Turbulent Flow around an Inclined Strut Mounted on a Plate and Effects of the Angle of Attack

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Summary

A numerical study on the turbulent flow around the strut-plate juncture is carried out for the inclined strut and for the flow with an angle of attack. Computations are made by solving three-dimensional incompressible Reynolds-averaged Navier-Stokes equation with MAC method. Turbulence is simulated by using Baldwin-Lomax model with a modified length scale for the treatment of corner flow. The flows, at the Reynolds number of 10^5 , show intensive unsteady behavior near the plate while the flows are steady enough off the plate. Inclination of the strut induces a lift which is generated mainly near the plate. On the other hand, the lift by an angle of attack reduces near the plate.

1. Introduction

Recently, juncture flows have received much attention in ship hydrodynamics due to the importance of their application to the ship appendage flow especially for high speed ships. As high speed ships require a high powering propulsion system and safe controllability, they often have more and larger appendages than conventional ships. So the estimation of the appendage resistance is critical for the prediction of the total resistance of the high speed ship. Besides, the juncture flow can affect the lift and stability/control characteristics of the appendages and the propellers located downstream by the generated horseshoe vortices from the appendages. However, there is no established method for estimating appendage resistance or appendage wake because detailed mechanism of the juncture flow is not clear yet.

To make it easy to understand and model the complicated juncture flow, many experimental and numerical studies have been carried out so far for simple strut-plate juncture models. They include the full measurements of the juncture flow for a circular cylinder⁽¹⁾ and for the strut with a foil section⁽²⁾⁻⁽⁶⁾ to provide a data base which is essential for the development of the computational codes. Some numerical studies⁽⁷⁾⁻⁽¹⁰⁾ have been carried out to validate their codes comparing with those data base. However, most studies on the juncture flow have been performed for the case of a strut mounted upright on the plate with zero angle of attack.

Considering actual application of the juncture flow such as the flow around the bracket attached to the ship, more general cases are required to be studied; studies on the effect of inflow angle, inclination of the strut, curvature of the plate and so on. Nevertheless such studies are very few.

When the strut mounted on the plate inclined, the flow characteristics become quite different from the one of the upright strut. However, little attention has been paid to this problem although inclined strut is commonly used in practical application. Hoerner⁽¹¹⁾ pointed out the increase of the drag due to the inclination of the strut. However, there have been no reports on the characteristics of the flow according to the authors' knowledges. Recently, Kim and Mori⁽¹²⁾ found out through the numerical computation, although laminar flow, the inclination of strut induces a large lift on the strut near the plate.

On the other hand, studies on the strut with an angle of attack are relatively more. Briley et al.⁽¹³⁾ computed the juncture flow for an idealized wing with an 5° angle of attack. It consists of an elliptical leading edge and a semi-infinite slab of constant thickness, so that the flow only near the leading edge is considered there. Kubendran et al.⁽¹⁴⁾ visualized the juncture flow with angle of attack of 4° and 8° where the separation becomes severe as the angle of attack increases. Özcan and Ölcmen^(15,16) measured the juncture flow with 30° angle of attack at the Reynolds number of 6.6×10^5 and found that the flow structure is very complicated in the downstream; a single tornado vortex and W-shaped footprint of horseshoe vortex were observed. Wood and Westphal⁽¹⁷⁾ investigated the spanwise distribution of the lift of the strut mounted on the plate by the measurement of the pressure and found that the lift coefficient near the plate

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is reduced by 16% from the freestream value. Kim and Mori¹⁸⁾ investigated the structure of the juncture flow with 5° angle of attack at the low Reynolds number by solving the N-S equations and showed that the lift coefficient is reduced near the plate.

In the present study, we extend the previous computations of the laminar flow^{12,18)} to the turbulent flow. The main objective is to investigate the characteristics of the turbulent juncture flow and forces acting on the strut for the inclined strut and the flow with an angle of attack.

The investigations are made by solving the Navier-Stokes equations with MAC method. To simulate high Reynolds number flows, turbulence is simulated by using Baldwin-Lomax model with a modified length scale for corner flow, although there are still negative opinions against the appropriateness for applying an algebraic eddy-viscosity model to the complicated juncture flow. The present code is validated through the comparative study¹⁹⁾ with the DTRC experimental data²⁾ for juncture flow.

