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Survey of Recent Developments in Rotorcraft Design Optimization

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Introduction

ROTORCRAFT engineering is highly interdisciplinary because the flexibility of the main rotor blades couples with the aerodynamics, dynamics, and control system. In addition, interaction between the rotor and fuselage further complicates helicopter system predictions. The multidisciplinary nature of the helicopter engineering problems has led researchers to investigate formal optimization methods for the design process. Applications of formal optimization methods for helicopter problems started in the early 1980s. Miura[1] provided a review of some of the early work on application of numerical optimization to helicopters. Friedmann,[2] Adelman and Mantay,[3] and Celi[4] provide further reviews of helicopter optimization. Sobieszczanski-Sobieski and Haftka[5] give a review of recent developments in multidisciplinary design optimization for aerospace problems and Gieseng and Barthelemy[6] provide an industrial perspective of multidisciplinary optimization research.

Whereas considerable studies have been conducted on helicopter design optimization, several issues have prevented it from becoming as popular or successful as structural optimization. Many finite element-based design packages today have builtin optimization capacity. However, the predictive capacity of even the most sophisticated helicopter aeroelastic analysis codes remains quite poor, as evidenced in a recent study by Hansford and Vorwald,[7] where hub load predictions from several codes are compared with flight-test data. In addition, because of the nature of helicopter problems, comprehensive aeroelastic codes are highly multidisciplinary and very difficult to understand and alter except by domain experts. This is because of the complexity of the physical modeling. For example, as the blade moves over one revolution, it encounters transonic flow, reverse flow, stall, and unsteady effects including dynamic stall. Large azimuthal variations in lift result from changes in dynamic pressure and angle of attack. The trailed and shed vortices leaving the blade result in a nonuniform wake. Besides these aerodynamic problems, the rotor blade is also long and slender and undergoes substantial elastic deformations, which requires moderate and large deflection theories for accurate structural modeling. Strong structural nonlinearities such as Coriolis forces and radial shortening make the helicopter analysis problem a nonlinear aeroelastic problem. Indeed, helicopter aeroelasticity remains a difficult and complicated problem. Bousman mentions several reasons, including engineering as well as cultural ones, for the poor vibration prediction capability of helicopter aeroelasticity.[8]

Another problem is the enormous computer time needed by aeroelastic analysis, especially when free-wake aerodynamic or aeroelastic stability calculations are included. This problem is increased to an even greater extent when aeromechanical stability is considered. Efforts to use computational fluid dynamics (CFD) analysis for predicting aerodynamic loads can further increase the computer time needed. Therefore, many nongradient methods, such as genetic algorithms, are difficult to apply to rotorcraft problems. The recent review by Celi,[4] discusses the algorithmic aspects of helicopter design optimization. He mentions that the predictions of optimization studies are suspect because of the poor predictive capability of aeroelastic analysis. However, he also points out that, in the experiments conducted to verify optimization results, a reduction in the desired objective function such as vibration has always been found. This shows that, although aeroelastic analyses may not accurately predict the absolute values of vibration and other helicopter system properties, they capture the essential physics of the problem and, therefore, the relative changes in the design between the baseline and the optimum design may be more reliable than the absolute values themselves. A study by Ganguli et al.[9] has shown that, whereas

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the loads are underpredicted by as much as 50% with even sophisticated aerodynamic modeling of the wake and unsteady flow, the relative reduction in load due to changes in mass and stiffness properties are adequately captured by present day aeroelastic analyses.

In this review, selected studies are discussed in detail along with their design predictions. The main objective of this paper is to present the current state of the art in the field of optimization as applied to rotorcraft. For convenience, the paper is divided into the following parts: 1) early studies, which laid the foundations in terms of objective functions, constraints, design variables, and formulation of the optimization problems that are still widely used in rotorcraft optimization today, 2) composite rotor optimization, 3) advanced geometry rotor optimization, 4) optimization in flight mechanics, 5) optimization for aeromechanical stability, 6) tilt rotor applications, 7) nongradient methods, 8) smart rotor optimization, 9) response surface methods, and 10) other recent studies. This classification is not crisp but fuzzy because some studies can fall under more than one category.

Early Studies

Some of the early pioneering studies are discussed. For convenience, we define all work published before 1995 as early studies.

In the early 1970s, Bielawa[10] considered minimum weight design problem for a helicopter rotor in hover. In the early 1980s, Bennett[11] considered minimizing vertical hub shear due to blade flapping. Peters et al.[12] used rotor blade frequency placements for vibration reduction. The optimization problem was solved using CONMIN.[13] This study addressed an articulated rotor, and a weight reduction of 26% was obtained.

Santhakumaran and Friedmann[14] considered a four-bladed hingeless rotor, attached to a rigid fuselage. The objective function minimized in this study was the vibratory vertical hub shear and the vibratory hub rolling moments. The design variables were the cross-sectional dimensions of the rotor blade modeled as a box-beam spar and nonstructural mass. Constraints were imposed on blade frequencies and aeroelastic stability. The aeroelastic stability constraints were applied in hover. Results were obtained at an advance ratio (nondimensional forward speed) of $\mu = 0.3$. The effect of coupling between blade response and the trim solution was not considered. The optimization problem was solved using new sequential unconstrained minimization technique (NEWSUMT),[15] a constrained optimization program based on the extended penalty function and Newton's method with approximate second derivatives. Numerical results showed a reduction in the 4 per revolution vertical hub shear of 15–40%. Results also showed that the choice of reducing vibration at a moderately high advance ratio ($\mu = 0.3$) also yielded reductions in the 4 per revolution hub shear at intermediate advance ratios.

The authors[14] pointed out that the computer time needed to run the optimization was excessive, and the optimization had to be performed in an interactive manner. During the 1980s computer time was a much more precious commodity than it is today. Therefore, attempts were made by researchers to address the computer time issue to make helicopter optimization more practical. Researchers addressed the computer time issue by three broad approaches: 1) analytical sensitivity analysis, 2) approximation methods, and 3) simple modeling.

Lim and Chopra[16–19] addressed the computer time issue using analytical sensitivity derivatives. The optimizer CONMIN[13] was used. Besides sensitivity analysis, the other contributions of this study were 1) the use of a coupled trim analysis that simultaneously solved the blade response and the helicopter trim equations, 2) the use of the concept of infeasible starting design to use the optimization process for increasing blade stability, and 3) the development of an objective function that included all three hub forces and three hub moments for a four-bladed rotor:

$$J = K_F\sqrt{\left(F_{xH}^{4P}\right)^2 + \left(F_{yH}^{4P}\right)^2 + \left(F_{zH}^{4P}\right)^2} + K_M\sqrt{\left(M_{xH}^{4P}\right)^2 + \left(M_{yH}^{4P}\right)^2 + \left(M_{zH}^{4P}\right)^2}$$

It was found that values of K_F and K_M could be selected to be one. Numerical results were obtained using blade flap, lag and torsion stiffness, and nonstructural mass and its offset from the elastic axis as design variables. The blade was discretized using five finite elements, and the design variables were defined at each element. Results were obtained at an advance ratio $\mu = 0.3$ and showed a reduction in the objective function of 20–50%.

Weller and Davis,[20] Davis and Weller,[21] and Weller and Davis[22] considered simpler approaches to reduce rotor vibration. By using less sophisticated analytical models, they reduced the computer time needed. They considered the problems of 1) maximization of bearingless rotor structural damping, 2) blade natural frequency placement, 3) minimization of hub modal shear, and 4) minimization of modal vibration indices. They found that reducing vibration indices was an effective approach to reduce vibration. Results showed a 40–70% reduction in vibration indices with blade flap, lag stiffness, and blade mass at 11 spanwise stations used as design variables. Weller and Davis[20,22] performed an experimental study to verify their computational results. They used 19 blade model configurations and three baseline designs. The largest vibration reductions (30–44%) are obtained at the higher range of advance ratios ($0.3 < \mu < 0.4$).

Celi and Friedmann[23] used a Taylor's series approximation of the objective function and constraints in terms of design variables and an approximation technique introduced by Vanderplatts.[24,25] They used an implicit aerodynamic formulation and developed an aeroelastic analysis for swept tip blades.[26,27] They carried out an optimization study to minimize the vibratory vertical hub shear for a hingeless rotor blade with both straight and swept tips. Constraints were imposed on frequency placement and blade stability in hover. The optimization problem was solved using CONMIN.[13] A reduction of 20–50% in the 4 per revolution vertical hub force was obtained. Using sweep angle as a design variable gave an additional vibration reduction of about 10%.

Celi[28] included flight mechanics as well as rotor dynamics and aeroelasticity constraints. The objective function was the real part of the complex-conjugate pair of eigenvalue corresponding to the phugoid mode in forward flight at the advance ratio of $\mu = 0.3$. This study was motivated by the fact that forward flight is destabilizing for the phugoid mode in a hingeless helicopter rotor, even in the presence of a horizontal tail. Design variables were torsional stiffness, offset between aerodynamic center and elastic axis of the blade, and offset between the center of mass and elastic axis. Constraints were imposed on aeroelastic stability, blade root loads, and cyclic pitch response. Celi[28] introduced the aeroelastic stability constraint in forward flight, with the reasoning that cross-sectional offsets of the aerodynamic center and center of mass from the elastic axis has a destabilizing effect on forward flight for both soft and stiff in-lane rotors. Therefore, he replaced the aeroelastic stability constraint in hover in earlier studies[23] with that in forward flight. Blade root load constraints were placed on maximum peak-to-peak flap bending moments and torsion bending moments so that they do not increase more than a predetermined fraction from their baseline value.

Approximation concepts were used, and CONMIN[13] was used to solve the optimization problem. Celi[28] showed that it is possible to design both soft and stiff in-plane hingeless rotors that are aeroelastically stable, stabilize the longitudinal dynamics of the helicopter, and satisfy pitch response requirements. The final designs have the center of mass placed ahead of the elastic axis and the aerodynamic center behind it. The offset between the center of mass and the elastic axis is close to zero for the stiff in-plane rotor.

A drawback of the optimization procedure followed by Celi[28] was that some of the intermediate designs were infeasible. This happened because the feasible directions based CONMIN[13] optimizer follows the behavior constraint closely and the approximate behavior constraint may not always be accurate, thereby pushing the optima into the infeasible region. He suggested that some other optimizer that pushes toward the inside of the feasible region, rather than move along the boundaries, may solve this problem of infeasible intermediate designs. When intermediate designs are infeasible, the optimizer cannot be stopped at any point, and the results from the current iteration still used.

Spence and Celi[29] developed a method for calculating of sensitivity derivatives of rotor blade loads and hub loads to changes in blade design variables using a chain rule differentiation approach. A new feature of their approach was that it was valid for both steady level flight and turning flight. They mention that directly combining an aeroelastic analysis and the optimizer and using finite difference derivatives was extremely computationally intensive for most rotorcraft problems of practical complexity. In addition, the approximation methods based on Taylor's series linear approximations of the objective functions and constraints are also very expensive because they need finite difference derivative calculations to build the approximations. Spence and Celi developed the sensitivity analysis for the implicit formulation developed by Celi and Friedmann.[26] The implicit formulation of the equations of motion for aeromechanical analysis does not need symbolic expansions of various algebraic equations that make up a mathematical model. Instead, the equations are assembled numerically as part of the solution process. Spence and Celi[29] exploited features of the implicit formulation to find sensitivity of the modal, blade, and hub inertia loads and modal structural loads to changes in mass, center of mass offset, and flap bending stiffness. By examining the equations of the sensitivities, they found that the terms that are most computationally expensive to calculate are already available as part of the analysis. The authors concluded that the semi-analytical technique was both accurate and computationally efficient.

Chattopadhyay et al.[30] performed an integrated aerodynamic/dynamic optimization to reduce blade weight and 4 per revolution vertical shear in forward flight for a four-bladed articulated rotor. The rotor blade model was for a modified Black Hawk blade developed for wind-tunnel testing. The authors used three sets of objective functions: 1) blade weight only, 2) 4 per revolution vertical hub shear, and 3) both weight and 4 per revolution vertical hub shear minimized using a global criteria approach. Constraints were imposed on blade frequency, autorotation, and stress due to centrifugal forces. Design variables included flap and lag stiffness, taper ratio, and root chord at seven spanwise stations. The analysis was based on the CAMRAD[31] code. First-order Taylor's series approximations were developed for objective functions and constraints. The optimization problem was solved using the CONMIN[13] code. Results showed that the combined minimization of vertical hub shear and weight lead to a reduction in vertical hub shear of about 77% and a 10% reduction in blade weight. The optimum design also had lower power requirement, although power was not included in the objective function. Chattopadhyay and McCarthy[32–34] and Chattopadhyay and Chiu[35] extended this work by including additional design variables and constraints and enhancing the objective function by including more components of the vibratory hub loads. Chattopadhyay and Seeley[36] developed a simulated annealing-based optimization for smart structures.

Bezard[37,38] conducted studies to minimize a weighted average of power needed at moderate and high speeds. The design variables were blade geometry and spanwise distribution of the airfoils. Numerical results showed a reduction, that is, 3–5% in the required powers. These studies were, however, limited by the use of rigid blade and uniform inflow aerodynamic modeling. Zibi et al.[39] extended this work to include the optimization program ORPHEE.

Pritchard et al.[40] used tuning masses for reducing vibratory hub loads. An effort was made to reduce loads by formulating objective functions and constraints without incurring an excessive weight penalty. Magnitude and spanwise position of the tuning masses were the design variables. The blade natural frequencies were limited by the additional behavior constraints. The code CAMRAD/JA[41] was used. Objective function and behavior constraints were expanded in linear Taylor series, and the resulting sequential programming problem was solved using CONMIN.[13]

Walsh[42] performed a study for performance optimization. Walsh et al.[43] extended this study and developed an integrated aerodynamic/dynamic procedure for rotor blade optimization. LaMarsh et al.[44] used neural networks as surrogate model for the analysis. Walsh et al.[45,46] added structural optimization to the work done by Walsh et al.[43]

Young and Tarzanin[47] evaluated the results of optimization of a four-bladed articulated rotor for vibration reduction; using spanwise mass and stiffness distribution were considered as the design variables and weighted average of the hub loads in the fixed system as the objective function. Some constraints on the static and dynamic behavior of the blade are included in the objective function. An experimental study using a four-bladed articulated Mach scale vector showed reductions in 4 per revolution vertical hub loads and overturning moments. The authors' mention that the gradient-based method (NPSOL) used in their studies appeared to get stuck in local minima.

Venkatesan et al.[48] presented a semianalytical method for hub load sensitivity formulated for the case of hover, which is governed by stability equations with constant coefficients. The eigenvalue sensitivity equations contain the sensitivities of the element matrices, which are calculated using finite difference approximations. Barwey and Peters[49] addressed rotor dynamics optimization. Cross-sectional dimensions, blade geometry parameters, and two fiber orientation were used as design variables to minimize weight subject to frequency placement constraints and autorotation inertia. The composite blade had an anisotropic cross section. The study showed the presence of local minima, which were dependent on the frequency placement constraints. Other early studies on helicopter optimization include those by Davis[50] and Banerjee and Santhakumaran.[51]

The early studies focused on reducing rotor-induced vibration as the key problem, although some studies also address the problem of weight reduction, performance improvement, and stability improvement. The primary design variables used included blade mass and stiffness properties, cross-sectional dimensions, and tip sweep. These studies were restricted in scope because of high computer time requirements, especially when comprehensive aeroelastic analyses were used for vibration predictions and stability analysis was included. Analytical sensitivity derivatives were used by some researchers to address the computer time problem. Modal-based approaches, although less accurate because they did not properly model the coupling between the rotor response and loads, were found to be quite successful. These studies almost universally used gradient-based optimization methods, and some studies observed the presence of local minima. Preliminary use of surrogate functions of the analysis for optimization was conducted.

Composite Rotor Optimization

The early studies discussed showed the potential of optimization methods in reducing vibration and blade weight and improving performance and aeroelastic stability. During the late 1980s and early 1990s there was a spurt of activity in the aeroelastic analysis of composite helicopter rotors. Superior fatigue characteristics and a high stiffness–weight ratio compared to metals lead to a widespread use of composite materials in the design of helicopter blades. However, other potential benefits of composites such as their flexibility in tailoring structural characteristics were not exploited by the rotorcraft industry. Some studies have shown that composite couplings can reduce helicopter vibrations, enhance blade stability, and reduce blade stresses.[52,53] These early works, however, did not precisely model the nonclassical effects that can become important for composite rotor blades. Smith and Chopra[54] addressed this issue by extending the earlier models to include nonclassical effects. They also investigated the aeroelastic stability, hub loads, and aeromechanical stability in forward flight.[55] Recent discussions on modeling of composite rotor blades are given in Refs. 56 and 57. Gurdal et al.[58] provide a good background on optimization of composite structures.

