유전자 알고리즘을 이용한 T-형 복합재료 날개의 플러터 속도 최적설계

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Optimum Design of a Composite T-tail Configuration for Maximum Flutter Speed Using Genetic Algorithm

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Abstract

In this paper, an efficient and robust analysis system for the flutter optimization of laminated composite wings has been developed using the coupled computational method based on the genetic algorithm. General three-dimensional doublet-lattice method is efficiently used to compute generalized aerodynamic forces of T-tail configuration in the frequency domain. Structural dynamic analyses of laminated composite T-tail models are conducted using finite element method. The classical P-k flutter analysis technique is applied to effectively solve the aeroelastic governing equations in the frequency domain. Optimum design studies using genetic algorithm have been conducted in order to obtain maximum flutter stability of a composite T-tail configuration. The results show that flutter stability can be significantly increased using composite materials with proper optimum design concepts even for the same weight and shape condition. In the view point of engineering design, it is also importantly shown that the optimization of the vertical wing part is highly effective comparing to the optimization of horizontal wing part.

Key Words: Composite Materials, Optimization, T-tail, Flutter, Aeroelastic Analysis, Unsteady Aerodynamics, Doublet-Lattice Method, Finite Element Method, Frequency Domain

1. Introduction

The optimum design of composite structures has been a subject of research for many years. However most of the previous researches were conducted on the forward swept composite wing structures model[1-3]. In this study, attention has been paid to the aeroelastic tailoring of composite T-tail structures. Some previous studies for flutter aeroelastic behaviors of generic T-tail structures using advanced computational method has shown that elastic coupling between vertical wing mode and horizontal wing mode and the stiffness of vertical wing have significant effect on flutter speed instability[4,5]. Therefore the focus optimization in this paper is to optimizing ply orientation angles of laminated composite T-tail structures for maximum flutter dynamic pressure (or speed).

For the optimization algorithm, genetic algorithm is chosen because of its well known performance as the robust and efficient global search algorithm. Since introduce by Holland[6], genetic algorithm has been used by many researchers as a useful tool for search and optimization. For the final step a general analysis system for dynamic-flutter optimization has been developed using coupled computational technique of doublet-lattice method, finite element method, efficient flutter analysis method and genetic algorithm. As a computational demonstration, the effects of fiber angle and stacking sequence on the flutter dynamic pressure have been investigated. Finally, the optimum results for composite wing model are also compared with the case of the isotropic wing model with the same configuration

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and weight.

2. Computational Background

2.1 Aeroelastic Analysis

In this study, the doublet-lattice method (DLM) was used for the calculation of linear unsteady aerodynamic forces named as generalized aerodynamic influence coefficient (GAIC) in the subsonic region. In DLM, the pressure distributions of an oscillatory lifting surface and their normal wash velocity can be related by the singular integral equation as follows

$$\omega(x,y)=\frac{1}{8\pi}\iint_S K(M,k_b)\triangle PdS \tag{1}$$

where x and y are the orthogonal coordinate, S is the wing surface, $\triangle P$ is the pressure difference between lower and upper surfaces, and K is the kernel function which is function of Mach number M and reduced frequency k_b. The same subsonic kernel function proposed by Rodden et al.[7,8] have been adopted here.

Generalized aerodynamic force coefficients in time domain are computed approximately by

$$Q(t)=\frac{1}{2}\rho_\infty U_\infty^2 c_r^2\iint_S (C_{pL}(t) - C_{pU}(t))\psi_i(x,y)\frac{dS}{c_r^2} \tag{2}$$

where ρ_∞ is the freestream air density, U_∞ is the freestream velocity, c_r is the reference chord length, S is the wing planform area, C_p is the unsteady pressure coefficient on the arbitrary lifting surface, subscript L and U means the lower and upper surface, respectively and ψ_i is the ith natural vibration mode shape.

