DESIGN AND ANALYSIS OF A MECHANISM FOR THE CHORD AND CAMBER MORPHING OF AN AIRCRAFT WING

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Abstract

What allows aircrafts to fly at different flight conditions are the wings. The nature and desire of creating new air vehicles which are more efficient in terms of fuel consumption, noise and aerodynamic drag at any flight conditions inspire human being to design aircraft wing which changes its shape/geometry during the flight. This is usually referred to as the "shape morphing of an aircraft wing"

The shape morphing of the aircraft wing can be classified by three main categories, which are planform alternation, out-of-plane transformation, and airfoil. This study covers both planform alternation by extending airfoil chord length and airfoil adjustment by changing its camber.

In this study, a novel mechanism, which replaces wing ribs, is synthesized by combination of various type of four-bar linkages and scissor-like elements. By assuming fully-elastic skin, with a developed computer routine based kinematic synthesis methodology, it can be achieved to create a deployable mechanism which is successfully utilized in order to extend/shorten the airfoil chord length and to interchange the type of airfoil with as minimum structural error as possible.

With proposed mechanisms, assuming flexible members, it is theoretically proven that the proposed mechanisms have the capability to do their tasks with small errors.

Keywords morphing wing; kinematic design; scissor-like element; deployable mechanism.

1. Introduction

The nature teaches us with birds that the flight action can vary according to different atmospheric conditions and desired flight paths as gliding soaring and flapping. Birds accomplish these flight actions, listed above, by altering their wings into various forms, so they benefit form that by getting more lift and thrust and reducing the drag (Ghommem, *et.al.*, 2014. The observation of nature and the direct comparison of nature and aircrafts motivate designers to think a wide range of wing configurations. In commercial aviation, alternation of aircraft wings is achieved by conventional flaps or slats. Although these conventional systems are easy to apply, with the increasing demand of efficiency; researchers focus on continuous deployment (without any clearance) of aircraft wing geometry, which often called as "morphing aircraft" (Barbarino, *et.al.*, 2011). There is not an exact definition for "shape morphing"; however, there is a general agreement that the conventional hinged control surfaces or high lift devices generally cannot be considered as "morphing" (Sofla, *et.al.*, 2010)

There are three generally accepted major groups for morphing aircraft concepts: planform alternation, airfoil adjustment and out-of-plane transformation. The detailed scheme of the types of wing morphing concepts are given in Fig 1.

The most effective way to control the forces and moments that occur on aircraft wings is to change the camber of the airfoil (Friswell, 2012) or to resize the airfoil chord length (Reed, *et.al.*, 2005) for aircrafts' being optimized for longer flights with certain volume restrictions Therefore, researchers in this area generally focus and put studies on the topic of aircraft wing profile, or simply "airfoil profile", adjustment. In Fig. 2, some of the works done in the airfoil profile adjustment (especially camber/ decamber) are presented.

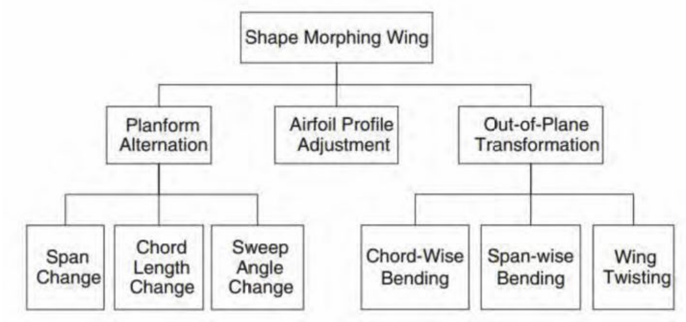

Fig. 1. A classification for shape morphing of wing (Sofla, *et.al.*, 2010).