With the availability of comprehensive aeroelastic analysis for composite rotors, Ganguli and Chopra[59] developed analytical sensitivity derivatives of blade rotating frequency, hub loads, and aeroelastic stability as an integral part of the composite rotor aeroelastic analysis. For applications, a soft-in-plane helicopter rotor with box-beam spar was selected. The aeroelastic optimization problem was reduction of all six 4 per revolution hub loads with constraints on blade stability and frequency placement. By means of a parametric study, the influence of ply angles on blade flap, lag and torsion stiffness, flap bending–torsion and lag bending–torsion couplings,

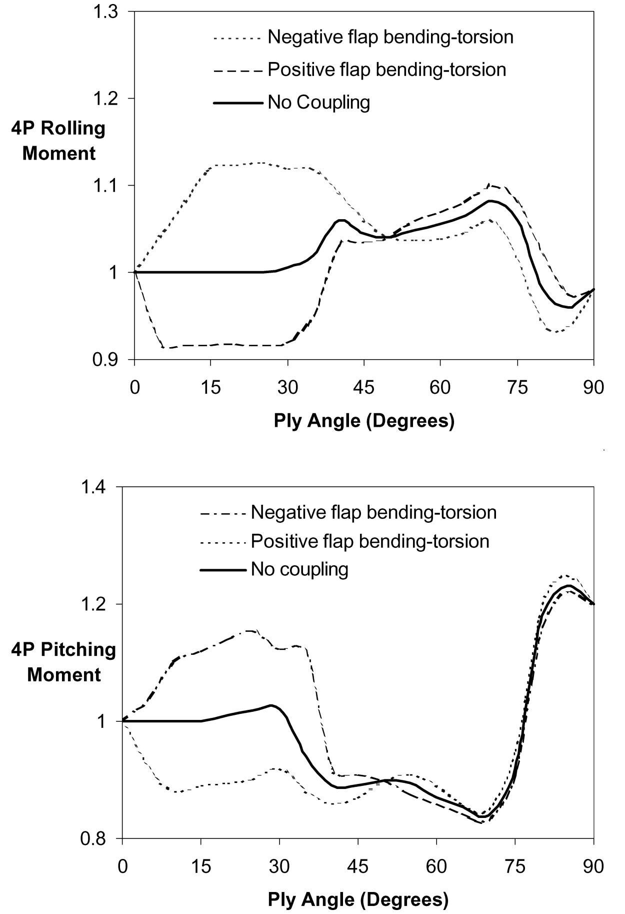

Fig. 1 Variation in 4 per revolution hub rolling and pitching moment for four-bladed rotor with ply angle design variable for composite coupled and uncoupled layups.

hub loads and aeroelastic stability was investigated. Though not explicitly mentioned in the paper, the parametric study showed the presence of local minima with respect to ply angle design variables. For example, Fig. 1 shows the 4 per revolution rolling and pitching moment variations with respect to ply angle design variable. The design space can be seen to have local minima and flat regions. The study showed that 1) significant changes in the elastic stiffness and composite couplings can be obtained by varying ply angles in the wall of the box-beam spar, 2) elastic stiffness and positive flap bending–torsion coupling can be tailored using ply angle variations to give a reduction in vibration reduction of as much as 50%, and 3) stability increase in the lag mode of over 200% can be obtained using ply angles tailored with negative lag bending–torsion coupling. The aeroelastic analysis was performed at an advance ratio of $\mu = 0.3$ with quasi-steady aerodynamics. However, the optimum designs show a reduction in the objective function at other advance ratios. In fact, even when unsteady aerodynamics and free-wake models were used, the vibration was reduced for the optimum design compared to the starting design. The beneficial effects of using ply angle tailoring of the composite rotor blade become more pronounced as the advance ratio increases.

The preceding study used a single-cell box beam model. Production rotor blades, however, are built as multicell airfoil sections. Because single-cell representation of a multicell rotor blade can result in an overestimation of torsion flexibility, it is important to model it as a multicell box beam. Therefore, Ganguli and Chopra[60] used a composite beam cross-sectional model based on Vlasov theory (see Refs. 61–63), along with a comprehensive rotor aeroelastic analysis to optimize composite rotors. The rotor analysis was divided into two levels. At the lower level, the two-cell box-beam elastic properties and composite couplings are calculated. At the higher level, the section properties are used to calculate blade frequencies, hub loads, and aeroelastic stability. Ply angles are used as design variables. The sensitivity derivatives of hub loads and aeroelastic stability are calculated with respect to ply angles using a two-step procedure. The derivatives with respect to the section properties are calculated as an integral part of the aeroelastic analysis using analytical differentiation. The derivatives of the section properties are calculated with respect to the ply angles using a finite difference approach. This allowed the authors to use different cross-sectional models without the need to recalculate the derivatives. In addition, analytical cross-sectional models such as those based on Vlasov theory are computationally fast, and finite difference derivatives do not take much time. Numerical results showed a 33% reduction in rotor vibration levels from the starting design when flap bending–torsion coupling is used and a lag mode damping increase of 140% when lag bending–torsion coupling is used. However, this study also showed that reducing 4 per revolution loads in the fixed frame can result in an increase in the other harmonics such as 1, 2, and 6 per revolution in the rotating frame, resulting in an increase in blade dynamic stresses and, therefore, a reduction in blade fatigue life.

Vibratory bending moments acting along the blade length cause dynamic stresses, at several harmonics, on the rotor blade. The critical dynamic stresses occur in the spanwise location where vibratory bending moments are highest; for hingeless rotors, this occurs at the blade root, and for articulated rotor this occurs at the blade midsection. Therefore, Ganguli and Chopra[64] adopted a direct approach to increasing blade life by minimizing the vibratory bending and torsion moments at the critical spanwise locations. Constraints were imposed on aeroelastic stability and blade frequency placement. Important features of this study were 1) nonuniform composite beam considered with stiffness and composite coupling varying at five elements along the blade span due to variations in ply angles and 2) minimization of dynamic stresses and a composite objective function with both vibration and dynamic stresses. When only dynamic stresses were minimized, 13 and 40% reduction in the peak-to-peak flap and lag bending moments, respectively, is obtained. However, this reduction in the dynamic stresses came at the expense of an increase on 4 per revolution vibrations of 10%. A combined reduction in the vibration and dynamic stress levels led to a reduction in the 4 per revolution hub loads of 15–60% and in the peak-to-peak flap and lag bending moments of 11 and 14%, respectively. The authors calculated maximum equivalent pitch–flap coupling angle to be 35 deg and pitch–lag coupling angle to be -10 deg for the optimum designs. Therefore, composites can be used to induce relatively large amounts of couplings in the rotor blade dynamics.

Paik et al.[65] looked at a new approach to realistic rotor blade cross-sectional optimization. They point out that the modeling tools for composite cross-section analysis such as VABS[66] have reached accuracies comparable to that of three-dimensional finite element methods at two or three orders of magnitude less cost. Therefore, they used VABS to solve the inverse problem of seeking blade cross-sectional designs that possess specified cross-sectional properties. The organization of VABS is shown in Fig. 2. The three main blocks of VABS are mesh preparation, eigensystem solution, and warping and stiffness calculations. When the problem is decomposed into two levels, the upper-level problem has cross-sectional stiffness and couplings as design variables and the lower-level problems has cross-sectional geometry and material property as design variables. If a tool existed to design the cross section from one-dimensional beam stiffness and couplings, it could greatly cut down computational cost because the upper-level problem has much fewer design variables than the lower-level problem. The design variables used in this study are ply angles, ply thickness/number, and spar location. The objective function involves minimization of the distance between the shear center and quarter chord. Upper and lower bounds are placed on bending and torsion stiffness. The values of composite couplings are constrained to be small compared to the diagonal stiffness terms. The optimization problem is solved using a feasible directions method in automated design synthesis (ADS)[67,68] for a baseline composite rotor blade for the XV-15 rotor. Numerical results showed oscillations before the objective function reached its

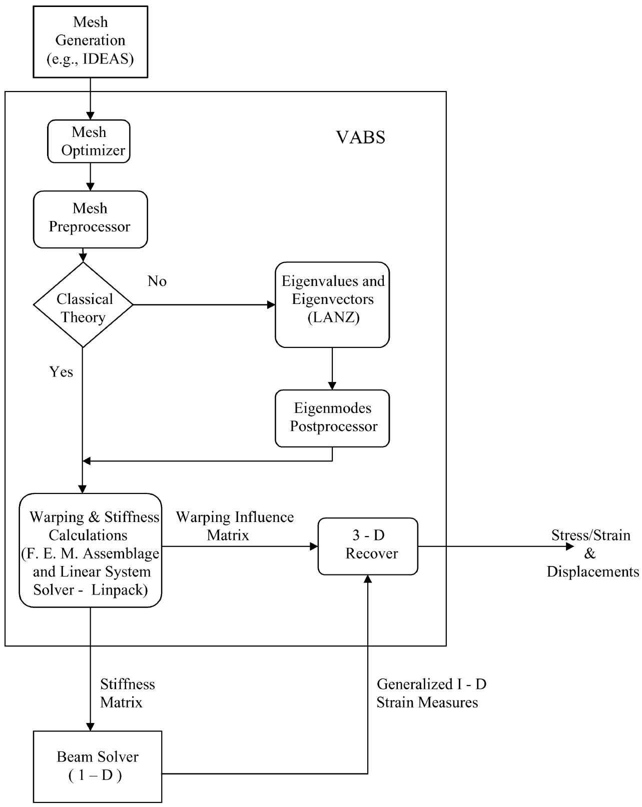

Fig. 2 Schematic organization of VABS.

minima near zero. The authors mention that the results are very sensitive to initial values because of the presence of various local minima when the ply angles and thickness are used as design variables. Move limits are upper and lower bounds on the design variables and need to be imposed to avoid excessive movement of design variables to neighboring regions. In Ref. 59, for instance, move limits were imposed at each iteration of the optimization process as the ply angle design variables. Rounding off the final optimization results to the nearest 15 deg for ply angles showed an increase in the objective function from 0.04 to 1.14% chord. It appears that this problem is highly suitable for genetic algorithm given the presence of local minima and discrete integer design variables.

The use of composites in helicopter rotor blades is widespread, and optimization methods allow the tailoring of properties of composite cross sections for improved vibration, performance, and stability characteristics. The composite design space contains discrete and integer design variables such as number of plies, stacking sequence, and ply thicknesses. In addition, local minima appear to be prevalent for composite optimization problem. Therefore, the use of stochastic optimization methods based on genetic algorithm appears to be useful for composite rotor optimization problems.

Advanced Geometry Rotor Optimization

Advanced geometry blades involve variable sweep, anhedral, pretwist, and planform taper along the blade length. Such blades are receiving growing attention from rotor designers seeking to reduce compressibility drag rise, stall effects, and acoustic signature. For example, swept tips reduce the drag associated with transonic flow conditions by reducing normal Mach number on the advancing blade. Advanced geometry blades also introduce couplings between the modes of deformation (flap, lag, torsion, and extension). For example, tip sweep causes flap–torsion coupling and tip droop causes lag–torsion coupling. These couplings significantly influence the aeroelastic behavior of the rotor. Research during the early 1990s showed that vibratory hub loads can be reduced and aeroelastic stability increased by tailoring the blade geometry to exploit the couplings and to reduce compressibility effects at the blade tip.[27,69–71] Recent work has also shown the beneficial impact of sweep on rotor noise.[72]

Ganguli and Chopra[73] used optimization methods along with analytical sensitivity analysis to minimize all six 4 per revolution hub loads in a four-bladed soft-in-plane hingeless rotor. Design variables included nonstructural mass and its placement, blade bending stiffnesses (flap, lag, and torsion), and blade geometry (sweep and anhedral and planform taper). Constraints were put on frequency placement, autorotational inertia, and aeroelastic stability in forward flight. Numerical results showed a reduction in vibration levels of about 45%. The optimal advanced geometry configuration has sweepback and droop throughout the blade length and is tapered for the outboard 60% of the blade with a taper ratio of 1.22. The results also show that using only tip sweep and anhedral and planform taper reduces the objective function by about 20% compared to the baseline design. The optimum design in this case is swept back at the tip by 29.3 deg, drooped down by 6.1 deg, and shows a reduction in tip chord by 14% compared to the starting design.

The preceding study[73] addressed isotropic swept tip blades. Ganguli and Chopra[74] then extended their analysis to composite rotor blades. They used a two-cell box-beam model based on Vlasov theory to model the composite beam. Design variables in this study were the ply angles of the laminated walls of the composite box beam, as well as blade sweep, anhedral and planform taper, and nonstructural mass and its offset from the elastic axis. The starting design is a straight blade with no composite coupling. Numerical results indicate that vibratory hub loads and blade root bending moments can be reduced by 1) distributed flap bending–torsion coupling along the blade span, 2) sweepback, droop, and anhedral and planform taper near the blade tip, and 3) nonstructural mass near the blade tip, distributed aft of the elastic axis. Numerical results show that the negative impact of blade sweepback on lag mode stability can be countered by introducing distributed composite lag bending–torsion coupling along the blade length. Compared to the starting design, which is a straight, uncoupled blade, an optimal solution achieves vibration reduction of 15–25% in the peak-to-peak vibratory flap and lag bending moments.

Yuan and Friedmann[75,76] developed an optimization process for composite helicopter rotors with swept tips. The aeroelastic analysis was based on a moderate deflection finite element model. The blade model used allowed for arbitrary cross section, generally anisotropic material behavior, transverse shear, and out-of-plane warping. Numerical results are obtained for a four-bladed hingeless rotor with uniform spanwise properties. The authors showed that the combined effects of blade sweep and composite ply angles cannot be simply predicted by a superposition of the respective individual effects. They also found that a combined objective function with all the six hub forces and moments was better than minimizing the vibratory vertical hub shear alone. Through a parametric study, they showed that tip sweep had a significant influence on optimization for vibration reduction. The parametric study also showed the presence of local minima. Design variables used were the ply angles in the horizontal and vertical walls of the composite cross section and the sweep and anhedral angles at the tip of the blade. The optimization problem was solved using the DOT[77] package. When a proper combination of tip sweep and anhedral is used, along with composite ply orientation, the need for excessive sweep angles is avoided. Yuan and Friedmann[75,76] used approximation methods. They constructed linear approximations of the objective function and a conservative approximation for the behavior constraints. The conservative approximation is a hybrid form of the linear and reciprocal approximation and is more conservative than either. Although the authors mention that the implicit formulation of the equations of motion used in this study has advantages over the explicit formulation, one disadvantage was that they were not able to calculate sensitivity derivatives analytically as an integral part of the solution process, as had been done by Lim and Chopra[19] and Ganguli and Chopra.[74]

An important limitation of the preceding studies is in the use of relatively simple aerodynamic models for the aeroelastic analysis. Whereas sweep and other advanced geometry design variables cause important dynamic couplings between the blade modes, their effect of the aerodynamic flow is also very important, and three-dimensional effects can become important at the blade tip. In addition, noise reduction is a key objective in advanced geometry rotor design, and the use of sophisticated aerodynamic models such as those based on CFD may be needed for better acoustic noise predictions. From an optimization perspective, when only advanced geometry design variables are used, the number of such variables is often selected at the blade tip leading to a small number of design variables. Therefore, for such problems with low number of design variables, there may be more flexibility in the choice of optimization methods with stochastic optimization methods and surrogate function approximations becoming possible.

Optimization in Flight Mechanics

Considerable coupling between the rotor and fuselage dynamics can exist for helicopters with hingeless and bearingless main rotors. For example, a low damped regressive mode can couple with the fuselage roll degree of freedom and result in air resonance instability. In addition, there is interaction between the rotor and the flight control system. These interactions become important in the reliable design of high-gain flight control systems. In standard design procedure, however, the rotor is designed based on performance, aerodynamics, and to some extent vibration criteria. Handling qualities are a secondary objective. However, accurate rotor models are needed to analyze the flight dynamics of hingeless and bearingless rotors because the elastic deformations of the main rotor blades can substantially influence the handling qualities. Optimization methods appear very suitable for including flight mechanics and control system design into the typical aeroelastic design framework.

Tischler et al.[78] developed an interactive optimization program called CONDUIT to address the problem of design of flight control systems. The multiobjective objective formulation allows tradeoff studies to be performed with different objectives. Gains and other parameters of the control system are used as design variables. Handling quality specifications are used as constraints.

Sahasrabudhe et al.[79] tried to determine if it was feasible to design the flight control system and rotor simultaneously. They conducted an optimization study to minimize the control effort using both rotor and flight control design variables. Constraints were imposed on aeroelastic stability and a representative set of handling qualities from the ADS-33 requirements.[80] Three rotor design variables and five control system design variables were used for each flight condition. However, the authors[79] found that the use of only three design variables for the helicopter rotor was too small to satisfy the entire set of handling quality and aeroelastic constraints. If the design is optimized for just one flight condition, optimizing the rotor and flight control system simultaneously leads to better design than sequentially optimizing the rotor first and the flight control system later. The strong coupling between the rotor and flight control system is clear from the fact that the designs obtained using the two optimization strategies are quite different.

