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On the Characteristics of a Wing with a Tip Clearance*

(Part 5, An Experimental Study on the Effect of End-Wall Boundary Layers)

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Aerodynamic effects of the thickness of a boundary layer (δ_s) developed on an end wall facing a wing tip, the size of a tip clearance (s) and the angle of attack (α) on the lift and drag of a wing in a low-velocity flow are considered, and the correlations between local or total lifts and drags are discussed. Variations of the spanwise lift depend merely on s under introduction of a dimensionless parameter, which includes a retained lift determined experimentally at the wing tip. Variations of the spanwise drag coefficient (c_D) against y_t/δ_s at $s=0$ depend on α in the flow region, in which aerodynamic effects of the boundary layer are predominant, but are independent of δ_s (where y_t denotes the spanwise coordinate). Variations of c_D against y_t at $s \neq 0$ are expressed approximately by an exponential function, by use of which the total drag is given by a simple expression.

1. Introduction

Many investigators have made their efforts to understand the effects of three-dimensional flows arising in the flow across a blade row on aerodynamic performances of axial flow machines. As well known, the inefficiency of the axial flow machines due to complicated three-dimensional flows is attributed mainly to a tip-clearance flow and a secondary flow. The tip-clearance flow is a flow passing through the tip clearance and is induced by the pressure difference between the pressure and the suction side of blades. On the other hand, the secondary flow occurs as the result of turning the vorticity vector included in a nonuniform stream flowing into a blade row. These flows form a major source for energy losses in the main flow through the machines. We know well that there is this undesirable source in the flow region where the tip of blades meets the end-wall boundary layer. In relation to the estimation of energy losses many investigations have been carried out to clarify the effect of aerodynamic properties of the end-wall boundary layer (say, velocity profiles and velocity gradients) and geometrical properties of the tip clearance (say, sizes and forms) on aerodynamic characteristics of a blade or a cascade. However, we cannot find the systematic investigation on aerodynamic characteristics of blades, which vary with the above properties. In addition to this we do not know also correlations between aerodynamic

characteristics of blades varying with the above properties.

In the present paper experimental results of the lift and drag acting on a stationary wing with a tip clearance are shown against three factors, i.e., size of the tip clearance, thickness of the end-wall boundary layer and angle of attack of the wing. A new factor in the correlation between aerodynamic characteristics of the wing is considered. B.Lakshminarayana and J.H.Horlock⁽⁶⁾, B.Lakshminarayana⁽⁵⁾ and J.H.Horlock⁽⁷⁾ report for a wing with a small size of the tip clearance that they have improved the theoretical total induced drags by introducing an experimental lift retained at a wing tip into their lifting-line theory. From their theory they give finally the relation⁽⁷⁾

$$C_{Di} = \frac{C_L^2}{(b/c)} (1-K') f\left(\frac{t}{c}, \frac{s}{t}, 1-K'\right)$$

where f shows a function; K' a factor, which means a lift retained at a wing tip; t the pitch of a cascade of wings; other symbols are defined in the following table. This expression indicates that the factor K' , which comes from the viscosity of a fluid around wings, has an influence on aerodynamic characteristics of a wing with the tip clearance. In view of this the author assumed that the spanwise lift distribution under an influence of the end-wall boundary layer is correlated to the retained lift at a wing tip, and then introduced a dimensionless expression of a local lift $(c_{L\infty} - c_L)/(c_{L\infty} - c_L(\text{tip}))$ into the present investigation (where $c_{L\infty}$ means the lift coefficient of the two-dimensional wing in a uniform flow). In fact the variations of $(c_{L\infty} - c_L)/(c_{L\infty} - c_L(\text{tip}))$ against Yt/c are not affected approximately by two

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factors, namely, thickness of end-wall boundary layer with a similar profile and angle of attack of a wing, provided the size of the tip clearance is fixed. In addition to this it is found that variations of $(c_{L\infty}-c_L)/(c_{L\infty}-c_L(\text{tip}))$ against y_t/c may be expressed approximately by an exponential function. The factor $(c_{L\infty}-c_L)/(c_{L\infty}-c_L(\text{tip}))$ is proportional to the decrease in lift from a lift of the two-dimensional wing, provided we fix the size of the tip clearance, the thickness of the end-wall boundary layer and the angle of attack.

