FLUTTER SPEED ESTIMATION FOR FOLDING WING SYSTEM

Y. Jung[1] J. Kim[2]*
[1] School of Mechanical and Aerospace Eng., Seoul National Univ., Seoul, Korea,
[2] Institute of Advanced Aerospace Technology, School of Mechanical and Aerospace Eng., Seoul National Univ., Seoul, Korea
* Corresponding author (jwhkim@snu.ac.kr)

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1 Introduction

Recently, morphing aircrafts with multiple mission capabilities are developed by several projects such as NASA or Defense Advanced Research Projects Agency. One of the morphing concepts is the folding wing system with out-of-plane motion. It can adjust flight performance from a cruise configuration to a high speed configuration.

A typical procedure of aeroelastic analysis, there are several parameters with important roles, such as fold angle and hinge stiffness. According to Ref. [1], the folding structural natural frequency and the flutter velocity are sensitive to the angle and the hinge stiffness. On the other hand, Flutter speed can be controlled by ply angle of a laminated composite plate due to directional dependency of strength and stiffness of a material.

In presented work, the structure is modeled by using Finite Element Method (FEM) and the flow is analyzed by Doublet Lattice Method (DLM). Additionally, the PK method is obtained for aeroelastic analysis.

2 Formulations

2.1 Structural modeling

The wing consists of three parts as body, inboard and outboard component. All parts are assumed as plates and distributed hinge spring connects each of them. The spring is assumed to have negligible mass compared with the wing. The initial fold angles are ϕ_1 and ϕ_2 , and these are the static equilibrium angles. The schematic configuration of the wing is shown in Fig. 1.

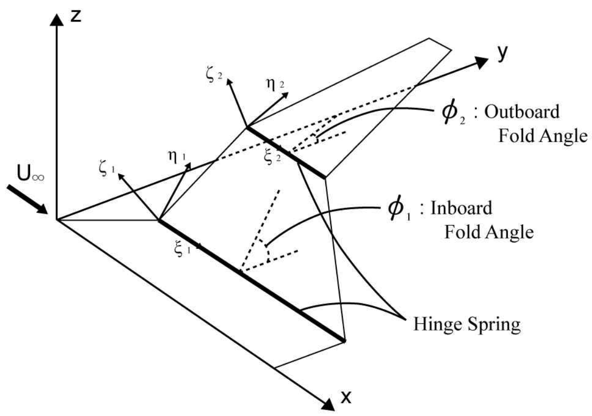


Fig.1. Schematic configuration of the wing

As the structural analysis, FEM is applied to the model based on First-order Shear Deformation Theory (FSDT). Also the laminate composite and isotropic materials are used to find out the effects of the ply angle. Using the principle of virtual work, the governing equation can be represented as follows.

$$\int_V \delta u^T F_b \, dV + \int_S \delta u^T F_s \, dS = \int_V \left(\delta u^T \rho \ddot{u} + \delta u^T c \dot{u} + \delta \varepsilon^T \sigma \right) dV \tag{1}$$

From the analysis, mode shapes and natural frequencies of the wing can be calculated for the PK method.

2.2 Aerodynamic modeling

The aerodynamic analysis is required to obtain the aeroelastic solution. DLM is widely used because of applicability to complex wing configurations and convincing results in regard to unsteady aerodynamics. Moreover, Aerodynamic Influence Coefficients (AIC) can be calculated directly. The procedure is started from Euler's equations with five unknown variables, air density, pressure and three velocity components. With the continuity equation, isentropic relation, velocity potential and small disturbance component, as a result, the following matrix notation can be obtained.

$$\{w\} = [Q]\{p\} \tag{2}$$

where Q is the normalwash factor from the combined effects of the steady vortices and the oscillatory doublets and it is the AIC.

2.3 Aeroelastic modeling

From the DLM, the AIC matrix is calculated as a function of reduced frequency k and Mach number M_a with $N \times N$ size where N is total number of elements of the aerodynamic model. The size of the coefficient matrix needs to be reduced to $n \times n$ for modal flutter analysis where n is number of natural modes used in the analysis. The mathematical transformation procedure is expressed as

$$[Q_{nn}] = [\Phi_{mn}]^T [G_{Nm}]^T [Q_{NN}][G_{Nm}][\Phi_{mn}] \tag{3}$$

where Q_{nn} is the generalized aerodynamic matrix, Φ_{mn} is a matrix of n-set normal mode vectors and G_{Nm} is the spline matrix for matching the aerodynamic and structural mesh. For the aeroelastic analysis, the PK method is performed. The fundamental equation for modal flutter analysis is

$$\left[M_{hh}p^2 + \left(B_{hh} - \frac{1}{2}\rho b V Q^I_{hh} / k\right)p + \left(K_{hh} - \frac{1}{2}\rho V^2 Q^R_{hh}\right)\right]\{u_h\} = 0 \tag{4}$$

The eigenvalues will be complex conjugate pairs and the oscillatory solutions require an iterative solution. The principal advantage of the PK method is producing results directly for given velocity.

