AEROELASTIC ANALYSIS FOR A THREE-DIMENSIONAL STRUCTURALLY NONLINEAR WING WITH A CONTROL SURFACE

1. INTRODUCTION

In this paper, a brand-new approach model capable of analyzing more realistic and complex composite wings with a control surface is suggested. The present analysis features two special schemes in order to reduce the size of the problem and the computational cost. First, a three-dimensional semi-monocoque main wing, which consists of the skins, spars, and ribs, is considered. Afterwards, a thin solid control surface is modeled as an equivalent plate. An expanded component mode synthesis is then applied while considering hinges with torsional springs. A significant reduction of the structural model size leads to an efficient aeroelastic analysis when combined with a panel-based commercial program ZAERO. The theoretical background of the present equivalent plate analysis resorts to the first-order shear deformation theory (FSDT), which is capable of considering a moderately thick wing configuration. The von-Karman nonlinear strain-displacement relation is applied to consider geometrical nonlinearity. A numerical solution is obtained by the finite element method. A comparison between the presently expanded equivalent plate analysis results and the three-dimensional FEA results obtained by MSC/NASTRAN is conducted. Finally, the flutter analysis is performed and compared with the results from ZAERO itself.

2. FORMULATIONS

This section describes the geometrically nonlinear governing equations for a plate-like aircraft composite wing structure. Numerically equivalent integrals, expanded component mode synthesis, and the flutter solution techniques of present analysis and ZAERO are described and used in the paper. The detailed nonlinear solution techniques and procedure are presented by Dr. NA.

3. NUMERICAL RESULTS

This section presents the numerical results, including a free vibration and flutter analysis of an isolated plate wing, and semi-monocoque composite wing with a control surface which is connected by torsional springs. The results are compared to those obtained from a three-dimensional wing analysis by MSC/NASTRAN. Then, flutter results of a plate wing, a semi-monocoque wing and composite wing are presented. In addition, the flutter boundary prediction results for the composite wing are presented in terms of the hinge stiffness magnitude.

3.1 Free Vibration Analysis

3.1.1 Isotropic Plate Wing

Geometry of the present isotropic plate wing is shown in Fig 1.

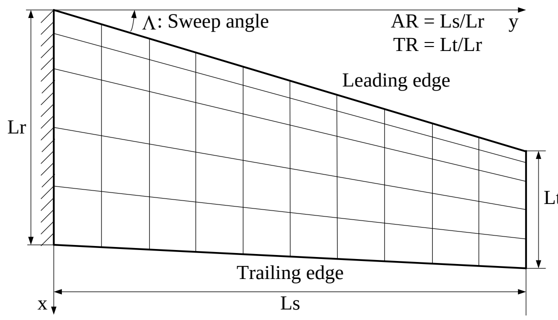
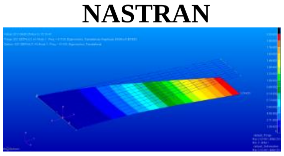


Figure 1. Planform of the present isotropic plate wing

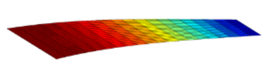
Natural frequencies and the corresponding mode shapes of the present wing are obtained and validated with those predicted by NASTRAN. The natural frequencies and the corresponding mode shapes obtained show good agreement with those by MSC/NASTRAN. Differences between the present and those by NASTRAN are found to be 0.2~1.1%.

NASTRAN

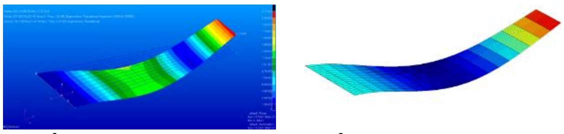


1st Mode: 4.110 Hz

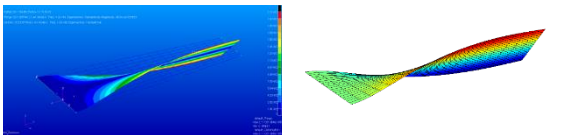
Present EP



1st Mode: 4.117 Hz



2nd Mode: 22.31 Hz 2nd Mode: 22.39 Hz



3rd Mode : 29.75 Hz 3rd Mode : 30.09 Hz

Fig. 2. Natural frequencies and the mode shapes comparison for the present isotropic plate wing

3.1.2 Semi-Monocoque Wing

The present equivalent plate wing analysis would require further validation regarding spars and ribs. The differences in the natural frequencies between the present equivalent plate analysis and NASTRAN are obtained to be 2.9~6.4%. It is also found that the thicker the airfoil becomes, the larger differences exist between the analyses. The natural frequencies and the corresponding mode shapes of the present semi-monocoque wing are shown, and those are compared with the prediction obtained by NASTRAN.

