Integrated Multidisciplinary Design Optimization of Rotorcraft

Howard M. Adelman* and Wayne R. Mantay†
NASA Langley Research Center, Hampton, Virginia 23665

This paper describes a joint NASA/Army research activity at the NASA Langley Research Center to develop optimization procedures aimed at improving the rotor blade design process by integrating appropriate disciplines and accounting for important interactions among the disciplines. The activity is being guided by a steering committee made up of key NASA and Army researchers and managers. The committee, which has been named IRASC (Integrated Rotorcraft Analysis Steering Committee), has defined two principal foci for the activity: a "white paper," which sets forth the goals and plans for the effort; and a rotor design project, which will validate the basic constituents as well as the overall design methodology for multidisciplinary optimization. The paper describes the optimization formulation in terms of the objective function, design variables, and constraints. The analysis aspects are discussed, and an initial attempt at defining the interdisciplinary coupling is summarized. At this writing, some significant progress has been made. Results are given in the paper that represent accomplishments in rotor aerodynamic performance optimization for minimum hover horsepower, rotor dynamic optimization for vibration reduction, rotor structural optimization for minimum weight, and integrated aerodynamic load/dynamics optimization for minimum vibration and weight.

Introduction

An emerging trend in the analytical design of aircraft is the integration of all appropriate disciplines in the design process.[1,2] This means not only including limitations on the design from the various disciplines, but also defining and accounting for interactions so that the disciplines influence design decisions simultaneously rather than sequentially. Because the terms "integrated" and "discipline integration" are frequently used imprecisely, a definition of an integrated disciplinary design process is offered. Such a process is integrated if 1) information output from any discipline is expeditiously available to all other disciplines as required, and 2) the effect of a design variable change proposed by one discipline on all other disciplines and the system as a whole is made known promptly. Adhering to these definitions is central to the plan to be described in this paper. The integated approach has the potential to produce a more systematic design process. In rotorcraft design (the rotor in particular), the appropriate disciplines include aerodynamics, dynamics, structures, and acoustics. The purpose of this paper is to describe a plan for developing the logic elements for helicopter rotor design optimization that includes the just mentioned disciplines in an integrated manner.

Rotorcraft design is an ideal application for integrated multidisciplinary optimization. There are strong interactions among the four disciplines cited previously; indeed, certain design parameters influence all four disciplines. For example, rotor blade tip speed influences dynamics through the inertial and air loadings, structures by the centrifugal loadings, acoustics by local Mach number and air loadings, and aerodynamics through dynamic pressure and Mach number. All of these considerations are accounted for in current design practice. However, the process is usually sequential, not simultaneous, and often involves correcting a design late in the design schedule.

Applications of rigorous and systematic analytical design procedures to rotorcraft have been increasing, especially in the past five years. Procedures have accounted for dynamics,[3-8] aerodynamics,[9] and structures.[10] Generally, these applications have only considered single-discipline requirements.

In early 1985, several occurrences led to an excellent opportunity at the NASA Langley Research Center to address the multidisciplinary design problem for rotorcraft. The Interdisciplinary Research Office was established and charged with the development of integrated multidisciplinary optimization methods. Nearly concurrently, the Army Aerostructures Directorate at NASA Langley established the goal of improving rotorcraft design methodology by "discipline integration." Close cooperation between the NASA and Army organizations led to initial plans for a comprehensive, integrated analytical design capability. A group of NASA/Army researchers recently formed a committee and began detailed planning for this activity. The committee, designated IRASC (Integrated Rotorcraft Analysis Steering Committee), has completed the planning and has formulated the approach described in this paper.

The development of an integrated multidisciplinary design methodology for rotorcraft is a three-phased approach. In phase 1, the disciplines of blade dynamics, blade aerodynamics, and blade structures will be closely coupled, while acoustics and airframe dynamics will be decoupled from the first three but will be accounted for by effective constraints on the other disciplines. In phase 2, acoustics will be integrated with the first three disciplines. Finally, in phase 3, airframe dynamics will be fully integrated with the other four disciplines. In all three phases, systematically validated methods are the principal products of the research.

This paper is primarily concerned with the phase 1 activity; namely, the rigorous mathematical optimization of a helicopter rotor system to minimize a combination of horsepower required at various flight conditions and hub shear transmitted from the rotor to the fuselage. The design will satisfy a set of design requirements including those on blade frequencies,

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*Deputy Head, Interdisciplinary Research Office. Member AIAA.
†Chief Aeromechanics Division, Aerostructures Directorate, U.S. Army Aviation Systems Command.

autorotational inertia, aerodynamic performance, and blade structural constraints. Additionally, the design is required to satisfy constraints imposed by response of the fuselage and also those constraints related to acoustics requirements.

