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**INTEGRATION OF DYNAMIC, AERODYNAMIC, AND STRUCTURAL
OPTIMIZATION OF HELICOPTER ROTOR BLADES**

by

David A. Peters
Principal Investigator
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

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Background

This report summarizes the first six years of research into the integration of structural, dynamic, and aerodynamic considerations in the design-optimization process for rotor blades. Actually, the work will continue at Washington University in St. Louis, where the Principal Investigator is moving. Thus, although this is a Final Report on the work done at Georgia Tech, it is an interim report on the whole work.

Personnel

The following personnel have worked on this project at Georgia Tech.

David A. Peters	PI
Y.P. Cheng	Post Doctoral Fellow
Chengjian He	Ph.D. student, Post Doc
Ay Su	Ph.D. student, Post Doc
Mnaouar Chouchane	Ph.D. student
Azhar Khan	Ph.D. student

Publications

The following publications were either totally or partially funded through this Grant.

Peters, David A., and Cheng, Y.P., "Optimization of Rotor Blades for Combined Structural, Performance, and Aeroelastic Characteristics," Proceedings of the Second NASA/Air Force Symposium on Recent Experiences in Multidisciplinary Analysis and Optimization, NASA - Langley Research Center, September 28-30, 1988.

Peters, David A., Chouchane, Mnaouar, and Fulton, Mark, "Use of an Optimized Controller and a Finite-State Stall Model to Find Trimmed Helicopter Flight Controls," Proceedings of the Fifteenth European Rotorcraft Forum, The Netherlands, September 12-15, 1989, Paper No. 44.

Peters, David A. and He, Chengjian, "Optimization of Rotor Blades for Combined Structural, Dynamic, and Aerodynamic Properties," Proceedings of the Third Air Force/NASA Symposium on Recent Advances in Multidisciplinary Analysis and Optimization, San Francisco, September 24-26, 1990.

Peters, David A. and He, Chengjian, "An Aeroelastic Analysis with a Generalized Dynamic Wake", Proceedings of the AHS International Technical Specialist's Meeting on Rotorcraft Basic Research, Atlanta, March 25-27, 1991.

Peters, David A. and Chiu, Danny Y., "Aerodynamic Parametric Studies and Sensitivity Analysis for Rotor Blades in Axial Flight," Proceedings of the AHS International Technical Specialists' Meeting on Rotorcraft Basic Research, Atlanta, March 25-27, 1991.

Peters, David A. and He, Chengjian, "Integration of Dynamic, Aerodynamic, and Structural Optimization of Rotor Blades", NASA Interdisciplinary Office Optimization Workshop, April 11, 1991.

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Hanagud, S.V., Peters, David A., and Chattopadhyay, Aditi, "Applications of Structural Optimization to Rotary-Wing Aircraft," Chapter in Forthcoming Book on Optimization, Prof. Kamat, Editor.

Peters, David A., Chouchane, M., and Fulton, M., "Helicopter Trim with Flap-Lag-Torsion and Stall by an Optimized Controller", *Journal of Guidance, Control, and Dynamics*, Vol. 13(5), September-October, 1990, pp. 824-834.

He, Chengjian and Peters, David A., "A Study of Multi-Disciplinary Optimization of Rotor Blades," submitted to the 48th Annual National Forum of the American Helicopter Society, June 1992.

Chouchane, Mnaouar, *Application of a Dynamic Stall Model to Rotor Trim and Aeroelastic Response*, Ph.D. Thesis, Georgia Institute of Technology, August 1989.

Khan, Azhar Mansur, *Rotor Performance and Helicopter Mission Optimization with Quasi-Linear Inflow*, Ph.D. Thesis Proposal, Georgia Institute of Technology, 19 August 1991.

Attached is a copy of the Book Chapter since it summarizes our work over the past six years and puts it into context with other work.

He, Chengjian and Peters, David A., "An Efficient Aeroelastic Analysis for Use in Rotor Preliminary Design and Optimization," submitted to the *Journal of Aircraft*.

