Effect of Wing Tip Strakes on Wing Lift-Drag Ratio

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The objective is to increase the wing lift-drag ratio by vortex induction method generated with wing tip strakes. Experimental results for a rectangular wing of aspect ratio 5 equipped with wing tip strakes indicated that the flat-plate strake was worse than a strake with dihedral angle and thickness for increasing the wing lift-drag ratio. Strakes cut off at 45 deg were the best at increasing the wing lift-drag ratio, while strakes with $\delta = 0$ deg were the best at improving the ratio. Also, the experimental results for rectangular wings of aspect ratios 5 and 2 equipped with wing tip strakes, relative to the equivalent simple wings (i.e., the spanwise length of strakes have been calculated into a simple wing aspect ratio), demonstrated that, for $C_L = 0.3$–0.9, $\Delta K/K$ was 7–14.4% for wings of $A = 5$ and 9–26.6% for wings of $A = 2$. The addition of strakes is beneficial for any aspect ratio at any speed (or C_L) up to high subsonic speeds.

Nomenclature

A = aspect ratio, $= \ell/\bar{C} = \ell^2/S$
BM = wing bending moment
$\bar{C}$ = mean chord length of wing
C = specific fuel consumption
C_{D_0} = wing drag coefficient
C_D = wing drag coefficient at zero lift
C_{Di} = wing-induced drag coefficient
C_L = wing lift coefficient
$C_{L\max}$ = maximum lift coefficient of wing
C_r = chord length of wing root
C_t = chord length of wing tip
E_1 = endurance of level flight
$\Delta E/E$ = percentage of increment of endurance
G_0 = airplane weight at beginning of level cruising flight
G_1 = airplane weight at end of level cruising flight
K = wing lift-drag ratio, $= C_L/C_D$
K_s = lift-drag ratio of strake wing
$\Delta K/K$ = percentage of increment of lift-drag ratio of the strake wing, $= (K_s - K)/K$
K = vortex drag factor, $= 1/e$
ℓ = wing span
m = lift curve slope of the wing
R = Reynolds number, $= \rho V_\infty \bar{C}/\mu$
R_1 = range of level flight
$\Delta R/R$ = percentage of increment of range
S = wing area
y = spanwise location of wing center of pressure from wing root
α = wing angle of attack
α_s = wing stalling angle of attack
δ = strake angle of incidence relative to tip chord line
η = propeller efficiency
λ = taper ratio, $= C_r/C_t$

Introduction

REDUCING the coefficients of induced drag and pressure drag is the most direct way of improving the induced efficiency of three-dimensional wings. An increase in wing aspect ratio A both reduces C_{Di} and increases the lift curve slope of a three-dimensional wing, thus reducing the two drag coefficients, but it also results in increasing the weight of the wing structure. Different design goals require different wing aspect ratios. If the effective wing aspect ratio is actually increased (by wing tip strakes), the wing lift-drag ratio will be substantially improved without increasing the weight of the wing structure.

Wind-tunnel tests of ARAVA airplane[1] equipped with winglets of the length of a wing chord indicated that $\Delta K/K$ of the airplane ($A \approx 4$–5, $\lambda \approx 2.5$) was about 2.564% at $C_L = 0.75$, 9.2896% at $C_L = 1.02$, and 14.416% at $C_L = 1.14$. If the length or height of the winglet were only 2/3 or 1/3 of a wing chord, $\Delta K/K$ of ARAVA airplane model would be less. Therefore, in order to get a larger $\Delta K/K$, the wing weight increment should be increased. The winglets on the wing tips will also result in less efficient flight maneuvering.

The purpose of the work described in this paper was to obtain the $\Delta K/K$ of rectangular wings of aspect ratios 5, 4, 3, and 2 and unswept tapered wings ($A = 7.066$, $\lambda = 3$; $A = 4.71$, $\lambda = 2$; $A = 2.826$, $\lambda = 1.5$; $A = 2.77$, $\lambda = 2$; and $A = 1.66$, $\lambda = 1.5$). The benefits of wing tip strake wings will be discussed.

Models and Experimental Apparatus

All experiments in this paper were conducted in the closed-jet (diameter of 1.5 m) low-speed wind tunnel at Beijing Institute of Aeronautics and Astronautics at a speed of about 25 m/s. The largest area of all the wing models was 0.2 m^2 and the largest angle of attack used was 26 deg. The largest projected wing area in the direction perpendicular to the freestream was 0.08768 m^2, which was less than 5% of the cross-sectional area (1.76715 m^2) of the wind-tunnel test section. The ratio of largest semispan of the wing model to the radius of the test section of the wind tunnel was 67%, which should also be allowable.

The airfoil sections of all wing models were made of the low-drag airfoil $65_2 - 415$, $a = 0.5$. The root chords of all the models were 0.2 m. Nine wing models were tested: four with rectangular wings and five with unswept tapered wings, as shown in Fig. 1.

Among the five tapered wing models, three strakes of different length, namely 66.667, 100, and 133.33 mm, were used (see Figs. 1e–1i). The dihedral angles of the three strake edges were 47 deg ($\lambda = 3$), 47 deg 20 min ($\lambda = 2$), and 45 deg ($\lambda = 1.5$), and that of the rectangular wing model was 53 deg. (See Figs. 2 and 3). The maximum thickness of the four strakes were 11.7, 11.5, 11.25 and 12.5%, respectively. The strakes were attached to the wing tips in such a way that the wing tip chord line coincided with that of the symmetrical strake. The leading-edge swept angle of all strakes used in this experiment was 75 deg.

