Adaptive Wing by Using a W-spar Concept

Suwin Sleesongsom[1], Satawat Nanthasenee[1], Julaporn Benjapiyaporn [1] and Sujin Bureerat[*1]

[1] Department of Mechanical Engineering, Faculty of Engineering, Khon Kaen University, Khon Kaen, Thailand 40002
* Corresponding Author: Tel: 089-7114229
E-mail: sujbur@kku.ac.th

Abstract

Adaptive or morphing wings can achieve its flight control through structural flexibility. This concept has been studied by many researchers throughout the world. Nevertheless, most of the wing internal structures in the literature are difficult or even impossible to construct practically. This paper studies the possibility to use a simple-to-construct W-spar for a morphing wing structure. The sizing optimization is posed to have the best wing thicknesses while design constraints include flutter, divergence, and stress. The optimization problem is solved by using hybridization of genetic algorithm and a response surface method. The results obtained are illustrated. It is shown that the W-spar concept is acceptable for use as an adaptive aircraft structure.

Key words: adaptive wing, aeroelasticity, lift effectiveness, W-spar, Vortex ring method

1. Introduction

At present, aircraft technologies are advanced greatly and expected to increase flight performance of modern aircrafts. It has been found that external shape and structures of an aircraft significantly affect its flight performance. The continuous shape change is termed morphing. The morphing aircraft technology has been investigated over the last decade because it can enhance a performance and efficiency over a wider range of flight conditions [1-2]. The most popular morphing concepts that have been considered including various types of shape adaptations such as variations in camber [3-7], span [2,7] and sweep [2] etc. The most popular methods are based on variation in camber, which means an internal mechanism of an aircraft wing need to be synthesized to achieve variable airfoil profile. This can be accomplished by using topology optimization in which an airfoil section is set as a design domain to find an optimum schematic of the internal mechanism [4-6]. From the literature, it has been revealed that design solutions usually gave an ordinary design like a wedge [6], a fish bone [4, 5] etc., which is considered impractical. Furthermore, as an aircraft wing has three-dimensional geometry, two-dimensional deign demonstration may not be realizable in some cases.

To deal with this limitation, we propose the new concept of internal wing structure termed a W-shape spar. This W spar can be loaded and displaced by external force at a half of semi-span wing (the connecting point of the "W"), thus, we expect it to modify wing aerodynamic performance. The design constraint such as stress is also considered in the design process. The structural analysis of the aircraft structure is carried out by using finite element analysis while aerodynamic forces are computed by means of the vortex ring method [8]. A simple un-swept wing box is used for design demonstration. A design problem is assigned to find wing sizing parameters such as rib, spar, and skin thicknesses such that wing aeroelastic characteristics are improved. The optimizer employed to tackle the optimization problem is a genetic algorithm (GA).

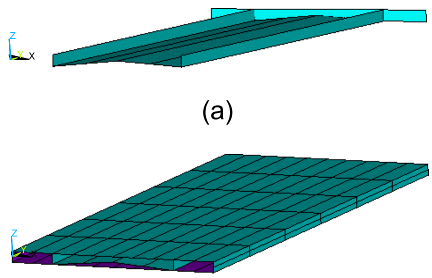
The rest of this paper is organized as follows. Section 2 briefly details aircraft wing modeling. This includes finite element, aerodynamic, and aeroelastic models. The optimum design problem is given in section 3 while design results and discussion are in section 4. The conclusions of the study are drawn in section 5.

2. Aircraft Wing Model

In the present study, the performances of the new W-spar structure that is used as an adaptive or morphing wing are predicted numerically. The new spar concept is expected to affect wing shape when being acted upon by an external force while still fulfilling structural safety constraints. The aluminum wing box has a chord length of 0.6 m in x-direction, and wing thickness of 0.015 m in ±z-direction. Other data of this wing are given in Table 1. The W-spar structure is composed of two main spars and two auxiliary spars to form the "W" shape as show in Fig.1.

