7. ANKARA INTERNATIONAL AEROSPACE CONFERENCE
11-13 September 2013 - METU, Ankara TURKEY

AIAC-2013-107

FLUTTER CHARACTERISTICS OF AN ADAPTIVE WING HAVING CAMBER CHANGE AND FREEPLAY NONLINEARITY

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ABSTRACT

The purpose of this study is to investigate the effects of the shape change on the flutter characteristics of an adaptive wing having trailing edge camber change. The control surfaces at the trailing edge of the wing are used as continuously shape changing flaperons. Depending on the type of the mission the air platform encountering, the camber adapts to the flight conditions to increase the flight performance. The continuous shape changes of the adaptive camber wing differentiate the locations of the aerodynamic, mass and shear centers. This deviation of central locations affects the flutter speed since they are directly involved in the reduced order three degrees of freedom flutter model, which are the plunge motion of the wing, the pitch motion of the wing and rotation of the control surface, which is referred as control surface flapping. The free play nonlinearity was applied on the control surface. The effect of camber change on the mass center and shear center locations, in the presence of free play nonlinearity were analyzed within the scope of this paper, whereas, the aerodynamic center assumed to be located at the same point on the reduced order flutter model for every different fundamental shape changes of the adaptive wing. Seven differential camber change positions of the control surface will be investigated in this study. The reduced order flutter model involves unsteady aerodynamic theory of Theodorsen and the formulation of the nonlinear problem was based on the harmonic balance method. The nonlinear flutter solver was an in-house developed code. In the future, the information obtained from this study will be used for the aeroelastic optimization of the wing structures involving various nonlinearities such as open-section adaptive wings like the one used in this study.

Keywords: Flutter, Nonlinear Structural Dynamics, Morphing Aircraft, Harmonic Balance Method

INTRODUCTION

The purpose of this study is to investigate the effects of the nonlinearities, which arise from the camber change capability of an uninhabited aerial vehicle (UAV) wing, on the flutter characteristics of the wing. The change of the camber and the shape of the wing during flight results in the change of the aerodynamic center, center of gravity and the elastic axis locations. The changes on these parameters drastically effects the flutter speed of the UAV. In addition to these, the adaptive mechanism used in the wing is an open cross-section structure. The structure being an open cross-section structure reduces its stiffness and the structure became subject to the free-play nonlinearity. The structural nonlinearities causes limit cycle oscillations, which may eventually results in the catastrophic failure of the structure. For this reason, the nonlinear aeroelastic behavior of the structure has to be considered carefully.

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In this study a nonlinear flutter solver will be developed for the investigation of the problem stated above. The code will be written in FORTRAN language. The code will first communicate with a commercial finite element code in order to conduct necessary analysis to compute the parameters, which will be used in flutter calculations. Then the code will construct the nonlinear equations of motion for a three degrees of freedom reduced order flutter model, called typical section model. Afterwards, by using the harmonic balance method the system of nonlinear ordinary differential equations will be solved.

In this study the scope mainly focused on the nonlinear aeroelastic effects of the morphing wing concept discussed in the first author's M.Sc. Thesis [Ünlüsoy, L., 2010]. In the mentioned morphing concept the control surfaces were designed as open cross-section structures which leads to a reduced stiffness for the control surface deflections. The actuator mechanism, which is responsible for the shape changing, inhabits some free play behavior resulting in a piecewise stiffness in the control surface flapping motion. Additionally, whenever the control surface is deflected as aileron or flap, the cross-sectional properties of the wing are altered drastically. This phenomenon results in a change in the shear center of the structural cross-section. The change of the location of the shear center leads to a change in both the dynamic and static aeroelastic description of the wing itself. The results of this location change of the shear center in terms of aeroelastic parameters will also be considered within the scope of this work.

The wing, which will be analyzed in terms of its aeroelastic characteristics in this study is a modified version of the previously analyzed wing [Ünlüsoy, L., 2010]. The changing camber concept used in that study will again be used, however the stiffness of the torque box will be reduced and the aspect ratio of the wing will be increased. These modifications will be done to increase the slenderness of the wing, which is inversely proportional to the flutter and divergence speeds of an aircraft. The structural model of the wing is shown in Figure 1.

