Thrust Vector Control of Supersonic Jet by Movable and Non-Movable Coanda Nozzles

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Abstract

Supersonic jet is used widely in the fields of aerospace engineering and other industries. Thrust vector control of supersonic jet is applied to jet and rocket engines, and is carried out using mechanical movable system mainly. However, it is very complicated system, and subsequently more simple method is desired. In this study, we first present a simple method for controlling the thrust vector of a supersonic jet using a movable system, and then a method without any movable systems. (1) The movable system is consisted of a pipe nozzle, Pi-nozzle, and linearly expanded Coanda nozzle, LC-nozzle. The outlet diameter of Pi-nozzle is smaller than the inlet diameter of LC-nozzle, and they are joined concentrically. In this case, the supersonic jet from Pi-nozzle flows straight along the nozzle axis through the LC-nozzle, but when the LC-nozzle moves radially and they are inscribed, the jet from Pi-nozzle is deflected in the inscribed direction due to the Coanda effect. We examined the flow characteristics, deflection characteristics, of supersonic jet from LCnozzle by the visualized flow pattern using Schlieren method and the measurements of velocity distribution. (2) Then, we propose a non-movable system by a fluidic Coanda nozzle, FC-nozzle. The FC-nozzle is consisted of Pi-nozzle, spacer, and linearly expanded Coanda nozzle, Co-nozzle, with eight suction pipes, Su-pipe, which are evenly spaced around the circumference of the entrance to the Co-nozzle. The jet from the Pi-nozzle flows straight with entrainment of surrounding fluid. When some suction pipes are closed, the pressure between the jet and Co-nozzle wall decreases and subsequently the jet deflects to the closed side of the Su-pipe and attaches to the wall by the Coanda effect. We also examined the flow characteristics, deflection characteristics, of supersonic jet from the FC-nozzle as before. As a result, we showed that by changing the number and loacation of closing of the Su-pipe the deflection angle and cicumferential position of the jet can be controlled.

Keyword: Supersonic jet, Thrust vector control, Movable and non-movable systems, Coanda effect, Fluidic Coanda nozzle

1. Introduction

Supersonic jets are widely used in the industrial field, such as jet and rocket engines, and others. There are many researches on the flow characteristics of supersonic under expanded jet [1]-[5]. There, the direction control, vector control, of the thrust is one of the important matters. That is, thrust vector control of supersonic jet is applied to jet engine, rocket engine and many other devices and is carried out using mechanical moving system mainly [6]-[8]. However, it is very complicated system, and subsequently more simple method is desired. Páscoa et al. [6] reviewed the studies on the thrust-vectoring in support of a V/STOL non-moving mechanical propulsion system. Also, Deere [7] summarized the research on fluidic thrust vectoring without moving mechanical system conducted at NASA Langley Research Center. However, it is though that the research on the thrust vector control of supersonic jet so far is not enough.

In this study, we first present a simple method for controlling the thrust vector of a supersonic jet using a moving part, nozzle, and then a method without any moving parts. The moving system consist of a pipe nozzle, Pi-nozzle, and a linearly expanded movable fluidic Coanda nozzle, LC-nozzle, appeared in Fig. 1.

The exit of Pi-nozzle is connected with the inlet of LC-nozzle, and LC-nozzle can be move in the radius direction while maintaining airtightness. The inlet diameter, d_{ic} , of LC-nozzle is larger than the exit diameter,

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 d_{ep} , of Pi-nozzle, $d_{ic} > d_{ep}$. When the LC-nozzle moves in the radius direction and the gap $(d_{ie} - d_{ep})$ becomes small or zero, the jet deflects and attaches to the inner wall of LC-nozzle by Coanda effect. The flow characteristics of deflected and attached jet are examined by flow visualization and measurements of pressure and velocity distributions. Next, we propose a simple method of vector control of supersonic jet by a fluidic Coanda nozzle, FC-nozzle, using the entrainment of the surrounding fluid [9]. The FC-nozzle is consisted of a pipe nozzle, Pi-nozzle, and linearly expanded Coanda nozzle, Co-nozzle, with eight suction pipes, Su-pipe. which are evenly spaced around the circumference of the entrance to the Co-nozzle. The jet from the Pi-nozzle flows straight with entrainment of surrounding fluid. When some suction pipes are closed, the pressure between the jet and Co-nozzle wall decreases and subsequently the jet deflects to the closed side of the Su-pipe and attaches to the wall by the Coanda effect. We examined the flow characteristics, deflection characteristics, of supersonic jet from FC-nozzle by the visualized flow pattern using Schlieren method and the measurements of velocity distribution. As a result, we showed that by changing the number and loacation of closing of the Su-pipe the deflection angle and cicumferential position of the jet can be controlled. Further, when there is no fluid to be entrained by the jet, that is, when the surroundings are in a vacuum state, the same control can be performed by blowing the fluid from the Su-pipe.

