The Flow Characteristics in Early Stages of the Close Tandem Symmetrical Airfoils

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***Abstract*—A numerical simulation was performed using a vortex method in order to investigate the flow fluid to two tandem airfoils which arranged closer at variable angles of attack. Based on the shape of a vessel or a submarine, the mutual distance between the two airfoils (distance ratio) and the range of angle of attack were chosen. A symmetrical airfoil NACA0012 was used and the Reynolds number which based on chord length of airfoil *c* was *Re* = 3.8×10^5. The setting of distance ratio was *L/c* = 2.0 (here, *L* denote distance between two lift center of airfoil), the angle of attack of airfoils were varied as α = 0, ±5, ±10 and ±15 degrees. The initial stage was observed in this study. As a result of calculations, the flow pattern in each case was obtained, the variation of the fluid force in each case was investigated, and the variation of an overall lift coefficient was shown. By the mutual interference of two airfoils, it was found that the rapid variation of the overall lift coefficient occurs in an early stage.**

***Index Terms*—interference, separation, two airfoils, NACA0012, numerical simulation**

I. Introduction

The "airfoil" is a device for generating lift, and is one of the important constituent factors on mechanical engineering. Moreover, the "airfoil" has the role which changes the direction of the flow like the stator of a turbine, the rudder of a ship, or the rudder of an airplane. Therefore, numerous studies on the performance about an "airfoil" and the performance of the machine constituted using the "airfoil" and many characteristic tests have been performed [1]. The airfoil in the case of being used as an element which constitutes a machine exists by plurality in many cases, the development and the performance test of airfoil shape which balanced on that occasion are performed, and there is accumulation of many data. On the other hand, in order to obtain a large lift, making velocity quick or enlarging surface area of an airfoil is known. In such a reason, the airplane which flies at a low speed, and the ship which cruises at a low speed have tried to obtain a large lift by increasing the number of airfoils. The angle of attack is applied in order to obtain the lift. It is one of the most interesting things to investigate the aspect of the flow when applying an angle of attack in the time of the mutual interference of arrangement occurring. By ship of long and slender types, such as a naval fleet and a submarine, in order to arrange the rudder, the width cannot be made wide. In this case, the setting interval of multiple airfoils is very close. If enough performance is expected, it is important to understand interference of the flow of airfoils.

Recently, as the study relevant to interference of the flow of airfoils, Lee et. al. [2] performed the numerical simulation for the aspect of interference of the two-sheet sail of a sailing yacht. As a result, it was shown that complicated flow fields, such as interference of flow and separation, are in the surroundings of the two-sheet sail. Utsugi et. al. [3] performed the numerical simulation of the flow around of the tandem arrangement two airfoil which carries out a flyby. It was compared with the case where the fluid force of each airfoil is a single airfoil, and was investigated. As a result, although there was no variation in a front airfoil so much, the rear airfoil was influenced in the arrangement position and it was shown that the grades of the influence differ. Since the problem of the interference flow between two airfoils is important on engineering, accumulation of many study is needed further. Yokoi [4] investigated the aspect of the interference flow wheal simulation. Furthermore, Yokoi et. al. [5] performed the numerical simulation of an interference flow about two symmetrical airfoils by which close setting was carried out, and they reported the flow characteristic around those airfoil. Yokoi [6] performed the numerical simulation of flow around an airfoil of tandem arrangement from the layout of the fin of a "tuna", and showed the fluid force characteristics and flow patterns. In tandem arrangement, if the interval of two airfoils is narrowed, they will contact and will become one body. Accordingly, the two airfoils will constitute one total airfoil (compound airfoil). Such the "compound airfoil" is already used also in the airplane or the ship. Since the compound airfoil is promising as an apparatus which obtains a high lift, there are many examples of study [7-11]. However, those many are carried out in a special design, and the fundamental data which combined the existing airfoil type is not obtained. It is one of the most interesting things to get to know the variation of the fluid force at the time of the basic shape

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airfoil which already exists carrying out mutual interference.

In this study, numerical experiment of flow around the two NACA0012 type airfoils which arranged in tandem with angle of attack was performed. The aspect of flow and the instantaneous fluid force act on symmetrical airfoil with angle of attack were investigated using a vortex method at the Reynolds number which based on chord length of airfoil $Re = 3.8\times10^5$, at the distance ratio $L/c = 2.0$ and the cases of angle of attack $\alpha = 0$, 5, 10 and 15 degrees.