Many photographs of strake vortices were taken using smoke streams. The smoke flow experiments were conducted in an elliptical open-jet tunnel at the Beijing Institute of Aero-

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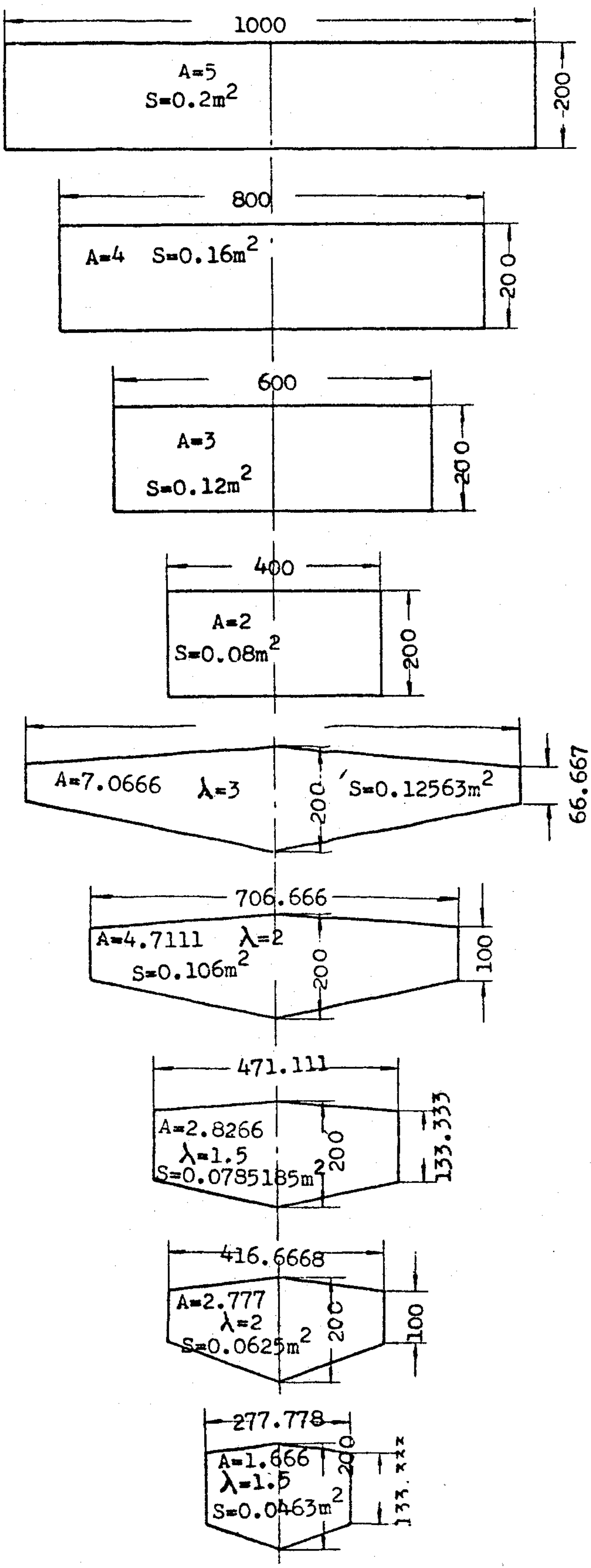


Fig. 1 Wing planforms used in experiments.

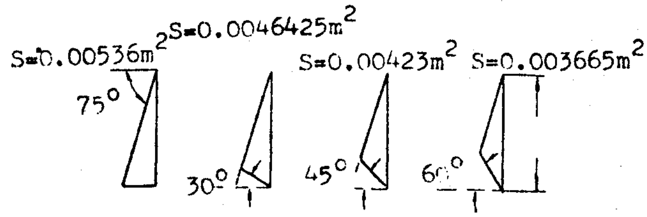


Fig. 2 Wing tip strakes.

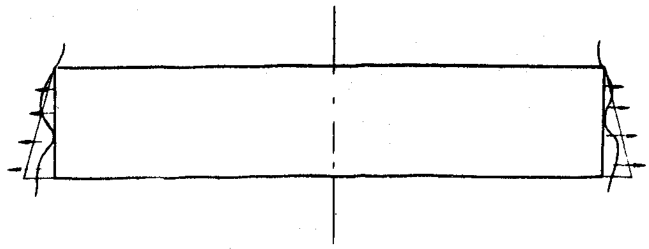
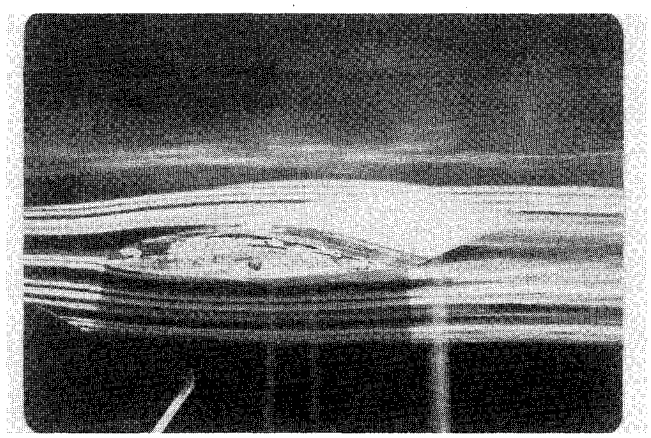
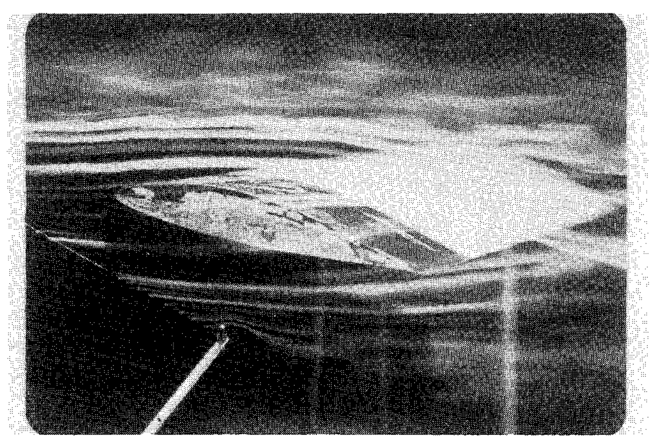


