Performance Study of Thrust Control Unit with the Various Geometric Shapes

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Abstract

This study aims to identify aerodynamic characteristics of the ramp tab, a mechanical deflector, by conducting a non-combustive experiment using compressed air and supersonic flow test equipment. With the ramp tabs installed symmetrically and asymmetrically on the outlet of the supersonic nozzle, the structure of the flow field, the thrust spoilage, the thrust deviation angle, and the lift/drag coefficients were derived and analyzed. The results show that the asymmetrically-installed ramp tabs are advantageous relative to the symmetrically-installed tabs in terms of the performance of thrust vector control, thrust deviation angle, and lift coefficient.

Keywords: Mechanical deflector, Drag coefficients, Flow field, Pressure distribution, Fluid flow characteristics.

1. Introduction

Methods for controlling the flight attitude of an aircraft can be broadly divided into aerodynamic control and thrust vector control. Utilizing the aerodynamic force generated from the surface of an aircraft or the control surface of its wings, aerodynamic control is directly correlated to the amount of aerodynamic force. For this reason, flight attitude control abilities are reduced in areas where the aircraft’s velocity is slow or air is scarcely present[1~3]. On the other hand, thrust vector control directly deviates thrust and gains power to control the aircraft’s direction. It operates regardless of whether there exists air; it is also possible to steeply turn the aircraft at the initial stage of launch. Thrust vector control can be classified into mechanical and fluid dynamic methods. The mechanical method utilizes mechanical deflectors such as ramp tabs, jet vanes, while the fluid dynamic method controls thrust by ejecting secondary injection gas from inside a nozzle and causing bow shock and flow separation[4~6]. When conducting thrust vector control on a ramp tab, a type of mechanical deflector, flow separation is not induced within the nozzle—as in the case of secondary injection gas—and ramp tabs are installed at the outlet of the supersonic nozzle instead to generate normal shock and oblique shock inside the ramp tabs and generates high pressure in this area.

Leslie ea al. developed a mathematical model of a one-dimensional flow field to predict the location of normal shock generated from inside the ramp tabs. He did not, however, conduct research on the control force affecting the ramp tabs, which is essential for performing thrust vector control[7]. Kyoung-Ryun Kim identified the structures of shock generated within the ramp tabs by the amount of ramp tabs used[8]. Installing ramp tabs symmetrically and asymmetrically, this study seeks to identify fluid flow characteristics by understanding flow phenomena appearing in and out of the ramp tabs. The control force, thrust spoilage, and thrust deviation angle affecting the ramp tabs are also analyzed in an effort to suggest a new method for designing thrust vector control systems.

2. Experimental Devices and Method

Supersonic flow test equipment is used to pressurize and store high-pressure air, turn on the on-off valve, and eject compressed air through the supersonic nozzle within a second to generate supersonic flow. As shown in Fig. 1, this equipment consists of a pressurizing system, storage container, control valve, chamber, nozzle, and measurement equipment.

Fig. 2 shows the outline of a device for testing the performance of ramp tab thrust vector control equipment. The device is comprised of a single-component load cell, a chamber, a supersonic nozzle, ramp tabs, a six-component load cell, a housing, and a support component. As illustrated in Fig. 2, three ramp tabs are installed, at 120-degree intervals, on the outlet of the supersonic nozzle. The thrust spoilage, the thrust deviation angle, and lift/drag coefficients were derived and analyzed.
nozzle. The housing, which binds the ramp tabs, is installed on the six-component load cell, which measures forces affecting each direction (i.e. ±Fx, ±Fy, ±Fz); the supporting part is movable back and forth as the length of the nozzle changes.