3.1.3 Three-dimensinoal Composite Wing

The lowest ten mode shapes and natural frequencies of the wing are compared to the MSC/NASTRAN results, the present expanded equivalent plate analysis accurately predicted the dynamic characteristics of the wing. The rigid body rotational mode of a control surface appeared, as zero torsional spring coefficients is applied in the comparison with the MSC/NASTRAN model. Regarding the size problem, the total number of degrees of freedom of the three-dimensional MSC/NASTRAN model is 2,724. Compared to that, the size of the present analysis is decreased by applying the two schemes. The total number of degrees of freedom is reduced to 1,825 (47.2%) after applying the equivalent plate model. A reduction of the problem size is then obtained. The size is finally reduced to 75 (2.75%) by applying the expanded component mode synthesis. Thus, the present analysis will be useful in upcoming aeroelastic analysis, such as a flutter analysis, due to the significant reduction of the size of the problem.

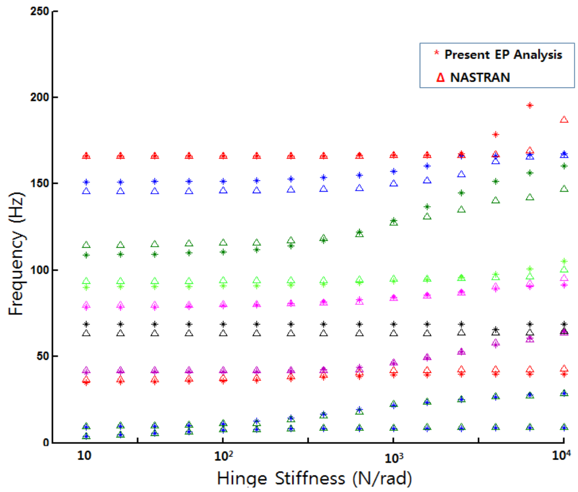


Figure 3. Trends of the natural frequencies in terms of the hinge stiffness magnitude

Trends of the natural frequencies are obtained in terms of the hinge stiffness magnitude. As shown in Figure 3, such trends are compared with those predicted by NASTRAN and the present result shows good agreement. Difference between the present equivalent plate analysis and NASTRAN is found to be 8.7%, at the largest.

3.2. Flutter analysis

By combining the presently developed analysis and ZAERO, the flutter analyses of a plate wing and a semi-monocoque wing are investigated. Comparisons are made using MSC/NASTRAN. Three combinations of structural models and flutter solution techniques are considered as follows:

Case 1: 3-D NASTRAN structural model + g- and k- methods in ZAERO

Case 2: 2-D EP Model + g- and k- methods in ZAERO

Case 3: 2-D EP Model + p-k method using extracted AIC from ZEARO

3.2.1 Plate Wing

A flutter analysis for a plate wing is performed. The lowest six elastic modes are used and Mach number is set to be 0.6 at sea level.

Table 4. Flutter speed and frequency of the plate wing

	Case 1 MSC/NASTRAN		Case 2 Present		Case 3 Present
	g-method	k-method	g-method	k-method	p-k method
V_f (m/s)	358.0	358.6	359.6	360.4	360.0
ω_f (Hz)	13.3	13.2	13.5	13.2	13.2

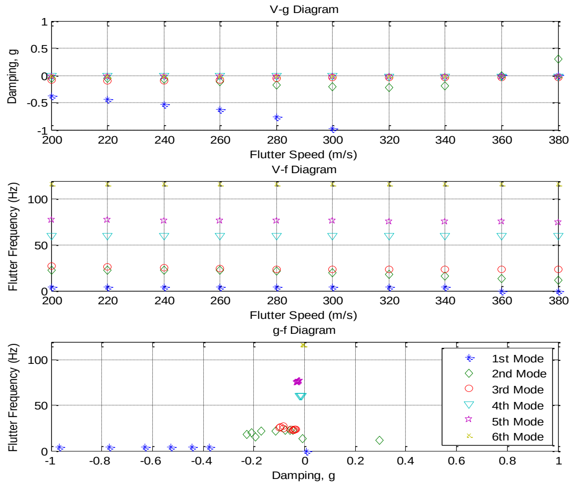


Figure 4. V-g, V-f and g-f plots for the plate wing (M=0.6)

3.2.2 Semi-monocoque Wing

Table 5 summarized the flutter results and V-g, V-f, and g-f plots for Case 3 are presented in Fig. 4. The flutter speed using EP model is predicted slightly higher than that using NASTRAN. The difference of flutter speeds is almost the same order of the maximum difference of natural frequencies. However, prediction of the flutter frequency is relatively accurate. The difference of flutter frequencies is almost the same order of the averaged difference of natural frequencies.