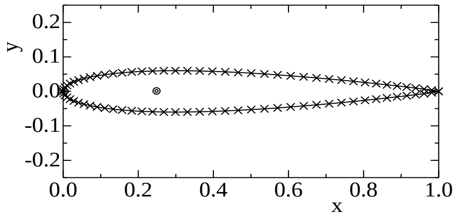


Figure 1. Layout of vortex panels

TABLE I. THE LIFT COEFFICIENT OF THE SINGLE AIRFOIL FOR EVERY ANGLE OF ATTACK (T = 5)

α	0	5	10	15
C_L	0.0000	0.5400	1.1831	1.6403

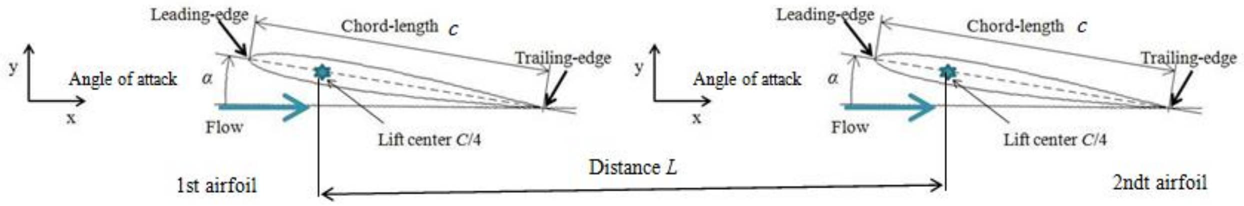


Figure 2. Shape of the airfoil, and explanation of the term

II. NUMERICAL CALCULATIONS

A. Calculation Apparatus and Method

The numerical experiment apparatus was a consisted of simulation software and a notebook type computer (NEC; LaVie LC958/T) as calculation hardware which are on the market. The software which named 'UzuCrise 2D ver.1.1.3 rev.H (College Master Hands Inc., 2006)' is used. This software used the vortex method which is based on the Lagrangian analysis. The vortex method is a direct viscid-inviscid interaction scheme, and the emanation of velocity shear layers due to boundary layer separation is represented by introduction of discrete vortices with viscous core step by step of time. The configuration of airfoil was represented 80 vortex panels using a boundary element method. The arrangement plan of vortex panels is shown in Fig. 1. Here, the double circle inside vortex panels shows the position of the center of lift. The separating shear layers were represented the discreet vortices which were introduced at the separation points. The details of calculation technique of vortex method and accuracy of calculation are shown in Kamemoto [12, 13].

B. Calculation Conditions and Parameters

The numerical experiment was performed at the two-dimensional calculation for incompressible and viscous flow. The symmetrical type airfoil "NACA0012" was used as objective form. Fig. 2 shows the configuration of the airfoil and explanation of the term on the airfoil. The symmetrical airfoil was divided into 80 panels which distributed the vortices. Here, the target object assumes the rudder of a submarine and assumes the velocity at the time of coming alongside the quay. So, the fluid is water and the chord length of airfoil was $c = 1.0$ m. Although the cruising speed of submarine is 20 knots, the velocity at the time of coming alongside the quay becomes about 1 knot. So, the main flow velocity U used by calculation was set to 0.5 m/s. (Here, the main flow velocity shall be given from the calculation start time.) The Reynolds number ($Re=Uc/\nu$, ν is kinematic viscosity of water) becomes $Re = 3.8\times10^5$. Our laboratory team sets development of the rudder equipped with "the slat and the flap" as the future purpose. The rudder is the compound airfoil which consists of a slat section, a support section (stay section), and a flap section. Since the slat section and the flap section are movable parts, the gap between the stay sections is required for them respectively. It is possible that the magnitude of this gap is the factor which influences the characteristic of the compound airfoil. So, grasp of the flow characteristic without the stay section as basic data is needed. In this study, the numerical simulation of the mutual interference flow of two airfoils which were brought close and have been arranged in series is performed. If airfoil chord length of each section is set to same length c, compound airfoil full length will be set to $3c$. So, the distance ratio of two airfoils was set to L/c=2.0 (here, L denote distance between two airfoils of lift center). Every calculation continued to more than non-dimensional time $T = N\Delta t\ U/c = 5$ at intervals of time step $\Delta t = 0.01$ s (N is the number of times of calculation (= 1000 times)). Here, the non-dimension time $T = 5$ is equivalent to 10 seconds in real time. The calculation area was from -2 m to 15 m in x direction, and ±10 m in y direction. The origin was set at lift center which is 1/4 chord length of airfoil from the leading edge. Here for convenience, in the case of two airfoils, the front side airfoil was called the 1st airfoil, and the rear side airfoil was called the 2nd airfoil. Main parameter of numerical experiment was the angle of attack α. Seven kinds of angles of attack were varied from -15 degrees to 15 degrees with 5 degrees step (α = -15, -10, -5, 0, 5, 10 and 15 degrees). The combination of the angle of attack in two airfoils is 13 kinds, and the numerical simulation was performed in each combination.