2. Experimental Apparatus and Procedure

Figure 1 shows movable linearly expanded Coanda nozzle which is consisted of the Pi-nozzle and LC-nozzle, and both nozzles are joined and the LC-nozzle can move radially. The inner diameter of Pi-nozzle is $d_{ie} = 4.0$ mm, and the inlet diameter, length, and opening angle of LC-nozzle are $d_{ep} = 6.0$, 12.0 and $\alpha = 7^{\circ}$, 10°, 14°, respectively. The exit of Pi-nozzle is connected with the inlet of LC-nozzle, and LC-nozzle can be move in the radius direction while maintaining airtightness. The inlet diameter, d_{ic} , of LC-nozzle is larger than the exit diameter, d_{ep} , of Pi-nozzle, $d_{ic} > d_{ep}$. When the LC-nozzle moves in the radius direction and the gap ($d_{ie} - d_{ep}$) becomes small or zero, the jet deflects and attaches to the inner wall of LC-nozzle by Coanda effect.



Fig. 1. Movable Coanda nozzle (consisted of Pi- and LC-nozzles)

Figure 2 shows the schematic diagram of the fluidic Coanda nozzle, FC-nozzle, with no moving parts. The FC-nozzle is a very simple system and is consisted of a pipe nozzle, Pi-nozzle, spacer with a thickness of 2.0 mm, and linearly expanded Coanda nozzle, Co-nozzle, with eight suction pipes, Su-pipe. The diameter of the Pi-nozzle is $d_0 = 4.0$ mm, the inlet diameter, length, and expansion angle the Co-nozzle is $d_{ic} = 5.0$ mm, $L_c = 12.0$ mm, and $\alpha = 20^{\circ}$, respectively. On the circumference of the Co-nozzle, eight Su-pipes with a diameter of $d_{is} = 2.4$ mm are installed. The origin of the coordinates is at the center of the Pi-nozzle exit, and the flow direction is the x axis and the direction perpendicular to thereto is as the r and r' axes as shown in Fig. 1. When all Su-pipes are opened, the jet entrains surrounding fluid from the Su-pipes and flows straight to the downstream as shown in Fig.1(a). On the other hand, when some Su-pipes are closed, the jet cannot entrain surrounding fluid from their side, and subsequently the pressure between the jet outer edge and the wall of Co-nozzle decreases and the jet deflects to the closed side of the Su-pipe as shown in Fig.1(b). Therefore, arbitrary circumferential vector control of the jet from the Pi-nozzle can be performed by changing the number and place of closing of the Su-pipe.

The compressed air supplied to the Pi-nozzle, and sub- and supersonic jet is issued from Pi-nozzle to the



(b) Deflected jet flow (Su-pipe 1)-3 and 6-8: close) Fig. 2. FC-nozzle (Fluidic thrust vector control of Pi-jet by FC-nozzle and Su-pipe)

ambient through the LC-nozzle or FC-nozzle. The supplied pressure was changed from $P_0 = 0.1 - 0.48$ MPa. The flow pattern was visualized by Schlieren method and the image was recorded. The velocity distribution was measured by total and static pressure Pitot tubes of diameter 1.0 mm.

3. Experimental Results and Discussions

Here, we will first present the results for the movable Coanda nozzle, and then the results for the non-movable Coanda nozzle.