Notations

b : span (see Fig.1)
 c : chord length
 c_D : $=d/(\rho U_0^2 c/2)$
 $c_D(\text{peak})$: see Fig.10(e)
 c_D : $=D/(\rho U_0^2 bc/2)$
 c_L : $=L/(\rho U_0^2 c/2)$
 $c_L(\text{tip})$: lift coefficient calculated from retained lift at wing tip (see Section 3.2)
 $c_{L\infty}$: lift coefficient of two-dimensional wing in uniform flow (In this paper $c_{L\infty}$ equals to the lift coefficient of a two-dimensional wing with RAF6-section with max. thickness of $0.1c$ (2)(8))
 C_L : $=L/(\rho U_0^2 bc/2)$
 c_p : $=(p-p_0)/(\rho U_0^2/2)$
 d : local drag per unit span
 D : total drag
 l : local lift per unit span
 L : total lift
 p : local pressure on wing
 p_0 : reference pressure(2)(4)
 P_t : total pressure of main flow
 Re : $=U_0 c/\nu$, Reynolds number
 t : size of slit (see Fig.1)
 u : local velocity in "x" direction
 U_0 : $=\sqrt{2(P_t-p_0)/\rho}$
 y_t : spanwise distance measured from wing tip

x : chordwise coordinate with origin at leading edge
 α : geometrical angle of attack (see Fig.1)
 δ : thickness of end-wall boundary layer ($\delta=[\eta]_{u=0.99u_{\max}}$)
 δ^* : displacement thickness of end-wall boundary layer
 η : coordinate (see Fig.1)
 Λ : $=b/c$, aspect ratio
 ν : kinetic viscosity of fluid medium
 ρ : density of fluid medium

Suffixes

s : left-hand side of stream in tunnel
 p : right-hand side of stream in tunnel
 $\max$: maximum
 i : induced

2. Experimental apparatus and method

The wind tunnel and the wing model used here are the same as those in ref.(2). The size of the wing model is unchanged through the present experiment. The aspect ratio of the model is always 8.57. However, the test section of the wind tunnel for the present experiment differs from that in ref.(2) or (4). The test section is reconstructed to change the thickness of the end-wall boundary layer meeting the wing. Thus, we can vary δ_s or δ_p by changing the size of a slit t_s or t_p and the length of the test section l_d (see Fig.1).

Figs.2(a) and (b) show velocity profiles of the boundary layer on the end wall facing a wing tip. Three kinds of the velocity profiles are similar to each other as shown in Fig.2(b), and these obey approximately the 1/7th-power law on the velocity profile of the boundary layer. Thus, we intend to investigate the effects of the end-wall boundary layer on the lift, the drag or the pressure distribution on a

wing surface on condition that velocity profiles of the end-wall boundary layer are similar. Fig.2(c) designates velocity profiles of the boundary layer on the opposite end wall, on which the model is fixed, and this velocity profile is unchanged through the experiment.

The experiments were made over four kinds of the displacement thickness of the end-wall boundary layer, i.e., $\delta_s^*(\text{mm})=0.4, 1.76, 3.79$ and $\delta_p^*(\text{mm})=1.76$: four kinds of the angle of attack, i.e., $\alpha(^{\circ})=6, 3, 0, -2$: and seven kinds of the size of the tip clearance, i.e., $s(\text{mm})$

δ_s^* mm	δ_s mm	δ_p mm	l_d mm	t_s mm	t_p mm
0.40	3.1	16	150	10	0
1.76	16.0	16	600	10	10
3.79	30.0	16	600	0	10

1. Bypass 2. Guide, 3. Test wing, 4. Holes for boundary layer measurement, 5. Taps for measuring p_0

Fig.1. Sketch of working section, showing notations

=0, 1, 2, 3, 5, 7, 10. Chordwise pressure distributions were measured at twenty stations along the span. The measured pressures were integrated graphically to obtain local lifts and drags at each spanwise position. Reynolds number based on U_0 and c was 1.4×10^5 through the experiment.