Table 1 Aircraft wing data

No.	Parameters	Values
1	Semi-span length, L(m)	1.5
2	Root chord length, RC (m)	0.6
3	Tip chord length, TC (m)	0.6
4	Sweep angle, Λ	0°
5	Number of rib (piece)	1
6	Number of spar (piece)	4
7	Front spar & Rear spar position	20%, 80% RC
8	Whole thickness (m)	0.0005-0.001
9	Material	aluminum $E = 70\,GPa$ $\nu = 0.34$ $\rho = 2700\ kg/m^3$ $\sigma_{yt} = 100\ MPa$



(a)

(b)

Fig. 1 Aircraft wing structure (a) W-shape spar (b) upper and lower skins

The structure has only one rib at a tip chord enabling the W-spar structure being displaced independently. The wing is made up of Aluminum. This W spar can be loaded and displaced by external forces at the connecting point of the "W" as shown in Fig. 1 a. With this concept, it is expected to change the whole wing shape and affect wing aerodynamic performance whilst still achieving structural safety.

Aeroelasticity is the physic dealing with the mutual interaction among inertia, elastic and aerodynamic forces. It is usually seen as the cause of structural failures and performance reduction in flight. Aeroelasticity can be divided into two groups as static and dynamic aeroelastic phenomena. The most important static aeroelastic parameters for aircraft design are divergence and lift effectiveness while the most significant dynamic aeroelastic parameter is flutter. Divergence can be described as the wind speed at which aerodynamic forces overcoming structural restoration (elastic forces). Flutter is referred to as wind speed causing structural dynamic instability. This phenomenon involves all three forces on the structure. Both divergence and flutter is thought of as a critical speed to be avoided in an aircraft design process. Lift effectiveness, on the other hand, is the ratio of total lift at a particular wind speed when flexibility is considered to the total lift when considering the wing being rigid. The parameter is also important in aircraft design. A wing that can vary its lift effectiveness in a wider range may not need control surfaces to achieve flight control.

2.1 Structural model

A linear dynamic finite element model of a wing structure can be written as:

$$M\ddot{\vec{u}} + C\dot{\vec{u}} + K\vec{u} = \vec{F}(t) \qquad (1)$$

where *M*, *C*, and *K* are the mass, viscous damping and stiffness matrix of a structure respectively. $\vec{u}$ is the nodal displacement vector, and $\vec{F}(t)$ is the vector of external forces.

Given that $[z_m] = [\{\vec{u}\}_1, \{\vec{u}\}_2, \ldots, \{\vec{u}\}_M]$ is the modal matrix containing the first *M* mode shapes of the structural system, by substituting $\vec{u} = [z_m]\vec{x}$ into (1) and pre-multiplying by $[z_m]^T$, the reduced-order structural model can be obtained as:

$$M_g\ddot{\vec{x}} + C_g\dot{\vec{x}} + K_g\vec{x} = \vec{F}_g(t) \qquad (2)$$

Where $M_g = [z_m]^T M[z_m]$, $C_g = [z_m]^T C[z_m]$ $K_g = [z_m]^T K[z_m]$, and $F_g = [z_m]^T F$.

Equation (2) can be altered to become a discrete-time state space model as

$$[DEOM_2]\vec{q}^{\,n+1} + [DEOM_1]\vec{q}^{\,n} + F^{n+\frac{1}{2}} = 0 \qquad (3)$$

Where

$$[DEOM_2] = \begin{bmatrix} \dfrac{M_g}{\Delta t} & \dfrac{C_g}{\Delta t} + \dfrac{K_g}{2} \\ \dfrac{-M_g}{2} & \dfrac{M_g}{\Delta t} \end{bmatrix}$$

$$[DEOM_1] = \begin{bmatrix} \dfrac{-M_g}{\Delta t} & \dfrac{-C_g}{\Delta t} + \dfrac{K_g}{2} \\ \dfrac{-M_g}{2} & \dfrac{-M_g}{\Delta t} \end{bmatrix}$$

$$F^{n+\frac{1}{2}} = \begin{Bmatrix} -F_g \\ 0 \end{Bmatrix}.$$

2.2 Aerodynamic model

The model of aerodynamic load on the aircraft wing was assumed to be subsonic flow. The fluid dynamic flow equation was reduced to the Laplace equation and irrotational flow. The aerodynamic loads on a wing herein can be computed by using the vortex ring method [9]. By using such a method, an airfoil is considered as a lifting surface without thickness. The lifting surface is then discretised into a number of panels for vortex rings. Based upon the Biot-Savart law, the aerodynamic model can be described as

