STRUCTURAL DESIGN OF MORPHING CONTROL SURFACE USING CORRUGATED PANELS

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Morphing wings are 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 panels is a solution to satisfy those demands. In this paper, in order to realize morphing control surface, the model which has corrugated panels driven by skins is proposed. The deformation analysis and the aerodynamic analysis are conducted. The parametric study showed the efficiency of this model compared with the plain flap.

Keyword: morphing, corrugated panel, Super-anisotropy, control surface, lift-drag ratio

1. INTORODUCTION

With the restricted environmental regulation and increasing fuel prices, airplanes are requested 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. 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 induction of noise. Morphing technology can realize a seamless deformation of wing section, optimized deformation at each flight condition 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 discussed1). Camber morphing wing is one type of morphing wing which is well discussed2)-4). However, two conflicting characteristics are required for camber morphing wing: stiffness for aerodynamic forces and flexibility for shape change ability. Super-anisotropy of corrugated panels is one of the feasible solutions to satisfy these conflicting characteristics (Fig. 1). The corrugated panel is stiff along the corrugation direction, but flexible in the transverse direction. Our previous works 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 devices5). In previous research, using film at intrados, wrinkles leading to reduce aerodynamic efficiency were observed. Also, this model can move downwards only. In this paper, aircraft wing with morphing control surfaces enabling the leading edge to move upwards and downwards flexibility is focused on. Morphing mechanism and deformation estimation are investigated using FEM analysis (Marc) combined with aerodynamic analysis (XFLR5). The parametric studies are carried out to maximize the lift-drag ratio (L/D) at the one engine inoperative take-off condition.

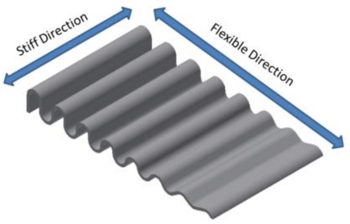

Figure 1: Super-anisotropic corrugated structures

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2. MODEL of MORPHING WING

(1) Airfoil

Symmetric airfoil, NACA64A010, is chosen considering deformation upwards and downwards and expecting to adopt as a vertical tail plane. Chord length of airfoil is 1000 mm considering wing tunnel test for future.

(2) Way of actuation

The part of morphing (corrugation) is from 65% chord length to 90% chord length. It is necessary to avoid skin buckling because intrados skin will be compressed as increasing camber. Morphing skin is one of the main problems for realization morphing wing[6)]. Many ideas about morphing skin are proposed, for example, using corrugated panel[7)], compliant mechanism[8)], or pneumatic muscle fibers[9)] for skin. In this paper, the skin is made of flexible sheet and corrugated panel is actuated by winding it. The intrados skin is drawn in while both side skins have tension.

(3) Detail of model

To keep symmetry, the corrugated panels are arranged symmetrically and there is a rib which transfers the reaction force at the center line. There are also guides to generate bending moment and prevent skins from separating from airfoil (Fig. 2)

