A Study on Juncture Flows ; Effects of the Inclination of Strut and the Curvature of Plate

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Summary

A computational study of the flow around the strut-plate juncture formed by the inclined strut and curved plate is presented. The characteristics of the flow are discussed by making use of the solution of the Navier-Stokes equations. To investigate the effects of the inclination angle of the strut and the curvature of the plate on the juncture flows, the computation has been made for three different inclination angles of strut and two different curvature of plate. The flow structure is changed greatly due to the inclination of strut and the forces acting on strut are affected greatly by the inclination angle. However the effects of the curvature of plate on the flow and the forces acting on strut are less than those of inclined cases. Although the plate is curved, the local angle is still 90° and it can be concluded that the local angle between strut and plate will be an important parameter for the flow structure around a juncture.

1. Introduction

When a strut is mounted on the plate, the oncoming boundary layer is separated in front of the strut due to the blocking effect and the separated flow becomes complicated three-dimensional flow by an interaction of the juncture of strut and plate.

Recently, interests in the juncture flow have been increased due to the importance of its application to the design of the appendages and propeller. The characteristics of the juncture flow are the formation of horseshoe vortices and three-dimensional separations. It has been known that the horseshoe vortices are very harmful for the performance of the appendages and propellers located downstream because they increase the drag and produce unsteady wake.

Therefore the study on the juncture flow is required to provide the information for the prediction of the appendage resistance and the unsteady wake. Furthermore, full understanding of the juncture flow will be helpful for the design of appendage which reduces horseshoe vortices to reduce drag and unsteadiness of the flow¹⁾.

The studies on the juncture flow have been performed with a simple configuration of a strut and plate. Several experimental data on the juncture flow, which provide the systematic measurements of the flow for the validation of the numerical computation, can be found in the literature^{2,3)}. Sung and Yang⁴⁾ have computed turbulent juncture flows and compared the flows with the experi-

mental results. Visbal⁵⁾ and Hung et al.⁶⁾ investigated the structure of laminar juncture flow by making use of the computed results. Suzuki et al.⁷⁾ also explained the structure of the juncture flow by numerical flow visualization.

The present study is the continuation of the previous works^{8),9)} where the effects of the Reynolds number and the incidence angle on the juncture flow were investigated by making use of the computational and experimental results. In this paper, we investigate the effects of the inclination of the strut and the curvature of the plate on the juncture flow. The flow is assumed to be laminar and computation is made at the Reynolds number of 10^3 ; this is to avoid the difficulties in analyzing the unsteady flow which would appear at higher Reynolds numbers. Computations with three different inclination angles are made to discuss their effects on the juncture flow and the effects of the curvature of the plate are investigated by making use of the results for the convex and concave plates with radius of two times of the chord length of the strut.

2. Computational Method

2.1 Governing Equation and Numerical Scheme

The governing equations are the Navier-Stokes equation and the continuity equation for the three-dimensional incompressible unsteady flow and they are written in the non-conservation law form in the curvilinear coordinates. All the variables are non-dimensionalized by the uniform velocity U_0 and the chord length of the strut L . The computational methods are the same as the previous ones⁸⁾. The governing equations are solved by MAC method^{10,11,8)} where Poisson equation for the pressure is derived by taking divergence of the momentum equation and satisfying

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Received 10th July 1992

Read at the Autumn meeting 9, 10th Nov. 1992

the continuity equation. Relaxation method is used to solve the Poisson equation for the pressure and the velocities are updated from the momentum equation.

The finite difference equations are derived on the regular grid system. So all the variables are defined on the grid nodes. For the spatial differencing scheme, the 2nd order central difference is used while the 3rd-order upwind scheme for the convective term. Euler explicit scheme is used for the time marching procedure. The computation starts from the still state and the flow is accelerated up to the given constant velocity for the numerical stability.

The no-slip condition is used for the boundary condition on the strut and the flat plate. The Neumann condition for the pressure at the body boundary is obtained from the momentum equation. Symmetric boundary conditions are applied on the symmetric planes by assuming that the flow is symmetric there.