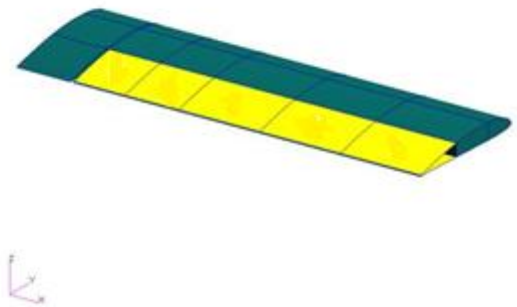

Figure 1: *Structural Model of the Wing*

The wing discussed in this study can perform the camber changes as shown in the Figure 2. The camber change parameter shown is a nondimensionalized parameter with respect to the chord of the wing. The effect of the differential shape changes shown in the Figure 2 on the flutter speed of the wing will be analyzed within the study.

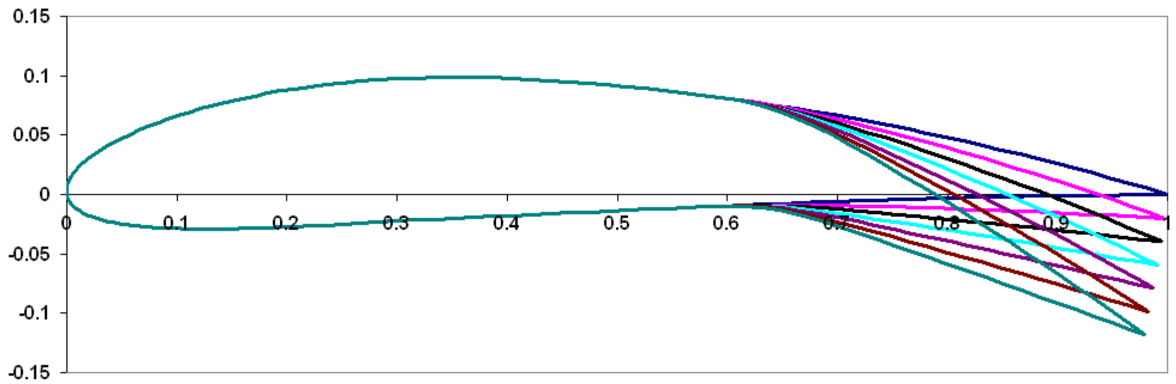

Figure 2: *Differential Shape Change of the Wing CS* ***(Δfk=0.0c, Δfk=-0.02c, Δfk=-0.04c, Δfk=-0.06c, Δfk=-0.08c, Δfk=-0.10c, Δfk=-0.12c)****[Yaman, Y., 2011]*

METHOD

Aeroelastic Modeling

The early aeroelasticity researches successfully showed that for the slender wings, the dynamic instability problems, if they exist, are related to the coupling between the first flexural and first torsional resonance frequencies of the wing. This fact makes it possible to introduce a reduced order model which is called typical section model. The model is the representation of the dynamic behavior of the wing under the influence of the air [Seber, G., Ünlüsoy, L., and Sakarya, E., 2009].

In this study a modified version of that mathematical model will be used. In that version control surface flapping with the presence of free-play nonlinearity is the modified part. The sketch of the modified version of the typical section model is given in Figure 3.

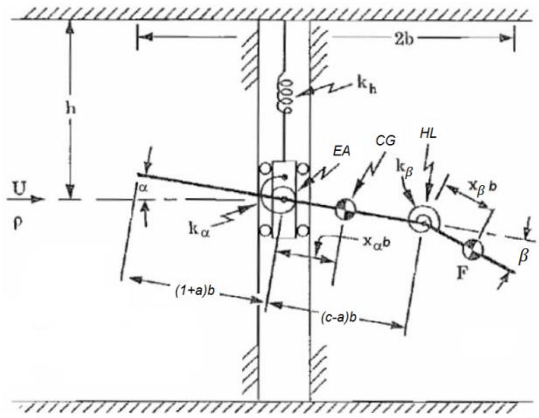

Figure 3: *Modified 3D Typical Section Model [Bryson, A. E., 1994]*

where a is the ratio of the distance between the CG and midchord to the half chord length, b, and c indicates the ratio of the distance between the hinge line and the midchord to the half chord length. One can then obtain the following system of equations;