Fig. 3 Strake vortices and sidewash velocities on the upper surface of strakes.



a) $\alpha = 2$ deg



b) $\alpha = 12$ deg

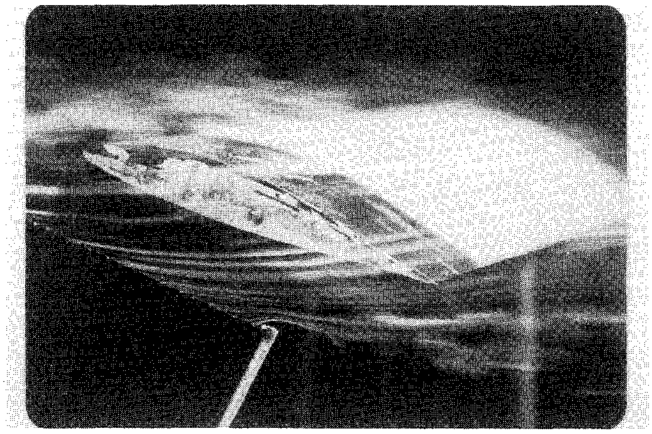
Fig. 4 Streamlines on upper surface of rectangular wing A = 4: a) $\alpha = 2$ deg, b) $\alpha = 12$ deg.

nautics and Astronautics. The smoke flow was obtained through a series of burning points of oil on a straight metal wire close to the wing tip strake. It is not easy to show the strake vortex to be a cone form above the strake upper surface, so a few extra points of oil were added to demonstrate that a clear cone vortex existed above the upper surface of the strake. (See Figs. 5a, 6a, and 6b). The test section wind speed for the smoke tests was 2 m/s.

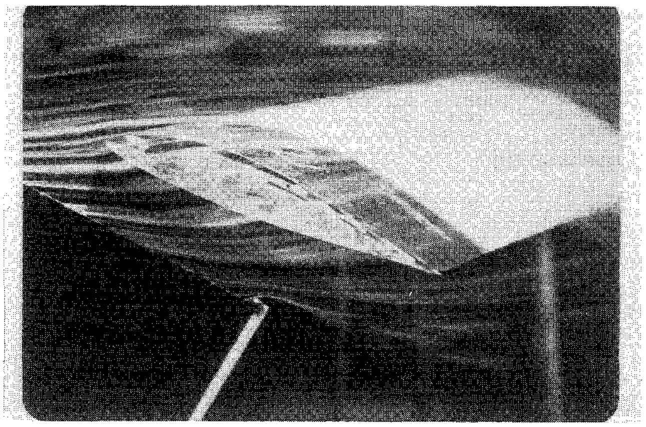
Results of Experiment and Analyses

Experimental Formation of Strake Vortices and its Effect on Flow Pattern on Upper Surfaces of Wing

Smoke flow photographs over a simple rectangular wing model of $A = 4$ at four angles of attack (2, 12, 18, and 22 deg)



c) $\alpha = 18$ deg



d) $\alpha = 22$ deg

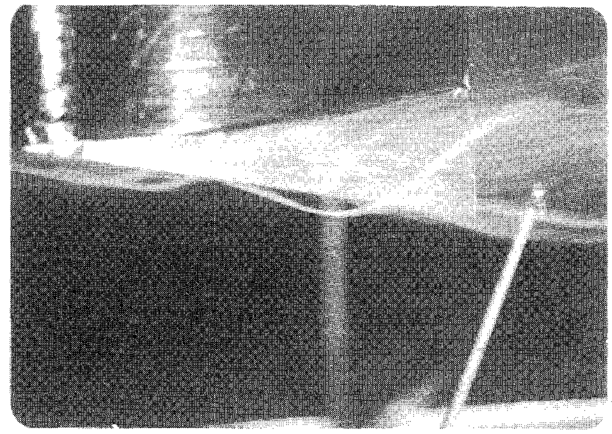
Fig. 4 (con't) Streamlines on upper surface of rectangular wing $A = 4$: c) $\alpha = 18$ deg, d) $\alpha = 22$ deg.

are shown in Fig. 4. The streamlines on the wing model upper surface inclined inward toward the wing root—the larger the α, the greater the inclination of the smoke streamlines. Another six photographs were taken, three for a plate strake of right triangular planform at angles of attack 2, 18, and 22.5 deg (Fig. 5), and three for strakes with a dihedral angle of 53 deg and a planform cut off 45 deg from its bottom edge at angles of attack 15, 18, and 22 deg (Fig. 6). The photographs of the strake vortices were quite clear and visible (see Figs. 5a, 6a, and 6b). The smoke streamlines were nearly straight and trailed downstream on the upper surface near the wing tip strakes (see Figs. 6a and 6b). Comparison with Fig. 4c indicates that the outward sidewash velocity generated by the strake vortices prevented, or partially prevented, the inward flow on the upper surface of the wing. Thus, the wing tip strakes substantially increased the wing aspect ratio and, consequently, the wing lift-drag ratio. All experimental results given hereafter will illustrate these observations.

