Aero-Structural Evaluation of Morphing Control Surface Using Corrugated Panels

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Morphing wing technology is anticipated as a way to improve efficiency over a wider range of flight conditions, but it is difficult to realize morphing because there are two conflicting demands, i.e. stiffness for aerodynamic forces and flexibility for morphing. Super-anisotropy of the corrugated panel is a solution to satisfy those demands. This paper focuses on applying camber morphing to vertical plane. Firstly, optimal deformation of airfoil for morphing control surfaces is defined by conducting airfoil analysis. For realizing optimal deformation, deformation analysis of corrugated panels is conducted and evaluated by using high flexible 2-D beam equations.

Key Words: Morphing Wing, Corrugated Panel, Structural Design

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>parameter of degree of camber line</td>
</tr>
<tr>
<td>b</td>
<td>span length</td>
</tr>
<tr>
<td>c</td>
<td>chord length</td>
</tr>
<tr>
<td>cL</td>
<td>lift coefficient</td>
</tr>
<tr>
<td>cpr</td>
<td>corrugate pitch rate</td>
</tr>
<tr>
<td>[D]</td>
<td>stiffness matrix</td>
</tr>
<tr>
<td>Dr</td>
<td>equivalent bending stiffness of corrugated panels</td>
</tr>
<tr>
<td>Do</td>
<td>bending stiffness of original plate</td>
</tr>
<tr>
<td>Et</td>
<td>equivalent stiffness of corrugated panels</td>
</tr>
<tr>
<td>e</td>
<td>strain at reference line</td>
</tr>
<tr>
<td>F</td>
<td>force</td>
</tr>
<tr>
<td>HFS</td>
<td>highly flexible structure</td>
</tr>
<tr>
<td>k</td>
<td>initial curvature</td>
</tr>
<tr>
<td>l</td>
<td>length of a line part of corrugated panels</td>
</tr>
<tr>
<td>M</td>
<td>moment</td>
</tr>
<tr>
<td>p</td>
<td>deformed curvature</td>
</tr>
<tr>
<td>q</td>
<td>distributed load</td>
</tr>
<tr>
<td>r</td>
<td>radius of a circular part of corrugated panels</td>
</tr>
<tr>
<td>s</td>
<td>the original arc length along the x axis from the beam root to the observed reference point</td>
</tr>
<tr>
<td>sw</td>
<td>arc length of half wavelength of corrugation</td>
</tr>
<tr>
<td>[T]</td>
<td>transformation matrix from original coordinate to deformed coordinate</td>
</tr>
<tr>
<td>t</td>
<td>thickness of original plate</td>
</tr>
<tr>
<td>u</td>
<td>displacement of x</td>
</tr>
<tr>
<td>w</td>
<td>displacement of y</td>
</tr>
<tr>
<td>wh</td>
<td>deflection at x = 1</td>
</tr>
<tr>
<td>xh</td>
<td>start point of the morphing</td>
</tr>
</tbody>
</table>

Subscripts

- c: camber line
- i: section number
- l: lower skin
- u: upper skin
- 1: x direction
- 2: y direction
- 3: z direction
- 5: rotation around y direction

1. Introduction

With the restricted environmental regulation and increasing fuel prices, airplanes are restricted to be more efficient. One way of achieving this is improving aerodynamic efficiency, and morphing wings are anticipated as a way to improve efficiency over a wider range of flight conditions. Traditional wings are made by stiff materials and only few wing sections can be realized in a flight. Therefore, wing design is mainly considered to optimize efficiency at cruising. When the plane is lifting, landing and maneuvering, airfoil is changed by using either high-lift devices or control surfaces. However, the traditional high-lift devices and control surfaces have some gaps such as hinges, leading to decrease in aerodynamic performance and noise induction. Morphing technology can realize optimized deformation at each flight condition, a seamless deformation of wing section and integrate those devices. These advantages will lead to improve aerodynamic efficiency and weight.
Morphing wing is researched enthusiastically all over the world and various forms of morphing wing are discussed\textsuperscript{1).} Among them, camber morphing wing, which is focused on deformed camber, is one type of morphing wing which is well discussed\textsuperscript{2-4).} There are two conflicting characteristics required for camber morphing wing: stiffness for aerodynamic forces and flexibility for shape change ability. Super-anisotropy of corrugated panel is one of the feasible solutions to satisfy these conflicting characteristics. The corrugated panel is stiff along the corrugation direction, but flexible in the transverse direction (Fig. 1).