3. Experimental results and considerations

3.1 Chordwise pressure distributions
Fig.3 illustrates the effects of δ_s^* and s on chordwise pressure distributions at several spanwise stations near the wing

(a) On end wall facing wing tip

(b) Similarity of velocity profiles shown in (a)

(c) On end wall at wing root

Fig.2 Velocity profiles of boundary layer on end walls

tip. The flow pattern formed by the main flow and the clearance flow in the region around the wing tip is scarcely affected by the velocity profiles of end-wall boundary layers.

3.2 Spanwise lift distributions and their similarity, and total lift

Fig.4 indicates an example of variations of c_L against η/c . At $s=0$ mm we recognize a great effect of δ_s^* on the lift distributions in the region of $y_t/c < 1$. It is inferred from this that the effect of end-wall boundary layers does not reach approximately the wing surface beyond $y_t/c \approx 1$, provided $\Lambda \gg \delta_s/c$ or δ_p/c . The distribution of c_L against y_t/c in the region of $y_t/c < 1$ depends largely on the size of δ_s^* .

We can see by comparing local lifts at $s=10$ mm with those at $s=0$ mm in Fig.4 that the effect of δ_s^* becomes small with the growth of the clearance flow. However, we

Fig.3 Chordwise pressure distributions at various boundary layer thicknesses ($\alpha=6^\circ$)

Fig.4 Spanwise lift distributions at various boundary layer thicknesses, sizes of tip clearance and angles of attack

find still small variations of c_L corresponding to those of δ_s^* on the c_L -curve at $s=10$ mm in the neighbourhood of the wing tip.

Fig.5 shows variations of $c_{L(\text{tip})}$ against s . The $c_{L(\text{tip})}$ means a hypothetical lift retained at the wing tip, which is obtained graphically by neglecting an additional increase in the lift due to the clearance flow in the neighbourhood of the wing tip and by extending curves of c_L against y_t/c to the wing tip (namely, to $y_t/c = s/c$ or $y_t/c=0$). B.Lakshminarayana and J. H.Horlock (6) concluded that in a uniform flow aerodynamic characteristics of a wing with a small size of the tip clearance are predicted well by lifting-line theory, provided the boundary condition for a cir-

Fig.5 Retained lift at wing tip

ulation at the wing tip is corrected by use of the empirical lift retained at the wing tip. Therefore, we must have an accurate boundary condition for the circulation or the lift at the wing tip, to be able to predict aerodynamic characteristics of the wing under such conditions as in the present experiment. However, we have not known hitherto such experimental data. Fig.5 illustrates particular data on the $c_{L(\text{tip})}$ obtained by the present experiment.

It is illustrated next how $c_{L(\text{tip})}$ is useful as a factor correlating the curves of c_L against y_t/c at various δ_s^* and α . Fig.6(a) to (d) show a similarity of curves of $(c_{L\infty} - c_L)/(c_{L\infty} - c_{L(\text{tip})})$ against y_t/c at various sizes of the tip clearance, where values of $c_{L(\text{tip})}$ are given by Fig.5, $c_{L\infty}$ by ref.(2) or (8). If s is fixed, we shall be able to express approximately with a single curve the variation of $(c_{L\infty} - c_L)/(c_{L\infty} - c_{L(\text{tip})})$ against y_t/c at various angles of attack with the exception of the region including the additional increase in the local lift in the immediate neighbourhood of the wing tip. The shapes of these curves are quantitatively similar to each other at $1 \leq s(\text{mm}) \leq 10$ [see Figs.6(b) to (d)]. It is found immediately at $s=0$ mm that the effect of δ_s^* is restricted approximately to the region of $y_t/c < 1$ [see Fig.6(a)]. On the other hand, the effect of the clearance flow at $s \neq 0$ mm is great and extends over the whole wing. In spite of the great effect of the clearance flow the region with a large decrease in $(c_{L\infty} - c_L)/(c_{L\infty} - c_{L(\text{tip})})$ is restricted to $y_t/c < 1$.