3.1 Thrust vector control by movable Coanda nozzle

3.1.1 Flow pattern

Fig. 3(a) and (b) show Schlieren visualization images at $P_0 = 0.38$ MPa from an LC-nozzle with $\alpha = 10^\circ$, which is installed concentrically with the Pi-nozzle. The dashed lines in the figures indicate the approximate outer edge of the jet. When the LC-nozzle is installed concentrically with the Pi-nozzle, there are two steady states: a straight jet [Fig. 3(a)] that flows straight down along the central axis of the nozzle accompanied by a shock wave of expansion and compression, and an expansion jet [Fig. 3(b)] that attaches to the entire inner wall of the nozzle and flows down expanding, and there is hysteresis in determining which state it is in.

Fig. 3(c) shows a Schlieren visualization image of the jet at $P_0 = 0.38$ MPa from an LC-nozzle with $\alpha = 10^{\circ}$, where the outlet plane of the Pi-nozzle and the inlet plane of the LC-nozzle are inscribed at one point [Fig. 1(b)]. The jet from the Pi-nozzle is deflected by the Coanda effect in an inscribed direction with no offset distance, and adheres to the inner surface of the LC-nozzle (deflection jet). The jet deflects at deflected angle $\beta = 6^{\circ}$ and the shock wave of expansion and compression can be seen. Therefore, by eccentricating the LC-nozzle as described above, the jet vector can be controlled.

3.1.2 Hysteresis of flow pattern

Figure 4(a), (b) show visualization images of the jet when the supply pressure P_0 of an LC-nozzle with $\alpha = 10^{\circ}$ arranged concentrically with the central axis of the Pi-nozzle is quasi-statically increased in the range of $P_0 = 0.28 - 0.39$ MPa and then increased. When P_0 is quasi-statically increased from $P_0 = 0.28$ MPa, the jet is a straight jet up to $P_0 = 0.38$ MPa and transitions to an expansion jet at $P_0 = 0.39$ MPa. On the other hand, when P_0 is quasi-statically decreased from $P_0 = 0.29$ MPa. In addition, for the LC-nozzle with $\alpha = 7^{\circ}$, when P_0 is quasi-statically increased, When the pressure was quasi-statically decreased from straight jet to expansion jet at $P_0 = 0.34$ MPa, the jet transitioned from expansion jet to straight jet at $P_0 = 0.25$ MPa. Therefore, the jet

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from the LC-nozzle, which is concentric with the central axis of the Pi-nozzle, exhibits a hysteresis phenomenon in which the flow pattern is path-dependent.

3.1.3 Deflection angle, β

Figure 5 shows the deflection angle β of the jet when the LC-nozzle is installed eccentrically at $P_0 = 0.38$ MPa. β increases with increasing α , reaching a maximum of $\beta = 6^{\circ}$ at $\alpha = 10^{\circ}$, and then decreasing. This is thought to be because at $\alpha = 14^{\circ}$, the opening angle of the LC-nozzle is too large and the jet cannot sufficiently adhere to the wall of the LC-nozzle.

3.1.4 Jet centerline velocity, u_c

Fig. 6 shows the centerline velocity distribution u_c at $\alpha = 10^\circ$ and $P_0 = 0.38$ MPa. The Pi-jet oscillates greatly as the flow expands and compresses, and flows downward at approximately $u_c = 400$ m/s. The straight jet from the LC-nozzle has small shock waves due to expansion and compression, and its velocity fluctuations are also small. This is due to the increase in flow loss caused by the installation of the LC-nozzle. In addition, the deflection jet adheres to only one end of the nozzle, so the nozzle flow loss is small, and u_c at x = 30.8 mm is almost equal to that of the Pi-jet, and then attenuates. In the expansion jet, the jet adheres to the nozzle wall and expands greatly in the radial direction, so u_c is extremely small near the nozzle exit, and as it flows downward, the jet gathers at the center and becomes somewhat larger.





3.1.5 Cross sectional velocity

Figure 7 shows the results of St-, Def- and Exp-jets at $\alpha = 10^{\circ}$ and $P_0 = 0.38$ MPa. *u* of the Def-jet reaches a minimum value at the center of x = 16.8 and 21.6 mm as with the Pi-jet, as a result of expansion and

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compression of the flow, and then becomes parabolic as it flows down. The velocity of the St- jet was somewhat smaller than that of the Def-jet. Also, both the St-jet and the Def-jet had a larger radial expansion than the Pi-jet. The expansion jet attaches to and expands all around the LC-nozzle wall, resulting in a distribution pattern in which the flow velocity is small near the center of the jet and large around the outer edge, and the maximum flow velocity is extremely small compared to St- and Def- jets. The flow state is completely different from other jets, and the nozzle flow loss is extremely large. The jet width is also larger than that of a straight jet.