Applications of Structural Optimization to Rotary Wing Aircraft

by

S.V. Hanagud, David A. Peters
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332

and

Aditi Chattopadhyay
Department of Mechanical &
Aerospace Engineering
Arizona State University
Tempe, Arizona 85203

Introduction

In recent years, structural optimization has become a practical tool which can expedite mechanical design. An extensive amount of work has been done in developing design optimization procedures to bring the state of the art to a very high level [1,2]. While these techniques have received wide attention for fixed-wing aircraft [3], they are less well known in the rotary-wing industry. In the past, conventional design methods mainly used the designer's experience and trial and error methods. However, today with sophisticated computing resources available, coupled with efficient optimization schemes and improvements towards understanding helicopter analysis, attempts are being made to address such issues at both preliminary and redesign stages using design optimization. This will help reduce the expensive man-in-the-loop iterations associated with the conventional design practices.

The helicopter rotor design process is multidisciplinary in nature and involves a merging of several disciplines, including structures, aerodynamics, dynamics, and acoustics. For example, the blade design must satisfy specified strength criteria and should be damage tolerant. The blade should be aeroelastically stable and the aerodynamic performance should be improved. The noise levels generated by the rotor

(which are a function of the local Mach number of airloads) should be reduced. Vibration has been a major source of problems in helicopters and its alleviation plays a major role in the rotor blade design process. In Ref. 4, Reichart presents a thorough survey describing all the complexities of the helicopter vibration problem and emphasizes the necessity of considering vibration throughout the development phase for the helicopter. The survey also outlines the various existing methods of reducing helicopter vibrations such as the use of special absorbers at the rotor blades or the hub. It also points to new and more innovative directions, such as active higher harmonic control and vibrational isolation of the fuselage from the rotor/transmission assembly based on anti-resonance and the use of structural optimization, at early states of the design process for the optimum design of the rotor and the whole helicopter.

The potential sources for vibrations in a helicopter are rotors, engines, and gear boxes each producing loads at a wide range of frequencies. Broadly speaking, the vibration can be categorized into low and high frequency vibrations. The high frequency vibrations are mainly acoustic and are not responsible for mechanical failures, except for some isolated cases of structural resonance. The low frequency vibration, on the other hand, causes all fatigue related failures and is of importance not only to the rotor system but also to the airframe. The airframe vibration is directly related to passenger discomfort. This chapter provides a detailed account of the application of structural optimization aimed at overcoming some of these major problems in a rotorcraft.

Optimum Rotor Blade Design

In this section the application of design optimization techniques for helicopter rotor blade is discussed. Although rotor blade design process is truly multidisciplinary in nature and involves the coupling of several disciplines, in most of the existing literature the blade design has been treated as a series of nearly-independent design tasks with little consideration of the coupling and interactions of the disciplines. Therefore, in the following sections, a review of the most pertinent literature in the field is present, firstly on the single discipline-based optimization and finally on the very recent efforts at multidisciplinary optimization.

Dynamic Optimization: Vibration control has been a problem in the past and it will continue to play an important role in future helicopter design as well. Due to more stringent requirements in the permissible vibration levels and requirements for increased reliability in a helicopter [4], the helicopter industry is exploring methods to reduce vibration.

For a helicopter in forward flight, the nonuniform flow passing through the rotor causes oscillating airloads on the rotor blades which are translated into vibratory shear forces and bending moments at the

hub. In the rotor system itself, loads are present at all harmonics of rotor speed, but the symmetry of the rotor system ensures that, in a steady state, significant loads are transmitted to the airframe only at multiples of the rotor passing frequency (i.e. $n\Omega$, where n represents the number of blades and Ω is the rotor r.p.m.). The biggest component of the airframe vibratory forces occurs at the fundamental blade passage frequency ($n\Omega$). This involves consideration of the rotor responses to airloads at $n\pm 1$ harmonics as well [5]. Therefore, reducing helicopter vibration by attacking the source, namely the blade, is an attractive concept. A rotor producing low hub loads will produce low vibration throughout the airframe. Vibration alleviation, therefore, plays a major role in the rotor blade design. Due to the importance of the problem, there has been a considerable amount of research aimed at reducing vibration, primarily at the blade level. Unfortunately, the conventional design approach uses lumped tuning masses, in the post-design stages, to accomplish this and causes significant increases in the blade weight. Compared to the amount of literature available concerning various devices [6] such as absorbers, isolators, higher harmonic control (h.h.c.) systems, and other active control options including the use of smart structures for reducing vibration, not much literature exists in the design of blade parameters, with due consideration for their effects on vibration. Since the recent availability of fast computers and the significant progress made in optimization methodologies, efforts are being made to apply design optimization strategies for effective blade design for reduced vibration.

