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Flutter Analysis of Adaptive Wing with the Adjustment of Spar Position

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ABSTRACT: In this paper, the flutter of an adaptive wing with the adjustment of spar position is studied. Despite the two-dimensional models which were used in earlier researches on this subject, in this study, a more realistic model of the wing with the adjustment of spar position contains sweep angle and unsteady aerodynamic loadings are employed. Two uniform spars which can move in chordwise direction are considered along the wing. The wing bending and torsion equations of motion have been derived by Hamilton's principle. To simulate the aeroelastic loading on the wing, Peter's unsteady aeroelastic model is used. The numerical results have been validated with previously published papers. To review and present the results, four different types of motion for two spars have been utilized. Comparison between the adaptive and simple wing, in the same conditions, shows that the flutter speed and frequency increase for the adaptive wing. Finally, the effects of different design parameters on the aeroelastic behavior of adaptive wing have been evaluated. Results show that increasing the thickness of the wing skins and spars reduces the wing flutter speed.

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1- Introduction

Nowadays, because weight saving in flight vehicles increases structural flexibility of aircraft, many new technologies like adaptive wings have been employed by designers to delay and overcome the aeroelastic instability and consequent vibrations. Adaptive structures are those which have the ability to adapt themselves in response to the surrounding environment. Indeed, they can change their geometric or physical properties in response to the external excitations [1]. In this paper, the flutter of an adaptive wing with the adjustment of spar position is studied. Two uniform spars which can adjust the stiffness of the wing by moving in the wing chordwise direction are considered. The flutter instability can be delayed by adjusting the wing stiffness in this manner. Due to the structure of this type of adaptive wing, the effects of spars design parameters on the flutter boundaries are evaluated.

2- Governing Equations of Adaptive Wing

The wing is modeled as a swept cantilever elastic beam containing two main spars. The equations of motion are obtained using Hamilton's principle which can be stated as follows [2]:

$$\int_{t_1}^{t_2} (\delta U - \delta T - \delta W)\, dt = 0 \tag{1}$$

where U and T are strain energy and kinetic energy, respectively and W is the work done by non-conservative forces. Variation in the wing kinetic energy can be represented as:

$$\int_{t_1}^{t_2} \delta T_w\, dt = -m_w \int_{t_1}^{t_2} \int_0^L \left[(\ddot{w} + e\ddot{\theta})\delta w + (k_m{}^2 \ddot{\theta} + e\ddot{w})\delta\theta \right] dx\, dt \tag{2}$$

where k_m is the mass radius of gyration, e is the distance between the center of gravity and elastic axis of the wing and m_w is the wing mass per unit length [3]. The first variation of spars kinetic energy can be written as:

$$\begin{aligned} \delta T_1 = m_1 \int_0^l \vec{r}_1 . \delta \vec{r}_1 dx = -m_1 \int_0^l \{ [\ddot{w} + (\dot{y}_1 + \dot{y}_2)\dot{\theta} + \\ \frac{y_1 + y_2}{2} \ddot{\theta}]\delta w + [\frac{y_1 + y_2}{2}\ddot{w} + \frac{1}{2}(\dot{y}_1 + \dot{y}_2) \\ (y_1 + y_2)\dot{\theta} + \frac{(y_1 + y_2)^2}{4}\ddot{\theta}]\delta\theta + (-\frac{\ddot{w}\theta}{2} + \frac{\dot{\theta}}{8}(\dot{y}_1 \\ + \dot{y}_2)\delta y_1 + (-\frac{\ddot{w}\theta}{2} + \frac{\dot{\theta}}{8}(\dot{y}_1 + \dot{y}_2)\delta y_2 \} dx \end{aligned} \tag{3}$$

$$\begin{aligned} \delta T_2 = m_2 \int_0^l \vec{r}_2 . \delta \vec{r}_2 dx = -m_2 \int_0^l \{ [\ddot{w} - (\dot{y}_1 + \dot{y}_2)\dot{\theta} - \\ \frac{y_1 + y_2}{2} \ddot{\theta}]\delta w + [-\frac{y_1 + y_2}{2}\ddot{w} + \frac{1}{2}(\dot{y}_1 + \dot{y}_2) \\ (y_1 + y_2)\dot{\theta} + \frac{(y_1 + y_2)^2}{4}\ddot{\theta}]\delta\theta + (-\frac{\ddot{w}\theta}{2} + \frac{\dot{\theta}}{8}(\dot{y}_1 \\ + \dot{y}_2)\delta y_1 + (-\frac{\ddot{w}\theta}{2} + \frac{\dot{\theta}}{8}(\dot{y}_1 + \dot{y}_2)\delta y_2 \} dx \end{aligned} \tag{4}$$