2. Computational Method

2.1 Governing Equation

The governing equations for the incompressible turbulent flow are given by the Reynolds averaged Navier-Stokes and continuity equations. By introducing Boussinesq's eddy viscosity hypothesis, they can be written in the nondimensionalized form as follows;

$$\begin{aligned} u_t + uu_x + vu_y + wu_z &= -p_x + \frac{1}{R_n} \nabla^2 u + \{\nu_t(2u_x)\}_x \\ &\quad + \{\nu_t(u_y + v_x)\}_y \\ &\quad + \{\nu_t(u_z + w_x)\}_z \\ v_t + uv_x + vv_y + wv_z &= -p_y + \frac{1}{R_n} \nabla^2 v + \{\nu_t(u_y + v_x)\}_x \\ &\quad + \{\nu_t(2v_y)\}_y + \{\nu_t(v_z + w_y)\}_z \\ w_t + uw_x + vw_y + ww_z &= -p_z + \frac{1}{R_n} \nabla^2 w \\ &\quad + \{\nu_t(u_x + w_x)\}_x \\ &\quad + \{\nu_t(v_z + w_y)\}_y + \{\nu_t(2w_z)\}_z \\ u_x + v_y + w_z &= 0 \end{aligned} \quad (1)$$

where subscripts represent partial differentiation with respect to the referred variables except ν_t and (u, v, w) and p are the velocity components in (x, y, z) -direction of the cartesian coordinates and the static pressure respectively. t is the time and ν_t represents the eddy viscosity.

All the variables are nondimensionalized by the chord length of the strut L , the uniform flow velocity U_0 , and the density of water ρ . R_n is the Reynolds number based on U_0 and L .

A body-fitted coordinate system is adopted and transformation is given by

$$\xi = \xi(x, y, z), \quad \eta = \eta(x, y, z), \quad \zeta = \zeta(x, y, z) \quad (3)$$

With this relations, the following transformed governing equations are obtained.

$$u_t + Uu_\xi + Vv_\eta + Ww_\zeta = -(\xi_x p_\xi + \eta_x p_\eta + \zeta_x p_\zeta)$$

$$+ \frac{1}{R_n} \nabla^2 u + R_x$$

$$v_t + Uv_\xi + Vv_\eta + Wv_\zeta = -(\xi_y p_\xi + \eta_y p_\eta + \zeta_y p_\zeta) + \frac{1}{R_n} \nabla^2 v + R_y \quad (4)$$

$$w_t + Uw_\xi + Vw_\eta + Ww_\zeta = -(\xi_z p_\xi + \eta_z p_\eta + \zeta_z p_\zeta) + \frac{1}{R_n} \nabla^2 w + R_z$$

$$\xi_x u_\xi + \eta_x u_\eta + \zeta_x u_\zeta + \xi_y v_\xi + \eta_y v_\eta + \zeta_y v_\zeta + \xi_z w_\xi + \eta_z w_\eta + \zeta_z w_\zeta = 0 \quad (5)$$

where U , V and W are the contravariant velocity components defined as

$$\begin{aligned} U &= \xi_x u + \xi_y v + \xi_z w \\ V &= \eta_x u + \eta_y v + \eta_z w \\ W &= \zeta_x u + \zeta_y v + \zeta_z w \end{aligned} \quad (6)$$

Laplacian ∇^2 can be expressed in the body fitted coordinates in the following form;

$$\begin{aligned} \nabla^2 q &= \bar{a} q_{\xi\xi} + \bar{b} q_{\eta\eta} + \bar{c} q_{\zeta\zeta} + 2\bar{d} q_{\xi\eta} + 2\bar{e} q_{\eta\zeta} \\ &\quad + 2\bar{f} q_{\xi\zeta} + \bar{g} q_\xi + \bar{h} q_\eta + \bar{i} q_\zeta \end{aligned} \quad (7)$$

R_x , R_y and R_z represent the Reynolds stress terms transformed from the last three terms of RHS of Eq. (1).