$$m\ddot{h} + S_\alpha \ddot{\alpha} + S_\beta \ddot{\beta} + k_h h = -L \quad (1)$$

$$S_\alpha \ddot{h} + I_\alpha \ddot{\alpha} + \left[I_\beta + b(c-a)S_\beta\right]\ddot{\beta} + k_\alpha \alpha = M_{EA} \quad (2)$$

$$S_\beta \ddot{h} + \left[I_\beta + b(c-a)S_\beta\right]\ddot{\alpha} + I_\beta \ddot{\beta} + k_\beta \beta = H \quad (3)$$

Some of the variables in the system of equations which are k_α, k_β, I_α, I_β and S_β will be computed by the finite element analysis tool with the directions given by the developed nonlinear flutter solver. The critical elements of the equations are the aerodynamic terms L, M_{EA}, and H which are lift, aerodynamic moment about the elastic axis, and aerodynamic restoring moment of the control surface. The aerodynamic term in the equations has to be calculated using an unsteady aerodynamic theory. In this study the unsteady solution of Theodorsen will be utilized [Theodorsen, T., 1935]. The nonlinear forcing term has to be calculated by harmonic balance method by using the mathematical model of the freeplay nonlinearity.

Implementation of the Freeplay Nonlinearity

In mechanical systems, when there exists a connection of elements driven by an actuator, the connection arms of the actuator and the driven elements most probably have gaps. Due to these gaps in the locked position of the actuators the actuator arm freely moves. This free motion is called free-play and it changes the linear stiffness properties into piecewise linear properties. This phenomena is called the freeplay nonlinearity in structural dynamics.

In the adaptive wing concept, the camber changing mechanism is actuated by a servo motor and the cross-section of the control surface is an open section. Due to being an open section beamlike structure the system freely vibrates with an assumed peak to peak amplitude of 2°. This free vibration may cause limit cycle oscillations and eventually may result in damage or failure of the structure. Therefore, the aeroelastic behavior under the influence of freeplay nonlinearity has to be investigated to prevent any catastrophe.

The mathematical model of the free-play nonlinearity of the system can be applied on the linear mathematical model of the system through harmonic balance method (HBM). In vibrating systems such as the wings of aircraft and especially when the system undergoes a self-excitation such as being in flutter, the method became much more effective.

In the solution procedure, a harmonic solution is assumed. According to the selection of the number of the harmonics of the assumed solution, the harmonics are decomposed into their components as of the equations of motion. The coefficients of the similar harmonic terms are tried to be balanced. When an equilibrium is reached the solution of the nonlinear system is obtained [Schmidt, G. and Tnodl, A. 2009].

The nonlinearities are applied to the system as some kind of harmonic excitations. Every type of nonlinearity has its own representation for the harmonic balance method. Free-play nonlinearity is commonly represented as the piecewise linear functions as shown in the Figure 4 [Liu, L and Dowell, E. H., 2005].

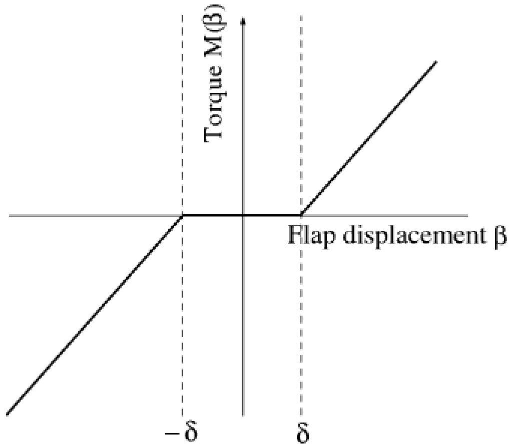

Figure 4: The Moment-Rotation Relation for a Free-play Nonlinearity Model [*Liu, L and Dowell, E. H., 2005]*

