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ABSTRACT

This paper presents the results of a survey of applications of mathematical programming methods to improve the design of helicopters and their components. More specifically, applications of multivariable search techniques in the finite dimensional space are considered; optimal control theories and their applications are not included. Five categories of helicopter design problems are considered: conceptual and preliminary design, rotor-system design, airframe structures design, control system design, and flight trajectory planning. In addition, key technical progress in numerical optimization methods relevant to rotorcraft applications are summarized. After publication of the first paper by Stepniewski et al. (Stepniewski, W. Z.; Kalmbac, C. F. Jr.: Multi-variable Search and Its Applications to Aircraft Design Optimization, Aeronaut. J. R. Aeronaut. Soc., vol. 74, no. 713, 1970.) in 1970, which included helicopter design optimization by means of mathematical programming techniques, continued interests in this area had been sustained, and there has been significant research in the last 2 to 3 years. This paper is intended to put these newer activities in a proper perspective from a view of a design optimization engineer.

1. INTRODUCTION

The term "optimization" has a wide range of meanings, but this survey is limited to studies that are directly or implicitly related to helicopter design problems formulated in the standard mathematical programming problems with the following form.

$$\begin{array}{llll} \text{Minimize (or Maximize)} & F(X) & & \\ \text{Subject to:} & G_j(X) \leq 0 & j = 1, 2, \ldots J & \\ & H_k(X) = 0 & k = 1, 2, \ldots K & \end{array} \qquad (1)$$

where $X = (x_1, x_2, \ldots x_n)$ is a vector of n scalar variables, which are usually continuous and real variables. These variables are called independent design variables and are not functions of time like the control variables that appear in optimal control problems. The function F(X) is a scalar function that provides a quantitative measure to rank the proposed designs, such as $X_1, X_2, \ldots,$ and is called an objective function. The functions $G_j(X)$ and $H_k(X)$ are also scalar functions;

they are called inequality and equality constraint functions, respectively. The sets of X that satisfy the conditions $G_j(X) \leq 0$ and $H_k(X) = 0$ are called feasible designs and can be visualized usually as a part of the n-dimensional space.

Numerical solutions for the problems expressed in the form given in equation (1) were studied extensively, by investigators engaged in the general field of operations research, as early as 1940s. However, the first paper pointing out that this formulation and solution methods could be applied to engineering design problems was published by Schmit in 1960 (ref. 1). As he stated later (ref. 2), he recognized that the essence of structural design for minimum weight was conceptually similar to scarce-resource allocation problems, which had been studied in operations research. It turned out that a significant class of engineering design problems could be regarded as general resource-allocation problems, and thus could be formulated in the form of equation (1) and solved by means of numerical techniques called, collectively, mathematical programming methods. If the number of variables that is changing simultaneously is small, say fewer than 3, and the number of constraints is also small, human judgments will be adequately effective in organizing data to improve the design. However, if the design problems involve more design variables and constraints, solution of problems in the form of equation (1) requires the high volume data-processing capabilities of modern computers.

Applications to rotorcraft design problems were first suggested by Stepniewski and Kalmbach as an example in their paper that addressed general concepts in applying numerical multivariable search method to aircraft design problems (ref. 3). That paper may be recognized as having made the first contribution indicating practical applicability of mathematical programming methods to helicopter rotor design. Ten years after publication of reference 3, Ashley documented a comprehensive review of "Aeronautical Uses of Optimization" with 177 references (ref. 4). But no contributions to rotorcraft design or operational problems were referenced by Ashley probably reflecting the fact that the amount of research and development effort in rotorcraft applications was very small compared with the vast amount of work done on airplane and spacecraft applications during 1970s.

There did exist a few excellent publications that considered helicopter design optimization problems in 1970s, but the U.S. helicopter community started taking the practical importance of this technology more seriously only in the last 2 or 3 years. The current interest of the helicopter industry may well be reflected in the organization of a special panel session at the national forum of the American Helicopter Society in 1983. It appears that the rotorcraft industry started late but began to accept this technology more readily than did other industries. Although a great deal of research and development work will be required to transform research activities on mathematical programming into practical tools for helicopter design, design optimization will still play increasingly important roles in improving the performance of future rotorcraft.