General Approach and Scope

Development Strategy

The general approach for the activity is illustrated in Fig. 1. In phase 1, the blade aerodynamic, dynamics, and structural analyses are coupled and driven by the optimizer. The optimization of the blade geometry as well as the internal structure is performed. The influences of the airframe dynamics and blade acoustics are accounted for in terms of design requirements (constraints) on the blade design. These requirements are described later in the paper. For a check on the efficacy of representing the acoustics requirements indirectly, the final design will be input to an acoustics analysis to determine how well the design was able to satisfy the actual acoustics design requirements.

The phase 2 procedure, wherein acoustics is fully integrated with the blade aerodynamics, dynamics, and structural analysis, is also illustrated in Fig. 1. The design produced in phase 2 (when converged) will satisfy the acoustics goal. Airframe dynamics in phase 2, as in phase 1, is accounted for by effective constraints on the blade dynamics, aerodynamics, and structural behavior. Finally, in phase 3, airframe dynamics is integrated and the result is a fully integrated optimization strategy.

Sequence of Tasks

Figure 2 depicts the general sequence of tasks that will lead to a fully integrated rotor blade aerodynamic/dynamic/structural optimization procedure that also accounts for acoustic and airframe dynamic influences. The dynamic optimization work is building on the work described in Refs. 5–7. The rotor aerodynamic activity has been separated into two parts. The first is aerodynamic performance optimization, which is a continuation of the work described in Ref. 9. The second is an integration of aerodynamic loads analysis with dynamics—a procedure wherein the local airloads can be adjusted by varying the planform dimensions and twist of the blade to reduce dynamic response. A merger of the rotor performance optimization with the airload/dynamics optimization will yield a fully integrated aerodynamic/dynamic procedure. The rotor structural optimization is a continuation of the work of Ref. 10. A merger of all the aforementioned procedures, with the acoustic and airframe constraints interfaces, will lead to the fully integrated phase 1 procedure. The resulting capability will be applied to a rotor test article to validate the procedures.

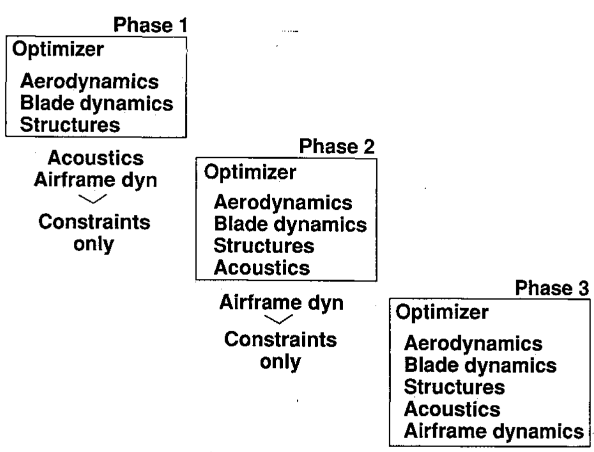


Fig. 1 Phased approach to development of integrated rotorcraft optimization procedures.

Overall Problem Formulation

This section of the paper contains details of the following: the objective function, design variables, constraints, and interactions among the disciplines.

Objective Function

The objective function will consist of a combination of the main rotor horsepower at five flight conditions plus a measure of vibratory shear transmitted from the rotor to the hub. Although several multiple objective function techniques are available,[11] one leading candidate is a linear combination whereby

$$F = k_1 \mathrm{hp}_1 + k_2 \mathrm{hp}_2 + k_3 \mathrm{hp}_3 + k_4 \mathrm{hp}_4 + k_5 \mathrm{hp}_5 + k_6 S \tag{1}$$

where F is the objective function, k_1–k_6 are weighting factors, hp_1–hp_5 are required horsepower at various flight conditions, and S is the vertical oscillatory hub shear. A candidate set of flight conditions is shown in Table 1.