Sahasrabudhe and Celi[81] developed a new method for calculating gradients of constraints associated with the moderate amplitude criteria of the ADS-33 helicopter handling qualities specification.[80] They[81] addressed the problem identified in the earlier work involving the very large computer time needed to solve the integrated rotor/control system optimization problem of realistic complexity. For example, formulations with 10 design variables and 30–40 constraints required CPU times of 70–80 h on typical workstations. The main reason for this computational cost is that handling quality specifications such as the criteria for moderate and large attitude change maneuvers in the ADS-33 call for calculation of time histories of the aircraft response to pilot inputs. In this study, the gradients were calculated using a low-order linear approximation to the full nonlinear model of the helicopter. The low-order models approximated the gradients well, and the additional cost of calculating the gradients by finite difference was reduced by a factor of about 50.

Celi[82] developed an inverse simulation methodology based on numerical optimization. The method was applied to the slalom maneuver, which is defined using a set of criteria, in contrast to the ADS-33D handling qualities requirement,[80] which depends on a prescribed path. The design variables are the collective pitch, longitudinal cyclic pitch, lateral cyclic pitch, and tail rotor collective pitch at selected discrete time points during the maneuver. Constraints are defined based on the description of the slalom maneuver, that is, paragraph 4, 2, 6 of the ADS-33D handling quality specification. One of the objective functions minimizes the difference between the required trajectory and the predicted trajectory as an unconstrained optimization problem. Celi[82] also found that when the trajectory is defined indirectly, there is an entire family of acceptable trajectories with different helicopter dynamics and pilot inputs. Multiple solutions can also exist when the trajectory is prescribed explicitly, as was found by starting from different initial designs.

Ribera and Celi[83] focused on the numerical calculation of the gradients of components of the main rotor inflow obtained using a free-wake methodology. Free-wake models are not only important for rotor aerodynamic loads, noise and vibratory load predictions, but also important for flight mechanics problems such as the prediction of cross couplings in response to pilot inputs. There are three ways to contribute sensitivity derivatives in general: analytical or semianalytical approaches, finite difference approaches, and automatic differentiation. In principle, all three methods can be used for calculation of the sensitivity of rotor wakes to design variables. However, the free-wake code implementations consist of nested loops, which make it difficult to perform analytical sensitivity. Automatic differentiation methods, when applied to iterative processes, lead to further iterative loops, which can greatly increased the computer time required. The authors,[83] therefore, conclude that the finite difference methods are most practical. Whereas most derivatives can be calculated using forward finite differences, the authors recommend using central finite differences for derivatives with respect to forward velocity. In addition, the authors suggest that an accurate way to calculate the perturbed wake is to start from an intermediate geometry that is close to the expected final result.

Fusato and Celi[84] investigated an efficient technique for calculating the sensitivities of handling quality characteristics with respect to helicopter system parameters. In this study, they considered the distance from the Level 1 boundary of the ADS-33 bandwidth specification[80] as the objective that required calculation of the sensitivities of the bandwidth and phase delay. The design variables used were blade torsion stiffness, the area of the horizontal tail surface, and gain of a pitch rate longitudinal feedback system. They calculated semi-analytical derivatives with the assumption that the trim state and normal modes are constant. The results showed that this assumption is reasonable. Note that this assumption is made in almost all analytical sensitivity derivative calculations such as those by Lim and Chopra[19] and Ganguli and Chopra.[74] The sensitivity derivatives were calculated using chain rule differentiation of the appropriate portions of the equations of motion. Some of the terms required for the sensitivity analysis calculations were found to exist as part of the baseline calculations and could easily be reused for sensitivity calculations. Numerical results showed the technique to be extremely efficient, and problems such as finite difference step size issues did not have to be considered.

The studies on rotor optimization including flight mechanics are very computationally intensive as observed from the extensive studies discussed earlier. Therefore, the sensitivity derivative have been explored for these problems to allow a reduction in computer time and an increase in the number of design variables for addressing more realistic problems. Some type of sensitivity analysis appears necessary for these problems at the current time due to the very high computer time requirements.

Optimization for Aeromechanical Stability

Aeromechanical instability in helicopters occurs because of coupling between the rotor and fuselage motion. Ground and air resonance are aeromechanical problems that are caused by the interaction of lagging motion of the rotor blades with other modes of helicopter motion. In ground resonance, the lagging motion of the blades reacts with the airframe producing hub motion, which further excites the lag motion. The ground resonance instability can be very violent and can lead to catastrophic failure. The air resonance problem appears in hingeless rotors. The large hub moments that occur when the rotor tilts can give rise to airframe oscillation even when the helicopter is in flight. This airframe motion can couple with the lag motion of the blades leading to air resonance.

The objective of the work of Spence and Celi[29] was to obtain sensitivity derivatives for aeromechanical problems. A typical aeromechanical problem has two parts. The first part is the calculation of the steady response and the trim state for the helicopter. The first part provides the control settings, fuselage attitudes, and rates for a given steady flight condition and the steady-state elastic deformations of the blade, which give its equilibrium condition. The second part is the solution of the aeromechanic stability problem involves evaluation of the coupled rotor–fuselage stability about the trimmed state. The governing equations of motion are linearized about the trimmed flight condition and their stability evaluated using Floquet theory. To facilitate the inclusion of aeromechanical stability in rotorcraft optimization, Shih et al.[85] developed a method to obtain semi-analytical sensitivities of the aeromechanical stability with respect to design variables. The method was called semi-analytic because both chain rule differentiation and finite difference calculations were used. An important feature of this study is that changes in the equilibrium position about which the equations are derived are taken into account. Previous sensitivity analysis such as those by Lim and Chopra,[16–19] and Ganguli et al., and Ganguli and Chopra,[59,60,64,73,74] neglected the possibility of changes in stability due to changes in the equilibrium position. This study included the main rotor, fuselage, and main rotor inflow, which are needed for accurately modeling aeromechanical stability.

Gandhi and Hathaway[86] used optimization methods to alleviate the ground resonance problem of soft in-plane rotors using aeroelastic-coupling parameters. They wanted to use aeroelastic couplings in the design of aeromechanically stable helicopters to obtain a helicopter that does not need auxiliary lag dampers. They used a rotor fuselage model with six degrees of freedom, which were cyclic flap (two degrees of freedom), cyclic lag (two degrees of freedom), fuselage roll and pitch. For optimization, the pitch–flap coupling and pitch–lag coupling are used as design variables. Optimization was carried out using the International Mathematical and Statistical Library subroutines. They studied three cases: 1) single-point optimization, 2) single-point optimization with multipoint constraints, and 3) moving-point optimization. Optimization at a prescribed rotational speed was not able to stabilize ground resonance because it results in moving the resonance frequency to a lower rotational speed. The aim of moving-point optimization procedure is to stabilize at the rotational speed where damping in minimum during each optimization iteration is able to stabilize the regressive lag mode at moderate collective pitch. However, the optimal aeroelastic couplings for this condition are destabilizing near zero-thrust conditions. The multipoint-optimization procedure attempting to stabilize ground resonance simultaneously at low as well as high collective pitch conditions restricts the instability to small values over a range of collective pitch values and eliminates the destabilizing trend of roll resonance as collective pitch increases. This final optimum configuration can then be easily stabilized by increasing body roll damping. The most beneficial couplings were negative pitch–lag coupling, positive pitch–flap coupling, flap flexibility outboard of pitch bearing, and lag flexibility inboard of pitch.

Hathaway and Gandhi[87] continued their study and included blade flap and lag stiffnesses as design variables, along with pitch–flap and pitch–lag couplings. They were motivated by that values of aeroelastic couplings that are generally stabilizing for ground resonance may lead to rotor frequencies that are unacceptable from a handling quality perspective. Constraints were imposed to prevent excessive changes in the rotor frequencies. A numerically efficient two-stage optimization procedure was developed. Numerical results for a soft in-plane helicopter rotor showed that aeroelastic couplings and blade stiffness properties, along with leading gear stiffness and damping properties, could be used to design a helicopter rotor without lag dampers. Also, a concurrent approach to optimization where the pitch–flap and pitch–lag couplings are simultaneously considered as design variables was superior to the sequential approach where the blade stiffness and frequency targets were set before any attempt to incorporate aeroelastic couplings.

Badre-Alam et al.[88] performed an optimization study to study the influence of active constrained layer damping treatments on flex beams of soft in-plane bearingless main rotors. The objective was to augment lag mode damping and aeromechanical stability augmentations. The flex beam with constrained layer damping was modeled using the finite element method. The design parameters include viscoelastic layer thickness, PZT actuator thickness, and edge element thickness. Results of this study showed that active constrained layer damping of flex beams can be used for rotor stability augmentation.

Liu and Chattopadhyay[89] studied the influence of segmented constrained damping layer (SCL) treatment and composite tailoring for improved aeromechanical stability using an optimization technique. The rotor blade was represented as a box beam of arbitrary thickness with surface bonded SCL. The SCLs are bonded on the upper and lower surfaces of the box beam to provide passive damping. A finite element model based on a hybrid displacement theory was used to capture accurately the transverse shear effects in the composite primary structure and the viscoelastic and the piezolayers with the SCL. The ground and air resonance analysis is developed for such a rotor blade. A hybrid optimization technique capable of handling both discrete and continuous design variables is used. Design variables were the stacking sequence of the composite laminates and the placements of the SCLs. Numerical results show that the optimum blade has significantly higher rotor lead–lag regressive modal damping compared to the baseline model.

Fusato and Celi[90] extended their work in Ref. 84 and maximized progressive lag mode damping for a hingeless helicopter rotor similar to the BO105 rotor. A 53-state simulation model including flexible blade dynamics and detailed representation of the fuselage and empennage was used. Constraints were placed on rotor stability, loads, and handling qualities. Design variables included effect of the rotor, airframe, and flight control system parameters. Numerical optimization results showed an increase in lag mode damping of over 90% caused primarily by a reduction in torsion stiffness of the blade. They found that the aeromechanical optimization problem is multidisciplinary because the constraint active at the optimum is the Level 1 handling quality requirement in the pitch axis. The most time-consuming constraint in this study was that related to the time history of response to pilot inputs. The use of semi-analytical sensitivity derivatives was found to result in substantial reduction in computer time. Finally, the authors point out that optimization provides a useful framework to handle such highly multidisciplinary problems.

The aeromechanical instabilities present in helicopters require the use of expensive lag dampers on helicopter rotors. The possibility of alternative and cost-effective approaches to add damping to the rotor blade lag mode appears very attractive. The use of tailored stiffness and pitch–flap and pitch–lag couplings has been studied by some researchers. Others have used smart structures concepts. Because the lag mode in rotors is very lightly damped, it appears useful to consider tailoring of couplings in the blades along with smart structures based concepts for stability enhancements. The pitch–lag and pitch–flap couplings in rotor blades can also be induced by tailoring the composite box-beam blade spars. From an optimization algorithm perspective, the air resonance problem is very computationally intensive due to the need to perform a Floquet stability analysis of a large periodic system of differential equations consisting of all of the rotor blades and the fuselage degrees of freedom. Therefore, analytical sensitivity derivatives may be needed to solve problems with a practical number of design variables at the present time.

Tilt-Rotor Applications

The tilt-rotor aircraft has appeared as the most viable design that combines high-speed capability with good hover performance. Successful military aircraft include the XV-15 and V-22 Osprey. The Bell/Augusta BA-609 is the civil tilt rotor. The tilt-rotor blade represents a compromise between a helicopter rotor blade and a propeller. The important parameters in tilt-rotor design are twist distribution, mass distribution, airfoil type, disk loading, downwash, rotor angular speed, and extension–twist and bending–twist coupling.[91]

In Refs. 92–100 a series of studies is performed and a multilevel decomposition-based optimization approach for tilt-rotor aircraft is developed. The aim of the study[100] was to improve high-speed cruise and hover performance and cruise for the tilt-rotor aircraft. The composite load carrying member was represented by a box-beam spar. The optimization problem was posed as a two-level problem. The upper-level objective was to minimize the high-speed cruise propulsive efficiency and the hover figure of merit using planform design variables. The design variables are chord, twist, thickness-to-chord ratio, and zero-lift angle of attack at each discretized node. Constraints are imposed on the physical dimensions of the blade to ensure that the load carrying member of the rotor is maintained within the airfoil dimensions. The optimization problem involves more than one objective, so that it is converted into a single objective problem using the Kreisselmeier–Steinhauser (K–S) function.[101] In this method, the multiple objectives and constraints are combined using the K–S function to form a single-envelope function that is then optimized. Depending on whether the individual objective functions are to be minimized or maximized, the reduced objective functions assume one of the two following forms:

$$F_k^*(\mathbf{\Phi}) = F_k(\mathbf{\Phi})/F_{k0} - 1.0 - g_{\max} \leq 0, \qquad k = 1, 2, \ldots, N_{\mathrm{OBJ_{min}}}$$

$$F_k^*(\mathbf{\Phi}) = 1.0 - F_k(\mathbf{\Phi})/F_{k0} - g_{\max} \leq 0, \qquad k = 1, 2, \ldots, N_{\mathrm{OBJ_{max}}}$$

where F_{k0} is the original value of the kth objective function F_k calculated at the beginning of each cycle and $\mathbf{\Phi}$ is the design variable vector. The largest constraint in the original constraint vector is $g_{\max}$, and $g_j(\mathbf{\Phi})$ is held constant during each cycle. The integers $N_{\mathrm{OBJ_{min}}}$ and $N_{\mathrm{OBJ_{max}}}$ are the number of objective functions that are to be minimized and maximized, respectively. Because the reduced objective functions are analogous to constraints, a new constraint vector $\boldsymbol{f}_m(F)$, $m = 1, 2, \ldots, N_C + N_{\mathrm{OBJ}}$ is introduced where N_C is the number of original constraints and N_{OBJ} is the total number of reduced objective functions. The K–S function can then be defined as

$$F_{\mathrm{KS}}(\mathbf{\Phi}) = f_{\max} + \frac{1}{\rho} \ln \sum_{m=1}^{\mathrm{NC+NOBJ}} e^{\rho[f_m(\Phi) - f_{\max}]}$$

where $f_{\max}$ is the largest constraint in the new constraint vector $\boldsymbol{f}_m(F)$. The K–S function can easily be minimized using any unconstrained optimization technique. The term ρ is called the draw down factor and is progressively increased so that as the optimization proceeds the K–S function more closely represents the largest constraint or the most violated objective function.

The K–S function has been found to perform very well in rotary wing multiobjective optimization problems. The lower level optimization problem in Ref. 100 is to minimize the tip vertical and torsion displacements in hover and in cruise. Ply orientations are used as design variables. To achieve practical designs, ply angles are chosen from a standard set of values. These values are 0, +15, −15, +30, −30, +45, −45, and 90 deg. The Tsai–Wu failure criteria are used to monitor ply failure. The upper level problem, thus, uses continuous design variables, and the lower level problem uses discrete design variables. The upper level problem is solved using the Davidson–Fletcher–Powell method, a standard gradient-based optimization method. The lower level problem is solved using simulated annealing. Numerical results are obtained for a three-bladed gimbaled XV-15 rotor blade at 300 kn (154.33 m/s) and show significant improvements in both structural and aerodynamic performance. Table 1 shows the ply orientation angles obtained are discrete variables showing the usefulness of the hybrid optimization approach.

Chattopadhyay et al.[102] later extended their analysis to include a refined structural modeling technique, which was based on a higher-order analysis.[103] In this approach, each wall of the box beam was modeled as a composite plate and was adequate for sections with moderately thick walls that are being used for tilt-rotor blades.

Studies by Moffitt and Rivera[104] and Davis et al.[105] addressed the aerodynamic optimization of a variable diameter tilt rotor in hover and cruise flight. The analysis consisted of a hover free-wake model based on iterative relaxation scheme. The sensitivities are obtained by finite difference approximations. The authors[104,105] carried out optimization using sequential linear programming. Using the chord, twist, and sweep at 16 spanwise stations as design variables, they showed that improvements in hover and cruise efficiency could be obtained without having to make complicated changes to the planform geometry.

Table 1 Ply orientation angles

	Optimum	
Reference, deg	Horizontal wall, deg	Vertical wall, deg
Outer ply		
0	15	0
0	−15	0
0	0	15
0	0	−15
15	15	30
−15	−15	−30
15	15	15
−15	−15	−15
45	30	45
−45	−30	−45
45	30	15
−45	−30	−15
Midplane		

Clements and Rais-Rohani[106] conducted a design optimization of a tilt-rotor wing, which was modeled as a thin composite wing-box structure. They used the finite element method to calculate the wing deflection, internal load distribution, and natural frequencies. The authors did not use a formal aeroelastic analysis of the preliminary wing design for whirl flutter calculations. Instead, they placed limits on the magnitudes of the primary vibration frequencies in bending and torsion and their placement relative to each other and with respect to the critical rotor frequencies in helicopter and airplane flight nodes. The skin and shear web panel buckling response are captured using multiple linear regression equations. Two skin ply patterns based on different placements of 0-, +45-, −45-, and 90-deg plies are considered for the laminated wing skin as design variables. Numerical results were obtained based on three maneuver loading conditions associated with the airplane mode. It is found that the first horizontal bending and first torsion frequency constraints are more critical than that associated with the vertical bending mode.

