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Vector Control of Two-dimensional Turbulent

Free Jet by One-side Flap*

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This paper presents an experimental investigation of the deflection angle and the characteristics of a two-dimensional turbulent free jet issued into a still air after deflected by a one-side flap. The flap was fitted up at the lower edge of a rectangular nozzle of aspect ratio 10. The center flow of the jet was confirmed to be two-dimensional. The velocity and static pressure distributions and the lines of the maximum velocity were measured for various flap widths and flap angles. It was found that the deflection angle of a jet is equal to the flap angle when the flap width exceeds 2.5 times the nozzle width and the decay of the maximum velocity and the spread of the deflected jet are different from those of a free jet in the absence of the flap.

1. Introduction

A turbulent two-dimensional free jet issued into a still air has been studied theoretically by Tollmien⁽¹⁾, Reichardt⁽²⁾, and Görtler⁽³⁾, and moreover numerous investigations have been done by Förtmann⁽⁴⁾, Howarth⁽⁵⁾, Albertson, et al.⁽⁶⁾, Kirshner⁽⁷⁾ and others. The results of those studies have been compiled in several books⁽⁸⁾⁻⁽¹¹⁾.

In practical use of a jet, a jet is seldom utilized as it is, but it is often necessary to control the direction of a jet for different purposes, as seen in a jet-flap of the airplane, a VTOL aircraft, dispersion of the agricultural chemicals and the air-conditioning. In spite of this, few investigations on this problem have been hitherto done, whence the vector control is used in practise, with some unknown problems left unsolved.

The vector control of a two-dimensional jet is performed by several methods; for example, using a flap and impinging with an auxiliary jet. Among them the method using a flap is found simple and convenient. This paper describes an experimental study on the vector control of a two-dimensional jet issued into a still air, using a flap fitted up at the lower edge of the nozzle exit. The variations of the deflection angle of a jet with the flap angle and the flap width, and the characteristics of the deflected jet are measured.

Nomenclature

x_1, y_1, z_1 : coordinates with origin O_1 at center of nozzle exit. x_1 is taken along center line of nozzle, y_1 vertically and z_1 horizontally (Fig.1)

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x, y, z : coordinates with origin 0 at downstream distance of flap width from center O_1 of nozzle exit. x is taken along line of maximum velocity; y and z normal to x .

d : width of nozzle exit

t : flap width

α : flap angle

ξ : distance of point on flap surface from flap root

U_0 : velocity at origin 0

U_{01} : velocity at origin O_1

U : velocity in section of jet

U_m : maximum velocity in section of jet

β : deflection angle of line of maximum velocity, measured from x_1 axis

L : length of potential core

b : half width of jet

$b_{1/2}$: half width at which $U=U_m/2$

ρ : density of air

ν : kinematic viscosity of air

p : static pressure, measured from atmospheric pressure

C_p : pressure coefficient $= p/(\rho U_0^2/2)$

Re : Reynolds number $= U_0 d/\nu$

Q : mass rate in section of jet

J : total momentum in section of jet

Fig.1 Nomenclature

2. Apparatus and Procedure of Measurement

A skeleton of the apparatus is shown in Fig.2. The wind produced by a three horse-powered centrifugal-type blower is issued from the contraction nozzle into a still air, passing through the diffuser having five screens with 30 to 50 meshes and through the regulating section. The wooden contraction nozzle is of Jones-Bell⁽¹²⁾ type with 500×50mm rectangular exit of 10 aspect ratio, the contraction ratio in area being 5. The carriage with a Pitot-tube and other probes is movable along the rails on the stand.

Measurements were made for various flap widths in the range from 0.5d to 2.5d and for flap angles from -30° to 45° , using an aluminum flap of 600mm length and 3mm thickness fitted up at the lower edge of the nozzle exit. After the deflection angle of the jet was measured by using a cylindrical yawmeter of 7mm outer diameter with three pressure holes, a Pitot-static tube of 2mm outer diameter was aligned in the direction of the deflected jet to measure the velocities and the static pressures in various sections

Fig.2 Apparatus ① blower, ② diffuser, ③ flap, ④ Pitot-static tube, ⑤ traverse carriage

Fig.3 Two-dimensionality of center flow

from $x/d=0$ to 16.