Blade Model and Design Variables

Figure 3 is a depiction of the rotor blade design model. Also shown in Fig. 3 are the design variables that are defined in Table 2. The blade model may be tapered in both chord and depth. The depth is linearly tapered from root to tip. The chord is constant from the root to a spanwise location (referred to as the point of taper initiation) and may be linearly tapered thereafter to the tip. Design variables that characterize the overall geometry of the blade include the blade radius, point of taper initiation, taper ratios for chord and depth, the root chord, the blade depth at the root, the flap hinge offset, and the blade maximum twist. Tuning masses located along the blade span are characterized by the mass values and locations. Design variables that characterize the spar box beam cross section include the wall thicknesses

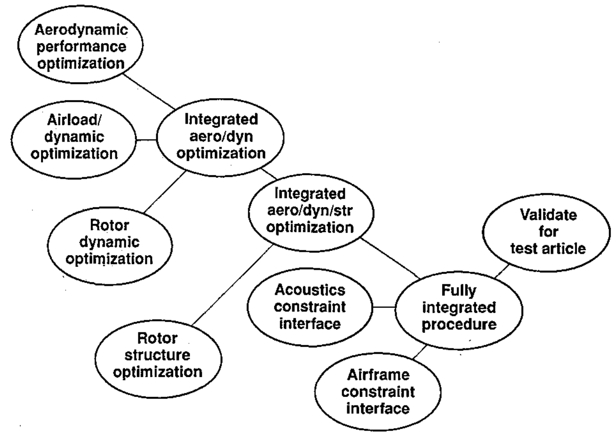


Fig. 2 Integrated rotorcraft optimization development plan.

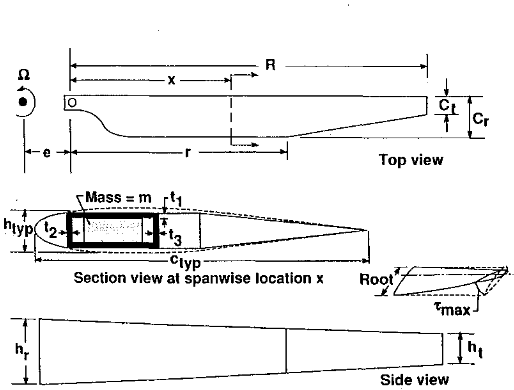


Fig. 3 Blade model and design variables.

Table 1 Flight conditions for objective function

Flight condition	Description	Velocity, kt	Load factor
1	Hover	0	1.0
2	Cruise	140	1.0
3	High speed	200	1.0
4	Maneuver	120	3.5
5	Climb	1000 fpm[a]	1.0

[a]Vertical rate of climb.

Table 2 Summary of design variables

Description	Symbol
Tuning mass at location *i*	m_i
Spanwise location of *i*th mass	x_i
Wing box dimensions	t_1,t_2,t_3
Ply thicknesses	t_{45},t_0
Depth of blade at root	h_r
Ratio of blade depths at tip and root	$\lambda_h = h_r/h_t$
Maximum pretwist of blade	τ_{max}
Percent blade span where taper begins	r
Blade root chord	c_r
Airfoil distribution	—
Hinge offset	e
Blade angular velocity	Ω
Number of blades on rotor	N
Blade radius	R
Ratio of root chord to tip chord	$\lambda_c = c_r/c_t$

Table 3 Summary of constraints

Constraint description	Form of constraint	Comments
Main rotor horsepower	$hp_i \leq$ hp available for *i*th condition	For five flight conditions
Airfoil section stall	$C_D \leq C_{D\max}$	Enforced at 12 azimuthal locations
Blade frequencies	$f_{i\ell} \leq f_i \leq f_{iu}$	
Blade vertical load	$V_{ik} \leq V_{max}$	
Blade inplane load	$H_{ik} \leq H_{max}$	
Transmitted in-plane hub shears	$X_k \leq X_{max}$ $Y_k \leq Y_{max}$	
Hub pitching moment	$P_k \leq P_{max}$	
Hub rolling moment	$R_k \leq R_{max}$	
Blade response	$q_k \leq Q_{max}$	
Autorotational inertia	$\Sigma m_i r_i^2 \geq \alpha$	
Aeroelastic stability	$\mathrm{Re}(\lambda) \leq -\varepsilon$	
Wing box stresses	$R \leq 1$	R = Tsai-Hill criterion
Blade tip deflection	$w \leq w_{max}$	
Blade twist	$\theta \leq \theta_{max}$	
Blade tip Mach number	$M \leq M_{max}$	Limits thickness noise
Blade thickness	$h \leq h_{max}$	
Blade lift distribution	$dC_l/dx \leq S_{max}$	Limits BVI and loading noise
Ground resonance	$\lvert\Omega - \omega_{L1}\rvert < \omega_{af}$	Effective airframe constraints
Rotor/airframe frequency coupling	$f_l \leq N\Omega \leq f_u$	