Fig. 3 presents the shape of the ramp tabs installed symmetrically and asymmetrically. In Model A, ramp tabs are installed symmetrically, and ramp tabs Nos. 1-3 move vertically at identical intervals, with the axis of the nozzle as the basis. In asymmetrical Model B, ramp tabs Nos. 2 and 3 are fixed symmetrically, and ramp tab No. 1 is set to be movable up and down, with the nozzle axis as the basis. To analyze how the taper half angle of the ramp tab affects the flow field, the experiment models of the ramp tab were designed and fabricated to have taper half angles of 5° and 14°. Changes in the taper half angle of the ramp tab may alter the area ratio, and therefore the location of oblique shock, the thrust deviation angle, and the thrust spoilage can be identified.

3. Experiment Results and Implication

3.1 Model “A”

The Mach number of the supersonic nozzle used in this study is 2.88; its under-expansion ratio is set to be 1.5. Under expansion ratio is that discharge fluid at an exit pressure is greater than the external pressure. Fig. 4 compares and diagrams the results visualizing the flow, using a shadow graph device, to identify the structure of shockwaves generated around the ramp tabs.
at a slope angle of 25°. The structure of the flow field generated inside ramp tab can be visualized using a shadow graph as shown in figure 4. Shadow graph is widely used for visualizing shock wave. It is a device which optically visualizes the heat, pressure, density distribution of fluid without causing any physical effect on fluid using the diffraction grid of the flight. When ramp tab is installed in supersonic nozzle exit, the structure of shock wave formed inside ramp tab and the flow characteristics of shear layer were verified through experiment and flow analysis. Consequently, this paper has been analyzed with the flow characteristic acting on ramp tab when the flow injected from supersonic nozzle exit impinges against structures. Also, the static pressure probe is installed to confirm the shock wave location as shown in figure 4.

Light reflections and moisture have not been entirely removed, and images gained from flow visualization were not accurate, but it has been possible to identify the structure of shockwaves and the factors having predominant impacts. Eight units of static pressure probe—used for measuring pressure—are installed in ramp tab No. 1; the numerical order of the static pressure probes are defined based on the horizontal direction starting from the outlet of the supersonic nozzle. Thus, the static pressure probe installed nearest to the supersonic nozzle is No. 1, and that installed at the end of the ramp tab is No. 8.

Fig. 4(a) is a picture of the flow field when \( R_1, R_2 = 21 \text{ mm} \) and the taper half angle is 5°. Ejected from the supersonic nozzle, the flow is hindered by the obstacles of the ramp tabs, generating oblique shock. Between the surfaces of rear ramp tabs located on static pressure probe No. 6, the oblique shock is reflected in a multiple manner and creates a shear layer, which, along with speed discontinuity, separates the flow generated by oblique shock. Fig. 4(b) is a picture of the flow when \( R_1, R_2 = 21 \text{ mm} \) and the taper half angle is 14°. Oblique shock is generated at static pressure probe No. 6. Weak normal shock is generated downstream of the ramp tabs; as the shock occurs in their downstream, it does not have significant impact on the force of the ramp tabs. The oblique shock wave formed in ramp tab crosses each other and escape through the gap of ramp tab structure. The flow generates multiple expansive waves at the end of the ramp tabs. As it moves completely beyond the ramp tabs, the flow generates a complicated web-shaped structure of a shock wave in the downstream.

![Schlieren photographs of symmetrically installed ramp tabs](image)

Fig. 5 shows the drag and lift coefficients affecting the ramp tabs depending on changes in the taper half angle. When the taper half angle is 14° and \( R_1=17 \), the drag coefficient is 0.33, 1.5 times greater than when the taper half angle is 5°. This is because the greater the taper half angle becomes, the more it affects the pressure drag. At a taper half angle of 5°, the lift coefficient remains constant regardless of change to \( R_1 \); when the taper half angle is 14°, however, the lift coefficient increases in proportion to \( R_1 \), as an increase in the area ratio generates normal shock.