The reduction of the vibratory shears and moments at the blade root can be achieved in one or more of the following ways:

- a) reduce the vibratory airload, e.g., by changing aerodynamic parameters or dynamic response,
- b) change the modal properties, e.g., change the mode shape to make it orthogonal to the forcing function, or promote intermodal cancellation, and
- c) properly place natural frequencies away from the critical frequencies (which cause fuselage vibration).

Blackwell [7] concludes that many of these items can be achieved through changes in blade spanwise and chordwise mass distributions, placement of natural frequencies, and changes in mode shapes. Therefore, most of the efforts, aimed at optimized blade designs for reduced vibration have used one or more of these techniques. An early review of the literature in the area of application of optimum design techniques with dynamic constraints is due to Friedmann [8] and Miura [9]. Successful applications of such techniques are presented in Refs. 10-23. Taylor [10] described the use of modal shaping to reduce vibrations. He defined "modal shaping parameters" which are functions of blade mass distributions and

mode shapes. These parameters can be interpreted as an "ad hoc" optimality criteria. Bennett [11] addressed the problem of reducing the vertical hub shear transferred from the blade to the rotor mast by combining conventional helicopter analysis (MYKLESTAD) with a nonlinear programming technique. Friedmann and Shantakumaran [12] address the problem of vibration reduction at the forward flight condition by reducing the 4/rev vertical shear. They recognized the fact that changes in mass and stiffness distributions can lead to problems with aeroelastic stability, and therefore used a constraint on the hover stability. Additional constraints were imposed on the natural frequencies. Peters, et.al. [13,14] used two different objective functions at two stages of the design.

In the first stage, the objective function was the sum of the squares of differences between actual natural frequencies and desired natural frequencies. This tended to drive the natural frequencies into safe "windows" away from resonances. Once a given frequency fell within this window, the frequency-placement was removed from the objective function and treated as an inequality constraint, $\omega_L < \omega < \omega_U$. Once all of the frequencies were within the constraint windows, then blade weight was made the objective function. This procedure avoided the difficulties of an unfeasible design. The design variables of this process were cross-sectional thickness and lumped masses. Other constraints included limitations to insure that the design could fit in the geometric airfoil space as well as a constraint on autorotational inertia. Chattopadhyay, et.al. [15] addressed the problem of minimum weight design of soft-inplane hingeless rotor with constraints on natural frequencies using an optimality criteria approach [16].

In the optimality criteria approach, an unconstrained objective function is formulated by adding the constraints to the original objective function through Lagrange multipliers. Recursion relations are then developed based on the Kuhn Tucker conditions of optimality [Arora, Introduction to Design, McGraw-Hill, 1989]. New, updated, values of design variables are obtained using the recursion relations. Pritchard and Adelman [17] used prescribed airloads in a rotor blade optimization problem for proper placement of tuning masses in order to reduce the modal shaping parameter. More recently Chattopadhyay and Walsh [18,19] addressed the problem of optimum blade designs with dynamic constraints. Minimum weight designs were obtained with constraints on frequencies, stresses and autorotational inertia for articulated blades with rectangular and tapered planforms. The nonlinear programming method, as implemented in the program CONMIN [19] was used, along with an approximate analysis technique. The approximate analysis technique was based on first-order Taylor series expansion and was used to provide values of objective functions and constraints required by CONMIN. The constraints on stresses were dynamic constraints because the blade is subject to a dynamic loading. Thus, vibratory stresses are computed, and an upper bound is given on these. The results of the above research indicate that by

appropriate selection of the blade inertial, structural and sometimes aerodynamic characteristics, it is possible to minimize blade vibration. For example, Figure 1 shows the root-mean-square shear force at the blade root due to a typical lift distribution that oscillates at a varying frequency (per rotor revolution). The response for both the initial design (an actual production rotor) and an optimized design are given. Now, since this is a collective excitation of a two-bladed rotor, the actual forcing frequencies in flight will be $\omega=2,4,6$. One can see that the optimized blade has lower loads at these points due to the fact that blade natural frequencies have been moved away from these resonances.