Table 4 Interactions among disciplines

Variable	Acoustics	Aerodynamics (performance and loads)	Dynamics	Structures	Fuselage dynamics
Airfoil distribution	S[a]	S	W	W	W
Planform	S	S	S	S	S/W
Twist	W[b]	S	S	W	W
Tip speed	S	S	S	S	S
Blade number	S	W	S	W	S
Stiffness	W	S	S	S	S/W
Mass distribution	W	W	S	S	S/W
Hinge offset	W	W	S/W	W	S/W

[a]S = strong interaction. [b]W = weak interaction.

at each spanwise segment and the ply thickness at 0 and ± 45 deg. Additional design variables include the number of rotor blades, the rotor angular speed, and the distribution of airfoils.

Constraints

The set of constraints is made up of two subsets. The first suoset consists of constraints evaluated directly from the first three disciplinary analyses and is a measure of the degree of acceptability of the aerodynamic, dynamic, and structural behavior. The second subset represents indirect measures of the satisfaction of constraints on the acoustics behavior and the requirement of avoiding excessive vibratory excitation of the airframe by the rotor.

The constraints are summarized in Table 3. The first two constraints are for aerodynamic performance and require that for all flight conditions, main rotor horsepower not exceed available horsepower and that airfoil section stall not occur at any azimuthal location. The next nine constraints address blade dynamics. The first requires that the blade natural frequencies be bounded to avoid approaching any multiples of rotor speed. The next five impose upper limits on the blade vertical and inplane loads, transmitted hub shear, hub pitching, and rolling moments. The next three dynamic constraints are an upper limit on blade response amplitude, a lower limit on blade autorotational inertia, and finally, the aeroelastic stability requirement. The structural constraints consist of upper limits on box beam stresses, blade static deflection, and blade twist deformation. The acoustic constraints are expressed as an upper bound on the tip Mach number and an upper bound on the blade thickness to limit thickness noise, and an upper bound on the gradient of the lift distribution to limit blade vortex interaction (BVI) and loading noise. The airframe constraints are expressed, first, as a separation of the fundamental blade inplane natural frequency in the fixed system from the fundamental pitching and rolling frequency of the fuselage to avoid ground resonance, second, as a bounding of the blade passage frequency to avoid the proximity to any fuselage frequency.

Interdisciplinary Coupling

Table 4 shows the interactions among the disciplines through the design variables. For example, rotor tip speed has driven past rotor designs based solely on acoustics, performance, or dynamics. This variable also influences blade structural integrity and fixed system response to transmitted loads. This provides the strong interdisciplinary coupling for tip speed shown in Table 4. There are variables, such as blade twist, that can strongly influence some disciplines, such as aerodynamics, while not perturbing others (e.g., structures) and other variables, such as a hinge offset, which, heretofore, have not greatly influenced conventional rotor design.

Implementation Method

Organization of System

The overall organization of the system to optimize a blade design for aerodynamics, dynamics, and structural requirements is shown schematically in Fig. 4. In order to perform the aerodynamic, dynamic, and structural analyses indicated in the blocks of Fig. 4, it is first necessary to transform or preprocess the design variables into quantities needed in the various analyses. For example, the dynamic and structural analyses both need stiffnesses *EI* and *GJ* and laminate properties. The aerodynamic analysis needs lift and drag coefficients for the airfoils used. This information is obtained by the design variable preprocessors, which act as translators of the global design variables into local variables needed in the analyses. The output of each analysis block, in general, serves two purposes. First, response-type output may be transmitted to another analysis block (e.g., airloads for aerodynamics to dynamics), and second, information is supplied to the objective function and constraints block (e.g., stress constraints from the structural analysis). A key part of the procedure is the sensitivity analysis. This block corresponds to the calculation of derivatives of the constraints and objective function with respect to the design variables. The derivatives quantify the effects of each design variable on the design and, thereby, identify the most important design changes to make enroute to the optimum design.

The sensitivity information is passed to the optimizer along with the current values of the design variables, constraints, and objective function. The optimizer uses the information to generate a new set of design variables, and the entire procedure is repeated until a converged design is obtained. For our purposes, a design is converged when all constraints are satisfied and the objective function has reached a value that has not changed for a specified number of cycles.