The aeroelastic equations of motion for an elastic wing may be formulated in terms of generalized displacement response vector $\{q(t)\}$which is a solution of the following equation:

$$[M_g]\{\ddot{q}(t)\}+[C_g]\{\dot{q}(t)\} + [K_g]\{q(t)\}=\{Q(t,q,\dot{q})\} \tag{3}$$

where t is the physical time, $[Mg]$ is the generalized mass matrix, $[Cg]$ is generalized damping matrix which is practically assumed as proportional damping, $[Kg]$ is the generalized stiffness matrix, and $\{Q\}$ is the vector of generalized aerodynamic forces as shown in Eq. (2).

Assuming harmonic oscillation for small wing motion as $\{q\}=\{\bar{q}\}e^{pt}$, Eq. (3) can be converted into eigenvalue problem in the frequency domain. The eigenvalue problem for classical flutter equation can be written as follows

$$[[M_g]p^2+[C_g]p+[K_g] - \frac{1}{2}\rho U^2[A(M,k_b)]]\{\bar{q}\}=0 \tag{4}$$

where p is eigenvalue defined by $p=\omega(\gamma\pm i)$, ω is circular frequency, γ is transient decay rate coefficient (TDRC), and $[A]$ is the generalized aerodynamic influence coefficient (GAIC) matrix of complex form as a function of Mach number M and reduced frequency k_b.

Here, the numerical interpolation of $[A]$ matrix is necessarily needed to calculate the GAIC matrices corresponding to randomly extracted reduced frequencies. Under the assumption of small damping value, extracted reduced frequency (including flutter frequency) and structural damping corresponding to eigenvalue p can be calculated by the following relations

$$k_b=\frac{\omega b}{U}=\frac{b}{U}Im(p), \quad g=2\gamma=2\frac{Re(p)}{Im(p)} \tag{5}$$

The computed aerodynamic forces will be interpolated into the finite element node points using the surface spline method that is based on the infinite plate theory.

2.2 Optimization Method

Genetic Algorithm is optimization technique that draws its analogy from nature and revolves around genetic reproduction processes and survival of the fittest strategies. In this study, the applied genetic algorithm is based on the theories from Ref.9.

The optimization model used in GA can be represented by

maximize $F(x)$ subject to

$$x \in \{A \mid (\theta_1, \theta_2, ... \theta_i)\},$$
$$\theta_i \in [0, \pm 30, \pm 45, \pm 60, 90] \quad (6)$$

where $F(x)$ is the objective function and is the flutter dynamic pressure defined by $q = \frac{1}{2}\rho V_f^{\,2}$, where V_f is the flutter speed. The ply orientation angles were used as the variables (x) in the algorithm to find the maximum flutter dynamic pressure for probable ply orientation angles.

Figure 1 illustrates the road map of the coupling technique between genetic algorithm, doublet-lattice method, finite element method and aeroelastic analysis used in this paper.

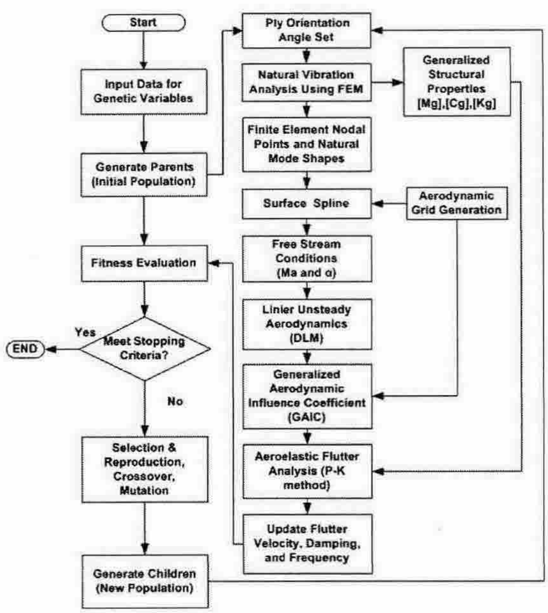


Fig. 1 Computational road map of the present flutter optimization method using genetic algorithm.