III. Results and Discussions

A. Single Airfoil Case

It is known that a two dimensional numerical calculation result will constitute a higher numerical value as compared with an experimental value. So, consultation of this calculation result was performed as compared with the case of a two dimensional single airfoil. The values of the lift coefficient for every angle of attack are shown in Table 1. Validity of this calculation was performed by checking the flow pattern. It is known that separation will not produce the NACA0012 type airfoil in the 12 or less degrees of angle of attack. The calculation results in the case of the non-dimension time T = 5 of each degree of angle of attack by this calculation technique (0 degree, 5 degrees, 10 degrees, and 15 degrees) are shown in Fig. 3, respectively. In the cases of angle of attack 0 degree, 5 degrees and 10 degrees, it was shown that the flow along the airfoil surface without separation in a pressure side and a suction side join in a trailing edge. On the other hand, when the angle of attack is 15 degrees, forming the large-scale separation bubble on the suction surface of the airfoil is seen. By having obtained such flow patterns, it seems that this calculation technique is appropriate.

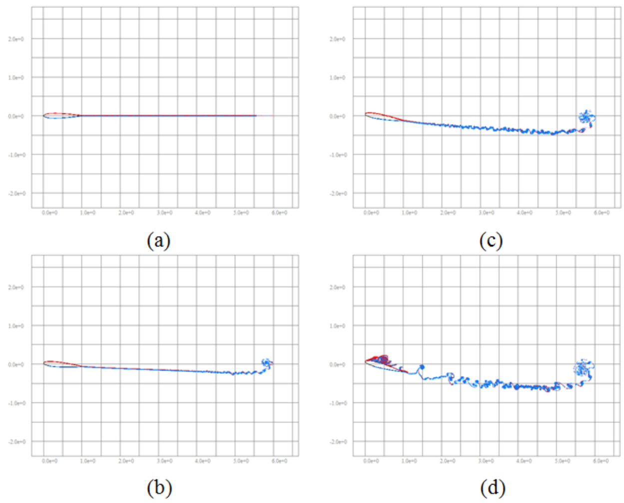


Figure 3. The flow pattern of a single airfoil in T = 5, (a) α = 0 degree, (b) α = 5 degrees, (c) α = 10 degrees, (d) α = 15 degrees, blue points mean a counterclockwise rotation vortex and red points mean a clockwise rotation vortex.

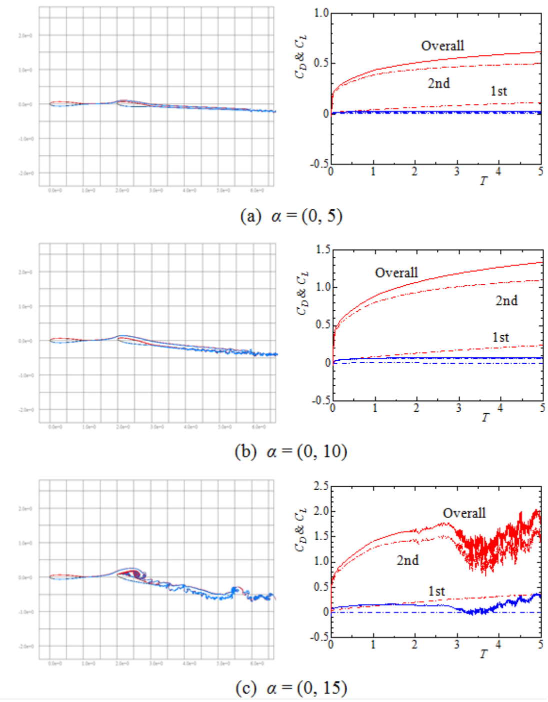
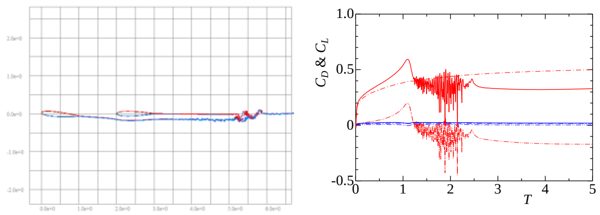


