFICATIONS OF THRUSTER

|	
Operating pressure	< 4035 kPa
Operating voltage	28±6 VDC, 3 A
Thrust level	22 N ~ 26 N(at vacuum)
Response time	Thrust rising time < 40 msec Thrust decaying time < 40 msec
Leakage	Internal : 10^{-1}sccs GN_2 at 4035 kPa External : bubble zero
Pull-in voltage	< 10 VDC
Thrust alignment	$< \pm 0.2^o$
Expansion ratio	2.75(nozzle #1, #2, #3)
Etc.	Pressure transducer mounting type Specific impulse > 50 sec Normally closed type
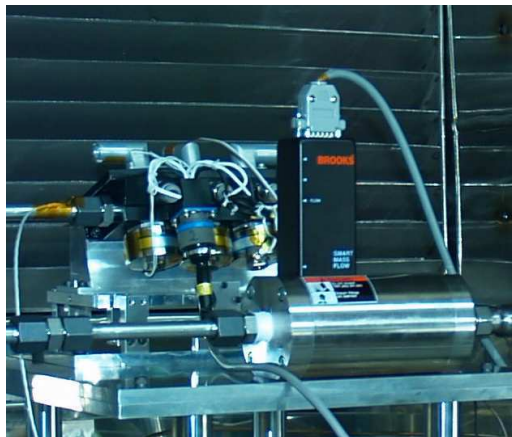
Fig. 3 Thruster on the thrust stand

B. Regulator

A regulator must provide thrusters with regulated nitrogen gas. Lock-up pressure shall not vary over 5%. The functional specifications of the regulator are shown in the following table. Fig. 4 shows the configuration of the regulator.

TABLE II
SPECIFICATIONS OF REGULATOR

Flow rate	0.25 kg/s at inlet pressure 600 psia
Operating media	Nitrogen, IPA, Heilum
Flow	>0.25kg/sec
Operating pressure	600 ~ 3,200 psia
Inlet port	1/2 inch
Outlet port	3/8 inch
Running time	No Limit(Regulating)
Leakage	Internal : 10^{-1}sccs GN_2 at MEOP External : Bubble Zero

Fig. 4 Regulator

C. Data acquistion system(DAQ)

The DAQ is consisted of a National Instrument DAQ board and self-made DAQ software that controlled and stored measurement data. The DAQ system also controls the operation of thruster valves and measured the solenoid valve driving voltages.

D. Thrust stand

The thrust stand is an inverted pendulum type with short thin stainless steel plates at four corners to act as load springs for the thrust force as well as to support the weight of the thruster assembly. The natural frequency of the thrust stand system including the thruster and gas tubing between the flow meter and the thruster is approximately 100Hz. The natural frequency of the thrust stand system is dictated by the gas tubing between the flow meter and the thruster. The tubing is much stiffer than the four thin plates. Schematic diagram of the thrust stand system is shown in Fig. 5.

The thruster is mounted on the thrust stand using the thruster adaptor, when the thruster is firing, the thrust stand pushes against the measurement load cell which is fixed on the base plate.
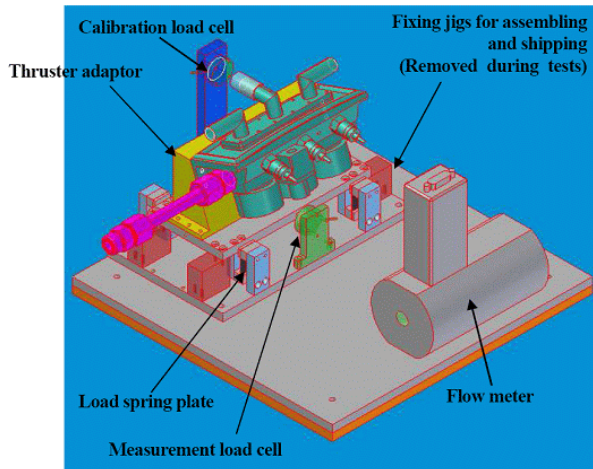

Fig. 5 Schematic diagram of thrust stand

E. Vacuum chamber and gas supply

Experiments are conducted in a vacuum chamber with 1m long and 1m diameter in KARI.(see Fig. 6) The vacuum chamber is pumped by two large rotary pumps, each of which has a maximum pumping speed of 7,200 L/min. The pumping path has a diameter of approximately 4 in. and a length of approximately 3 m. The conductance of the pumping path is roughly 1,100,000 L/min for viscous flow. The ambient vacuum pressure is kept below 13.3 kPa(in most cases, below 6.7 kPa) in all tests.