3 Results and Discussions

3.1 Validation

With these formulations, the validation is performed by using 15 degree-sweptback wing model in Ref. [3]. The natural frequencies and mode shapes are equivalent to the results of the reference. Also the flutter speed and frequency from the PK method are well agreed with the presented results as shown in Table 1.

Table 1. Validation of flutter speed and frequency

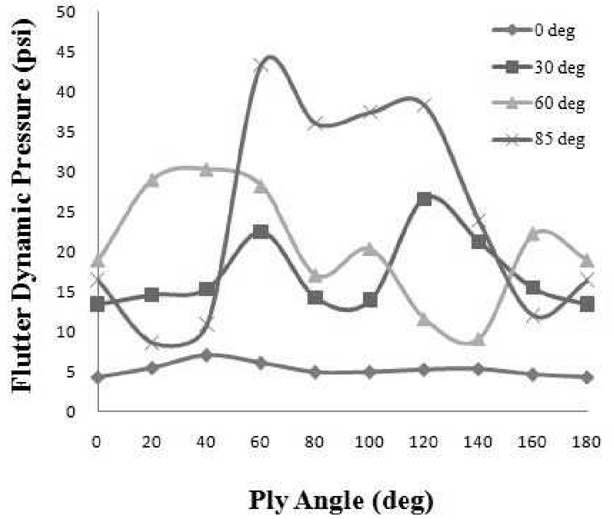
Analysis Type	V_f (ft/sec)	ω_f (Hz)	Method
PATRAN	483	113	KE
Present	496	108	PK

3.2 The effect of ply angle

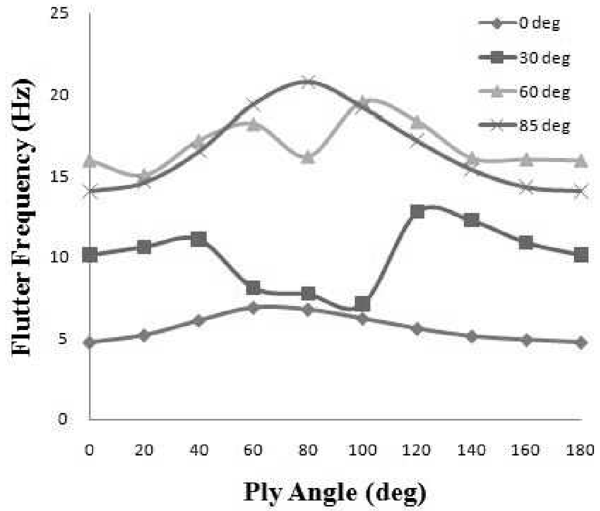
In the current study, the angle of the outboard wing is assumed as constant. Thus, the results are computed using these parameters, fold angle of inboard wing, hinge stiffness and ply angle of laminates. And two materials are obtained, aluminum and T300/5208 Graphite/Epoxy. To compare the tendency of two models, two models make have same mass by control the thickness. A number of total aerodynamic elements is 324 and structural elements is 260. Computational results for an inboard wing fold angle of 0 to 85 deg with 5 deg increment. For simplicity of study, the ply angle is determined as $[0_2/\theta_2]_S$. Additionally, the geometric configuration is represented in Table 2.