$$[AIC]\Gamma = \{RHS\} \quad (4)$$

where [AIC] is an aerodynamic influence coefficient, {RHS} is a right hand side vector and Γ is a vortex strength. Equation can be converted to be a discrete-time equation as

$$[CDR_2]\Gamma^{n+1} + [CDR_1]\Gamma^{n} = W^{n+1} \quad (5)$$

Consequently, the pressure difference between the upper and the lower surface of the panels can be determined by using the relation

$$\Delta P^{n+\frac{1}{2}} = [C2P_2]\Gamma^{n+1} + [C2P_1]\Gamma^{n} \quad (6)$$

2.3 Interfacing aerodynamic forces to a structural model

Interface between structural and aerodynamic forces is carried out by means of surface spline interpolation. Let $\vec{u}_A$ be the displacements at the collocation points on the panel forces, the relation between the displacements of structural nodal points and displacements of the collocation points can be approximate as

$$\vec{u}_A = [G]\vec{u} \quad (7)$$

where $[G]$ is a transformation matrix. Also, the downwash vector due to structural deformation can be calculated as

$$W^{n+1} = U_\infty [H]\vec{u} \quad (8)$$

where $[H]$ is a transformation matrix and U_∞ is a free stream velocity. Combining equation (5) - (8), the aerodynamic forces can be transformed to be structural nodal forces as:

$$F^{n+\frac{1}{2}} = [CNFR_2]\Gamma^{n+1} + [CNFR_1]\Gamma^{n} \quad (9)$$

where [$CNFR_2$] and [$CNFR_3$] are force transformation matrices [8].

2.4 Flutter analysis

A discrete-time aeroelastic analysis of a wing structure can be achieved by combining equation (3), (5), (8), and (9) leading to

$$\begin{bmatrix} [CDR_2] & -[WDR] \\ [CNFR_2] & [DEOM_2] \end{bmatrix} \begin{Bmatrix} \Gamma \\ q \end{Bmatrix}^{n+1} + \begin{bmatrix} [CDR_1] & [0] \\ [CNFR_1] & [DEOM_1] \end{bmatrix} \begin{Bmatrix} \Gamma \\ q \end{Bmatrix}^{n} = 0 \quad (10)$$

Flutter analysis can be carried out in such a way that, at a particular wind speed, the eigensystem (10) is obtained, and the eigenvalues can be computed. The speed at which one of the real parts of the continuous-time eigenvalues starts to become positive is taken as the flutter speed [10].

2.5 Lift effectiveness

The lift effectiveness determines the ratio of lift force on flexible structure to its rigid counterpart. Static aerodynamic forces acting on the collocation points of wing panels, considering that the lifting surface is rigid, can be expressed as

$$L_R = qS_a[AIC]\vec{\alpha} \quad (11)$$

where $q = \frac{1}{2}\rho_{air}Q_\infty^2$ is the dynamic pressure, S_a is the diagonal matrix of panel areas, and $\vec{\alpha}$ is the vector of the panels' angles of attack.

The resulting lift due to flexible surface is of the form

$$L_F = qS[AIC]_F\,\alpha \quad (12)$$

where L_F is the vector of lift on the panels, and $[AIC]_F$ is the flexible surface aerodynamic influence coefficient matrix [11]. The lift effectiveness therefore can be computed as

$$\eta_L = \sum L_{F,i} / \sum L_{R,i} \quad (13)$$

In cases that the structure is applied by the combination of aerodynamic loads and external forces F_e, lift effectiveness can be computed by the following equation (this is derived from the model presented in [11])

$$\eta_{L,Fe} = \frac{q\bar{S}^T[AIC]_F(\bar{\alpha} + [SIC]F_e)}{L_R} \qquad (14)$$

where $[SIC] = HK^{-1}G^T$ and H, G are transformation matrix.