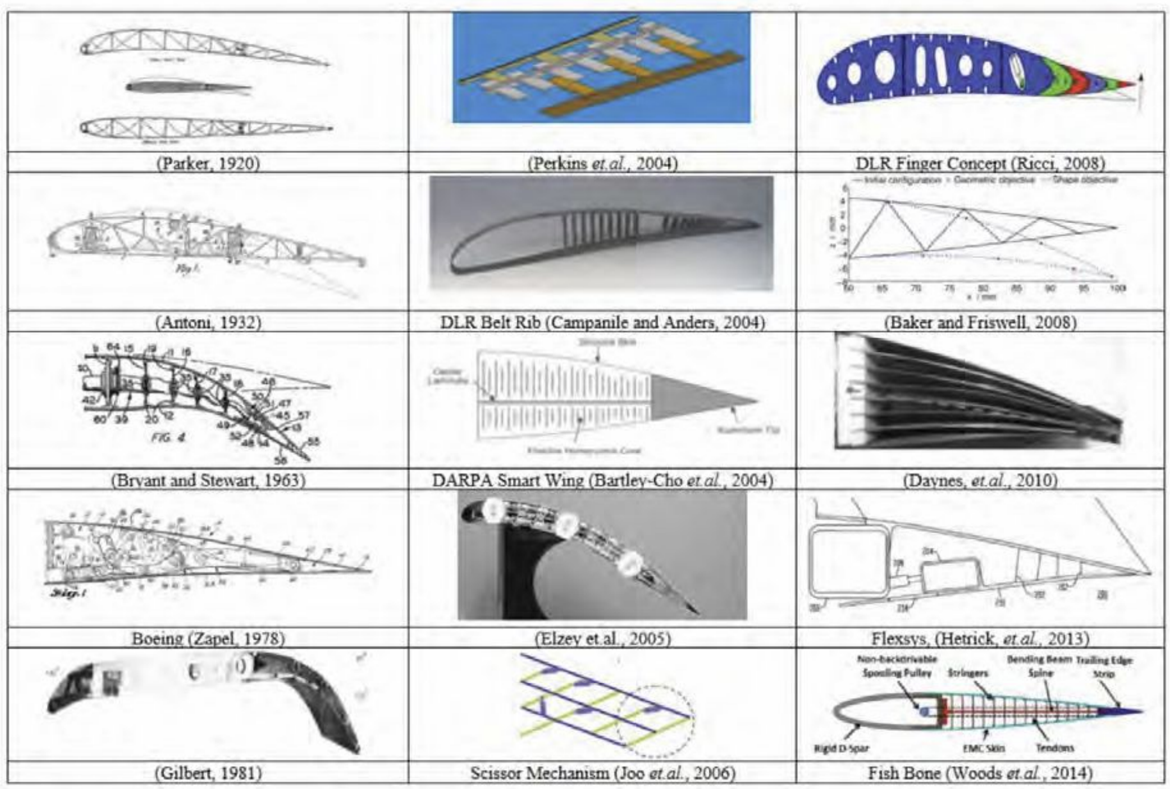

Fig. 2. Some of "shape morphing" studies from 1920 2014.

From these works one can notice that form past to today, airfoil profile adjustment still a big problem waiting for an acceptable solution. Since there are more than 300 studies in this area, one can observe that almost all works are at the level of conceptual design in terms of kinematics. Studies focus on aerodynamics of the design rather than detailed kinematic synthesis approaches.

In this paper, a new methodology to design a deployable mechanism for aircraft wings to camber/ decamber and resize the chord length is presented. While deployment process it is assumed that the aircraft wing skin and the structure provide the necessary material properties.

2. Conceptual Design of the Deployable Mechanism

Deployable structures are a good solution for the need of mobile and reusable structures with fast and easy movements and exist for a long period. These structures were widely used in engineering with the increasing needs of complex space missions. One of the simplest deployable structure can be obtained by combining pairs of linkages with revolute joints often called as "scissor like structure". Scissor like structures are composed of several "scissor like elements" (SLE) which has a pair of equal length linkages/bars connected to each other at an intermediate point with a revolute joint shown in Fig.3 (Zhao, *et.al.*, 2012).