Table 2. Geometry of the folding wing model [4]

Chord	**Body**	180 (root)	144 (tip)
	Inboard	144	60
	Outboard	60	21
Span	**Body**	36	
	Inboard	54	
	Outboard	84	
Sweepback Angle (deg)		45	
Thickness	**Isotropic Plate**	1.05	
	Composite Plate	1.80	



(a) Flutter dynamic pressure vs. ply angle



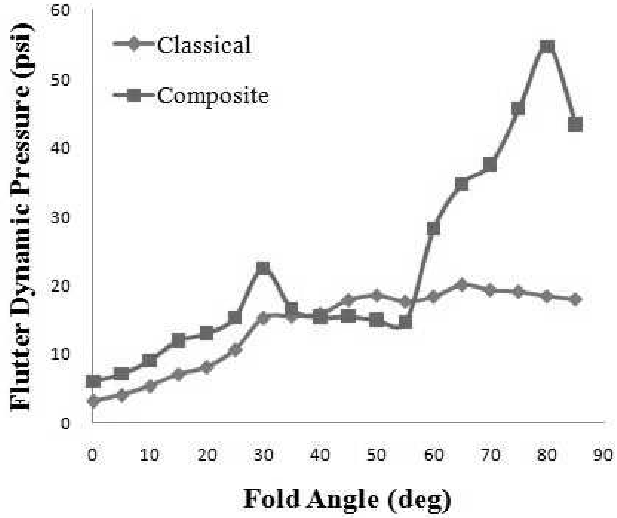
(b) Flutter frequency vs. ply angle

Fig. 2. The effect of ply angle

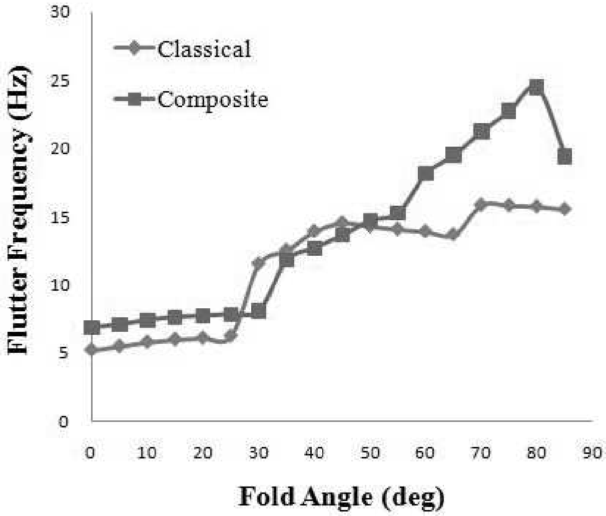
As shown in Fig. 2, the flutter dynamic pressure is changed dynamically. When the fold angle is 0 deg, effect of ply angle is not large. However, as the fold angle larger, the effect increases. The largest average flutter dynamic pressure is obtained at 60 deg, ply angle.

3.3 The effect of fold angle

The analysis is performed in range of 0 to 85 deg fold angles with 5 deg increments for the first five modes.



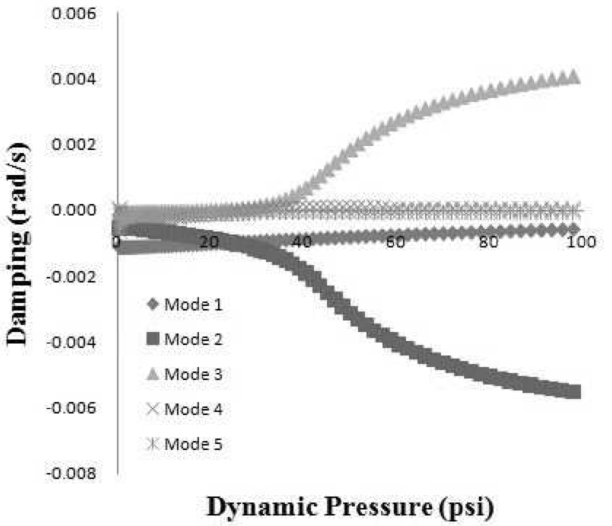
(a) Flutter dynamic pressure vs. fold angle



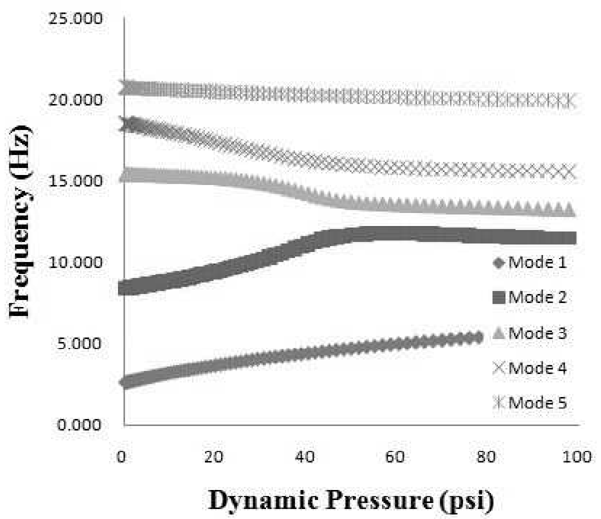
(a) Flutter dynamic pressure vs. fold angle

Fig. 3. The effect of fold angle

As shown in Fig. 3 (a), the flutter dynamic pressure is increased at 55 deg. Also Fig. 3(b) shows the relation between the flutter frequency and the flutter dynamic pressure. When there is a large increment of the pressure, the flutter frequency is also varied largely. Fig. 4 and 5 are shows V-g and V-f plots for 55 deg and 60 deg which has large increments of the pressure.