Table 1 Material properties of T-tail model

Vertical Wing and Horizontal Wing			
Al 6061-T6			
E=70 GPa	μ=0.33	ρ=2700 kg/m^3	t=5.61 mm
T300/5208 Graphite/Epoxy			
E_1 =138 GPa	μ=0.28	ρ=1580 kg/m^3	t=0.4 mm
E_2 =9.7 GPa	G_{12}=5.5 GPa		(ply thickness)

3. Results and Discussion

The geometric configuration of T-Tail model considered here is presented in Fig.2. Also, Corresponding finite element model is shown in Fig.3. The model has two main part, vertical wing section and horizontal wing section. Each of them is simply assumed as platelike structures for the purpose of clear academic research. Root of the vertical wing part is fixed to impose structural boundary conditions. Material properties used here for isotropic and composite cases are presented in Table 1.

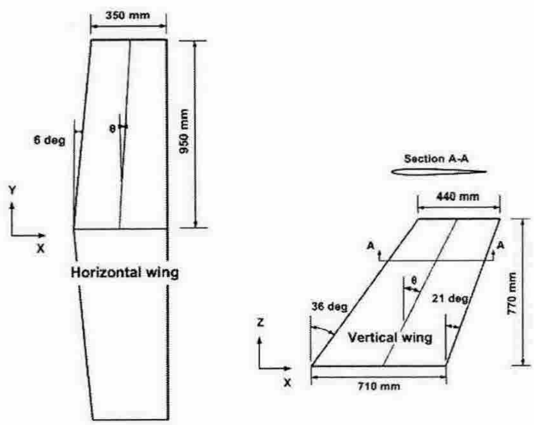


Fig. 2 Geometric configuration of the T-tail.

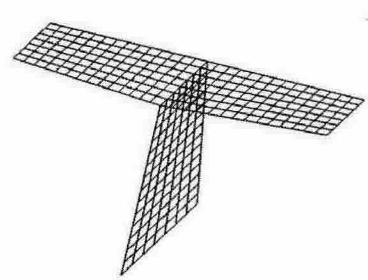
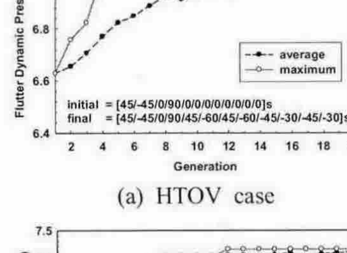


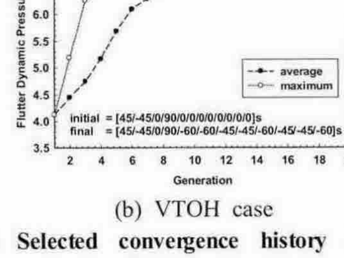
Fig. 3 Finite element mesh for the T-tail.

In this paper, an efficient and robust analysis system for the flutter optimization of laminated composite wings has been developed using the coupled computational method based on the genetic algorithm in the frequency-domain. Structural dynamic analyses of laminated composite T-tail models are conducted using commercial finite element code such as MSC/NASTRAN. The finite element model consists of the quadrilateral (CQAD4) plate element with PCOMP entry. The total number of plies assumed is 24 and among them inner 16 plies can be changed to yield optimum flutter speed. The lamination sequence is practically assumed as symmetric lamination of [45/-45/0/90/...θ...]$_S$. Here, the variable angles of θ sets are practically selected using the combination of $0°, \pm 30°, \pm 45°, \pm 60°$ and $90°$ angles. Symmetric flow boundary conditions on the x-y plane is assumed for unsteady aerodynamic analysis. The design studies of aeroelastic tailoring are performed under flutter stability problem. The flight condition is set-up at sea-level condition with freestream Mach number of 0.5.

