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Aeroelastic Analysis and Optimization of High-aspect-ratio Composite Forward-swept Wings

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Abstract: In order to analyze the effects of forward-swept angle and skin ply-orientation on the static and dynamic aeroelastic characteristics, the aeroelastic modeling and calculation for high-aspect-ratio composite wings with different forward-swept angles and skin ply-orientation are performed. This paper presents the results of a design study aiming to optimize wings with typical forward-swept angles and skin ply-orientation in an aeroelastic way by using the genetic/sensitivity-based hybrid algorithm. Under the conditions of satiated multiple constraints including strength, displacements, divergence speeds and flutter speeds, the studies are carried out in a bid to minimize the structural weight of a wing with the lay-up thicknesses of wing components as design variables. In addition, the effects of the power of span-wise variation function of lay-up thicknesses of skins and lugs on the optimized weights are also analyzed.

Key words: aeroelasticity; structural optimization; high-aspect-ratio wing; forward-swept wing; composite

大展弦比复合材料前掠翼气动弹性分析与优化. 万志强, 颜虹, 刘德广, 杨超. 中国航空学报(英文版), 2005, 18(4): 317-325.

摘 要: 对具有不同前掠角和蒙皮偏轴角的大展弦比复合材料机翼进行了气动弹性建模与计算, 以分析前掠角和蒙皮偏轴角对这类结构的静、动气动弹性特性的影响。使用遗传/敏度混合优化算法对几种典型前掠角和蒙皮偏轴角情况下的机翼进行了气动弹性优化设计研究, 在满足强度、位移、发散速度和颤振速度等约束条件的前提下, 以机翼各部件复合材料铺层的厚度为设计变量, 对结构进行重量最小化设计。此外, 还分析了蒙皮和突缘的铺层厚度沿展向变化的函数的幂次对优化结果的影响。

关键词: 气动弹性; 结构优化; 大展弦比机翼; 前掠翼; 复合材料

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The high-respect-ratio aircraft has been drawn wide attention recently. This category of aircraft has high respect ratio while the structural weights are very low, because of the requirement on long endurance *etc*[1, 2]. The deformation of the structure under the aerodynamic load is very large and the aeroelastic problem is relatively serious due to the requirements on high respect ratio and low structural weight. Therefore, it is necessary to pay high attention to the aeroelastic problem and perform sufficient analysis[3].

In order to chase the better aerodynamic performance, the forward-swept wings have been a trend in the design of high-aspect-ratio aircraft recently, and the corresponding researches have been carried out. The forward-swept wings have better aerodynamic performance as compared with the conventional straight wings and aft-swept wings, however, they have fatal disadvantage of low divergence speed[4]. The studies indicate that it is benefit for high-respect-ratio forward-swept wings to meet the requirements on weight and deformation and eliminate aeroelastic divergence thoroughly, when composite material is used in structure as well as aeroelastic optimization technology in design[5]. The aeroelastic problem of high-aspect-ra-

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tio wings becomes more complex because of the application of forward-swept configuration and composite material.

For composite wings, swept angle and skin ply-orientation have great effects on aeroelastic performance and structural optimization. The two parameters should be considered emphatically in structure design, and there are many studies in this field recently[6].

In order to obtain satisfied results in aeroelastic structural optimization, it is key technology to select appropriate optimization methods. In the past, the optimization methods for the aeroelastic optimization studies focused on the conventional sensitivity-based algorithms, therefore, the researcher could only attain the local optimums based on initial design, and the analysis results were very limited. Recently, the authors and their co-researchers started the studies of genetic/sensitivity-based hybrid optimization algorithm for composite aeroelastic structures[7, 8], and the algorithm has been used in aeroelastic structural optimization of a forward-swept composite aircraft with medium aspect ratio. The application impact is satisfied.

The aeroelastic modeling and the corresponding calculation were performed on the high-aspect-ratio composite wings with different forward-swept angles and skin ply-orientation to analyze the effects of forward-swept angle and skin ply-orientation on the static and dynamic aeroelastic performance of the wings. Furthermore, in order to provide reference for aircraft overall design, the genetic/sensitivity-based hybrid algorithm was used for aeroelastic structural optimization of some wings to analyze the effects of forward-swept angle, skin ply-orientation and the power of spanwise variation function of lay-up thickness of skins and lugs on the optimized weights. The effects of geometric nonlinearity on aeroelastic analysis and optimization have not been considered because the bending and torsional deformations of the analysis objects were relatively small and the geometric nonlinearity was comparatively slight.