Corrugated panel is widely used, such as architecture, civil engineering, and aerospace engineering. Because of its flexibility, Iman et al.\textsuperscript{5) attempt to apply it to skin of morphing wing. In this paper, corrugated panel is used as a main structure of camber morphing wing by set corrugation direction to chord direction and stiff direction to span direction. Our previous work\textsuperscript{6) suggested that the corrugated panels have the potential to be applied to camber morphing wings consisting of morphing leading edge and trailing edge for high-lift devices. In previous research, the film was used at compressive side in order to avoid buckling and there is a stiff plate at another side. Thus, this model could deform in only one direction.

In this paper, aircraft wing with morphing control surfaces, enabling leading to move positive and negative angle flexibly, is focused on. The objective of this study is to apply camber morphing wing to rudder because vertical plane is usually symmetric airfoil and seems to be easy to realize for both plus and minus sign deformation as first study. Firstly, optimal deformation airfoil for morphing rudder is defined by conducting airfoil analysis (by XFOIL). Then, for realizing optimal deformation, deformation analysis of corrugated panels is conducted and evaluated by using 2-D beam’s HFS equation.

2. Optimal Deformation Analysis

Morphing wing should realize optimal deformation for any flight conditions. Therefore, it is necessary to know the optimal deformation at first. To define optimal deformation, the aerodynamic performance of 2D airfoils are calculated by XFOIL. XFOIL is based on panel method integrating viscous effect (friction drag and flow separation).\textsuperscript{7) The coordinate of airfoil surface is written as follows,}

\begin{align}
X_u &= x - Y_t \sin \theta \\
X_l &= x + Y_t \sin \theta \\
Y_u &= Y_c + Y_t \cos \theta \\
Y_l &= Y_c - Y_t \cos \theta \\
\theta(x) &= \tan^{-1}(dY_t/dx) \\
\end{align}

The thickness of NACA64A010, $Y_t(x)$, is derived by curve fitting and

\begin{align}
Y_t(x) &= 0.1154\sqrt{x} - 0.04631x + 0.06375x^2 - 0.3082x^3 + 0.1754x^4 \\
\end{align}

Note that camber length is normalized, that is trailing edge is at $s = 1$. The coordinate system is shown in Fig.3.

The camber line for the morphing portion of the airfoil is defined from a third order polynomial shape function. A third order polynomial is useful for describing the shape of any morphing camber concept which relies on bending of
In Analysis 1, which changes start of the morphing, the camber line is defined as shown in Ref. 8,

$$ F(x) = 0 \quad (0 \leq x \leq I) $$

$$ F(x) = -J \frac{I}{I(x - I)} \frac{A}{A(1 - I)} $$

(3)

Here, \( x_h \) is varied from 0.65 to 0.90 by 0.05. Figure 4 shows each \( x_h \) of deformation shape at \( \theta_r = 30 \text{ degrees} \).

In Analysis 2, which is changing degree of camber line, the camber line is derived by extending Eq. (3) and

$$ Y_c(x) = 0 \quad (0 \leq x \leq x_h) $$

$$ Y_c(x) = -w_h(x - x_h)^3 \frac{(x_h - x)^2}{(1 - x_h)^2} \quad (x_h \leq x \leq 1) $$

(4)

Eq. (4) describes the deflection curve of cantilever taken a point load. The parameter “\( a \)” is varied from -1/2(1-\( x_h \))\(^3\) to 1/(1-\( x_h \))\(^3\) by 1/2(1-\( x_h \))\(^3\). There is an assumption that the camber line is monotone decreasing function and second derivatives is always negative. This assumption means that the end of airfoil cannot warp back. If \( a = 1/(1-x_h) \), Eq. (4) coincides with Eq. (3) and the camber is the sharpest at end.