Outer boundaries are taken on the plate including the inflow and the lateral boundaries where the Blasius velocity profile with constant pressure is prescribed. The height of the strut is assumed to be infinite and the zero gradient conditions are used on the top boundary for all the variables. On the downstream boundary, the pressure is linearly extrapolated in the streamwise direction which means the diffusion of pressure in the streamwise direction is negligible.

2.2 Grid Generation

C-type grid is adopted for the computation. The coordinate system and grid topology are shown in Fig. 1. In the physical domain, space-fixed cartesian coordinate 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 directions 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 is the strut's spanwise direction. Therefore the surface of the strut lies in the η -constant plane and the plate lies in the ζ -constant plane.

Two-dimensional C-type grids about the strut are generated by using a geometrical method¹²⁾ and three-dimensional grids are obtained by stacking them algebraically. The range of outer boundaries are as follows.

$$-2.3 \leq x \leq 3.0, -1.8 \leq y \leq 1.8, 0.0 \leq z \leq 1.2$$

Fig. 1 shows one of grids used in computation.

The necessity of orthogonality is required for the grids near the body boundary because they make the application of boundary conditions more straightforward and reduce numerical errors near the boundary. However, orthogonality cannot be always satisfied for the general three-dimensional bodies. If orthogonality of the grids is strictly satisfied near a complicated body, unsmooth or over-skewed grids may be generated apart from the body surface and they will also deteriorate the accuracy of numerical solution.

For the inclined strut and plate configuration treated

Fig. 1 Grid and Coordinate System

in this study, it may be difficult to generate grids satisfying orthogonal condition near the body especially near the juncture. Fig. 4 shows the grids used here where non-orthogonal grids are adopted. The boundary conditions involving normal derivative are represented by interpolation for the physical variables between neighboring points of the boundary to keep the accuracy. The errors can be reduced as possible by using fine grids.

In order to check the accuracy of the present implementation of the boundary condition with interpolation, computations of the flow over the plate are carried out on the non-orthogonal grids at the Reynolds number of 10^3 . Three kind of grids with different inclinations of ζ -direction of 30° on the plate are used with the same number of grids ($35 \times 3 \times 30$) shown in Fig. 2. The Blasius profile and uniform flow are applied for the inflow and external flow boundary condition respectively and the velocities and pressure are linearly extrapolated at the exit boundary. The minimum spacing in ζ -direction is 0.001. Fig. 3 shows the computed shear stress which agrees well with the Blasius' regardless of the inclination of ζ -grid.

Fig. 2 Grids for Flat Plate

Fig. 3 Shear Stress on a Flat Plate

3. Results and Discussion

Computations of the juncture flow have been carried out for three models shown in Fig. 4; the inclined strut mounted on the flat plate and the vertical strut mounted on the convex and concave plates. The effects of inclination angle of the struts are investigated through the computational results of three different inclination angles ϕ ; 15° , 30° , 45° . For all the cases the strut inclines to the negative y -direction. The radius of convex and concave plates are 2. The profile of the strut section is the same as that used in the previous study⁸⁾. The leading edge of the plate is at $x = -3.5$ and the plate expands to infinite in lateral and downstream directions. The boundary layer thickness at the leading edge of the strut is 0.274 which is estimated from the Blasius solution.

All of the computations are carried out at the Reynolds number of 10^3 . Number of grids for the computation of the cases of inclined strut are $113 \times 27 \times 20$ while those for the curved plate are $57 \times 27 \times 20$ where the symmetry condition is used.

3.1 Inclined Strut

In this section, the characteristics of the juncture flow for the inclined strut are investigated by making use of the computational results for the inclined angle of 15° , 30° and 45° . Only the results for the flow with inclined angle of 30° are shown and other results will be shown

Fig. 5 Velocity Vectors on the plane $z=0.004$: $\phi=30^\circ$

only when necessary. In the discussions hereafter we express the both sides of the strut in terms of the angle between strut and plate such as 60° -side and 120° -side or narrower-side and wider-side.