Aeroelastic Optimization: In an effort to reduce vibration when the mass and stiffness distributions of the blade are changed, either spanwise or chordwise, it is important to ensure that the aeroelastic stability of the rotor is not degraded. This further complicates the design problem, since a proper formulation requires the coupling of a comprehensive aeroelastic analysis procedure, along with other analyses, inside the optimization loop. Davis and Weller [20] imposed aeroelastic stability constraints using a simplified rotor analysis code and quasi-steady airloads to optimize blades for i) maximum inplane structural damping of a bearingless rotor, ii) placement of blade natural frequencies, iii) minimum vibratory hub shears and, iv) minimum vibratory indices. Celi and Friedmann [21] addressed optimum designs of blades with swept tips with aeroelastic stability constraints. Chopra, et.al., [22] addressed the problem of minimizing a combination of critical vibratory shear forces and moments using a single objective function subject to aeroelastic constraints.

In all of this work, the primary focus was on the vibration of hingeless and bearingless rotors. Therefore, the active aeroelastic constraint is on flap-lag stability with a secondary emphasis on bending-torsion flutter. The primary design parameters that affect these are frequency placement, location of mass centroid, elastic coupling, and blade static deflection. Blade stability in forward flight was calculated using Floquet theory and constraint was imposed on the real part of the stability root. Weller and Davis [23] presented an experimental verification of their optimized bearingless rotor blade, designed for reduced vibration, with aeroelastic constraints. The tests confirmed the increase in structural damping predicted by the optimizer in order to satisfy the stability constraint. In general, for articulated blades, aeroelastic stability is not an issue provided the cross-sectional center of mass stays forward of the elastic axis. However, for more exotic rotors, aeroelastic constraints must be an integral part of the optimization. Therefore, because blade stability in forward flight is a difficult computational problem, future research needs to concentrate on streamlining the eigenvalue, eigenvector, and sensitivity derivative computations.

Aerodynamic/Performance Optimization: The rotor blade aerodynamic design process consists of selection

of variables such as blade planform, airfoil shaping, twist, and tip shape. The process is further complicated by often conflicting requirements between forward flight conditions and hover. As indicated by Magee, et.al., [24] the *best* twist for hover produces a negative angle of attack on inboard sections in forward flight conditions, whereas the *best* twist in forward flight causes the blade to stall inboard in hover. Similar conflict also occurs in the choice of the chord distribution. Therefore, a designer must conduct careful trade-off studies prior to a selection of these parameters. Such studies involving a "man-in-the-loop" can be very tedious and can be replaced by use of design optimization strategies. Walsh, et.al., [25] performed aerodynamic/performance optimization using hover horsepower as the objective function with constraints on the horsepower required at five other flight conditions and the airfoil section drag coefficients. A combination of rotor horsepower in forward flight and hover was minimized by Kumar and Bassett [26] to obtain optimum rotor geometry for a future light helicopter. Constraints were imposed on total blade twist and rotor solidity. Most aerodynamic optimization drives blades to high twist and taper in hover but to less twist in forward flight. When solidity is not constrained, optimum designs also tend to lower solidity.

Structural Optimization: A preliminary structural optimization of rotor blades was studied by Nixon [27]. The total blade weight was used as the objective function and constraints were imposed on torsional deformation, stresses, and autorotational inertia. Two different structural configurations were tested, one with a titanium spar where the only design variable was the spar thickness, the other with a single T300-5208 graphite/epoxy D-spar with the percentage of the $\pm 45^\circ$ plies being used as the design variable.

Multidisciplinary Optimization: In most of the previous work, where optimization techniques were used to address blade designs, attempts were made to satisfy certain design requirements and criteria related to a single discipline. Also, in the majority of the work dealing with optimum blade designs for reduced vibration, the blades were either considered to be in vacuum; or, as an alternative, a simple forced response analysis was performed. In cases where a complete rotor analysis was used, quasi-steady airloads were used and the effects of the design changes, during optimization, on changes in the blade airloads were ignored. For example, blade vibration reduction was achieved without consideration of rotor aerodynamic performance or structural integrity in References [8-20]. Helicopter rotor blade design is, however, a multidisciplinary design process by nature and involves the coupling of several disciplines. The necessity of merging appropriate disciplines to obtain an integrated design procedure is being recently recognized. With improved understanding of helicopter analyses and optimization schemes it is now possible to include the couplings between the disciplines in the optimization procedure. Some initial investigations at partially integrating some of these disciplines are presented in Refs. 21,22, and 28. Celi