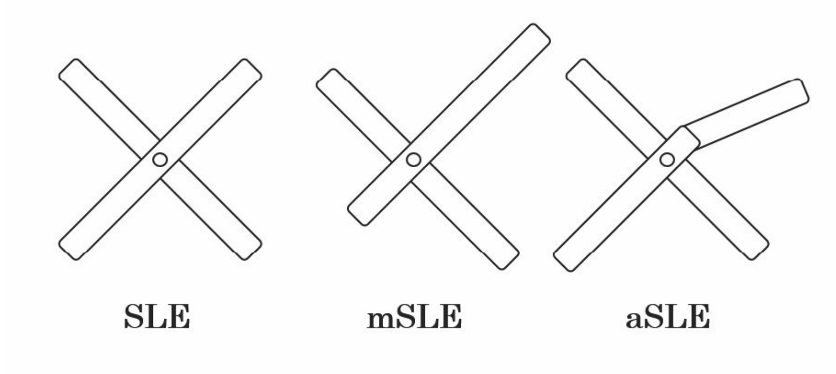

Fig. 3. Some types of scissor like structures.

If the dimensional characteristic of the SLEs is changed, a modified scissor like element (mSLE), if angular characteristics of the SLEs is changed an angular scissor like element (aSLE) can be obtained. However, these minor changes in SLE don't effect the mobility of scissor like structure.

In this paper a computer routine is presented which allows users to design a deployable mechanism based on modified scissor like elements. With this computer routine one can get a one degree of freedom deployable mechanism which changes its shape from any NACA 4-digit airfoil profile to another NACA 4-digit airfoil profile with minimum error as possible. Moreover, for size restrictions of the aircraft wing, in order to put the prime mover to the most suitable space, addition of one more four bar mechanism is considered and another computer routine is developed and presented before (Şahin and Yaman, 2016).

In most of commercial aircrafts, wings have longitudinally (in span-wise direction) aligned substructures, ribs, and laterally (in chord-wise direction) aligned spars. In Fig.4 a sketch of the mechanism is demonstrated. In this concept, the mechanism is assumed to be assembled to the rear spar of the aircraft wing. In other words, the rear-spar accepted as a ground of the mechanism, and the rib structures along rear spar to the rear tip of the airfoil is assumed to be replaced with deployable mechanism.

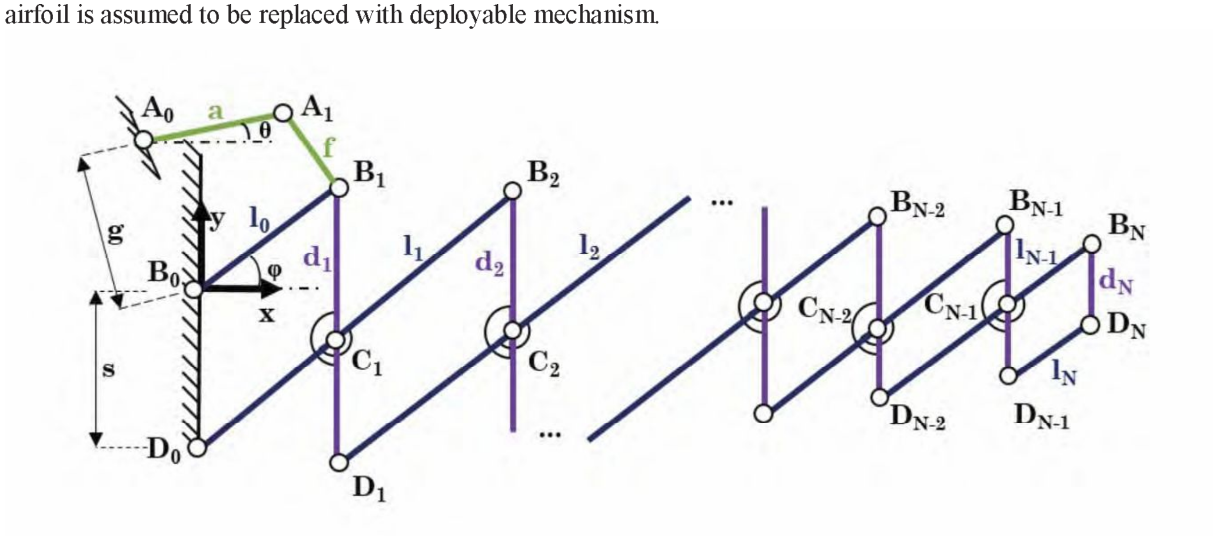

Fig. 4. Conceptual design of the mechanism.

