과팽창 노즐 내에 발생하는 FSS-RSS 현상에 관한 실험적 및 수치해석적 연구

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Experimental and Computational Studies of FSS-RSS Phenomena in an Over-Expanded Nozzle

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Abstract. The interaction patterns between shock wave and boundary layer in a rocket nozzle are mainly classified into two categories, FSS(Free Shock Separation) and RSS(Restricted Shock Separation), both of which are associated with the thrust characteristics as well as side loads of the engine. According to the previous investigations, strong side loads of the engine are produced during the period of transition from FSS to RSS or vice versa. The present work aims at investigating the unsteady behavior of the separation shock waves in a two-dimensional supersonic nozzle, using experimental method and CFD. Schlieren optical method was employed to visualize the time-mean and time-dependent shock motions in the nozzle. The unsteady, compressible N-S equations with SST K- ω turbulence closure were solved using a fully implicit finite volume scheme. The results obtained show the separation shock motions during the transition of the interaction pattern.

Key Words: Compressible flow(압축성 유동), Over-expanded flow(과팽창 유동), FSS(자유 충격 파 박리), RSS(제한 충격파 박리), Side-Load(횡력), Shock wave and boundary layer interaction(충격파 경계층 간섭)

Nomenclature

M : Mach Number
 P_a : Ambient pressure [Pa]
 P_b : Back pressure [Pa]
 P_0 : Total pressure [Pa]
 P_w : Wall pressure [Pa]
 T_0 : Total temperature [K]
 X : Distance from nozzle throat [mm]
 L : Length of nozzle divergent part [mm]

1. Introduction

The nozzle of the first stage rocket engine of present launchers (like Ariane 5, SSME or LE-7A) is usually designed in order to achieve full flowing

at sea level for the nominal chamber pressure. One of the possible improvements for the main engines of launchers is the development of supersonic nozzles with large area ratio, which provide higher specific impulse at high altitude with a consequent saving of a large amount of propellant⁽¹⁾. In general, rocket engine nozzles, designed for high altitudes, will inevitably encounter flow separation during transient startup and shutdown processes. The flow separates in supersonic nozzles whenever the wall pressure (p_w) is much lower than ambient pressure (p_a) with an oblique shock on the nozzle wall. At high altitudes, the flow will be expanded up to lower pressures. But during sea-level operation, due to highly over-expanded condition, the flow separation will take place within the nozzle. This will cause shock wave-boundary layer interaction (SWBLI) accompanied by the asymmetric forces called side-loads which might damage the nozzle. In these days, therefore, the side-load assessment is an important and difficult issue.

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Fig. 1. Schematic of separation patterns in an over-expanded TOC nozzle⁽²⁾.

According to previous investigations on rocket nozzles the interaction pattern between shock wave and boundary layer is mainly classified into two categories, FSS (free shock separation) and RSS (restricted shock separation), as shown in Fig.1, both of which are associated with the thrust characteristics as well as dangerous lateral forces, the so called side-loads, of the engine which can damage the structure⁽²⁾.

In FSS, the flow separates fully from the nozzle wall due to an oblique shock that originates from the wall and is directed towards the nozzle centerline. The separated boundary layer continues as a free jet as shown in Fig. 1(a). Since no re-attachment occurs downstream of the separation location, this interaction pattern is called as free shock separation. In RSS, the flow separation is restricted over a short axial distance. The separated boundary layer reattaches to the nozzle wall, thereby reflecting shocks and expansion waves in supersonic jet. Due to the very short separated region, this interaction pattern is called restricted shock separation as shown in Fig. 1(b). Both FSS and RSS can exist in such nozzles at different operating conditions. Although, From the early 70s, many investigations on side-load behavior have been conducted by methods of experiment and CFD, their origin is not perfectly understood. And the

lack of information on transitional behavior of shock separation flows in supersonic nozzles still remains.

According to the work of Nave and Coffey⁽³⁾, the pioneer milestone for the field, separated flow is first governed by the FSS. It is then replaced by the RSS, when the chamber pressure exceeds certain critical value. And Hysteresis of the FSS to RSS transition and vice versa was also clearly identified. Chen et al.⁽⁴⁾ have first reported the reattached flow in their computational simulations, and shown a trapped vortex immediately downstream of the central normal shock. Later, Nasuti et al.⁽⁵⁾, explained that an inviscid mechanism causes the generation of vortex which generates side loads. Frey et al.⁽⁶⁾, have shown the existence of specific cap shock patterns which is a key driver for the transition from FSS to RSS and vice versa. The measurements of side loads were also conducted. According to Hagemann et al.⁽⁷⁾, momentum balance across the cap-shock pattern, with the radial momentum towards the wall generated by the reflected internal shock causes the re-attachment. Nasuti et al.⁽⁸⁾ have reported that the flow re-attachment at the wall depends on the values and kind of upstream pressure gradient, irrespective of the existence of internal shock. More recently, Lee et al.⁽⁹⁾, have shown by CFD that the transition of FSS to RSS was generated due to the development of a vortex ring in the inviscid jet core region. However, no evidence was given to support the assumptions made.