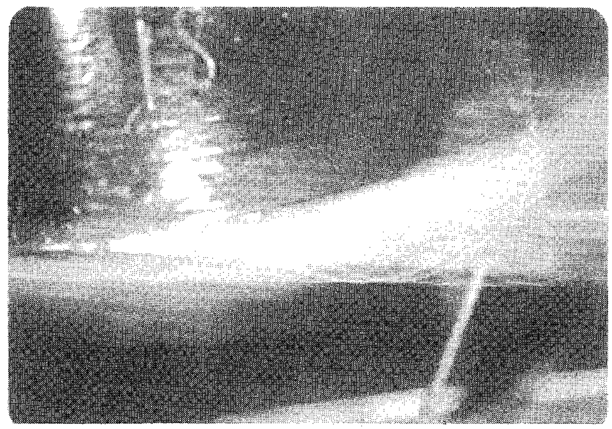
Experimental Results and Analysis of Nine Wing Models

All experimental results noted in this paper have been corrected for wind-tunnel wall influences, including corrections of the angles of attack and lift and drag coefficients.

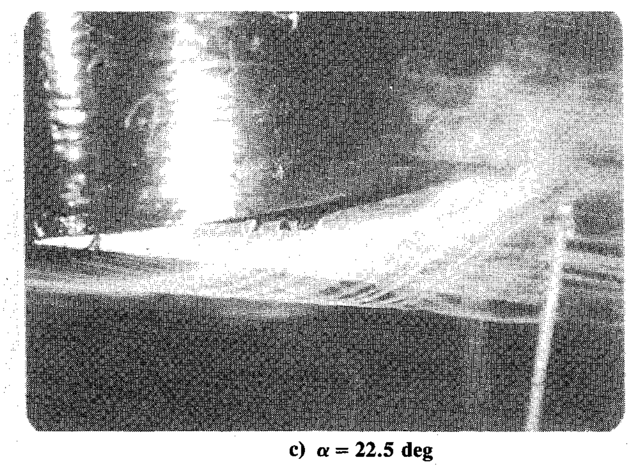
The comparison of experimental results for four rectangular wings of aspect ratio $A = 5$, 4, 3, and 2 with and without the same wing tip strakes are shown in Figs. 7–10, respectively. From these four figures, it is obvious that the lift curve slopes of strake wings are always greater than that of its simple wing and the C_D of the strake wings are always less than those of the simple wings at angles of attack below α_s, so that under same C_L or flight speed the lift-drag ratios K of strake wings are all larger than those of the simple wings, as shown in Figs.



a) $\alpha = 2$ deg



b) $\alpha = 18$ deg

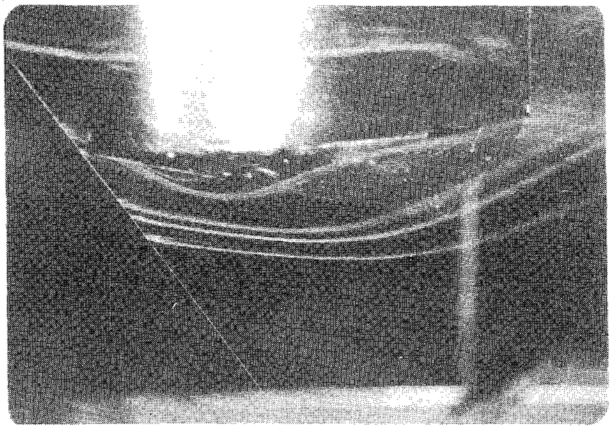


c) $\alpha = 22.5$ deg

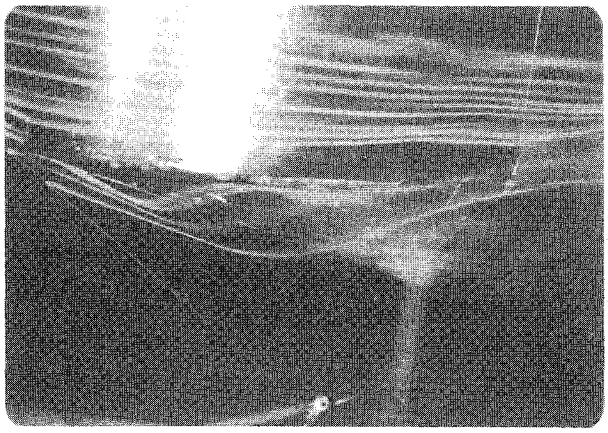
Fig. 5 Cone vortices above plate right triangular strakes: a) $\alpha = 2$ deg, b) $\alpha = 18$ deg, c) $\alpha = 22.5$ deg.

7b and 8–10, respectively. The percentage increment in K of two rectangular wings of same A with and without wing tip strakes is, in general, smaller for a wing of $A = 5$; for wings of $A = 4$, 3, and 2, $\Delta K/K$ is successively larger.

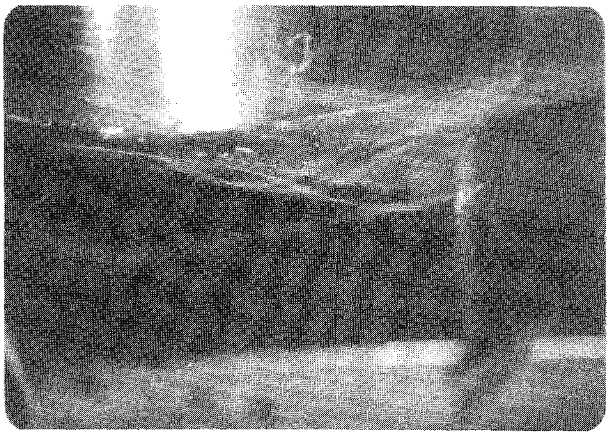
The loss of lift and increments of induced drag and pressure drag of a wing caused by trailing vortices behind the wing exist mainly in regions near the wing tip—the closer to the wing root, the less those influences. Therefore, the average influence of the wing tip and other portions of the wing on the aerodynamic coefficients is smaller for wings of larger aspect ratio. On the other hand, for wings of low aspect ratio, the influence of the wing tip on the aerodynamic coefficients extends almost to the whole span, the average value of the influence of the wing tip on the whole wing are higher, and the



a) $\alpha = 15$ deg



b) $\alpha = 18$ deg



c) $\alpha = 22$ deg

Fig. 6 Cone vortices above strakes of dihedral angle and cutoff at 45 deg: a) $\alpha = 15$ deg, b) $\alpha = 18$ deg, c) $\alpha = 22$ deg.