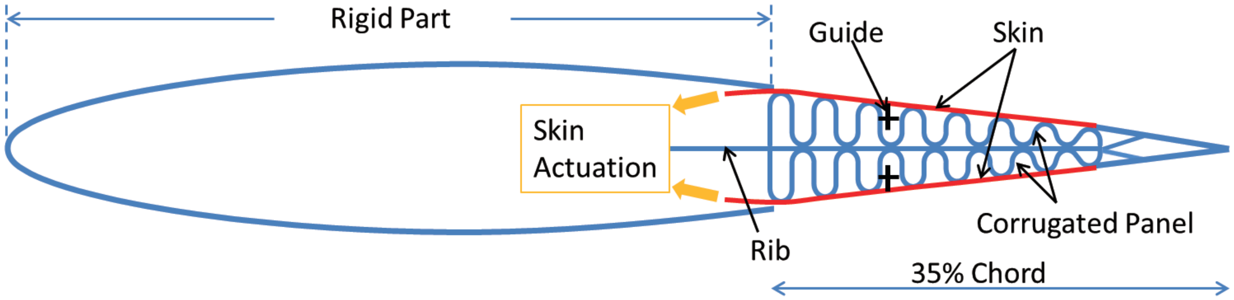

Figure 2: Schematic model of morphing control surface

3. NUMERICAL ANALYSIS

(1) FEM analysis

Deformation analysis and airfoil analysis were conducted to validate this model. Morphing mechanism and deformation estimation are investigated using FEM analysis (Marc). Focusing on two-dimensional deformation in airfoil cross section, plain strain was assumed. Element length was about 1 mm or smaller at curved area and near load area. Solid element was adapted to skin, and beam element was adapted to other parts. The geometric parameters and material properties of each part are given in Tab .1 and Tab. 2, respectively. The properties of CFRP were from JAXA Advanced Composites Database System[10)]. The contact was defined between all parts.

Table 1: Geometric parameters of the model

Baseline airfoil	NACA64A010
Chord (c) [mm]	1000
Span (b) [mm]	1000
Start of morph [mm]	0.65c = 650
End of morph [mm]	0.9c = 900
Number of corrugation	7.5
Corrugate thickness [mm]	1
Skin thickness [mm]	0.186
Rib thickness [mm]	1.5
Guide thickness [mm]	1
Rigid part thickness [mm]	2.2

Table 2: Material properties

Part	Material	E (GPa)	ν
Corrugated panel, Rigid part and Guide	Aluminum 2024	74	0.34

Part	Material	E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	ν_{12}	ν_{23}	ν_{31}	G_{12} (GPa)	G_{23} (GPa)	G_{31} (GPa)
Rib	UD CFRP	153	8	8	0.34	0.3	0.02	4.03	3.07	4.03
Skin	Stain CFRP	74	74	8	0.05	0.34	0.037	12	4.03	4.03

UD CFRP: Unidirectional CFRP

Front rigid part and the first line of corrugation were fixed for all degrees of freedom. The end of the rib was fixed for only displacements. Displacement boundary condition was applied at end of the skins to simulate skin winding. Another end of the skins sheared nodes with the corrugated panel. Non-linear analysis for large displacement was conducted.

(2) Airfoil analysis

The deformation data derived by FEM was inputted and two-dimensional airfoil aerodynamic analysis was conducted by XFLR5. Aerodynamic load case assumes one engine inoperative condition which is a critical case at take-off. Tab. 3 shows this condition. Because morphing wing deforms the whole structure of morphing part, the rudder angle cannot be defined by using rotation angle around hinge like traditional rudder. In reference to previous work5), morphing rudder angle is defined as a rotation angle of plain flap whose hinge is the same position of the start of the morph and trailing edge coincides with morphing trailing edge (Fig. 3). As the performance index of wing, each aerodynamic coefficient, i.e. lift coefficient (C_L), drag coefficient (C_D) and moment coefficient (C_M) were obtained. The case of a plain flap whose hinge line is 65% chord was also calculated to show the efficiency of this mode.

Table 3: Condition of aerodynamic analysis

Re (Reynolds number)	M (Mach number)	Angle of attack (deg)	Morphing angle (deg)
2.0×10^7	0.3	0	30