Soykasap and Hodges[107] undertook performance enhancement of a composite tilt rotor. They mention that the difference in hover and forward-flight modes cause a change in the blade centrifugal forces so that extension–twist structural coupling can be optimized for the tilt rotor. They also considered the effect of other couplings such as bending–twist and extension–bending, the effect of pretwist on blade cross-sectional properties and relaxation of the thin-walled assumption. They used a mixed variational principle based on the exact intrinsic equations of motion for beams attached to moving frames. They also used the finite state dynamic inflow model of He and Peters.[108,109]

Optimization was performed on the figure of merit in hover and the axial efficiency in forward flight. The rotor was modeled as three identical composite blades, with each rotor blade modeled as a composite box beam inside an airfoil shaped cavity with nonstructural mass. The analysis is divided into two levels. At the lower level is the two-dimensional cross-sectional analysis of the rotor blade. At the higher level is the one-dimensional finite element aeroelastic analysis of the isolated rotor. An analytical two-dimensional analysis developed by Berdichevsky et al.[110] was used, even though it neglected pretwist and curvature effects. The authors[107] mention that such parameters are not as significant in two-dimensional cross section analysis as in one-dimensional aeroelastic analysis. However, their effect is not negligible. The authors also mention that the highly accurate numerical cross section analysis based on the VABS[66] code, which uses finite element modeling, is extremely computer intensive and, therefore, unsuited for an optimization analysis.

For optimization, the figure of merit in hover and the axial efficiency in forward flight are combined together into a single objective function using weighting factors and then maximized. The design variables are blade twist, box width and height, horizontal and vertical thickness, and nonstructural mass concentrated at the quarter chord at 12 finite element locations. The ply angles are assumed constant along the blade length for manufacturing ease. Constraints are imposed on blade weight, autorotational inertia, strength, geometry, and aeroelastic stability. Some interesting constraints are imposed in this study. One is a constraint ensuring the validity of thin-walled theory for box beams that requires that the ratio of the wall thickness to the box-beam major dimensions be less than 10%. Another is a constraint on blade stall, which constrains the angle of attack at three-fourths radius. The Tsai–Wu failure criterion was used to check for ply failure. Other constraints imposed are that the rotor wing remains stable in forward flight. Optimization is performed using ADS[67,68] and the gradients of the objective and constraints are calculated using forward finite difference. Numerical studies show that extension–twist coupling is the most effective parameter to enhance performance. The Tsai–Wu failure criterion does not predict any material failure for the optimal blade design. Whereas the optimum design is stable, it does have some frequencies near integer multiples of the rotor speeds. The authors[107] mention that, in future studies, constraints should be imposed to avoid certain frequency ranges.

Tadghighi[111] performed an innovative study for aeroacoustic optimization of a proprotor. He mentions that the vision of using optimization methods to design a rotor blade with low blade vortex interaction (BVI) noise has recently stimulated considerable investigation in the aeroacoustic community. Minimizing the aerodynamic response to the vortex at its generation and interaction location can significantly reduce acoustic intensity of BVI. The key design parameters for reducing BVI noise are the airfoil leading-edge radius, maximum thickness, maximum camber, and thickness and camber distributions. The objective of this study was to minimize the strength of proprotor BVI noise while maintaining aerodynamic efficiency in hover and forward flight. Constraints were, therefore, applied to hover figure of merit, cruise efficiency, and the C_T/σ in the descent flight condition. Design variables were blade twist, sweep, chord, and airfoil distributions. A multiobjective decomposition-scheme-based code OPTI-KS,[112,113] which is suitable for tilt-rotor aerodynamic and acoustic optimization, was used. The aeroacoustic optimization code OPTI-KS[112,113] used the CAMRAD.mod1 program for aerodynamic load calculations and the WOPWOP[114] code for rotor tonal noise calculations. A reference model JVX proprotor was used as the baseline design. Numerical results showed that design improvements in the rotor blade for BVI noise reduction are possible without any significant detrimental effect on aerodynamic performance. An analysis of the optimal result showed that there was negative twist in the tip region, which is expected because rotor blades almost always have negative twist. Thus the blade tip is unloaded for favorable effects toward blade vortex strength reduction. The optimum tip chord in smaller than the baseline and also results in a weaker tip vortex. Finally, the sweep increases by about by about 2% along the blade, but the tip region has a forward tip sweep for 1.5 deg. The forward swept tip for this aeroacoustic design is different from the sweepback obtained for the low-vibration blade designs by Ganguli and Chopra.[73,74]

Optimization studies for tilt rotors have focused on advanced geometry and composite design variables. Aeroacoustic optimization has been studied for the proprotor problem at a level of complexity that appears greater than that used for helicopter rotor problems. The availability of improved analysis codes should be used to formulate more comprehensive optimization studies addressing performance, vibration, and noise.

Nongradient Methods

Nongradient methods such as genetic algorithms have become increasingly popular among engineering optimization researchers because of their ability in finding global minima and permitting the use of integer or discrete design variables. The most popular nongradient methods are genetic algorithms (GA) and simulated annealing (SA). Hajela[115] provides details about several nongradient methods. Coello[116] gives a review on constrained optimization using GA. Trosset gives a discussion on SA.[117] The GA takes several points in the design space at random to create a population of individuals. Then some operators are applied to this population. These genetic operators are reproduction, crossover, and mutation and lead to a new and improved population. The mutation operator prevents the GA from ending up in local minima. The SA algorithm also has the capability of escaping from local minima. The search takes place randomly, and the acceptance of a new design, which can be worse than the current design, is permitted to allow the search to escape a local minima. Both GA and SA methods need a large number of calls for the analysis. For many structural optimization problems, the issue of computer time, which was earlier a limitation on the application of GA, is no longer a problem because of the increasing power of computers. Another approach to address the computer time problem is to construct high-quality approximations to the analysis problem. Hajela also gives a recent review[118] on application of soft computing to aircraft design including the use of neural networks and fuzzy logic for function approximation.

Lee and Hajela[119] applied GA for the rotor design problem. They found that the design space for rotor design problems was often nonconvex and that design variables for actual rotor cross sections could be continuous, discrete, or integer in nature. For convex functions, the local minimum is also a global minimum. Nonconvex functions can have multiple local minima and gradient-based optimization algorithms can get stuck at a local minimum point. In addition, the analysis for rotor problems is nonlinear and computationally expensive. The authors divided the optimization problem into a set of subproblems and followed a decomposition-based strategy. The decomposed problems were then solved in parallel. Neural network function approximations including backpropagation (BP) and counterpropagation networks were used to create input–output mapping for the subproblems linking the design variables with the objective functions and constraints. For numerical results, the authors considered a hingeless composite rotor blade. The objective was to design the blade geometry and structure to minimize a weighted sum of the rotor hub shear force and bending moments for a hingeless rotor in forward flight. Constraints were imposed on power requirement in hover and forward flight, the figure of merit, lift performance, blade weight, local buckling stresses in the structural box-beam section, and failure criteria for the composite structure. The design variables were tuning mass, thickness of the blade spar, blade twist, taper, rotation speed, and ply layup angle in the vertical web of the wall. The thickness of the plies was treated as a discrete variable to select an integer number of plies. Numerical results showed the effectiveness of the decomposition-based approach over traditional strategies, with lower computer time requirements.

Crossley et al.[120] and Crossley[121,122] studied rotor design for minimum weight and power for the design variables such as number of blades, airfoil sections, solidity, twist, tip speed, disk loading, and taper. Crossley[122] developed an algorithm for collapsing the constraints and objective functions into a single objective function using the K–S function. Crossley and Laananen[123,124] and Crossley et al.[125] focused on conceptual helicopter design using GA. This study aimed at power and weight minimization subject to performance and mission constraints. There were two integer, two discrete, and five continuous design variables. The design string was 28 bit long. The design variables included true discrete variables such as number of rotors, rotor blades, wings, propellers, engines, etc. Wells et al.[126] performed optimization studies using GA. The number of blades, airfoil sections, solidity, twist, tip speed, disk loading, and taper were design variables for an acoustic optimization study. Wells[127] studied the acoustic design of tilt rotors using GA.

Fanjoy and Crossley[128] used a GA to design helicopter rotor airfoils. The objective was to maximize the lift–drag ratio of the airfoil as the blade passes through 90-, 180-, and 270-deg azimuth angles. Constraints were imposed on lift and moment coefficients at these three conditions based on the aim that the new airfoil design must be at least as good as the NACA 0012 section.[129] A constraint on flow separation at the airfoil surface was also imposed to prevent the GA from moving toward unrealistic designs. The aerodynamic analysis consisted on an inviscid panel method combined with a boundary-layer method for drag estimation. However, the aerodynamic analysis used did not have the capability of representing shocks in transonic flight conditions. Design variables used were the ordinates of the control points of a third-order B spline. There were 10 variables representing the upper surface of the airfoil, and 10 variables representing the lower surface. The trailing-edge control point has one variable. Therefore, a total of 21 design variables were used. A binary tournament, uniform crossover GA was used. The GA was found to design a better airfoil compared to the NACA 0012 configuration[129] and the VR-7 section. However, note that the quality of results is directly proportional to the quality of the underlying aerodynamic analysis involved.

Chattopadhyay and Guo[130] developed an analytical design sensitivity procedure to calculate the sensitivity of energy absorption of composite plates undergoing rate elastoplastic deformation. They used a direct differentiation approach. The sensitivity analysis procedure was combined with an optimization procedure to maximize the energy absorption capability of composite plates. The design was motivated by rotorcraft crashworthiness requirements. The more energy a structure can absorb, the better its crashworthiness. Constraints were imposed on critical buckling load and midplane deflection. The K–S function[101] is used to combine the objective function and constraints into one objective function. A hybrid optimization technique capable of using both continuous and discrete design variables is used. The procedure combines a gradient-based optimization procedure for the continuous design variables into an SA algorithm to reduce the number of evaluations of the objective function and constraints. An approximate analysis technique based on the two-point exponential expansion approach[131] is used for evaluation of the objective function and the constraints to reduce the number of expensive nonlinear finite element analysis.

Anusonti-Inthra and Gandhi[132] studied optimal multicyclic variation of blade root flap and lag stiffness for reducing the vibratory loads of a four-bladed hingeless rotor. The control algorithm in this study involved minimizing a composite quadratic function defined as

$$J = Z_n^T W_z Z_n + \Delta K_n^T W_k \Delta K_n^T$$

where W_z are the weightings on output vibration and W_k the penalty weighting on input. In addition, Z_n is the 4 per revolution hub vibration in the presence of variation in stiffness ΔK_n. This type of function is widely used for multicyclic control of rotor vibration and is given by Johnson.[133] An interesting feature of this study was that both gradient- and nongradient-based methods were used to minimize J and determine the optimal input (stiffness variation). Results obtained in this study for a four-bladed hingeless rotor similar to BO105 rotor showed that in some cases, a nongradient-based optimization yields a different solution than a gradient-based method. In this study, GA was used for the nongradient algorithm. The GA results lead to a design with greater reduction in objective function than the gradient-based method. It can, therefore, be concluded that local minima are present in the typical optimal-control-type problems that occur routinely in smart structures applications to helicopter rotors and nongradient-based methods such as GA should be considered for those problems. Later, authors extended the work to include discrete controllable stiffness devices in the blade root region.[134]

Jones et al.[135] used parallel GA to develop airfoil cross sections that addressed rotorcraft aerodynamic and aeroacoustic issues. The aerodynamic analysis was performed using the XFOIL code.[136] Pressure and shear distributions and lift and drag force were predicted by XFOIL.[136] Thickness and loading noise predictions were provided by the aeroacoustic code WOPWOP.[114] The flow conditions were taken at azimuth angles of 90, 270, and 180 deg at 75% blade radius at an advance ratio of 0.3. Constraint limits were placed on the flow condition on lift curve slope and absolute value of drag and pitch moment. These constraints assured that the lift generated by the airfoil was equal to or greater than the airfoil discussed by Prouty[137] and that the moment magnitude was smaller than in the example. The GA approach allows the discovery of nontraditional airfoil shapes because it does not need an initial design point. Pareto optimal designs of airfoils were obtained for low-noise helicopter airfoils. The results showed nontraditional airfoils shapes with waviness on the top and bottom surfaces. The authors recommend these airfoil shapes as starting designs for further study.

Heverly et al.[138] examined optimal actuator distribution for active control of helicopter vibrations using a hybrid optimization methodology. An optimal control formulation was coupled to an SA code. Numerical results showed that actuators placed on the airframe could control some of the dominant airframe modes better than compared to actuators placed near the main rotor assembly. One of their results showed that, although a typical centralized actuator configuration reduced vibration by 49%, the optimally placed actuator configurations reduced vibration by 90% and required 50% less control effort. The authors[139] conducted an experimental study on a scaled model of a helicopter tailboom to verify these optimization results and to study actuator design issues associated with integrating dual-point actuation into a semimonocoque structure. They obtained excellent correction between analytical tailboom model predictions and experimental data. When a piezoelectric stack actuator was installed on the tailboom, sufficient bending moment could be generated to suppress vibration induced by external shaker loads.

Tarzanin and Young[140] reviewed 12 years of research at The Boeing Company in the field of rotorcraft optimization. They mention encountering local minima for problems leading to premature convergence. A key discussion in this paper is the evaluation of several optimization methods for one problem. The authors created a three-bladed geometry including planform geometry including blade tip sweep. The problem had 56 design variables, which represented the level of section mass, stiffness, and chordwise c.g. position at different blade sections along the spar of the blade. The 3 and 6 per revolution loads were minimized. Constraints were put that limited the rotor weight to 1.685 times the nominal weight. Table 2 is a summary of the result for the various approaches used to solve this problem. It is clear that the derivative-free methods gave lower function values than the best gradient-based results. The authors suggest a hybrid approach that finds a good point using a nongradient method then used this point as the starting design for a gradient-based method.

Tarzanin et al.[141] investigated the use of nongradient methods for selecting a good initial starting design and avoiding local minima. They used the Tech-02 rotor analysis developed for Boeing helicopters combined with traditional gradient-based optimization. Numerical studies were conducted for a four-bladed rotor with the objective being to increase thrust produced by 30% with no increase in vibration or weight. The optimal blade design was able to achieve the desired thrust while reducing vibration levels by 48% and total flapping weight by 7%. The authors also investigated workstation

Table 2 Comparison of the resulting designs

Design	Normalized total blade weight	Normalized vibration objective function
Baseline	1.000	1.000
NPSOL (Boeing)	1.452	0.559
Design of experiments with response surfaces, by Boeing[185,186]	1.680	0.644
Evolutionary programming, by Boeing[187]	1.635	0.487
Parallel direct search, by Boeing, IBM, and Rice University[186–188]	1.289	0.501
Analytical derivatives using ADIFOR	1.323	0.564
GA with a neural net, by Rensselaer Polytechnic Institute	1.685	0.512

parallel processing to utilize unused CPU cycles and use several workstations simultaneously to conserve cycle time.

Narkiewicz and Done[142] investigated a vibration suppression device mounted inside the rotor blade of a helicopter. In this study, the vibration reduction depends on the flight condition and design parameters of both the blade and the vibration suppressor. The Powell algorithm,[143] which is a nongradient direct search method, was used. The method uses the concept of a penalty function with self-adjusting direction and step size to search for the minimum point. The objective function was a performance index for a prescribed blade load component. Constraint was imposed on the rotor thrust coefficient so that it does not vary more than a prescribed fraction from the baseline value. This constraint was found to prevent the optimizer from reducing the vibration level to zero by applying very high control loads.

Bisagni et al.[144] developed an optimization procedure for the design of helicopter structural components under crashworthiness requirements. The authors used the commercial finite element code PAMCRASH[145] for their crash simulations. They then developed response surface approximations of the finite element analysis using neural networks. Neural networks were used rather than the traditional polynomial (mostly second-order) approximations due to the highly nonlinear, nonconvex, and often disjointed design space of crash problems. Multilayer perception neural networks were used with feedforward architecture, and the training was done using the popular BP algorithm. Once the neural network was trained, it allowed quick evaluation of the structural behavior with respect to design variables, thereby reducing the total computational costs. The objective function used was a combination of the crash force efficiency and specific absorbed energy. The values of the maximum and mean forces were constrained to meet crashworthiness requirements. Other constraints are applied to define the feasibility of the structural solutions. Design variables were the thickness of the webs, thickness of the angle elements, position of the angle elements, and number of vertical rivets of the helicopter subfloor structure. During the optimization, the thicknesses were treated as continuous variables and later rounded off to the nearest commonly available discrete values. Optimization was performed using sequential quadratic programming algorithm, which is a gradient-based method, and using GA. A typical aluminium alloy helicopter subfloor was considered in the study. A total of 45 examples were created of which 36 were used for tracing the neural network and 9 for testing it. The optimization procedure led to an increase in the mean force equal to 6%, a decrease in the maximum force equal to 10%, an increase of the crash force efficiency of 18%, and a decrease in mass equal to 8%.