value of K becomes relatively smaller. The same strake installed on the tips of two wings of different aspect ratio should generate strake vortices of the same strength and exert the same effect on wings of different aspect ratios. But, on the small-aspect-ratio wing, the strake vortices improve the aerodynamic characteristics at nearly all cross sections along the span. Thus, the $(K_s - K)/K$ or $\Delta K/K$ of small-aspect-ratio wings will be much larger than that of large-aspect-ratio wings, since on the latter the average effect of strake vortices on the improvement of aerodynamic characteristics of the whole wing is smaller.

If the taper ratios λ of two different tapered wings are equal, the strength and influence exerted by strake vortices on the wings $(\lambda_1 = \lambda_2, A_1 \neq A_2)$ are same. But, if the aspect ratio

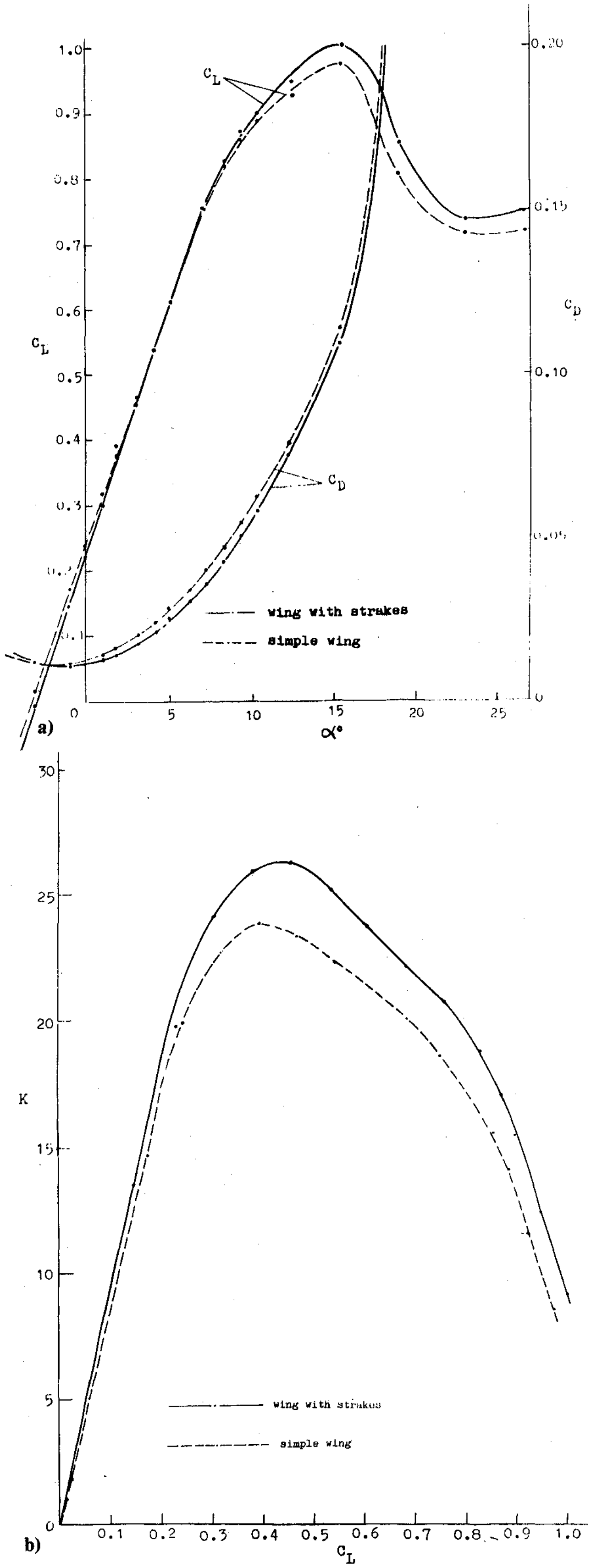


Fig. 7 Comparison of C_L, C_D, and K between rectangular wings ($A = 5$): a) C_L and C_D, b) K.

of two tapered wings are unequal, $\Delta K/K$ is smaller for wing having the larger aspect ratio and larger for wing with the smaller aspect ratio. This conclusion agrees with that for rectangular wings.