In this study, four different cases for optimization have been considered: *NOP* is the case without conducting optimization, *HTO* is the case of horizontal wing optimization only with initially given ply orientation angles of vertical wing part, *VTO* is for the optimization of vertical wing part with initially given ply orientation angles of horizontal wing part, *HTOV* is for the optimization horizontal wing using firstly optimized ply orientations for vertical wing part, and finally *VTOH* is for the optimization of vertical wing using firstly optimized ply orientations for horizontal wing part. In the present application of genetic algorithm, the variable ply angles considered is expressed as binary numbers such as [0]=000, [30]=001, [-30]=010, [45]=011, [-45]=100, [60]=101, [-60]=110, and [90]=111. The genetic algorithm parameters for optimum design process are set as follows: population size is 30, crossover probability is 0.5, and mutation probability is 0.02.



(a) HTOV case



(b) VTOH case

Fig. 4 Selected convergence history for several cases of optimization.

The convergence histories samples with respect to the global iterations of genetic algorithm for each case are presented in Fig.4. It shows that at least about 15 global iterations are required to obtain converged maximum solutions. The results for optimum flutter design computations are summarized in Table 2. It is shown that most of the optimized flutter dynamic pressures are largely higher than the case of isotropic T-tail model with the exactly same structural weight and aerodynamic shape.

Table 2 Comparison of flutter dynamic pressure and flutter frequency.

Model Case	Stacking Sequence	Object Fn. Maximum q_f (kPa)	Flutter Freq. f_f (Hz)
Isotropic	NA	1.41	2.71
Composite NOP	VT: [45/-45/0/90/...θ...]$_S$ θ= 0/0/0/0/0/0/0/0 HT: [45/-45/0/90/...θ...]$_S$ θ= 0/0/0/0/0/0/0/0	3.73	5.47
Composite HTO	VT: [45/-45/0/90/...θ...]$_S$ θ= 0/0/0/0/0/0/0/0 HT: [45/-45/0/90/...θ...]$_S$ θ= -60/45/30/-45/45/-45/-60/0	4.12	5.48
Composite VTO	VT: [45/-45/0/90/...θ...]$_S$ θ= 45/-60/-60/-60/-60/60/-45/-30 HT: [45/-45/0/90/...θ...]$_S$ θ= 0/0/0/0/0/0/0/0	6.69	5.64
Composite HTOV	VT: [45/-45/0/90/...θ...]$_S$ θ= -60/-60/-60/-45/45/-45/-45/-60 HT: [45/-45/0/90/...θ...]$_S$ θ= 45/-60/45/-60/-45/-30/-45/-30	7.12	5.52
Composite VTOH	VT: [45/-45/0/90/...θ...]$_S$ θ=-60/-60/-45/-45/-60/-45/-45/-60 HT: [45/-45/0/90/...θ...]$_S$ θ= -45/-45/45/-45/30/30/90/-60	7.15	5.50

Flutter dynamic pressure for the isotropic model is just 1.41 kPa for the given flight condition. NOP case inherently indicates the most lower flutter dynamic pressure among composite models. The flutter dynamic pressure of HTO case is 2.92 times greater than that of the isotropic wing model. Also, the obtained flutter dynamic pressure of VTO case is 62.4% higher than that of the HTO case for the present T-tail model. This is 4.74 times greater than that of the isotropic wing model. The maximum flutter dynamic pressure can be achieved for the VTOH case. The maximum flutter dynamic pressure of VTOH case is about 5.1 times greater than the isotropic case. However, when it compares to the case of VTO, it shows just 6.9% increment of flutter dynamic pressure. In the view point of engineering design, it is importantly indicates that optimization of the vertical wing part is highly effective comparing to the optimization of horizontal wing part. In other words, it means that the optimization study of vertical tail wing only is practically enough to yield good flutter stability of the present T-tail model case.