2.6 Divergence Analysis

Aeroelastic divergence can be modeled in such a way that the neutral equilibrium takes place when the inducing aerodynamic forces are balanced by the inducing structural forces. Thus,

$$qS_a[AIC]_R[\Delta\alpha] = [SIC]^{-1}[\Delta\alpha]. \qquad (15)$$

Rearrange the previous equation gives the eigenvalue problem

$$\{[SIC]S_a[AIC]_R - \lambda I\}[\Delta\alpha] = 0. \qquad (16)$$

The maximum eigenvalue of (16) gives the minimum divergence speed.

2.7 Mass, elastic and aerodynamic axes

In two-dimension, we have mass, elastic, and aerodynamic centers to represent the three aeroelastic forces. The elastic center is the shear center of a wing, which can be imagined as the point that has no deflections when the structure is under twisting moment. The mass center is the centroid of a wing cross-section while the aerodynamic center is the centroid of the lift force distribution on the wing. In three-dimension, the aerodynamic axis (a.a.) is the locus of the centers of aerodynamic pressure along the wing span. Similarly, the elastic axis (e.a.) is the locus of the shear centers of the wing cross-sections along the wing span. The aerodynamic and elastic axes play an important role in both static and dynamic analysis whereas the mass axis has an impact on dynamic aeroelastic phenomena.

3. Optimization Design Problem

In order to enable flight control without the use control surfaces, wing shape needs to be morphed to meet an aerodynamic requirement. The W-spar structure as showed in Fig. 1 will be acted by an external force at the half of the wing semi-span so as to modify its aerodynamic characteristics during flight. The force is acting upwards in *z* direction and the maximum magnitude is 400 N. Boundary conditions are given in such a way that wing's attachments are fixed.

The objective of designing an aircraft wing in this paper is to make it produce various levels of lift force with the given applied load. To obtain the best possible wing geometry for such operation, an optimization problem is set to find wing structural dimensions such that maximizing lift effectiveness. The design problem is expressed as follows:

$$\max_{\bar{x}} \eta_L \qquad (17)$$

Subject to $V_F \geq$ 100 m/s

$V_D \geq$ 100 m/s

$\sigma_{\max} \leq \sigma_{all}$

$t_{\min} \leq x_i \leq t_{\max}$

where **x** is the vector of design variables, V_F is a flutter speed, V_D is a divergence speed, $\sigma_{\max}$ is maximum equivalent stress on the wing structure, and σ_{all} is allowable stress to be specified. Design variables include 31 values defining the thicknesses of spars, ribs and skins of the wing with the bounds as $t_{\min} = 0.0005$ m, and $t_{\max} = 0.001$ m.

All parts of the wing are made up of Aluminum. The optimum solution is attained by means of the hybrid genetic algorithm and response surface model. Fig. 2 displays the flowchart for the optimization process implemented in this work. The procedure starts with sampling a set of design solutions by using the Latin hypercube technique. The solutions are then brought to construct a response surface model. Genetic algorithm is subsequently applied to solve the design problem based upon the response surface model. Having obtained the optimum results, the actual function values of the optimum solution is evaluated.

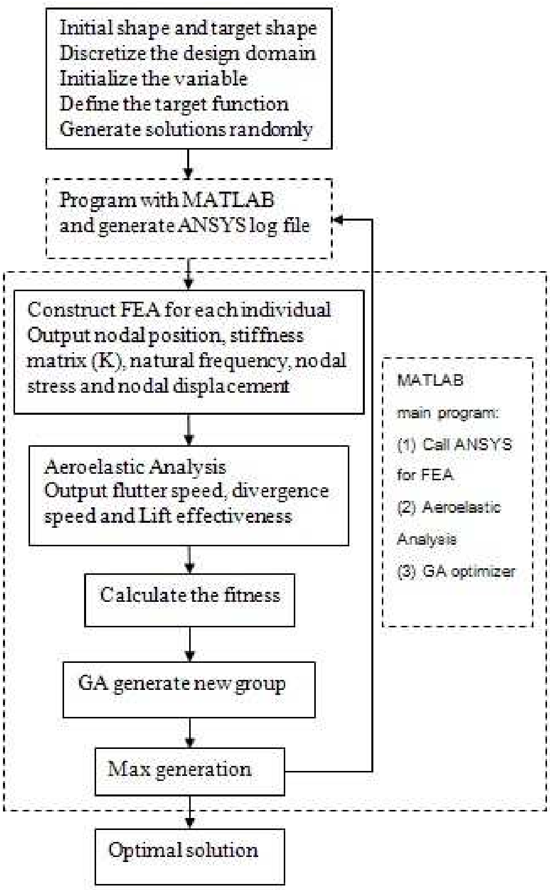
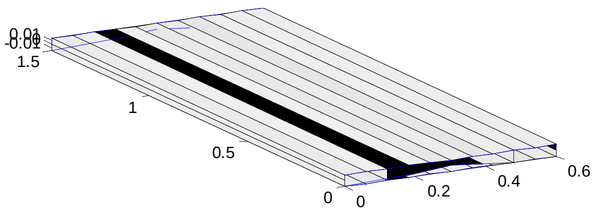


