Experimental Study about the Deformation and Aerodynamic Characteristics of the Passive Morphing Airfoil

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In order to investigate the deformation and aerodynamic characteristics of the morphing airfoil model passively deformable by the dynamic pressure, two-dimensional wind tunnel experiment was conducted. The trailing edge portion (0.3 ≤ s/C ≤ 1.0) of the model was made of flexible materials so as to be deformable by the dynamic pressure without using any actuator. The upper and lower surfaces were connected by spokes inside the airfoil. The aspect ratio of the model was 1.0 and the Reynolds number based on the chord length was 1.78 × 10^5 in the wind tunnel experiment. The deformed geometries were measured optically, and the lift coefficient was measured with a force sensor. The morphing airfoil deformed to increase its camber in the high angle-of-attack, and this deformation caused higher lift coefficient than that of the rigid airfoil. Also, by the measurement of Cp distribution around the rigid airfoil and the morphing airfoil, it was found that the morphing airfoil had larger difference of pressure between upper and lower surface than the rigid airfoil in the trailing edge portion.

Key Words: Aerodynamics, Wind Tunnel Testing

Nomenclature

α: angle-of-attack
C: chord length of the airfoil
C_l: lift coefficient based on the free stream static and dynamic pressures
C_p: pressure coefficient based on the free stream static and dynamic pressures

1. Introduction

Demand for the aircraft transportation has been increasing year by year, and the development of fuel-efficient aircraft has been pursued in terms of cost and environment. As one solution to these requirements, an idea called “morphing airfoil” has been proposed. Morphing is the technology to deform the wing shape of aircraft so as to be optimum for different flight conditions.1) Because morphing airfoils have a possibility to optimize to several flight conditions with a single steering device, the reduction of the structure weight and the fuel is expected. Several concepts of morphing wings to change the camber of airfoil with various materials and mechanisms have been investigated.2–5) For example, Campionle et al. proposed an unique mechanism which is called “belt-rib concept,” shown in Fig. 1.6) This airfoil is easily deformed because upper and lower skin made of flexible materials are supported not by ribs but by spokes. The shape of this airfoil is controlled by an actuator. They showed that the workload of the actuator required for the deformation was smaller when the belt-rib concept was introduced as the trailing edge high lift device than conventional hinged flaps.7) On the other hand, belt-rib concept has another characteristic. Figure 2 shows the airfoil model with the belt-rib concept. The model deforms its trailing edge in the opposite direction to the force from the finger. Usually, when a single beam is set in the freestream, it deforms in the direction of the freestream as shown in Fig. 3(a). However, as the belt-rib concept, two beams which are connected with at their ends deform in the direction opposite to the freestream as shown in Fig. 3(b). If this mechanism is applied as the trailing edge portion of the wing, higher lift force can be expected due to

Fig. 1. The belt-rib concept.

Fig. 2. The airfoil model with the belt-rib concept.
the passive increase of the camber caused by the pressure difference between the upper and lower surfaces. However, the characteristic of the passive deformation is not clearly understood. Also, its aerodynamic characteristic is unknown.

The purpose of this research is to investigate the deformation and aerodynamic characteristics of the airfoil that deforms against the freestream only by dynamic pressure without any actuator. In particular, the relationship between the deformation and the change of the lift coefficient \( C_l \) was measured. A two-dimensional airfoil model with the deformable trailing edge portion was manufactured and a two-dimensional wind tunnel experiments were conducted. Also, the distribution of the pressure coefficient \( C_p \) was measured to investigate the deformation.

2. Methods

2.1. Wind tunnel and force measurement system

A low-speed blow-down wind tunnel (Fig. 4) at the University of Tokyo was used in this research. The test section is an open type and the outlet is a square of 600 \( \times \) 600 mm. Table 1 summarizes the specification of the experiment. The experiment was conducted at wind speed of 13.1 m/s. The Reynolds number based on the chord length \( \bar{c} \) of 200 mm was \( 1.78 \times 10^5 \). Two end plates were set parallel to the ground as shown in Fig. 5 in order to perform two-dimensional wind tunnel test. The wing model was installed vertically between the two end plates to exclude the effect of the deformation due to the gravity because the model was flexible.

In order to investigate the relationship between the angle-of-attack \( \alpha \) and the deformation, the forces were measured at \(-30^\circ \leq \alpha \leq 30^\circ \) with 2\(^{\circ}\) interval. The force sensor attached to the wing airfoil model was set above the rotary stage. The specifications of those systems are summarized in Tables 2 and 3, respectively.

