759. Feasibility and principle analyses of morphing airfoil used to control flight attitude

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Abstract. Morphing airfoil technology can enable an aircraft to adapt its shape to enhance mission performance and replace the traditional flap, ailerons, elevator and rudders to optimize flight attitude control efficiency. A set of optimal airfoil shapes are obtained aimed to minimize the aerodynamic drag character by optimizing morphing configurations at different C_l under the two-dimensional steady-flow simulation. The traditional airfoil and morphing airfoil at different C_l are compared. It is proved that morphing wing can be used instead of a traditional wing. Couples of traditional control surface and morphing airfoil are chosen to simulate and analyze the aerodynamic difference. The flow mechanism is described on the basis of aerodynamic simulations performed by CFX. It is demonstrated why the morphing wing can provide the same C_l with a small C_d.

Keywords: morphing airfoil, control surface, compliant structure, polar computation, aerodynamic analysis, streamlines.

Introduction

Aircraft designers are focused on improving the flight efficiency of aircraft. In particular, airline companies are anxious to improve the efficiency of commercial aircrafts. Traditional aircraft wings are designed to be the most efficient at cruising speed but suffer performance penalties at other flight conditions, such as taking off, landing and controlling flight attitude. Inspired by the bald eagle, which can change its own flap configuration to fit different flight conditions and control the rolling, pitching and yawing performance [1], many researchers have investigated different ways to improve the flight efficiency in different environments. Smart wing and morphing aircraft technique research have been published in recent years.

These morphing wing technology were used to optimize the airfoils [2-6], wings' platform configuration [7] and the three dimension configuration [8-10] of the aircraft in order to control flow [11], change the deform of shock wave [12] and improve the aerodynamic and aeroelastic performance of military aircrafts [13-18].

New advances in morphing technology allow aircraft wing changing its configurations not only at different flight attitude [19] and stages [20], but also control flight attitude at any time with the most optimal polar ratio and take the place of the traditional control surface.

In this paper, the morphing concept which can deform the configuration of the airfoil and control flight attitude with minimized cost is proposed. The aerodynamic characters of optimal morphing airfoils and traditional hinged control surfaces (which can be used in flaps, ailerons, elevating and yawing rudders) are compared. The flow mechanism is represented based on the aerodynamic simulation. The conclusions are provided with comments on the benefits and drawbacks of the morphing airfoil concept.

Conceptual structure design

There are two basic morphing concepts in the development of morphing wing: one is changing the surface configuration of the wing [21] and the other is deforming the section shape (the airfoil shape) of the morphing wing [22, 23].

In Fig. 1, the morphing airfoil compliant concept that can change the section shape is represented. It can deform the configuration of the leading edge, trailing edge, and the chamber to fit flight environment and control the attitude [24-26]. It is axially symmetric about the chord.

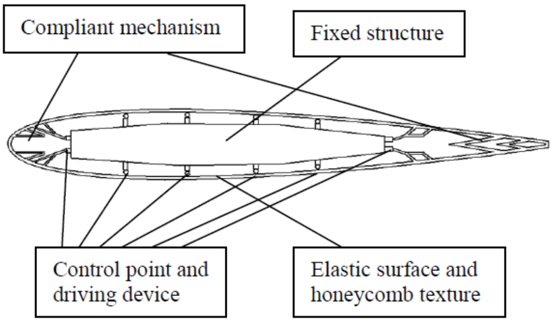

Fig. 1. The morphing structure concept

Optimization of the morphing airfoil

Numerous mathematic methods have been devised to represent airfoil geometry in aerodynamic design, optimization and parametric studies. The “CST” mathematical method [27-29] proposed by Brenda Kulfan is chosen to describe the airfoil configuration. There are n control parameters which can be used to control the different parts of airfoil configuration and defined by the customer according to the required accuracy.

