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CHARACTERISTICS OF UNSTEADY FLOW FIELD OF LAMINAR SEPARATION BUBBLE ON A NACA0012 AIRFOIL AT LOW REYNOLDS NUMBERS

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ABSTRACT: In order to examine and clarify details of unsteady flow field around an airfoil involving laminar separation region and a separation bubble, PIV measurements for the flow field around a NACA0012 airfoil were performed in three types of Reynolds numbers of 10,000, 20,000 and 30,000 as representative cases of low Reynolds number flows. By time averaged results of the flow field, differences in flow state according to separated flows on the airfoil were confirmed in terms of appearance of the separation bubble on the airfoil; the separation bubble cannot be observed in \( \text{Re} = 10,000 \), can be observed in the other Reynolds numbers. Instantaneous results of the flow field show unsteady reattachment of the separated flow as time advances in all Reynolds number cases. The unsteady reattachment occurs intermittently in \( \text{Re} = 10,000 \), on the other hand occurs periodically in \( \text{Re} = 20,000 \) and \( \text{Re} = 30,000 \). The changes of flow state on the airfoil are depend on these flow phenomena involving separation regions due to increasing of instability and vortex structures in the separated flow. And, it contributes to changes of aerodynamic characteristics of the airfoil at low Reynolds number flows consequently.

1 Introduction

Flow field on an airfoil at low Reynolds number flows show different flow state compared with the high Reynolds number flows[1] because of appearance of laminar separation, reattachment of separated shear layer, and formation of a separation bubble on the airfoil. Although the separation bubble is confirmed on an airfoil surface in high Reynolds number flows, it is formed as a short stream-wise length below 1% order of the chord length and exists at nearly leading edge of the airfoil. On the other hand, in low Reynolds number flows, the separation bubble becomes more longer than the high Reynolds number’s bubble and it widely exists on the airfoil surface until occurring the wing stall[2],[3]. These flow features involve reversed flow region on the airfoil and are unsteady flows state in nature, it makes the flow field complicate on the airfoil at low Reynolds number flows. It is found that the changes of flow state on the airfoil due to involving separation regions in boundary layer affect aerodynamic characteristics of the airfoil at Reynolds number flows of \( 10^4(O) \) based on the airfoil chord length[4],[5],[6].

In using a thicker airfoil, for example NACA0012, it was found that the aerodynamic performance becomes worse as decreasing its Reynolds number[7]. This change is mainly caused by reason of deterioration of lift force due to boundary layer separation on the airfoil. On the other hand, in using a thinner airfoil, its thickness ratio of airfoil thickness to airfoil chord length as \( t/c \) is below several percent,
the aerodynamic performance shows better values than the thicker airfoil’s one in low Reynolds number flows. Using a thinner airfoil for an actual airplane which operated in low Reynolds number condition means that strength of its main wing is weakened instead of giving a better aerodynamic performance than using of a thicker airfoil. If a thicker airfoil will have a good aerodynamic performance by controlling the flow field involving a separation region on the airfoil, it can solve some problems in use a thinner airfoil for airplane’s main wing in low Reynolds number flows. Therefore, it is meaningful to understand what kind of flow structures appear on an airfoil so that we do effective control of separated flow on the airfoil. And, it will contribute to realize development of an actual airplane having good performance which operated in low Reynolds number flows.

However, there are many uncertain points in details of flow structures on an airfoil at low Reynolds number flows and it makes difficult to understand mechanism of transition from separated shear layer to reattached flow on the airfoil. The flow field involving reversed flows around an airfoil is also difficult to measure velocity components and distributions in general. We applied an unsteady PIV technique to acquire spatial velocity components of the flow field around the airfoil. Measurements of the flow field are performed in three cases of Reynolds number of 10,000, 20,000 and 30,000 with a two-dimensional wing model which applied NACA0012 airfoil to cross section of the wing model.

In this paper, we firstly describe fundamental characteristics of flow state on the airfoil as increasing of angle of attack in all cases of Reynolds numbers by using time-averaged flow field, that is, we can understand static behaviors of a separation region on the airfoil. And, by using the acquired time series data, we describe unsteady flow field on the airfoil including complicated flow structures which caused by both increasing of flow instability and existing of vortex structures. Comparison with both flow states on the airfoil, we discuss details of complicated flow structures due to appearance of both separation and reattachment of the flow field on the airfoil at low Reynolds number flows.