2.2 Numerical Scheme and Boundary Condition

The computations are made by MAC method where Poisson equation for the pressure is derived by taking a divergence of the momentum equation and satisfying the continuity equation. The Poisson equation for the pressure is solved iteratively by using the relaxation method and the velocities are updated from the momentum equation.

The finite difference equations are derived on a regular grid system. So all the variables are defined on the grid nodes. For the spatial differencing scheme, 2nd order central difference is used while the upwind scheme for the convective term. The Euler explicit scheme is used for the time marching procedure. The computation starts from the still state and the flow is accelerated up to a given constant velocity for the numerical stability.

A C-type grid is adopted for the computation. The coordinate system and grid topology are shown in Fig. 1. In the physical domain, a space-fixed cartesian coor-

Fig. 1 Grid and Coordinate System

dinate system is used whose origin is located at the center of the strut on the plate and x -, y - and z -axes are in the uniform flow, lateral and vertical direction respectively. In the transformed body-fitted coordinate system, ξ - and η -axes are the girthwise of the strut and the normal to the surface of strut and ζ -axis coincides with z -axis. Therefore the surface of strut lies in the η -constant plane and the plate lies on the ζ -constant plane.

On the strut and the plate, no-slip condition is used for the velocity and Neumann condition is obtained from the momentum equation for pressure. Outer boundaries are taken on the plate including the inflow and the lateral boundaries where a $1/7$ -th boundary layer profile with constant pressure is prescribed while the v -component of velocity is obtained from the momentum equation. The inflow profile is determined by specifying the position of the leading edge of the plate. The height of the strut is assumed to be infinite and the zero gradient conditions are used for all the variables. On the downstream boundary, the velocities are linearly extrapolated in the streamwise direction by assuming that the diffusion in the streamwise direction is negligible but zero gradient condition is used for the pressure.

2.3 Turbulence Model

The turbulence model for the flow around the junction is complicated and not well developed yet. In this study, the turbulence transport is described by using an algebraic eddy-viscosity model proposed by Baldwin & Lomax²⁰⁾ which has been used widely in computational fluid dynamics for its simplicity. Modified length scale²¹⁾ is incorporated into a Baldwin-Lomax model to treat the corner flow where the turbulence is influenced by both plate and strut.

The procedure of applying Baldwin-Lomax model for the corner flow is as follows. As sketched in Fig. 2, in each (J-K) sectional plane, the computational domain is a corner formed by two walls. The local coordinates (n_y , n_z) will be used for the discussion which has an origin on the corner. The eddy viscosity ν_t is computed in the inner and outer regions separately. In the inner region, the eddy viscosity is given by the Prandtl-van Driest formulation

$$(\nu_t)_{\text{inner}} = (\kappa D l)^2 |\omega| \quad (8)$$

where $\kappa=0.4$ is von Kármán's constant and $|\omega|$ is the magnitude of the vorticity. The definition of l is critical for the evaluation of the eddy viscosity. Bleev's mixing length²¹⁾ for the open corner formed by the normal intersection of two planes is used for the present study.

$$l = \frac{2n_y n_z}{n_y + n_z + (n_y^2 + n_z^2)^{1/2}} \quad (9)$$

When the open corner has an arbitrary intersection angle ϕ , more general formula¹⁹⁾ for characteristic length l is given by

$$l = \frac{2r n_y n_z}{r(n_y + n_z) + \bar{y}(n_y + n_z \cos \phi) + n_z^2 \sin \phi} \quad (10)$$

Fig. 2 Definition for the Corner Flows

where the definition of notation is shown in Fig. 2(b).

The van Driest damping factor D is given by

$$D = 1 - \exp(-l^+/26) \quad (11)$$

and

$$l^+ = \frac{u_\tau l}{\nu} = \frac{l}{\nu} \sqrt{\frac{\tau_w}{\rho}} \quad (12)$$

where τ_w is the wall shear stress.