The airfoil was optimized to get the optimal airfoil shapes which can provide the same C_l with a much smaller C_d punishment than any other shapes. To achieve this, a tool that can search for the optimal airfoil geometry is used. First the generic constraint was represented by the Bernstein polynomial. Second the XFOIL program [30] is used to get the polar ratio of the airfoil shape in the aerodynamic analysis. Then the polar ratio is compared with the target parameter and the former ones’ ratio and the airfoil shape control parameter which will be used in the next cycle obtained with Isight.

The controlling moment is determined by the lift on the different control surface and the distance of control surface and weight center. So the compare of the rolling, pitching and yawing moment can transfer to the compare of the lift of the control surfaces. The aerodynamic shape optimization problem can be stated as minimization of the drag coefficient with regard to a confirmed lift coefficient.

A set of optimal airfoil shapes which can provide different C_l with the minimum drag is obtained by the procedure at Mach 0.045, Re 300000. The relationship between C_l, C_d of the traditional hinged control surfaces and the optimal morphing airfoils is proposed. Flap 0, Flap 3, and Flap 5 shows the polar ratio character of the traditional airfoil followed with the changing angle of the hinged control surface when the angle of attack is 0, 3, 5 degree separately. It shows that the traditional airfoil at different angles of attack provide the same C_l with a bigger C_d than the morphing airfoil.

Take the traditional airfoil at angle of attack 5° and the morphing wing for example. Table 1 shows the C_m, C_l, C_d character of traditional airfoil with and without gap when the control surface is at different angle of attack (3°, 5°, 8°).

C_m, C_l and C_d is the moment coefficient, lift coefficient and drag coefficient of the airfoil in Table 1. From Table 1 it can be determined that the morphing airfoil can provide a much smaller C_d and a bigger than the traditional airfoil when they provide a same C_l. So it is more efficient to use the morphing airfoil instead of the traditional hinged control surfaces on the flaps, ailerons, elevators and rudders in general aircraft. The morphing airfoil can provide a much bigger than the traditional airfoil when they provide a same C_l, it can improve the pitching character of the flying wing layout aircraft.

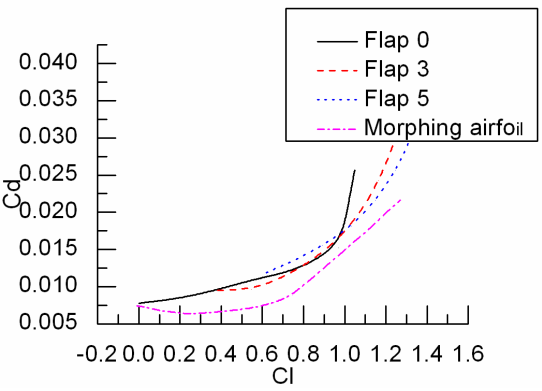

Fig. 2. The relationship between C_l, C_d of the traditional flap and morphing airfoil

Table 1. The C_m, C_l, C_d character of different airfoil and angle of attack of the control surface

	Angle of attack of the control surface (degree)	C_m	C_l	C_d
Traditional airfoil with gap	3	0.023	0.61	0.0230
	5	0.063	0.85	0.0350
	8	0.100	1.05	0.0482
Traditional airfoil without gap	0	0.010	0.61	0.011
	3	0.048	0.85	0.0187
	5	0.108	1.055	0.029
Morphing airfoil	0	0.095	0.61	0.0139
	0	0.108	0.85	0.0162
	0	0.132	1.060	0.0222

Aerodynamic analysis

The flow over a morphing airfoil and the airfoil with traditional control surface (with and without a gap) is simulated by the CFX of ANSYS to analysis the causes why the morphing airfoil can provide the same C_l with a smaller C_d punishment in comparison to the airfoil with traditional control surface. Three groups of 2D case, all of which have the same C_l with the traditional airfoil at the angle of attack of 5 degree when the angle of attack of the control surface is 3, 5, 8 degree separately, was simulated.