2.2. Airfoil model

A rigid and a morphing airfoil model were manufactured in order to investigate the effect of the passive morphing. Table 4 shows the specifications of these models. The span length of the model is the same as the distance between end plates in the wind tunnel, and the chord length is 200 mm. A rigid airfoil model is shown in Fig. 6. The ribs of the model were manufactured by using 3D printer, and the material is ABS resin. The shape of the model is the same
as that of NACA0024 airfoil. The stringers were inserted so as to connect the ribs, and the skin made of chloroethene sheet (0.3 mm thickness) was covered around the airfoil.

Figure 7 shows the morphing airfoil model used in this experiment. The morphing airfoil model was manufactured to match the NACA0024 airfoil under no force condition. The morphing airfoil model consists of the leading edge portion \(0 \leq x/c \leq 0.3\) and the trailing edge portion \(0.3 \leq x/c \leq 1.0\). The leading edge portion is rigid, and the cross sectional shape is the same as the leading edge of NACA0024 airfoil \(0 \leq x/c \leq 0.3\). Stringers were inserted in order to prevent the spanwise deformation.

Figure 8 shows the internal mechanism of the trailing edge portion which consists of skin and spokes. The upper and lower skin were connected by the spokes. The stringers were attached to the skin every 10%\(c\), and the housings which hold the bearings were attached at both ends of the stringers. The spokes were connected by the pins to the bearing and were rotatable, therefore the cross-sectional shape of the trailing edge portion was flexible.

### 2.3. Image analysis of the deformation measurement

The deformation of the airfoil model was optically measured with a camera from the outside of the upper end plate. Based on the image data, the amount of the deformation was measured quantitatively as described below. As shown in Fig. 9, four green reference markers were plotted at the vertex of 15 cm \(\times\) 25 cm rectangle on the OHP sheet, and the sheet was attached to the end plate. The reference markers were optically measured from the image data. Pixels which exceed a certain value of RGB in the image were recorded, and K-means clustering was performed to find the center coordinate for each marker. Using the coordinates of the reference markers, projective transformation was performed so that the reference markers fit the rectangle of 15 cm \(\times\) 25 cm in order to eliminate the distortion of the image.

The edge of the airfoil skin was painted red, and its position was also optically measured as shown in Fig. 10. Some representative points were picked up from the skin line recognized as red by using K-means method. The pickup method is described below. The red pixels which existed in a band-like region extending in the \(y\) direction were recorded. K-means clustering with 2 clusters was performed among the recorded data, and the representative points of the skin on the upper and lower surfaces were determined. Similarly, the same operation was carried out for the band-like region extending in the \(x\) direction, and the representative points of the leading edge portion were acquired with high accuracy.

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<th>Table 3. The specification of the rotary stage.</th>
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<td>Positioning accuracy</td>
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<th>Table 4. The specification of the rigid and morphing airfoil model.</th>
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<td>Chord length</td>
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<td>Aspect ratio</td>
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<td>Referenced airfoil</td>
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Fig. 6. The rigid airfoil model.

Fig. 7. The morphing airfoil model.

Fig. 8. The internal mechanism of the morphing airfoil model.

Fig. 9. The image of projective transformation.
These representative points were interpolated with a spline curve, and a smooth airfoil shape was extracted. The number of representative points was approximately 100.

The accuracy of this method was evaluated as described below. Four reference markers and NACA0024 airfoils were printed on the paper with the correct position and shape. The paper was pasted on the upper end plate and the image data of the markers and airfoil was obtained. Figure 11 shows the comparison between the shape acquired with the method described above and the shape of defined NACA0024 airfoil. The average error between them was 0.26 mm, which was 0.13% to the chord length.

2.4. Measurement of $C_p$

In order to measure the distribution of $C_p$ around the airfoils, two rigid models with pressure holes were manufactured as shown in Fig. 12. One is the model with the shape of NACA0024 airfoil, and the other is the model with the shape of the morphing airfoil which was deformed in the wind tunnel experiment at $\alpha = 18^\circ$. The deformed shape was acquired with the method described in 2.3.

Some pressure holes were opened along the mid-span of the models. Figure 13 shows the enlarged view of the static pressure hole of the NACA0024 airfoil model. The rib with pressure holes were manufactured by 3D printer, and the copper pipes (inner diameter $= 0.8$ mm) were fitted into the holes. The pressure of each hole was measured with the pressure transducer, and the specification was shown in Table 5. The number of pressure holes were 27 for the NACA0024 model and 25 for the morphing model, respectively. Figure 14 shows the position of holes of each model.
3. Experimental Results

3.1. Deformation characteristic

Figure 15 shows the photo of the deformed airfoil in the wind tunnel experiment at $\alpha = 8^\circ$, $12^\circ$, $18^\circ$. The result of the image analysis described in 2.3 is shown in Fig. 16. The shape of the NACA0024 airfoil and the trailing edge portion of the morphing airfoil model which is deformable were compared by rotating by angle-of-attack. The deformation increased as angle-of-attack increased. At $\alpha = 8^\circ$, the airfoil deformation was not significant compared to the NACA0024 airfoil. At $\alpha = 12^\circ$ and $18^\circ$, the trailing edge rose and the camber increased. The characteristic of deformation could be summarized as shown in Fig. 17.