When installed on the outlet of the supersonic nozzle, ramp tabs deviate the flow, generating shock and deviating thrust. Thrust spoilage is caused when the ramp tabs, i.e., mechanical deflectors, are exposed. Fig. 6 illustrates the thrust spoilage caused by ramp tabs. Thrust spoilage declines dramatically as \( R_1 \) increases, values in a range of 5.1-9% are obtained at a ramp tab taper half angle of 5° and 6.7-14.1% at 14°. When the ramp tab’s taper half angle is 5° and \( R_1=21 \), the thrust spoilage is approximately 7.1%; when the taper half angle is 14° and \( R_1=21 \), it amounts to 9.9%—about 1.4 times greater than when the angle is 20°. These results can be explained as follows: when the taper half angle increases, the larger flow contact surface and viscous of the ramp tabs have a relatively greater impact.

The high-turning capacity of thrust vector control is based only on thrust, and hence it is necessary to consider the thrust deviation angle and the magnitude of thrust generated by thrust vector control devices. Here the thrust deviation angle can be derived, as in Equation (1), based on the ratio of the axis-direction thrust \( F_a \), which takes thrust spoilage into account, and the side force \( F_s \). Fig. 7 shows the respective thrust deviation angles for the ramp tab taper half angles of 5° and 14°. At a taper half angle of 5°, the thrust deviation angle approaches 0° regardless of changes in \( R_1 \). At 14°, the angle increases slightly as \( R_1 \) becomes larger. Generated by the supersonic nozzle, shock collides with ramp tabs and causes an increase in the level of pressure. This does not have a significant impact on the entire thrust, as forces affecting the ramp tabs, which are installed symmetrically, are offset in a symmetrical manner. The thrust deviation angle increases the taper half angle; hence, increasing it does not necessarily translate into better performance. In other words, the taper half angle of the ramp tabs should be selected properly in order to generate a thrust deviation angle that is appropriate to the designer’s aims.

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\phi = \tan^{-1} \left( \frac{F_s}{F_a} \right)
\]  

(1)
Fig. 5 Drag and lift coefficient with variation of R1

Fig. 6 Thrust spoilage with R1 variation

Fig. 7 Thrust deviation angle with R1
3.2 Model “B”

Fig. 8 shows a picture of the flow field generated when ramp tab No. 1 is installed asymmetrically and ramp tabs Nos. 2-3 are installed symmetrically. In Fig. 8(a), oblique shock generated from ramp tab No. 1 flows out of the interior of the rear ramp tab, which is located in static pressure probe No. 6. Regarding oblique shock waves generated in ramp tabs Nos. 2 and 3, their exact location cannot be identified, because they are obstructed by the ramp tabs. As illustrated in Fig. 8(a), however, they are generated somewhere before static pressure probe No. 6. Oblique shock waves generated in ramp tabs Nos. 1-3 do not cross each other at the central line of the ramp tabs. However, they do cross near ramp tab No. 1, as the ramp tabs involved are installed asymmetrically. In Fig. 8(b), oblique shock generated from ramp tab No. 1 is located in static pressure probe No. 6. However, oblique shock waves generated in ramp tabs Nos. 2-3 do move toward the downstream of the ramp tabs, as the outlet diameter of the ramp tabs is increased. Also, these oblique shock waves do not collide with the end of ramp tab No. 1, because ramp tabs Nos. 2-3 are at greater vertical distance from the center of the supersonic nozzle outlet.

In Fig. 8(c), it is seen that the area of the ramp tabs increases as their taper half angle becomes larger. Compressed within the ramp tabs, oblique shock generates reflection shock, a shear layer, and normal shock as it moves downstream. Control force is believed to increase due to normal shock generated within the ramp tabs. Generated in ramp tabs Nos. 1-3, respectively, the three waves of oblique shock cross each other and slip to the downstream of the ramp tabs. Flowing on the surface of the ramp tabs, the flow generates multiple expansion waves at the end of the ramp tabs. As it moves completely beyond the ramp tabs, the flow generates a complicated, web-shaped structure of a shock wave in the downstream, with normal shock, a shear layer, and multiple expansion waves crossing each other.