Fig. 5 shows the velocity vectors on the $z=0.004$ plane very close to the plate. The effects of juncture are clearly seen. The singular point near the leading edges is a nodal point of attachment at which the flow is spread out in all directions and the shear stress is zero. This nodal point is shifted to the 60° -side like the flow with an angle of attack where it is shifted to the pressure side (Fig. 17 in ⁸⁾). However, the separation occurs earlier on the 60° -side while it occurs earlier not on the pressure side but on the suction side for the flow with an angle of attack.

Fig. 6 shows the pressure distributions on the plate and $z=0.74$ plane. The effects of the inclination of strut is great on the plate but they decrease as z increases. The pressure distribution on the plate is unsymmetric; the position of maximum pressure i. e., stagnation point, shifts to the 60° -side due to the inclination of the strut. On the other hand the pressure distribution on the $z=0.74$ plane is almost two-dimensional.

Fig. 7 and Fig. 8 show the velocity vectors and pressure distributions on the closest plane to the strut. Large vertical velocity component observed along the leading edge are just transverse component due to the inclination of the strut. Thus, the angle between this velocity

Fig. 4 Geometry of the Juncture

Fig. 6 Pressure on the Plate and on the plane $z=0.74$:
 $\phi=30^\circ$

vectors and x-axis becomes almost equal to the inclination angle as z increases but a strong downwash changes this angle near the plate. The pressure near the juncture is changing in the vertical direction on the 120° -side but almost constant on the 60° -side. The separa-

tion of the flow on the strut is greatly influenced by the plate, which makes an unsymmetric distribution of the pressure on the both sides of the strut up to a considerable height.

Fig. 7 Velocity Vectors on the Developed Surface of the Strut and Wake Plane : $\phi=30^\circ$

Fig. 8 Pressure on the Developed Surface of the Strut and Wake Plane : $\phi=30^\circ$

Fig. 9 shows the contours of the x-component of the shear stress on the plate for the flows of $\phi=30^\circ$ and $\phi=45^\circ$. Here, the magnitude of contours represents the ratio of the computed shear stress to the Blasius solution in the absence of the strut. The ratio is smaller than 1.0 just near the strut but it exceeds 1.0 a little apart from the strut and the shear stress on the narrower-side is larger than the wider-side. The highest shear stress is larger for $\phi=30^\circ$ than for $\phi=45^\circ$ while its position moves farther from the strut for $\phi=45^\circ$ than for $\phi=30^\circ$. The higher shear stress region becomes wider on the narrower-side as the inclination angle increases. The negative shear stress is seen in front of the strut and behind the strut whose region also becomes wider as the inclination angle increases.

The flow pattern on the surface can be described succinctly by limiting streamlines. The limiting streamlines on the plate are shown in Fig. 10. They are obtained by tracing particles on the plane of $\zeta=2$ (closest plane from the plate) by the integration of the tangential velocity components to the plate. As we discussed in the previous paper (Fig. 8 in⁹⁾), two singular points in front of the strut are attachment points; one is a saddle point and the other is a nodal point (indicated by S_1 and N_1). They shift to the narrower-side due to

the influence of the inclination angle and the shift becomes larger as the inclination angle increases. The flow attached at the saddle point of attachment makes attachment line (indicated by A) surrounding the strut with a large radius. The attachment line separates the outer flow from the inner flow. The attachment line on the wider-side ends at the juncture of the strut where the streamlines of the outer flow and those originating from the nodal point of attachment converge and the flow leaves from the plate. On the other hand, the attachment line on the narrower-side is open to downstream. As inclination angle increases, the attachment line moves to the narrower-side and the area of inner region on the wider-side becomes smaller. Such characteristics of the attachment line is similar to those of the flow with an angle of attack (Fig. 12 in⁹⁾). However, the flow structure near the trailing edge and behind the strut is quite different from the flow with an angle of attack. The flow turns from the wider-side to the narrower-side around the trailing edge and the streamlines converge into two spiral nodes or foci (indicated by N_2 and N_3); one is near the trailing edge and the other is on the narrower-side, where the flow separates from the plate. These foci also move to the narrower-side as inclination angle increases. We can find separation line which connects the focus point (N_3) on the narrower-side to the half-saddle point (S'_1) on the strut. This line separates the fluid coming from the outer region on the wider-side from the fluid whose origin is the nodal point of attachment. Open type of separation can be suspected along this line.