Fig. 2 Flow chart of the structural optimization program

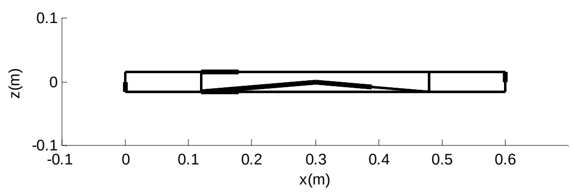
4. Results and Discussion

The optimum wing structure is illustrated in Fig. 3 where the darker elements mean the higher thickness value. Fig. 3 a) displays a 3D view of the wing while Fig. 3 b) displays the thicknesses of the W spar. The optimum structure has divergence and flutter speeds as 100.205 m/s and 141.379 m/s respectively while the maximum stress is 75.771 MPa. The maximum lift effectiveness is 1.0534 when the actuator force is equal to 400 N.

Fig. 4 shows stress and deformation of the wing box and W-spar structure due to the actuating force at the middle of the W spar. The maximum stress occurs at the rear of the root chord, which is reasonable compared to a typical cantilever beam.



(a)



(b)

Fig. 3 Aircraft wing with optimum thickness members

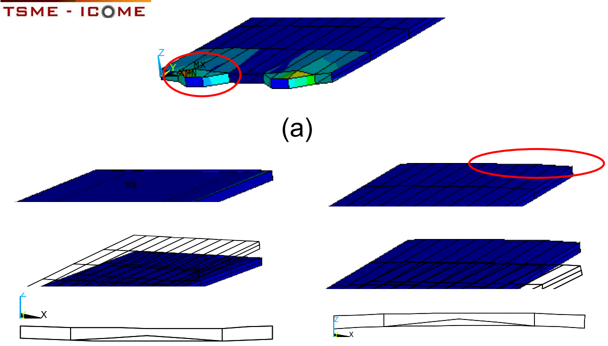


Fig. 4 (a) stress at a root chord (b-c) tip chord deformation

Table 2 shows the aeroelastic characteristics and maximum stress due to varying the actuator force. Both divergence and flutter speed remain constant whereas the maximum stress and the lift effectiveness change depending on force magnitude and direction. The lift effectiveness value can vary in the range of [0.9573, 1.0534], which means, by applying various actuating force, aircraft flight control can be achieved without any help from traditional control surfaces.

Table 3 shows the wing box flexible shape due to the actuator force. The airfoil cross-section is bent up and down due to the magnitude and direction of actuator force. The lift effectiveness increases when the airfoil profile bends up and decreases when the airfoil profile bends down.

Table 4 shows the elastic axis changing by the actuator force with respect to the aerodynamic axis. An elastic axis can be viewed as a beam representing the wing box. When applying positive (upward) actuating force, the wing behaves like a forward swept wing according to the elastic axis. This can lead to higher wing lift effectiveness. In contrast, the downward actuating force results in a backward swept elastic axis which usually produces lower lift effectiveness.