2.1. *Mobility of the deployable mechanism*

One of the universally accepted and simple theory to calculate the degree of freedom (DOF, or mobility) of mechanisms is that of Kutzbach-Grübler The Kutzbach-Grübler formula generally presented as follows (Zhao, *et.al.*, 2004).:

$$M = \lambda(n - j - 1) + \sum_{i=1}^{j} f_i \quad (1)$$

In Equation (1) λ is "3" for planar and spherical mechanisms, while "6" for spatial mechanisms. M is the DOF of the mechanism, n is the total number of links, j is the total number of joints and the f_i is the DOF of the ith joint. In the computer routine, user defines the number of closed loops for the mechanism which is designed. If number of closed loops (n_{CL}) is $n_{CL}=N$, then $n=2N+2$ and $j=3N+1$. Since the mechanism is planar λ=3; and all joints are the type of revolute with 1DOF; f_i=1 for $i=1,...,j$. Then from the Equation (1) mobility becomes "1" (1DOF) for all "N" values without the included four-bar mechanism. In other words, whatever the user selects the number of closed loops, the mechanism is guaranteed to be 1DOF or to need only one prime mover to deploy.

3. Synthesis of the Deployable Mechanism

Theoretically, in order to synthesize such a deployable mechanism shown in Fig. 1, two extreme positions should be provided. However, in this case, the number of closed loops, the position of the origin (B_0 in Fig. 4) and the rocker angle f are not known. Moreover, two extreme positions on two arbitrary NACA 4-digit airfoil profiles cannot be determined exactly. In order to overcome these problems, the user of the computer routine is allowed to choose and compare variant of these parameters. With the defined error provided, the most suitable deployable mechanism, which suits for desired function with minimum error, can be selected.

NACA 4-digit airfoil profiles are created through a subroutine, which is written through instructions of "G Applied Computational Aerodynamics ". In the computer subroutine, the user defines any NACA 4-digit airfoil as NACA MPXX, where M is the maximum value of the mean line in hundreds of chord, P is the chord wise position of the maximum camber in tenths of the chord, XX is the maximum thickness in percent chord. Then the NACA 4-digit thickness distribution is:

$$\frac{y_t}{c} = \left(\frac{t}{c}\right)\left[a_0\sqrt{\frac{x}{c}} - a_1\left(\frac{x}{c}\right) - a_2\left(\frac{x}{c}\right)^2 + a_3\left(\frac{x}{c}\right)^3 - a_4\left(\frac{x}{c}\right)^4\right] \quad (2)$$

Where $a_0=1.4845$, $a_1=0.6300$, $a_2=1.7580$, $a_3=1.4215$, $a_4=0.5075$ for finite thick trailing edge and, $a_4=0.5180$ for zero thick trailing edge. The camber line is given by for $(x/c) < P$:

$$\frac{y_c}{c} = \frac{M}{P^2}\left[2P\left(\frac{x}{c}\right) - \left(\frac{x}{c}\right)^2\right] \quad (3)$$

$$\frac{dy_c}{dx} = \frac{2M}{P^2}\left[P - \left(\frac{x}{c}\right)\right] \quad (4)$$

And for $(x/c) \geq P$:

$$\frac{y_c}{c} = \frac{M}{(1-P)^2}\left[1 - 2P + 2P\left(\frac{x}{c}\right) - \left(\frac{x}{c}\right)^2\right] \quad (5)$$

$$\frac{dy_c}{dx} = \frac{2M}{(1-P)^2}\left[P - \left(\frac{x}{c}\right)\right] \quad (6)$$

Then calculating θ=atan (dy_c/dx), coordinates of the airfoil can be found for any distribution of x as:

$$x_u = x - y_t(x)\sin(\theta), y_u = y_c(x) + y_t(x)\cos(\theta) \quad (7)$$

$$x_l = x + y_t(x)\sin(\theta), y_l = y_c(x) - y_t(x)\cos(\theta) \quad (8)$$

where x_u, y_u are the upper portion coordinates of the airfoil profile and x_l, y_l are the lower portion coordinates.

