Numerical Experiment on Initial Flow Patterns and Fluid Force Characteristics of Two Tandem Symmetrical Airfoils

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***Abstract*— A numerical simulation was performed using a vortex method to investigate the fluid mechanical interferences of two tandem airfoils at variable angles of attack. The distance between two airfoils (distance ratio) in a vessel or submarine and the range of angle of attack were chosen based on the shape of the vessel or submarine. A symmetrical airfoil NACA0012 was used, and the Reynolds number was Re = 3.8 × 10^5. The distance ratio was L/C = 5.0, and different attack angles α = 0°, ±5°, ±10°, and ±15° were considered. The flow characteristic of an initial stage was observed in this study. The flow pattern in each case was obtained via calculations, and the variation in the fluid force in each case and that in the overall lift coefficient were examined. The mutual interference of two airfoils indicated that the rapid variation in the overall lift coefficient occurs at the early stage.**

***Index Terms*— interference, separation, vortex flow, two airfoils, naca0012, numerical simulation**

I. Introduction

The airfoil is a device for generating lift and is an important component in mechanical engineering. The airfoil plays an significant role in changing the direction of the flow, much like the stator of a turbine, the rudder of a ship, or the rudder of an airplane. Therefore, the performance of airfoils and that of the machine equipped with airfoils have been well researched, and many characteristic tests have been performed [1]. Cases of use of multiple airfoils in a vessel and the development and performance of different airfoil shapes, which are specific to the vessel shape, have been extensively studied, leading to the accumulation of a large amount of data. To realize a large lift, the velocity should be increased rapidly or the surface area of the airfoil should be increased. For instance, to obtain a large lift, the number of airfoils in airplanes or ships traveling low speeds is increased. The attack angle is controlled to obtain the lift. The aspect of the flow for a specific attack angle along with the mutual interference of airfoils presents an interesting study. For long and slender ships, such as the ships of a naval fleet and submarines, the width cannot be increased to arrange the rudder; then, the multiple airfoils are very closely arranged. To realize sufficient performance, it is important to understand the interference of the airfoil flows.

Recently, Lee et al. [2] numerically simulated the interference of the two-sheet sail of a sailing yacht. Complicated flow fields, such as those resulting from the interference of flows and separation, were observed around the two-sheet sail. Utsugi et al. [3] numerically simulated the flow around of two tandem airfoils in an airplane during a fly-by. The results were compared with those for the case in which the fluid force of each individual airfoil. Although there was no large variation in the case of the front airfoil, the rear airfoil was influenced by the arrangement position, and the degree of influence of the position on the two airfoils differed. Since the problem of the interference flow between two airfoils is important in engineering, extensive research on this subject is essential. Yokoi [4] simulated the interference flow. Furthermore, Yokoi et al. [5] numerically simulated an interference flow about two closely placed symmetrical airfoils and reported the flow characteristic around the airfoils.

In this study, flows around two airfoils arranged in tandem for different attack angles were numerically examined. The flow and the instantaneous fluid force acting on symmetrical airfoils (NACA0012) were investigated for different attack angles using a vortex method. The Reynolds number of airfoil was set as Re = 3.8 × 10^5 based on the cord length, and the distance ratio of the airfoils was L/C = 5.0. The different attack angles considered were α = 0°, ±5°, ±10°, and ±15°. The results showed that for the tandem arrangement, the total lift was not necessarily large. Further, the fluid force characteristic of each airfoil in the two-airfoil arrangement differs from that of the corresponding airfoil in a single-airfoil arrangement.

II. Numerical Calculations

A. Calculation and Method

For the numerical experiment, simulation software and a notebook-type computer (NEC; LaVie LC958/T) were used. The software used was UzuCrise 2D ver.1.1.3 rev.H (College Master Hands Inc., 2006). The vortex method, which is based on Lagrangian analysis, was employed. The vortex method is a direct viscid-inviscid interaction

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scheme, and the creation of velocity shear layers because of boundary layer separation is represented by the introduction of discrete vortices with a viscous core in timesteps. The airfoil configuration was represented using 80 vortex panels by the boundary element method. The separating shear layers were represented as discreet vortices, which were introduced at the separation points. The details of calculation technique and calculation accuracy are reported by Kamemoto [6, 7].