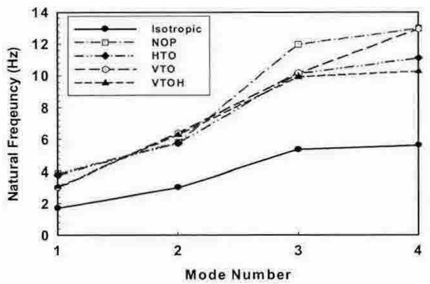
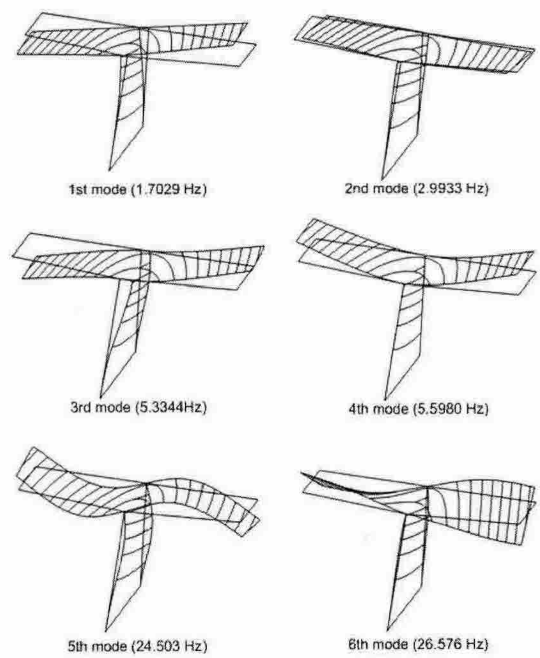


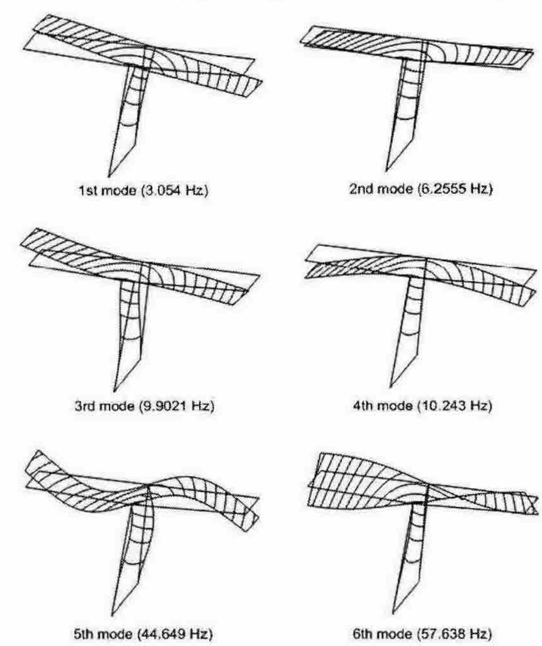
Fig. 5 Comparison of natural frequency between isotropic and optimized composite T-tail models.

Figure 5 represents the comparison of natural frequcies between isotropic and optimized composite models. Isotropic model case shows lower frequency level compared to the case of composite models. It is noted here that although first natural frequencies of VTO and VTOH models are lower than the cases of NOP and HTO, the frequency differences of VTO and VTOH models between the first mode and the second mode are much lagger than the case of NOP and HTO. It is well known from the classical aeroelastic theory that an oscillatory instability where one natural 'mode' of motion is driven to resonance by a second mode. Both modes have usually coalesced to the same frequency. This is why is the flutter dynamic pressures of VTO and VTOH models are much larger than the case of NOP and HTO.

Figure 6 shows the comparison of natural vibration modes. We can see very similar natural mode shapes between the isotropic model and the optimized composite model although natural frequencies are different. Comparison of Q-g and Q-f diagrams are presented in Fig.7. For all models, it can be observed that the second mode is the dominant flutter model for the present T-tail configuration. Also, we can see the different flutter dynamic pressure levels for each case.