Fig. 9 shows the drag and lift coefficients affecting ramp tabs in accordance with changes in R2 and the taper half angle. At a taper half angle of 14°, the drag coefficient increases by around 30% compared to when the taper half angle is 5°. As the taper half angle of ramp tabs increases, the area vertically contacting the flow expands, and the drag coefficient affecting the ramp tabs also increases sharply. The drag coefficient has significant impact on relative to symmetrically-installed ramp tabs; it does not decline dramatically as R1 increases. In contrast, the lift coefficient has greater impact when R1 is increased. When the taper half angle is 14° and R1=25, the lift coefficient suddenly increases compared to when the angle is 5°. This is believed to be because the force of lift increases as normal shock is generated within the ramp tabs. When R2 increases, the flow ejected from the supersonic nozzle does not remain stagnant within the ramp tabs, immediately slipping out of them instead. For this reason, the drag and lift coefficients, when R2=17, exert smaller force on the ramp tabs and are less than when R2=11.

Fig. 10 represents the thrust spoilage generated in the ramp tabs. When the taper half angle is 5° and R2=11, the thrust spoilage sharply declines as R1 increases; values in a range of 8.9-10% are obtained; when R2=17, the values range from 6.8-8.1%. If ramp tabs are installed asymmetrically at the outlet of the supersonic nozzle, a decrease in R1 and R2 increases the area ratio and the drag toward the Y direction, thereby generating considerable thrust spoilage. As shown in Fig. 10, when the taper half angle is extremely large, the flow area of the ramp tabs increases, and significant thrust spoilage is generated. Against this backdrop, this study seeks to identify the maximum deviation angle and control force, considering thrust spoilage generated by changes in the diameter of ramp tabs and taper half angle.

The thrust deviation angle is illustrated in Fig. 11. At a taper half angle of 5°, the thrust deviation angle tends to be linearly proportionate, within a range of 0-2.5°, to R1 of the ramp tabs. As R1 of the ramp tabs increases, the thrust deviation angle becomes proportionately larger; when R2=11 and the taper half angle is 14°, the thrust deviation angle is 30-35% greater than when the taper half angle is 5°. When R2=17, the thrust deviation angle is smaller than when R1=11. This is because, as the outlet diameter of the ramp tabs is increased, normal shock is generated outside the ramp tabs, failing to stimulate side force.

(a)R1=21, R2 = 11 mm  (b)R1=21, R2 = 17 mm
(c)R1=21, R2 = 11 mm  (d)R1=21, R2 = 17 mm

Fig. 8 Schlieren photographs of asymmetrically installed ramp tabs
Fig. 9 Drag and Lift coefficient with variation of R1

(a) R2 = 11 mm

(b) R2 = 17 mm
Fig. 10 Thrust spoilage with variation of R1

Fig. 11 Thrust deviation angle with R1
4. Conclusion

This study has conducted various experiments with ramp tabs, devices for enhancing thrust vector control over the direction of an aircraft, installed symmetrically and asymmetrically on the outlet of a supersonic nozzle. The following conclusions have been derived:

(a) The drag coefficient tends to increase dramatically when the taper half angle of ramp tabs is increased, as the area that vertically contacts the flow increases. The lift coefficient rises when R1 increases due to normal shock generated within the ramp tabs.

(b) When the ramp tabs are installed symmetrically, the thrust deviation angle becomes smaller as forces affecting the ramp tabs are offset in a proportionate manner. They consequently do not have significant impact on the side force. When the ramp tabs are installed asymmetrically, side force is not offset, increasing in proportion to R1.

(c) Normal shock is nonexistent at a taper half angle of 5°, but at 14°, normal shock that can induce side force is generated. This normal shock is stronger when ramp tabs are installed asymmetrically than otherwise. Therefore, ramp tabs should be installed asymmetrically for enhanced thrust vector control over an aircraft.

Nomenclature

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\begin{array}{ll}
R & \text{Radius distance [mm]} \\
C_D & \text{Drag coefficient} \\
C_L & \text{Lift coefficient} \\
\beta & \text{Taper half angle [°]} \\
\phi & \text{Thrust deviation angle [°]}
\end{array}
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References