Fig. 6 Vacuum chamber facility

High pressure nitrogen gas propellant of up to 27,484 kPa was supplied to the regulator from a high pressure tank through a high pressure regulator and on/off ball valve.(see Fig. 7)

Fig. 7 High pressure nitrogen tank and propellant supply line

III. THRUST MEASSUREMENT

A. Data acquisition

The measured data in the test were summarized in the following Table III. The mass flow rate measurement was not used in any analysis due to a reason which the flow meter could not operate properly in vacuum environment. Therefore the flow rate is calculated from the measured chamber pressure, temperature, and regulated pressure along with the specified throat diameter. The specific heat ratio is assumed to be 1.4(a good approximation for diatomic gases such as nitrogen), and the specific impulse, Isp, is determined by the calculated flow rate and the measured thrust. The thruster chamber pressures, regulated pressure, and nitrogen supply pressure were measured by Kulite ETM-375 pressure transducers. The low vacuum pressure was measured by a thermal conductance type vacuum gauge. The thruster gas tubing and nozzle temperature were measured by Omega SRTD-2 temperature sensors. The thrust calibration and measurement were done using TEAC TC-USR29-50N load cells and TD-270 indicators. The indicators converted the digital signals to analog output signals that would be read by the DAQ. The DAQ system also controlled the operation of thruster valves and measured the solenoid valve driving voltages.

TABLE III
LIST OF MEASUREMENT DATA

Pressure	Thruster nozzle #2 (chamber pressure)
	Thruster nozzle #3 (chamber pressure)
	Regulator outlet pressure (regulated pressure)
	Nitrogen supply pressure
	Tank pressure(high source pressure)
	Vacuum (low vacuum)
	Vacuum (medium vacuum)
	Vacuum (high vacuum)
Temperature	Thruster gas tubing
	Thruster nozzle
Flow rate	Mass flow rate
Force	Thrust (1 axis)
Actuator command voltage	Solenoid valve driving voltage

B. Signal processing

An example of the above initial data analysis sequence for the thrust data is shown in Fig. 8. The pink line indicates the raw thrust data of the thruster nozzle #2 in vacuum test. The noise in the raw thrust data, which is attributed to mechanical vibration caused by the two large rotary pumps, is removed by the Wave Metrics IGOR's smoothing operation resulting in the purple line. IGOR is a publication quality scientific and engineering graphics program. The zero offset is determined from the purple smoothed line by selecting a point at each interval where the thruster is closed. Finally, the red zero offset line is subtracted from the purple smoothed line to give the corrected data, the green line in the Fig. 8. An example result of the whole analysis is shown in Fig. 9. Note that the radical variation of Isp during the thruster off time in Fig. 9 is not a real phenomenon. Similar data analysis was performed on each of the continuous firing tests.
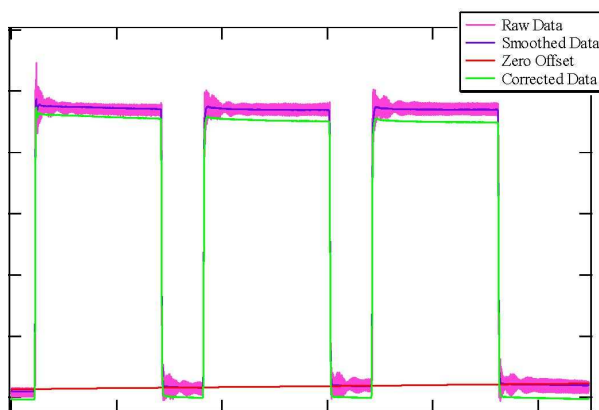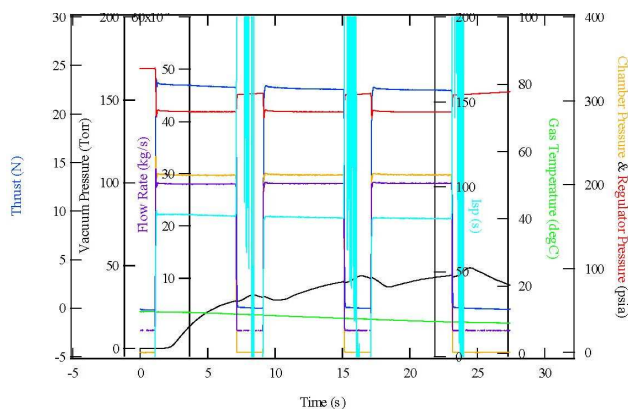