and Friedmann [21] addressed the coupling of dynamic and aeroelastic criteria when quasi-steady aerodynamics are used for blades with straight and swept tips. Lim and Chopra [22, 28] also coupled a comprehensive aeroelastic analysis code (developed in-house) with the nonlinear programming code CONMIN [29] to reduce all six of the 4/rev hub loads for a hingeless rotor in order to reduce vibrations without losing aeroelastic stability in forward flight. Design variables, such as nonstructural masses, chordwise location of center of gravity (c.g.) and blade stiffnesses, were used. The objective function was formulated as the square root of the sum of the squares of the individual hub loads.

Due to the importance of the problem, at Langley Research Center there is currently an on-going effort [30] between the Army and NASA to develop optimum design procedures with the coupling of several disciplines, such as dynamics, aerodynamics, performance, structures, and acoustics (Fig. 2). As a first step, towards the integrated design, single discipline level optimizations were performed [8,19,25,27]. A first step towards integrated optimization is presented by Chattopadhyay, et.al. [31]. The 4/rev vertical shear was minimized along with the blade weight using a multiobjective formulation called the "Global Criteria Approach" [32]. With this approach, a single or global objective function is defined to be the sum of the squares of the deviations of the individual objective functions from their respective optimum values. The individual optimum values are obtained from design optimization with the single objective subject to the actual set of constraints. Constraints are imposed on elastic coupled lead-lag and flapping dominated frequencies, blade autorotational inertia, and centrifugal stress. The design variables are the blade stiffnesses at the root, the taper ratio, the root chord, the radius of gyration at the blade root, and magnitudes of the nonstructural weights, located spanwise. The blade preassigned properties and the rotor performance parameters are used from an existing reference blade data. The integration of aerodynamic loads and dynamics is achieved by the coupling a comprehensive helicopter analysis code, CAMRAD [33] to an optimizer comprising CONMIN and an approximate analysis technique [19]. The use of the program CAMRAD permitted the design of the blade with calculated airloads and its presence in the closed loop optimization procedure allowed the inclusion of the effects due to changes in these airloads with changes in design variables. The paper demonstrated a significant reduction in the 4/rev vertical shear and blade weight, which were objective functions, along with overall reductions in the amplitudes of the oscillatory vertical airloads both azimuthal and radial. As a byproduct, it was shown that optimization also reduced the total power required by the rotor while maintaining the same C_T/σ , and C_X/σ , C_T being the rotor thrust coefficient, C_X the propulsive force coefficient and σ the thrust weighted solidity of the blade. Now, the 4/rev vertical shear need not be the most critical load; and often the inplane shears and the overturning moments can be more important depending on hub impedance and

fuselage characteristics. Therefore, in Ref. 34, Chattopadhyay and Chiu extended the work of Ref. 31 to include the 3/rev inplane and radial shears, the 3/rev flapping and torsional moments and the 4/rev lagging moment in the optimization formulation in the form of objective functions and constraints. Most importantly, while maintaining the same C_T/σ and C_X/σ as the reference blade, the total thrust of the optimized blade in Ref. 31 was reduced from the reference blade value due to the smaller solidity, σ , of the optimum blade. To avoid this loss in the rotor thrust, an additional constraint was imposed on the total thrust in Ref. 34.

A combined structural, dynamic and aerodynamic optimization of rotor blades was performed by Peters and He [35]. A box beam model was used to represent the structural component in the blade, and the blade performance was optimized using the power required in hover as the objective function. Constraints were imposed on natural frequencies, blade stress, and fatigue life. More recently, Straub, et.al. [36] addressed the problem of combined performance and vibration optimization by using the rotor analysis code CAMRAD/JA [37]. A linear combination was used for the multiple design objective problem. Chattopadhyay and McCarthy [38] recently completed a study in which an investigation was done to select multiobjective formulation procedures that are less judgmental in nature and are efficient in the nonlinear multidisciplinary optimization of rotor blades. Three different approaches were used, the Global Criteria approach [32], a Min $\sum \beta$ formulation [23] and a Kreisselmeier-Steinhauser (K-S) function approach [39]. The Min $\sum \beta$ formulation is a further modification of the Global Criteria approach in which the optimized values of the individual design objectives are replaced by specified target values. This considerably reduces the computational effort. The objective function is also linear and is defined as the summation of the parameters β_i , e.g., $F = \sum \beta_i$ where N denotes the total number of single objectives and β_i are pseudo design variables. The quantities β_i are also used as upper and lower bounds on the actual objective functions.