In order to synthesize the mechanism, first of all, two arbitrary NACA 4-digit airfoil profiles are chosen. These airfoil profiles are the beginning and the target airfoils of the user. Then number of closed loops (n_{CL}) is determined. With these inputs, for an initial angle φ, the first mechanism is created. Since the mechanism has parallel links, the position analysis of the mechanism is straightforward (not depends on the number of links). With small perturbations of the angle φ the computer routine starts to calculate the error for various deployable mechanisms. The error is defined in the computer routine as follows:

$$err_i = \frac{\sqrt{(x_i - x_i^*)^2 + (y_i - y_i^*)^2}}{c} \quad (9)$$

$$err_{cum} = \frac{\sum_{i=1}^{j} err_i}{j} \quad (10)$$

In Equation (9), e_i denotes the error and $p_i=(x_i,y_i)$ denotes the position of ith joint. In the error definition, it is critical to determine perturbed position of the ith joint neatly. $p_i^*=(x_i^*,y_i^*)$ is calculated through creating a new mechanism on the desired airfoil profile with resized chord length. Also in Equation (9) c represents the initial chord length (one can also use the resized chord length).

Since the number of joints and their errors are different than each other, a cumulative error is defined in Equation (10) to compare different deployable mechanisms with each other.

4. Results

With developed computer routine, three example deployable mechanism has been created with minimum structural error as possible. In order to create these mechanisms the gap "s" shown in Fig. 4 has been selected as zero. Then the rocker angle is chosen as $\varphi=75^o$, $\varphi=60^o$, $\varphi=45^o$. Through this process, the number of closed lops is optimized.

In the first result the maximum allowable n_{CL} is 22. Then, when the rocker angle moves only $15°$, the mechanism almost fits the desired airfoil profile.

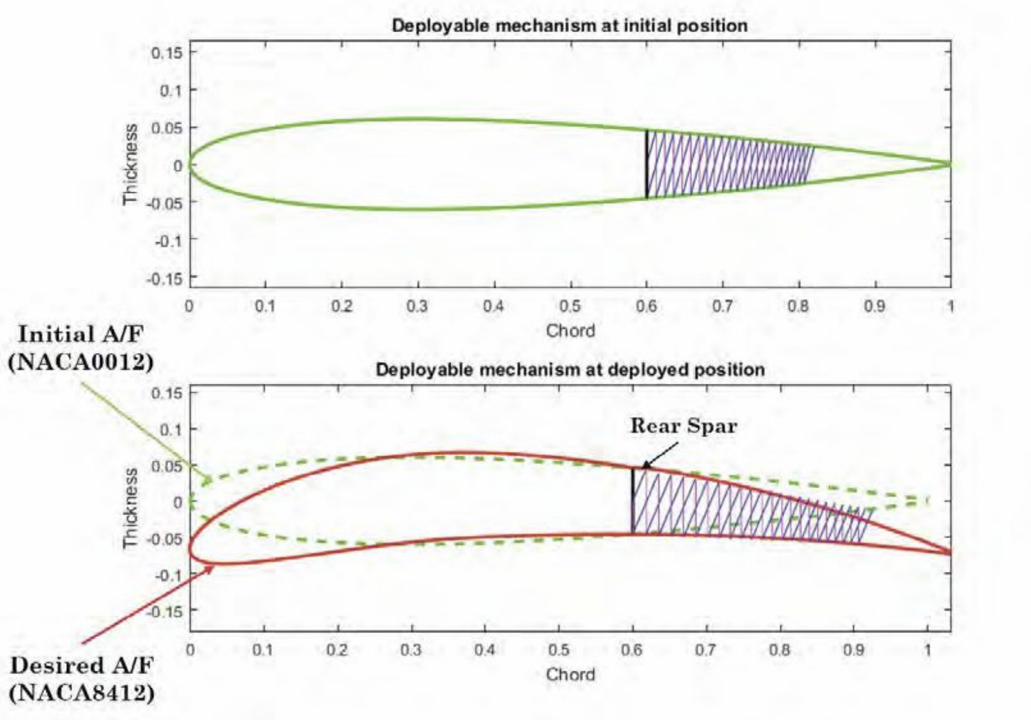

Fig. 5. Synthesized deployable mechanism with zero gap and the initial rocker angle of $\varphi=75°$.