2 Experimental Apparatus and Method

We performed PIV measurements of flow field around a NACA0012 airfoil. Experimental apparatus is shown in Fig.1. A two-dimensional wing model which applied NACA0012 airfoil to the model’s cross section is used for measurements and it has chord length and span-width length, \( c = 65 \text{ mm} \) and \( b = 150 \text{ mm} \), respectively. Wind tunnel has a cross section area of 150 mm \( \times \) 150 mm at nozzle exit and side walls are installed in the test section in order to keep span-wise two-dimensionality of the flow field in the test section. The model is installed among the side walls as shown in Fig. 1. Three types of Reynolds numbers are conducted to measurements as \( Re = 10,000, 20,000 \) and \( 30,000 \) based on the chord length \( c \). The angle of attack \( \alpha \) was varied from \( \alpha = 0 \) to \( 20^\circ \). Tracer particles of olive-oil are injected immediately behind fan-unit of the wind tunnel. Laser light sheet is made by a CW Nd:Yag laser unit (G5000K: Kato Koken Co., Ltd.) with a cylindrical lens unit. High-speed camera is used to acquire time series of particle images around the airfoil. A lens having focal length of 105 mm is also used with the high-speed camera. Two-dimensional velocity components of \( \mathbf{v} \) around the airfoil, \( x \)-directional velocity of \( u \) and \( y \)-directional of \( v \), are analyzed from the acquired images using Flow Expert 2D2C (Kato Koken Co., Ltd.) with recursive correlation method.
3 Results and Discussions

3.1 Time-averaged Flow Field on the Airfoil

Figs. 2 to 4 show results at $\alpha = 10^\circ$ as a representative case of in Reynolds number of 10,000 to 30,000 including both velocity field of time-averaged velocity component $\bar{u}$ as a horizontal directional component of the uniform velocity $U$ and stream lines on the upper surface of the airfoil. In these figures, a filled darkest blue area shows a reversed flow region due to occurring boundary layer separation on the airfoil, that is, laminar separation region is also confirmed on the airfoil. The appearance of laminar separation is confirmed in all testing Reynolds numbers. Reattachment of the separated flow, however, could not confirm on the airfoil in only Reynolds number of 10,000 as varying the angle of attack. In the other Reynolds number cases of 20,000 and 30,000, reattachment of the separated flow is confirmed on the airfoil, that is, a separation bubble is formed on the airfoil. The separation bubble has rather long length about any tens percentage of the chord length and this bubble exists on the airfoil in widely range of the angle of attack before occurring the wing stall. By these time averaged results, it is found that fundamental flow state involving the separation region or the separation bubble is changed depending on Reynolds number changing nearby $Re = 10,000$.

Figs. 5 to 7 show variations of changes of separation points and reattachment points on the airfoil at Reynolds number from 10,000 to 30,000 calculating by velocity gradient $\partial \bar{u} / \partial y$ nearly the airfoil surface. By these results, the separation bubble is not formed on the airfoil at $Re = 10,000$, on the other hand the separation bubble is formed on the airfoil over $Re = 20,000$. The separation bubble on the airfoil is reducing its length gradually as increasing of the angle of attack, however the bubble is increasing its length as a border through a certain angles of $\alpha \geq 10^\circ$ in $Re = 20,000$ and $\alpha \geq 13^\circ$ in $Re = 30,000$. These angles also agree with the angles of occurring stall of the airfoil. The flow state involving the bubble might be shown greatly changes corresponding with change of the aerodynamic characteristics, as a result characteristics of the separation bubble changes from short-bubble to long-bubble and we can find behaviors of the separation bubble by using the time-averaged flow field.
Fig. 2. Distribution of velocity \( \vec{u} \) and streamlines on NACA0012 airfoil (\( Re = 10,000, \, \alpha = 10^\circ \))

Fig. 3. Distribution of velocity \( \vec{u} \) and streamlines on NACA0012 airfoil (\( Re = 20,000, \, \alpha = 10^\circ \))

Fig. 4. Distribution of velocity \( \vec{u} \) and streamlines on NACA0012 airfoil (\( Re = 30,000, \, \alpha = 10^\circ \))
3.2 Unsteady Flow Field on the Airfoil

In case of \( Re = 10,000 \), reattachment of the separated shear layer could not be confirmed in time averaged results as shown in Fig. 2. The flow field on the airfoil is commonly unsteady in nature, it is predicted that flow state involving a separation region on the airfoil will change as time advances. Instantaneous results of the flow field, as shown in Fig. 8, show that the flow field is unsteady state on the airfoil due to existing of separation regions and increasing of instability in the separated shear layer. A rather large vortex structure is formed in latter part of the separated shear layer and it is divided and sheds from the separated shear layer. The shedding vortex advects to downwards of the airfoil and it induces push-down flow toward the airfoil surface from outside of the separated shear layer, the separated flow is deflected and reattaches to the airfoil surface, that is, a separation bubble is formed at the moment. After the reattachment position, according to existing and advecting of the vortex structure near the airfoil, the flow field is composed by turbulent flow state involving small reversed flow regions and vortex structures. The reattachment position of separation bubble is moving toward the trailing edge as time advances, the flow state shows unsteady reattachment and separation with a weak periodicity. Therefore reattachment of the separated flow appears intermittently on the airfoil, that is, a large separation bubble,
it cannot be confirmed in the time averaged result, is formed intermittently on the airfoil at $Re = 10,000$ with a certain intermittency time period of $T = 0.05$ sec; this period time is determined by the local reattachment. And, extensively separation of the boundary layer is dominant to the unsteady flow state on the airfoil nevertheless varying the angle of attack, that is, reattachment of the separated flow cannot be confirmed in time averaged results at $Re = 10,000$. These flow state due to separated regions does not encourage development of pressure distribution on upper side of the airfoil as increasing of the angle of attack, it brings about showing both deterioration of aerodynamic forces and uncertain stall in the lift force of NACA0012 airfoil at $Re = 10,000$ consequently.