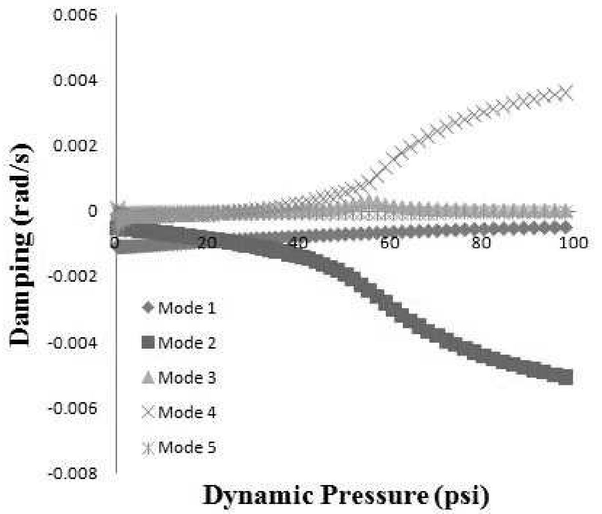
(a) V-g plot



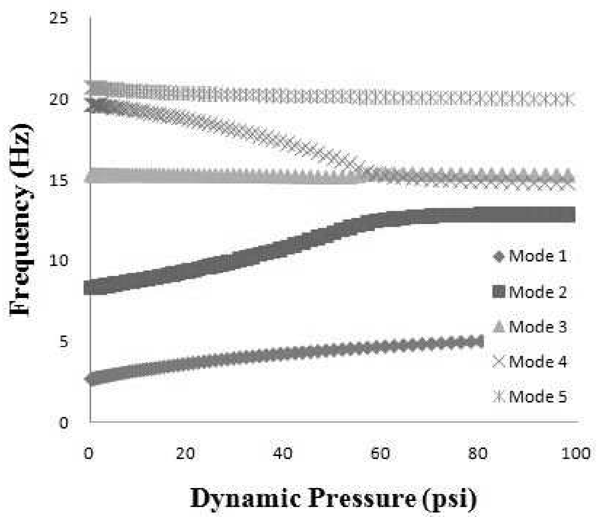
(b) V-f plot

Fig. 4. V-g and V-f plots for 55 deg, fold angle

As shown in Fig. 4, 2nd mode and 3rd mode are coupled and flutter is occurred at 3rd mode. However, in Fig. 5, coupled modes are changed to 3rd and 4th mode. Moreover, flutter is occurred at 4th mode. During fold angle increases 5 degree, the flutter mode is changed from 3rd to 4th mode. Due to this situation, the flutter dynamic pressure is very sensitive to the fold angle variation.