1 Formulations

The aeroelastic analysis method based on finite element method is performed on the basis of matrix decomposition, matrix combination and matrix transformation. In order to manage matrix operation conveniently, it is necessary to define the displacement vector sets, and assign the degree of freedom for every displacement vector sets. In fact, different displacement vector sets appear in different analysis stages.

1.1 Equation for static aeroelastic response

The basic equation of static aeroelastic response analysis[9, 10] is generally stated as follows:

$$(\boldsymbol{K}_{aa} - \bar{q}\boldsymbol{Q}_{aa})\boldsymbol{u}_a + \boldsymbol{M}_{aa}\ddot{\boldsymbol{u}}_a = \bar{q}\boldsymbol{Q}_{ax}\boldsymbol{u}_x + \boldsymbol{P}_a \quad (1)$$

where $\boldsymbol{K}_{aa}$ is structure stiffness matrix; $\bar{q}$ is dynamic pressure; $\boldsymbol{Q}_{aa}$ is aerodynamic influence coefficient matrix; $\boldsymbol{u}_a$ is displacement vector; $\boldsymbol{M}_{aa}$ is structure mass matrix; $\boldsymbol{Q}_{ax}$ is unit aerodynamic load matrix; $\boldsymbol{u}_x$ is vector of "aerodynamic extra point", which is used to define deflection of aerodynamic control surface and overall rigid body motion; $\boldsymbol{P}_a$ is vector of applied loads, *e. g.*, mechanical and thermal loads.

When the correlative derivation and calculation are performed by Eq. (1), the elastic aerodynamic derivatives and corresponding trim parameters can be obtained directly. The same goes for deformation, stress and strain of structure.

1.2 Equations for flutter and divergence

The *p-k* and *v-g* method are two common methods for flutter analysis, in which the *p-k* method is more suitable for optimization analysis, for the results acquired are closer to the experiments. The *p-k* flutter analysis method is stated as follows:

$$\left[\left(\frac{V}{b}\right)^2 p^2\boldsymbol{M}_{hh} + \frac{V}{b}p\boldsymbol{B}_{hh} + \boldsymbol{K}_{hh} - \frac{1}{2}\rho V^2\left(\boldsymbol{Q}_{hh}^{\mathrm{R}} + \frac{p}{k}\boldsymbol{Q}_{hh}^{\mathrm{I}}\right)\right]\boldsymbol{u}_h = 0 \quad (2)$$

where V is flow speed; b is reference chord length; p is eigenvalue; $\boldsymbol{B}$ is damping matrix; k is reduced frequency; subscript h is mode analysis sets $h-set$; subscript R is real part; subscript I is imaginary part.

The above equation can also be used to calculate divergence speed when the reduced frequency decreases to zero.

1.3 Mutidisplinary optimizaton

In the paper, the design studies are proved to be a standard problem in finding values of design variables $\boldsymbol{v}$ which

minimize

$$F(\boldsymbol{v}) \tag{3}$$

subject to

$$g_j(\boldsymbol{v}) \leqslant 0 \qquad j = 1, \cdots, n_c \tag{4}$$

$$(\boldsymbol{v}_i)_{\text{lower}} \leqslant \boldsymbol{v}_i \leqslant (\boldsymbol{v}_i)_{\text{upper}} \quad i = 1, \cdots, n_d \tag{5}$$

where $F(\boldsymbol{v})$ is an objective function which means the weight of the structure here. Eq. (4) is used to define the inequality constraints. Eq. (5) is used to specify the upper and lower bounds (side constraints) on each of the design variables.

The genetic/sensitivity-based hybrid algorithm was selected for design studies of aeroelastic structural optimization. Aimed at improving the global and local search capability, the hybrid algorithm combines the genetic algorithm and sensitivity-based algorithm. In the hybrid algorithm, the genetic algorithm is used to perform global search to avoid local optima and make the search direction point to excellent zone at the initial stage or after some generations, while the modified method of feasible directions algorithm is further used to fine-tune the excellent individuals of every generation optimized by genetic algorithm to achieve the local optima and further the global optima.

