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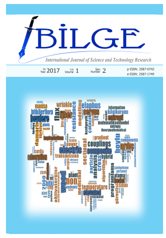

Optimization of Composite Couplings in Helicopter Rotor Blade Spar Using Hybrid Particle Swarm-Gradient Algorithm

H. Arıol Taymaz[1]*

Abstract: Modern helicopter rotor blades are made of advanced composite material due to higher stiffness/mass ratio, superior fatigue characteristic along with capability of aeroelastic tailoring. In composite materials, circumferentially uniform stiffness (CUS) and circumferentially asymmetric stiffness (CAS) layup configurations, which offer convenience in terms of production methods, are widely used in the design of fiber angles. However, the purpose of this study is to test the possibility of achieving better results with an active modification without CUS and CAS distributions. When the gradian based classical methods are tested, the results are the same as the CUS and CAS distributions. It is a fact that gradient-based optimization algorithms were quite popular in the years when computers had not been so powerful yet. Furthermore, the hybrid particle swarm-gradient algorithm by means of C#, VABS, Abaqus, MATLAB proposes better results on the composite couplings of blade spar such as extension torsion, lead-lag torsion and flap torsion.

Keywords: Composite couplings; VABS cross-sectional analysis; Hybrid particle swarm-gradient algorithm

1. Introduction

Around the 400 BC, the first vertical flight was seen in Chinese children's bamboo flying toys. In 1480s, Leonardo Da Vinci presented some invention such as aerial screw-helicopter, ornithopter that gives inspiration today flight systems. Tremendous changes have been recorded by ambitious researchers since those days. Aerial screw could only make vertical movements whereas today's helicopters have multidirectional capability owing to rotor blades aeroelastic, aerodynamic and material properties' cumulated knowledge.

According to researchers' studies for maximizing helicopters performance, it is seen that the major role is rotor blades talents. Ganguli (2013) described the research papers starting with the first paper on optimal design of composites by Khot et al. (1973) as "pioneering research", the 1980s as "early research", the 1990s as "moving towards design", the 2000s as "the new century" and from 2010 to present as "current research". In pioneering research duration, objectives and constraints were related with weight, strain energy distribution, frequency, epoxy matrices and fibers, panel buckling, strength, displacement and ply angles distribution and laminate design (Bert, 1977; Starnes and Haftka, 1979). However, computers performance did not satisfy sufficient conditions to optimize mentioned parameters realistically. In early research period, mathematical programming algorithms began to appear in aerospace engineering field and laminated composite application rules were improved with new approaches for discrete and continuous type of design variables, constraints and objectives (Schmit and Fleury, 1980; Nshanian and Pappas, 1983).

Along with 1990's a huge development took place in computer science. With this improvement, objectives and constraints was expanded and classical optimization techniques such as Taylor series, polynomial and interpolation approximation gained importance in aerospace calculations (Venter et al., 1998). Also, heuristic studies such as genetic algorithm also was becoming prominent in aerospace field. Nagendra et al. (1996) and Kodiyalam et al. (1996) started to utilize heuristic algorithms to reach discrete variables and global

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optimum values. Meanwhile, multiple objectives, and constraints were being combined and the combined functions were more successful in comparison to previous researches. In the new century period, computer performances have reached great capability to calculate more complex optimization models with stochastic algorithms in less time. The algorithms, which has been inspired from nature, such as genetic algorithm and particle swarm optimization techniques are useful in avoiding local minima. Also, Apalak et al. (2014) applied the artificial bee colony(ABC) algorithm, a new approach for optimizing numerical problems, in layer optimization. In the current research period, different failure criteria have been observed such as Tsai-Wu, maximum stress and failure mechanism based (FMB) in the field (Satheesh et al., 2009; Banos et al., 2011).

Sarangapani and Ganguli (2013) have explained that robust design, one of the most important issue of composites, is related to unwanted uncertainty in the ply angles and thicknesses. According to the study, the reason of unwanted uncertainty is undesirable couplings in laminates designed without regarding couplings. Mentioned uncertainties must be taken into account throughout the design process.

This study benefitted from a hybrid particle swarm-gradient algorithm in MATLAB in order to optimize the composite couplings. Particle swarm, stochastic population-based algorithm, has advantages of wide scanning solution space whereas the gradient based algorithms can reach accurate results in the vicinity of a starting point. Gradients based methods can find one of the local minimums and stop the optimization process and thus prevent reaching global minimum. The particle swarm algorithm uses a learning algorithm which calculates particles new points in the search space with particles' best and population-global best values. In the hybrid algorithm, particle swarm velocity vector is calculated as a gradient descent instead of the learning algorithm. Thus, the hybrid algorithm has the advantages of both methods to reach global best solution.