(a) V-g plot

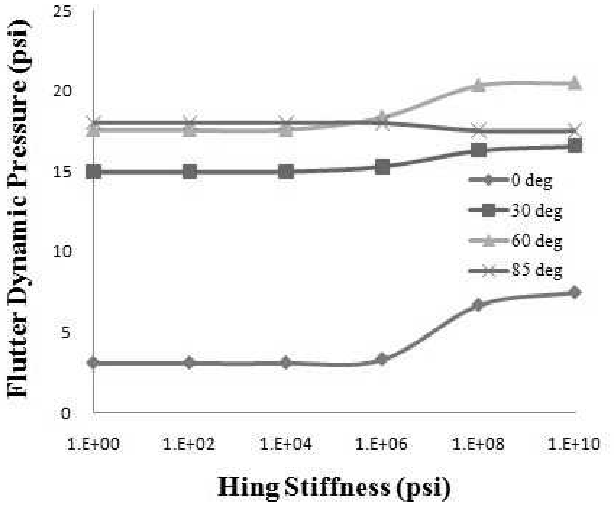


(b) V-f plot

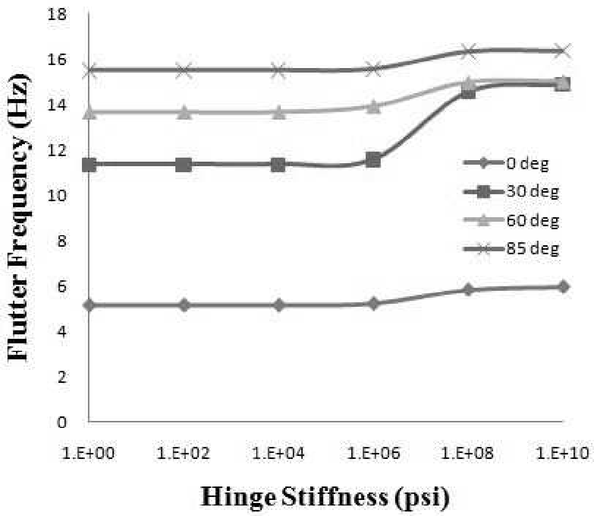
Fig. 5. V-g and V-f plots for 60 deg, fold angle

3.3 The effect of hinge stiffness

The effect of the hinge stiffness on the flutter boundary of the folding wing structure are considered. The boundary is measured for 4 fold angles with 6 hinge stifness values. As shown in Fig. 4, flutter boundaries have almost constant value before $10^6 lb \cdot in / rad$ and then variation starts from $10^8 lb \cdot in / rad$ for an isotropic plate model.



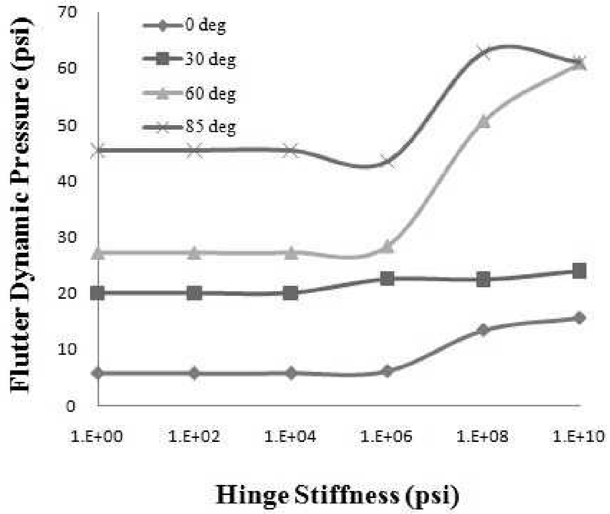
(a) Flutter dynamic pressure vs. hinge stiffness



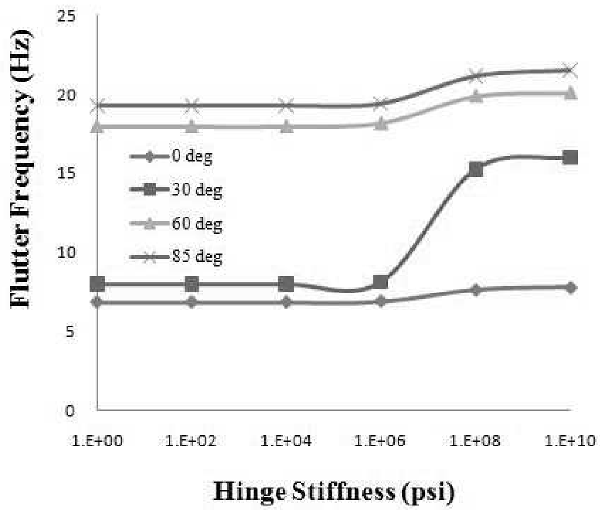
(b) Flutter frequency vs. hinge stiffness

Fig.4. The effect of hinge stiffness for isotropic plate model

On the other hand, in case of a composite plate model, variation is more apparent than a case of the isotropic plate model. When the fold angle is 60 deg, the flutter dynamic pressure almost increases twice.



(a) Flutter dynamic pressure vs. hinge stiffness



(b) Flutter frequency vs. hinge stiffness

Fig.5. The effect of hinge stiffness for composite plate model

4 Conclusions

The aeroelastic stability of a folding wing model is studied using finite element method based on laminated composite theory and FSDT, doublet lattice method and PK method. The results are calculated for various fold angles, hinge stiffness and ply angles of laminates.

The effect of the parameters is obtained and obviously the flutter boundaries are very sensitive to them.

According to the results the composite plate model is more stable than the isotropic plate model when the ply angle is 60 deg.

References

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