Optimization Algorithm

The basic optimization algorithm to be used in this work is a combination of the general-purpose optimization program CONMIN[12] and approximate analyses for computing the objective function and constraints. Because the optimization process requires many evaluations of the objective function and constraints before an optimum design is obtained, the process can be very expensive if complete analyses are made for each function evaluation. However, as Miura[3] points out, the optimization process primarily uses analysis results to move in the direction of the optimum design; therefore, a complete analysis needs to be made only occasionally during the design process and always at the end to check the final design. Thus, various approximation techniques can be used during the optimization to reduce costs.

Analysis Aspects

The aerodynamic analysis for rotor performance prediction will include a hover momentum/strip theory code for hover

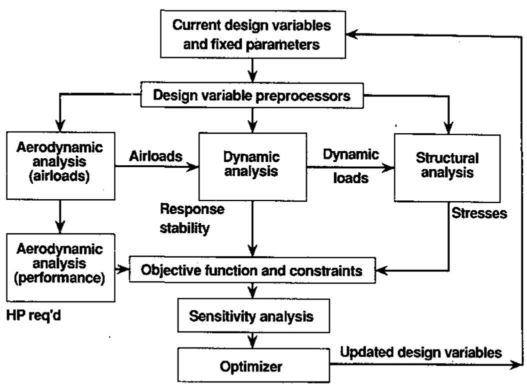


Fig. 4 Integrated aerodynamic-dynamic-structural optimization of rotor blades.

and climb applications.[13] The Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics (CAMRAD) program[14] will be used for forward flight and maneuver performance. In order to assure that the latest developments in inflow analyses are available, some modularity will be provided in the inflow modeling.

Rotor dynamics will utilize CAMRAD for forced response calculations. Finite element modeling[15] and the modified Galerkin technique in CAMRAD will form the tools for the dynamic analysis, and the global analysis will predict the final blade loads, response, and rotor stability.

The structural codes involve a combination of beam analysis and laminate analysis. The analysis (e.g., Ref. 10) is applied to the blade planform model. The laminate analysis will be applied to one or more cross-section models. The beam model consists of equivalent stiffness and masses from which displacements and forces are computed. The internal blade structure is represented by cross-section models to calculate resultant stresses associated with each beam model segment. The laminate analysis then uses these stresses to determine critical structure margins of safety.

The effectiveness of imposing phase 1 acoustic constraints will be quantified by using the WOPWOP code[16] with appropriate loading inputs from CAMRAD. Low-frequency loading, thickness, and BVI noise will be generated from this analysis.

Airframe dynamics constraints for phases 1 and 2 will result from fixed-system frequency predictions and will neglect hub motion. Phase 3 of the effort will involve finite element modeling and impedance tailoring to effect favorable rotor-body coupling in the design process.

Validation Strategy

Validation of Procedures

The analyses used in optimizing the rotor during phase 1 will be examined for predictive fidelity and design technique validation. The usefulness of the basic tools involves not only accuracy of analysis, but also a reliable parametric sensitivity capability. Several opportunities are available to assess the fidelity of the analyses. For example, rotor performance, dynamics, and acoustics predictions need accurate inflow distributions for various flight conditions. Recent experimental efforts (e.g., Ref. 17) and code validations[18] are helping to provide confidence in the available inflow models. Rotor geometric design variable sensitivity (e.g., effect of taper on performance), which was reasonably well known for past rotor designs, is being re-examined in light of recent correlation anomalies for high-speed flight. Acoustic source mechanisms and modeling validity are also being examined,[19] especially for parametric sensitivity of the acoustic energy to rotor state. Structural coupling mechanics are being exploited in new rotor designs to assess the structural tailoring benefits while satisfying structural integrity requirements.[20]

Proof of the fidelity of the design techniques is crucial to the overall design optimization effort. For example, aerodynamics and dynamics interact so strongly in rotor design that basic aeroelastic tailoring efforts must be validated. Such a validation effort is being undertaken at NASA Langley, as well as other research centers.[21] Also, because rotor speed is a strong driver for aeroelastic response, a program to assess variable rpm designs is underway at NASA Langley. The objective of this effort is to define the benefits and limitations of an aerodynamically and dynamically designed multispeed rotor.

Overall Design Validation

For the overall phase 1 validation effort, the NASA Langley team is defining a rotor task that requires maneuverability, speed, and efficiency (see Table 5). Specifically, the rotor mission must be accomplished with minimum power and vibration while satisfying predefined acoustic, stability, and

Table 5 Candidate task and mission for phase 1 design activity[a]

Description	Specification
Condition	4000 ft 95 deg
Aircraft gross weight	16875 lb
Installed power limit	3400 hp
V_{cruise}	140 kt
V_{max}	200 kt
g at 120 kt	3.5
Vertical rate of climb	1000 fpm
Airframe structure	UH-60B

[a]Other constraints and guidelines are specified in Table 3.