Since it was already known⁽¹³⁾ that the characteristics of a turbulent free jet is independent of Reynolds number so long as $Re > 1.7 \times 10^4$, measurement was made at Reynolds number of 7.61×10^4 only. However, the Coanda effect on the flap flow was examined at various Reynolds numbers in the range from 0.9×10^4 to 7.6×10^4 .

3. Results and Discussion

3.1 Two-dimensionality of center flow

Although it is difficult, strictly speaking, to realize a two-dimensional free jet, it is well known that if the end plates are fitted up at the sides of a rectangular nozzle of large aspect ratio the flow in the central section will be considered two-dimensional. Moreover, Okamoto, et al⁽¹⁴⁾ have shown that, provided that the downstream distance (x) is less than about $15d$, the flow in the central section of a jet issued from the rectangular nozzle of 10 aspect ratio will be considered two-dimensional over in the absence of the end plates.

The discussion above mentioned is concerned with a free jet in the absence of the flap, hence it is necessary to examine the two-dimensionality of the center flow of the jet deflected by the flap. The velocity and static pressure profiles in the horizontal plane ($y=0$) in the case of $t/d=2$ and $\alpha=30^\circ$ are shown in Fig.3, from which it will be seen that the two-dimensionality in the center flow of the deflected jet is also confirmed provided that x/d is less than 16.

For this reason, in this experiment the measured sections were limited to the range of $x/d < 16$ and the end plates were removed for the sake of convenience of observation except in the case of large flap angles.

3.2 Distributions of velocities and static pressures

Figs.4 and 5 show the variations in the velocity and static-pressure distributions across the nozzle exit with the flap angle in the case of $t/d=2.0$ and

Fig.4 Velocity and static pressure profiles across nozzle exit. ($t/d=2.0$)

with the flap width in the case of $\alpha=+15^\circ$ respectively. It is found that the velocity distribution across the nozzle exit is almost invariable with the flap width, while it varies remarkably with the flap angle.

Although the velocity distribution across the nozzle exit is not uniform, it becomes uniform in the section of the flap edge (Fig. 6). The velocity and static pressure profiles in the sections downstream of the flap edge are shown in Figs. 7 and 8, comparing with the theoretical values by Tollmien, Görtler and Albertson, et al.

Although the velocity profile is asym-

metrical for small values of x/d , it becomes symmetrical gradually with an increasing downstream distance. The velocity profile at $x/d=10$, which is seen to be the beginning position of the similar profile region, is in good agreement with Görtler's theoretical value, as shown in Fig. 7 for the case of $t/d=2.0$ and $\alpha=+30^\circ$. However, in the case of $\alpha=-15^\circ$ shown in Fig. 8, the symmetrical velocity profile is not yet attained even at $x/d=16$. In both figures the low pressure occurring at the free-boundary side opposite to the flap seems to be due to the vortices generated in that region.

Fig.5 Velocity and static pressure profiles across nozzle exit ($\alpha=15^\circ$)

Fig.6 Velocity and static pressure profiles in section of flap edge ($t/d=2.0$)

Fig.7 Velocity and static pressure profiles in sections of jet ($t/d=2.0$, $\alpha=30^\circ$)

Fig.8 Velocity and static pressure profiles in sections of jet ($t/d=2.0$, $\alpha=-15^\circ$)

The length L of the potential core is almost independent of the flap angle, while it decreases with an increasing flap width in the range for which t/d is less than 2.5, as shown in Figs.9 and 10, and the value of L/d for $t/d=2.5$ is 3.60.

3.3 Deflection angle of line of maximum velocity

The variations of the line of the maximum velocity, which is obtained by connecting the points of the maximum velocity in any section of a jet, are shown in Fig.11, from which it is found that the line of the maximum velocity is a straight line after deflection and is invariable with Reynolds number if Re is greater than 1.7×10^4 . In this figure the broken line is a line parallel to the flap surface from the origin O_1 .