Sun et al.[146] used response surface methods for design of a rotor in forward flight. They constructed the response surface model from a flow analysis and solved the optimization problem using GA. The flow analysis used a two-dimensional compressive Navier–Stokes equation to analyze the aerodynamic behavior for a airfoil. This analysis was validated using experimental data for a NACA 0012 (Ref. 129) airfoil with periodic pitching motion.[147] For a rotor blade analysis, a free-wake panel method was used. Second-order polynomial response surfaces were created using the D-optimal criteria for selecting the data points. A four-bladed scaled down rotor model was used for optimization results. The NPL9615 airfoil at $r/R = 0.85$ and NPL9617 airfoil at $r/R = 1.0$ are selected as the baseline airfoils. Shape functions suggested by Hicks and Henne[148] are used to define the airfoil geometry. The design variables are applied to both the upper and lower sides of an airfoil. These design variables are the parameters defining the approximation functions of Hicks and Henne. The objective function involves maximization of the time-averaged lift–drag ratio. Constraints are put such that the time-averaged lift and pitching moment coefficients do not exceed a baseline value. It was found that the quadratic response fitted the objective and constraints quite accurately. The optimized airfoil was better than the baseline airfoil at every azimuth considered. Response surfaces were also used for the range of rotor design variability using a free-wake panel method with the optimized airfoil. The objective was to minimize the torque coefficient C_Q and to maintain constant thrust coefficient C_T. The optimal design reduced the chord length and increased the twist distribution at every radial position. The work was restricted in terms of dynamic and aeroelastic modeling but did show the potential of response surfaces in helicopter design optimization.

Akula and Ganguli[149] used GA to solve the inverse problem of creating the rotor blade mass and stiffness properties given the blade's natural frequencies. A finite element model was used for a rotating beam, and the mass and stiffness at each element was used as design variable. The objective function minimized the difference between the frequencies predicted by the model and the desired (or test) frequencies. Constraints were placed on the blade total mass and inertia. It was found that the algorithm could be used to construct a finite element model of the rotor blade from its frequencies given its total mass and inertia. Excellent results were obtained using the first 10 frequencies, but the results became less accurate when only the first 4 frequencies were used.

The rapidly increasing power of computers in the last decade has lead to the increasing use of gradient-free optimization methods for rotor problems. The calculation of gradients is a major problem in rotor design problems. Finite difference derivatives can be inaccurate unless proper step sizes are used. Analytical derivatives require extensive changes to the computer program. The use of a gradient-free method is, therefore, convenient because it removes the problems associated with gradients. Furthermore, the stochastic optimization problems such as those based on GA do not get stuck in local minima and can handle discrete or integer design variables. However, most of the cited work does not use GA in conjunction with a comprehensive aeroelastic analysis. In addition, comparative studies of gradient-based algorithms and GA for the same rotor optimization problem need to be done.

Smart Structure Applications

Smart materials allow active tailoring of structural and aeroelastic behavior of rotorcraft. Several researchers are looking at smart materials for design of rotorcraft with low vibration and augmented stability.[150−152] In fact, the use of smart materials is leading to a renaissance in rotorcraft aeroelasticity.[153] Two approaches have emerged as the most useful for the design of a low-vibration smart rotor. They are the trailing-edge flap and the active twist approaches. As progress is made in modeling of smart rotors, some researchers have started using optimization methods for such problems.

Chattopadhyay et al.[154] used formal optimization methods to design curved polymeric actuators called C-block actuator for a smart rotor blade. The optimization problem involved both continuous design variables such as flap size and discrete design variables such as number of actuators. The hybrid optimization procedure, which can handle both discrete and continuous variables, was used to maximize the flap performance using C-block actuators.

Zhang et al.[155] developed a hybrid design optimization approach with the focus on reducing vibration while minimizing control effort. They combined the active approach of using trailing-edge flaps for vibration reduction with the passive approach of structural optimization of a blade to minimize vibration. The objective function included vibratory hub loads, control inputs for the active flap, and a penalty function on the blade root loads. Constraints were placed on blade frequency and autorotational inertia. Design variables were nonstructural mass, flap, lag, and torsional stiffness of the blade. Move limits were placed on the design variables. The objective function was minimized using an optimal control/optimization process using the software DOT.[177] The authors demonstrated that both the hub vibratory loads and active flap control efforts could be reduced with no detrimental effects on the blade loads. This active–passive hybrid method could reduce the active flap deflections needed by 60% at high advance ratios and 20–40% at low advance ratios.

Sahasrabudhe et al.[156,157] modeled the smart actuation mechanism for trailing-edge flaps using a simple low-order model that matches test data. This model was then used in conjunction with a helicopter flight dynamics model to perform an optimization of flap sizing and placement for minimizing fixed-frame vibration. They recognized that robust control design and the flap design are optimization problems and developed an integrated framework for simultaneous design of the flap and the robust control system. The vibration level of the helicopter was measured using the fixed frame N per revolution hub loads. The handling quality requirements were posed as behavior constraints to enforce compliance with ADS-33C requirements.[80] Behavior constraints were also included on aeroelastic stability of the rotor. A robustness constraint is added as a limit of the H_∞ norm of an appropriate transfer function.

In the last few years, some researchers have started including smart materials in comprehensive rotor aeroelastic analysis to study their effects on helicopter vibration. These studies provide an opportunity to tailor the use of smart materials for optimal rotor performance. Furthermore, because smart materials are often used in conjunction with composites, the combined effect of tailoring smart materials and composites can be investigated.

Response Surface Methods

Application of optimization methods to complex engineering problems is often a cumbersome and labor-intensive process because of the need to integrate large computer programs involving analysis and optimization. In fact, the cumbersome process of integrating large computer programs has discouraged the use of optimization procedures by the aerospace industry. Response surface approximations of the analysis problem offer a way to shift the burden from the integration of large computer programs to the problem of constructing the approximations. Response surfaces for the objective and constraint functions are created by sampled numerical experiments over the design space. Response surfaces are obtained by using more analysis than regression coefficients, thereby, overfitting the regression model using the theory of design of experiments. Once the response surfaces are obtained, the optimum can be found at low cost because the response surfaces are merely algebraic expressions. Taylor's series approximations are local in nature. However, because response surface approximations are global in nature, they have witnessed widespread application to optimization as well as other fields in recent years.[158–161]

Most often, lower order-polynomials are used for response surfaces. Response surfaces have the advantage that they filter out the noise inherent in most numerical analyses and simplify the integration with optimization codes because of smooth functions. Numerical noise manifests itself as low-amplitude, high-frequency variations in the computation results with changes in the design variables. These variations are present in any numerical method with iterative solution procedure or discrete representations of continuous geometric shape or physical phenomenon such as fluid flow. Numerical noise creates problems for gradient-based search algorithms because they cause spurious local minima. Response surfaces, therefore, offer a useful way to approximate analyses models and filter out numerical noise. The low computational costs of evaluating response surfaces once they are obtained allow the use of global optimal search strategies such as GA and exhaustive search methods. The disadvantage of response surface methods is that the computational demands to obtain them can grow rapidly as the number of design variables increase. However, with growing power of computers, this so-called curse of dimensionality problem is decreasing. An excellent introduction to response surface methods may be found in Ref. 162.

Henderson et al.[163] reformulated the lower level optimization in Refs. 45 and 46 using response surface method. Here the objective function of the lower-level problem was replaced by a quadratic Taylor series in terms of the upper-level design variables. Although this approach uses response surface polynomials, it does not make use of the theory of design of experiments to evaluate the statistically best points for creating response surface.[164]

Kim et al.[165] studied the specific maneuvers, which are performed by helicopter in aerial encounters and the performance and handling quality characteristics that influence maneuverability agility. Optimization was achieved using the response surface methodology. The design synthesis and analysis codes were captured using response surfaces for the most significant design variables.

Ganguli[166] used response surfaces for helicopter rotor optimization. The objective of the improved design is to reduce vibratory loads at the rotor hub that are the main source of helicopter vibration. Constraints are imposed on aeroelastic stability, and move limits are imposed on the blade elastic stiffness design variables. When aeroelastic analysis is used, response surface approximations are constructed for the objective function (vibratory hub loads). It is found that second-order polynomial response surfaces constructed using the central composite design of the theory of design of experiments adequately represents the aeroelastic model in the vicinity of the baseline design. Optimization results show a reduction in the objective function of about 30%.

The study by Ganguli[166] used only one response-surface-based iteration and an exhaustive search procedure to find the optimal point. Murugan and Ganguli[167] extended this approach to using a sequence of response surface approximations. They also added constraints to ensure that the design variables remain within the region where the second-order polynomial expansions are valid. The objective function in this study was minimization of vibratory hub loads while constraints were placed on dynamic stresses caused by the first and second harmonic bending moments. Design variables include blade mass and flap, lag, and torsion stiffness. Numerical results showed that the response surface approach to optimization was effective in reducing the hub loads without resulting in an increase in dynamic stresses.

Response surfaces appear attractive for helicopter optimization problems because they decouple the analysis and optimization problems. This reduces the effort involved in integrating large computer programs, which encourages the use of optimization methods in the helicopter industry. However, because the number of points needed for creating response surfaces increases dramatically with the increase in the number of design variables, such as approach is only suitable for problems with less than about 15 design variables.

Other Recent Studies

In this section, selected studies are discussed that did not fall under the earlier discussed categories. Walsh and Young[168] have proposed an entirely different approach for the sensitivity analysis using automatic differentiation code ADIFOR,[169] which converts any computer program into a new program and computes sensitivities of given dependent variables corresponding to given independent variables. Here ADIFOR is used with the CAMRAD/JA code.[41]

The ERATO program[170] used aerodynamic and acoustic codes that were validated and upgraded using experimental data. Extensive parametric studies were done, an initial design was selected, and the optimization was performed using this initial design as a starting point. The design was tested in a wind tunnel, and it was found that acoustic gains of up to 7 dB at descent flight conditions and up to 13 dBA at high-speed flight conditions were obtained. Significant performance gains of up to 12% were found for high-speed flight.

Kim and Sarigul-Klijn have conducted several studies in the field of helicopter optimization.[171–175] In Ref. 175, the authors designed an articulated rotor blade using minimum weight, minimum vibration, and maximum material strength requirements. They divided the rotor blade analysis into two subproblems. The first subproblem was an elastic analysis to provide efficient material reassignment for the minimum weight design. The second subproblem was a dynamic analysis for optimum natural frequency placement and vibratory vertical hub shear reduction. The modal shaping technique developed by Taylor[176] was used. Three methods were compared for the multi-objective optimization. These methods were the utility function approach, the global criteria formulation, and the multilevel decomposition approach. Results were compared with single-objective optimization. The authors found that the multi-objective approach gives better optimal solutions than a single-objective approach. In addition, among the multi-objective approaches, the multilevel decomposition approach was the best. The authors suggest that blade natural frequency placement is more useful for hub shear reduction than modal shaping. This appears to contradict the results of Weller and Davis,[20] Davis and Weller,[21] and Weller and Davis.[22] The authors[175] also found many local minima that they attributed to the nonlinear nature of both objective functions and constraints. Because existence of such local minima is a weak point of gradient-based optimization algorithms, the authors suggested the use of several starting points to locate better local minima or the global optimal design.

Cheng and Celi[177] studied the optimum 2 per revolution input required to minimize rotor power, maximize thrust, or minimize rotor speed using optimization methods. It has been observed by Cheng et al.[178] that a properly phased 2 per revolution input can reduce the power required by rotor up to 16%. The physical mechanism involved a change in distribution of profile drag coefficient C_D over the rotor disk. The work of Cheng et al. was limited to linear inflow models and rigid rotor blades. Cheng and Celi[177] used a free-wake model[179] and a flexible rotor blade model. Optimization was performed using the BFGS optimization algorithm included in DOT.[77] The conclusions from the results were that 1) trim should be carried out for every value proposed by the optimization, 2) an appropriate 2 per revolution input can increase the rotor maximum thrust at high speeds by about 10%, and 3) the optimal 2 per revolution inputs predicted by the linear inflow wake model are accurate. The authors suggest that a good strategy for optimizing the 2 per revolution input is to conduct an initial study with a simple linear inflow model and then refine it with a more sophisticated one.

Sensitivity derivatives are the ratio of variation in system characteristics to the variation in design variables. System characteristics could be natural frequency, blade and hub loads, aeroelastic stability, stress levels, and other such properties, which occur as the objective function or constraints of an optimization problem. Design variables can include mass, stiffness, blade geometry, cross-sectional dimensions. Gradient-based methods need sensitivity information to find the search direction. Murthy and Haftka[180] discuss methods for calculating sensitivity derivatives of general algebraic problems. Murthy and Lu[181] review sensitivity analysis methods of eigenvalue problems, including those of periodic systems. Giunta[182] provides a recent discussion on sensitivity analysis methods.

Murthy et al.[183] developed a general formulation based on the transfer matrix to calculate the sensitivity derivatives of eigenvalue problems of one-dimensional discrete and distributed structural systems. They applied the formulation to calculate sensitivity derivatives of eigenvalue of a helicopter blade. Governing differential equations derived by Houbolt and Brooks[184] for bending–torsion vibration of twisted nonuniform rotating blades was used. The authors[183] point out that the method is very appealing because it is directly applicable to distributed systems. Thus, the intermediate step of generating a suitable discrete model representing the distributed system is eliminated. The authors showed that their sensitivity derivatives compared very well with finite difference derivatives. Also, for an optimization problem involving weight minimization of a discrete cantilever beam with a tip mass subjected to frequency constraints, the CPU time reduced was much less for the transfer matrix method than for the adjoint method and the finite difference method. As the number of beam elements and degrees of freedom and design variables of the problem increased, the advantages of the adjoint method became larger. See Table 2 and Refs. 185–188 for results for several optimatizational methods for one problem. Other recent works in the optimization area which are useful sources of ideas for rotorcraft design optimization are given in Refs. 189–201.

Conclusions

From the literature reviewed in this paper, the following conclusions can be drawn about the nature of the helicopter optimization problem. These problems involve 1) computationally expensive and unwieldy aeroelastic or finite element analysis, 2) presence of local minima, and 3) presence of numerical noise and/or convergence difficulties. The increasing power of computers decreases the problem of expensive aeroelastic and finite element analysis. However, the search for better modeling is resulting in the use of CFD for aerodynamic predictions and full finite element method formulations for the composite rotor blade structural analysis. The use of computer power to advance modeling and analysis of systems always appears to precede the use in optimization. Therefore, it is unlikely that the rotor aeroelastic problem will be computationally cheap for quite some time.

Whenever gradient-based methods are used for optimization, a large portion of the computer time is taken up by gradient calculation. Finite difference-based derivatives are prohibitively expensive. In addition, finite difference derivatives need a good estimation of step size. In some case, forward difference derivatives may not be sufficiently accurate leading to the requirement of central difference derivatives and the resultant increase in computer time.[83] Whereas the use of analytical or semi-analytical sensitivity derivatives can alleviate the computer time requirements to a great extent, they need major and time-consuming changes to be made to computer programs. Whereas this may be possible in an academic setting, it is almost impossible in an industrial setting, where proprietary computer codes are guarded carefully. Furthermore, any changes to the computer code or inclusion of new design variables or objective functions and constraints require a rederivation of the analytical derivatives and subsequent recoding into the computer program. The analysis and sensitivity calculations will deviate with the passage of time unless proper code management is done. Finally, the time saved in terms of computer expense by analytical derivatives should be weighed with the cost of labor involved on the part of skilled domain experts.

For the analysis conducted in the early 1990s, computer time was a major problem. This lead to the development of optimization methods that focused more on computer time reduction such as those based on analytical sensitivity analysis. Computer time is not a major issue today provided analyses of the same level of complexity as that used in the early 1990s are used. Therefore, for problems involving vibration prediction with quasi-steady aerodynamics, uniform or linear inflow models and a finite element/normal mode-based dynamic analysis, the computer time issue is not very important today. However, if acoustic noise predictions are needed, then the aerodynamic models become computationally expensive, and computer time becomes a significant issue for optimization. A similar computationally intensive problem occurs in flight mechanics–rotor coupled optimization and in aeromechanical optimization.

The second issue involved the presence of local minima, which has been observed in several studies in recent years. There are two approaches to address the presence of local minima. The first is to choose different starting designs and a local search method such as a gradient-based optimizer. The second is to use a nongradient-based global stochastic optimization method such as GA or SA. Hybrid approaches can also be used where GA or SA using a coarse grid searches the design space, and then the best point from this search is used as a starting point for a gradient-based method. This approach exploits the strong global search properties of GA and SA with the fast local convergence properties of gradient methods such as the quasi-Newton methods. The issues of discrete and integer design variables, which can occur in the design of composite rotor blades, are also better dealt with using a GA-type approach. However, the relative advantage offered by the global minimum should be considered. For most problems, the engineer is satisfied with an improved design, and a global minimum is useful only if it is substantially better than the local minimum.

