533.69.01:532.527

Paper No. 151-14

Decay and Modification of Trailing Vortex*

By Shuji TANAKA^{**}, Makoto KAIBARA^{***} and Akifumi TANAKA^{****}

Some experiments of decay and modification of a trailing vortex, which is shed from the tip of a lifting wing are described. Flow fields of the trailing vortex are shown and the effects of the air jet injection from the wing-tip on the attenuation of the disturbances caused by the trailing vortex are discussed.

When the air jet is not injected, changes in the flow fields near the trailing vortex in the flow direction are quite small and the total circulation and the disturbances due to the trailing vortex such as the large circumferential velocity, defects in the axial velocity and the static pressure are maintained in the region far downstream of the wing.

When the air jet is injected, vortex filaments are distributed over a wide region and the disturbances can be suppressed to small quantities. The turbulence caused by the trailing vortex increases with the distance from the wing when the air jet is not used, but the jet injection has an effect to attenuate the turbulence.

1. Introduction

A number of studies of a trailing vortex, which is shed from the tip of a lifting wing have been done, and most of them have dealt with the distribution of the circulations on a three-dimensional wing or the method of the correction of the boundary effect for the wind tunnel testing.

In recent years, however, the trailing vortex shed from a preceding aircraft has come to present a hazard to the following one with the advent of huge jet transports and overcrowded use of an airport. Then the studies of a trailing vortex began to attract new attention from a view point of "wake turbulence." Concerning the situation, analyses of the flow field near the trailing vortex(1) or the stability of pair line vortices have been made(2)(3), but most of them have treated only the natural decay of the trailing vortex. Vortex shedding from a lifting wing with a finite span is essentially inevitable, and some steps to modify the trailing vortex must be taken in order to attenuate the wake turbulence. Some methods to modify the trailing vortex have been examined(4), but the results seem to be somewhat insufficient for a practical use.

In the present paper, the flow field, the aerodynamic performance and the turbulence with or without the wing-tip jet injection are shown and the effects of the wing-tip jet on the modification of the trailing vortex are discussed.

Symbols

ϕ	; axial velocity coefficient $=v_x/U$
χ	; circumferential velocity coefficient $=v_\theta/U$
v_x, v_θ	; axial and circumferential velocity components
U	; main flow velocity
$\bar{\Gamma}$	; normalized circulation $=\Gamma/(Uc)$
$\bar{j}$	; normalized mass flow rate of wing tip jet $=G/\rho g U c^2$
$\bar{\omega}_z$	; normalized vorticity $=\omega_z/(U/c)$
$\bar{P}_s$	; normalized static pressure $=P_s/(\rho U^2/2)$
Γ	; circulation
c	; chord length
G	; mass flow rate of wing-tip jet
P_s	; static pressure
ω_z	; z-component of vorticity
ρ	; air density
g	; acceleration of gravity
l	; distance from a trailing edge of a wing
r	; radius measured from the center of a trailing vortex
y	; distance measured along a wing span from the center of a vortex
α	; angle of attack
c_L	; lift coefficient
c_D	; drag coefficient
T	; turbulence

2. Experimental apparatus and procedure

A scheme of the test rig is shown in Fig.1. The wind tunnel used is an open-circuit type with an axial-flow blower of 900mm in diameter, a settling chamber of 5.5m in length and a contraction① of which contraction ratio is 5.3. The test section is 600×450mm and the flow velocity is about 21m/s with a turbulence of 0.15%. The test section② is made of clear acrylate plates, in which the flow fields of the trailing vortex are measured.

* Received 31st April, 1975.

** Research assistant, Faculty of engineering, Osaka Univ., Suita.

*** Engineer, Matsushita Electric Ind. Co.

**** Engineer, Nihon Steel Co.

Fig.1 Scheme of test rig

The test wing and the tip configurations are illustrated in Fig.2. The test wing is 70mm in chord, 280mm in span (NACA 0012-64), in which a channel for the wing-tip jet of 45X3mm is contained. The jet is supplied from another end through the wall of the test section. In the tests, two types of tip configurations, A and B type, are used; for type A the jet is injected in the direction perpendicular to the wing span and the chord, and for type B it is parallel to the wing span as shown in Fig.2. The jet is supplied from the eddy blower (4) and controlled by the valves (5) (6), of which mass flow rate is obtained with stagnation pressure tube (9) and static pressure taps (8) using pressure transducer (12), strain meter (13) and volt meter (14). The density of jet is obtained with the thermometer (7) and pressure taps (8).

The flow fields near the trailing vortex are measured with an arrow-head type yaw meter which is made of tubes of 1mm in diameter.

The co-ordinate system (r, θ, z) is chosen such that the z -direction coincides with the center line of the trailing vortex (see Fig.3). In general, the flow fields of the trailing vortex are three-dimensional, but the radial velocity component v_r is small enough in comparison with the axial and circumferential velocity components, v_z and v_θ , the flow fields are determined as two-dimensional flow. The yaw meter is travers-

Fig.3 Co-ordinate system

Fig.2 Test wing and wing-tip configurations

ed in the direction parallel to the wing span through the center of the trailing vortex, and pressures are measured with Betz type manometer.