In the outer region,

$$(\nu_t)_{\text{outer}} = k C_{cp} F_{\text{wake}} F_{\text{kleb}} \quad (13)$$

where

$$F_{\text{wake}} = \text{the smaller of } \begin{cases} l_{\text{max}} F_{\text{max}} \\ 0.25 l_{\text{max}} U_{DIF}^2 / F_{\text{max}} \end{cases} \quad (14)$$

The quantity U_{DIF} is the difference between the maximum and the minimum resultant velocity in the profile.

$$U_{DIF} = (\sqrt{u^2 + v^2 + w^2})_{\text{MAX}} - (\sqrt{u^2 + v^2 + w^2})_{\text{MIN}} \quad (15)$$

In the above formulation, $k=0.0168$ is the Clauser's constant and the quantity F_{max} is the maximum value of $F(l) = l|\omega|D$, and l_{max} is the value of l at which F_{max} occurs. The Klebanoff intermittency factor F_{kleb} is given by

$$F_{\text{kleb}} = \left[1 + 5.5 \left(\frac{C_{\text{kleb}} l}{l_{\text{max}}} \right)^6 \right]^{-1} \quad (16)$$

In the outer formulation, the constants C_{cp} and C_{kleb} depend on the condition of flow²²⁾. In this study, however, $C_{cp}=1.6$ and $C_{\text{kleb}}=0.3$ are used, which were recommended originally by Baldwin and Lomax²⁰⁾. There are some ambiguity in finding F_{max} because several peaks are present in the profile of F for the complex flow as pointed out by Visbal and Knight¹²⁾. The outermost peak is chosen as F_{max} among several peaks to avoid the abrupt change of the computed length scale in the streamwise direction. However, if the chosen peak is smaller than the 20% of the maximum value of F in the profile, it is discarded to avoid finding the peak in the outside of the boundary layer.

The plane is divided into four regions I, II, III and IV as shown in Fig. 2. In regions I and II, D is evaluated at the wall $n_y=0$ for region I and in regions III and IV, it is evaluated at the wall $n_z=0$. The search for F_{max} proceeds outward from the wall either from $n_y=0$ for the region I or from $n_z=0$ for the region IV. The values

of $F_{\max}$ in the regions II and III are constant, equal to the value of $F_{\max}$ at M and N respectively.

Similar treatment is also applied to the wake region by assuming the slip wall on the center wake plane.

3. Results and Discussion

Computations are made for two cases which are the flow with an angle of attack of -5° and for the inclined strut by 30° . Both are at the Reynolds number of 10^5 . The angle of attack and inclination angle are denoted here by α and ϕ respectively. The flow is assumed to be fully turbulent so that the transition on the strut is not considered.

The strut has a spanwise constant section of NACA 16-018 with a thickness of 18% of the chord length L . The leading edge of the plate is $10.5L$ apart from the center of the strut but infinite in lateral and downstream directions. The oncoming boundary layer thickness is $0.234L$ at the leading edge of the strut.

The computing conditions and grids for the two cases studied in this paper are summarized in Table 1.

3.1 Inclined Strut

The most prominent feature of the juncture flow for the inclined strut is that the flow becomes unsymmetric close to the plate due to the interaction of the flow with the plate. This is clearly shown in Fig. 3 where the velocity vectors and the pressure close to the plate are shown. Here, the side of the strut is expressed in terms of the angle between this strut and the plate such as 60° -side and 120° -side. The flow near the leading edge is similar to the flow with an angle of attack (see Figs. 14 and 15); both the nodal point of attachment and the stagnation point are shifted to the 60° -side. The unsymmetric pressure distribution suggests an existence of a lateral (lift) force. Such characteristics of the flow are similar to those of the laminar flow¹²⁾ but the flow near the trailing edge is much more complicated.

Fig. 4 shows the time history of the forces acting on the strut where C_{df} , C_{dp} , C_{lf} and C_{lp} represent the coefficients of the frictional drag, pressure drag and the frictional and pressure lift respectively. All the coefficients are nondimensionalized by $0.5\rho U_0^2 L^2$. The forces are oscillating with a period of about 3.0 nondimensional time. The Strouhal number based on the maximum thickness of the strut is 0.07. The sectional force coefficients at three different z are plotted versus time in Fig. 5 where the sectional force is the force acting on the strip of the strut with unit height of span. They show the same period of oscillation with the same

Fig. 3 Velocity Vectors and Pressure on the Plane of $z=0.0002$: $\phi=30^\circ$, $t=14.0$

Fig. 4 Time Histories of the Forces Acting on the Strut: $\phi=30^\circ$

phase regardless of the height while the amplitude rapidly decreases as z increases so that the flow is almost steady aparting from the plate. The result makes us eliminate the Kármán vortex shedding as a possible source of the oscillation, for it would decrease near the plate due to the viscous damping contrary to the results. Thus the oscillatory forces can be supposed due to the unsteadiness of the flow near the plate.