Fig. 9 Contours of x-component of the Skin-Friction on the Plate: $\phi=30^\circ, 45^\circ$ (ratio to the ones without strut)

Fig. 10 Limiting Streamlines on the Plate: $\phi=30^\circ, 45^\circ$

Fig. 11 shows the limiting streamlines on the strut for the flow with $\phi=30^\circ, 45^\circ$. The limiting streamlines converge into two lines near the juncture but they meet to become one line at the upper part of the strut near the trailing edge. It can be suspected that the flow leaves from the surface of the strut along this converging line on the upper part of the strut. Two lines near the juncture separates the upwash near the juncture from the upstream flow and reverse flow. The upwash is stronger on the wider-side. Compared with the flow with zero inclination angle (Fig. 9 in⁹⁾), the separation near the trailing edge is affected greatly by the inclination angle. It occurs earlier on the narrower-side but delays on the wider-side. However, the difference is not so large between $\phi=30^\circ$ and $\phi=45^\circ$.

Fig. 12 shows the computed particle paths in a steady three-dimensional flow around a strut with $\phi=30^\circ$. Fig. 12 (a), (b), (c) show the particle paths started from $x=\text{constant}$ line on the closest plane from the plate. The flow near the plate is separated in front of the strut and wraps the strut with large radius. The region which is vacant in Fig. 12 (a) is filled with the fluid originating from the nodal point of attachment which has higher momentum as they downwashed from the higher position. Therefore the shear stress in this region is higher than that in the other region. This region can be identified by the flow visualization because the paint is stripped away quickly. It can be seen that higher stress region is wider on the 60° -side as we have already found in Fig. 9. The particles having turned around from 120° -side to the 60° -side separate from the plate and make an upwash flow at the two foci (N_2 and N_3 in Fig. 10) which are near the trailing edge and on the 60° -side respectively. The particles started from the inside of the

Fig. 11 Limiting Streamlines on the Strut : $\phi=30^\circ, 45^\circ$

attachment line near the trailing edge ($x=0.9$) separate at the three places ; at the two foci and near the juncture on the 120° -side. There are strong reverse flow behind the strut and they are separated at the two foci (Fig. 12(c)). The flow beyond the boundary layer makes upwash flow behind the strut only on the 60° -side as shown in Fig. 12(d). Fig. 12(e) shows the particle paths starting from the vertical line in front of the strut. The particles near the plate wraps the 120° -side with a large radius but they go to the 60° -side along the surface of strut as height increases, which are similar to the flow with angle of attack (Fig. 15(e) in⁹⁾).

Fig. 12 Particle Path : $\phi=30^\circ$

Fig. 13 Spanwise Distribution of the Sectional Drag and Lift Coefficients of the Strut : $\phi = 30^\circ$

Fig. 13 shows the spanwise distribution of the sectional drag and lift coefficients of the strut; C_{df2D} , C_{dp2D} and C_{lp2D} here represent the sectional coefficients of frictional drag, pressure drag and pressure lift respectively. All the coefficients are nondimensionalized by $0.5\rho U^2 L$ where ρ , U and L are density of the fluid, uniform velocity and the chord length of the strut respectively. Each sectional coefficient is computed for the horizontal strip. As the strut is inclined, the thickness of this section becomes larger than that of original section. The frictional drag coefficient increases as z increases and it become constant above the boundary layer thickness. The pressure drag coefficient is smaller near the plate than that beyond the boundary layer thickness. This may be somewhat unexpected results because it has been known that the junction flow makes the drag increase. However, the separations on the strut are much changing in spanwise direction as can be seen in Fig. 11 at the low Reynolds number. Such an earlier separation of the flow near the juncture may be the reason for the decrease of drag. On the other hand, the

Fig. 14 Drag and Lift Coefficients of the Strut as a Function of the Inclination Angle

Fig. 15 Pressure on the Convex Plate and Concave Plate

lift near the juncture is remarkable but it decreases as z increases. Although the lift is expected to become zero as z increases, it still have a finite value even beyond the top of the boundary. A computation with a large computing domain may be required to check.