In the K-S function approach, a transformation of the original objective functions into reduced objective functions is necessary. These reduced objectives are of the form

$$f_x(\phi) - \frac{f_x(\phi)}{f_{x_0}} - 1 - g_{\max} \leq 0$$

$$f_z(\phi) - \frac{f_z(\phi)}{f_{z_0}} - 1 - g_{\max} \leq 0$$

where f_{x_0} and f_{z_0} are the values of the objective functions f_x and f_z respectively, calculated at the beginning of each iteration. The quantity g_{\max} is the value of the largest constraint corresponding to the design variable vector ϕ and taken to be constant for this iteration. The reduced objective functions are used as additional design constraints and the new objective function is defined as

$$F(\phi) - g_{\max} + \frac{1}{\delta} \log_e \sum_{k=1}^K e^{\delta(g_k(\phi) - g_{\max})}$$

where the multiplier δ can be considered analogous to a draw-down factor with δ controlling the distance from the surface of the K-S objective function to the surface of the maximum function value. The K-S function approach proved to be the most efficient. Since all optimum blade design problems are formulated with specific design objectives and constraints, it was of interest to investigate the overall behavior of an rotor optimized to meet certain design requirements at specific flight conditions, at other "off-design" flight conditions. Therefore Chattopadhyay and Jones [40] conducted a study on the rotor blade designed for minimum weight and 4/rev shear, in Ref. 30, to analyze its other dynamic characteristics and also its aerodynamic performance. The 4/rev vertical shear, which was minimized at a particular flight condition, was also calculated at other flight conditions. The study showed that the blade performed well over the entire flight range; and the aerodynamic characteristics, not included in the optimization formulation, were also improved. However, the conclusions were drawn based on specific assumptions such as uniform inflow.

Optimum Airframe Design

In this section, the application of optimization procedures to helicopter airframe design is discussed. As already mentioned, the major sources of airframe vibrations are caused those occurring at frequencies $i\Omega$, where i is an integer. Because the magnitude of the harmonic airloads reduce with increase in the harmonic number, the loads occurring at the frequency Ω are the most important. Although, aeroelastically and dynamically tailored rotors can be designed to reduce these vibratory loads that are filtered through to the fuselage and thereby reduce airframe vibration, it is also essential to design the airframe for minimum response to such airloads. An airframe structural tuning method has been suggested Shipman et.al. [41]. In this method, tuning weights are added at certain nodes in order to cancel vibrations at a particular frequency. The use of formal design optimization procedures for optimum airframe design has been rather limited. In Refs. 42-46, several methods have been suggested to identify structural members that need modification for tuning airframe natural frequencies or reducing airframe

responses under dynamic loads. However, although the word "optimization" was used, ad hoc criteria were invoked in identifying the structural members; and formal optimization techniques were not used. Perhaps some of the first applications of design optimization techniques are reported in Refs. 47 and 48, where the airframe was modeled using simple elastic-line finite elements. As a part of the integrated optimum helicopter design at Langley, Sreekanta Murthy [48] presented some preliminary studies in airframe optimization. A computer code called DYNOPT has been developed for this purpose. More recently, Sreekanta Murthy addressed a more detailed airframe optimization problem where some of the design considerations were natural frequency, steady-state dynamic response to rotor-induced loads, and aerodynamic drag.