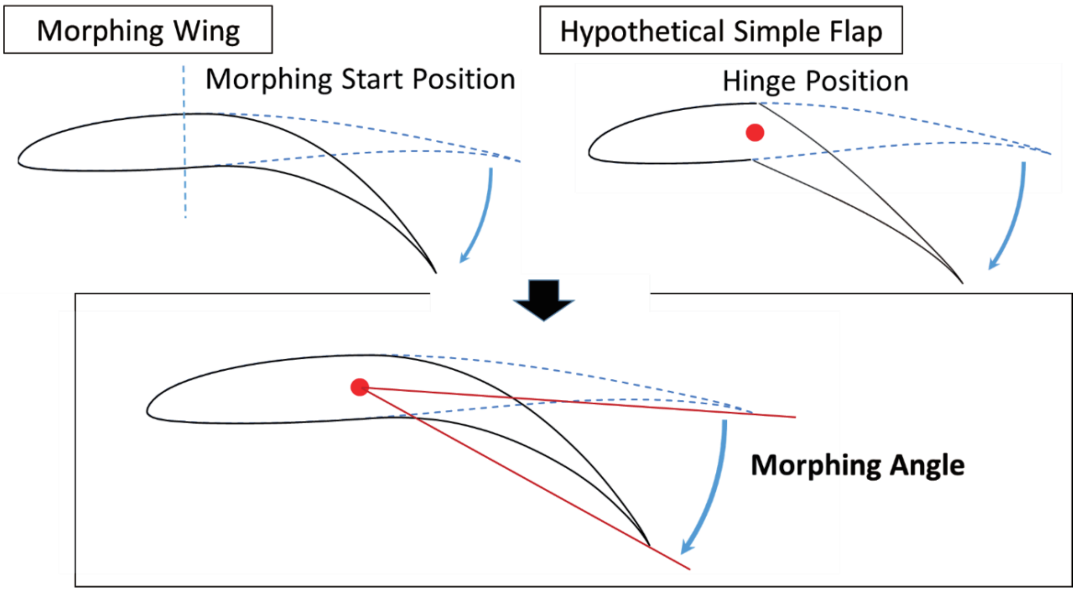

Figure 3: Definition of morphing angle5)

(3) Parametric study

The configuration of corrugated panel or the number and the position of guide will affect the final deformation of morphing and then the aerodynamic coefficients. Therefore, the parametric study was conducted. Parameters were corrugated pitch rate and the number and position of guide. Corrugated pitch rate means a common ratio of two adjoining circles of radius. An example of different corrugate pitch rate shows in Fig. 4. The guides were inserted in the rear five openings because deformation of corrugation will be too large if there are guides in other openings. The expression of the position of the guide is as follows. 1 means a guide and 0 means no guide in an opening and for example, the position of guide in Fig. 5 expresses as from front opening 0011010. The objective function is maximum lift to drag ratio (L/D).

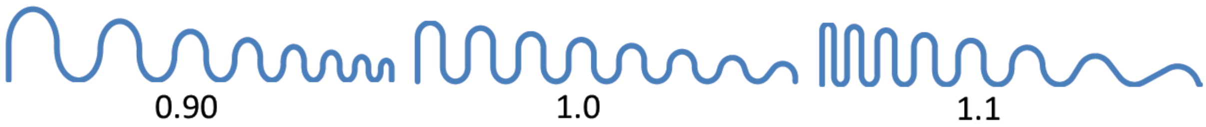

Figure 4: Corrugated pitch rate

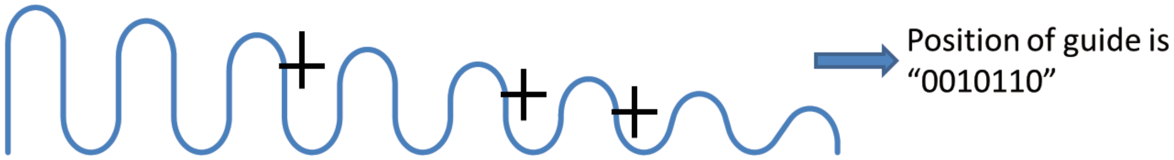

Figure 5: Example of position of guide

4. RESULT and DISUCUSSION

The best configuration is that corrugated pitch rate is 0.90 and the position of guide is 0011100. Fig. 6, Fig. 7 and Tab. 4 show wing section after 60% chord, pressure distribution and aerodynamic coefficients compared with plain flap, respectively.