2 Model Description

The MSC/NASTRAN software was used to build the structural finite model and the corresponding aerodynamic model of the tri-spar high-aspect-ratio composite wings with different forward-swept angles and skin ply-orientation.

The models og high-aspect-ratio composite wings with different forward-swept angles and skin ply-orientation are similar in structure and layout. The authors built a model in detail at first, and on the basis of which the authors attained the models with other forward-swept angles and skin ply-orientation using coordinate transformation. In the design studies, only the thickness of composite lay-up of upside skin, downside skin and lugs of spars were selected as design variables.

2.1 Aerodynamic model

The five wings with forward-swept angles of 0°, 5°, 10°, 15° and 20° were built. The aerodynamic model of the wing with forward-swept of 0° is shown in Fig. 1. The subsonic double lattice method is used for aerodynamic calculation.

2.2 Structural finite element model

The structural finite element model of the wing with forward-swept angle of 0° is shown in Fig. 1. The structure is tri-spar form, which includes upside skin, downside skin, leading-edge skin, trailing-edge skin, spars, stringers and ribs. The wing is divided into inside wing and outside wing. The inside wing consists of the inside and outside parts.

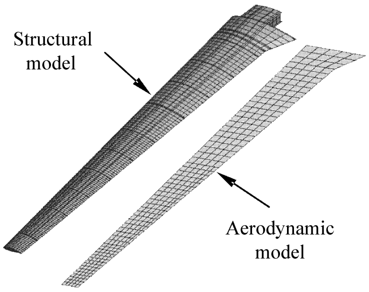

Fig. 1 Aerodynamic and structural finite element model

According to the criterion to build the model of high-aspect-ratio composite wings, the 3-D structural finite element models were used to simulate the left wing with different forward-swept angles and ply-orientation, in which the composite shell elements were used for all parts. The composite lamination shells for the wing were laid according to the following criterion.

(1) The thickness of the skins, the lugs, the webs and the stringers were decreased from wing root to wing tip.

(2) All the parts used symmetric balanced lamination shells including lay-up of 0°, 90° and ±45°.

(3) The thickness of lay-up of 0°, 90° and ±45° for the skins, the lugs and the stringers were

55%, 8% and 37% of the total thickness, while the scales for webs and ribs were 10%, 10% and 80%.

(4) For all the wings with different forward-swept angles, the ply-orientation of the upside and downside skins were coincident with the values of −10°, −5°, 0°, 5°, 10°, 15° and 20°. The ply-orientation was zero when the orientation of ply-up of 0° was parallel to the center line of the middle spar of the wing. The ply-orientation is positive when the lamination shells turn forward around the wing root.

3 Aeroelastic Analysis

In order to analyze the effects of forward-swept angle and ply-orientation on the static and dynamic aeroelastic characteristics, the aeroelastic analysis on the wings with different forward-swept angles and ply-orientation were performed in different flight cases.

3.1 Flutter and divergence analysis

The flutter and divergence characteristics of the wings with different forward-swept angles and ply-orientation were analyzed on the basis of the analysis results of normal modes of the wings fixed at the root. The first eight modes including the first torsional mode were selected for flutter and divergence analysis. The analysis results show that the divergence speeds are lower than the flutter speeds in all the cases, *i. e.*, the wings will be damaged due to divergence. The analysis results of the wing with ply-orientation of 0° and different forward-swept angles are shown in Fig. 2. The Fig. 3 includes the divergence analysis results of the wing with forward-swept angles of 0°, 5° and 10° in the case of different ply-orientations.