Table. 2 Aeroelastic characteristics and maximum stress due to various actuator forces

Divergence (m/s)	Flutter (m/s)	Lift eff.	Stress (MPa)	Force (N)
100.205	141.379	1.0534	75.771	+400
		1.0414	56.828	+300
		1.0294	37.885	+200
		1.0174	18.943	+100
		1.0054	0	0
		0.9934	18.943	-100
		0.9814	37.885	-200
		0.9694	56.828	-300
		0.9573	75.771	-400

Table. 3 Airfoil profile shapes due to actuator forces

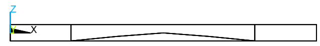
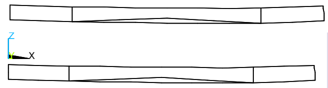
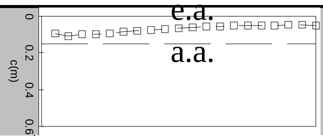
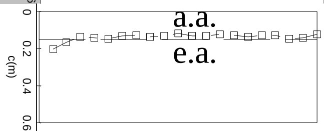
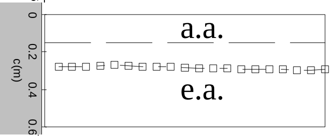
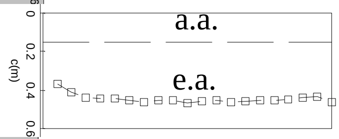
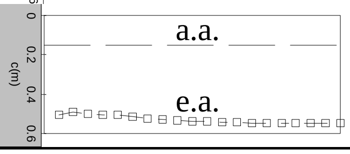
Shape changing	Force(N)
	+400
	+300
	+200
	+100
	0
	-100
	-200
	-300
	-400

Table. 4 Elastic axes due to actuator forces

Elastic Axis	Force(N)
	+400
	+200
	0
	-200
	-400

5. Conclusions and future work

The new W-spar structure can change the wing shape and improve the aircraft aeroelastic characteristics while meeting safety requirement. The new structure can change airfoil profile and the whole wing shape upon various magnitude and direction of actuator load, which consequently alter its lift effectiveness and elastic axis. The new W-spar concept is said to be acceptable to be used as an aircraft adaptive wing. In the future work, buckling constraint will be considered. Also, some unconventional internal structures of an aircraft wing will be studied.

Acknowledgement

The authors are grateful for the financial support provided by the Thailand Research Fund and the Royal Golden Jubilee Ph.D. Program and the Sustainable Infrastructure Research and Development Center (SIRDC), KKU.

References

[1] Wagg, D., Bond, I., Weaver, P. and Friswell, M. (2007). Adaptive Structures: Engineering Applications, John Wiley & Sons Ltd., England.

[2] Thill, C., Etches, J., Bond, I., Potter, K. and Weaver, P. (2008). Morphing skins, The Aeronautical Journal, vol. 38, pp. 1139-1146.

[3] Perry, B., Cole, S.R., and Miller, G.D. (1995). Summary of an active flexible wing program, Journal of Aircraft, vol. 32(1), pp.10-15.

[4] Saggere, L. and Kota, S. (1999). Static shape control of smart structures using compliant mechanisms, AIAA journal, vol. 37(5), pp. 572-578.

[5] Lu, K.J. and Kota, S. (2003). Synthesis of shape morphing compliant mechanisms using load path representation method, Smart structures and materials, Proceedings of SPIE, Vol. 5049, pp.337-348.

[6] Maute, K. and Reich, G.W. (2006). Integrated Multidisciplinary Topology Optimization Approach to Adaptive Wing Design, Journal of Aircraft, Vol. 43(1), pp. 253-263.

[7] Gandhi, F. and Anusonti-Inthra, P. (2008). Skin Design Studies for Variable Camber Morphing Airfoils, Smart Mater. Struct., Vol 17(1), pp. 15-25.

[8] Lee, H.T., Kroo, I.M. and Bieniawski, S. (2002). Flutter Suppression for High Aspect Ratio Flexible Wings Using Microflaps, presented in the 43rd AIAA/ASME/ASCE/AHS/ASC Structures,

Structural Dynamics, and Materials Conference, Denver, USA.

[9] Katz, J., Plotkin, A. (1991). Low-speed Aerodynamics from Wing Theory to Panel Methods, MCgraw-Hill, Singapore.

[10] Hall, K.C. (1994). Eigenanalysis of Unsteady Flows About Airfoil, Cascades, and Wings, AIAA Journal, vol. 32(12), pp. 2426-2432.

[11] Lerner E. and Markowitz J., “An Efficient Structural Resizing Procedure for Meeting Static Aeroelastic Design Objectives,” *Journal of Aircraft, Vol. 16, No. 2*, pp. 65-71, 1979.