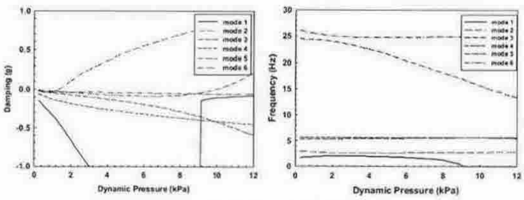


(a) Isotropic model

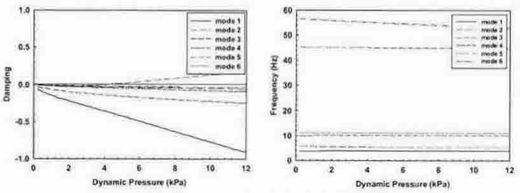


(b) Composite Model (VTOH)

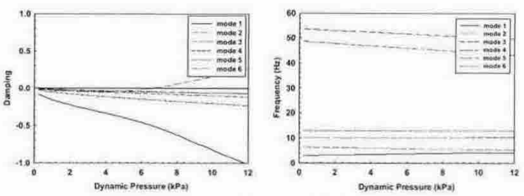
Fig. 6 Natural mode shapes of isotropic and composite models.



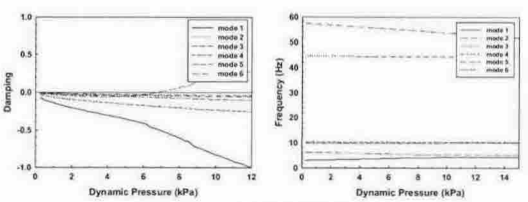
(a) Isotropic Model (Al 6061-T6)



(b) Composite Model (HTO)



(c) Composite Model (VTO)



(d) Composite Model (VTOH)

Fig. 7 Comparison of Q-g and Q-f plots for isotropic and optimized composite models.

4. Conclusions

The design studies of aeroelastic tailoring in different cases were conducted on a T-tail configuration. An efficient and robust analysis system for flutter optimization of laminated composite structures has been successfully developed using coupled computational method based on the genetic algorithm. The present results show that flutter stability can be significantly increased using composite materials with proper optimum design concepts for the same weight and shape condition. In the view point of engineering design, it is also importantly shown that the optimization of the vertical wing part is highly effective comparing to the optimization of horizontal wing part. In other words, the optimization study focused on the vertical tail part is practically enough to yield good flutter stability for the T-tail configuration.

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References

1. Lottai, I., "Flutter and Divergence Aeroelastic Characteristics for Composite Forward Swept Cantilevered Wing," *Journal of Aircraft*, Vol. 22, No. 11, 1985, pp. 1001-1007.
2. Librescu, L. and Khdeir, A. A., "Aeroelastic Divergence of Swept-Forward Composite Wings Including Warping Restraint Effect," *AIAA Journal*, Vol.26, No. 11, 1988, pp. 1373-1377.
3. Librescu, L. and Simovich, L., "General Formulation for the Aeroelastic Divergence of Composite Swept-Forward Wing Structures," *Journal of Aircraft*, Vol. 25, No. 4, 1988, pp. 364-371.
4. Kim, D. H., "Vibration and Aeroelastic Characteristics of a T-tail Configuration Using Parallel Processing Technique", *Journal of Korea Institute of Military Science and Technology*, Vol. 7, No. 3, 2004, pp.149-156.
5. Kim, D. H., Oh, S. W., and Lee, I., "Aeroelastic Computation of a T-tail Configuration in the Compressible Flow," *International Forum on Aeroelasticity and Structural Dynamics(IFASD) 2005*, Munich, Germany, June 28-July 1, 2005.
6. Holland J. H., *Adaptation in Natural and Artificial Systems*, University of Michigan Press, Ann Arbor, 1975, pp. 183.
7. Albano, E., and Rodden, W. P., "A Doublet-Lattice Method for Calculating Lift Distributions on Oscillating Surfaces in Subsonic Flows," *AIAA Journal*, Vol. 7, 1969, pp. 279-285.
8. Rodden, W. P., Giesing, J. P., and Kalman, T. P., "Refinement of the Nonplanar Aspects of the Subsonic Doublet-Lattice Lifting Surface Method," *Journal of Aircraft*, Vol. 9, 1972, pp. 69-73.
9. Goldberg, D. E., *Genetic Algorithm in Search, Optimization and Machine Learning*, Addison-Wesley, 1989.