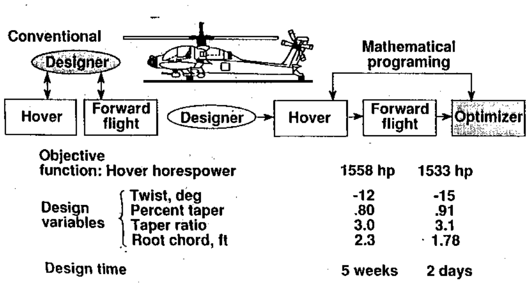


Fig. 5 Results of aerodynamic performance optimization.

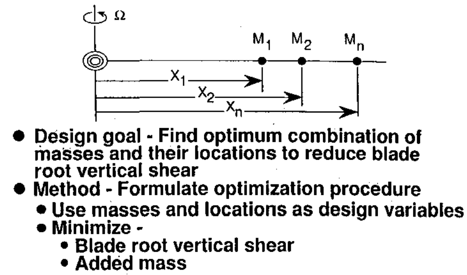


Fig. 6 Selection of optimum locations of tuning masses for vibration reduction.

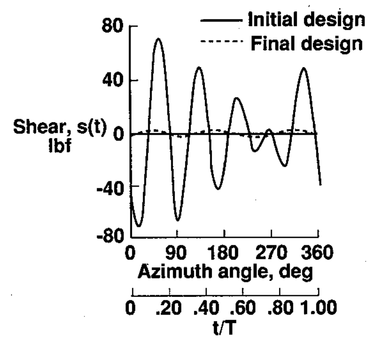


Fig. 7 Time history of vertical root shear minimized for two modes/three harmonics.

fuselage dynamics requirements. This validation activity is, in effect, a design project that will produce a rotor test article.

The assessment of the phase 1 design methods will involve model rotor hover and wind-tunnel tests. The models (a baseline and an advanced design) will be aerodynamically and dynamically scaled. Provisions for varying key design parameters are necessary to complete the validation process. In other words, the tests need to quantify not only the minima but the gradients. The testing possibilities include a series of 1/5-scale model rotors, mounted on a variable drive system and tested in hover and simulated forward flight in a tunnel that can eliminate many testing excuses such as inappropriate Reynolds, Mach, and Froude numbers. The NASA Langley Transonic Dynamics Tunnel is the candidate facility for the major segments of the validation process.

Results Obtained to Date

Progress has been made in the areas of aerodynamic performance optimization, optimum placement of tuning masses for vibration reduction, structural optimization, and integrated aerodynamic load/dynamic optimization. Selected results from these activities are highlighted in this portion of the paper.

Results—Aerodynamic Peformance Optimization

A mathematical programming technique[9] has been developed to minimize the hover horsepower of a rotor for a helicopter with a specified design gross weight operating at a specified altitude and temperature (Fig. 5). A conventional design approach is usually a two-step iterative method. The first step is a design for optimum hover performance by varying taper ratio, point of taper initiation, and twist until the rotor blade configuration with the lowest hover horsepower is obtained. In the second step, this best hover design is modified by changing the root chord to meet forward flight and maneuverability requirements. The mathematical programming approach used the same performance analyses as the conventional approach but coupled a general-purpose optimization program to the analyses. The conventional and mathematical programming approaches have been used to define the blade configuration that provides the lowest hover horsepower and satisfies forward flight and maneuverability requirements. Figure 5 summarizes results for the final design variable values and the main rotor horsepower required for hover from each approach. The mathematical programming approach produced a design with more twist, a point of taper initiation further outboard, and a smaller blade root chord than the conventional approach. The mathematical programming design required 25 less hover horsepower than the conventional design. Most significant, the mathematical programming approach obtained results more than 10 times faster than the conventional approach.

Results—Optimum Locations of Vibration Tuning Masses

The objective of this work (described in Ref. 22) is to develop a method for optimally locating, as well as sizing, tuning masses to reduce vibration using formal mathematical optimization techniques. The design goal is to find the best combination of tuning masses and their locations to minimize blade root vertical shear without a large mass penalty. Figure 6 shows an arbitrary number of masses placed along the blade span. The optimization strategy reduces the oscillatory shear as a function of time during a revolution of the blade.