One commonly expressed concern about the use of design-optimization methods in helicopter design applications is the availability of adequate analytical techniques. For example, in order to design a rotor system that applies minimum vibratory forces and moments to the hub, it is necessary to be able to estimate dynamic air loads for a given and for modified rotor designs, but the theoretical prediction of dynamic air loads is still a subject of research. Under such circumstances, is it reasonable to postpone design optimization and to concentrate on the development of prediction capabilities?

There are various ways to approach to this problem. The first is to modify intermediate properties that affect directly the responses that are of interest and that can be obtained with more reliable techniques. For the vibration problem mentioned above, natural vibration frequencies and mode shapes of the rotating blade may be regarded as such intermediate properties. This approach is a variation of approximation concepts described later in this paper, and the quality of the design depends on the quality of information carried by the intermediate properties or approximate model. For example, the consequence of the design depends on the effectiveness of the vibration reduction by means of the placement of natural frequencies and tuning mode shapes. This type of approach can be found frequently in traditional design procedures; hence, it might readily be accepted in practical applications. But identifing effective intermediate properties and making adequate use of them may be difficult and will require highly skilled engineering judgment.

The second approach, which appears to be practical at this moment, is to build a design-optimization system with modular program architecture, so that the system can accommodate alternative analysis programs. This architecture also makes it possible to replace obsolete modules without affecting other parts of the system. One can visualize this system as a framework within which a design-optimization program that works with the best available technology modules can be built. As is described later, incorporation of approximation concepts makes it possible to include large-scale comprehensive analysis programs as one of the component modules. The program architecture will require an efficient engineering database management system and a flexible, high-level control language. Fortunately, recent trends in computer engineering indicate that such capabilities will be available for engineering purposes, together with higher data processing speed and more affordable, large memory capacities. Realistically, most of the best technical modules now available are written by engineers, not by programming specialists, and they are constantly be modified throughtout their effective lives. The key idea of this approach is to build a system that can keep up the with advancements in the technology, by taking advantage of tools supplied by modern computer software.

The third approach is a variation of the second, but in the event that reliable analytical capabilities are not available, or if the accuracy of analytical results is questionable, test data for the corresponding design are used in place of analytical results. Design optimization based on experimental data could be an effective technique, as shown in reference 5, in achieving better designs with fewer function evaluations than are required by any of the traditional approaches. The key idea here is to recognize that the only prerequisite to working with mathematical programming methods is that the functions $F(X)$, $G_j(X)$, and $H_k(X)$ be evaluated for a given design X. It does not matter whether the response quantities used to evaluate these functions are obtained by analytical methods or from experiments, as long as they are reliable. Funcion evaluations through the experimental data-acquisition process will be slow and expensive. In industry, however, if an extremely high payoff is expected, systematic design optimization based on test data could be an effective and realistic approach. Theoretical analyses and experiments may work together to complement each other or they may compete against each other within the design procedure.

Rotorcraft designers are confronted with a number of challenging problems. For example, external noise reduction may be one of the key factors that will eventually make possible expanded roles for helicopters in public transportation systems. Althought it may be possible to decrease noise by changing operational procedures or flight trajectories or both, it should be more effective if the rotor components that are primary noise sources can be designed to generate less noise without degrading performance. This is clearly a multidisciplinary problem, aspects of which are related to, for example, aerodynamics, rotor performance, aeroelastic stability, vibration, and handling qualities. Fundamental concepts of design optimization with mathematical programming methods will be useful in organizing thoughts and solution strategies for this type of problem. Engineers have been the only means by which analytical and test results could be linked with engineering design, and they will remain the primary factor in the design process. But automated design optimization based on mathematical programming methods will become a powerful tool and will revolutionalize the traditional parametric study techniques.