The next case of $Re = 20,000$, on the other hand, a separation bubble was confirmed on the airfoil in time averaged flow field as shown in Fig. 3. Although the time averaged flow state is different in case of $Re = 10,000$, we will obtain similar characteristics of unsteady flow state due to behavior of a separated shear layer as well as it could be observed in $Re = 10,000$. Instantaneous flow fields of $Re = 20,000$, as shown in Fig. 9, show clear differences in the flow state compared with its time averaged flow field. Reversed flow region, note again as showing filled darkest blue colors, due to both flow separation and reattachment becomes larger than the one in the time averaged flow field. As time advances, the shape of reversed flow region shows a periodic change on the airfoil with period time of $T = 0.05$ sec; it is coincidence with the intermittency period time of reattachment in $Re = 10,000$. The separation region looks like extending its length, and then dividing into some small separation regions simultaneous with vortex shedding near the reattachment position as determined by time-averaged results. The small separation regions also advect to the trailing edge on the airfoil, that is, small separation bubbles are formed near the reattachment position and it advect to the trailing edge. By these facts, the reattachment position of the separated shear layer is also unsteady on the airfoil, and the flow state on the airfoil is composed by complicated turbulent flow structures due to increasing of instability and generating vortex structures in the separated shear layer at $Re = 20,000$. Appearance of these complicated turbulent structures means that three-dimensionalized of the flow field is encouraged, it contributes to changing the separated shear layer into reattachment flow on the airfoil effectively than the case of $Re = 10,000$.

The last case of $Re = 30,000$, time averaged flow state as shown in Fig. 4 is similar to the results in $Re = 20,000$ of Fig. 3 as existing of separation bubble on the airfoil, however, length and height of the bubble becomes shorter and lower than the bubble in $Re = 20,000$, respectively. Observing of shorter length in the separation bubble means that the reattachment point moves forward to the separation position in the separation bubble. In this $Re = 30,000$ case at $\alpha = 10^\circ$, the reattachment position was determined at nearly $50\%$ of chord length from the leading edge as shown in Fig. 7. After the reattachment position, the flow state will become turbulent reattachment flow, it is predicted that unsteady flow field is composed by two different flow states on the airfoil; unsteady separated-reattached flow involving vortex structures and unsteady turbulent boundary layer region after the reattachment position. Instantaneous flow results, as shown in Fig. 10, also show periodic change on the airfoil with period time of $T = 0.043$ sec. Complicated flow structure due to both vortex shedding and advecting of vortexes appears around the reattachment position and that turbulent reattached flow also exists after the reattachment position because of stream lines are showing many sinuous lines and closing loops on the airfoil. And, the reattachment position is moving periodically with the period time. Comparing with the instantaneous flow results in $Re = 20,000$, it is confirmed that the reversed flow region on the airfoil is decreasing and that the vortex size is also decreasing, and turbulent area in the boundary layer becomes narrow above the airfoil than the case of $Re = 20,000$. These facts means that reattached flow due to both existing of vortexes and increasing of instability in the separated shear layer, showing rather strong turbulent intensity, is dominant to the flow state after the reattachment position on the airfoil. This flow states is
Fig. 8. Progress of instantaneous flow field on NACA0012 airfoil in a period ($Re = 10,000$, $\alpha = 10^\circ$, $T = 0.050$ sec)
Fig. 9. Progress of instantaneous flow field on NACA0012 airfoil in a period ($Re = 20,000$, $\alpha = 10^\circ$, $T = 0.050$ sec)
Fig. 10. Progress of instantaneous flow field on NACA0012 airfoil in a period ($Re = 30,000$, $\alpha = 10^\circ$, $T = 0.043$ sec)
having unsteady flow state as a matter of course, it is very interesting for us and we intend to measure and to clarify more details of the flow structures in our future works.

4 Conclusions

We performed PIV measurements of flow field around a NACA0012 airfoil at low Reynolds number flows as Re = 10,000, 20,000 and 30,000 in order to examine characteristics and details of flow structures involving laminar separation region and a separation bubble on the airfoil. By time averaged measurements results of the flow field, separated shear layer cannot be reattached on the airfoil at Re = 10,000, on the other hand the separated shear layer is reattached at downward of the separation position, that is, a separation bubble is formed and it exists on the airfoil in widely range of the angle of attacks until occurring of airfoil stall at Re = 20,000 and 30,000. However, according to instantaneous results of the flow field, unsteady reattachment of the separated shear layer is confirmed as time advances with vortex shedding on the airfoil at all cases of Reynolds numbers. And, complicated flow state on the airfoil is also confirmed that a separation bubble is varying its reattachment position simultaneous with periodic vortex shedding and turbulent reattached flow involving some separated regions due to appearance of vortex structures is developing after the reattachment position. We can find both characteristics and behaviors of the unsteady flow field involving a separation bubble depending on Reynolds number change in condition of low Reynolds number flows. And, differences in these flow phenomena contribute to aerodynamic characteristics in low Reynolds number flows consequently.

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