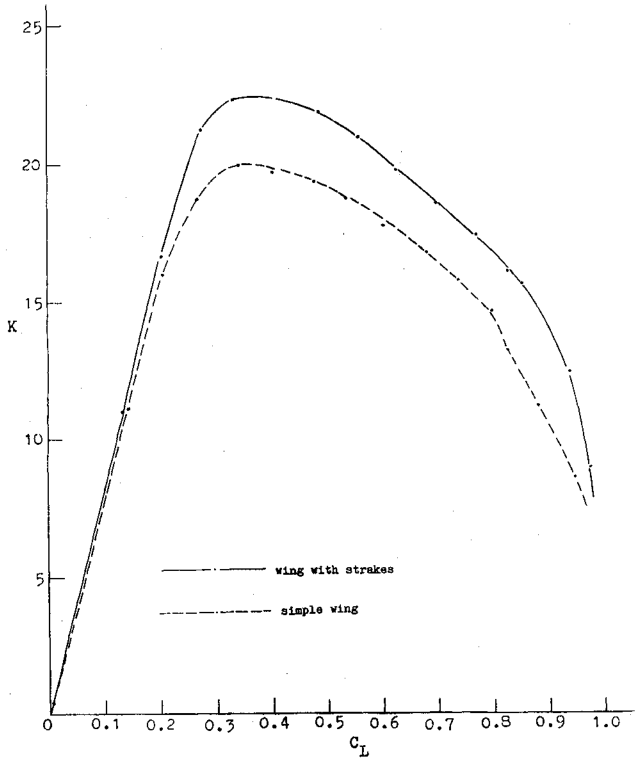


Fig. 8 Comparison of K between rectangular wings ($A = 4$).

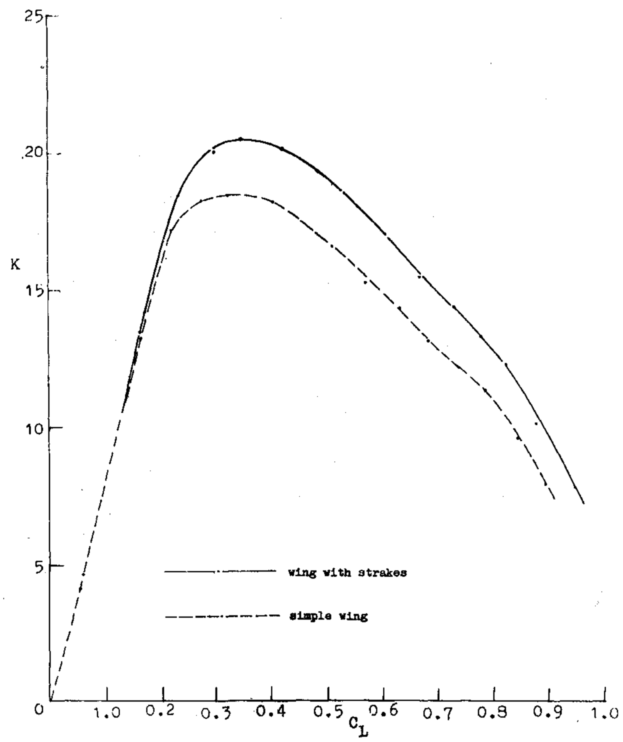


Fig. 9 Comparison of K between rectangular wings ($A = 3$).

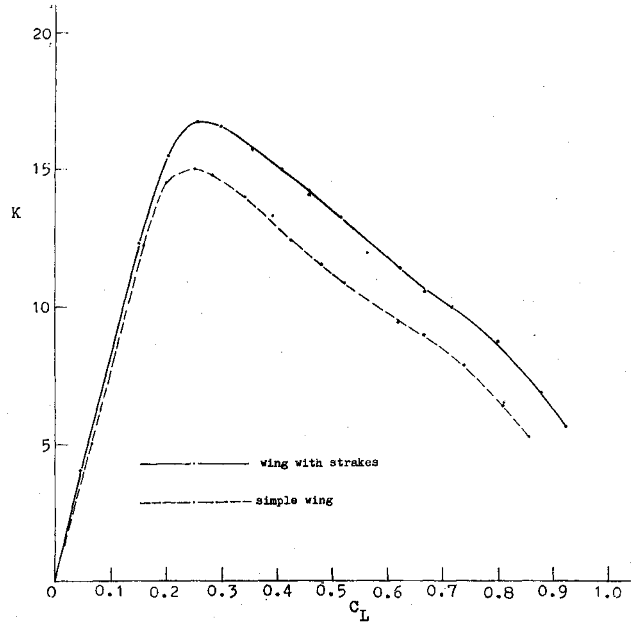


Fig. 10 Comparison of K between rectangular wings ($A = 2$).

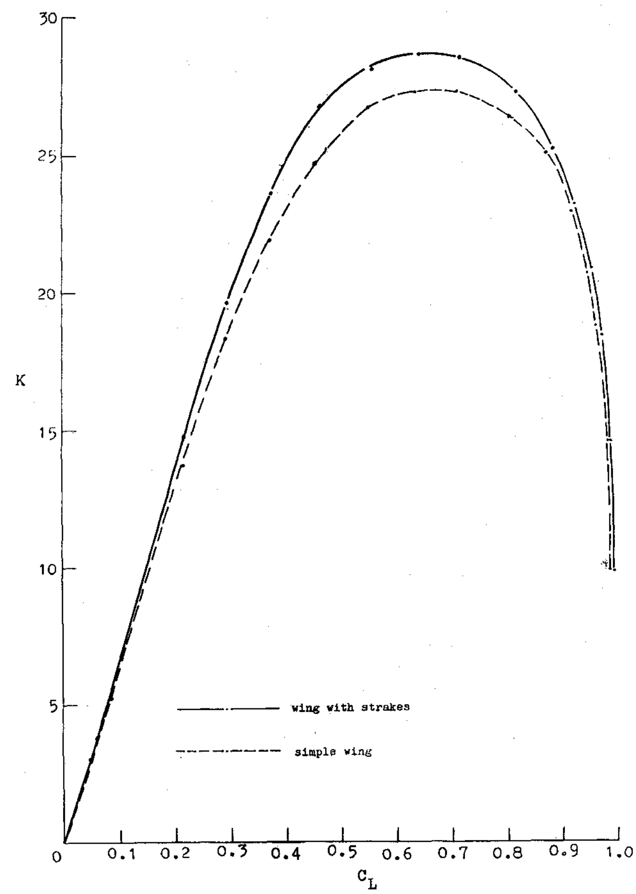


Fig. 11 Comparison of K between tapered wings ($A = 7.066$, $\lambda = 3$).