The method was applied to a beam representation of an articulated rotor blade. The beam is 193 in. long with a hinged end condition and is modeled by 10 finite elements of equal length. The model contains both structural mass and lumped (nonstructural) masses. Three lumped masses are to be placed along the length of the beam. The strategy was applied to a test case of two modes responding to three harmonics of airload. Figure 7 shows for the initial and final design, the shear s plotted as a function of the time and azimuth for one complete revolution of the blade. The peaks on the initial curve have been reduced dramatically. For example, the maximum peak oscillatory shear for the initial design is 78.00 lbf, and, for the final design, the maximum peak is 0.60 lbf.

Results—Rotor Structural Optimization

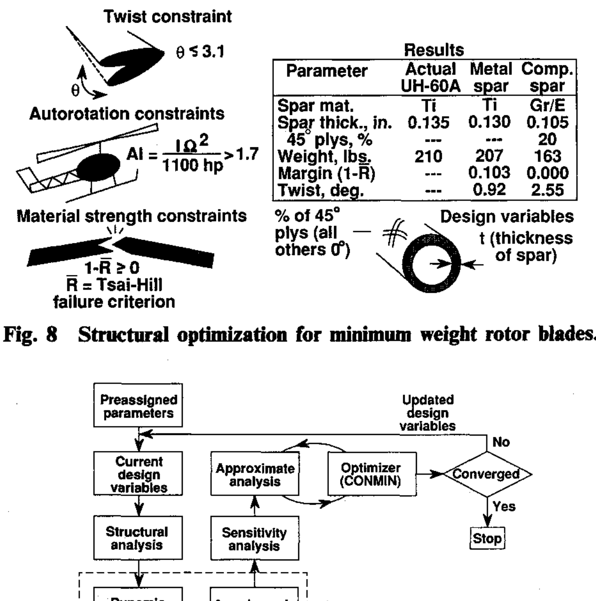
A structural optimization procedure applicable to metal and composite blades has been developed in which the objective function is blade mass with constraints on frequencies, stresses in the spars and in the skin, twist deformation, and autorotational inertia (Fig. 8). This procedure and additional applications of the method are described in detail in Ref. 10.

This section describes two example rotor blade designs that were developed using the structural design methodology. Both designs are based on the UH-60 Black Hawk blade. The first design is for a titanium single spar cross section. The second case has a graphite/epoxy spar in a single spar cross-section configuration. The composite spar design is compared to the metal spar design to explore potential weight savings obtained from use of the design methodology in conjunction with composite materials.

Titanium Cross Section

For the titanium spar blade, the cross-section model was based on the UH-60 rotor blade with identical skin, core, trailing-edge tab, leading-edge weight, and spar coordinates. Only the spar thickness was used as a design variable. The beam model representation of the blade used a rectangular planform similar to the UH-60 planform, but without any tip sweep. A maximum elastic torsional deformation of 3.1 deg is based on the effective aerodynamic performance constraint.[10] The structural constraint is based on the Tsai-Hill failure criterion.

As shown in Fig. 8, the minimum spar thickness needed to satisfy all the constraints was 0.130 in., which corresponds to a blade weight of 207 lb. The actual UH-60 titanium spar is 0.135 in. thick, producing a 210-lb blade.



Parameter	Actual UH-60A	Metal spar	Comp. spar
Spar mat.	Ti	Ti	Gr/E
Spar thick., in.	0.135	0.130	0.105
45° plys, %	---	---	20
Weight, lbs.	210	207	163
Margin (1-R̄)	---	0.103	0.000
Twist, deg.	---	0.92	2.55

Fig. 8 Structural optimization for minimum weight rotor blades.

Composite Cross Section

A second design was developed using a single T300-5208 graphite/epoxy D-spar. The design variable was the percentage of ±45-deg plies in the laminate. The remaining plies of the laminate are understood to be oriented at 0 deg. Constraints on twist deformation, material strength, mass moment of inertia, and dynamic tuning were the same as those used for the metal design. Results shown in Fig. 8 show that the composite design satisfied the required constraints. Further, the minimum weight design had a 0.105-in.-thick spar with 20% of the plies oriented at ±45 deg, which resulted in blade weight savings of 21.5%.