The forces acting on the strut are displayed as a function of the inclined angle in Fig. 14; C_{df} , C_{dp} and C_{lp} here represent the force coefficients of frictional drag, pressure drag and pressure lift respectively. The forces are obtained by integrating the sectional forces up to $z=0.3$ and nondimensionalized by $0.5\rho U^2 L l$ where l represents the spanwise length of strut over which the integration is carried out ($l=0.3/\cos \phi$). The lift and pressure drag increases while the frictional drag decreases as the inclination angle increases.

3.2 Strut on the Curved Plate

The computation has been done for the convex plate and concave plate which are circular with the radius of 2 shown in Fig. 4.

Fig. 15 shows the distribution of the pressure on the strut for the convex plate and the concave plate. Both

Fig. 16 Shear Stress on the Convex Plate and Concave Plate

are very alike except the region near the juncture where the change of pressure is more hindered on the concave plate than on the convex plate.

Fig. 16 shows the distribution of the shear stress on the plates. The difference of the shear stress between the convex plate and the concave plate is similar to that between the wider-side and the narrower-side in the inclined case but the difference is small. Behind the strut, a wider negative shear stress region is seen for the concave plate.

The limiting streamlines on the plates shown in Fig. 17 does not deviate much from those of the flat plate (Fig. 8 in⁹⁾). There are not so much significant differences in the flow structure for the different radius of curvature of the plate as observed in the flow where the angle of attack or inclined angle are changed. This may suggest that the structure of the juncture flow is largely dependent on the local angle between strut and plate; in other words, although the curvature of the plate is changed, the structure of the juncture flow is not affected much as far as the local angle remains 90° . However, the position of the attachment points are affected by the curvature of the plate. The saddle point of attachment (S_1) in front of the strut moves farther from the strut and the nodal point of attachment (N_2) behind the strut moves also farther behind the strut when the plate has a concaved curvature. The latter makes the reverse-flow region wider on the concave plate.

The limiting streamlines on the strut are shown in Fig. 18. The separations near the plate occurs earlier for the concave plate which can be inferred by the analogy with the result of the inclined strut.

Fig. 19 shows the spanwise distribution of the sectional drag coefficients of the strut. They are almost the same but the pressure drag is a little bigger on the concave plate.

4. Conclusion

The effects of the inclination angle of strut and the curvature of plate are investigated by a numerical study. Findings are summarized as follows.

Fig. 17 Limiting Streamlines on the Plate: convex & concave plate

Fig. 18 Limiting Streamlines on the Strut: convex & concave plate

1) The inclination of strut changes the flow structure greatly by shifting two attachment points to the inclined side and by making two spiral nodes on the plate near the trailing.

2) The inclination angle induces large lift on the strut near the plate. As the inclination angle increases, the frictional drag decreases but the lift and pressure drag acting on the strut increases.

3) The curvature of the plate does not much change the flow structure and the effect on the forces acting on the strut is also small as far as the local angle between strut and plate remains 90° . The local angle between strut and plate is an important parameter for juncture flow.

4) The sectional drag acting on the strut does not increase near the juncture due to an earlier separation near the juncture.

The present calculation is still limited to low Reynolds number flows. Computations of juncture flow at high Reynolds number are necessary for the realistic information about appendage design as a future study.

Fig. 19 Spanwise Distribution of the Sectional Drag Coefficients of the Strut: convex & concave plate

The authors express their appreciation to Prof. Y. Doi at Hiroshima University for his discussions. The present study is partially supported by SR213 project of Shipbuilding Research Association of Japan.

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