2. NUMERICAL OPTIMIZATION TECHNOLOGY AND SOFTWARE DEVELOPMENT

Mathematical programming methods are numerical techniques for solving optimization problems formulated in the form of equation (1). They are classified either as linear programming (LP) techniques or nonlinear programming (NLP) techniques. If all the functions involved are linear with respect to the design variables X, linear programming should be used, because it is the most reliable and mathematically rigorous method and because it always converges to the global optimal design, if such exists. However, most of the engineering design problems involve nonlinear functions and, furthermore, important functions are usually not explicit functions of design variables. For example, if the fundamental natural frequency f_1 of a structure must be higher than 20.0 Hz, a corresponding inequality constraint is expressed as

$$1.0 - f_1 / 20.0 \leq 0.0 \qquad (2)$$

The left-handside of inequality (2) is not an explicit function of the design variables; instead, it is a function of a system response that must be computed by dynamic analysis of a structure described by the design variables, X. This implicit relation among design variables and objective and constraint functions makes the solution schemes more difficult and expensive. But there have been significant research and development efforts to find efficient NLP algorithms and, as a result, many programs are available. Because these products will be sufficient to support helicopter design-optimization activities, it is imperative that our efforts be directed toward applying available techniques and tools to rotorcraft design problems. For example, a recent textbook by Vanderplaats (ref. 6) will serve as an excellent reference to the currently available methods. He also developed a computer program that contains within one package most of the known and useful algorithms (ref. 7), so that the user can select appropriate algorithms from input data.

It is most important when applying mathematical programming methods to practical problems to recognize that any optimizer must evaluate objective and constraint functions many times, say, 50 to 200 times or even more, before the design process converges. If the system responses required to evaluate these functions are computed by large-scale analytical programs, such as finite-element structural analysis or numerical solution of the Navier-Stokes equation, straightforward combination of a mathematical programming program with such analytical programs will result in a large program that cannot be processed, even on today's fastest computers. Structural optimization procedures developed in early 1970s provides valuable ways of overcoming this efficiency barrier as explained in reference 8.

What is important is to make full use of approximations to reduce the extent of the data processing effort. Except for evaluation of the final design, accurate evaluation of system responses is not necessarily required; instead we need only information to guide the design into the neighborhood of a practical optimal design. There are many types of effective approximation schemes, including the following:

1. Use of simplified analytical models within the boundary where such analysis provides sufficiently accurate trends for design changes
2. Fast reanalyses of systems with perturbed designs based on the detailed analytical results of the unperturbed system
3. Reduction of the number of design variables through linear transformation of variables
4. Dynamic deletion of constriants to reduce the number of constriants that are handled by an optimization program
5. Generation of approximate functions which are explicit functions of design variables for the implicit functions appearing in equation (1) and periodic updating of approximate functions based on accurate and reliable data.

Items (1) and (2) are problem-dependent and they are straightforward. The last three are fundamenatal schemes for building modern, practical design-optimization programs that can overcome the efficiency barrier mentioned previously. Figure 1 describes the basic structure of such programs. With these schemes, an optimization program works with only a relatively small number of explicit approximate functions involving only a manageable number of design variables. Evaluation of approximate functions requires an almost insignificant amount of computational effort, thus, we can afford to compute them as many times as the optimizer requests. It is also very common to use optimization repeatedly on successively improving approximate models, but total computational effort for repeated optimization with respect to approximate models is usually very small compared with execution of large-scale analytical programs. For example, a practical structural design optimization example showed that optimization with respect to the approximate problems required less than 2% of total CPU time used for the entire design process. In other words, more than 98% of the CPU time was used to carry out finite-element analyses to build approximate-function representations.