Fig. 3 illustrates the pressure of the flow domain of airfoil with traditional control surface, airfoil with traditional control surface without gap between the control surface of the wing and the morphing wing when they provide the same C_l with the traditional airfoil.

Fig. 4 shows the streamline of different airfoils when they provide the same C_l with the traditional airfoil at different angles of attack.

When the C_l is 0.61 (the angle of attack of traditional airfoil control surface is 3 degree), the streamline of the flow of all the airfoils are smooth, the traditional airfoil without gap can provide the same C_l with a smaller angle of attack of control surface and C_d. The morphing airfoil has a narrow section with respect to traditional airfoil so it can induce a smaller pressure C_d punishment than the traditional airfoil.

When the C_l is 0.85 (the angle of attack of the control surface is 5 degree), the streamline of the flow of the traditional airfoil without gap and the morphing airfoil is smooth, the flow of traditional airfoil start to be turbulent at the trailing edge, which can increase the energy consumption.

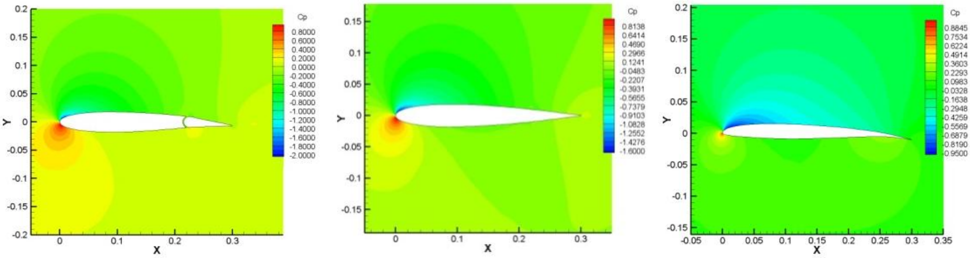

Fig. 3. 1 The control surface angle of attack is 0 degree

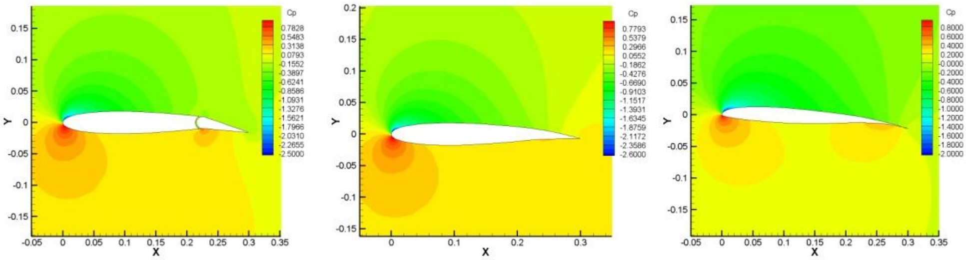

Fig. 3. 2 The control surface angle of attack is 3 degree

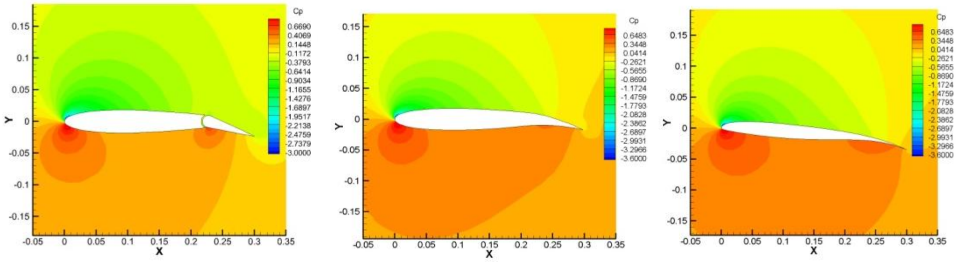

Fig 3. 3 The control surface angle of attack is 5 degree

Fig. 3. The pressure domain of different airfoils when they provide the same C_l with the traditional airfoil at different angles of attack.