3.2.3 Three-Dimensional Composite Wing

Flutter analysis results for a three-dimensional composite wing are obtained in terms of the hinge stiffness magnitude. Those flutter speed and frequencies are obtained at a constant flight Mach number 0.6, and sea level altitude.

Table 5. Flutter speed and frequency of the semi-monocoque wing

	Case 1 MSC/NASTRAN		Case 2 Present		Case 3 Present
	g-method	k-method	g-method	k-method	p-k method
V_f (m/s)	403.8	401.8	439.0	437.4	437.0
ω_f (Hz)	26.9	27.2	27.7	27.7	27.7

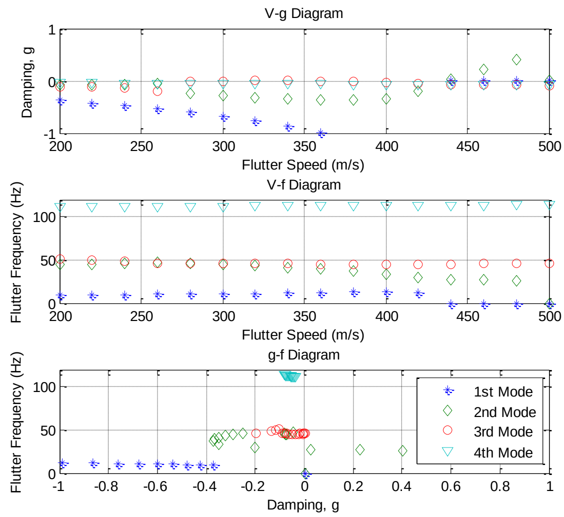
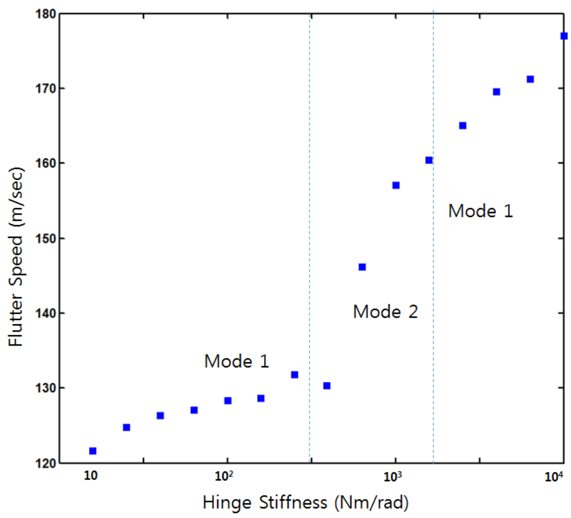
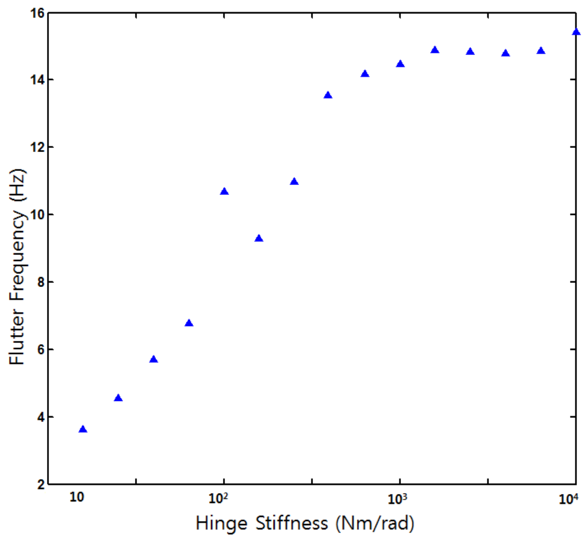


Figure 5. V-g, V-f and g-f plots for the semi-monocoque wing (M=0.6)

The non-matched point flutter analysis was conducted to obtain the present flutter prediction results by using NASTRAN structural analysis and ZAERO. In Figure 6, the flutter speed is varied drastically within the region of the hinge stiffness magnitude 10^2~10^3 Nm/rad. This significant change is due to the flutter mode switch. In the lower hinge stiffness region, the dominant flutter mode is the 1st mode. And then it is changed to the 2nd mode in the high hinge stiffness region. In the higher magnitude region, the dominant flutter mode is further changed back to the 1st mode. However, flutter frequencies are found to be continuously increased in terms of the hinge stiffness magnitude.