The idea of hybrid search is not new. In fact, it can also be used in conjunction with the classical direct search methods such as the Powell's method, which can be used for zooming in on a good starting point before switching on to a gradient based method (see Ref. 189). Despite the problems of computer time that inhibit gradient-based methods in helicopter optimization, it appears that direct search methods have not found much use in this field. However, nonstochastic global optimization methods have been used in aircraft design optimization.[190] Direct search methods appear to be good area for investigation because there appears to be a renaissance under way in the direct search methods.[191,192]

The third issue involves the presence of numerical noise and/or numerical fragility of the analysis. Rotor aeroelastic analyses are often numerically fragile and may not converge at every point created by the optimizer.[193] In these conditions, engineers often relax the convergence criteria on rotor blade response or trim to get a useable solution. This is especially true when free-wake or unsteady or stall aerodynamics is used. Lack of using the same convergence criteria for all runs also introduces numerical noise. Furthermore, the nonconvergence of the code at any point can cause serious problems for any numerical optimization algorithm. Response surface methods have found use in the design where CFD predictions are used for aerodynamic loads calculations.[194] For CFD problems, numerical noise occurs due to discretization of the governing partial differential equations and causes two key problems. The first is that, as the design changes, the grid usually does not vary continuously, particularly if unstructured grids are used. This produces small discontinuities in the objective function. The second problem is that of inadequately resolved flow features caused by too course a grid or discontinuities in the solutions such as shocks that cause small-amplitude wavelike oscillations in the design space superimposed on the objective function hypersurface.[195] Whereas polynomial response surfaces are widely used, those based on neural networks[196] or kriging[197] can give better global approximations, albeit at the expense of increased complexity. The response surface methods smooth out the numerical noise and prevent the optimizer from getting stuck into a local minimum. Lack of convergence at same points can be compensated by running the code at other points in the vicinity where convergence can be achieved. The response surface methods also allow the use of GA or SA for optimization because the approximate functions are typically polynomials, or nested sigmoidal functions in the case of neural networks, that are very easy to evaluate computationally.

It appears that a good strategy for future work is to create high quality approximations or surrogates for the helicopter analysis. These surrogates can be polynomial response surfaces, kriging models, neural networks, or fuzzy logic systems. Using surrogates transfers the typical problem of integrating large computer programs containing the analysis and optimization algorithms to that of constructing approximations. The surrogate problem can then be solved using the powerful nongradient methods such as GA or SA. The key issue here is determining the region over which approximations are valid. Often engineering judgment can be used to determine this, although more rigorous methods such as trust region methods can be used.[198,199]

Because the predictions of helicopter analyses are often uncertain, use can be made of fuzzy optimization techniques allowing soft constraint satisfaction.[200] The use of stochastic optimization methods for obtaining the Pareto frontier for multi-objective optimization problems is also possible.[201] Finally, as parallel computing becomes easier with personal computer or workstation cluster computing, the ability of stochastic optimization methods for solving helicopter optimization problems on personal computer clusters should be explored.[185]

An issue that would greatly help the helicopter optimization community is the presence of test problems. Because the analysis codes used differ for different problems, one approach can be to create an approximate problem using surrogate functions from an established aeroelastic analysis and present it as a test problem.

In conclusion, we see that the state of the art in helicopter optimization has advanced considerably, and key issues and problems facing the field are much clearer than they were 10 years ago. Unfortunately, the rotary wing industry is not investing heavily in developing optimization packages because they do not have the resources. However, with the ever increasing power of computers, development of efficient sensitivity analysis, and improved predictability of comprehensive rotorcraft analyses, the time is now appropriate for creating optimization solutions that can be easily used by the helicopter industry.

References

[1]Miura, H., "Applications of Numerical Optimization Methods to Helicopter Design Problems—A Survey," *Vertica*, Vol. 9, No. 2, 1985, pp. 141–154.

[2]Friedmann, P. P., "Helicopter Vibration Reduction Using Structural Optimization with Aeroelastic/Multidisciplinary Constraints—A Survey," *Journal of Aircraft*, Vol. 28, No. 1, 1991, pp. 8–21.

[3]Adelman, H. M., and Mantay, W. R., "Integrated Multidisciplinary Design Optimization of Rotorcraft," *Journal of Aircraft*, Vol. 28, No. 1, 1991, pp. 22–28.

[4]Celi, R., "Recent Applications of Design Optimization to Rotorcraft—A Survey," *Journal of Aircraft*, Vol. 36, No. 1, 1999, pp. 176–189.

[5]Sobieszczanski-Sobieski, J., and Haftka, R. T., "Multidisciplinary Aerospace Design Optimization: Survey of Recent Developments," *Structural Optimization*, Vol. 14, No. 1, 1997, pp. 1–23.

[6]Gieseng, J., and Barthelemy, J. F. M., "Summary of Industry MDO Applications and Needs," AIAA Paper 98-4737, Sept. 1998.

[7]Hansford, R. E., and Vorwald, J., "Dynamics Workshop on Rotor Vibratory Loads Prediction," *Journal of the American Helicopter Society*, Vol. 43, No. 1, 1998, pp. 76–87.

[8]Bousman, W. G., "Putting the Aero Back into Aeroelasticity," NASA TM-2000-209589, March 2000.

[9]Ganguli, R., Chopra, I., and Weller, W. H., "Comparison of Calculated Vibratory Rotor Hub Loads with Experimental Data," *Journal of American Helicopter Society*, Vol. 43, No. 4, 1998, pp. 312–318.

[10]Bielawa, R. L., "Techniques for Stability Analysis and Design Optimization with Dynamic Constraints of Non Conservative Linear Systems," AIAA Paper 71-388, 1971.

[11]Bennett, R. L., "Application of Optimization Methods to Rotor Design Problems," *Vertica*, Vol. 7 , No. 3, 1983, pp. 201–208.

[12]Peters, D. A., Ko, T., Korn, A., and Rossow, M. P., "Design of Helicopter Rotor Blades for Desired Placement of Natural Frequencies," *Proceedings of the 39th Annual Forum of the American Helicopter Society*, American Helicopter Society, Alexandria, VA, 1983, pp. 674–689.

[13]Vanderplaats, G. N., "CONMIN—A Fortran Program for Constrained Function Minimization," User's Guide, NASA TM-X 62282, Aug. 1973.

[14]Shanthakumaran, P., and Friedmann, P. P., "Optimum Design of Rotor Blades for Vibration Reduction in Forward Flight," *Journal of the American Helicopter Society*, Vol. 29, No. 4, 1984, pp. 70–80.

[15]Grandhi, R. V., Thareja, R., and Haftka, R. T., "NEWSUMT-A: A General Purpose Program for Constrained Optimization Using Constraint Approximations," *Journal of Mechanisms, Transmission and Automation in Design*, Vol. 107, March 1985, pp. 94–99.

[16]Lim, J. W., and Chopra, I., "Aeroelastic Optimization of a Helicopter Rotor," *Journal of the American Helicopter Society*, Vol. 34, No. 1, 1989, pp. 55–62.

[17]Lim, J. W., and Chopra, I., "Response and Hub Loads Sensitivity Analysis of a Helicopter Rotor," *AIAA Journal,* Vol. 28, No. 1, 1990, pp. 75–82.

[18]Lim, J. W., and Chopra, I., "Stability Sensitivity Analysis of a Helicopter Rotor," *AIAA Journal,* Vol. 28, No. 6, 1990, pp. 1089–1097.

[19]Lim, J. W., and Chopra, I., "Aeroelastic Optimization of a Helicopter Rotor Using an Efficient Sensitivity Analysis," *Journal of Aircraft*, Vol. 28, No. 1, 1991, pp. 29–37.

[20]Weller, W. H., and Davis, M. W., "Wind Tunnel Tests of Helicopter Blade Designs Optimized for Minimum Vibration," *Journal of the American Helicopter Society*, Vol. 34, No. 3, 1989, pp. 40–50.

[21]Davis, M. W., and Weller, W. H., "Helicopter Rotor Dynamics Optimization with Experimental Verification," *Journal of Aircraft*, Vol. 28, No. 1, 1991, pp. 38–48.

[22]Weller, W. H., and Davis, M. W., "A Modal-Based Procedure for Efficiently Predicting Low Vibration Rotor Design," *Journal of the American Helicopter Society*, Vol. 38, No. 1, 1993, pp. 62–72.

[23]Celi, R., and Friedmann, P. P., "Structural Optimization with Aeroelastic Constraints of Rotor Blades with Straight an Swept Tips," *AIAA Journal*, Vol. 28, No. 5, 1990, pp. 928–936.

[24]Vanderplaats, G. N., "Approximation Concepts for Numerical Airfoil Optimization," NASA TP-1370, March 1979.

[25]Vanderplaats, G. N., *Numerical Optimization Techniques for Engineering Design: with Applications,* McGraw–Hill, New York, 1984.

[26]Celi, R., and Friedmann, P. P., "Rotor Blade Aeroelasticity in Forward Flight with an Implicit Aerodynamic Formulation," *AIAA Journal*, Vol. 26, No. 12, 1988, pp. 1425–1433.

[27]Celi, R., and Friedmann, P. P., "Aeroelastic Modeling of Swept Tip Rotor Blades Using Finite Elements," *Journal of American Helicopter Society*, Vol. 33, No. 2, 1988, pp. 43–52.

[28]Celi, R., "Optimum Aeroelastic Design of Helicopter Rotors for Longitudinal Handling Qualities Improvement," Vol. 28, No. 1, 1991, pp. 49–57.

[29]Spence, A. M., and Celi, R., "Efficient Sensitivity Analysis for Rotary-Wing Aeromechanical Problems," *AIAA Journal*, Vol. 32, No. 12, 1994, pp. 2337–2344.

[30]Chattopadhyay, A., Walsh, J. L., and Riley, M. F., "Integrated Aerodynamic Load/Dynamic Optimization of Helicopter Rotor Blades," *Journal of Aircraft*, Vol. 28, No. 1, 1991, pp. 58–65.

[31]Johnson, W., "A Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics, Part I: Analysis Development," NASA TM 81182, June 1980.

[32]Chattopadhyay, A., and McCarthy, T. R., "Multiobjective Design Optimization of Helicopter Rotor Blades with Multidisciplinary Constraints," *Optimization of Structural Systems and Industrial Applications*, Elsevier, London, 1991, pp. 451–462.

[33]Chattopadhyay, A., and McCarthy, T. R., "Multidisciplinary Optimization of Helicopter Rotor Blades Including Design Variable Sensitivity," *Engineering Composites*, Vol. 3, No. 1, 1993, pp. 585–599.

[34]Chattopadhyay, A., and McCarthy, T. R., "A Multidisciplinary Optimization Approach for Vibration Reduction in Helicopter Rotor Blades," *Computer and Mathematics, with Applications*, Vol. 25, No. 2, 1993, pp. 59–72.

[35]Chattopadhyay, A., and Chiu, Y. D., "An Enhanced Integrated Aerodynamic/Dynamic Approach to Optimum Rotor Blade Design," *Structural Optimization*, Vol. 4, 1992, pp. 75–84.

[36]Chattopadhyay, A., and Seeley, C. E., "A Simulated Annealing Technique for Multiobjective Optimization of Intelligent Structures," *Smart Materials and Structures*, Vol. 3, No. 2, 1994, pp. 98–106.

[37]Bezard, H., "Numerical Optimization of Helicopter Rotor Blade Airfoils Using Unsteady Aerodynamic Calculations," ONERA, TP 1991-187, Oct. 1991.

[38]Bezard, H., "Rotor Blade Airfoil Design by Numerical Optimization and Unsteady Calculations," *Proceedings of the 48th Annual Forum of the American Helicopter Society*, American Helicopter Society, Alexandria, VA, 1992, pp. 1283–1294.

[39]Zibi, J., Defresne, G., and Costes, M., "A Numerical Procedure for Aerodynamic Optimization of Helicopter Rotor Blades," *Proceedings of the 18th European Rotorcraft Forum*, European Aerospace Societies, 1992.

[40]Pritchard, J. I., Adelman, H. M., Walsh, J. L., and Wilbur, M. L., "Optimizing Tuning Masses for Helicopter Rotor Blade Vibration Reduction and Comparison with Test Data," *Journal of Aircraft*, Vol. 30, No. 6, 1993, pp. 906–910.

[41]Johnson, W., "A Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics–Johnson Aeronautics Version," Johnson Aeronautics, Palo Alto, CA, 1988.

[42]Walsh, J. L., "Performance Optimization of Helicopter Rotor Blades," NASA TM-104054, April 1991.

[43]Walsh, J. L., LaMarsh, W. J., II, and Adelman, H. M., "Fully Integrated Aerodynamic/Dynamic Optimization of Helicopter Rotor Blades," *Mathematical and Computer Modelling*, Special Issue on Rotorcraft Modelling: Part 1, Vol. 18, No. 3/4, 1993, pp. 53–72.

[44]LaMarsh, W. J., II, Walsh, J. L., and Rogers, J. L., "Aerodynamic Optimization of a Rotor Blade Using a Neural Network as the Analysis," AIAA Paper 92-4837, Sept. 1992.

[45]Walsh, J. L., Young, K. C., Pritchard, J. I., Adelman, H. M., and Mantay, W. R., "Multilevel Decomposition Approach to Integrated Aerodynamic/Dynamic/Structural Optimization of Helicopter Rotor Blades," NASA TM-109084, May 1994.

[46]Walsh, J. L., Young, K. C., Pritchard, J. I., Adelman, H. M., and Mantay, W. R., "Integrated Aerodynamic/Dynamic/Structural Optimization of Helicopter Rotor Blades Using Multilevel Decomposition," NASA TP 3465, Jan. 1995.

[47]Young, D. K., and Tarzanin, F. J., Jr., "Structural Optimization and Mach Scale Test Validation of a Low Vibration Rotor," *Journal of the American Helicopter Society*, Vol. 38, No. 3, 1993, pp. 83–92.

[48]Venkatesan, C., Friedmann, P. P., and Yuan, K.-A., "A New Sensitivity Analysis for Structural Optimization of Composite Rotor Blades," *Mathematical and Computer Modeling*, Special Issue on Rotorcraft Modeling: Part 1, Vol. 19, No. 3–4, 1994, pp. 1–25.

[49]Barwey, D., and Peters, D. A., "Optimization of Composite Rotor Blades with Advanced Structural and Aerodynamic Modeling," *Mathematical and Computer Modelling*, Special Issue on Rotorcraft Modelling: Part 2, Vol. 19, No. 3–4, 1994, pp. 37–52.

[50]Davis, M. W., "Optimization of Helicopter Rotor Blade Design for Minimum Vibration," CP-2327, NASA, Sept. 1984, pp. 609–625.

[51]Banerjee, D., and Santhakumaran, P., "Application of Numerical Optimization Methods in Helicopter Industry," *Vertica*, Vol. 13, No. 1, 1989, pp. 17–42.

[52]Hong, C. T., and Chopra, I., "Aeroelastic Stability Analysis of a Composite Rotor Blade," *Journal of the American Helicopter Society*, Vol. 30, No. 2, 1985, pp. 57–67.

[53]Panda, B., and Chopra, I., "Dynamics of Composite Rotor Blades in Forward Flight," *Vertica*, Vol. 11, No. 1/2, 1987, pp. 187–210.

[54]Smith, E. C., and Chopra, I., "Formulation and Evaluation of an Analytical Model for Composite Box-Beams," *Journal of the American Helicopter Society*, Vol. 36, No. 3, 1991, pp. 23–35.

[55]Smith, E. I., and Chopra, I., "Air and Ground Resonance of Helicopter with Elastically Tailored Composite Rotor Blades," *Journal of American Helicopter Society*, Vol. 38, No. 4, 1993, pp. 50–61.

[56]Jung, S. N., Nagaraj, V. T., and Chopra, I., "Assessment of Composite Rotor Blade Modeling Techniques," *Journal of the American Helicopter Society*, Vol. 44, No. 3, 1999, pp. 188–205.

[57]Volovoi, V., Hodges, D. H., Cesnik, C., and Papescu, B., "Assessment of Beam Modeling for Rotor Blade Application," *Mathematical and Computer Modelling*, Vol. 33, No. 10–11, 2001, pp. 1099–1112.

[58]Gurdal, Z., Haftka, R. T., and Hajela, P., *Design and Optimization of Laminated Composite Materials*, Wiley, New York, 1999.

[59]Ganguli, R., and Chopra, I., "Aeroelastic Optimization of a Helicopter Rotor with Composite Coupling," *Journal of Aircraft*, Vol. 32, No. 6, 1995, pp. 1326–1334.

[60]Ganguli, R., and Chopra, I., "Aeroelastic Optimization of a Helicopter Rotor with Two-Cell Composite Blades," *AIAA Journal*, Vol. 34, No. 4, 1996, pp. 835–854.

[61]Vlasov, V. Z., *Thin-walled Elastic Beams*, National Science Foundation and Department of Commerce, TT-61-11400, Washington, DC, 1961.

[62]Chandra, R., and Chopra, I., "Experimental Theoretical Investigation of the Vibration Characteristics of Rotating Composite Box Beams," *Journal of Aircraft*, Vol. 29, No. 4, 1992, pp. 657–664.

[63]Chandra, R., and Chopra, I., "Analytical–Experimental Investigation of the Free-Vibration Characteristics of Rotating Composite I Beams," *Journal of Aircraft*, Vol. 30, No. 6, 1993, pp. 927–934.

[64]Ganguli, R., and Chopra, I., "Aeroelastic Optimization of a Helicopter Rotor to Reduce Vibration and Dynamic Stresses," *Journal of Aircraft*, Vol. 12, No. 4, 1996, pp. 808–815.