Now we shall turn to a discussion of experimental results of the total lift C_L . As we stated previously, we reached the conclusion that the great effect of the end-wall boundary layer on the local lift along the span does not reach the midspan,

Fig.6 Similarity of spanwise lift distributions ($\Lambda=8.57$)

for it is restricted approximately to the region of $y_t/c < 1$. On the basis of this conclusion we shall be able to divide the aerodynamic effects of boundary layers developed on two opposite end-walls on the spanwise lift into those of individual end-wall boundary layers. The velocity profile of the boundary layer on the end wall, on which the test wing is fixed, is unchanged through the experiments [see Fig. 2(c)]. Therefore, effects of the boundary layer developed on the end wall at wing root on the aerodynamic characteristics of the wing are unchanged regardless of the size of the tip clearance. By use of Eqs. (18) to (20) in ref.(4) we determine firstly the decrease in local lift at $s=0$ mm due to the boundary layer on the end wall at the wing root. Secondly, we add the above decrease in local lift at $s=0$ mm to the local lift at $s \neq 0$ mm. Then we obtain the variations of c_L against y_t/c at $s \neq 0$ mm, which do not include aerodynamic effects of the boundary layer on the end wall at the wing root. The remainder of this section is devoted to the consideration of the relation between s and C_L calculated by use of c_L deduced from the above procedure.

C_L is given as :

$$C_L = \frac{1}{b} \int_0^b c_L dy_t = c_{L\infty} - \frac{1}{b} \int_0^b (c_{L\infty} - c_L) dy_t$$

Putting

$$C'_{L(wall)} = \int_0^{b/c} \frac{c_{L\infty} - c_L}{c_{L\infty} - c_{L(tip)}} d\left(\frac{y_t}{c}\right)$$

we have

$$\frac{c_{L\infty} - c_L}{c_{L\infty} - c_{L(tip)}} = \frac{C'_{L(wall)}}{\Lambda} \quad \dots\dots\dots (1)$$

Since $C'_{L(wall)}$ is approximately a function of s only (Fig.6), Eq.(1) is approximately a function of s only. Fig.7 is a plot obtained by substituting the experimental data into Eq.(1). From Fig.7 we find that $(c_{L\infty} - c_L) / (c_{L\infty} - c_{L(tip)})$ varies scarcely with s at $s > 5$ mm. By use of Fig. 7 together with $c_{L\infty}$ and $c_{L(tip)}$ we can get easily C_L as a function of s .

We deduce Eq.(1) for the rectangular wing of fixed span and chord length. In other words, Eq.(1) holds true when Λ and R_e have the same values as those in the present experiment. For instance, we suppose that

there is a wing with nonrectangular plan-form, and that its aspect ratio calculated from the expression $\Lambda = A/c^2$ is equal to that of the wing in the present experiment, where A means the wing area. If we intend

Fig.7 Representation of total lift coefficients by $c_{L(tip)}$

(a) $\alpha = 6^\circ, 3^\circ$

(b) $\alpha = -2^\circ$

Fig.8 Spanwise variations of drag coefficient at various boundary layer thicknesses, sizes of tip clearance and angles of attack

to apply Fig.7 based on Eq.(1) to predict C_L of this wing with nonrectangular plan-form, Fig.7 must be modified for Re prior to the application of Fig.7.

3.3 Spanwise drag distributions and correlations, and total drag

Figs.8(a) and (b) show variations of c_D against η/c at various s , α and δ_s^* . It is found from Fig.8(a) that at every α and s the values of c_D increase in the region of $\eta/c < 0.5 \sim 1.0$ as δ_s^* decreases, but the values of c_D decrease in the region of $\eta/c > 0.5 \sim 1.0$ as δ_s^* decreases. We consider in the first place the origin of the above phenomenon.