2. Composite Rotor Blades Structural Analysis

The helicopter rotor system, shown in Figure 1, gives the helicopter lift and land ability. According to principle of helicopter operation, the main load carrying component is the rotor blades. To reach structural analysis result of rotor blades, VABS and Abaqus are used. VABS uses material properties and mesh coordinates of blade cross-sections, see Figure 2 to calculate stiffness matrix which then can be used to estimate material behaviors like extension torsion, lead-lag torsion and flap torsion couplings. VABS generates Timoshenko stiffness matrix with the asymptotic energy.

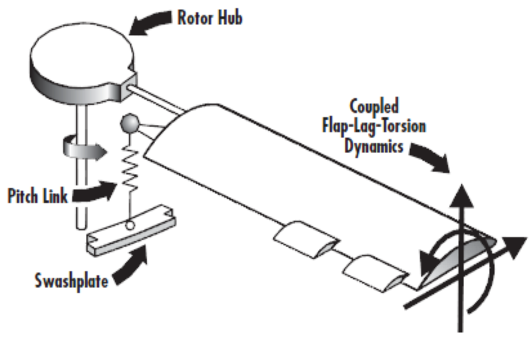


Figure 1. Helicopter rotor system (Glaz et al., 2006).

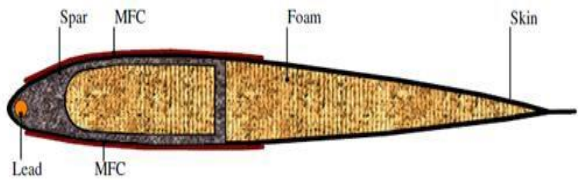


Figure 2. Blade cross-section (Kovalovs et al., 2007).

In order to optimize the helicopter rotor blade performance, cross-sections of the box beam, which is composed of laminated composite plies, must be examined. The layered structure of laminated composite plies is given in Figure 3.

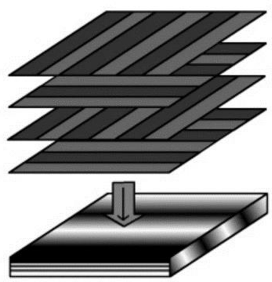


Figure 3. Laminated composite plies (Williams, 2017).

Researchers benefitted from circumferentially uniform stiffness (CUS) and circumferentially asymmetric stiffness (CAS) composite layup configurations for a thin-walled beam (Berdichevsky et al., 1992; Chun et al., 2006; Warminski et al., 2014; Beshay et al., 2015; Fu et al., 2015), given Figure 4, first presented by Rehfield and Atilgan (1989).

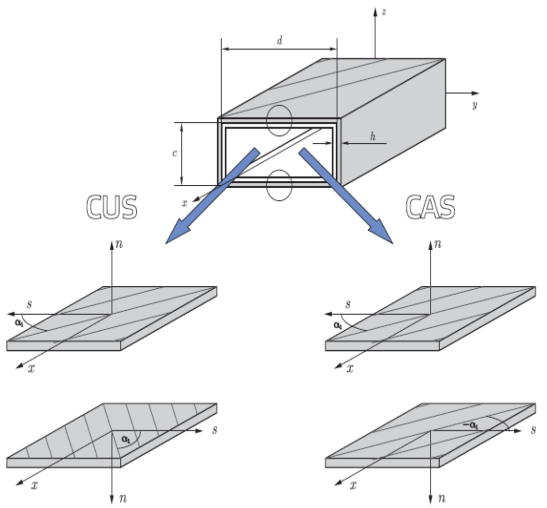


Figure 4. Laminate configurations frequently encountered in structural composite design (Warminski et al., 2014).

CUS configuration is convenient for minimizing extension torsion coupling in flanges and webs of the box beam and CAS configuration is preferred for lead-lag and flap torsions to decrease bending coupling effect. For the sake of simplicity in lead-lag torsion flanges ply angles and in flap torsion web ply angles are assumed as zero. In this study, all mentioned coupling types are tested without any restriction as opposed to frequently used ply angle distributions.