The aerodynamic performance is determined in the following manner. The test wing is supported as a cantilever with bearings (11) through a flexible tube (10), then lift and drag forces are measured with strain gauge.

The turbulence of the flow field is measured with an anemometer and recorded with an electro-magnetic oscillograph. The tests are made at the Reynolds' number based on U and c of 1×10^5 .

3. Experimental results and discussions

3.1 Natural decay of the trailing vortex

The flow field of the trailing vortex without the jet injection was examined. The most hazardous disturbance caused by the trailing vortex was the circumferential velocity component, v_θ . The distribution of χ is given in Fig.4. The vortex filaments shed from the wing rapidly rolled up to Rankine-type vortex within the distance of 2 chord-lengths downstream of the

Fig.4 Distribution of circumferential velocity component

trailing edge. The maximum value of χ decreased and the core radius gradually increased with the distance from the wing, but the change in flow fields was quite small. The relations between χ and α are illustrated in Fig.5, which shows that the circumferential velocity component rapidly increases with the angle of attack.

Fig.6 illustrates the distribution of ϕ , which indicates that the axial velocity in the core of the vortex becomes as small as $0.8U$ and the change in ϕ in the flow direction is quite small.

Next, the circulation of the flow field of the trailing vortex will be discussed. Assuming that the flow fields near the vortex are axisymmetric and denoting the vorticity component of z -direction as ω_z , we can write the circulation around the circle of radius r , which is in the plane perpendicular to z -direction, as follows.

$$\Gamma = 2\pi \int_0^r \omega_z r dr$$

The distribution of $\bar{\Gamma}$ is given in Fig.7, which indicates the flow field is not perfectly axisymmetric but the distribution of $\bar{\Gamma}$ in the wing side ($y > 0$) is somewhat different from that in the space side ($y < 0$). But the shapes of the distributions of $\bar{\Gamma}$ are almost similar at any distance from the wing, and $\bar{\Gamma}$ reaches the same value as the radius increases. From the wing theory of a finite span, the asymptotic value coincides with the maximum circulation around the mid-span (in the case, mid-span means the supported side of the wing), and it can be concluded that the circulation shed from the wing is maintained without experiencing a noticeable natural decay.

As described above, the changes in the flow field of the trailing vortex are quite small and the disturbances are maintained in the region far downstream of the wing.

3.2 Modification of the trailing vortex

The effects of wing-tip configuration on the attenuation of the disturbances are shown in Fig.8. Almost the same effect can be expected for every configuration but the availability is somewhat favorable for the cases of $A=0.5$ and $A=1.0$. According to the experimental data of ϕ , the defects in the axial velocity component for $A=0.5$ and $A=1.0$ are smaller than those for the others.

Fig.8 Influences of wing-tip configuration on attenuation effect

Fig.5 Relations between circumferential velocity component and angle of attack

Fig.6 Distribution of axial velocity components

Fig.7 Distribution of circulations in flow field

In addition, from the view point of the power required for the jet, the area of nozzle must be chosen as large as possible, therefore the configuration of $A=1.0$ was used in the following tests.

Fig.9 Effects of mass flow rate of jet on circumferential velocity

The effects of the mass flow rate of the jet on the modification of the trailing vortex are illustrated in Fig.9, which shows that the circumferential velocity component rapidly decreases with an increase in the jet. Almost the same results can be obtained in the tests at any other angle of attack. The results shown in Figs.8 and 9 imply that the most important factor for the modification of the trailing vortex with the wing-tip jet is not the momentum rate but the mass flow rate of the jet.

The effect of $\bar{J}$ on the axial velocity component, ϕ , are given in Fig.10, where the defect in ϕ in the core region decreases with $\bar{J}$, and ϕ in the core region recovers to almost $0.95U$ for $\bar{J}=0.04$.

The relations between the maximum circumferential velocity, $\chi_{\max}$, and $\bar{J}$ are shown in Fig.11. The attenuation effects of the wing-tip jet are remarkable especially at high angles of attack, but the effects seem to have a tendency to saturate at every angle of attack. The maximum defect in the axial velocity component, $1-\phi_{\min}$, has the same tendency to saturate for $\bar{J} > 0.05$ as shown in Fig.12. The static pressure distributions are illustrated in Fig.13, from which it is seen that the wing-tip jet makes the static pressure field quite uniform, and the disturbances of the static pressure are negligible when the wing-tip jet is used.

Next, the mechanism of the modification will be discussed. Fig.14 gives the distribution of the circulations, Γ . In comparison with the case of the natural decay ($\bar{J}=0$), Γ more gradually increases towards the outer region of the vortex core, and the radius at which Γ reaches the asymptotic value becomes large as $\bar{J}$ increases, but the values are almost same in every case. The result implies that the total circulation in the flow field near the trailing vortex is not modified by the wing-tip jet, which may be reasonable from the fact that the jet is injected without a swirl.