In Analysis 2, start of the morphing is fixed 65% chord length (\( x_h = 0.65 \)), thus “\( a \)” is varied from -11.66 to 23.32 by 11.66. Fig. 5 shows each “\( a \)” of deformation shape at \( \theta_r = 30 \text{ degrees} \).

### 2.2. Aerodynamic conditions

Aerodynamic load case is assumed at take-off or landing because there is potential for being the severest angle of attacks conditions. Table 1 shows this condition. Therefore, this analysis searched for optimal deformation shape at any angles of attack at one speed.

The aerodynamic performance of the 2D airfoils is estimated by the XFOIL.

<table>
<thead>
<tr>
<th>Reynold number</th>
<th>Angle of attack</th>
<th>Morphing angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2×10^6</td>
<td>-20°~20°</td>
<td>-30°~30°</td>
</tr>
</tbody>
</table>

Fig. 4. Deformation shape in Analysis 1 (\( \theta_r = 30 \text{ degrees} \)).

Fig. 5. Deformation shape in Analysis 2 (\( \theta_r = 30 \text{ degrees} \)).

Fig. 6. \( C_L-\theta_m \) graph at 0-degree angle of attack, Analysis 1.

Fig. 7. \( C_L-\theta_m \) graph at 10-degree angle of attack, Analysis 1.
2.3. Result and discussion

In this study, the rudder that can generate the largest lift with smaller deformation is defined as the best deformation. This is because the role of rudder is generating yaw moment. If the rudder can produce large lift with small deformation, the driving force by actuator can become small leading to decrease weight. Thus, Fig. 6 and Fig. 7 show the relationship between \( C_L \) and morphing angle of Analysis 1 at 0-degree angle of attack and 10-degree angle of attack, respectively. Note that these figures do not show \( C_L-\alpha \) curve. This is because the negative pressure drop of upper surface at 65 % chord is the least of all, and deformation at 65 % chord makes the largest negative pressure. The reason why the gap between start = 70 % and 75 % is big below -20 degrees in Fig. 7 is that the surface pressure near the leading edge of start = 75 % has much sharper peak than 70 % below -20 degrees.

Fig. 8 and Fig. 9 show the relationship between \( C_L \) and morphing angle of Analysis 2 at 0-degree angle of attack and 10-degree angle of attack, respectively. Difference between each “\( a \)” is not clearer than Analysis 1, but the configuration when \( a \) equals 23.32, which is the sharpest camber at the end (see Fig. 5), can generate the largest lift with smaller deformation at both angles of attack. The smaller \( a \) is, the sharper the camber at start of morphing is. Thus, the separation of flow occurs at an early stage if \( a \) is small. Therefore, the configuration when \( a \) equals 23.32 can produce the largest lift. From these analyses, start of the morphing at 65 % chord length and the sharpest camber at the end is the best configuration.

3. Flexible Beam Deformation Analysis

To realize optimal deformation shape obtained in section 2 by corrugated panel, structural optimization is conducted. In this study, because deformation is large, deformation analysis becomes non-linear analysis. Furthermore, because the corrugated panel is flexible, aerodynamic load cannot be negligible. Therefore, FEM analysis requires much time and is unsuitable for initial design. In this paper, by introducing equivalent stiffness of corrugated panel and regarding it as two-dimensional flexible beam, structural optimization is conducted by solving HFS equation.

3.1. HFS equation

Details of HFS equation can be seen in Ref. 9). It is assumed that shear stress is negligible and steady. Three coordinate systems are used. Firstly, the \( a-c \) system is a rectangular coordinate system for reference use. Secondly, the \( x-z \) system is an orthogonal curvilinear coordinate
system with x axis (i.e., the reference line) connecting the reference points of all cross sections of the original beam. Thirdly, the $\xi-\zeta$ system is a local orthogonal curvilinear coordinate system with the $\xi$ axis representing the deformed reference line and the $\zeta$ axis representing the deformed $z$ axis (see Fig. 10).