Fig. 8 Example of data analysis

Fig. 9 Example of a whole analysis

C. Calibration mechanism

Before measurements, the thrust stand system is calibrated by the calibration load cell which is located right in front of the test nozzle. Using a calibration adaptor, the nozzle is pushed against the calibration load cell, and in turn, the thrust stand pushes against the measurement load cell. The output of the calibration load cell is the same force that the nozzle would generate as thrust, and the output of the measurement load cell is the thrust stand system response to the input thrust force. The relationship of these two load cell outputs as Fig. 10 gives a true thrust force from the measured load cell output. After calibration, the relationship of these two load cell signals is shown in Fig. 11. Before testing, the calibration load cell and its stand are removed.
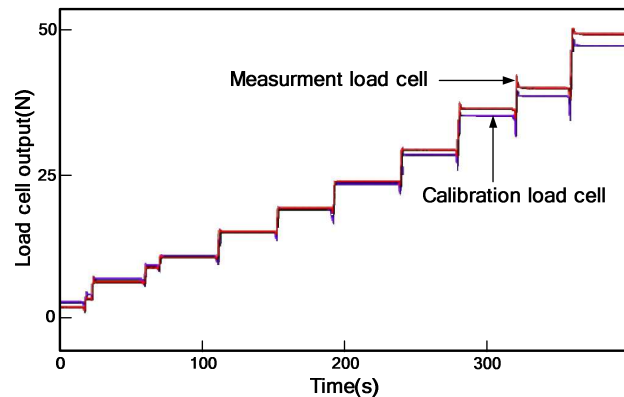

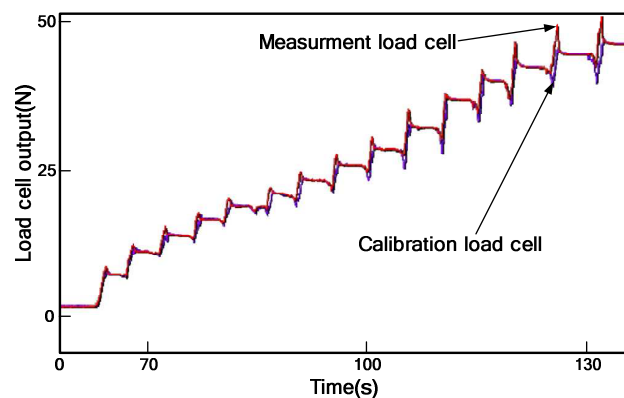Fig. 10 Load cells output signals before calibration

Fig. 11 Load cells output signals after calibration

D. Measurment error

The data in the thrust measurement tests such as thrust, pressure, and temperature are subject to errors associated with the uncertainty in the measurement system and sensors. The measurement error associated with the load cell/indicator is ±0.76 %. The error associated with the misalignment of the thruster nozzle axis can be attributed to the thrust stand machining tolerances. The worst case would be 1.2 mm displacement over 200 mm length which corresponds to 0.34 deg. misalignment. This misalignment gives rise to an error of 0.002 % in the thrust measurement. Therefore, the error in thrust force measurements related to the thrust stand system is conservatively estimated to be ±0.8 %.

The measurement error associated with the various pressure measurements depends on linearity, hysteresis, repeatability, and zero shift of the pressure transducers. The error in the pressure measurements is ±1.5 % of full scale according to the specification of Kulite ETM-375 pressure transducers. Since the full scale of the sensor used in the experiment is 6,793 kPa, the error in the pressure measurements is ±102 kPa. The accuracy of the Omega SRTD-2 temperature sensors is ±-0.5 % of the measured temperature according to its manual. The stability is said to be less than 0.2 °C

drift per year at rated service temperature with proper mounting. This drift would be less than 0.008 °C for duration of two weeks for the thrust measurement tests. Thus, the error in temperature measurement is conservatively estimated to be ±0.6 %.

Errors that arise from the processes of data analyses are significant. The most important one is an error from zero offset correction in the data analyses. For example, the thrust measurement data are first filtered to reduce noise from the nearby pumps and power sources. Then, the zero offset is determined by selecting thrust measurement values when the thruster is closed. The source of the error in determining zero offset is the fact that the offset itself is varying during the thruster firing. Upon examining the results of zero offset determination, the error associated with zero offset analyses is estimated to be ±2 % for the thrust measurements and ±20 kPa in pressure measurements. The error in time measurement is dictated by the sampling time and the DAQ board. Since the DAQ board has the capability of resolving much higher sampling rate than the actual sampling rate, the error in time measurement is estimated to be less than ± the sampling time which is either 1ms or 10ms.