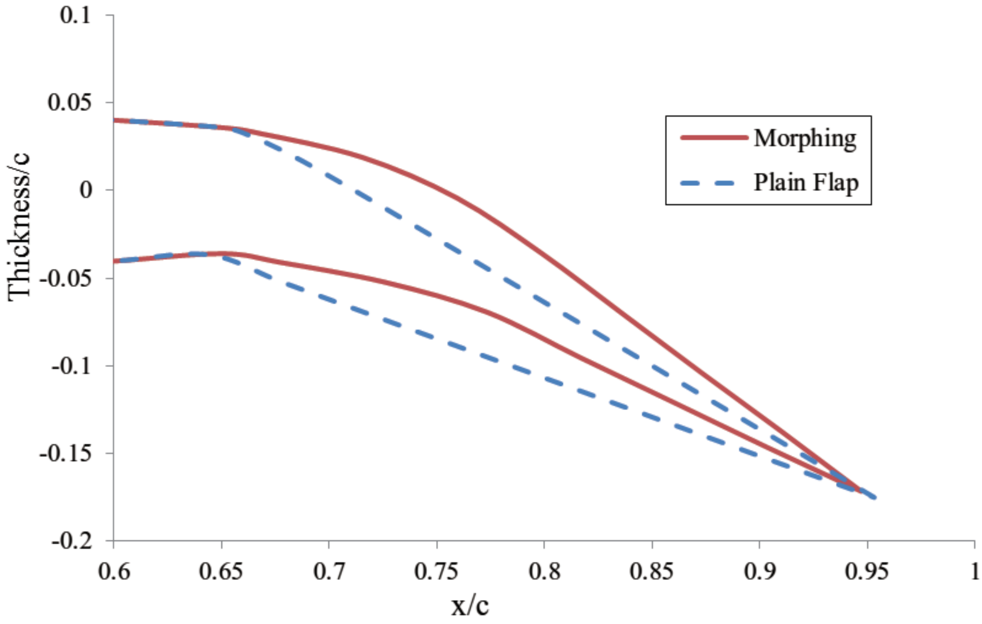

Figure 6: Comparison of wing section after 60% chord

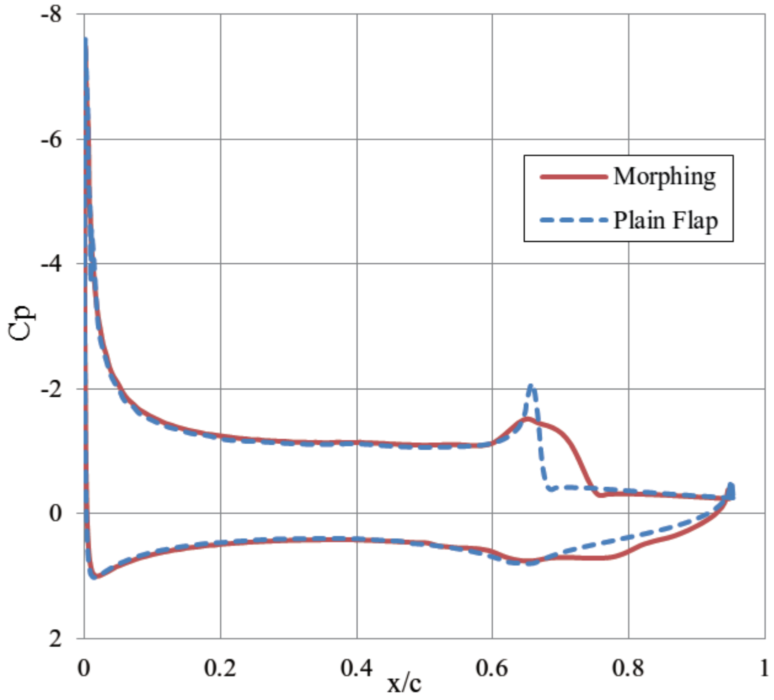

Figure 7: Comparison of pressure distribution

Table 4: Comparison of aerodynamic analyses

	Morphing	Plain flap	Ratio
C_L	1.58	1.49	1.07
C_D	0.0523	0.0593	0.0881
C_M	-0.214	-0.177	1.21
L/D	30.3	25	1.21