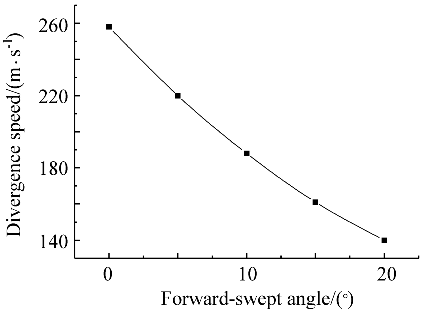

Fig. 2 Divergence speeds *vs*. forward-swept angles in the case of the same skin lay-up and ply-orientation

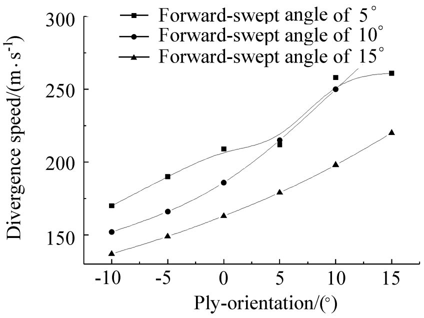

Fig. 3 Divergence speeds *vs*. skin ply-orientation in the case of the same skin lay-up and different forward-swept angles

It is clear from the variation of divergence speeds *vs*. forward-swept angles that the divergence speed will decrease with the forward-swept angle increasing. The reason is that the increase of forward-swept angle makes the bending-torsional coupling of the wings more intense and hence the in-wash more violent. The wing appear in-wash when the torsional angle is positive under the condition of upper bending deformation.

It could be found from the variation of divergence speeds *vs*. ply-orientation that the divergence speeds of the wings with the three different forward-swept angles will increase when the ply-orientation varies from −10° to 15° in the case of the same skin lay-up. The divergence speed decreases as compared with the case of ply-orientation of 0° due to the increase of in-wash when the ply-orientation is negative, while the divergence speed increases due to the decrease of in-wash when the ply-orientation is positive. Therefore, the divergence speed could be increased by reducing in-wash with the measure of increasing ply-orientation.

3.2 Static aeroelastic analysis

The elastic corrections of deformation and lift slope of the wings were analyzed on the request. The static aeroelastic results shown in the paper include the variation of the maximal vertical deformation of wing tips, the twist angles of wing tips and the ratios of elastic-rigid lifting curve slopes *vs*.

forward-swept angles and ply-orientation in the case of a typical load. The static aeroelastic analysis results of the wings with different forward-swept angles and ply-orientation of 0° are shown in Figs. 4-6, while the results of the wings with different ply-orientation and forward-swept angles of 5°, 10° and 15° in Figs. 7-9.

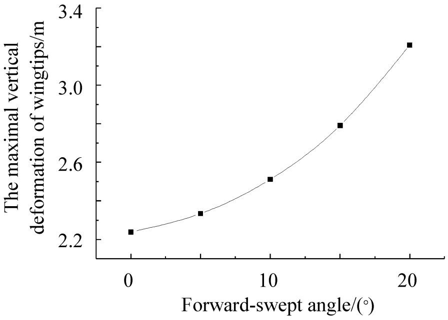

Fig. 4 The maximal vertical deformation of wing tips *vs*. forward-swept angles in the case of the same skin lay-up and ply-orientation

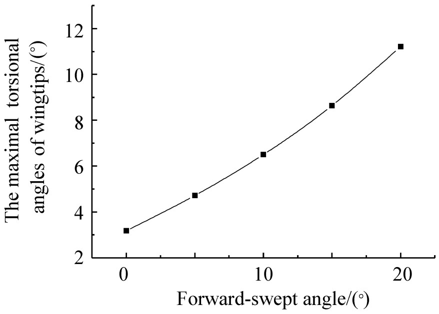

Fig. 5 The maximal torsional angles of wing tips *vs*. forward-swept angles in the case of the same skin lay-up and ply-orientation

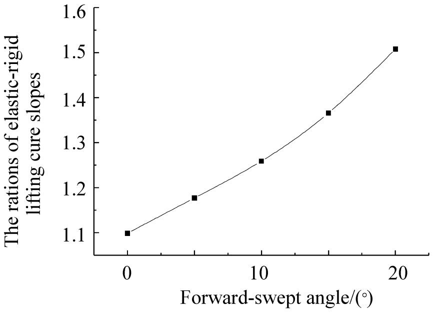

Fig. 6 The ratios of elastic-rigid lifting curve slopes *vs*. forward-swept angles in the case of the same skin lay-up and ply-orientation