[65]Paik, J., Volovoi, V. V., and Hodges, D. H., "Cross-Sectional Sizing and Optimization of Composite Blades," AIAA Paper 2002-1322, April 2000.

[66]Cesnik, C. E. S., and Hodges, D. H., "VABS: A New Concept for Composite Rotor Blade Cross-Sectional Modeling," *Journal of the American Helicopter Society*, Vol. 42, No. 1, 1997, pp. 27–38.

[67]Vanderplaats, G. N., Sugimoto, H., and Sprague, C. M., "ADS-1: A New General Purpose Optimization Program," *AIAA Journal*, Vol. 22, No. 10, 1984, pp. 1458–1459.

[68]Vanderplaats, G. N., and Sugimoto, H., "A General Purpose Optimization Program for Engineering Design," *Computers and Structures*, Vol. 24, No. 1, 1986, pp. 13–21.

[69]Benquet, P., and Chopra, I., "Calculated Dynamic Response and Loads for an Advanced Tip Rotor in Forward Flight," *Proceedings of 15th European Rotorcraft Forum*, 1989.

[70]Kim, K. C., and Chopra, I., "Aeroelastic Analysis of Helicopter Blades with Advanced Tip Blades," *Journal of the American Helicopter Society*, Vol. 38, No. 1, 1992, pp. 15–30.

[71]Bir, G. S., and Chopra, I., "Aeromechanical Stability of Rotorcraft with Advanced Geometry Blades," *Computers and Mathematics with Applications: Special Issue on Rotorcraft*, Vol. 19, No. 3–4, 1994, pp. 159–161.

[72]Baeder, J. D., "Passive Design of High Speed Impulsive Noise Rotor," *Journal of the American Helicopter Society*," Vol. 43, No. 3, 1998, pp. 222–234.

[73]Ganguli, R., and Chopra, I., "Aeroelastic Optimization of an Advanced Geometry Helicopter Rotor," *Journal of the American Helicopter Society*, Vol. 41, No. 1, 1996, pp. 18–28.

[74]Ganguli, R., and Chopra, I., "Aeroelastic Tailoring of Composite Coupling and Blade Spanwise Geometry of a Helicopter Rotor Using Optimization Methods," *Journal of the American Helicopter Society*, Vol. 42, No. 3, 1997, pp. 218–228.

[75]Yuan, K. A., and Friedmann, P. P., "Structural Optimization, for Vibration Reduction, of Composite Helicopter Rotor Blades with Swept Tips," NASA CR-4665, May 1995.

[76]Yuan, K. A., and Friedmann, P. P., "Structural Optimization for Vibratory Loads Reduction of Composite Helicopter Rotor Blades with Advanced Geometry Tips," *Journal of the American Helicopter Society*, Vol. 43, No. 3, 1998, pp. 246–256.

[77]DOT Users Manual, Ver. 4.20, Vanderplaats Research and Development, Inc., Colorado Springs, CO, May 1995.

[78]Tischler, M. B., Colbourne, J. D., Morel, M. R., Biezad, D. J., Levine, W. S., and Moldoveanu, V., "CONDUIT—A New Multidisciplinary Integration Environment for Flight Control Development," NASA TM 112203, USAATCOM TR 97-A-009, 1997.

[79]Sahasrabudhe, V., Celi, R., and Tits, A., "Integrated Rotor-Flight Control System Optimization with Aeroelastic and Handling Qualities Constraints," *Journal of Guidance, Control, and Dynamics*, Vol. 20, No. 2, 1997, pp. 217–225.

[80]"Handling Qualities Requirement for Military Rotorcraft," U.S. Army Aviation and Missile Command, Rept. ADS-33E-PRF, March 2000.

[81]Sahasrabudhe, V., and Celi, R., "Efficient Treatment of Moderate Amplitude Constraints for Handling Qualities of Design Optimization," *Journal of Aircraft*, Vol. 34, No. 6, 1997, pp. 730–739.

[82]Celi, R., "Optimization Based Inverse Simulation of a Helicopter Slalom Maneuver," *Journal of Guidance, Control, and Dynamics*, Vol. 23, No. 2, 2000, pp. 289–297.

[83]Ribera, M., and Celi, R., "Maneuvering Free Wake Sensitivity for Design Optimization Applications," *Proceedings of the 57th American Helicopter Society Annual Forum*, American Helicopter Society, Alexandria, VA, 2001, pp. 14–25.

[84]Fusato, D., and Celi, R., "Formulation of a Design-Oriented Helicopter Flight Dynamic Simulation Program," *Proceedings of the 57th American Helicopter Society Annual Forum*, American Helicopter Society, Alexandria, VA, 2001, pp. 320–332.

[85]Shih, I.-C., Spence, A. M., and Celi, R., "Semi-Analytical Sensitivity of Floquet Characteristic Exponents with Application to Rotary Wing Aeroelasticity," *Journal of Aircraft*, Vol. 33, No. 2, 1996, pp. 322–330.

[86]Gandhi, F., and Hathaway, E., "Optimized Aeroelastic Couplings for Alleviation of Helicopter Ground Resonance," *Journal of Aircraft*, Vol. 35, No. 4, 1998, pp. 582–589.

[87]Hathaway, E., and Gandhi, F., "Concurrently Optimized Aeroelastic Couplings and Rotor Stiffness for Alleviation of Helicopter Aeromechanical Instability," *Journal of Aircraft*, Vol. 38, No. 1, 2001, pp. 69–80.

[88]Badre-Alam, A., Wang, K. W., and Gandhi, F., "Optimization of Enhanced Active Constrained Layer (EACL) Treatment on Helicopter Flexbeam for Aeromechanical Stability Augmentation," *Smart Materials and Structures*, Vol. 8, No. 2, 1999, pp. 182–196.

[89]Liu, Q., and Chattopadhyay, A., "Improved Helicopter Aeromechanical Stability Using Segmented Layer Damping and Hybrid Optimization," Society of Photo-Optical Instrumentation Engineers, SPIE Paper 3985-08, March 2000.

[90]Fusato, D., and Celi, R., "Multidisciplinary Design Optimization for Aeromechanics and Handling Qualities," *28th European Rotorcraft Forum*, 2002, pp. 2.1–2.15.

[91]Corso, L. M., Popelka, D. A., and Nixon, M. W., "Design Analysis and Test of a Composite Tailored Wing," *Journal of American Helicopter Society*, Vol. 45, No. 3, 2000, pp. 207–215.

[92]Chattopadhyay, A., and Narayan, J., "Optimum Design of High Speed Prop-Rotors Using a Multidisciplinary Approach," *Engineering Optimization*, Vol. 22, No. 1, 1993, pp. 1–17.

[93]Chattopadhyay, A., McCarthy, T. R., and Madden, J. F., "Structural Optimization of High Speed Prop Rotors Including Aeroelastic Stability Constraints," *Mathematical and Computer Modelling*, Special Issue on Rotorcraft Modelling: Part 2, Vol. 18, No. 3/4, 1993, pp. 101–113.

[94]Chattopadhyay, A., and McCarthy, T. R., and Seeley, C. E., "A Multiple Design Point Optimization of High-Speed Prop-Rotors," *Proceedings of the 20th European Rotorcraft Forum*, 1994.

[95]McCarthy, T. R., Chattopadhyay, A, Talbot, P. D., and Madden, J. F., "A Performance Based Optimization of High Speed Prop-Rotors," *Journal of the American Helicopter Society*, Vol. 40, No. 3, 1995, pp. 92–110.

[96]McCarthy, T. R., and Chattopadhyay, A., "A Coupled Rotor/Wing Optimization Procedure for High-Speed Tilt-Rotor Aircraft," *Journal of the American Helicopter Society*, Vol. 41, No. 4, 1996, pp. 360–369.

[97]Chattopadhyay, A., McCarthy, T. R., and Madden, J. F., "An Optimization Procedure for the Design of Prop Rotors in High Speed Cruise Including the Coupling of Performance, Aeroelastic Stability, and Structures,"*Mathematical and Computer Modelling*, Special Issue on Rotorcraft Modelling: Part 2, Vol. 23, No. 3, 1995, pp. 239–254.

[98]Chattopadhyay, A., McCarthy, T. R., and Madden, J. F., "A Design Optimization Procedure for Minimizing Drive System Weight of High Speed Prop-Rotors," *Engineering Optimization*, Vol. 23, No. 3, 1995, pp. 239–254.

[99]Chattopadhyay, A., and McCarthy, T. R., and Seeley, C. E., "A Decomposition Based Optimization Procedure for High Speed Prop-Rotors Using Composite Tailoring," *Journal of Aircraft*, Vol. 32, No. 5, 1995, pp. 1026–1033.

[100]Chattopadhyay, A., and McCarthy, T. R., and Seeley, C. E., "Multiple Design Point Optimization of High-Speed Prop-Rotors," *Journal of Aircraft*, Vol. 33, No. 3, 1996, pp. 625–627.

[101]Kresselmeier, G., and Steinhauser, R., "Systemic Control Design by Optimizing a Vector Performance Index," *Proceedings of International Federation of Active Controls Symposium on Computer-Aided Design of Control Systems*, 1979, pp. 113–117.

[102]Chattopadhay, A., McCarthy, T. R., and Rajadas, J. N., "Multidisciplinary Optimization of Tiltrotor Blades Using Comprehensive Composite Modeling Technique," *American Helicopter Society 53rd Annual Forum*, American Helicopter Society, Alexandria, VA, 1997, pp. 809–817.

[103]McCarthy, T. R., and Chattopadhyay, A., "A Refined Higher Order Composite Box-Beam Theory," *Composites, Part B*, Vol. 28, No. 5–6, 1997, pp. 523–534.

[104]Moffitt, R. C., and Rivera, S., "An Implicit Multipoint Lifting Line Optimizer for Twist and Chord," *Proceedings of the AHS Specialist Meeting on Rotorcraft Multidisciplinary Design Optimization*, American Helicopter Society, Alexandria, VA, 1993.

[105]Davis, S. J., Moffitt, R., Quackenbush, T. R., and Wachspress, D. A., "Aerodynamic Design Optimization of a Variable Diameter Tilt Rotor," *Proceedings of the 51st Annual Forum of the American Helicopter Society*, American Helicopter Society, Alexandria, VA, 1995, pp. 101–111.

[106]Clements, T. M., and Rais-Rohani, M., "Design Optimization of a Composite Tilt-Rotor Wing with Stability Approximations," *Proceedings of the 41st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*, AIAA, Reston, VA, 2000.

[107]Soykasap, O., and Hodges, D. H., "Performance Enhancement of a Composite Tilt-Rotor Using Aeroelastic Tailoring," *Journal of Aircraft*, Vol. 37, No. 5, 2000, pp. 850–858.

[108]He, C. J., and Peters, D. A., "Optimization of Rotor Blades for Combined Structural, Performance, and Aeroelastic Characteristics," *Structural Optimization*, Vol. 5, No. 1–2, 1992, pp. 37–44.

[109]He, C. J., and Peters, D. A., "Optimum Rotor Interdisciplinary Design with a Finite State Aeroelastic Modeling," *Mathematical and Computer Modeling*, Special Issue on Rotorcraft Modeling: Part 1, Vol. 18, No. 3/4, 1993, pp. 37–52.

[110]Berdichevsky, V., Armanios, E., and Badir, A., "Theory of Anisotropic Thin Walled Closed-Cross-Section Beams," *Composites Engineering*, Vol. 2, No. 5–7, 1992, pp. 411–432.

[111]Tadghighi, H., "An Aeroacoustic Optimization Model—A Multiobjective, Multilevel Decomposition Based Optimization Technique," *Proceedings of the 54th AHS Annual Forum*, American Helicopter Society, Alexandria, VA, 1998, pp. 197–215.

[112]Boyd, D. D., Brooks, T. F., Burley, C. L., and Jolly, J. R., Jr., "Aeroacoustic Codes for Rotor Harmonic and BVI Noise-CAMRAD.mod1/HIRES: Methodology and Users' Manual," NASA TM 110297, June 1997.

[113]Chattopadhyay, A., Jury, R. A., IV, and Rajadas, J. N., "An Enhanced Multiobjective Formulation Technique for Multidisciplinary Design Optimization," AIAA Paper 97-0104, Jan. 1997.

[114]Brentner, K. S., "Prediction of Helicopter Rotor Discrete Frequency Noise," NASA TM 87721, Oct. 1986.

[115]Hajela, P., "Nongradient Methods in Multidisciplinary Design Optimization: Status and Potential," *Journal of Aircraft*, Vol. 36, No. 1, 1999, pp. 255–265.

[116]Coello, C. A., "Theoretical and Numerical Constraint Handling Techniques used with Evolutionary Algorithms: A Survey of the State of the Art," *Computer Methods in Applied Mechanics and Engineering*, Vol. 191, Nos. 11–12, 2002, pp. 1245–1287.

[117]Trosset, M. W., "What is Simulated Annealing?" *Optimization and Engineering*, Vol. 2, No. 2, 2001, pp. 201–213.

[118]Hajela, P., "Soft Computing in Multidisciplinary Aircraft Design—New Direction for Research," *Progress in Aerospace Sciences*, Vol. 38, No. 1, 2002, pp. 1–21.

[119]Lee, J., and Hajela, P., "Parallel Genetic Algorithm Implementation in Multidisciplinary Rotor Blade Design," *Journal of Aircraft*, Vol. 33, No. 5, 1996, pp. 962–969.

[120]Crossley, W. A., Wells, V. L., and Laananen, D. H., "The Potential of Genetic Algorithms for Conceptual Design of Rotor Systems," *Engineering Optimization*, Vol. 24, No. 3, 1995, pp. 221–238.

[121]Crossley, W. A., "Genetic Algorithm Approaches for Multiobjective Design of Rotor Systems," *Proceedings of the AIAA/NASA/ISSMO 6th Symposium on Multidisciplinary Analysis and Optimization*, AIAA, Reston, VA, 1996, pp. 384–394.

[122]Crossley, W. A., "A Genetic Algorithm with the Kreisselmeier-Steinhauser Function for Multiobjective Constrained Optimization of Rotor Systems," *Proceedings of the AIAA 35th Aerospace Sciences Meeting and Exhibit*, AIAA, Reston, VA, 1997.

[123]Crossley, W. A., and Laananen, D. H., "The Genetic Algorithm as an Automated Methodology for Helicopter Conceptual Design," *Journal of Engineering Design*, Vol. 8, No. 3, 1997, pp. 231–250.

[124]Crossley, W. A., and Laananen, D. H., "Conceptual Design of Helicopters Via Genetic Algorithm," *Journal of Aircraft*, Vol. 33, No. 6, 1996, pp. 1062–1070.

[125]Crossley, W. A., Regulski, J. J., Wells, V. L., and Laananen, D. H., "Incorporating Genetic Algorithms and Sizing Codes for Conceptual Design of Rotorcraft," *Proceedings of the American Helicopter Society Vertical Lift Aircraft Design Conference*, 1995, pp. 1.4.1–1.4.14.

[126]Wells, V. L., Han, A. Y., and Crossley, W. A., "Acoustic Design of Rotor Blades Using a Genetic Algorithm," *Aerodynamics and Aeroacoustics of Rotorcraft*, CP-552, AGARD, Aug. 1995, pp. 1–10.

[127]Wells, V. L., "Genetic Algorithms in Conceptual Design of a Light-Weight, Low-Noise, Tilt-Rotor Aircraft," NASA CR-201404, June 1996.

[128]Fanjoy, D. W., and Crossley, W. A., "Aerodynamic Shape Design for Rotor Airfoils via Genetic Algorithm," *Journal American Helicopter Society*, Vol. 43, No. 3, 1998, pp. 263–270.

[129]Abbott, I. H., and Von Doenhoff, A. E., *Theory of Wing Sections*, Dover, New York, 1959, pp. 462, 463.

[130]Chattopadhyay, A., and Guo, R., "Energy Absorption in Composite Plates Undergoing Elastoplastic Deformation Using Analytical Sensitivity and Hybrid Optimization," *52nd American Helicopter Society Annual Forum*, 1996, pp. 961–970.

[131]Fadel, G. M., Riley, M. F., and Barthelemy, J. F., "Two-Point Exponential Approximation Method for Structural Optimization," *Structural Optimization*, Vol. 2, 1990, pp. 117–124.

[132]Anusonti-Inthra, P., and Gandhi, F., "Optimal Control of Helicopter Vibration Through Cyclic Variations in Blade Root Stiffness," *Proceedings of the 26th European Rotorcraft Forum*, 2000, pp. 32.1–32.11; also *Journal of Intelligent Materials Systems and Structures*, Vol. 11, No. 2, 2000, pp. 153–166.

[133]Johnson, W., "Self-tuning Regulators for Multicyclic Control of Helicopter Vibration," NASA TP 1996, March 1982.

[134]Gandhi, F., and Anusonti-Inthra, P., "Helicopter Vibration Reduction Using Discrete Controllable Stiffness Derives at the Rotor Hub," *Journal of Aircraft*, Vol. 39, No. 4, 2002, pp. 668–677.