The above guess is supported by the flows shown in Fig. 6 which are much changing with the height. The stagnation point is shifted to the 60° -side near the plate but it moves to the leading edge to be symmetry as z increases. The flow separated from the plate around

Table 1 Computing Conditions

Case	5° Angle of Attack	30° Inclined Strut
Computing Domain	$-2.3 \leq x \leq 3.0$ $-1.8 \leq y \leq 1.8$ $0.0 \leq z \leq 1.0$	$-2.3 \leq x \leq 3.0$ $-1.8 \leq y \leq 1.8$ $0.0 \leq z \leq 3.0$
No. of Grids	$79 \times 31 \times 27$	$79 \times 31 \times 35$
Minimum Grid Spacing	0.0002	0.0002
Time Increment	0.0002	0.0002

Fig. 5 Time Histories of the Sectional Forces of the Strut at Three Different Heights: $\phi = 30^\circ$

$x=0.35$ and $y=-0.2$ (Fig. 6(a)) makes a large scale of uprising vortical flow (Fig. 6(b)) while the flow is almost two-dimensional on the plane of $z=0.4$.

Fig. 7 shows the cross-flow velocity at several planes of $x=\text{constant}$. It shows quite different flows on both sides. At the plane of $x=0.4$, close to the trailing edge, an uprising separated flow from the plate is clearly seen on the 60° -side which has shown in Fig. 6, too. In the wake, $x=0.7$, there is only one dominant trailing vortex with an anti-clockwise direction on the 60° -side. Attachment of the flow can be also seen there.

Fig. 8 shows the instantaneous velocity vectors at three different times on the closest plane to the plate. Except around the leading edge, the flows are much changing especially on the 60° -side. There are several singular points such as spiral nodal points of separation and nodal points of attachment whose patterns are changing with time. This means that the patterns of the separation and the attachment of the flow are changing with time near the plate.

Fig. 9 shows schematically the evolution of the flow topology on the plate correspondig to the flows shown in Figs. 4, 7 and 8. They satisfy the following topology rule²³⁾

$$(\Sigma_N + 1/2\Sigma_{N'}) - (\Sigma_S + 1/2\Sigma_{S'}) = -1 \quad (17)$$

Fig. 6 Velocity Vectors on the Plane of $z=\text{constant}$: $\phi = 30^\circ$, $t = 15.0$

where Σ_N , $\Sigma_{N'}$, Σ_S and $\Sigma_{S'}$ represent the number of nodes (N), half-nodes (N'), saddles (S) and half-saddles (S') respectively. The flow at $t=14.0$ shows the simplest topology among all shown in Fig. 9. There are three saddle points and four half-saddle points. The nodal points, N_1 and N_4 are the nodal points of attachment while N_2 and N_3 are the focal nodal points of separation. That is to say, the flow attaches to the plate and spreads over the plate at N_1 and N_3 while the flow separates at N_2 and N_3 to become an uprising spiral vortical flow. A new nodal point of separation (N_5) appears at $t=15.0$ but it changes its type from a regular nodal point to a focal nodal point at $t=15.5$. At $t=16.0$, that type of focal nodal point disappears while a new nodal point of attachment (N_5) appears with a focal nodal point of separation (N_6) which disappears at $t=16.5$.

The entire process is repeated periodically. From the above process, we can understand that the main mechanism of the unsteady flow is due to the periodic separa-

Fig. 7 Cross Flow Velocity Vectors at the Plane of $x=\text{constant}$: $\phi=30^\circ$, $t=15.0$

tion of the flow at N_6 in Fig.9(c) and at N_6 in Fig.9(d).