When the C_l is 1.05 (the angle of attack of the control surface is 8 degree), the streamline of the flow of morphing airfoil is smooth, the flow of traditional airfoil and traditional airfoil without gap is turbulent at the trailing edge, the traditional airfoil without gap have a smaller turbulence. The morphing airfoil still has a smooth streamline.

The traditional airfoil with gap have a vortex at the control surface, the vortex will increase followed with the increasing C_l. The flow of traditional airfoil without gap changes from a smooth to vortex followed with the increasing C_l, the vortex is smaller than the ones with gap when they provide the same C_l. The morphing airfoil will not cause a vortex followed with the increasing C_l, so it can waste less energy than the other two, and its narrow section will decrease the pressure drag.

There are three reasons why the morphing wing can provide the same C_l with a small C_d punishment:

1. It has no gap which can increase the pressure difference of low and up surface.

2. The smooth shape can ensure the streamline around the airfoil to be smooth.
3. It has a narrow section which can decrease the pressure drag.

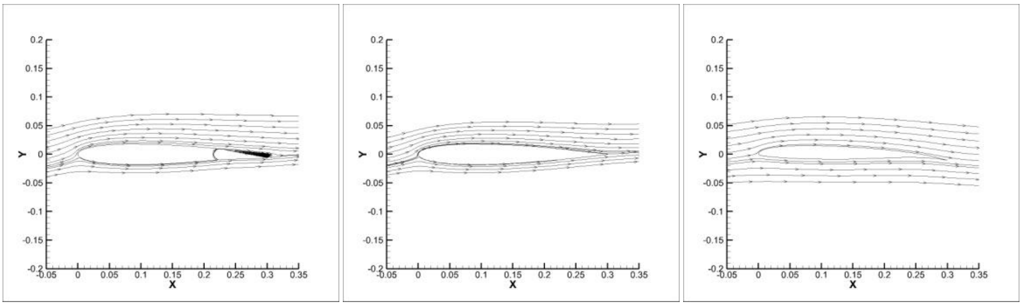

Fig. 4. 1 The control surface angle of attack is 0 degree

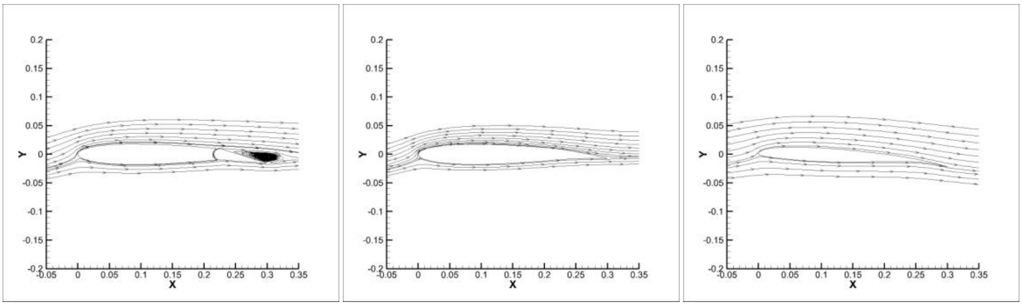

Fig. 4. 2 The control surface angle of attack is 3 degree

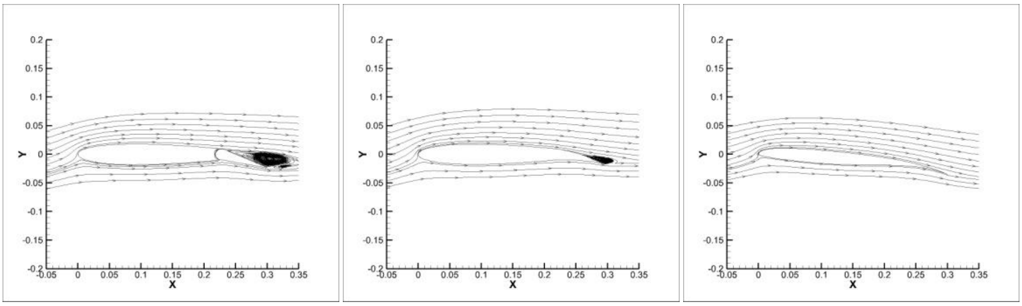

Fig. 4. 3 The control surface angle of attack is 5 degree

Fig. 4. The streamline chart of different airfoils when they provide the same C_l with the traditional airfoil at different angles of attack