[135]Jones, B. R., Crossley, W. A., and Lyrintzis, A. S., "Aerodynamic and Aeroacoustic Optimization of Rotorcraft Airfoils via a Parallel Genetic Algorithm," *Journal of Aircraft*, Vol. 37, No. 6, 2000, pp. 1088–1098.

[136]Drela, M., "XFOIL: An Analysis and Design System for Low Reynolds Number Airfoils," *Proceedings of the Third International Conference on Aerodynamic at Low Reynolds Numbers*, Springer-Verlag, New York, 1989, pp. 1–12.

[137]Prouty, R. W., *Helicopter Performance, Stability and Control*, Krieger, Malabar, FL, 1990, pp. 140–162.

[138]Heverly, D., Smith, E. C., and Wang, K. W., "An Optimal Actuator Placement Methodology for Active Control of Helicopter Airframe Vibrations,"*Journal of American Helicopter Society*, Vol. 46, No. 4, 2001, pp. 251–261.

[139]Heverly, D., Wang, K. W., and Smith, E. C., "Optimal Actuator Placement and Active Structure Design for Control of Helicopter Airframe Vibrations," *Proceedings of 58th American Helicopter Society Forum*, American Helicopter Society, Alexandria, VA, 2002, pp. 2149–2166.

[140]Tarzanin, F., and Young, D. K., "Boeing Rotorcraft Experience with Rotor Design and Optimization," AIAA Paper 98-4733, Sept. 1998.

[141]Tarzanin, F., Young, D., and Panda, B., "Advanced Aeroelastic Optimization Applied to an Improved Performance, Low Vibration Rotor," *Proceedings of the 55th American Helicopter Society Annual Forum*, American Helicopter Society, Alexandria, VA, 1999, pp. 183–194.

[142]Narkiewicz, J., and Done, G. T. S., "A Smart Internal Vibration Suppressor for a Helicopter Blade—A Feasibility Study," *Journal of Sound and Vibration*, Vol. 215, No. 2, 1998, pp. 211–229.

[143]Powell, M. J., "An Efficient Method for Finding the Minimum of a Function of Several Variables Without Calculating Derivatives," *Computer Journal*, Vol. 7, No. 2, 1964, pp. 155–162.

[144]Bisagni, C., Lanzi, L., and Ricci, S., "Optimization of Helicopter Subfloor Components Under Crashworthiness Requirements Using Neural Networks," *Journal of Aircraft*, Vol. 39, No. 2, 2002, pp. 296–304.

[145]"PAMCARSH Users Manuals, Pam Generic Reference Manual and Pamview Reference Manual," Ver. 2000, ESI/PSI, Inc., Paris, March 2000.

[146]Sun, H., Kim, Y., Lee, S., and Lee, D., "Aerodynamic Design of Helicopter Rotor Blade in Forward Flight Using Response Surface Methodology," *Proceedings of 58th American Helicopter Society Forum*, 2002; also *Journal of the American Helicopter Society*, Vol. 48, No. 4, 2004, pp. 300–304.

[147]McCrosky, W. J., Mcalister, K. W., Carr, L. W., Pucci, S. L., Lambert, O., and Indergrand, R. F., "Dynamic Stall on Advanced Airfoil Sections," *Journal of American Helicopter Society*, Vol. 26, No. 3, 1981, pp. 40–50

[148]Hicks, R. M., and Henne, P. A., "Wing Design by Numerical Optimization," *Journal of Aircraft*, Vol. 15, No. 7, 1978, pp. 407–412.

[149]Akula, V. R., and Ganguli, R., "Finite Element Model Updating of a Helicopter Rotor Blade Using Genetic Algorithm," *AIAA Journal*, Vol. 41, No. 3, 2003, pp. 554–556.

[150]Giurgiutiu, V., "Review of Smart Materials. Actuation Solutions for Aeroelastic and Vibration Control," *Journal of Intelligent Material Systems and Structures*, Vol. 11, No. 7, 2000, pp. 525–543.

[151]Chopra, I., "Review of State of Art of Smart Structures and Integrated Systems," *AIAA Journal*, Vol. 40, No. 11, 2002, pp. 2145–2187.

[152]Garg, D. P., Zikray, M. A., and Anderson, G. L., "Current and Potential Future Activities in Adaptive Structures: An ARO Perspective," *Smart Materials and Structures*, Vol. 10, No. 4, 2001, pp. 610–623.

[153]Friedmann, P. P., "The Renaissance of Aeroelasticity and Its Future," *Journal of Aircraft*, Vol. 36, No. 1, 1999, pp. 105–121.

[154]Chattopadhyay, A., Seeley, C. E., and Mitchell "Design of a Smart Flap Using Polymeric C-block Actuators and a Hybrid Optimization Technique," *Smart Materials and Structures*, Vol. 6, No. 2, 1997, pp. 134–144.

[155]Zhang, J., Smith, E. C., and Wang, K. W., "Active–Passive Hybrid Optimization of Rotor Blades with Trailing Edge Flaps," *Journal of the American Helicopter Society*, Vol. 49, No. 1, 2004, pp. 54–65.

[156]Sahasrabudhe, V., Chen, P. C., Thompson, P. M., and Aponso, B. L., "Integrated Design of Smart Rotor and Robust Control," *Proceedings of SPIE*, International Society for Optical Engineering, Vol. 3329, Bellingham, Washington, 2000, pp. 343–353.

[157]Sahasrabudhe, V., Thomson, P. M., Aponso, B. L., and Chen, P. C., "Smart Rotor Active Control," *American Helicopter Society 54th Annual Forum*, American Helicopter Society, Alexandria, VA, 1998, pp. 1057–1063.

[158]Baker, C. A., Grossman, B., Haftka, R. T., Mason, W. H., and Watson, L. T., "High Speed Civil Transport Design Space Exploration Using Aerodynamic Response Surface Approximation," *Journal of Aircraft*, Vol. 39, No. 2, 2002, pp. 215–220.

[159]Sevant, N. E., Bloor, M. I. G., and Wilson, M. J., "Aerodynamic Design of a Flying Wing Using Response Surface Methodology," *Journal of Aircraft*, Vol. 37, No. 4, 2000, pp. 562–569.

[160]Hosder, S., Watson, L. T., Grossman, B., Mason, W. H., Kim, H., Haftka, R. T., and Con, S. E., "Polynomial Response Surface Approximations for the Multidisciplinary Design Optimization of a High Speed Civil Transport," *Optimization and Engineering*, Vol. 2, No. 4, 2001, pp. 431–452.

[161]Venter, G., Haftka, R. T., and Starnes, J. H., Jr., "Construction of Response Surface Approximations for Design Optimization," *AIAA Journal*, Vol. 36, No. 12, 1998, pp. 2242–2249.

[162]Myers, R. H., and Montgomery, D. C., *Response Surface Methodology-Process and Product Optimization Using Designed Experiments*, Wiley, New York, 1995.

[163]Henderson, J. L., Walsh, J. L., and Young, K. C., "Application of Response Surface Techniques to Helicopter Rotor Blade Optimization Procedure," *Proceedings of the AHS National Technical Specialist Meeting on Rotorcraft Structures: Design Challenges and Innovative Solutions*, 1995.

[164]Montgomery, D. C., *Design and Analysis of Experiments*, Wiley, New York, 1997.

[165]Kim, H. S., Schrage, D. P., and Mavris, D. N., "Conceptual Design Optimization for Military Helicopter Maneuverability and Agility," *53rd American Helicopter society Annual Forum*, American Helicopter Society, Alexandria, VA, 1997, pp. 775–782.

[166]Ganguli, R., "Optimal Design of a Low Vibration Helicopter Rotor Using Response Surface Approximation," *Journal of Sound and Vibration*, Vol. 258, No. 2, 2002, pp. 327–344.

[167]Murugan, S. M., and Ganguli, R., "Design of Experiments Approach to Helicopter Rotor Optimization," 29th European Rotorcraft Forum, 2003.

[168]Walsh, J. L., and Young, K. C., "Automatic Differentiation Evaluated as a Tool for Rotorcraft Design and Optimization," *Proceedings of the AHS National Specialist Meeting on Rotorcraft Structures: Design Challenges and Innovative Solutions*, American Helicopter Society, Alexandria, VA, 1995.

[169]Bischof, C., Carle, A., Corliss, G., Griewank, A., and Hovland, P., "ADIFOR—Generating Derivative Codes from Fortran Programs," *Scientific Programming*, Vol. 1, No. 1, 1992, pp. 1–29.

[170]Prieur, U., and Splettstoesser, W. R., "ERATO—an ONERA–DLR Cooperative Programme on Aeroacoustic Rotor Optimization," *25th European Rotorcraft Forum*, Sept. 1999.

[171]Kim, J. E., and Sarigul-Klijn, N., "An Application of Multidisciplinary Design Optimization to an Articulated Rotor Blade in High Speed," *Proceedings of Opti-Conf 99*, 1999.

[172]Kim, J. E., and Sarigul-Klijn, N., "Aeroelastic Optimization of an Articulated Rotor Blade," 36th Technical Meeting of SES, Dynamic Systems, 1999.

[173]Kim, J. E., and Sarigul-Klijn, N., "Structural Optimization For Light-Weight Articulated Rotor Blade," *Proceedings of the 41st AIAA/ASME/AHS SDM Conference*, AIAA, Reston, VA, 2000.

[174]Kim, J. E., and Sarigul-Klijn, N., "An Efficient Multidisciplinary Design Optimization Method and Applications to Rotor Design," *AIAA Journal* (to be published).

[175]Kim, J. E., and Sarigul-Klijn, N., "Elastic-Dynamic Rotor Blade Design with Multiobjective Optimization," *AIAA Journal*, Vol. 39, No. 9, 2001, pp. 1652–1661.

[176]Taylor, R. B., "Helicopter Vibration Reduction by Rotor Blade Modal Shaping," *American Helicopter Society 38th Annual Forum*, American Helicopter Society, Alexandria, VA, 1982, pp. 90–101.

[177]Cheng, R., and Celi, R., "Optimum 2/rev Inputs for Improved Rotor Performance," *Northeast Region Active Controls Technology Conference of the American Helicopter Society*, American Helicopter Society, Alexandria, VA, 2000, pp. 120–127.

[178]Cheng, R. P., Theodore, C. R., and Celi, R., "Effects of Two/Rev Higher Harmonic Control on Rotor Performance," *Journal of the American Helicopter Society*, Vol. 48, No. 1, 2003, pp. 18–27.

[179]Bagai, A., and Leishman, J. G., "Aerodynamic Analysis of a Helicopter in Steady Maneuvering Flight Using Free-Vortex Rotor Wake Model," *Journal of the American Helicopter Society*, Vol. 44, No. 2, 1999, pp. 109–120.

[180]Murthy, D. V., and Haftka, R. T., "Survey of Methods for Calculating Sensitivity of General Eigenproblems," *NASA Symposium on Sensitivity Analysis in Engineering*, N87-18867, 1987, pp. 177–196.

[181]Murthy, V. R., and Lu, Y., "Sensitivity Analysis of Eigendata of Aeroelastic Systems," *Control and Dynamic Systems, Advances in Theory and Applications*, edited by C. T. Leondes, Vol. 54, Academic Press, San Diego, CA, 1992, pp. 297–340.

[182]Giunta, A. A., "Sensitivity Analysis for Coupled Aero-Structural Systems," NASA TM-1999-209367, Aug. 1999.

[183]Murthy, V. R., Lin, Y., and O'Hara, S., "Sensitivity Derivatives of Eigendata of One-Dimensional Structural Systems," *AIAA Journal*, Vol. 38, No. 1, 2000, pp. 115–122.

[184]Houbolt, J. C., and Brooks, G. W., "Differential Equations of Motion for Combined Flapwise Bending, Chordwise Bending, and Torsion of Twisted Nonuniform Rotor Blades," NASA Rept. 1346, 1958.

[185]Weissman, J. B., "Predicting the Cost and Benefit of Adapting Data Parallel Applications in Clusters," *Journal of Parallel and Distributed Computing*, Vol. 62, No. 8, 2002, pp. 1248–1271.

[186]Booker, A. J., "DACE—Design and Analysis of Computer Experiments," 7th AIAA/USAF/NASA/ISSOMO Multidisciplinary Analysis and Optimization Symposium, AIAA, Reston, VA, Sept. 1998, pp. 118–128.

[187]Booker, A. J., Dennis, J. E., Jr., Frank, P. D., Serafini, D. B., Torczon, V., and Trosset, M. W., "A Rigorous Framework for Optimization of Expensive Functions by Surrogates," Technical Rept. SSGTECH-98-095, Boeing Shared Services Group, Applied Research and Technology, March 1998.

[188]Hirsh, J. E., and Young, D. K., "Evolutionary Programming Strategies with Self-Adaptation Applied to the Design of Rotorcraft Using Parallel Processing," *7th Annual Conference on Evolutionary Programming*, Springer-Verlag, New York, 1998, pp. 147–156.

[189]Lewis, R. M., Torczon, V., and Trosset, M. W., "Direct Search Methods: Then and Now," *Journal of Computational and Applied Mathematics*, Vol. 124, No. 1–2, 2000, pp. 191–207.

[190]Cox, S. E., Haftka, R. T., Baker, C. A., Grossman, B., Mason, W. H., and Watson, L. T., "A Comparison of Global Optimization Methods for the Design of a High-speed Civil Transport," *Journal of Global Optimization*, Vol. 21, No. 4, 2001, pp. 415–432.

[191]Wright, M. H., "Direct Search Methods: Once Scorned, Now Respectable," *Numerical Analysis*, edited by D. F. Griffiths and G. A. Watson, Addison Wesley Longman, Reading, MA, 1996, pp. 191–208.

[192]He, J., Watson, L. T., Ramakrishnan, N., Shaffer, C. A., Verstak, A., Jiang, J., Bae, K., and Tranter, W. H., "Dynamic Data Structures for a Direct Search Algorithm," *Computational Optimization and Applications*, Vol. 23, No. 1, 2002, pp. 5–25.

[193]Booker, A. J., Dennis, J. E., Frank, P. D., Serafani, D. B., and Torczon, V., "Optimization Using Surrogate Objectives on a Helicopter Test Example," *Computational Methods in Optimal Design and Control*, edited by J. Borggaard, J. Burns, E. Cliff, and S. Schreek, Birkhauser, Boston, 1998, pp. 49–58.

[194]Rai, M., and Madavan, N. K., "Aerodynamic Design Using Neural Networks," *AIAA Journal*, Vol. 38, No. 1, 2000, pp. 173–182.

[195]Burman, J., and Gebart, B. R., "Influence from Numerical Noise in the Objective Function for Flow Design Optimization," *International Journal of Numerical Methods for Heat and Fluid Flow*, Vol. 11, No. 1, 2001, pp. 6–19.

[196]Stelmack, M., and Batill, S. M., "Neural Network Approximations of Mixed Continuous/Discrete Systems in Multidisciplinary Design," AIAA Paper 98-0916, Jan. 1998.

[197]Simpson, T. W., Mauery, T. M., Korte, J. J., and Mistree, F., "Kriging Model in Simulation Based Multidisciplinary Design Optimization," *AIAA Journal*, Vol. 39, No. 12, 2001, pp. 2233–2241.

[198]Alexandrov, N., Dennis, J. E., Lewis, R. M., and Torczon, V., "A Trust Region Framework for Managing the Use of Approximation Models in Optimization," *Structural Optimization*, Vol. 15, No. 1, 1998, pp. 16–23.

[199]Booker, A. J., Dennis, J. E., Frank, P. D., Serafani, D. B., Torczon, V., and Trosset, M. W., "A Rigorous Framework for Optimization of Expensive Functions by Surrogates," *Structural Optimization*, Vol. 17, No. 1, 1999, pp. 1–13.

[200]Rao, S. S., and Chen, L., "Generalized Hybrid Method for Fuzzy Multiobjective Optimization of Engineering System," *AIAA Journal*, Vol. 34, No. 8, 1996, pp. 1709–1717.

[201]Cheng, F. Y., and Li, D., "Genetic Algorithm Development for Multiobjective Optimization of Structures," *AIAA Journal*, Vol. 36, No. 6, 1998, pp. 1105–1112.

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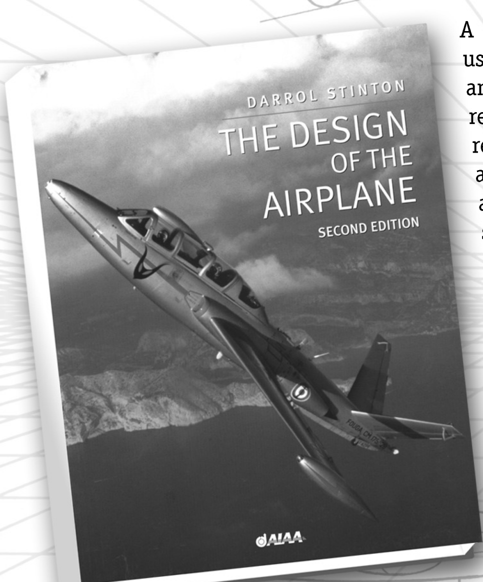

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