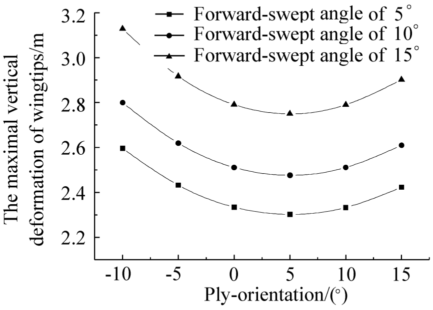

Fig. 7 The maximal vertical deformation of wing tips *vs*. skin ply-orientation in the case of the same skin lay-up and different forward-swept angles

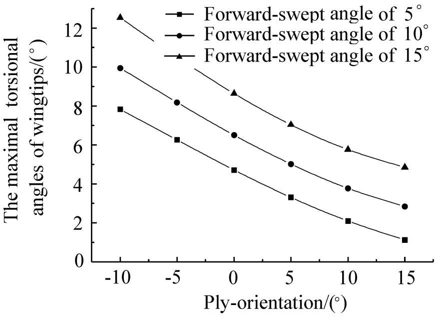

Fig. 8 The maximal torsional angles of wing tips *vs*. skin ply-orientation in the case of the same skin lay-up and different forward-swept angles

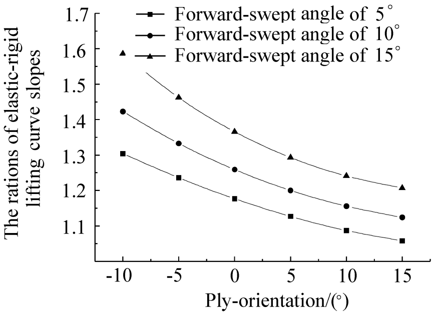

Fig. 9 The ratios of elastic-rigid lifting curve slopes *vs*. skin ply-orientation in the case of the same skin lay-up and different forward-swept angles

It is clear from the variations of the static aeroelastic characteristics *vs*. forward-swept angles that the maximal vertical deformation of wing tips, the maximal twist angles of wing tips and the ratios of elastic-rigid lifting curve slopes all increase when the forward-swept angle increases in the case of the same skin lay-up and ply-orientation.

It could be found from the variations of static aeroelastic characteristics *vs*. ply-orientation that the maximal vertical deformation of wing tips decrease at first and then increase with the lowest value appearing near ply-orientation of 5° in the case of the same skin lay-up when ply-orientation varies from − 10° to 15°, while both the maximal twist angles and the ratios of elastic-rigid lifting curve slopes decrease.

The further static and dynamic aeroelastic analysis results of the wings with different forward-swept angles and ply-orientation show that there is some inherent relationship among the divergence speed, twist angle and the ratio of elastic-rigid lifting curve slopes. The last two variation trends are the same, and contrary to the first one. It relates to the effect of forward-swept angle or ply-orientation on the bending-torsional coupling of the wing, *i. e.*, in-wash and out-wash.

4 Aeroelastic Optimization Design

The results of the former section show that the forward-swept angle and ply-orientation have great effects on the static and dynamic aeroelastic characteristics of the high-aspect-ratio composite wings. In order to meet the requirements on static and dynamic aeroelastic characteristics of high-aspect-ratio wings with different forward-swept angles and reduce the structural weight, the ply-orientation should be adjusted in design while the lay-up thickness should be designed through optimization. The genetic/sensitivity-based hybrid algorithm was used for aeroelastic structural optimization of the wings with several typical forward-swept angles and ply-orientation, while the lay-up thickness of upside skins, downside skins and lugs were acted as design variables.

4.1 Constraints

There were three constraints including flutter, divergence and static aeroelastic response in the aeroelastic design study. The flutter, divergence and static aeroelastic response only in symmetric flight condition were considered based on the design requirement. The constraints on the wing include strength, displacement, flutter speed and divergence speed, where the displacement constraints were used to limit the maximal vertical deformation and twist angle of the wing tip.

4.2 Design variables

It is clear from the results of sensitivity analysis and the characteristics of the structure to endure and transfer load that, the thickness of upside skin, downside skin and lugs are the primary parameters which have effects on total deformation, flutter speed and divergence speed. Therefore, the design variables were only used to control the thickness of upside skin, downside skin and lugs. In order to simplify the design, the lay-up for upside skin and downside skin were the same as well as the upside and downside lugs of each spar.