In these equations, m_1 and m_2 are mass per unit length and y_1 and y_2 are position vectors of the front and rear spars, respectively.

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Also, the variation of the wing potential energy is:

$$\delta U = \int_0^l [-GJ(x)\theta''\delta\theta + EI_y w''''\delta w]dx + \\ +[GJ(x)\theta'\delta\theta + EI_y w''\delta w' - EI_y w'''\delta w]_0^l \tag{5}$$

Herein k_w is bending stiffness and k_θ is Torsional stiffness. F_1 and F_2 are the forces acting on the front spar and rear spar, respectively. The virtual work done by these two forces is:

$$\delta w_{webs} = \int_0^l (F_1\delta y_1 + F_2\delta y_2)dx \tag{6}$$

Furthermore, the virtual work of aerodynamic forces can be represented as:

$$\delta W_A = \int_0^l (L_0\delta w + M_0\delta\theta)dx \tag{7}$$

where L_0 and M_0 are aerodynamic lift and moment, respectively.

$$(m_1+m_2+m_w)\ddot{w} + m_w e\ddot{\theta} + (m_1-m_2)(\dot{y}_1+\dot{y}_2)\dot{\theta} \\ +(m_1-m_2)(\frac{y_1+y_2}{2})\ddot{\theta} + EIw'''' + K_w w = L \tag{8}$$

$$m_w K_m{}^2\ddot{\theta} + m_w e\ddot{w} + (m_1-m_2)(\frac{y_1+y_2}{2})\ddot{w} - \\ (m_1-m_2)(\frac{\dot{y}_1+\dot{y}_2}{2})(y_1+y_2)\dot{\theta} - \\ (m_1-m_2)\frac{(y_1+y_2)^2}{4}\ddot{\theta} + \\ \frac{2Gh^2}{l}\frac{(y_1+y_2)^2}{(\frac{h}{t_w}+\frac{y_1+y_2}{t_s})}\theta = M_0 \tag{9}$$

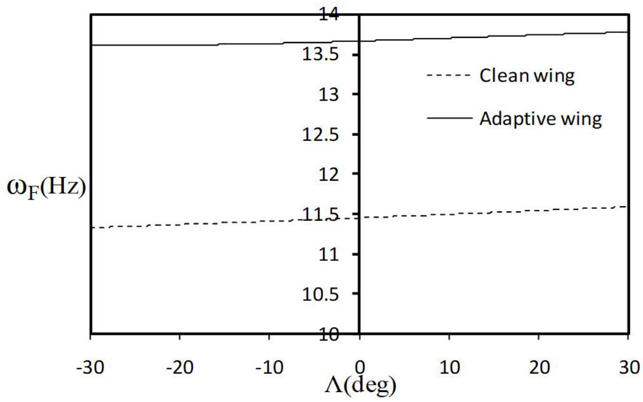
$$(m_1+m_2)\frac{\theta\ddot{w}}{2} + (m_1-m_2)\frac{\dot{\theta}}{8}(\dot{y}_1+\dot{y}_2) + \\ \frac{2Gh^2}{l}\frac{(y_1+y_2)}{\frac{h}{t_w}+\frac{y_1+y_2}{t_s}}\theta^2 - \frac{(y_1+y_2)^2}{t_s(\frac{h}{t_w}+\frac{y_1+y_2}{t_s})^2} = F_1 \tag{10}$$

$$(m_1+m_2)\frac{\theta\ddot{w}}{2} + (m_1-m_2)\frac{\dot{\theta}}{8}(\dot{y}_1+\dot{y}_2) + \\ \frac{2G_s h^2}{l}\frac{(y_1+y_2)}{\frac{h}{t_w}+\frac{y_1+y_2}{t_s}}\theta^2 - \frac{(y_1+y_2)^2}{t_s(\frac{h}{t_w}+\frac{y_1+y_2}{t_s})^2} = F_2 \tag{11}$$