Now, it has long been a recognized fact that the interaction of the rotor and the airframe are important in analyzing helicopter vibrations [57]. However, due to the complexity of the problem, the rotor is usually analyzed with the assumption of a fixed hub. The loads thus calculated, are then applied to the airframe to calculate the airframe response. Thus, the interaction of the rotor and the fuselage have not been considered. Naturally, to obtain a true optimum design of a helicopter for reduced vibration, it is necessary to account for the rotor/airframe coupling early in the design process. A first attempt at coupling the design considerations of the rotor and the fuselage are presented by Kvaternik and Sreekanta Murthy [50]. However, in this research, it was assumed that the airframe design is held fixed and the rotor design was optimized subject to constraints arising from airframe dynamics. Such sequential treatment may not produce a truly coupled rotor/airframe optimum design

Sensitivity Analysis

One of the key ingredients in an optimization procedure is an efficient procedure for calculating system sensitivities with respect to design variables used. In most of the existing rotor optimization problems, finite difference techniques are used to calculate these simulations [13, 14, 18, 19]. This means that several calls to the analysis routines are necessary for every perturbation of the design variable value. Such a process can make optimization, as such, computationally prohibitive. Due to the complexities associated with rotary wing analysis, very little literature exists in the formulation of analytical or semi-analytical sensitivities. Pritchard and Adelman [17] proposed a hybrid approach for the derivatives of the modal shaping parameter using Nelson's approach [51]. Lim and Chopra [28] addressed this issue by formulating analytical derivatives of aeroelastic and dynamic quantities such as stability, natural frequencies, and hub loads. The rotor dynamic analysis used was based on a finite element method in space and time. The analytical derivatives were obtained using a finite element approach and the chain rule of differentiation. This direct analytic approach for calculating the derivatives proved to be very

efficient.

Chiu and Chattopadhyay [52] were the first to derive analytical sensitivities of aerodynamic functions pertaining to a rotary wing aircraft in axial flight. A three-dimensional undistorted wake model was used along with a curved lifting line theory. The governing equations were solved using Multhopp Interpolation technique. (Multhopp Interpolation technique is a special case of Fourier Series method and is widely used in fixed wing case). Parametric studies were also performed to assess the effects of design variables, such as, tip shape, chord, twist, solidity, taper, inplane and out of plane curvatures and inflow ratio on aerodynamic functions such as total lift coefficient, local circulation, total induced drag coefficient, power and lift/drag ratio. With the growing interest in the effort to develop integrated dynamic, aerodynamic, structural and possible acoustic optimization procedures for helicopters, it is essential to continue this effort in developing efficient sensitivity analysis procedures.

Approximate Analysis

Since 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 full analyses are made for each function evaluation. The objective function and constraints are therefore approximated by linear Taylor series expansions based on the design variable values from CONMIN and the sensitivity information from the full analysis. Specifically, if the objective function F , the constraint g , and their respective derivatives are calculated for the design variable ϕ using an exact analysis, their values for an increment in the design variable $\Delta\phi$ are as follows:

$$\hat{F} = F + \sum_{k=1}^{NDV} (\partial F / \partial \phi_k) \Delta \phi_k$$

and

$$\hat{g} = g + \sum_{k=1}^{NDV} (\partial g / \partial \phi_k) \Delta \phi_k$$

where the underlined quantities represent approximate values and NDV denotes the number of design variables. The assumption of linearity is valid over small increments in the design variable values and does not introduce large errors if the increments are small. A 'move limit', defined as the maximum fractional change of each design variable value, has been imposed as upper and lower bounds on each

design variable ϕ . Since the objective function and the constraints are all linearized, the optimization problem essentially reduces to a sequential linear programming (SLP) procedure. In general, there is a trade-off between a good local minimum and increased computer time. For instance, a small move limit may guarantee an optimum result, but the rate of convergence is very slow. A large move limit gives a faster rate of convergence with often the risk of running into a mathematical singularity (i.e., negative value of the objective function). Therefore a variable move limit procedure is usually used by Chattopadhyay and Chiu [34] in which the optimization procedure is started with a large move limit and the process continued until the approximation yields negative objective functions. At this point a switch is made to several sets of smaller move limits. The best local minimum is selected to be the optimum design. Finite difference approaches are most commonly used in generating these approximations. However, Lim and Chopra [28] presented a sensitivity analysis procedure which can be used in the approximation. It has often been found [34, 38] that very small move limits are required when highly nonlinear functions, such as hub loads, are approximated. This essentially increases the convergence time during optimization. To overcome this linearization, Celi and Friedmann [21] retain the second order term in the Taylor series expansion. A procedure for approximating the Hessian, as proposed by Vanderplaats [53], is then used to reduce the computational effort. However, the method is limited to only very few design variables.