The deflection angle of a jet is defined by the angle of the line of the maximum velocity measured from the x_1 axis. Fig. 12 shows the variation of the deflection angle β with the flap angle α . If the flap angle is positive, the deflection angle increases with an increasing flap angle and the flap width in the range for which t/d is less than 2.5.

Fig.9 Variation of length of potential core with flap angle

Fig.10 Variation of length of potential core with flap width

Fig.11 Line of maximum velocity

Even if the flap angle is negative, a jet is deflected owing to the Coanda effect. However, if the flap angle increases over a critical value (i.e. critical flap angle, say), the flow separates from the flap surface, hence the jet is not deflected.

In order to visualize the flow over the flap, the movements of threads of 8mm length stuck on the flap surface were photographed. Fig.13 illustrates the photographs in the case of $t/d=2.0$ in which the critical flap angle was -25° , the upper photo showing a smooth flow in the case of $\alpha=-15^\circ$ and the lower are a separated flow in the case of $\alpha=-30^\circ$.

Since the Coanda effect is expected to be dependent on Reynolds number, the variation of the critical flap angle with Rey-

Fig.12 Variation of deflection angle (β) with flap angle (α)

Fig.13 Visualization of flow over flap surface by tuft method ($Re=7.6 \times 10^4$)

nolds number in the case of $t/d=1.0$ was examined. Fig.14 shows that the critical flap angle decreases with an increasing Reynolds number and ceases to decrease at Reynolds number 2.4×10^4 , and it is found from Fig.15 that the critical flap angle increases with an increasing flap width.

3.4 Pressure on flap surface

Fig.16 shows the pressure distribution on the flap surface for $t/d=2.0$. In the case of positive flap angle, the value of the pressure coefficient almost vanishes at the flap edge and increases toward the flap root, near which it decreases because of generation of the vortices at the corner, as shown in Fig.17.

For comparison, the surface pressure was calculated by the potential-flow theory

Fig.14 Variation of critical flap angle with Reynolds number ($t/d=1.0$)

Fig.15 Variation of critical flap angle with flap width ($Re=7.61 \times 10^4$)

of the corner flow (Fig.18). The complex potential of the corner flow is $w=U_\infty Z^{\pi/\theta}$, where $Z=x+iy$ and $\theta=\pi-\alpha$. The complex velocity is

$$dw/dZ=U_\infty(\pi/\theta)Z^{\pi/\theta-1}$$

and the pressure coefficient becomes

$$C_p=(p-p_\infty)/(\frac{1}{2}\rho U_\infty^2)=1-|dw/dZ|^2/U_\infty^2$$

The pressure coefficient on the inclined surface ($Z=\xi e^{i\alpha}$) is

$$C_p=1-(\pi/\theta)^2 \xi^{2(\pi/\theta-1)} \dots (1)$$

Writing the point at which C_p vanishes as ξ_0 , we have

$$C_p=(\pi/\theta)^2 \xi_0^{2(\pi/\theta-1)} (1-(\xi/\xi_0)^{2(\pi/\theta-1)}) \dots (2)$$

From Fig.16, it is found that $\xi_0=t$. The calculated results, which are indicated by the

Fig.16 Comparison of measured pressure on flap surface with calculated value ($t/d=2.0$)

Fig.17 Visualization of flow over flap surface by aluminum powder method in water tank ($t/d=2.0$, $\alpha=30^\circ$, $Re=1.94 \times 10^4$)

broken line in Fig.16, are in good agreement with the measured results, except in the case of negative or large positive flap angles.

3.5 Decay of maximum velocity

The length of the potential core, which is 5.2d for the free jet without flap, is remarkably shortened by deflection of a jet. In consequence a decay of the maximum velocity of the deflected jet occurs earlier than with a free jet without a flap, as shown in Fig.19.