3. Methods of Computation/Operations Research

In optimization loop, in each iteration/evaluation; new mesh coordinates of new geometries must be calculated for VABS input file to reach stiffness matrix. Therefore, in each iteration/evaluation; VABS and Abaqus must be run. A mesh update is needed because the geometry parameters change in each generation/iteration during the optimization process. This is achieved by developing a script code for Abaqus that exports new mesh coordinates, using Python language. Because Abaqus runs on script code without the graphical user interfaces, optimization loop can avoid consuming computer resources by the graphical processes. Hence, a code implementation is written with C#, which is a strong and generic programming language, to integrate Abaqus, VABS and optimization loop to calculate objective function with new stiffness matrix for each iteration.

In each iteration/evaluation MATLAB calls this code implementation, which is shown in optimization loop and given in Figure 5. MATLAB m-file includes optimization algorithms options such as algorithm type, upper bounds, lower bounds, plotting options.

MATLAB optimization toolbox provides hybrid solution with particle swarm and gradient-supplied techniques for user to benefit from the advantages of both stochastic and deterministic classical methods. To elaborate on the definitions, *MATLAB-fmincon* is a gradient-based method which is useful for objective and constraints functions only when the functions are both continuous and also first derivatives are not discrete. Because the gradient-based methods need continuous objective and constraints, local optimum is the inevitable result. The second solution; particle swarm is a stochastic algorithm that optimizes objective function trying to iteratively reach better candidate solutions with regard to a given measure of quality for objective and constraints and can be used for both the discrete and continuous functions. Particles move to new position with a velocity which is influenced by the particles' local best and global best values known. In the aforementioned hybrid solution, velocity is calculated as a gradient descent vector. Although, stochastic algorithms can scan a very large area of solution space, they do not guarantee an optimal solution.

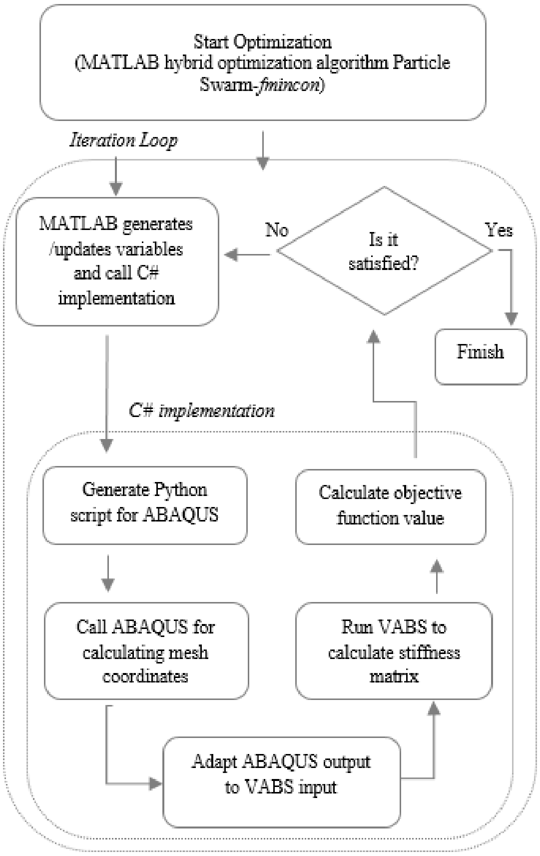


Figure 5: Flowchart of optimization loop.

The 4x4 classical stiffness matrix includes extension, twist and bending deformations whereas 6x6 Timoshenko stiffness matrix, illustrated in Eq. 1, is more accurate because of containing shear deformations as well. (Yu, 2013).

$$\begin{Bmatrix} F_1 \\ F_2 \\ F_3 \\ M_1 \\ M_2 \\ M_3 \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{12} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{13} & S_{23} & S_{33} & S_{34} & S_{35} & S_{36} \\ S_{14} & S_{24} & S_{34} & S_{44} & S_{45} & S_{46} \\ S_{15} & S_{25} & S_{35} & S_{45} & S_{55} & S_{56} \\ S_{16} & S_{26} & S_{36} & S_{46} & S_{56} & S_{66} \end{bmatrix} \begin{Bmatrix} \gamma_{11} \\ 2\gamma_{12} \\ 2\gamma_{13} \\ K_1 \\ K_2 \\ K_3 \end{Bmatrix} \quad (1)$$

Each type of couplings is handled separately as extension torsion, lead-lag torsion, flap torsion by objective functions β_{14}, β_{46}, β_{45} respectively. To minimize couplings, in other words maximizing objective functions, 6x6 Timoshenko stiffness matrix is quite necessary. Also, the optimization algorithms tend to minimize as it is usually the norm, so the objective function is multiplied by minus one for maximization.