Next, the distribution of the vorticities will be shown. In the flow field near the vortex, the radial velocity component can be neglected in comparison with the axial and circumferential velocity components, and the vorticity in z -direction, ω_z , can be written in the form.

$$\omega_z = \frac{1}{r} \frac{\partial(rv_\theta)}{\partial r}$$

Fig.13 Changes in static pressure distributions by jet injection

Fig.10 Effects of mass flow rate of jet on axial velocity

Fig.11 Effects of mass flow rate of jet on maximum circumferential velocity

Fig.12 Effects of mass flow rate of jet on maximum defect in axial velocity

Fig.14 Changes in circulation distributions by jet injection

The vorticity distributions calculated from the velocity fields are shown in Fig.15. In the case of $\bar{J}=0$, a remarkable peak of $\bar{\omega}$, appears in the center of the vortex core, which rapidly decreases towards the outer region, and almost vanishes at $r/c= (0.2 \sim 0.3)$. When the wing-tip jet is used, the vorticity in the core region becomes relatively small and spreads over a wide region. The fact indicates that the vortex filaments are dispersed over a wide region by the wing-tip jet injection. Then, the induced velocity due to the trailing vortex becomes quite small and the disturbances can be suppressed to small quantities. The aerodynamic performances of the wing with or without jet are given in Fig.16. Because of the relatively small Reynolds' number, a stall occurs at about $\alpha = 11\text{deg.}$, but the influence of wing-tip jet cannot be observed at all. As described above, the total circulation is maintained downstream of the wing, then the down-wash velocity induced by the trailing vortex is not modified and the induced drag is not affected by the wing-tip jet injection.

3.3 Measurement of the turbulence

It seems that the wing-tip jet injection is a cause to the turbulence and gives a new disturbance to the flow field, thus the intensity of the turbulence was measured. In the tests, the velocity fluctuation Δv_{rms} in the tangential velocity $v(\equiv \sqrt{v_x^2 + v_y^2})$ was obtained and the turbulence T was given as $T = \Delta v / v \times 100$.

The distribution of T for $\bar{J}=0$ is illustrated in Fig.17. A remarkable peak of the turbulence appears in the core region, and the peak value gradually increases with the distance from the wing. Fig.18 gives the turbulence with the wing-tip jet injection. For small flow rate ($\bar{J}=0.016$), the peak of the turbulence in the core region rapidly decreases, but a large mass flow rate of the wing-tip jet results in a high turbulence level due to the mixing of the jet and the main flow. Then, the change in the peak value of the turbulence, T_0 , in the flow direction is shown in Fig.19. In the case of $\bar{J}=0$, T_0 increases in the flow direction. But when the wing-tip jet is used, the turbulence of a high intensity can be observed only just downstream of the wing, and it rapidly decreases with the distance from the wing.

In order to clarify the fact, the trace of the turbulence was analysed. Figs.20(a) and (b) indicate that the turbulence without the wing-tip jet ($\bar{J}=0$), the fluctuation near the wing ($l/c=8$) rapidly decreases towards the outer region of the vortex core. In the region far downstream of the wing ($l/c=30$), however, another type of fluctuation with a large amplitude and a low frequency appears, which frequently occurs in or near the core.

The results suggest that the fluctuation is caused by an unsteady spacial migration of the velocity field, and such a migration increases with the distance from the wing, thus the turbulence for $\bar{J}=0$ increases in the flow direction as described above. On the other hand, when the wing-tip jet

Fig.15 Changes in vorticity distributions by jet injection

Fig.16 Effects of jet injection on aerodynamic performance of wing

Fig.17 Turbulence of flow field without jet injection

Fig.18 Effects of jet injection on turbulence distribution

Fig.19 Changes in maximum turbulence level by jet injection

Fig.20 Traces of velocity fluctuation

is used, a turbulence of quite high frequency caused by a mixing of the jet with the main flow appears, but the fluctuation of low frequency appearing for $\bar{J}=0$ is not observed at all.

4. Conclusions

The effects of the wing-tip jet injection on the attenuation of the disturbances caused by the trailing vortex are examined and the validity of the results is shown. The results obtained are summarized as follows;

(1) When the wing-tip jet is not injected, the change in the flow field near the trailing vortex in the flow direction is quite small and the circulation shed from the wing is maintained in the region far downstream of the wing.

(2) The disturbances caused by the trailing vortex such as a large circumferential velocity or a defect in the axial velocity can be suppressed by the use of the wing-tip jet injection.

(3) When the wing-tip jet is used, the total circulation of the trailing vortex is not changed but the vortex filaments are spread over a wide region, and the induced disturbances can be suppressed to small quantities.

(4) The turbulence of the flow field near the trailing vortex increases in the flow direction, but the wing-tip jet has the effect to suppress the turbulence.

References

- (1) Batchelor, G.K., J. Fluid Mech., Vol.20, Pt.4(1964-4), p.645.
- (2) Narain, J.P., Phys. Fluids, Vol.16, No.6(1973-6), p.761.
- (3) Crow, S.C., AIAA J., Vol.8, No.12(1970-12), p.2127.
- (4) Jarvinen, P.O., J. Aircraft, Vol.10, No.1(1973-1), p.63.