The decay of the maximum velocity in the similar profile region ($x/d > 10$) is expressed as

$$U_m/U_0 \propto (x/d)^{-n}$$

and the value of n for the free jet without a flap is in good agreement with Tollmien's

Fig.18 Corner flow in Gaussian plane

Fig.19 Decay of maximum velocity

Fig.20 Values of n in decay formula

theoretical value $n=0.5$. Fig.20 shows that the value of n for the deflected jet increases with an increasing flap angle and decreases with an increasing flap width in the range for which t/d is less than 2.5.

3.6 Spread of jet

Figs.21 and 22 illustrate the variations of the spread of half the width $b_{1/2}$ with the flap angle in the case of $t/d=2.0$ and with the flap width in the case of $\alpha=15^\circ$ respectively. In both cases, the curve of spread is

a straight line in the range for which x/d is greater than 8.0 and the spread of the deflected jet is greater than that of the free jet without a flap.

The spread of half the width $b_{1/2}$ in the similar profile region is expressed as

$$b_{1/2} = a(x - S)$$

where S is the position of the virtual origin. The values of a and S/d are shown in Fig.23, from which it is found that the value of a for the deflected jet is greater than

Fig.21 Spread of half width at half depth ($t/d=2.0$)

Fig.22 Spread of half width at half depth ($\alpha=15^\circ$)

(a) Variations of value of a

(b) Variations of value of virtual origin

Fig.23

that for the free jet without a flap ($\alpha = 0.094$) and is almost independent of the flap angle in the range for which α is less than 20° , while it increases with an increasing flap width.

The value of S/d for the deflected jet is greater than that for the free jet without a flap ($S/d=0.55$) and increases with an increasing flap width and an increasing flap angle in the range for which α is less than 20° , but for the flap angles beyond 20° it decreases conversely with an increasing flap angle. It seems that the values of α and S/d remain constant for t/d beyond 2.5.

3.7 Mass rate and total momentum

The mass rate in any section of a jet is expressed as

$$Q = \rho \int_{-b}^b U dy$$

Let Q_0 denote the mass rate in the section of the flap edge ($x=0$). Figs. 24 and 25 show the variations of Q/Q_0 with the flap angle in the case of $t/d=2.0$ and with the flap width in the case of $\alpha=15^\circ$ respectively. It is found from those figures that the value of Q/Q_0 increases linearly with an increasing downstream distance and the slope of its curve is greater than that of the free jet without a flap. The value of Q/Q_0 is almost independent of the flap angle, while it increases with an increasing flap width. The mass rates for the flap widths in the range from $t/d=0$ to 2.0 are empirically expressed as

Fig. 24 Variations of mass rate and total momentum ($t/d=2.0$)

Fig. 25 Variations of mass rate and total momentum ($\alpha=15^\circ$)

$$Q/Q_0 = 1 + \{0.085 + 0.021(t/d)\}(x/d)$$

The total momentum in any section of a jet is expressed as

$$J = \rho \int_{-b}^b U^2 dy + \int_{-b}^b p dy$$

Let J_0 denote the total momentum in the section of the flap edge ($x=0$). The values of J/J_0 are almost constant and equal to unity over the downstream distances, as shown in Fig. 25, which confirms conservation of the total momentum for the deflected jet.

4. Conclusions

The results of this study are summarized as follows:

- (1) The deflection angle of the jet increases with an increasing flap angle and an increasing flap width. When the flap width is 2.5 times the nozzle width, the deflection angle is equal to the flap angle.
- (2) Even when the flap angle is negative, the jet can be deflected owing to the Coanda effect. There exists a critical value of the flap angle at which the Coanda effect appears. The jet can not be deflected if the flap angle is larger than the critical value. The critical flap angle increases with an increasing flap width and with a decreasing Reynolds number.
- (3) The length of the potential core of the deflected jet is smaller than that of the free jet without a flap. It is almost independent of the flap angle, while it decreases with an increasing flap width.
- (4) The decay of the maximum velocity of the deflected jet takes place earlier than with the free jet without a flap.
- (5) The spread of the deflected jet is greater than that of the free jet without a flap.
- (6) The mass rate in any section of the deflected jet is greater than that of a free jet without a flap. It is almost independent of the flap angle, while it increases with an increasing flap width.

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