In optimization model benefitted from XV-15 rotor blade spar geometry and material properties, given in Table 1.

Table 1. Material properties of AS4/3501-6 graphite epoxy (Jung et al., 2002).

Property	Dimension
ρ (kg/m^3)	1603
E_1 (N/m^2)	1.42 x 10^{11}
E_2 (N/m^2)	9.8 x 10^9
E_3 (N/m^2)	9.8 x 10^9
G_{12} (N/m^2)	6 x 10^9
G_{13} (N/m^2)	6 x 10^9
G_{23} (N/m^2)	4.83 x 10^9
v_{12}	0.42
v_{13}	0.42
v_{23}	0.5

Optimization variables are box beams width(x_1), height(x_2), and thickness (x_3, x_4) and 16 ply angles. From the inside out x_5, x_6, x_7, x_8 are top wall ply angles, x_9, x_{10}, x_{11}, x_{12} are left wall ply angles, x_{13}, x_{14}, x_{15}, x_{16} are bottom wall ply angles and x_{17}, x_{18}, x_{19}, x_{20} are right wall ply angles.

Objective function for extension torsion

$$\beta_{14} = S_{14}/\sqrt{(S_{11} * S_{44})} \quad (2)$$

Objective function for Lead-Lag Torsion

$$\beta_{46} = S_{46}/\sqrt{(S_{44} * S_{66})} \quad (3)$$

Objective function for flap torsion

$$\beta_{45} = S_{45}/\sqrt{(S_{44} * S_{55})} \quad (4)$$

Constraints for all torsion types

$0.20 \geq x_1 \geq 0.12$ *(meter)*

$0.10 \geq x_2 \geq 0.06$ *(meter)*

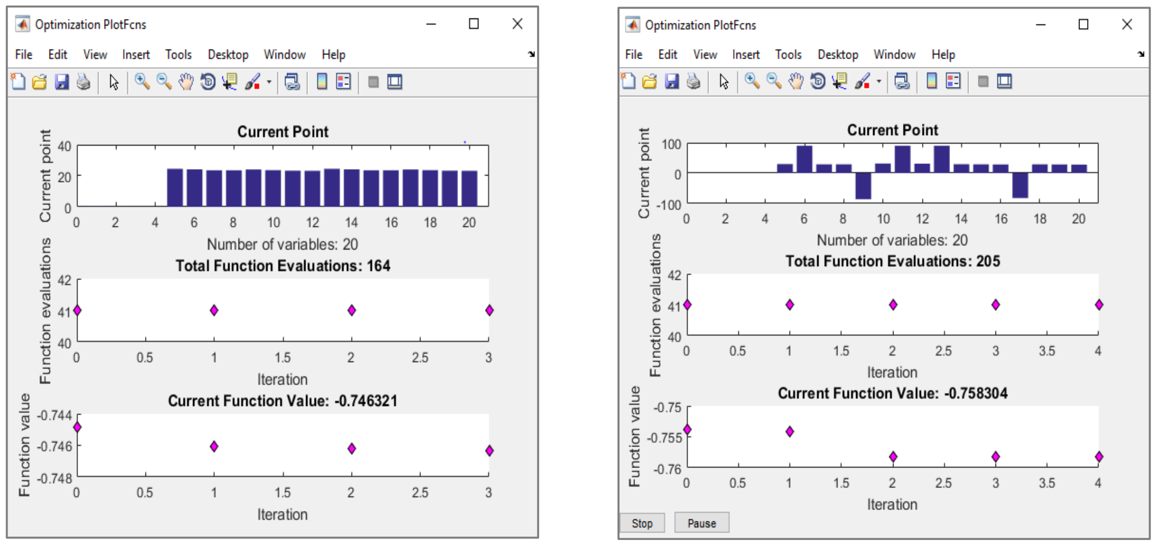
$0.20 \geq x_3, x_4 \geq 0.12$ *(meter)*