Firstly, we discuss the variation of c_D against η/c in the region of $\eta/c < 0.5 \sim 1.0$. The pressure difference between the upper and lower surfaces of the wing in the neighbourhood of the wing tip is smaller in case of the low velocity within the end-wall boundary layer (for example, at $\delta_s^* = 3.79$ mm) than in case of the high velocity (for example, at $\delta_s^* = 0.4$ mm). This may result in a decline of the clearance flow in case of the low velocity within the end-wall boundary layer, and then in a decline of the negative pressure due to the separation of the clearance flow from the upper surface in case of the low velocity within the end-wall boundary layer. Thus we can conclude that c_D in the region of $\eta/c < 0.5 \sim 1.0$ is smaller in case of the low velocity ($\delta_s^* = 3.79$ mm) than in case of the high velocity ($\delta_s^* = 0.4$ mm) within the end-wall boundary layer.

Secondly, we consider the variation of c_D against η/c in the region of $\eta/c > 0.5 \sim 1.0$. The clearance flow does not affect spanwise drag distributions in this region as the clearance flow does in the region of $\eta/c < 0.5 \sim 1.0$. However, the secondary flow due to the end-wall boundary layer plays now an important role instead of the clearance flow in this region, namely, the downwash from the secondary flow has a great influence on the spanwise drag distributions. We know well that the part of a wing which is immersed in an end-wall boundary layer contributes to the generation of a secondary flow in the wake of the wing, and that the downwash from the secondary flow has influences on aerodynamic characteristics of the wing. On the basis of this we can say that since the part of the wing which is im-

mersed in the end-wall boundary layer is larger in a thick end-wall boundary layer ($\delta_s^* = 3.79$ mm) than in a thin one ($\delta_s^* = 0.4$ mm), the downwash at $\eta/c > 0.5 \sim 1.0$ can be larger in the former than in the latter, provided s is fixed. Therefore, we can say from the above that c_D increases at $\eta/c > 0.5 \sim 1.0$ as δ_s^* increases. Thus we conclude finally from the considerations in this section that c_D increases at $\eta/c < 0.5 \sim 1.0$ as δ_s^* decreases, but c_D decreases at $\eta/c > 0.5 \sim 1.0$ as δ_s^* decreases.

We find further another particular behaviour of c_D against η/c in the neighbourhood of the wing tip by referring to Fig.8(a). Even though the tip clearance is as small as $s \approx 1$ mm, the effect of the clearance flow on the variation of c_D against η/c is great. Therefore, the decrease in c_D due to the end-wall boundary layer is cancelled by the increase in c_D due to the clearance flow. On the other hand, Fig.8(b) shows that the effect of the clearance flow at $\alpha = -2^\circ$ is always smaller than that of the end-wall boundary layer at $1 < s(\text{mm}) < 7$, and is approximately equal to that of the end-wall boundary layer at $7 < s(\text{mm}) < 10$.

Fig.9, which is deduced from Fig.8(a), shows plots of c_D against y_t/δ_s at $s = 0$ mm in the neighbourhood of the wing tip. This figure means that variations of c_D against y_t/δ_s at various δ_s^* are expressed approximately by a single curve at $s = 0$ mm on condition that α is fixed. We can express the total drag C_D by the following relation in the case of Fig.9, where the secondary flow exists solely.

Fig.9 Effects of δ_s^* on c_D ($s = 0$ mm)

Fig.10 Values of various factors in Eq.(3), and $C_D(\text{peak})$

$$C_D = \frac{1}{(b/2)} \int_0^{b/2} c_D dy_t = c_{D\infty} + \frac{\delta_s}{(b/2)} C'_{D(wall)} \quad \dots\dots\dots (2)$$

where

$$C'_{D(wall)} = \int_0^{b/2\delta_s} (c_D - c_{D\infty}) d\left(\frac{y_t}{\delta_s}\right)$$

and $C'_{D(wall)}$ is approximately independent of δ_s^* or δ_s at a given α . Eq.(2) is similar to a relation which was given by N. Scholz⁽³⁾ as a correlation between the dimensionless loss coefficient and the aspect ratio. He deduced his correlation from experimental results on the wake of a wing spanned across a channel, namely, of a wing without the tip clearance.