Figures 7-15 show that, at all C_L (or flight speeds), the lift-drag ratios K of wings with wing tip strakes are always greater than that of a simple wing. Even for a large-aspect-ratio wing flying at high speed (or low C_L), $\Delta K/K$ may approach zero, but never becomes negative. Therefore, wing tip strakes should be of benefit for any wing flying at any speed up to high subsonic.

Discussion

The effect of wing tip strakes on increasing lift-drag ratio is greatest in low-speed flight, such as landing and takeoff or low-speed maneuvering. It also contributes in cruise flight for which the endurance is proportional to K of the airplane and for flight of transports for which the range is also proportional to K, i.e.

$$E_1 = \frac{\eta}{C} K \ln \frac{G_0}{G_1} \quad (1)$$

$$R_1 = \eta \frac{V}{C} K \ln \frac{G_0}{G_1} \quad (2)$$

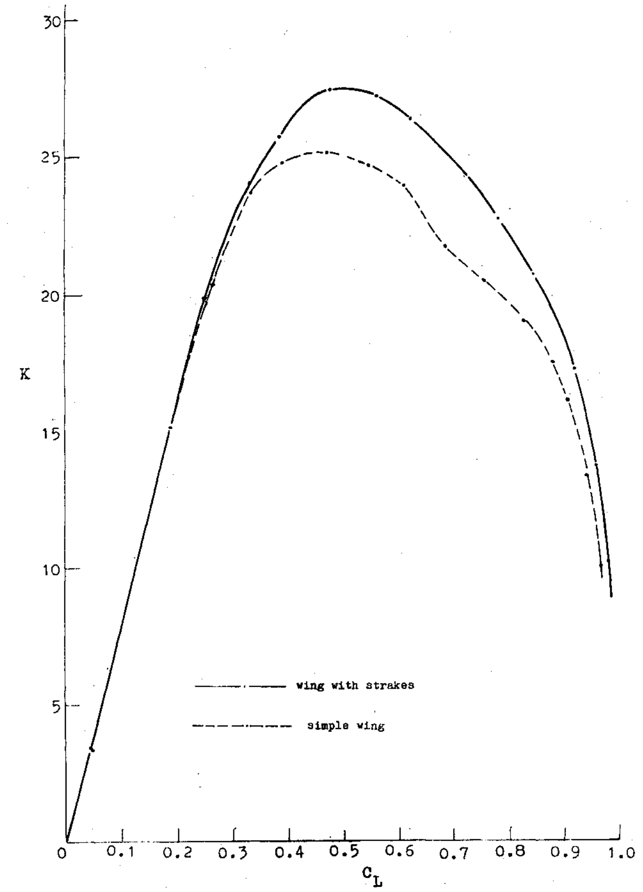


Fig. 12 Comparison of K between tapered wings ($A = 4.711$, $\lambda = 2$).

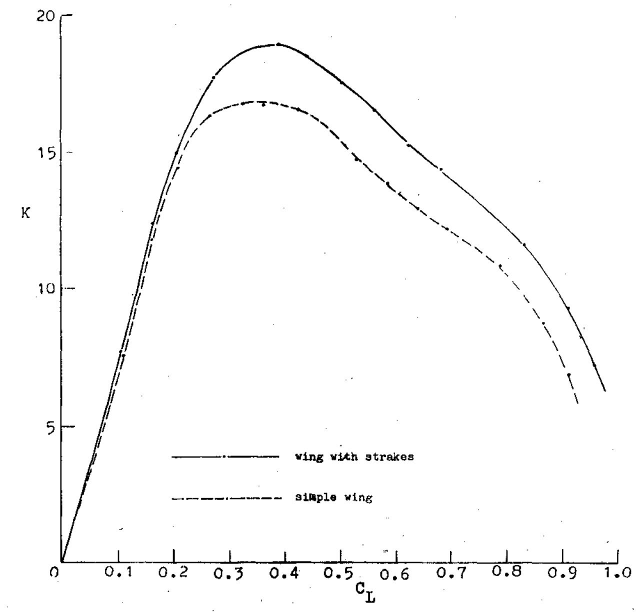


Fig. 13 Comparison of K between tapered wings ($A = 2.827$, $\lambda = 1.5$).

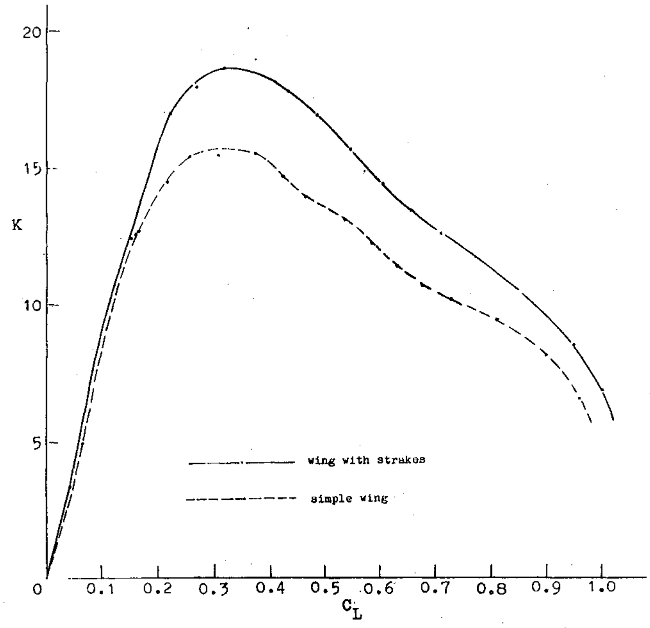


Fig. 14 Comparison of K between tapered wings ($A = 2.778$, $\lambda = 2$).