In the second result the maximum allowable n_{CL} is 16. Then, when the rocker angle moves only $14°$, the mechanism almost fits the desired airfoil profile.

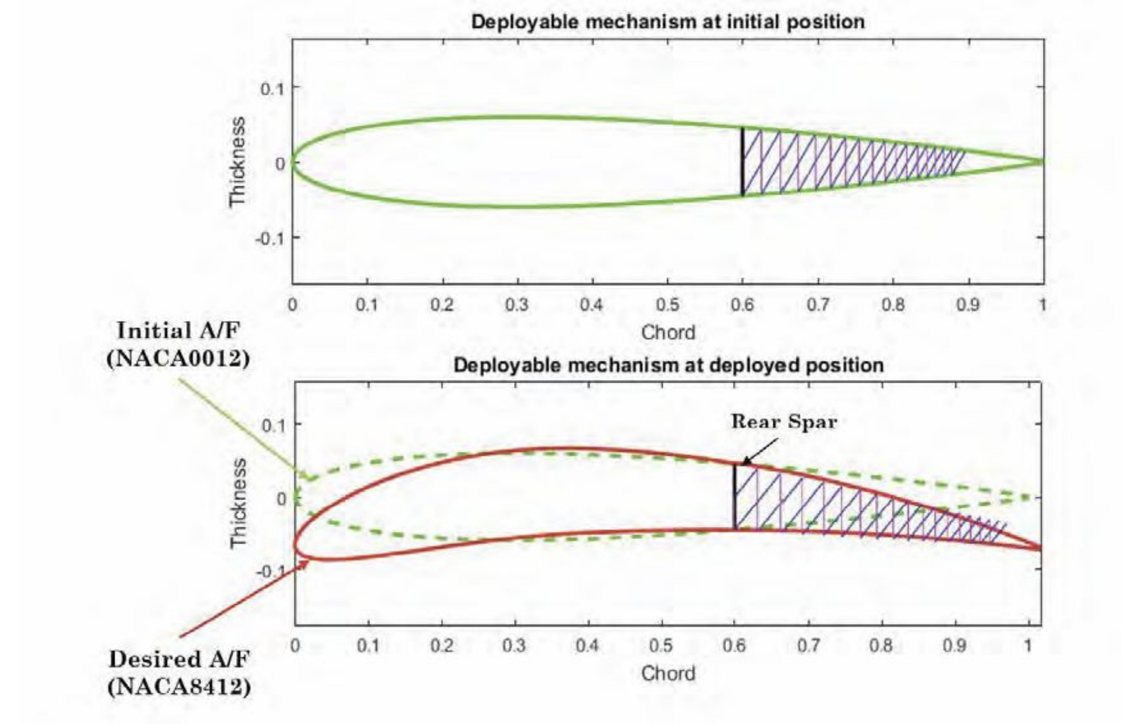

Fig. 6. Synthesized deployable mechanism with zero gap and the initial rocker angle of $\varphi=60°$.

In the third result the maximum allowable n_{CL} is 12. Then, when the rocker angle moves only $13°$, the mechanism almost fits the desired airfoil profile.