$90 \geq x_5, \ldots, x_{20} \geq -90$ *(θ)*

4. Result and Discussion

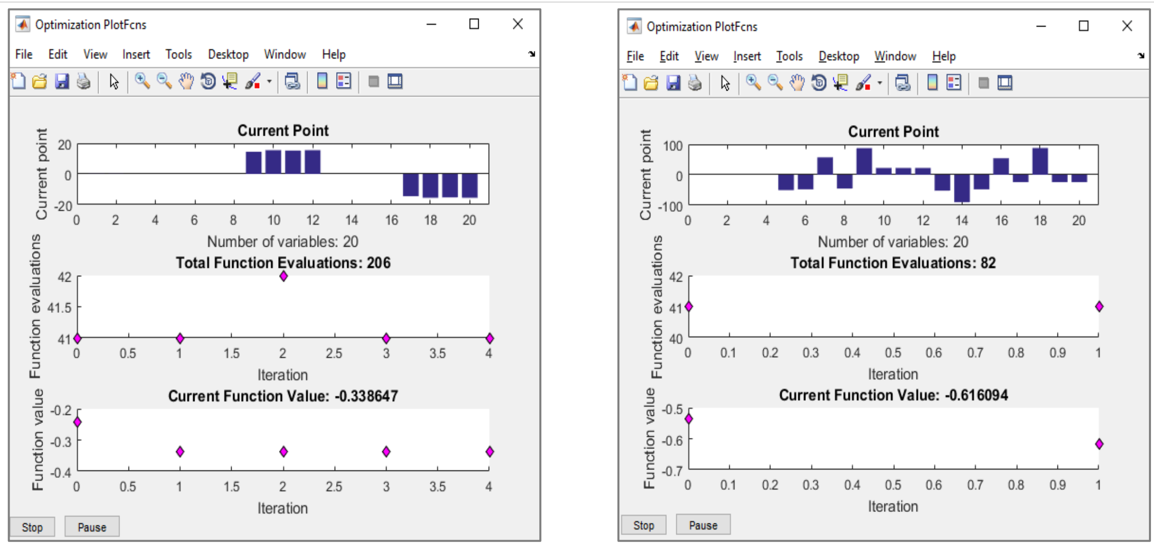
Upon analyzing the results, CUS-CAS layup approach and *fmincon* give almost identical outcomes and hybrid solver produces a much better objective function value than them. This study presents that symmetrical-balanced layup approach calculated with gradient-based algorithm results in a grind to a halt in local optima. After all, stochastic and hybrid algorithms are preferable alternatives to reach global optimum solution. The comparison of gradient based algorithm with stochastic method results are given in Figure 6, Figure 7 and Figure 8.

In extension torsion coupling optimization, no significant improvement has been observed, given results Figure 6a, Figure 6b. Even gradient based *fmincon* has given almost the same result as CUS, see Figure 6a. Hybrid algorithm gives a remarkably better result in lead-lag torsion optimization, nearly double the improvement on coupling minimization. In the case of lead-lag torsion CAS layup and *fmincon* gives similar results as in extension torsion. The benchmark results are shown in Figure 7a, Figure 7b.



a) b)

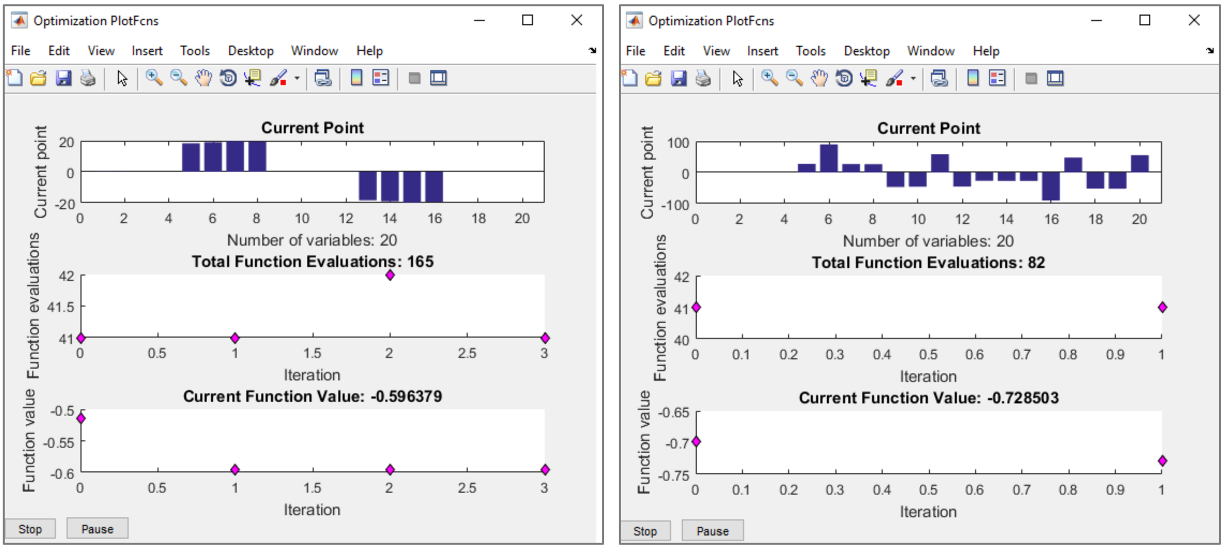
Figure 6. Extension torsion results. **a**) *fmincon*, **b**) Hybrid algorithm.