Constitutive equation can be written as

$$\begin{bmatrix} F_1 \\ M_2 \end{bmatrix} = [D] \begin{bmatrix} e \\ k_2 \end{bmatrix}$$

(5)

2-D beam’s HFS equations can be written as

$$F_1 = -\rho_2 F_3 - T_{11} q_1 - T_{13} q_3$$
$$F_2 = \rho_2 F_1 + T_{13} q_1 - T_{11} q_3$$
$$M_1 = (1 + e) F_3 - q_5$$
$$T_{13} = \rho_2 T_{11} + T_{13} k_2$$
$$T_{13} = \rho_2 T_{11} + T_{13} k_2$$
$$w = -1 - w k_2 + (1 + e) T_{11}$$
$$w = u k_2 + (1 + e) T_{13}$$

(6a) 
(6b) 
(6c) 
(6d) 
(6e) 
(6f) 
(6g)

From eq. (5), the seven dependent variables are $F_1, M_2, F_3, T_{11}, T_{13}, u,$ and $w$. These equations are solved by multiple shooting method. The boundary condition is fixed:

At $s = 0$, $T_{11} = 1, T_{13} = u = w = 0$

(7)

3.2. Corrugated panel model

Yokozeki et al.\textsuperscript{10} show that equivalent stiffness and bending stiffness of corrugated panel can be written as

$$E_T = 24 r D / (2 r + l) (24 r^2 l + l^3 + 6 r^3 \pi + 3 r^2 \pi^2)$$
$$D_T = 2 r D / (l + \pi r)$$

(8) 
(9)

The radius of circular part or length of line part of corrugated panel along with airfoil shall change. Xia et al.\textsuperscript{11} show that equivalent of bending stiffness of corrugated panel can be written as

$$D_T = \lambda_h D / s_w$$
$$\lambda_h = 2 r$$
$$s_w = \pi r + 2 l (l = l/2)$$

(10a) 
(10b) 
(10c)

Though Eq. (10) coincides with Eq. (9), equivalent bending stiffness of corrugated panel along with airfoil will be calculated by expanding Eq. (10) which describes by the length of half wavelength. The equivalent bending stiffness at $i$-th half wave length like Fig. 11 is written as

$$D_T(i) = \lambda_h D / s_{wi}$$
$$\lambda_{hi} = 2 r_i$$
$$s_{wi} = \pi r_i + l_i/2 + l_{i+1}/2$$

(11a) 
(11b) 
(11c)

Equivalent stiffness is used Eq. (8) at each $i$-th half wave length. Therefore, the stiffness of corrugated panel along with airfoil has distribution.

In this paper, two types of corrugated panel are considered, i.e. Asymmetric corrugated plate and Symmetric corrugated plate (Fig. 12).

3.3. Analysis flow

The deformation of the camber line is calculated in this method. The initial curvature of corrugated panel is 0 and...
The goal of morphing angle deformation shape is aimed by applying driving load. Corrugated panel is actuated by skin in this study and the model of driving force is shown in Fig. 13. One of the problems of morphing wing is skin. Morphing wing deforms very large. It is necessary to avoid buckling in compression side skin. Various material for morphing skin have been invented, but this model prevents buckling to bring in skin and load tension. First, the direction of the skin is calculated from the optimal deformation. Then, driving force is modeled and inputted. Bisection algorithm is used to get objective deformation shape. From this shape, skin angle is calculated again. Until skin angle converges, deformation analysis is iterated. After convergence, deformation airfoil is calculated from deformation camber line by Eq. (1), and then aerodynamic load is conducted. Here the lower skin is assumed to be straight line as shown in Fig. 13. Under this load, additional deformation analysis is conducted until deformation converges (See Fig. 14). It takes 0.05 seconds to conduct one deformation analysis by this equation, otherwise 60 seconds by FEM.

3.4. Validation

For evaluating HFS equations and equivalent stiffness of corrugated panel, experiment is conducted. The geometry of the sample is the symmetric corrugated panel with a length of 250 mm, a width of 200 mm, a thickness of 1.2 mm, a cpr (corrugate pitch rate, see Fig. 17 and Section 3.5) of 0.9, and number of corrugation of 7.5. This corrugated panel is along with airfoil shape whose chord length is 1000 mm, start of corrugation is at 650 mm and end of corrugation is at 900 mm. The way of driving this sample is by the skin, that is, the skin is attached at the end of corrugated panel and winded at the start point. This sample is made by 3D printer and its material is polyamide and modulus is 1.586 GPa. The skins are made of nylon and thickness of 0.152 mm (See Fig. 15).