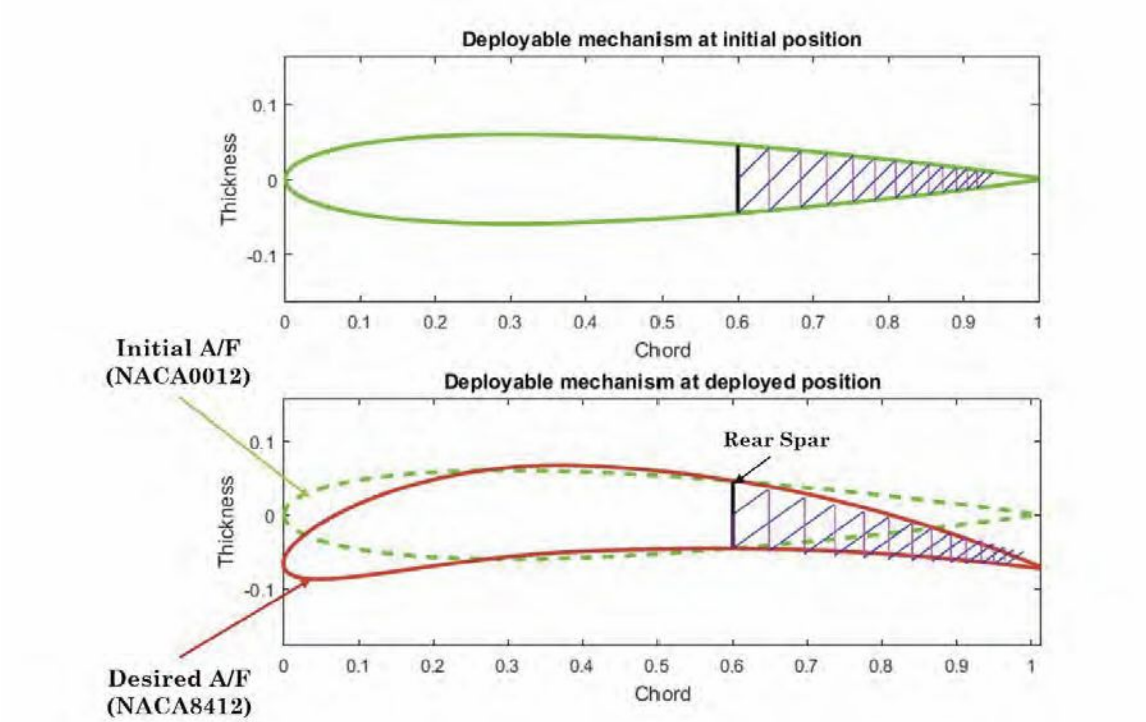

Fig. 7. Synthesized deployable mechanism with zero gap and the initial rocker angle of $\varphi=45°$.

5. Conclusion

In this study a computer routine, which synthesizes a novel deployable mechanism by the combination of various type of four-bar linkages and scissor-like elements, is presented. The mechanism can take two NACA airfoil forms. By assuming the existence of the fully-elastic skin, the synthesized mechanism, can be extended or shortened in order to change the planform of the airfoil with the minimum structural error.

References

Antoni, U., 1932. Construction of flexible aeroplane wings having a variable profile, US Patent No. 1,886,362, November 8

Baker, D., Friswell, M.I., 2008. The design of morphing aerofoils using compliant mechanisms, 19th International Conference on Adaptive Structures and Technologies, Ascona, Switzerland, 6-9 Ekim

Barbarino, S., Bilgen, O., Ajaj, R.M., Friswell, M.I., Inman, D.J., 2011. *A review of morphing aircraft, Journal of Intelligent Material Systems and Structures*, Volume 22, June

Bartley-Cho, J.D., Wang, D.D., Martin, C.A., Kudva, J.N., West M.N., 2004. *Development of high-rate adaptive trailing edge control surface for the smart wing phase 2 wind tunnel model*, Journal of Intelligent Material Systems and Structures, Volume 15, s.279-291

Bryant, G.D., Stewart, A.W., 1963. *Variable camber airfoil*, US Patent No. 3,109,613, November 5

Campanile, L.F., Anders, S., 2005. *Aerodynamic and aeroelastic amplification in adaptive belt rib airfoils,* Aerospace Science and Technology, Volume 9

Campanile, L.F., Sachau, U., 2000. T*he belt-rib concept: A structural approach to variable camber*, Journal of Intelligent Material Systems and Structures, 11(3)