a) b)

Figure 7. Lead-Lag torsion results. **a**) *fmincon*, **b**) Hybrid algorithm.

In the flap torsion coupling, *fmincon* and CAS layup produce identical results like other coupling types. Hybrid solver, combined stochastic and deterministic algorithms, yields 20% improvement in flap torsion coupling, the outcomes are given in Figure 8a and Figure 8b.



a) b)

Figure 8: Flap Torsion Results. (**a**) *fmincon*, (**b**) Hybrid Algorithm

As a consequence of this study, hybrid algorithm produces global solution despite the fact that gradient based *fmincon* gives local optimum. Hence, hybrid of deterministic and stochastic techniques is an efficient alternative solution for both of them, the summary of optimization results is shown in Table 2. Also, hybrid optimization algorithm, free layup angle distribution and developing composite manufacturing techniques provides better solution for maximizing performance of helicopter rotor.

Table 2. The comparison of algorithms results

	Extension Torsion		**Lead-Lag Torsion**		**Flap Torsion**	
Variables	***fmincon***	***Hybrid***	***fmincon***	***Hybrid***	***fmincon***	***Hybrid***
x1[*]	0.2	0.2	0.12	0.12	0.2	0.2
x2[**]	0.1	0.06	0.1	0.1	0.06	0.06
x3[§]	0.002	0.002	0.0026	0.003	0.0021	0.002
x4[§§]	0.002	0.002	0.002	0.002	0.003	0.003
x5[¶]	24.5	29.6	0.0	-50.3	18.4	27.5
x6[¶]	24.2	90.0	0.0	-47.8	19.0	90.0
x7[¶]	23.5	29.0	0.0	57.4	19.7	27.0
x8[¶]	23.5	28.7	0.0	-45.4	19.4	26.9
x9[¶¶]	24.1	-85.6	14.5	87.3	0.0	-46.5
x10[¶¶]	23.6	31.4	15.6	22.3	0.0	-45.9
x11[¶¶]	23.3	90.0	15.2	22.4	0.0	58.6
x12[¶¶]	23.2	31.2	15.5	22.3	0.0	-45.3

x13‡	24.5	90.0	0.0	-52.0	-18.4	-26.7
x14‡	24.2	29.3	0.0	-89.9	-19.0	-27.0
x15‡	23.5	28.8	0.0	-48.0	-19.7	-27.3
x16‡	23.5	28.3	0.0	54.4	-19.4	-90.0
x17‡‡	24.1	-82.0	-14.5	-24.0	0.0	47.7
x18‡‡	23.6	29.0	-15.6	87.9	0.0	-51.9
x19‡‡	23.3	28.5	-15.2	-24.2	0.0	-52.1
x20‡‡	23.2	28.1	-15.5	-24.3	0.0	55.7
F(x)&	**-0.746**	**-0.758**	**-0.338**	**-0.616**	**-0.596**	**-0.728**

(*width, ** height, § flange thickness, §§ web thickness, ¶ top wall ply angles, ¶¶ left wall ply angles, ‡ bottom wall ply angles, ‡‡ right wall ply angles, & objective function value)

5. Conclusion

The summary of this paper, stochastic methods' wide scanning ability and gradient-based methods' less time and accuracy advantages are combined to attain global solution of helicopter rotor blade performance. Also, free layup angles approach gives better solution than CUS and CAS laminate distribution, given in Figure 6. The effect of both the optimization technique and the free angle distribution is great in achieving much better compared to the initial design. The optimized results of a carbon fiber reinforced polymer(CFRP) box-beam show that the couplings of lead-lag torsion and flap-torsion increase almost 100% and 20% respectively, by the hybrid algorithm.

In order to reach realistic solution in design process, the optimization model of the helicopter rotor blade performance should be expanded with aeroelastic and aerodynamic parameters, constraints and objective functions and the hybrid of stochastic and gradient based algorithms should be used in the blended model.

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