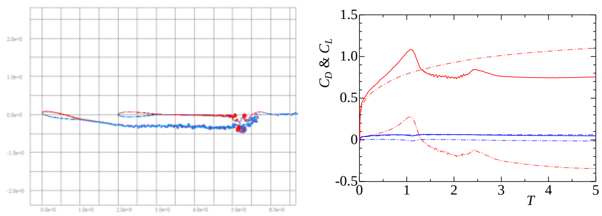
Figure 4. Instantaneous flow pattern at non-dimentional time T = 5 and time histories of drag (blue color) and lift (red color) coeficients, in the case of 1st airfoil withount angle of attack, (a) α; 0,5 degrees, (b) α; 0, 10 degrees, (c) α; 0, 15 degrees

B. One of the Two Airfoils Has No Angle of Attack

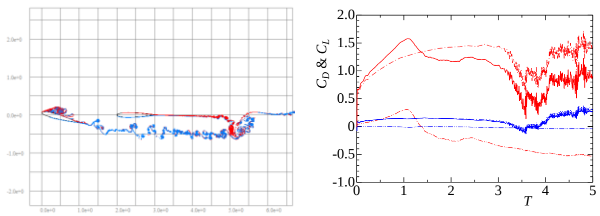
There are two kinds of airfoil setting situations. One of which is in the situation which does not have an angle of attack in the 1st airfoil, and another is in the situation which does not have an angle of attack in the 2nd airfoil. The flow patterns in those situations and the time histories of fluid force are shown in Figs. 4 and 5. Here, the flow pattern shows the aspect of the non-dimensional time T = 5. In the Fig. 4, the case where there is no angle of attack in the 1st airfoil, and an angle of attack is attached to the 2nd airfoil is shown. It is not dependent on the angle of attack of the 2nd airfoil, and separation is not produced on the 1st airfoil surface. And the flow discharged from the trailing edge does not have turbulence, and is flowing into the suction surface side of the 2nd airfoil. From the time history of fluid force, the 2nd airfoil can be seen have produced the overall lift (red solid line). Moreover, although there is no angle of attack in the 1st airfoil, it is found that the lift has occurred with time progress. It is in the tendency for such a large lift that an angle of attack be large to be obtained. However, in 15 degrees of angles of attack, it is shown that the rapid fall of the lift occurs at non-dimensional time T = 2.8 (real time 5.6 seconds). If sudden transfer is expected, it can imagine that what is necessary is just to enlarge an angle of attack, but it is found that the retention time must be imposed on mind.



(a) α = (5, 0)



(b) α = (10, 0)



(c) α = (15, 0)

Figure 5. Instantaneous flow pattern at non-dimentional time T = 5 and time histories of drag (blue color) and lift (red color) coeficients, in the case of 1st airfoil withount angle of attack, (a) α; 5, 0 degrees, (b) α; 10, 0 degrees, (c) α; 15, 0 degrees

The case where there is no angle of attack in the 2nd airfoil, and an angle of attack is attached to the 1st airfoil is shown in the Fig. 5. In this case, the 2nd airfoil can consider being influenced by downwash from the 1st airfoil. When an angle of attack is attached to the 1st airfoil, the flow from the trailing edge is flowing into the left hand side of the 2nd airfoil. In all the state, it is found that there is no separation of the flow on the 2nd airfoil surface. Moreover, as for the wake from two airfoils, joining in the position of x/c = 5.25 in any case can be found. When the time history of fluid force is seen, it turns out that the 1st airfoil produces the overall lift actively. When angles of attack are 5 degrees and 10 degrees, the lift (red one-pointed line) produced with the 1st airfoils can be seen be developed with progress of time. As an interesting thing, although there is no angle of attack in the 2nd airfoil, the positive lift is acting till non-dimensional time T = 1.1. The negative lift is acting on the 2nd airfoil after that. The rapid variation shown at non-dimensional time T = 1.1 is considered for the vortex discharged to the beginning from the 1st airfoil to reach the 2nd airfoil. In order that a negative lift might act on the 2nd airfoil, it was found that an overall lift becomes lower than the lift of the 1st airfoil. As a thing interesting again, when an angle of attack was attached to the 1st airfoil, the time taken to obtain the maximum overall lift to the case where an angle of attack is attached to the 2nd airfoil was seen become short. When the case of 10 degrees of angles of attack is taken for an example, the time when the value of the lift coefficient is set to C_L = 1.0 is T = 1.0 when the 1st airfoil has an angle of attack, and when the 2nd airfoil has an angle of attack, it is T = 1.5.