Fig.10 shows the pressure distributions along the strut at $z=0$. at three different times. The pressure does not vary with time near the leading edge but it changes drastically on the aft part of the strut especially on the 60° -side due to the influence of the periodic separation of the flow from the plate which is the main cause for the oscillation of the lift and drag for strut shown in Fig.4.

In Fig.11, the computed pressures on the strut are compared with the experimental data²⁰⁾ which were measured in the circulating water channel at the Reynolds number of 1.45×10^5 . The computed pressures are the averaged data from $t=12.0$ to $t=18.0$ while the measured data are the average for 12 seconds (15 nondimensional time). Although exact quantitative comparison cannot be made because of the difference of the oncoming flow in the boundary layer on the plate, they agree qualitatively well with each other; the difference of the pressure between the 60° -side and 120° -side is large near the plate but it decreases as z

Fig.8 Velocity Vectors on the Plane of $z=0.0002$ at Different Times: $\phi=30^\circ$

increases. In the middle and aft part of the strut, the computation underpredicts the pressure near the plate but the difference becomes smaller as z increases. In the computed results, there are large differences of the pressure between the 60° -side and 120° -side around the aft-body of the strut but they are not seen in the experimental results. The difference between the computed and the experimental pressure in the aft-body of the strut cannot be explained reasonably at present although the blockage effect of the channel may be considered as a possible source for the difference.

Fig.12 shows the spanwise distribution of the sectional drag and lift coefficients of the strut; C_{d2D} , C_{dp2D} and C_{lp2D} here represent the sectional coefficients of the frictional drag, pressure drag and pressure lift respectively. All the coefficients are nondimensionalized by $0.5\rho U_0^2 L$. The computed force coefficients are obtained by averaging the data between $t=12.0$ and $t=18.0$. The frictional drag coefficient increases as z increases and it becomes constant beyond the boundary layer thickness. The pressure drag is greater near the

Fig. 9 Evolution of the Flow Topology on the Plate: $\phi = 30^\circ$

Fig. 10 Pressure Distribution along the Strut at Different Times; $\phi = 30^\circ$, $z = 0.0002$

plate than that beyond the boundary layer while the pressure drag was smaller near the plate in the laminar flow¹²⁾. The lift near the plate is striking and it is generated even beyond the oncoming boundary layer thickness.

Fig. 13 shows the comparison of the forces acting on the strut between computation and measured data²⁵⁾. The computed forces are obtained by integrating sectional forces up to $z = 0.866$ which corresponds to the height of the strut in experiments. The force coefficients are nondimensionalized by $0.5\rho U_0^2 L^2$. The experimental data shows considerable lift all over the measured Reynolds number range. The computed forces show an agreement with experimental data. However, it should be noted that there are some differences in condition between the computation and the experiment such as oncoming boundary layer flows and finite span of the strut. Anyway it may be worthwhile to point out again that a lift force is produced by the inclination of the strut whose magnitude is about 20% of that with an attack angle of 5° (see Fig. 20).

3.2 Flow with Angle of Attack

Fig. 14 and 15 show the comparison of the velocity and the pressure between on the plane closest to the plate and the plane above the boundary layer. Here we can see also significant effects of the plate on the flow around the strut. The flow close to the plate is very similar to that about the inclined strut near the leading

Fig. 11 Comparison of the Pressure Distribution along the Strut between Computations and Experimental Data[24]: $\phi=30^\circ$

edge but it is quite different near the trailing edge (see Fig. 3); the separation occurs earlier on the opposite side to the side on which the nodal point of attachment or the stagnation point appears. It can be seen that there are many singular points around the trailing edge which make the flow complicated and three-dimensional. On the plane above the boundary layer, their

Fig. 12 Spanwise Distribution of the Sectional Drag and Lift Coefficients of the Strut: $\phi=30^\circ$

Fig. 13 Comparison of the Forces acting on the Inclined Strut between Computation and Measured Data[25]

effects disappear so that the separation is much delayed very close to the trailing edge and the flow is two-dimensional without any effects of the plate. Near the plate, the stagnation pressure becomes lower due to the velocity defect of the oncoming boundary layer and the pressure does not so much drops on the suction side. This is because the acceleration of flow is hindered by the boundary layer on the plate as seen in Fig. 14.