The purpose of this article, therefore, is to present a detailed description of the side-load aspects of shock separation flows in a 2D supersonic nozzle with symmetric and asymmetric shock structure configurations using experimental method and to measure the side-load behavior simulating an unsteady shut-down process.

In the present work, Schlieren visualization method was employed to visualize the time-mean and time-dependent shock motions in the nozzle. Steady and unsteady wall pressures along the nozzle wall were obtained by using scanning system and fast response pressure transducers (Kulite XT-190 7bar G) respectively. The computational results were validated with previous experimental data. The results obtained shows the separation shock

Fig. 2. Schematic of experimental system set-up.

motions during the transition of interaction pattern which showed a good agreement between the experimental and CFD works.

2. Experimental Set-up

The experimental facility consists of a compressor, a reservoir tank, a plenum chamber, a supersonic nozzle, the pressure measurement systems and Schlieren optical system as shown in Fig. 2. The compressed and dried air in the common reservoir is at first supplied to the plenum chamber, where the flow is in stagnation condition, and the air is then discharged into the atmosphere through the nozzle.

The present experiments are performed using visualization technique and pressure measurement simultaneously for the flow within the nozzle.

The configuration of the supersonic nozzle is illus-

Fig. 3. Schematic of 2D supersonic nozzle.

trated in Fig. 3. It is constituted by two half nozzles for which design Mach number, $M = 3.7$ in the exit plane. Nozzle throat diameter, nozzle exit diameter and stream-wise length from throat are designed as 6.6 mm, 15 mm and 70 mm, respectively.

2.1 Measurement

In order to measure the wall pressure distribution at various NPR by using scanning system, 14 static pressure holes with 0.5 mm diameter were drilled on the lower wall in the axial direction from throat to exit and are arranged along the centerline of the nozzle. And, three piezo-resistive pressures transducers (Kulite XT-190 7Bar G) were installed on the upper wall. However, in the present work, only the scanning system was employed.

2.2 Optical method

The sidewalls of the nozzle incorporate optical windows for visualization of the internal flow fields, from the throat of nozzle to exit. The Schlieren system employed a nano spark as a light source (KOMI Model-PMAS), and concave mirrors with 200 mm diameter along with a charged coupled device (CCD) camera for acquiring the images.

3. Computational Method

Computational study was conducted to measure the quantitatively side-load during shut-down process of supersonic nozzle. The 2D nozzle geometry having same configuration as the nozzle employed in the experiments was used in the initial steady computation to validate the experimental results.

The governing equation was used unsteady RANS equation which was solved using a fully implicit finite volume scheme. AUSMDV and second order upwind scheme were used to solve the convective terms. SST K- ω turbulence model, which was proposed by Menter⁽¹⁰⁾, was employed in the present work for modeling turbulence. The length of each time step was 2.0×10^{-6} . The computational domain and boundary conditions used in the present study are illustrated in Fig. 4. The pressure inlet and pressure outlet boundary conditions, where the inlet total pressure(P_0) and back pres-

Fig. 4. Computational domain.

Fig. 5. Computational grid.

sure (P_a) of nozzle, were given respectively. The adiabatic, no-slip conditions are applied to the solid walls. In the present study, the inlet total pressure is varied in the range of 2 to 10 bar with fixed total temperature, $T_0 = 300\text{ K}$. And outlet static pressure and temperature are given as fixed ambient pressure and 300 K .

Figure 5 shows the computational grid system. A structured grid system with about 69,000 grid points was employed in the present computations. The grids were densely clustered in the boundary layers, the nozzle throat and nozzle exit so as to provide reasonable solutions. Several preliminary computations have been performed to ensure the grid independent solutions, using the present experimental data.

4. Results and Discussion

In this study, nozzle pressure ratio P_0/P_a is defined as NPR. In the case of $\text{NPR}=1$, nozzle inlet pressure is equal to the ambient pressure. In experiments, NPR is varied between 2 and 10. Fig. 6 gives the comparison of Schlieren image and computed Mach number contours at various NPRs.