Cummings R.M., Mason W.H., Morton S.A., McDaniel D.R., 2015. *Applied Computational Aerodynamics: A Modern Engineering Approach*, Cambridge Aerospace Series, June

Daynes, S., Weaver, P., Potter, K., 2010. *Device which is subject to fluid flow*, US Patent No. 2010/0213320, February 17

Elzey D.M., Soa A.Y.N., Wadley H.N.G., 2005. *A bio-inspired, high-authority actuator for shape morphing structures*, Smart Structures and Materials 2003: Active Materials: Behavior and Mechanics, Proceedings of SPIE Volume 5053

Friswell, M.I., 2012. *Hierarchical models of morphing aircraft*, 19th International Conference on Adaptive Structures and Technologies, Nanjing, China, October 11-13

Gilbert, W.W., 1981. *Mission adaptive wing system for tactical aircraft*, AIAA 80-1886R, Volume 18, July

Ghommem M., Hajj M.R., Beran P.S., Puri I.K., 2014. *Role of wing morphing in thrust generation,* Theoretical and Applied Mechanics Letters, Volume 4

Hetrick, J.A., Kota, S., Ervin, G.F., 2013. Compliant structure design of varying surface contours, US Patent No. 8,418,966, 16 Nisan

Joo, J.J., Sanders, B., Johnson, T., Frecker, M.I., 2006. *Optimal actuator location within a morphing wing scissor mechanism configuration*, Smart Structures and Materials 2006: Modelling, Signal Processing, and Control, edited by Lindner, D.K., Proceedings of SPIE Volume 6166

Parker, H.F., 1920. *Variable camber rib for aeroplane wings*, US Patent No. 1,341,758, June 1

Perkins, Reed, Havens, 2004. *Adaptive wing structures*, Smart Structures and Materials 2004: Industrial and Commercial Applications of Smart Structures Technologies, edited by Anderson, E.H., Proceedings of SPIE Cilt.5388, Bellingham

Ramrkahyani, D. S., Lesieutre, G. A., Frecker, M., Bharti, S., 2004. *Aircraft Structural Morphing using Tendon Actuated Compliant Cellular Trusses*, 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Palm Springs, California, 19-22 Nisan

Reed, J.L., Hemmelgarn, C.D., Pelley, B.M., Havens, E., 2005. *Adaptive wing structures*, Smart Structures and Materials 2005: Industrial and Commercial Applications of Smart Structures Technologies, edited by White, E.V., Proceedings of SPIE Cilt.5762, Bellingham

Ricci S., 2008. *Adaptive camber mechanism for morphing experiences at DIA-PoliMi*, Advanced Course on Morphing Aircraft, Mechanisms and Systems, Lisbon, Portugal, November

Sinapius, M., Monner, H.P., Kintscher, M., 2012. *DLR's morphing wing activities within the European network*, 23rd International Congress of Theoretical and Applied Mechanics, ICTAM2012

Sofla, A.Y.N., Meguid, S.A., Tan, K.T., Yeo, W.K., 2010. *Shape morphing of aircraft wing: Status and challenges*, Materials and Design, Volume 31

Şahin H.L, and Yaman Y., 2016. A design of mechanism in order to provide morphed wings (Büyük Oranda Şekil Değiştirebilen Kanatlar İçin Kambur Değişimi Sağlayan Bir Mekanizmanın Tasarımı), UHUK2016, VI. National Aeronautics and Space Conference (VI. Ulusal Havacılık ve Uzay Konferansı), September 28-30

Woods, B.K.S., Bilgen, O., Friswell, M.I., 2014. *Wind tunnel testing of the fishbone active camber morphing concept*, Journal of Intelligent Material Systems and Structures, February 5

Zapel, E.J., 1978. *Variable camber trailing edge for airfoil*, US Patent No. 4,131,253, December 26

Zhao J-S, Zhou K, Feng Z-J, 2004. *Mechanism Synthesis of a Foldable Stair,* Mechanisms and Machine Theory, Volume 39

Zhao J-S, Wang J-Y, Chu Fulei, Dai J.S., 2012. *Mechanism Synthesis of a Foldable Stair,* Journal of Mechanisms and Robotics