B. Calculation Conditions and Parameters

Two-dimensional calculations were performed for incompressible and viscous flows. The symmetrical airfoil NACA0012 was used as objective form. Fig. 1 shows the configuration of the airfoil. The symmetrical airfoil was divided into 80 panels, over which the vortices were distributed. Here, the target object is assumed as the rudder of a submarine, and the velocity at the time of coming alongside the quay is assumed. So, the fluid is water, and the chord length of the airfoil is set as C = 1.0 m. Although the cruising speed of a submarine is 20 knots, at the time of coming alongside the quay, the velocity reduces to about 1 knot. So, the main flow velocity U used in the calculation was set as 0.5 m/s. The Reynolds number was set as $Re = 3.8 \times 10^5$. Two tandem airfoils in the form of a tuna were considered. One was set near the middle position of the hull, and the other, at the stern. So, the distance ratio of the two airfoils was set as L/C = 5.0 (here, L denotes the distance between the centers of lift of the two airfoils). Every calculation was continued beyond the nondimensional time $T = N\Delta t\ U/C$ = 5 at time steps Δt = 0.01 s (N is the number of times the calculation was performed (=1000 times)). The calculation area extended from −2 m to 15 m in the x direction, and from −10 m to +10 m in the y direction. The origin was set at the center of lift, which is 1/4th the chord length of the airfoil from the leading edge. Here for convenience, in the case of two airfoils, the airfoil at the front is called the 1st airfoil and that at the rear is called the 2nd airfoil.

The main parameter in the numerical experiment was the attack angle α. Seven values of attack angles were considered: from −15° to 15° in steps of 5° (α = −15°, −10°, −5°, 0°, 5°, 10°, and 15°). In all, 28 combinations of the attack angles for the two airfoils were considered for numerical simulation.

III. Results and Discussions

A. Case of the Single Airfoil

It is known that a two-dimensional numerical calculation will yield a numerical value higher than an experimental value. So, the calculation result was compared with the case of a two-dimensional single airfoil. The values of the lift coefficient for every attack angle are listed in Table 1.

TABLE I. Lift Coefficients of the Single Airfoil for Every Attack Angle (T = 5)

α	0	5	10	15
C_L	0.0000	0.5400	1.1831	1.6403

B. One of the Two Airfoils Has no Attack Angle

There are two kinds of airfoil-setting scenarios. In one scenario, the 1st airfoil has no attack angle, and in another scenario, the 2nd airfoil has no attack angle. The flow patterns in these scenarios and the time histories of fluid force are shown in Figs. 2 and 3, respectively. Here, the flow pattern for the nondimensional time T = 5 is seen. In Fig. 2, the scenario in which the 1st airfoil has no attack angle is shown. It is obtained that not dependent on the attack angle of the 2nd airfoil, and no separation is produced on the 1st airfoil surface. The flow discharged from the trailing edge is not turbulent, and it flows into the suction surface side of the 2nd airfoil.