In order to meet the requirement of thickness variation of upside skin, downside skin and lugs as mentioned in the former section, the different linear functions were used to define the spanwise variation of the thickness of these parts, and eight design variables were defined. The former four design variables are initial thickness of lay-up of 0° of upside and downside skins! at wing tip, spanwise thickness increment of lay-up of 0° per unit length of outside wing skin, spanwise thickness increment of lay-up of 0° per unit length of outside part of middle wing skin, and spanwise thickness increment of lay-up of 0° per unit length of inside part of middle wing skin. The last four design variables are the above-mentioned parameters for lugs.

In order to meet the above-defined lay-up design criterion about the thickness scale of each lay-up, the initial thickness and thickness increment per unit length of other lay-up of upside skin, downside skin and lugs were linked with the above-mentioned parameters with linear function.

On the other hand, in order to improve the optimization efficiency and meet the technical requirement, the design variables were defined as continuum form prior to optimization, and then the thickness of each lay-up of every part were rounded off after the optimization.

4.3 The effects of forward-swept angle and ply-orientation on the optimized weight

The wings with forward-swept angles of 5°, 10°, 15°, and ply-orientation of − 5°, 0°, 5°, 10°, 15°, were optimized. The optimization results are shown in Fig. 10 and Fig. 11. Fig. 10 shows the variation of optimized weights of the wings with different forward-swept angles *vs*. ply-orientation, and Fig. 11 shows the variation of optimized weights *vs*. forward swept angles. Here, the optimized weights with a certain forward-swept angle used the minimal values in the case of different ply-orientation and forward-swept angles.

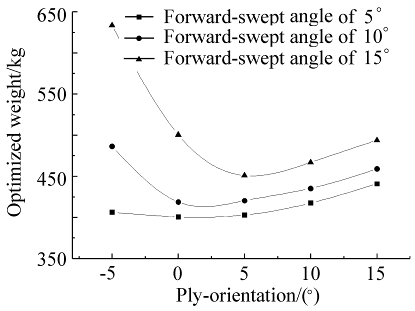

Fig. 10 The optimized weights *vs*. skin ply-orientation in the case of different forward-swept angles

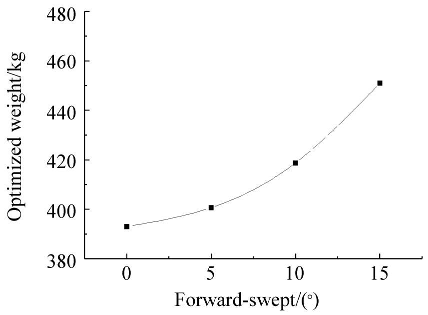

Fig. 11 The optimized weights *vs*. forward-swept angles

The optimization results show that the final optimized weights increase with forward-swept angle increasing, and the sensitivity of the final optimized weights with respect to ply-orientation also increase. The results also demonstrates that, for the cases of different forward-swept angles, the lowest or approximatively lowest optimized weights could be attained when ply-orientation is close to zero, and the optimized weight could be reduced by increasing ply-orientation when forward-swept angle increases.

In order to analyze the reason of the above results, Table 1 presents the hardest-satiated constraints in the case of different forward-swept angles and ply-orientation. Here, the symbol of "DEF" stands for the maximal displacement at the wing tip, "DIV" for divergence, "FSA" for forward-swept angle and "PO" for ply-orientation.

Table 1 The hardest-satiated constraints in the case of different forward-swept angles and skin ply-orientations

PO FSA	− 5°	0°	5°	10°	15°
5°	DEF	DEF	DEF	DEF	DEF
10°	DIV	DEF	DEF	DEF	DEF
15°	DIV	DIV	DEF	DEF	DEF

On the basis of the analysis results in Table 1 and the variation trends of divergence speeds and the maximal vertical displacement at wing tips *vs*. forward-swept angles and ply-orientation in Section 3, it could be found that, it is propitious to increase divergence speed when the ply-orientation is changed from negative to positive, while the deformation at wing tip will increase when the ply-orientation is changed from zero to negative or positive. Therefore, the difficulty degree to satiate displacement constraints and divergence constraints are different for the cases of different forward angles. In a word, the hardest-satiated constraint is changed from displacement constraint to divergence constraint with forward-swept angle increasing, and that is the reason for the above variation trends of optimized results *vs*. forward-swept angle and ply-orientation.