The mathematical representation of the free-play nonlinearity referring to the Figure 4 in the related reference is given by;

$$M(\beta) = \begin{cases} \beta + \delta & \beta < -\delta \\ 0 & -\delta \le \beta \le \delta \\ \beta - \delta, & \delta < \beta \end{cases} \tag{4}$$

Equation (4) is just given in order to introduce the free-play model generically. In order to use HBM, the nonlinear system of equations has to be represented in a specified form. The generic free-play model given should be introduced in a more meaningful manner. The model given is conducted by using unit control surface stiffness approach [Liu, L and Dowell, E. H., 2005]. This is a good approach, however when the case of this study is considered the model should also be given with nondimensional rotation since one of the golals of the study was to generate a generic nonlinear solver. The model should be non-dimensionalized by dividing it with the generalized coordinate β. In addition, the moment term M(β) will be replaced with H_N(β), since in the typical section model the control surface flapping moment was prescribed as H. The subscript N denotes nonlinearity. Therefore Equation (4) can be restated as;

$$H_N(\beta) = \begin{cases} 1 + \frac{\delta}{\beta}, & \beta < -\delta \\ 0, & -\delta \le \beta \le \delta \\ 1 - \frac{\delta}{\beta}, & \delta < \beta \end{cases} \tag{5}$$

Now if a single harmonic solution is assumed the flapping motion can be defined as;

$$\beta = \mathrm{B}_s \sin \omega t + \mathrm{B}_c \cos \omega t = \mathrm{B} \sin(\omega t + \phi) \tag{6}$$

Letting $\psi = \omega t + \phi$ one can write that $\beta = \mathrm{B} \sin \psi$.
Define $\delta = \mathrm{B} \sin \psi_1$ or in other words, $\psi_1 = \sin^{-1} \frac{\delta}{\mathrm{B}}$
Keeping these definitions in mind, one can express the nonlinear hinge moment in terms of Fourier series as follows;

$$H_s = \frac{1}{\pi} \int_0^{2\pi} H_N \sin \psi \, d\psi \qquad \textit{sine component of the harmonic forcing} \tag{7}$$
$$H_c = \frac{1}{\pi} \int_0^{2\pi} H_N \cos \psi \, d\psi \qquad \textit{cosine component of the harmonic forcing} \tag{8}$$

Note that piecewise stiffness (or free-play) nonlinearity is a symmetric function and it has no memory, therefore, the functions can be restated as;

$$H_s = \frac{4}{\pi} \int_0^{\pi/2} H_N \sin \psi \, d\psi \tag{9}$$
$$H_c = \frac{4}{\pi} \int_0^{\pi/2} H_N \cos \psi \, d\psi \tag{10}$$

Substituting the defined parameters ψ , β, δ and $\psi_1$inside the integral relation (9);

$$\begin{aligned} H_s &= 0 + \frac{4}{\pi} \int_{\psi_1}^{\pi/2} \left(1 - \frac{\delta}{\beta}\right) \sin \psi \, d\psi \\ &= \frac{4}{\pi} \int_{\psi_1}^{\pi/2} \left(1 - \frac{\delta}{\mathrm{B} \sin \psi}\right) \sin \psi \, d\psi \\ &= -\frac{1}{\pi} \left[2\delta \sqrt{1 - \left(\frac{\delta}{\mathrm{B}}\right)^2} + \mathrm{B}(2\psi_1 - \pi) \right] \end{aligned} \tag{11}$$

and

$$H_c = 0 \tag{12}$$

By using the terms calculated the nonlinear forcing may be approximated as;

$$H_N(\beta) \cong H_s(\beta) \sin \psi + H_c(\beta) \cos \psi \tag{13}$$

This nonlinear forcing term should be multiplied with the control surface rotational stiffness at the left hand side of the third equation of motion of the linear system of equations. The system of equations given as Equations (1), (2) and (3) became;

$$m\ddot{h} + S_\alpha \ddot{\alpha} + S_\beta \ddot{\beta} + k_h h = -L \tag{14}$$

$$S_\alpha \ddot{h} + I_\alpha \ddot{\alpha} + [I_\beta + b(c - a) S_\beta] \ddot{\beta} + k_\alpha \alpha = M_{EA} \tag{15}$$

$$S_\beta \ddot{h} + [I_\beta + b(c - a) S_\beta] \ddot{\alpha} + I_\beta \ddot{\beta} + k_\beta H_N(\beta) \beta = H \tag{16}$$