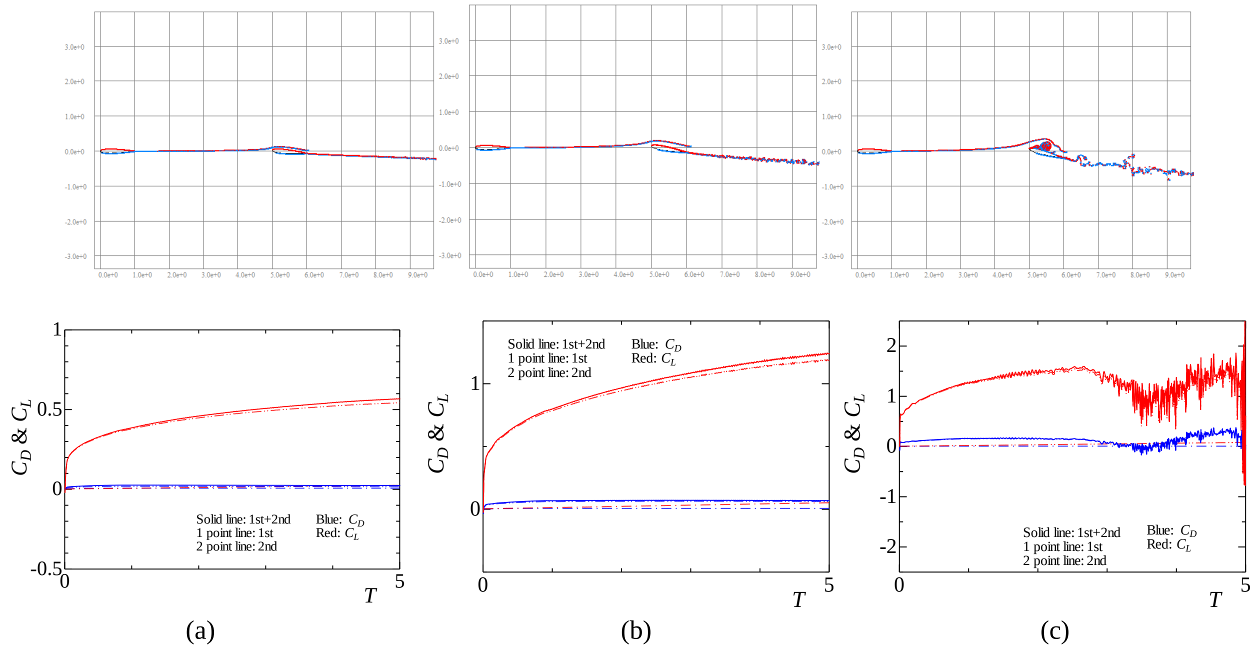

Figure 2. Instantaneous flow patterns at non-dimensional time T = 5 and time histories of drag and lift coeficients for the 1st airfoil without attack angle, (a) α = 0°, 5°, (b) α = 0°, 10°, and (c) α = 0°, 15°

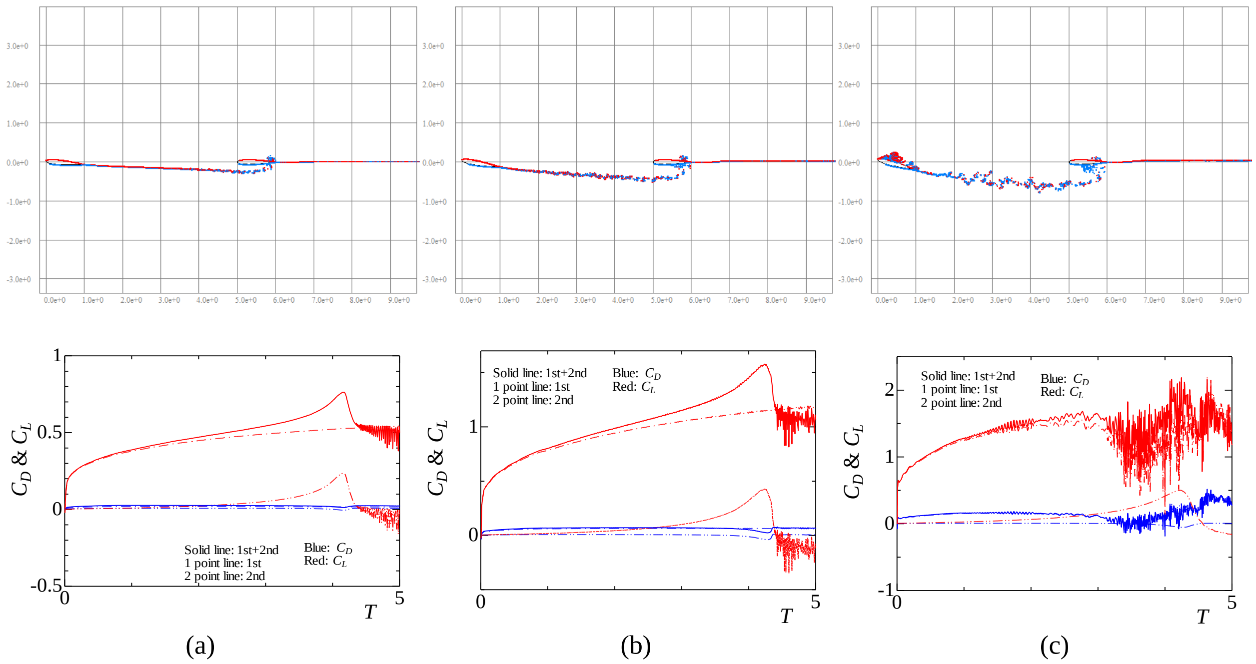

Figure 3. Instantaneous flow patterns at non-dimensional time T = 5 and time histories of drag and lift coeficients for the 2nd airfoil without an attack angle, (a) α = 5 °, 0 °, (b) α = 10 °, 0 °, and (c) α = 15 °, 0 °

The scenario in which the 2nd airfoil has no attack angle is shown in Fig. 3. When an attack angle is attached to the 1st airfoil, the flow from the trailing edge flows into the pressure surface side of the 2nd airfoil. Therefore, rapid variation appeared by T = 4 in the time history of the 2nd airfoil because the first vortex discharged from the 1st airfoil collided with the 2nd airfoil. Moreover, since the pressure is reduced by the vortex flow, a negative lift occurs at the 2nd airfoil. The vortex flow discharged from the 1st airfoil turns into a complicated turbulent flow as the attack angle increases.