In order to evaluate the deformability at each angle-of-attack quantitatively, the rising distance of the trailing edge and the increase of the camber were measured and summarized in Fig. 18. Definitions of each axis are shown in Fig. 17.

The dash-dotted line represents the original chord line of NACA0024 airfoil which is the referenced airfoil. The rising distance of the trailing edge is the distance between the original chord line and the trailing edge of the morphed airfoil. On the other hand, the solid line represents the chord line of the deformed airfoil. The increase of the camber is defined as the maximum distance between the chord line and the camber line of deformed airfoil. Both values are defined positive when they are located on the upper side from the referenced line. As shown in Fig. 18, the deformation has the overall tendency that the trailing edge rises and the camber increases together as $\alpha$ increases. Since the rise of the trailing edge means the rise of the chord line relative to the free stream, the lift will decrease. On the other hand, the increase of the camber has the effect to increase the lift force. Therefore, the measurement by the force sensor was conducted to investigate which effect is more dominant to the overall characteristics of the morphing airfoil.

3.2. Aerodynamic characteristic

Figure 19 shows the $C_l$–$\alpha$ of rigid NACA0024 and the morphing airfoil measured by the force sensor. Note that error bars are also plotted in the figure. The $C_l$ of the morphing airfoil increased as $\alpha$ increased, similar to that of NACA0024 airfoil. When $\alpha$ was positive, $C_l$ of the morphing airfoil is larger than that of NACA0024 at $\alpha = 10^\circ$ or more. The improvement in $C_l$ for the morphing airfoil over the NACA0024 airfoil was present until stall. The maximum lift coefficient $C_{l_{\text{max}}}$ of the morphing airfoil was 0.88, which was 22% higher than that of the NACA0024 airfoil. These tendency was also observed when $\alpha$ was negative ($\alpha = -10^\circ$ or less). The $C_l$–$\alpha$ was not symmetry in low $|\alpha|$ even though...
The models were symmetry airfoil. This is assumed to be caused by the manufacturing error of the model.

In summary, the deformation caused the increase of $C_l$. This indicates that the effect of the camber increase is more remarkable than the effect of the trailing edge rising.

3.3 Pressure distribution

Figure 20 shows the comparison of $C_p$ distribution at $\alpha = 18^\circ$ between NACA0024 and the morphing airfoil which deformed at $\alpha = 18^\circ$ in the wind tunnel experiment. The shape of the deformed airfoil model at $\alpha = 18^\circ$ in the experiment is also shown in the upper part of the figure. The $C_p$ difference of the morphing airfoil was larger than that of NACA0024 airfoil on the down streamside from $x/c = 0.40$. The point $x/c = 0.40$ was the inflection point of deformation at $\alpha = 18^\circ$. The difference of the pressure became large after the inflection point by re-accelerating/re-decelerating the flow of the upper/lower surfaces.

The larger pressure difference on the morphing airfoil means the force increased in the direction from the lower surface to the upper surface. Therefore, the deformation was further promoted by the force caused by the deformation itself.

4. Conclusions

The deformation and aerodynamic characteristics of the passive morphing airfoil was investigated through a two-dimensional wind tunnel experiment. The deformed shape was optically measured to investigate the deformation and $C_l$ was measured with the force sensor. The $C_p$ distribution was also investigated to discuss the characteristic of the deformation. It was found that the passive morphing airfoil deformed to rise its trailing edge and to increase the camber. This deformation led to the increase of $C_l$ compared to the rigid airfoil, and $C_{l_{\text{max}}}$ increased by 22%. Therefore, the effect of the camber increase was more remarkable than the effect of the trailing edge rising. By measuring $C_p$ distribution of the morphing airfoil shape which was deformed in the wind tunnel experiment $\alpha = 18^\circ$, it was suggested that the deformable trailing edge portion has larger pressure difference than the rigid airfoil and the deformation was further promoted by the deformation itself.

In this study, the basic performance of the passive morphing airfoil that generates larger $C_l$ than the rigid airfoil without any actuator was shown. It was shown that new type of airfoil devices which have higher aerodynamic performance than rigid airfoils could be obtained by positively coupling aerodynamics and structure for the airfoil shape.

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References


Song Fu
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