The skin is winded by suspended weight, and deformation is taken by high speed camera CASIO EX-F1 with frame rate of 300. From this picture, the displacement of camber line at the cross points of the two corrugated panels is measured by image analysis software Photron FASTCAM Viewer.

Fig. 16 shows the comparison between the deformation result of the sample and the calculated deformation by HFS equations. Note that the sample is shorter because it has only the corrugated panel parts. The HFS’s deformation is in good agreement with the experimental deformation. The experiments are slightly stiffer than calculations near the start of deformation. This is because the difference of boundary condition at the root of beam. The corrugated panel has the effect of the displacement amplification because of its straight part and all straight parts are considered in calculation of equivalent stiffness. In the experiment, the straight line at the start of corrugation is fixed. In the case of symmetric corrugated panel, the first half wave length part cannot show its displacement amplification effect because of this boundary condition. On the other hands, homogenized stiffness is allocated in calculation. Therefore, the sample has slightly larger stiffness at the start point.

From this result, the deformation shape from HFS equations and equivalent stiffness can be used for aerodynamic analysis and its performance can be evaluated.

3.5. Analysis conditions

The best configuration of corrugated panel to realize the optimal deformation is searched by HFS equations.

There are two steps in this analysis. First, parametric study is conducted. In this analysis, aerodynamic case, i.e. angle of attack and morphing angle, are chosen because if all cases are calculated, it will take long time. Under this aerodynamic condition, the best parameter is searched. The best parameter means that its deformation is the closest to the optimal camber line (\( \alpha = 23.32 \)) and the lightest (cross section area is the smallest). Analysis conditions are shown in Table 2. Parameters of analysis are thickness of original plate and corrugate pitch rate (cpr). “cpr” means a common ratio of two adjoining circles of radius (See Fig. 17). The ranges of parameters are shown in Table 3.

The reason why given thicknesses are different is that the stiffness in symmetric case is higher than the one in asymmetric case.
Second, deformations of the best parameter from first analysis under other angles of attack and morphing angles are calculated. In this analysis, the ranges of angle of attack and morphing angle are shown in Table 4. Because the base airfoil is symmetric, morphing angles are taken only positive. The value of aerodynamic performance at $\alpha$-degree angle of attack and $-\theta_m$-degree morphing angle is the same as at $-\alpha$-degree and $\theta_m$-degree morphing angle.

Table 2. Condition of HFS analysis.

<table>
<thead>
<tr>
<th>Chord length [mm]</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span length [mm]</td>
<td>1000</td>
</tr>
<tr>
<td>Start of the morphing [mm]</td>
<td>0.65$c$ = 650</td>
</tr>
<tr>
<td>End of corrugation [mm]</td>
<td>0.9$c$ = 900</td>
</tr>
<tr>
<td>Number of corrugation</td>
<td>7.5</td>
</tr>
<tr>
<td>Reynolds number</td>
<td>$4.2\times10^6$</td>
</tr>
<tr>
<td>Angle of attack [deg]</td>
<td>0</td>
</tr>
<tr>
<td>Morphing angle [deg]</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 3. Range of parameters.

<table>
<thead>
<tr>
<th>$t$ (Asymmetric) [mm]</th>
<th>1.5~3.5 by 0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t$ (Symmetric) [mm]</td>
<td>0.5~2.0 by 0.1</td>
</tr>
<tr>
<td>$cpr$</td>
<td>0.9~1.1 by 0.1</td>
</tr>
</tbody>
</table>

Table 4. Aerodynamic condition.