The values of the lift coefficient (C_L value) in the nondimensional time T = 5 for each attack angle are listed in Table 2. Lift also occurs for the airfoils without an attack angle owing to the mutual interference flow. Here, the underline values in the table are larger than the values for the single airfoil. The scenarios in which the effect of two airfoils was obtained corresponded to 2nd airfoil attack angles 5 ° and 10 °. To obtain a large total lift, the 2nd airfoil should have a large attack angle.

TABLE II. VALUES OF LIFT COEFFICIENTS IN DIFFERENT SCENARIOS

	1st airfoil without attack angle			2nd airfoil without attack angle		
α(1st,2nd)	(0, 5)	(0, 10)	(0, 15)	(5, 0)	(10, 0)	(15, 0)
1st C_L	0.0251	0.0521	0.0774	0.5421	1.1828	1.3418
2nd C_L	0.5421	1.1885	0.5267	-0.0397	-0.1138	-0.1588
Total	0.5672	1.2406	0.6047	0.5024	1.0690	1.1830

C. *Two airfoils Have Attack Angles*

Two types of airfoil-setting situations are considered. In one setting, airfoils are set in the same direction, and in the other, they are set in different directions. The setting angle of the 1st airfoil was fixed, and that of the 2nd airfoil was varied. Several series calculations were performed. Fig. 4 shows the change in the value of the sum total lift coefficient when fixing the attack angle of the 1st airfoil and varying the attack angle of the 2nd airfoil. Since the positive attack angle is set for the 1st airfoil, the negative angle in the figure indicates a different direction. The black dot in the figure shows the case of the single airfoil. When there is no attack angle for the 1st airfoil, the value of the sum total lift is the same as that for the single airfoil; however, the situation is different when the attack angle of the 2nd airfoil is 15 °.When the 1st airfoil has an attack angle, the sum total lift coefficient exceeds that for the single airfoil in almost all cases. However, the combination from which the lift effect is obtained 2 times was only three cases. These combinations of the attack angles of the 1st airfoil and 2nd airfoil were "10 ° and 5°," "15 ° and 5 °," and "15 ° and 10 °." When an airfoil had no attack angle, , the second airfoil was dominant in the sum total lift calculation, as presented in Table 2. When both airfoils had an attack angle, the 1st airfoil contributed to the sum total lift coefficient. Although the 2nd airfoil might contribute, it was found that a dominant part is the 1st airfoil. This is an interesting observation. The present calculation shows that separation arises for an attack angle of 15°. The separation flow produces noise, which is inconvenient for ships such as submarines that need silence. Therefore, it is important to choose an angle that does not cause separation. So, it is found that "10° and 5°" is the best combination of the setting angle for the two airfoils. This is an important result indicating that large lifts can be obtained by combining airfoils with attack angles that do not cause the production of separation.

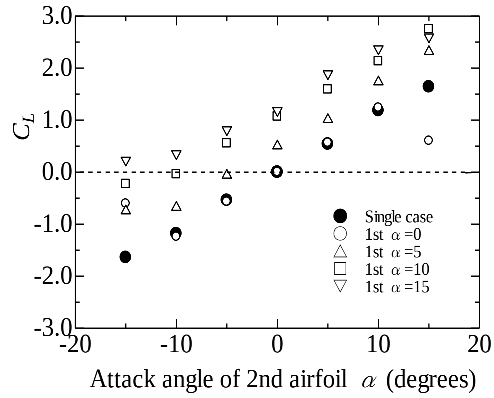

Figure 4. Relationship between the attack angle and the total lift coefficient

IV. Conclusions

Numerical simulations of the initial flow around two tandem airfoils with different attack angles were performed by using the vortex method. The following conclusions were obtained.

(1) Lift occurred by the mutual interference flow even when the airfoils did not have an attack angle.

(2) When the 1st airfoil had no attack angle, the value of the sum total lift was the same as that for a single airfoil; the results differed when the attack angle of the 2nd airfoil was 15°.

(3) When the 1st airfoil had an attack angle, the sum total lift coefficient exceeded the case of the single airfoil for almost all cases.

(4) When both airfoils had attack angles, the 1st airfoil contributed to the value of the sum total lift coefficient.

(5) In the scenario mentioned in point (4), the best combination of attack angles of the 1st and 2nd airfoils was "10° and 5°." .

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