Results—Integrated Aerodynamic Load/Dynamic Optimization

In Ref. 23, an integrated aerodynamic load/dynamic optimization procedure was developed. The procedure minimized blade weight and 4/rev vertical hub shear for a rotor in forward flight. The coupling of aerodynamics and dynamics was accomplished by the inclusion of air load calculations inside the optimization loop wherein the air loads varied with design variables. The design model used for this procedure is the same as that in Fig. 3. The design variables include the stiffnesses *EI* for spanwise and chordwise bending, torsional stiffness *GJ*, taper ratio, root chord, radius of gyration at the root, and nonstructural masses at each spanwise location. The constraints include upper and lower bounds on the first four frequencies, a lower bound on autorotational inertia, and an upper bound on centrifugal stress. Both single and multiple objective function formulations were used and compared. In the single objective function formulations, blade weight and 4/rev shear were each individually minimized. For the multiple objective function formulation, a combination of the weight and shear was minimized by use of the global criteria approach.[11]

A flowchart showing the logic of the optimization procedure is shown in Fig. 9. The aerodynamic and dynamic response analyses are performed using CAMRAD. CAMRAD is used to calculate the section loads from the airfoil two-dimensional aerodynamic characteristics. Lifting line theory is used with corrections for yawed and three-dimensional flow effects. The blade is trimmed in each pass through the optimization loop using the wind-tunnel trim option. The dynamic analysis in CAMRAD includes calculations of the frequencies and mode shapes (using a modified Galerkin technique) and the calculation of the 4/rev vertical shear at the hub. A sensitivity analysis calculates derivatives of the objective function and the constraints with respect to the design variables.

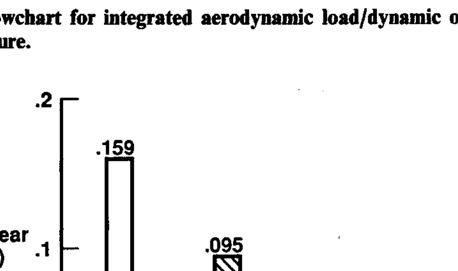


Fig. 9 Flowchart for integrated aerodynamic load/dynamic optimization procedure.

This procedure has been applied to a model of the Growth Black Hawk rotor blade (see Ref. 23 for details of this model). The baseline (analytical) model is linearly tapered from root to tip with a taper ratio of 3.0; it has eight structural nodes, 14 aerodynamics segments, and a single airfoil for all segments. The aircraft is in forward flight with an advance ratio of 0.3. Figure 10 presents comparisons of optimum vertical shear from the three formulations. As shown in the figure, the global criteria approach provides a significant hub shear reduction.

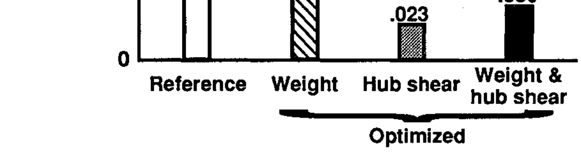


Fig. 10 Results from integrated aerodynamic load/dynamic optimization procedure.

Concluding Remarks

This paper has described a joint activity involving NASA and Army researchers at the NASA Langley Research Center to develop optimization procedures aimed at improving the rotor blade design process by integrating appropriate disciplines and accounting for all of the important interactions among the disciplines. The disciplines involved include rotor aerodynamics, rotor dynamics, rotor structures, airframe dynamics, and acoustics. The work is focused on combining the five key disciplines previously listed in an optimization procedure capable of designing a rotor system to satisfy multidisciplinary design requirements.

Fundamental to the plan is a three-phased approach. In phase 1, the disciplines of blade dynamics, blade aerodynamics, and blade structure will be closely coupled, while acoustics and airframe dynamics will be decoupled and be accounted for as effective constraints on the design for the first three disciplines. In phase 2, acoustics is to be integrated with the first three disciplines. Finally, in phase 3, airframe dynamics will be fully integrated with the other four disciplines.

This paper dealt primarily with the phase 1 approach. The paper included the following: the optimization formulation, design variables, constraints, and objective function, as well as discipline interactions, analysis methods, and methods for validating the procedure. The paper described how the acoustics and airframe dynamics behaviors are incorporated as constraints into the design procedure. Finally, some representative results from work performed to date are shown. These include aerodynamic optimization results for performance, optical placement of tuning mass for reduction of blade shear forces, blade structural optimization for weight minimization subject to strength constraints, and integrated airload/dynamic optimization results for vibration reduction.

The results of the individual optimization procedures demonstrate the potential of optimization in design of future rotorcraft, both from the standpoint of efficiency of the process as well as potentially improved products. The results of the integrated airload/dynamic optimization procedure demonstrate that there are significant opportunities awaiting analytical designers who pursue interdisciplinary design approaches.

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