Conclusion

It is proved that the morphing airfoil can replace the hinged control surfaces to control the rolling, pitching and yawing moment with a smaller drag and increase the flight efficiency at different rolling, pitching and yawing moments.

The morphing airfoil control element can reduce the drag from 20 % to 60 % (showed in Fig. 2) with respect to the traditional airfoils with control surface when they provide a same C_l, if the C_l is bigger than 0.1. The morphing airfoil can lead to a smaller adverse yaw when they provide the same rolling moment.

Reasons why the morphing wing can provide the same C_l with a small C_d are determined. The morphing airfoil is more efficient because of absence of gap, smooth shape and narrow cross-section.

Future work stages will include design of morphing mechanism components, materials and further wind-tunnel test of the morphing wing at different flight speeds and attitude control requirements.

References

[1] **Bowman J., Sanders M. B., Weisshaar T.** Evaluating the Impact of Morphing Technologies on Aircraft Performance. 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Denver, Colorado, 22–25 April 2002.

[2] **Huyse L., Padula S., Lewis R., Li W.** Probabilistic Approach to Free-Form Airfoil Shape Optimization under Uncertainty. AIAA Journal, Vol. 40, No. 9, Sept. 2002, p. 1764–1772.

[3] **Namgoong H., Crossley W. A., Lyrintzis A. S.** Global Optimization Issues for Transonic Airfoil Design. 9th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, AIAA Paper 2002-5641, 4–6 Sept. 2002.

[4] **Lee S. W., Kwon O. J.** Robust Airfoil Shape Optimization Using Design for Six Sigma. Journal of Aircraft, Vol. 43, No. 3, May–June 2006, p. 843–846.

[5] **Winnemoller T., Van Dam C. P.** Design and Numerical Optimization of Thick Airfoils Including Blunt Trailing Edges. Journal of Aircraft, Vol. 44, No. 1, Jan.–Feb. 2007, p. 232–240.

[6] **Secanell M., Suleman A.** Numerical Evaluation of Optimization Algorithms for Low Reynolds Number Aerodynamic Shape Optimization. AIAA Journal, Vol. 43, No. 10, Oct. 2005, p. 2262–2267.

[7] **Peigin S., Epstein B.** Multipoint Aerodynamic Design of Wing-Body Configurations for Minimum Drag. Journal of Aircraft, Vol. 44, No. 3, May–June 2007, p. 971–980.

[8] **Nadarajah S. K., Jameson A., Alonso J. J.** Sonic Boom Reduction Using an Adjoint Method for Wing-Body Configurations in Supersonic Flow. 9th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, AIAA Paper 2002-5547, 4–6 Sept. 2002.

[9] **Reuther J., Alonso J., Jameson A., Eimlinger M., Saunders D.** Constrained Multipoint Aerodynamic Shape Optimization Using an Adjoint Formulation and Parallel Computers: Part 1. Journal of Aircraft, Vol. 36, No. 1, 1999, p. 51–60.

[10] **Reuther J., Alonso J., Jameson A., Eimlinger M., Saunders D.** Constrained Multipoint Aerodynamic Shape Optimization Using an Adjoint Formulation and Parallel Computers: Part 2. Journal of Aircraft, Vol. 36, No. 1, 1999, p. 61–74.