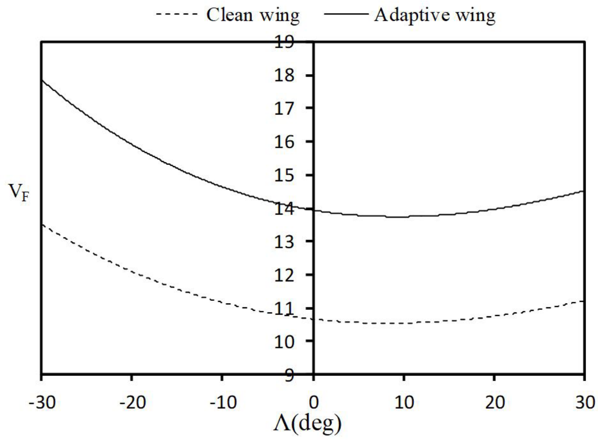
where t_s and t_w are the skin and spars thickness, respectively and h is the average height of the wing,

3- Results and Discussion

In this paper, the wing characteristics are selected as the same as those considered by Ajaj et al. [4]. Fig. 1 shows the flutter speed and frequency of a clean wing compared to an adaptive wing. Furthermore, the effects of some design parameters like wing sweep angle and spars thickness are indicated on the flutter instability boundary, in Fig. 2.



(a)



(b)

Figure 1. The effect of the adaptive wing on (a) flutter frequency and (b) flutter speed

4- Conclusions

In this paper, aeroelastic governing equations are derived for an adaptive wing with two movable spars. Results show that stability region can be expanded by using adaptive wings instead of classic wings. Like classic wings, increasing the adaptive wing sweep angle will increase the flutter speed. Results also indicate that adaptive wing design parameters can significantly influence the flutter boundary. Increasing the thickness of the wing skins and spars increases the wing flutter speed. Furthermore, the spars chordwise velocity can affect the flutter speed and frequency of the wing.

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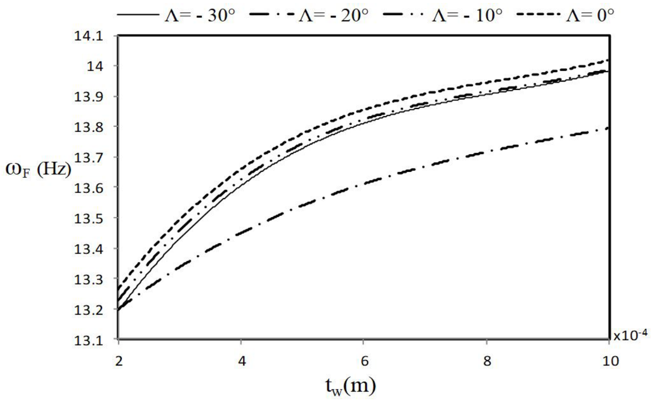

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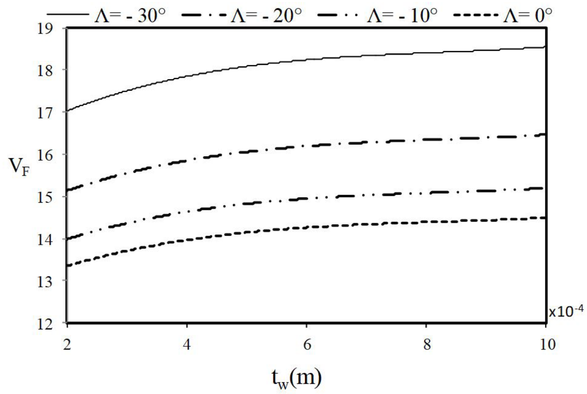

(b)

Figure 2. The effect of spar thickness on (a) flutter frequency and (b) flutter speed, for selected values of the wing sweep angle

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