Fig. 16 shows the time history of the forces acting on the strut. As same with the flow for inclined strut, the flow is unsteady, although the flow has not reached the periodic state even at $t=25$.

Fig. 17 shows the pressure distributions along the strut at two typical times which correspond to the time at which the hump ($t=20.46$) and hollow ($t=21.96$) of

Fig. 14 Comparison of the Velocity Vectors between on the Plane of $z=0.0002$ and on the plane of $z=0.45$: $\alpha=-5^\circ$

Fig. 15 Comparison of the Pressure between on the Plane of $z=0.0002$ and on the plane of $z=0.45$: $\alpha=-5^\circ$

lift appears in Fig. 16. Near the plate, the pressure changes greatly with time near the trailing edge especially on the suction side. On the other hand, it does not change so much on the plane above the boundary layer. The mechanism of the unsteadiness for the flow is similar to that for the flow about the inclined strut. That is, the unsteady flow near the plate is due to the unsteady separation and attachment of the flow on the plate. In case of the inclined strut, the pressure oscillates largely on the 60° -side (see Fig. 10) where the flow

Fig. 16 Time History of the Forces Acting on the Strut: $\alpha=-5^\circ$

pattern changes largely with time. On the other hand, in case of the flow with an angle of attack, the flow pattern changes mainly on the suction side as can be expected from Fig. 14, so that the main change of the pressure is made on the suction side near the trailing edge as seen in Fig. 17. Note that the fluctuation of the pressure contributes to the increase of the lift for the flow for inclined strut but it does to the opposite for the flow with an angle of attack.

Fig. 18 shows the cross-flow velocity vectors and contours of the streamwise velocity at the corresponding times to those in Fig. 17; the section is the plane of $x=0.4$ on the suction side. They show quite different flows. At $t=21.96$, a new attachment point is seen around $y=0.06$ which makes the flow more complicated and seems to be the cause of the increase of the pressure on the suction side shown in Fig. 16. Such an unsteadiness of the flow is responsible for the fluctuation of the lift shown in Fig. 16, although further deep study must be necessary.

Fig. 17 Pressure Distribution along the Strut at Different Times; $\alpha = -5^\circ$

Fig. 18 Cross Flow Velocity Vectors (above) and Contours of the Streamwise Velocity on the Plane of $x=0.4$ on the Suction Side: $\alpha = -5^\circ$

Fig. 19 shows the spanwise distribution of the sectional drag and lift coefficients of the strut. The computed force coefficients are obtained by averaging the data between $t=18.0$ and $t=24.0$. Frictional drag is similar to the case of the inclined strut while the pressure drag is rather small near the plate contrary to the inclined case. The lift reduces considerably near the plate which

is due to the effects of plate. It should be also pointed out that appreciable effects of the plate up to the height far above the boundary layer.

4. Conclusion

Turbulent flow around the strut mounted on the plate is studied by solving Navier-Stokes equation. Turbu-

Fig. 19 Spanwise Distribution of the Sectional Drag and Lift Coefficients of the Strut: $\alpha = -5^\circ$

lence is simulated by Baldwin-Lomax model together with the Blevins's modified length scale which is introduced to treat the corner flow. The method is applied for two juncture flow simulations, one for the inclined strut and the other for the flow with an angle of attack.

At the Reynolds number of 10^5 , both flows show intensive unsteady behaviours near the plate while enough off the plate it is almost steady. It is seen that the main mechanism of the unsteadiness is due to the unsteady flows on the plate. The topology of the flow on the plate changes periodically which makes the forces acting on the strut oscillate.

It is found that the inclination of the strut induces a lift which is generated mainly near the plate. The measured pressure and forces also support this conclusion with which the computed results agree qualitatively well. The lift induced by the inclination of the strut by 30° is almost equivalent to that by an angle of attack by 1° for the strut with an one chord length of span.

On the other hand, the lift by an angle of attack reduces near the plate because of the low momentum of the oncoming boundary layer flow and insensitive change of the pressure along the strut near the plate.

The present computations are carried out with a relatively coarse grid. For further investigation of the flow characteristics, computations with finer grid are expected. Also, computations for higher Reynolds number flows would be interesting in the practical sense.

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