The morphing model exhibits 20% higher L/D than the plain flap. This is mainly because of the reduction of drag coefficient. In this case, the deformation of airfoil becomes sharper as approaching to the trailing edge (see Fig. 6) and this mitigates the flow separation (see Fig. 7). In XFLR5, the drag coefficient was obtained by measuring the momentum thickness at downstream infinity. This means that drag coefficient was calculated by reduction of momentum, thus mitigation of the flow separation leads to the reduction of wake, which translates into decreasing reduction of momentum and then drag. It also produces longer area of negative pressure at upper surface and improvement of lift. From Fig. 7, the peak of pressure also becomes blunting which could translate into weight saving.

5. CONCLUSION

As a result of comparison of two cases, the morphing model performs higher L/D than the plain flap, meaning that the aerodynamic efficiency can be improved by using morphing control. This property results from the smooth deformation which mitigates the flow separation. The parametric study shows that shape deformation of airfoil can be changed by altering the corrugated panel configuration and the position of guide. The results demonstrated that morphing control surfaces are realized using corrugated panels, and applicable to the high-performance rudder structure.

In this study, deformation analysis was conducted under no aerodynamic forces and optimized deformation shape by skin actuation was obtained. The possibility of obtaining this shape by this morphing model is shown. However, it is necessary to combine aerodynamic effects and structural elastic effect. This could be the aim of future study.

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6. REFERENCES

1) Solfa, A. Y. N., Meguid, S. A., Tan, K. T., Yeo, W. K. : Shape morphing of aircraft wing: Status and Challenges, *Materials and Design*, Vol. 31, pp.1284-1292, 2010.

2) Lyu, Z., Martins, R. R., Joaquim, A. : Aerodynamic shape optimization of an adaptive morphing trailing edge, *15th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, Atlanta, USA, June 16-20, 2014.

3) Kota, S., Osborn, R., Ervin, G., Maric, D. : Mission adaptive compliant wing - design, fabrication and flight test, *RTO Applied Vehicle Technology Panel (AVT) Symposium*, RTO-MP-AVT-168, 2009.

4) Woods, K. S. B., Bilgen, O., Friswell, I. M. : Wind tunnel testing of the fish bone active camber morphing concept, *Journal of Intelligent Material Systems and Structures*, Vol.25, No.7, pp.772-785, 2014.

5) Yokozeki, T., Takahashi, H., Hirano, Y. : Variable camber morphing wing using corrugated composites. *26th International Conference on Adaptive Structures and Technologies*, Kobe, Japan, October 14-16, 2015

6) Thill, C., Etches, J., Bond, I., Ptter, K., Weaver, P. : Morphing skins, *The Aeronautical Journal*, Vol.112, No.1129, pp.117-139, 2008.

7) Dayyani, I., Khodaparast, H. H., Woods, K. S. B., Friswell, I. M. : The design of a coated composite corrugated skin for the camber morphing airfoil, *Journal of Intelligent Material Systems and Structures*, Vol.26, No.13, pp. 1592-1608, 2015.

8) Berglind, A. L., , Summers, D. J. : Direct displacement synthesis method for shape morphing skins using compliant mechanisms, *International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, Montreal, Canada, August 15-18, 2010.

9) Fenf, N., Liu, L., Liu, Y., Leng, J. : A bio-inspired, active morphing skin for camber morphing structures, *Smart Materials and Structures*, Vol.24, No.3, 035023, 2015.

10) Advanced Composite Database System: JAXA-ACDS; Ver.06-1 http://www.jaxa-acdb.com/