4.4 The effect of spanwise variation form of lay-up thickness on optimized weight

In order to study the effects of spanwise variation form of lay-up thickness on optimized results, optimizations of the wings with forward-swept angle of 0° and ply-orientation of 0°, and different spanwise variation forms of lay-up thickness for skins and lugs were performed. The spanwise variation forms of lay-up thickness of upside skin, downside skin and lugs for middle wing and outside wing include: ① linear form, ② quadric form, and ③ cubic form. The detail spanwise variation trends of lay-up are shown bellow.

The thicknesses of upside skin, downside skin and lugs vary from wing tip to wing root according to the following equation

$$t_{ij} = a_{ij}x^k + b_{ij}$$

where t_{ij} is lay-up thickness; $i = 1, 2$, indicating outside wing and middle wing, respectively; $j = 1, 2$, standing for skin and lug, respectively; $a_{ij} \cdot x^k$ is increment per unit length along contrary spanwise direction; b_{ij} is lay-up thickness at the wing tip ($i = 1$) or inside lay-up thickness of outside wing ($i = 2$); the subscript k is function power, $k = 1, 2, 3$, standing for linear form, quadric form and cubic form, respectively.

The optimized weights of the wings with different spanwise variation forms of lay-up thickness are shown in Fig. 12, where the x-coordinate is the k power of variation function of lay-up thickness. The analysis results show that the optimized weight of the wing in the paper will increase when the power of spanwise variation function of lay-up thickness increases. Therefore, the linear form is appropriate for spanwise variation function of skin lay-up thickness, and the increase of the function power could lead to structural weight increasing and make machining technics more difficult.

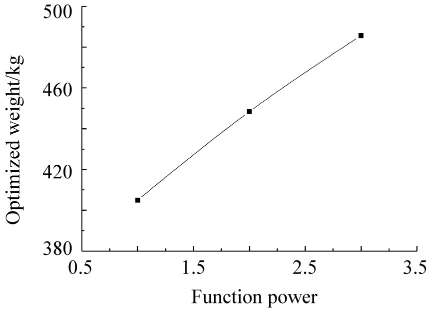

Fig. 12 The effects of power of spanwise variation function of lay-up thickness of skins and lugs on the optimized weights

5 Conclusion

For the tri-spar structure with above-mentioned lay-up, the following conclusions are drawn by the aeroelastic analysis results of high-aspect-ratio composite wings with different forward-swept angles and ply-orientation, and the corresponding aeroelastic optimization results using genetic/sensitivity-based hybrid optimization algorithm.

(1) In the case of the same lay-up and ply-orientation, the divergence speed decrease with the increase of forward-swept angle, while the maximal vertical deformation of wing tip, the maximal twist angle and the ratio of elastic-rigid lifting curve slopes increase.

(2) In the case of the same forward-swept angle and lay-up, the divergence speed of the wing increase when ply-orientations vary from negative to positive, while the maximal vertical deformation decrease at first and then increase, however, the maximal twist angle and the ratio of elastic-rigid lifting curve slopes decrease.

(3) Both the final optimized weight and its sensitivity with respect to ply-orientation increase with forward-swept angle increasing. Therefore, the forward-swept angle of the high-aspect-ratio composite wing should not be too large, otherwise, it will cost structural weight.

(4) The ply-orientation should be near zero when forward-swept is relative small, while ply-orientation should be increased to reduce the optimized weight when forward-swept angle is relative large, however, it should not be too large.

(5) It is relative appropriate when the power of spanwise variation function of lay-up thicknesses of skins and lugs equals to one. The increase of power will result in the increase of structural weight and complexity of process techniques.

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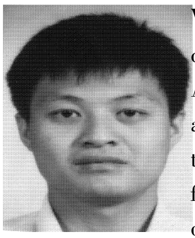
Biographies:



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