Once the nonlinearity of the problem is defined the rest of the solution is an iteration routine to obtain the response of the system to the harmonic excitation. The method used for the solution is p-k Method [Rodden, W. P., Harder, R. L. and Bellinger, E. D., 1979].
All the analyses will be conducted by the in house developed Nonlinear Flutter Analysis Routine, and the code can call for the commercial package program MSC/NASTRAN in order to obtain the stiffness, mass and geometric variables necessary for the reduced order model. For each of the differential shape change of the control surface, the locations of the shear center and the center of gravity are calculated which are used in the flutter model and in the calculation of the Theodorsen aerodynamic coefficients.

RESULTS AND DISCUSSION

While the wing structural model is investigated, the warping effect due to the open section was neglected during the shear center calculations. This was practical since the morphing mechanism was believed to sustain a uniform camber change along the wing span.

The shifting of the locations of shear center and the center of gravity is considered together during the flutter analyses of different cases since it is more convenient. In other words, both changes are applied simultaneously to the Equations (14), (15) and (16). The differential camber changes given in Figure 2 are used for the calculation of the location of the shear center and the center of gravity. There are two distances which are important in flutter calculations. First one is the normalized distance from shear center to the midchord location with respect to half chord length (denoted as a in the Equations (14), (15) and (16)). The second one is the normalized distance between shear center and the center of gravity locations with respect to the half chord length (denoted as x_α in the Equations (14), (15) and (16)). These values are both related with the equations of motion as well as the Theodorsen constants [Theodorsen, T., 1935]. The values of these normalized parameters are given for each differential camber change in the Table 1.

Table 1: *Normalized Shear Center and Center of Gravity Locations w.r.t. Midchord*

Differential Camber Change Value (Δfk)	|a|	x_α
-0.00c	0.285	0.046
-0.02c	0.278	0.031
-0.04c	0.270	0.016
-0.06c	0.263	0.002
-0.08c	0.255	-0.013
-0.10c	0.249	-0.027
-0.12c	0.244	-0.037

As it can be understood from the values listed in the Table 1 that, the shear center shifts backward (through the trailing edge) and the center of gravity shifts forward (through the leading edge) as the camber change applied starting from zero Δfk and rotating the trailing edge downward. This downward rotation is referred as negative camber change and can be seen in Figure 2 [Yaman, Y., 2011]. This opposite shifting affects the flutter speed as shown in the Figure 5. The flutter speed value is nondimensionalized with respect to the ωb, where ω is the corresponding damped frequency and b is the half chord length.