Now we study variations of c_D against η/c at $s \neq 0$ mm. For simplification of our discussions we shall express the relation of c_D against η/c shown in Fig.8(a) by a simple equation. We express approximately this with the following relation in the region of $0.1429 \leq y_t/c \leq 2.1429$,

$$c_D = c_{D(y_t/c=2.1429)} + M e^{-N(y_t/c)} \quad (y_t = \eta - s) \quad \dots\dots\dots (3)$$

where values of M and N are determined from the experimental data which are given by Figs.10(a) and (b) in the present investigation, and $c_{D(y_t/c=2.1429)}$, which means c_D at $y_t=150$ mm, is given by Fig.10 (d). In addition to Eq.(3) if we use a straight line connecting the two points ($y_t/c=0$, $c_{D(peak)}$) and ($y_t/c=0.1429$, $c_{D(y_t/c=0.1429)}$ from Eq.(3)) instead of the experimental curve of c_D against η/c in the region of $y_t/c \leq 0.1429$, we can describe easily the experimental curves of c_D against η/c . The above $c_{D(peak)}$ is given by Fig.10(c).

Fig.11 Total drag coefficients

Now we study the variation of total drag C_D with δ_s^* and α at $s \neq 0$ mm. Modifying the experimental curves of c_D against η/c in Fig.8(a) by use of both c_D from Eq. (3) in the region of $y_t/c \leq 2.1429$ and c_D of a constant $c_{D(y_t/c=2.1429)}$ in the region of $b/2c > y_t/c > 2.1429$, we have the following expression

$$C_D = \frac{1}{(b/2)} \int_0^{b/2} c_D dy_t = c_{D(y_t/c=2.1429)} + \frac{2}{\Lambda} \frac{M}{N} \quad \dots\dots\dots (4)$$

or

$$\frac{C_D}{c_{D(y_t/c=2.1429)}} = 1 + \frac{2}{\Lambda} \frac{1}{c_{D(y_t/c=2.1429)}} \frac{M}{N} \quad \dots\dots\dots (4')$$

In the process of the derivation of Eq.(4) or (4') we adopt Eq.(3) not only in the region of $0.1429 \leq y_t/c \leq 2.1429$, but also in the region of $y_t/c \leq 0.1429$. However, this does not introduce a large error into C_D . Fig. 11 presents a data correlation using Eq. (4'). Data points plotted on Fig.11 are calculated by substituting experimental data into the left and right side of Eq.(4') and the solid line on the figure is the correlating equation (4'). Thus, using Figs.10 and 11, we reproduce easily C_D at three parameters s , α and δ_s^* , which we cover in the present experiment, and further, we can predict C_D at three parameters deviating from these in the present experiment.

Eqs.(2) to (4') hold true at the same Λ and Re as we adopted in the present experiment. Therefore, if we want to apply the present results to a case where both Λ and Re , or one of them, differ from those in the present experiment, we must modify empirical values in Eqs.(2) to (4') by making another experiment. However, it seems that the features of Eqs.(2) to (4') on the correlation are also true at other values of Λ and Re differing from them in the present experiment.

4. Conclusions

Though it appears that aerodynamic characteristics of a wing with tip clearance vary complicatedly with factors, we shall be able to guess a similarity of the spanwise distribution of the lift coefficient and the drag coefficient by use of parameters shown below. This simplifies the problem by arranging the number of factors affecting the aerodynamic characteristics of the wing.

(1) $c_{L(tip)}$ is a factor concerning a similarity of spanwise lift distributions. Variations of $(c_{L\infty} - c_L)/(c_{L\infty} - c_{L(tip)})$ against y_t/c depend on s , but are approximately independent of δ_s^* and α . Thus, $(c_{L\infty} - C_L)/(c_{L\infty} - c_{L(tip)})$ is expressed as a

function of s only.

(2) In the neighbourhood of the wing tip, where the effect of the end-wall boundary layer on c_D is great, variations of c_D against y_t/δ_s at $s=0$ mm depend on α , but are approximately independent of δ_s . We have Eq.(2).

(3) At $s \neq 0$ mm we can express approximately variations of c_D against y_t/c by an exponential function [see Eq.(3)] in the region of y_t/c where the effect of the clearance flow is great. Using Eq.(3), we can show briefly C_D by Eq.(4') independently of α and δ_s^* .

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