In conclusion, the errors are estimated to be ±2.8 % in thrust measurements, ±122 kPa in pressure measurements, ±0.6 % in temperature measurements, and ±1ms or 10 ms depending on the sampling time, in time measurements.

E. Flow rate measurements problem

Flow rate measurementes by a mass flow meter were first expected to give a great insight into thruster performance in continuous firing tests. However, the collected data showed an unexpected behavior of the flow meter(Brooks Instrument 5863S). The flow meter reading exceeded its upper range at first when the thruster was opened and then settled to a steady value 20 s after the initial activation of the thruster. This behavior appeared only during vacuum tests. The manufacture of the flow meter, Brooks Instrument, later admitted that the flow meter might not operate properly in vacuum environment due to the fact the thermal mass flow sensor was not contained in a sealed vessel. So, we used the calculated flow rate. The flow rate was calculated from the measured chamber pressure, temperature, and regulator pressure anlong with the specified throat diameter. The specific heat ratio is assumed to be 1.4(a good approximation for diatomic gases such as nitrogen), and the specific impulse, Isp, is determined by the calculated flow rate and the measured thrust.

IV. CONCLUSION

The primary purpose of the vacuum thrust measurement facility was to measure thrust force of the qualification models of RCS cold gas thrusts in vacuum environment. We designed and manufactured a thrust measurement device that included thrust calibration mechanism. We also designed and manufactured interface brackets to mount thruster on the thrust stand, data acquisition, valve control system, and high pressure propellant feed system. This system was used to thrust measurment for the cold gas thruster of KSLV-I [13].

REFERENCES

[1] Gwang-rae Cho: Research and Development of KSLV-I(V), *MOST*, 2007.
[2] Shimshon Adler, Abraham Warshavsky, and Are Peretz, "Low-cost cold-gas reaction control system for slohsat FLEVO small satellite," *Journal of Spacecraft and Rocket*, vol. 42, no. 2, March-April. 2005, pp. 345-351.
[3] Willian C. Stone, "Fast variable-amplitude cold gas thruster," *Journal of spacecraft and rockets, vol. 32, no. 2,* 1995, pp. 335–343.
[4] J. Brouseau, R. Maynard, A. Singaraju, and H. Richter, "A testbed for attitude control using cold gas thrusters," Proceedings of IMEC2006, 2006 ASME International Mechanical Engineering Congress and Expsition, November 5-10, 2006, pp. 595-604.
[5] R. L. Bayt and K. S. Breuer, "Fabrication and testing of micron-sized cold-gas thrusters," *Progress in astronautics and aeronautic AIAA 2000*, pp. 381-397.
[6] Claudio Lugini and Marcello Ronmano, "A ballistic-pendulum test stand to characterize small cold-gas thruster nozzle," *ACTA Astronautica*, 2009, pp. 615-625.
[7] S. Kang, H. Cho, and Y. Chang, "Development and testing of a micro-thruster impulse characterization system utilizing pendulum swing time measurements," *Sensors and Actuators A*, 2008, pp. 381-387.
[8] K. Toyoda, K. Komurasaki, and Y. Arakawa, " Thrust performance of a CW laser thruster in vacuum," *Vacuum*, vol. 65, 2002, pp. 383-388.
[9] K. Kondo, S. Tankaka, H. Habu, S. Tokudome, K. Hori, H. Sito, A. Itoh, M. Watanabe, and M. Esahi, "Vacuum test of a micro-solid propellant rocket array thruster," *IEICE Electronics Express*, vol. 1, No. 8, 2004, pp. 222-227.
[10] S. Wu, W. H. Steyn, and R. E. Bordany, "In-orbit thruster calibration techniques and experiment results with UoSAT-12," *Control Engineering Practice*, 2004, pp. 87-98.
[11] Nikos A. Gatsonis and Richard A. Nanson : Simulations of cold-gas nozzle and plume flows and flight data comparisons, *Journal of Spacecraft and Rocket*, vol. 37, no. 1, January-February, 2000, pp. 39-48.
[12] Nikos A. Satsonis, R. E. Erlandson, P. K. Swaminathan, and C. K. Kumar : Analysis of pressure measurements during cold-gas thruster firings onboard suborbital spacecraft, *Journal of Spacecraft and Rocket*, vol. 36, no. 5, September-October, 1999, pp. 688-692.
[13] S. Jeon and S. Jung, "Hardware in the Loop Simulation for the Reaction Control System using PWM-based Limit Cycle Analysis," *IEEE Trans. Control Systems Technology*, vol. 20, no. 2, March, 2012, pp.538-545.