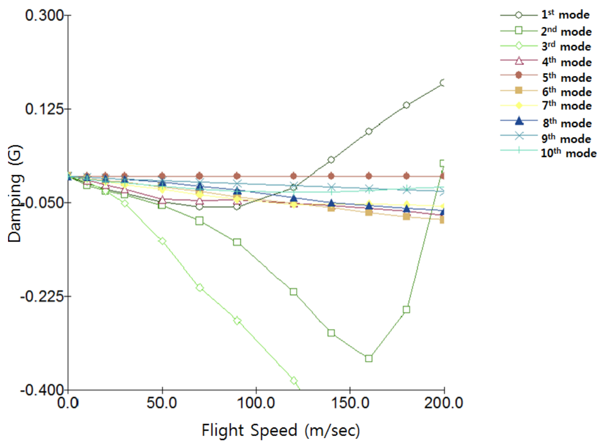
(a) flutter speed in terms of the hinge stiffness magnitude



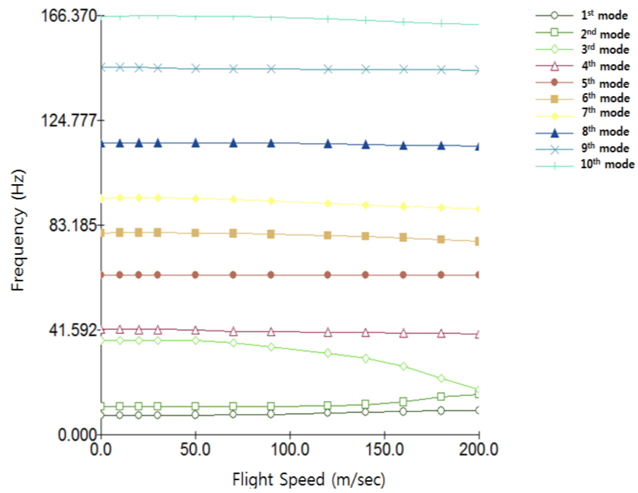
(b) Flutter frequencies in terms of the hinge stiffness magnitude

Figure 6. Flutter prediction result for the three-dimensional composite wing predicted by NASTRAN and ZAERO (M=0.6, Sea level)

The flight speed-damping and flight speed-frequency plots corresponding to the hinge stiffness magnitude of 100 Nm/rad are shown in Figure 7. As shown in Figure 7 (a), damping magnitude for the first mode is increased and become near zero. Thus, the first mode is found to be dominant flutter mode. In addition, Figure 7 (b) shows flight speed-frequency plot. This clearly shows a frequency coalescence occurred between the first and second mode. The present flutter prediction for the three-dimensional composite wing is conducted by using NASTRAN and ZAERO only. In the future, similar aeroelastic analysis will be performed by the present equivalent plate structural analysis and the relevant unsteady wing aerodynamics.



(a) Flight speed-damping



(b) Flight speed-frequency

Figure 7. Additional results for the present three- dimensional composite wing flutter analysis

4 CONCLUSIONS

A brand-new approach capable of analyzing realistic and complex composite wings with a control surface is developed by combing EPA and expanded CMS. A comparison between the presently expanded equivalent plate analysis results and the three-dimensional FEA results obtained by MSC/NASTRAN is conducted and validated. The present results obtained for the lowest ten modes and the natural frequencies are predicted to within a difference of 5% compared to those of a detailed three-dimensional model. In addition, the size of the present system matrix is 2.8% compared to that of NASTRAN. Thus, it is concluded that the presently expanded EPA has sufficient accuracy and effectiveness. Moreover, flutter analyses using present EPA and the NASTRAN model are performed. ZAERO is adopted to calculate unsteady aerodynamic forces. The theoretical background of ZAERO is briefly reviewed in Section 2.4. The results by using the present structural model are moderately accurate for the flutter speed up to maximum difference of natural frequencies and for the frequency up to averaged difference of natural frequencies. Finally, flutter speed and frequencies are predicted in terms of the hinge stiffness magnitude by using NASTRAN and ZAERO only. When the hinge stiffness of the control surface is increased, the flutter speed and flutter frequency are found to be increased, too. In detail, the flutter speed shows a significant discrete increase at a certain value of the hinge stiffness magnitude. This is due to switch in a dominant flutter mode. In the future, similar aeroelastic analysis will be performed by the present equivalent plate structural analysis and the relevant unsteady wing aerodynamics.