3.1.6 Thrust, F

Figure 8 shows the thrust F in the direction of the jet from the LC-nozzle with $\alpha = 10^{\circ}$ at $P_0 = 0.38$ MPa. The thrust F in the direction of the jet was calculated by integrating the cross-sectional velocity distribution at x = 17 mm (just after the LC-nozzle exit) of the jet shown in Fig. 6 around the central axis to calculate the mass flow rate. The temperature of the atmosphere was 20°C, and the air density was 1.18 kg/m³.

$$F = \int_0^\infty \rho u^2 2\pi r dr \tag{1}$$

The thrust F is 3.1, 4.3, and 2.1 [N] for the St-, Def-, and Exp jets, respectively. The F of the St-jet is smaller than that of the Def-jet due to the flow loss of the nozzle, and the F of the Exp-jet is much smaller than the other jets. For example, the F of the Exp-jet is about 56 % of that of the St-jet.

3.2 Thrust vector control by non-movable Coanda nozzle

3.2.1 Flow visualization

Figure 9(a) shows the visualized flow pattern of the FC-jets issued from the FC-nozzle when the all Supipes are opened, 0-close. The supplied pressure is $P_0 = 0.38$ MPa. The jet flows straight to the downstream entraining the surrounding fluid from the Su-pipes. The shock waves can be seen in the jet, and the white and black colored areas from the nozzle exit are the expansion and compression shock waves, respectively.



by Schlieren method (Effect of suction flow, $P_0 = 0.38$ MPa)

3.2.2 Deflection angle, β

Figure 10 shows the relationship between the deflection angle, β , and the number of closed Su-pipe, n_c . β increases with increasing n_c and it takes the maximum of $\beta = 10^\circ$ at $n_c = 6$. In the figure, the results for $P_0 =$ 0.48 MPa are also shown, and both are approximately same. By changing the number and loacation of closing of the Su-pipe the deflection angle and cicumferential position of the jet can be controlled.

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3.2.3 Thrust, *F*

The thrust, F, of the jet was calculated by Eq. (1) under the assumption of the cross section of the jet is approximately circular. Figure 11 shows the thrust, F, of the FC-jet calculated at $x/d_0 = 5.4$ ($s/d_0 = 1.9$) for $P_0 = 0.38$ MPa. F of the 6-closed is smaller than that of the 0-closed because the entrainment from the surroundings of the 6-closed is restricted. On the other hand, F of the 8-closed is larger than that of the 0-closed because this seems to be due to the jet approaching proper expansion. The differences in F when the static pressure is atmospheric pressure and when the measurements are used are ± 6 % for the 0- and 8-closed and ± 29 % for the 6-closed. The large difference of the 6-closed is probably due to the deformation, asymmetry, of the shape of the jet.

4. Conclusions

In this study, we proposed a new method of thrust vector control of supersonic jet using the Coanda effect, namely movable and non-movable systems, which is extremely simpler than conventional methods, and clarified their flow characteristics.

*Movable system: The deflection angle β of the deflection jet varies depending on the nozzle opening angle α , and when the supply pressure $P_0 = 0.38$ MPa, $\alpha = 10^\circ$ and the maximum deflection angle $\beta = 6^\circ$.

*Non-movable system: The deflection angle β of the jet from the FC-nozzle at a supply pressure of $P_0 = 0.38$ MPa is a maximum of $\beta = 10^{\circ}$ when all six suction tubes are closed. This corresponds to opening angle of the Coanda nozzle. The thrust *F* of the jet from the FC-nozzle at $P_0 = 0.38$ MPa is a maximum of F = 5.0 [N] when all suction tubes are closed. This is greater than that from a pipe nozzle.

In this case, the non-movable system is superior than the movable system in terms of its simplicity and the deflection and attachment characteristics of the jet.

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