<table>
<thead>
<tr>
<th>Angle of attack [deg]</th>
<th>-15~15 by 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morphing angle [deg]</td>
<td>5~30 by 5</td>
</tr>
</tbody>
</table>

3.6. Results and discussion

Relationships between bending stiffness at start of the morphing and driving force of Asymmetric corrugation and Symmetric corrugation are shown in Fig. 18 and Fig. 19, respectively. In both case, the deformation under airflow cannot keep stability below about $0.2~0.5\times10^8$ Nmm$^2$ of bending stiffness at morphing start. Minimum thickness of the plate can be decided by this limitation.

Relationship between cross section area and “$a$” is shown in Fig. 20. Symmetric corrugation whose $cpr = 0.9$ and $t = 1.1$ mm is the lightest and asymmetric corrugation whose $cpr = 0.9$ and $t = 2.5$ mm is the closest to $a = 23.32$. Fig. 21 shows the deformation camber line of symmetric corrugation whose $cpr = 0.9$ and $t = 1.1$ mm. Under airflow, deformation shape is risen from windless deformation shape because of aerodynamic force. The thinner the plate is, the more rising the deformation shape is. Thus, $a$ becomes close to 23.32 as the thickness becomes thin in Fig. 20.

Fig. 22 shows bending stiffness distribution of each $cpr$ of symmetric corrugated plate ($t = 2.0$ mm). Only when $cpr$ is 0.9, bending stiffness becomes decreasing at the end.
corrugated panel along with airfoil is tapering and straight part of corrugation will become very short at the end. This part generates the effect of the displacement amplification. When \( cpr = 0.9 \), the radius of corrugation is the largest at first and becomes small to the end. Thus, the length of straight part won’t change a lot. A a result, the ratio of the radius to the length of straight part becomes small and bending stiffness decrease (See, Eq. (11)). Therefore, the smaller \( cpr \) is, the sharper at the end and closer to the optimum the deformation is.

Next, aerodynamic performance of other angles of attack and morphing angles are calculated. The configuration of this analysis is that symmetric corrugated panel whose \( cpr \) is 0.9 and \( t \) is 1.2 mm. In above analysis, \( cpr = 0.9 \) and \( t = 1.0 \) mm is the best parameter of symmetric corrugated panel, but in this analysis, \( t \) is 1.2mm for safety.

Fig. 23 and Fig. 24 show the relationship between \( C_L \) and morphing angle at 0-degree angle of attack and 10-degree angle of attack, respectively. In this graph, the cases of optimal deformation and simple flap deformation are put on for comparison. Simple flap deformation is rotation after 65 % chord. Thus, camber line is straight and deformation is discontinuity at 65 % chord.

From Fig. 23 and Fig. 24, the aerodynamic performance of the corrugated panel is closer to the optimal value than the simple flap. The maximum lift coefficient of the corrugated panel is nearly to the optimum but there is a room for improvement at small morphing angle. This is because rise-up deformation is induced by aerodynamic forces at large morphing angle, but the deformation by airflow is small at small morphing angle, leading to separate from optimal deformation, and parametric study is conducted to optimize corrugated panel at 30-degree morphing angle.

4. Conclusion

The optimal deformation of symmetric camber morphing wing is derived. This is only one deformation shape for any angles of attack and the sharpest camber at the end.

For initial design to realize it by corrugated panel, simple analysis method using highly flexible structure’s equation is developed. This method can analyse more quickly than FEM analysis and be suitable for initial design. By using this method, the optimal configuration of corrugated panel is searched. Symmetric corrugated panel shows higher specific stiffness, and the smaller corrugate pitch rate is, the sharper at the end and closer to the optimum the deformation is.

Deformation analysis is subjected to 0-degree angle of attack and 30-degree morphing angle. The aerodynamic performances of the obtained configuration at other angles of attack and morphing angles are investigated. Optimal configuration can perform better than simple flap configuration, but the performance at small morphing angles is less than the one at 30-degree morphing angle. This is because aerodynamic force which raises the deformation shape and makes it close to the optimum is smaller at small morphing angles. In order to obtain better performance, additional actuations should be installed.

In this deformation analysis, aerodynamic effects and elastic effects are calculated independently. For future work, the method of unsteady analysis will be developed and the behavior combined aerodynamic and elastic effects will be searched.
Acknowledgments

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References