FINAL REPORT
For Japan-Korea Joint Research Project

AREA	
	1. Mathematics & Physics 2. Chemistry & Material Science 3. Biology ④ Informatics & Mechatronics 5. Geo-Science & Space Science 6. Medical Science 7. Humanities & Social Sciences

1. Research Title:

A Study of Side Force Fluctuation in a Propulsion Nozzle and Its Control Method

2. Term of Research: From 7.1.2009 To 6.30.2011

3. Total Budget

a. Financial Support by JSPS: Total amount: 2,400 thousand yen

1st Year 900 thousand yen 2nd Year 1,200 thousand yen

3rd Year 300 thousand yen

b. Other Financial Support : Total amount: 0 thousand yen

4. Project Organization

a. Japanese Principal Researcher	
Name	Toshiaki Setoguchi
Institution / Department Position	Institute of Ocean Energy, Saga University Professor
b. Korean Principal Researcher	
Name	Heuy Dong Kim
Institution / Department Position	School of Mechanical Engineerign, Andong National University Professor

c. List of Japanese-side Participants (Except for Principal Researcher)

Name	Institution/Department	Position
Shigeru Matsuo	Department of Advanced Technology Fusion, Saga University	Professor
Tokitada Hashimoto	Department of Advanced Technology Fusion, Saga University	Lecturer
Kenichi Nishi	Graduate School of Science & Engineering, Saga University	Master student
Kenta Ono	Graduate School of Science & Engineering, Saga University	Master student
A. B. M. Toufique Hasan	Graduate School of Science & Engineering, Saga University	Ph. D student
Soichiro Koyama	Graduate School of Science & Engineering, Saga University	Master student
Junji Nagao	Graduate School of Science & Engineering, Saga University	Master student
Seiya Tokuda	Graduate School of Science & Engineering, Saga University	Master student

d. List of Korean-side Participants (Except for Principal Researcher)

Name	Institution/Department	Position
Lijo Vincent	School of Mechanical Engineering, Andong National University	Ph. D student
Joo Young Park	School of Mechanical Engineering, Andong National University	Master student
Choon Sik Shin	School of Mechanical Engineering, Andong National University	Master student
Jong Sung Lee	School of Mechanical Engineering, Andong National University	Master student
Suryan Abhilash	School of Mechanical Engineering, Andong National University	Ph. D student

5. **Number of Exchanges during the Final Fiscal Year***

a. from Japan to Korea *Japanese fiscal year begins April 1.

Name	Home Institution	Duration	Host Institution
For Final Fiscal Year(FY2010) Total: 0 persons		For Final Fiscal Year(FY2010) Total: 0 man-days	
Numbers of Exchanges during the past fiscal years			
FY2008: Total 0 persons FY2009: Total 5 persons			

b. from Korea to Japan

Name	Home Institution	Duration	Host Institution
For Final Fiscal Year(FY2010) Total: 0 persons		For Final Fiscal Year(FY2010) Total: 0 man-days	
Numbers of Exchanges during the past fiscal years			
FY2008: Total 0 persons FY2009: Total 0 persons			

6. Objective of Research

A large scale launch vehicle requires nozzle which can produce maximum specific impulse and thrust. Various supersonic nozzles such as thrust optimized (TO) and compressed truncated perfect (CTP) contours have been developed to meet such demands. Propulsion nozzle of rocket engine is often subject to fluctuations of the side forces which are generated during the transient processes of engine startup and shutdown.

In general, two types of separation patterns are observed in the transient process of over-expanded CTP and TO nozzle flows. One is free shock separation (FSS) and the other is restricted shock separation (RSS). FSS structure can be observed in various types of nozzles such as conical contour nozzles and bell type nozzles including TO and CTP nozzles. FSS is a regular type of the separation pattern and the flow separates fully from the nozzle wall due to an oblique shock that originates from the nozzle wall and is directed towards the nozzle center line. In RSS, the flow separation is restricted over a short axial distance. The separated shear layer reattaches to the nozzle wall generating shock waves and expansion waves. RSS is a peculiar type of separation pattern observed only in TO and CTP nozzles at a certain range of pressure ratios and it is believed that the serious side load is caused by the restricted shock separation (RSS).

These undesirable side forces can lead to serious problems in the rocket engine performance as well as stable operation. Very complicated interaction between shock wave and nozzle wall boundary layer is responsible for the flow unsteadiness that remains unsolved.

The present study aims at investigating the generation cause of the unsteady side forces, and developing an effective control method to alleviate them. Both experimental and computational works are planned to achieve the final goals of the present study.

7. Methodology

In order to effectively achieve the objectives of the present study, both experimental and computational methods were planned to investigate the detailed flow characteristics associated with FSS (Free Shock Separation) and RSS (Restricted Shock Separation), and then developed some control methods appropriate to reduce the undesirable side force fluctuations due to the transition from FSS to RSS.

Several types of propulsion nozzles were designed to obtain the FSS and RSS flows at pressure ratios of 2 to 60, and these were installed into the test section of existing supersonic wind tunnel. Experimental works involved the measurements of both time-mean static wall pressures and time-dependent wall pressures along nozzle wall surface, flow visualizations using schlieren optical system. From the experimental measurements planed above, the generation cause of FSS and RSS was explored, together with transition characteristics from FSS to RSS and/or RSS to FSS. These were also used to clarify the unsteady side forces, due to very complicated interaction between shock wave and nozzle wall boundary layer.

Computational analysis was also planned to investigate the detailed flow physics of the unsteady FSS and RSS which were difficult to disclose them in the experimental works. TVD MUCL numerical scheme was employed to discretize the full 3-dimensional, unsteady, compressible Navier-Stokes equations, together with two equation turbulence models. For the transient flow analyses, Reynolds Stress Model (RSM) was planned to investigate FSS and RSS transition responsible for the unsteady side forces.

Several control methods were applied to reduce the undesirable side forces. These make use of steps, cavity and so on to hold the interaction flow stable or stationary.