Experimental Verification

Some of the most recent work on optimization has involved experimental correlations of the optimization process. In Ref. 54, a new airloads analysis is developed for use in optimization. However, before optimization begins, the model is compared against existing data bases to make sure that it is adequate. In Ref. 55, a rotor is tested in the wind tunnel after optimization to see if the predicted vibration levels are achieved. Finally, and certainly the most impressive, in Ref. 56 a rotor is wind-tunnel tested both before and after optimization. Although the rotor is optimized with an open-loop loading spectrum (no aeroelastic feedback), yet the optimized blade shows significant vibration reduction. This is verification that optimization does work and that it can be done without a complete aeroelastic analysis at every iteration.

Conclusions

In recent years there has been a growing emphasis on integrated synthesis and design optimization procedures for large scale mechanical systems. The necessity of coupling the necessary disciplines, inside a closed-loop optimization process, for a realistic system design is currently being recognized. Rotary

wing aircraft are perfect examples of such vehicles where the coupling of various disciplines is important. There is strong interaction among the disciplines such as aerodynamics, structures, dynamics, aeroelasticity, acoustics, etc.(e.g., the unsteady aerodynamics and vortex interactions cause oscillatory blade loads which complicate the blade structural dynamics and the aeroelastic responses of the blade). Therefore, the need for developing procedures for multidisciplinary design optimization of rotorcraft is obvious.

However, true multidisciplinary design optimization cannot take place without efficient sensitivity analysis. If numerical schemes are used to supply these derivatives, the computational burden can often be prohibitive. Therefore, there is a need to develop analytical or semi-analytical procedures for obtaining derivatives of the necessary functions with respect to individual design variables. More research on such developments is necessary.

It is also important to perform research in developing approximate analysis procedures used to evaluate objective functions and constraints required by the optimizer. For highly nonlinear problems, second order based procedures are necessary; and the approximations obtained from linear Taylor series-based expansion are often inaccurate. The use of small move limits to avoid this inaccuracy can slow down the convergence rate. The current second-order based methods are limited by the design variable sizes used. Therefore, there is also the need for performing further research in this area. Finally, for a realistic integration of the necessary disciplines inside an optimization environment, the level and accuracy of the analysis procedures used must be carefully examined and verified by experimental data.

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Figure 1. **Sum of Squares of Shears versus Forcing Frequency for Both Initial and Final Designs with Damping**

Applications and Results

The implementation of structural optimization into the helicopter design process of industry has been slow to progress. Although small structural components (such as a flex-strap) may have been optimized, we have yet to see structural optimization applied to a large system such as the rotor. Nevertheless, research applications in the literature have been made on very realistic rotor hardware, and the results to date give a good indication of how structural optimization would affect the final rotor design.

The primary feature of an optimized rotor is the placement of natural frequencies, [13,14]. Therefore, an optimized rotor tends to have structural material added or removed at points of highest modal curvature; and it tends to have non-structural mass added at modal maxima or minima. If loads at the blade root are minimized, then this frequency placement tends to tune some blade modes (particularly torsion) to be integer multiples of the rotor speed. This turns the blade into an isolator. Thus, hub loads are minimized but blade stresses are increased. Thus, blade stresses need to be included in the optimization. References [35,54] show that the addition of blade stresses in the design tends to limit the amount of material that can be removed at any station.

Another by-product of the minimization of hub loads, is that the optimized blade can be unstable in several aeroelastic modes including bending-torsion flutter, [8,12,21,22,28]. This is due to the tendency for modes to coalesce in order to isolate vibrations. For hingeless and bearingless rotors, this tendency to aeroelastic instability implies that a full stability analysis must be included in the optimization loop. Optimum blades designed in this way tend to have limits on the closeness of modal frequencies and tend to use elastic coupling to stabilize the rotor, provided that those couplings are design variables. For articulated blades, conventional bending-torsion flutter dominates, but this can be alleviated by placement of the center of mass forward of the elastic axis (usually the quarter-chord).

As pointed out in Refs. [10,20,23], however, frequency placement is not the only attribute of a structurally optimized rotor. The placement of both structural and non-structural mass also tends to alter the mode shape (at any given frequency) so as to be orthogonal to the distributed force at or near that frequency. Thus, optimized rotors tend to have lumped, non-structural mass placed forward of the quarter-chord in such a way as to tune modes and frequencies.

