초음속 노즐에서 발생하는 비대칭 유동의 제어에 관한 연구

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Control of the Asymmetric Flow in a Supersonic Nozzle

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Abstract. Several previous works on rocket nozzle flows have revealed the existence of the transition from FSS to RSS and the occurrence of asymmetric flow associated with the boundary layer separation, which can cause excessive side-loads of the propulsion system. Thus, it is of practical importance to investigate the asymmetric flow behaviors of the propulsion nozzle and to develop its control method. In the present study, the asymmetric flow control method using a cavity system was applied to supersonic nozzle flow. Time-dependent asymmetric flow was experimentally investigated with the rate of change of the nozzle pressure ratio. The results obtained showed that the cavity system installed on nozzle wall would be helpful in fixing the unsteady motions of the boundary layer separation, consequently reducing the possibility of the occurrence of the asymmetric flow.

Key Words: Compressible fluid(압축성유동), supersonic nozzle(초음속 노즐), shock wave(충격파), boundary layer flow(경계층유동), flow control(유동제어)

1. Introduction

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. In the propulsion nozzles of rocket engines, it is reported that an excessive side load is formed in the course of a transient process during startup and shutdown of some engines. 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)^{(1),(2)}.

Recently, the nozzle with a step has been proposed as a technique to control the occurrence of RSS in the course of a transient process in the nozzle flow and it was reported that this is effective for control of the flow^{(2),(3)}.

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In the present study, the separation control technique using a cavity⁽⁴⁾ was proposed and the possibility of the control was demonstrated experimentally. Further, the relationship between the asymmetric separation and the rate of change of the pressure ratio with time in a transient phase at the shutdown was investigated from the point of view of the occurrence of the asymmetric flow in the supersonic nozzle.

2. Experimental Setup

2.1 Experimental Set Up

In the present experiments, a blow-down supersonic wind tunnel was used in order to investigate the flow in the supersonic nozzle. Figures 1 and 2 show the schematic diagram of the experimental apparatus and detailed nozzle configuration, respectively. The apparatus is consisted of compressor, air drier, air reservoir, electric control valve, plenum chamber and nozzle. The compressed air was used as a working gas. The design geometries of Figs. 2(a), (b) and (c) are ideal nozzle, ideal nozzle with step and ideal nozzle with cavity, respectively. The design Mach number of the ideal nozzle⁽¹⁾ in Fig. 2(a) is $M_e = 2.11$ and heights of nozzle throat and exits are $D_t = 6.6$ mm and $D_e = 13.2$ mm, respectively. The height of step of in Fig. 2(b) is $0.133 D_t$ ⁽³⁾. For the ideal nozzle with cavity, height h and length l of the cavity are 0.5 mm and 8.0 mm⁽⁴⁾, respectively (Fig. 2(c)). Positions of the leading edges in cases of step and cavity were decided based on schlieren photographs of the flow in

Fig. 2. Nozzle geometry.

the ideal nozzle (Fig. 2(a)).

2.2 Experimental Method

Pressure ratio ($\phi = p_0/p_b$) was continuously changed with time from 8.0 to 3.0 for all cases using the electronic control valve. The symbols p_0 and p_b represent the stagnation pressure in the plenum chamber and back pressure, respectively. The rates of change of the pressure ratio with time $\dot{\phi}$ are -10.2 (1/s) and -37.4 (1/s). Internal flow with shock waves was visualized by a schlieren optical method. Visualization and measurement of pressure ratio were conducted

Fig. 1. Experimental apparatus.

Fig. 3. Time histories of pressure ratio ϕ in plenum.

Fig. 4. Schlieren photographs (Ideal nozzle, $\dot{\phi} = -37.4$ (1/s)).

simultaneously. The location of the shock wave was obtained from schlieren photographs.

3. Results and Discussion

In the present experiments, the effect of $\dot{\phi}$ on the transition from FSS to RSS was investigated

experimentally. Figure 3 shows time histories of ϕ for $\dot{\phi} = -10.2$ (1/s) and -37.4 (1/s). In this figure, the ranges of transition from FSS to RSS for each $\dot{\phi}$ are also indicated for ideal nozzle and ideal nozzle with step. As seen from this figure, there exists also the range of transition in case of $\dot{\phi} = -10.2$ (1/s) for both nozzles. There is an overlapping range between both

Fig. 5. Schlieren photographs (Ideal nozzle with step, $\dot{\phi} = -37.4$ (1/s)).

nozzles. Further, the range of transition for $\dot{\phi} = -10.2$ (1/s) is small compared with that of $\dot{\phi} = -37.4$ (1/s).

Figure 4 shows schlieren photographs for the ideal nozzle ($\dot{\phi} = -37.4$ (1/s)) in the shutdown transient. As seen from this figure, there exists the asymmetric flows with FSS and RSS during $\phi = 5.59 - 5.09$ in the nozzle.

For $p_0/p_b = 5.59$, FSS is symmetrically observed on upper and lower sides of the nozzle. FSS and RSS are seen on the upper and lower sides in case of $p_0/p_b = 5.59$, respectively and the flow becomes asymmetric. Occurrence of the asymmetric flows means the generation of side load. For $p_0/p_b = 5.09$, RSS is

Fig. 6. Schlieren photographs (Ideal nozzle with cavity, $\dot{\phi} = -37.4$ (1/s)).

symmetrically observed on upper and lower sides.

Figure 5 shows schlieren photographs for the ideal nozzle with step ($\dot{\phi} = -37.4$ (1/s)) in the shutdown transient from FSS to RSS. From this figure, separations during shutdown transient are observed in the same manner as the results of Fig. 4. In the previous research for the nozzle with step, it was reported that the nozzle with step reduced the occurrence of RSS. However, the transition from FSS to RSS is confirmed in the present experiment.

Figure 6 shows schlieren photographs for the ideal nozzle with cavity ($\dot{\phi} = -37.4$ (1/s)) during the shutdown transient.

As seen from this figure, the transition from FSS to RSS is not observed for separation of the flow and the flow is kept at separation pattern of RSS. As a result, the flow becomes symmetric in the process of change of $\dot{\phi}$. Change of the flow for $\dot{\phi} = -10.2$ (1/s) was almost similar to that of $\dot{\phi} = -37.4$ (1/s). This means that side-loads do not occur in the ideal nozzle with cavity. However, shock waves are observed around the cavity in the flow field.

The present experimental results show that both the step and cavity can be helpful in reducing the possibility of the occurrence of the asymmetric FSS and RSS flows. However, these control methods should take account for the pressure losses that are generated by the step and cavity. Further work is required to assess the detailed control performance.

4. Conclusion

In the present study, the flow characteristics in

supersonic nozzles with step and cavity were investigated experimentally. As a result, existence of transition range from FSS to RSS was confirmed regardless of the rate of change of the pressure ratio with time. The separation control technique using a cavity was proposed and the possibility of the control was demonstrated experimentally.

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