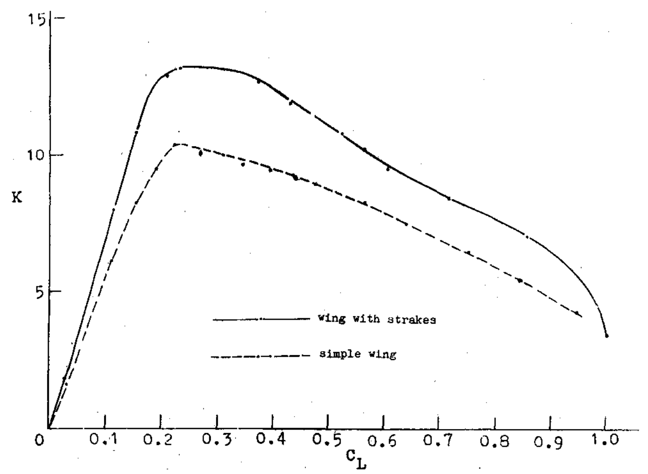


Fig. 15 Comparison of K between tapered wings ($A = 1.667$, $\lambda = 1.5$).

The object of this paper is to improve the performance of fighters and the economics of transports, both of which require higher values of K and lower values of the weight fraction. Under the condition of constant C_L for level steady flight, the weight increment of the wing structure should be due only to the wing bending moment increment caused by the outward movement of the wing center of pressure. A relation between vortex drag factor $K'(=1/e)$ and spanwise location of wing center of pressure from wing root ($y/\ell/2$) is given in Ref. 2 as

$$K' = 1 + \left(\frac{75\pi^2}{16}\right)\left(\frac{y}{\ell/2} - \frac{4}{3\pi}\right)^2 \tag{3}$$

From the principles of structural mechanics, the percentage of increment in the weight of the wing bending moment material should be same as the value of $\Delta BM/BM$. Also, based upon the airplane's weight estimation, the weight of the wing bending moment material to the weight of the whole wing is about 40% and the ratio of wing weight to the weight of the whole airplane is about 27%.

The percentage increments in range or endurance for an airplane with rectangular wings of aspect ratios 5 and 2 having wing tip strakes with respect to that without strakes have been calculated. G_0/G_1 is taken as $9018.6/6500 = 1.387$, the average value of various data of civil transports, namely, 1.37716, 1.377, 1.387, and 1.4888, from the 1964 McDonnell Aircraft Handbook. At low-speed maneuvering or takeoff, the $\Delta K/K$ are 8.65 and 16% for the airplane having wings of aspect ratios 5 and 2, respectively.

The maximum $\Delta E/E$ or economy of specific fuel consumption are 8.11 and 15.15% for cruise with rectangular wings of aspect ratios 5 and 2, respectively.

Table 1 Comparison of $\Delta K/K$ between a wing with winglet and a strake, %

C_L	Tapered wing with winglet $A \approx 4$–5, $\lambda \approx 2.5$ (Ref. 1)	Tapered wing with wing tip strakes, $A = 4.711$, $\lambda = 2$
0.75	4.273	14.67
0.80	6.25	12.31
0.85	8.1667	10.546
0.90	10.10	11.998

It is difficult to compare $\Delta K/K$ of the wing with strakes in this report to that with winglets in Ref. 1, due to the fact that the planform A and λ of the two wings are not exactly same. A rough comparison can be made to illustrate the effect of wing tip strakes and winglets on increasing wing lift-drag ratios. In Table 1, a comparison of $\Delta K/K$ is listed for wings with winglets and wing tip strakes. It indicates that for normal C_L the effect of a wing tip strake on increasing $\Delta K/K$ is larger than that of a winglet.

Conclusions

In this paper, the wing tip strakes generated cone vortices rotating in opposite directions over the upper surface of strakes at $\alpha > 2$ deg. The induced velocities of these vortices resulted in sidewashes at strakes on the upper surface of the wing, which resisted the normal inward flow velocities on the upper surface. So, on the upper surface, the suction pressure will not be reduced, or reduced only partially, with respect to that of a two-dimensional wing. It is obvious that wing tip strakes increase the lift on the upper surface, but have little effect on the lower surface. Therefore, the lift and lift curve slope m of the whole wing increase. As the wing aspect ratio is substantially increased with the wing tip strakes, the wing-induced drag should be decreased. For a certain required lift coefficient C_L, a wing of high lift curve slope needs a smaller angle of attack; consequently, it has a lower value of pressure drag. Hence, the wing lift-drag ratio should be increased by wing tip strakes. In this report, the percentage of increment of K ($\Delta K/K$) of a wing with strakes relative to the equivalent simple wing was 7% at $C_L = 0.3$ and 14.4% at $C_L = 0.9$ for a rectangular wing of aspect ratio 5. It was 9% at $C_L = 0.3$ and 26.7% at $C_L = 0.85$ for a rectangular wing of aspect ratio 2. Finally, under consideration of the structural weight increment of the whole airplane by wing tip strakes, the maximum $\Delta R/R$ was 8.11 and 15.2% for transport airplanes having rectangular wings of aspect ratios 5 and 2, respectively.

References

[1] Darel, I., Eliraz, Y., and Barnett, Y., "Winglets Development at Israel Aircraft Industries," ICAS, Paper 80-1.2.5, 1980.

[2] Garner, H.C., "Some Remarks on Vortex Drag and its Spanwise Distribution in Incompressible Flow," *Journal of the Royal Aeronautical Society,* July 1968, p. 623.