The values of the lift coefficient (C_L value) in the non-dimensional time T = 5 in each angle of attack are shown in Table 2. Here, the underline in the table means being larger than the value of the single airfoil. It is shown that the lift has occurred also with the airfoils without an angle of attack by the mutual interference flow. In order to obtain the large sum overall lift value, it became clear that the large angle of attack was attached to the 2nd airfoil.

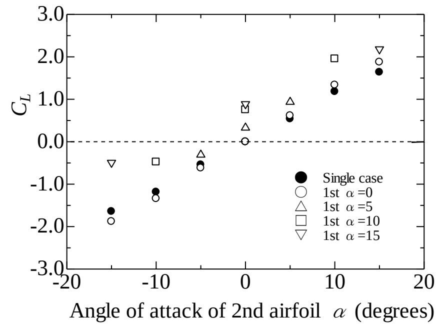


Figure 6. The Relationship between the angle of attack and the total lift coefficient

TABLE II. THE VALUES OF THE LIFT COEFFICIENT IN EACH ANGLE OF ATTACK

	1st airfoil without angle of attack			2nd airfoil without angle of attack		
α(1st,2nd)	(0, 5)	(0, 10)	(0, 15)	(5, 0)	(10, 0)	(15, 0)
1st C_L	<u>0.1159</u>	<u>0.2379</u>	<u>0.3577</u>	0.4999	1.1010	1.4262
2nd C_L	0.5011	1.1007	1.5201	-0.1706	-0.3468	-0.5380
Total	<u>0.6170</u>	<u>1.3386</u>	<u>1.8778</u>	0.3293	0.7542	0.8882

C. *Two Airfoils Have Angle of Attack*

There are two kinds of airfoil setting situations. One of which is the same direction set, and the other is the different direction set. In this case, the setting angle of the 1st airfoil was fixed, the setting angle of the second airfoil was varied, and several series calculation was performed. Fig. 6 shows change of the value of the sum overall lift coefficient when fixing the angle of attack of the 1st airfoil and varying the angle of attack of the 2nd airfoil. Since the positive angle of attack is set to the 1st airfoil here, the negative angle in the figure means a different direction setup. The black dot mark in the figure shows the case of the single airfoil. When there is no angle of attack of the 1st airfoil, the value of the sum overall lift is the same as the case of the single airfoil, but differing is shown when the angle of attack of the 2nd airfoil is made into 15 degrees. When an angle of attack is in the 1st airfoil, it is seen that the value of the sum overall lift coefficient exceeds the case of the single airfoil by almost every cases.

When an angle of attack did not have one of airfoils, the second airfoil was dominant in the sum overall lift calculation as shown in Table 2. To such a matter, when an angle of attack is set as both airfoils, the 1st airfoil has contributed to the value of the sum overall lift coefficient. When based on zero of an abscissa in Fig. 6, the angle of attack of same direction is right-hand side, and the angle of attack of different direction is left-hand side. In order to obtain the overall lift exceeding the lift of single airfoil, it turns out clearly that what is necessary is just to carry out both of angles of attack in the same direction. Here, the time of the angle of attack of both airfoils being 15 degrees can be seen able to obtain the maximum lift. However, when the angle of attack is 15 degrees, don't forget for separation to occur. This is an important thing. It is shown by present calculation that separation arises that an angle of attack is 15 degrees. The separation flow produces noise. The produced noise is an inconvenient thing for the ship which was able to search for silence like a submarine. It is important to choose the angle which does not cause separation. So, it was found that "10 degrees and 10 degrees" is the best as for the combination of the setting angle of two airfoils. It is an industrial very important result that the big lift can be obtained by combining airfoils by the angle of attack which does not produce separation.

IV. Conclusions

Numerical simulations of initial flow around the tandem arranged two airfoils with angle of attack were performed by use of the vortex method. The following conclusions were obtained.

(1) It is shown that the lift has occurred also with the airfoils without an angle of attack by the mutual interference flow.

(2) When there is no angle of attack of the 1st airfoil, the value of the sum overall lift is the same as the case of the single airfoil, but differing is shown when the angle of attack of the 2nd airfoil is made into 15 degrees.

(3) In this situation of numerical experiment, it was found that "10 degrees and 10 degrees" is the best as for the combination of the setting angle of two airfoils.

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