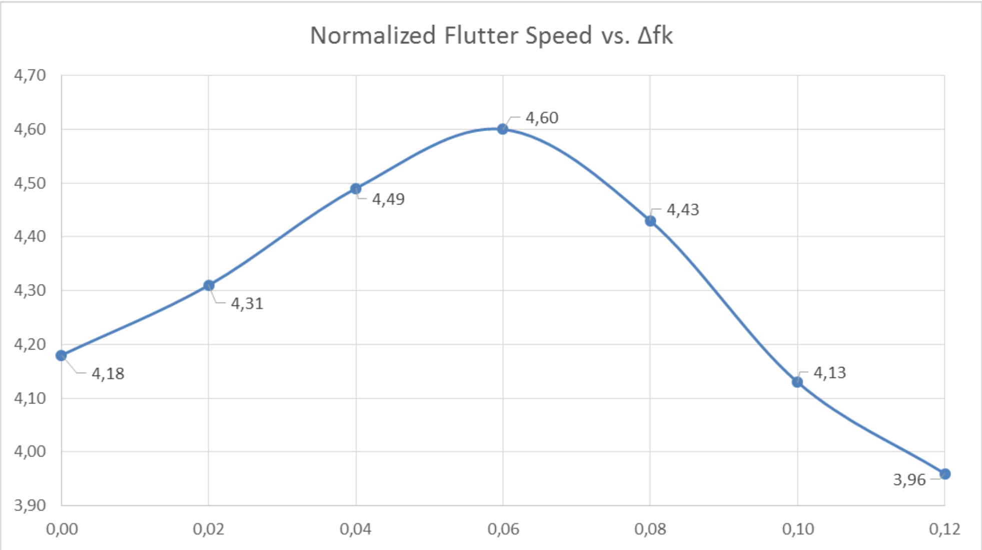

Figure 5: *The Effect of the Camber Change on the Nonlinear Flutter Speed*

The camber change shifts the locations of the elastic axis and the center of gravity. Due to these location changes the nonlinear flutter speed of the wing significantly deviates. At the position where Δfk equals 0.06 of the chord, the center of gravity and the elastic axis are very close to eachother. This is the condition for an ideal aeroelastic behavior so the flutter speed is maximum. For the other cases, lower flutter speeds are calculated.

Moreover, when the center of gravity location takes place at a forward position with respect to the elastic axis, the flutter speed tends to decrease in a steeper manner. This is also an expected behaviour since the restoring moment of the pitching motion becomes opposite to the moment caused by own weight of the wing structure. This condition leads an unstability at pitch direction.

CONCLUSION

In this study, the effect of camber change on the flutter speed of a nonlinear reduced order wing model was investigated. The free-play nonlinearity was inserted into the linear form of the aeroelastic model. Harmonic balance method with single harmonic was used for the implementation of the nonlinear behavior.

The system was analyzed with an in-house developed nonlinear flutter solution algorithm written in FORTRAN. The solution algorithm was based on the p-k method. The unsteady aerodynamic model used was adapted from Theodorsen model.

The results showed that, the shape change effects the flutter speed of the wing. However, it can never be predicted whether the effect is advantageous or disadvantageous since it depends on the position of the center of gravity with respect to the elastic axis. The condition that they are coincident is believed to be the best condition from flutter characteristics point of view.

The outcome of this study will be used in aeroelastic optimization and nonlinear flutter prediction of the fully morphing aircraft wings. The flutter speed may be controlled, or even suppressed by using adaptive structures those shift the center of gravity and elastic axis to favorable locations.

References

Yaman, Y. (2011) *Taktik İnsansız Hava Araçlarının Göreve Uyumlu Kanatlarında Kambur ve Burulma Etkisinin Çırpma ve Kontrol Yönünden Analizi,* TUBITAK Proje Sonuç Raporu, Proje No:107M103,

Ünlüsoy, L. (2010) *Structural Design and Analysis of the Mission Adaptive Wings of an Unmanned Aerial Vehicle,* METU, MSc. Thesis

Seber, G., Ünlüsoy, L., and Sakarya, E. (2009) *Flutter Characteristics of a Typical Section Model with a Trailing Edge Control Sufrace,* AIAC-2009, AIAC-2009-072, 17-19 August 2009, METU, Ankara, TURKEY

Schmidt, G. and Tnodl, A. (2009) *Non-linear Vibrations*, Cambridge University Press, 2009

Liu, L and Dowell, E. H., (2005) *Harmonic Balance Approach for an Airfoil with a Freeplay Control Surface,* AIAA Journal, Vol. 43, No. 4

Bryson, A. E., (1994) *Control of Spacecraft and Aircraft*, Princeton University Press

Rodden, W. P., Harder, R. L. and Bellinger, E. D., (1979) *Aeroelastic Addition to NASTRAN,* NASA CR 3094

Theodorsen, T., (1935) *General Theory of Aerodynamic Instability and the Mechanism of Flutter,* NACA Report No. 496