Working fluid in the present work, dried air was employed by using of air dryer, but which was not perfectly operated leading to occurring the condensation of air. As a result, because of the rapidly expanding the nozzle area, two black point was captured at the downstream of throat in Schlieren image.

In the present 2D supersonic nozzle, interaction flows are obtained three patterns, such as FSS, symmetric RSS and asymmetric RSS. At $\text{NPR}=3, 4$ and 5 , interaction patterns are RSS, which is characterized by the reattachment of the boundary layer to the wall after separation. Except at $\text{NPR}=3$, RSS shock structures are shown to be symmetric. However, from $\text{NPR}=6$, we can see the transition of RSS to FSS regime, with the interaction flow pattern becoming asymmetric and unstable as depicted in Fig. 6 (d). And then, after $\text{NPR}=10$, flow pattern evolved is FSS, which has a symmetric structure again. In other words; when NPR increases (start-up process) or decreases (shut-down process), shock wave-boundary layer interaction structure has asymmetry accompanied by transition of RSS to FSS. This asymmetry of the flow could be the manifestation of a *Coanda effect* which is

Fig. 6. Comparison of Schlieren images (Exp.) and Mach number contours (CFD).

Fig. 7. Comparison of wall pressure distributions between experiment and CFD.

directly connected to side-loads according to previous work⁽¹¹⁾. Consequently, we can confirm from the acquired images that the origin of side loads is in the asymmetric nature of shock wave-boundary layer interaction structure, when the separation pattern changes in the 2D supersonic nozzle.

Figure 7 shows the normalized static pressure distribution along the nozzle wall for various NPR in order to compare results between experiment and CFD. The results are indicated at NPR (P_0/P_a) = 4, 5, 6, 8, 9 and 10 respectively and the axial distance (X) from nozzle throat is normalized by length (L) of the nozzle divergent part. Basically, from the one dimensional gas dynamics point of view, wall pressure of choked flow through the nozzle throat has to decrease due to the acceleration of flow unless there is separation in the nozzle. However, the static pressures along the nozzle wall increase until peak value with the distance, and then decrease. Met with flow separation and the oblique shock wave on the wall, the pressure gradually recovers and reaches the ambient value. This means that the internal shock, due to the re-compressed flow from throat, influence the wall boundary layer since the pressure is increased. When boundary layer is free of the influence of internal shock, pressure again decreases due to the acceleration of flow.

Another important feature of the results is that the pressure fluctuations occur along the upper and lower nozzle walls simultaneously as can be seen at NPR=4, 5 (RSS pattern) in Fig. 7. This means that the reflections of shock and expanded waves were occurred frequently in between wall and free shear layer. In other words, in RSS pattern, the flow field inside the nozzle has complicated the pressure behavior which results in very unstable and strong unsteady shock structure. when increase NPR, separation point also are moved downstream of the nozzle.

It has well predicted qualitatively the separation point and a tendency of interaction flow fields as depicted in Fig. 6 and 7.

Figure 8 shows computed side-loads, which are normalized by peak value 278KN, during shut-down process (NPR=10 to 2) in 0.1sec. As mentioned in the previous section, three interaction patterns were observed in the present CFD such as FSS, symmetric RSS and asymmetric RSS. It can also be confirmed that two transition regions were occurred depending on the nozzle pressure ratio(NPR), respectively.

Indeed, strong unsteady pressure vibrations were occurred before transition of FSS to RSS during NPR=10 to 5.75, this is why, it can be known that transitional flow fields have a many unstable fac-

Fig. 8. Computed nondimensional side-load during shut-down process.

tors such as trapped vortex and shock wave and boundary layer interaction. Consequently, two peak side-load regions are observed, during the transient transition of FSS to symmetric RSS and symmetric RSS to asymmetric RSS.

5. Conclusion

Experimental and computational investigations were conducted to clarify the detailed unsteady behavior of the shock waves in a two-dimensional supersonic nozzle. The results obtained show the separation shock motions during the transition of the interaction pattern with good agreements between the experimental and CFD works.

It is confirmed from the obtained images that the origin of side-loads is in the asymmetry structure of shock wave-boundary layer interaction patterns (FSS and RSS). Especially, in RSS pattern, the flow field inside the nozzle has complicated the pressure behavior which results in very unstable and strongly unsteady shock structure.

It can also be confirmed that interaction patterns were occurred depending on the nozzle pressure ratio (NPR), respectively. And two peak side-load regions are observed, during the transient transition of FSS to symmetric RSS and symmetric RSS to asymmetric RSS.

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