[11] **Stanewsky E.** Adaptive Wing and Flow Control Technology. Progress in Aerospace Sciences, Vol. 37, 2001, p. 583–667.

[12] **Siclari M. J., Nostrand W. V., Austin F.** The Design of Transonic Airfoil Sections for an Adaptive Wing Concept Using a Stochastic Optimization Method. AIAA Aerospace Sciences Meeting and Exhibit, 34th, Reno, NV, Jan. 15–18, 1996.

[13] **Weisshaar B. T., Sanders B.** Evaluating the Impact of Morphing Technologies on Aircraft Performance. 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Denver, CO, United States, 22–25 Apr. 2002.

[14] **Florance P. J., Burner A. W., Gary A. F., Craig A. H., Hunter C. A.** Contributions of the NASA Langley Research Center to the DARPA/AFRL/NASA/NORTHROP Grumman Smart Wing Program. 44th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference, Norfolk, Virginia, 7–10 April 2003.

[15] **Larson R. R.** Flight Control System Development and Flight Test Experience with the F-111 Mission Adaptive Wing Aircraft. NASA Technical Memorandum 88265.

[16] **Hardy R.** AFTIF-111 Mission Adaptive Wing Technology Demonstration Program. AIAA-1983-1057, 1983.

[17] **Smith S. B., Nelson D. W.** Determination of the Aerodynamic Characteristics of the Mission Adaptive Wing. Journal of Aircraft, Vol. 27, No. 11, p. 44–46.

[18] **Wrobleski M. S., Henderson J., Jonathan D. B.** BAC 1-11 and MAW F-111 Control Surface Weight Estimation for SWIFT Study. 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Austin, Texas, 18–21 April 2005.

[19] **Rusnell M. T., Gano S. E., Pérez V. M., Renaud J. E., Batill S. M.** Morphing UAV Pareto Curve Shift for Enhanced Performance. 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA, Paper 2004-1682, 19–22 Apr. 2004.

[20] **Gano S. E., Renaud J. E.** Optimized Unmanned Aerial Vehicle with Wing Morphing for Extended Range and Endurance. 9th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, AIAA Paper 2002-5668, 4–6 Sept. 2002.

[21] **Lee D. H., Weisshaar T. A.** Aeroelastic Studies on a Folding Wing. 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Austin, Texas, 18–21 April 2005.

[22] **Gandhi N., Jha A., Monaco J.** Intelligent Control of a Morphing Aircraft. 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, 23–26 April 2007.

[23] **Lafountain C., Cohen K., Abdallah S.** Camber Controlled Airfoil Design for Morphing UAV. 47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition, Orlando, Florida, 5–8 January 2009.

[24] **Lu K. J., Kota S.** Compliant Mechanism Synthesis for Shape-Change Applications: Preliminary Results. Smart Structures and Materials, Proceedings of SPIE, Vol. 4693, 2002.

[25] **Santer M., Pellegrino S.** Topological Optimization of Compliant Adaptive Wing Structure. AIAA Journal, Vol. 47, No. 3, March 2009.

[26] **Lu K. J., Kota S.** Design of Compliant Mechanisms for Morphing Structural Shapes. Journal of Intelligent Material Systems and Structures, Vol. 14, June 2003.

[27] **Kulfan B. M., Bussoletti J. E.** "Fundamental" Parametric Geometry Representations for Aircraft Component Shapes. AIAA-2006-6948, Sept. 2006.

[28] **Kulfan B. M.** A Universal Parametric Geometry Representation Method - "CST". AIAA-2007-0062, Jan. 2007.

[29] **Kulfan B. M.** "CST" Universal Parametric Geometry Representation Method with Applications to Supersonic Aircraft. Fourth International Conference on Flow Dynamics, Sendai, Japan, Sept. 26-28, 2007.

[30] **Drela M., Youngren H.** XFOIL 6.94 User Guide. Published by the Authors, Cambridge, MA, 10 Dec. 2001.