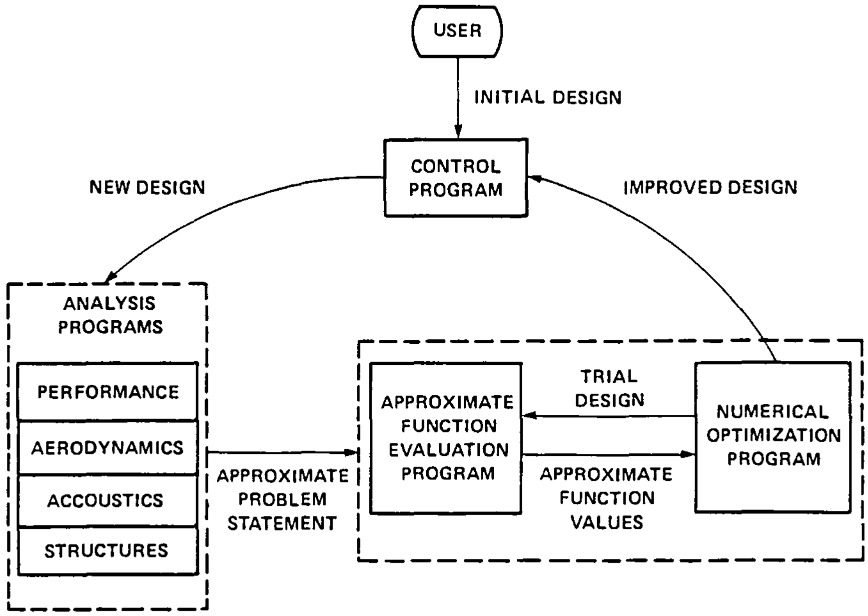

Fig. 1 Basic Architecture of Design Optimization Program

It may be appropriate to point out that there are various approaches to building approximate function $f_a(X)$ for a difficult implicit function $f(X)$. For example, if at a design X_0, a function value $f(X_0)$ and the sensitivity information

$$\Delta f(X_0) = \left(\frac{\partial f}{\partial x_1}, \frac{\partial f}{\partial x_2}, \ldots, \frac{\partial f}{\partial x_n}\right) \tag{3}$$

are available, it is possible to have a Taylor series approximation in the neighborhood of X_0,

$$f_a(X_0) = f(X_0) + \sum_{i=1}^{n} \frac{\partial f}{\partial x_i} (x_i - x_{i0}) \tag{4}$$

If all the implicit functions are expressed in this form, the optimizer can work with the approximate model in the neighborhood of X_0. It is important to make sure that the design modification with respect to this model is within the valid range of this linearization by introducing artificial step-size limitations in the optimization process. Since we do not usually have a priori knowlege of the nonlinear nature of the original function $f(X)$, we may have to select the step size conservatively small, resulting in re-generation of approximate functions many times before the design converges. To alleveiate this problem, various ideas have been proposed, but the introduction of intermediate variables described in references 8 and 9, and the mixed variable scheme presented in references 10 and 11 will be of general importance to any design optimization. In case the function values at m distinct designs, $f(X_1)$, $f(X_2)$,..., $f(X_m)$, are available, interpolation models are built by means of regression analysis techniques. In reference 12, an interesting scheme was described, in which relatively simple models based on a small amount of avialable data were used at the beginning, and as the design optimization proceeded, more analytical results were obtained to improve the approximate models by introducing higher-order terms.

There are a number of ongoing research programs that have as their objectives the advancement of design optimization technology. The following may by of interest for future rotorcraft applications:

1. Sensitivity of optimal design to parameter variations (refs. 13-15)
2. Discrete variable problems (ref. 16)
3. Multi-level design strategy (refs. 17 and 18)
4. Multiobjective design optimization (ref. 19)

The consequences of this research may be important to helicopter design, but a discussion of these studies is beyond the scope of this paper.

Computation of sensitivity information given in equation (3) is an important feature in applying numerical optimization methods. Finite difference schemes may be used, but if sensitivity can be computed more efficiently within the analysis programs, it is possible to reduce the overall computation effort significantly. For example, sensitivity of linear structural responses can be computed efficiently as a part of the finite element structural analysis program. Development of sensitivity analysis techniques will be an important basis for applications of numerical optimization methods to helicopter design problems.

3. CONCEPTUAL AND PRELIMINARY DESIGN

Any design optimization scheme will be more effective, if it is applied in the early design stages, when important decisions are yet to be made and when the basic design is not frozen. This is obvious and is frequently discussed, but in practice, there are many considerations that mitigate against introduction of formal optimization schemes in the early engineering design phase. The conceptual and preliminary design procedures for rotorcraft are not well defined, even though most of helicopter manufacturers have some aircraft sizing programs. Also, significant parts of the design decisions are of necessity heuristic and are not readily formulated in the form of equation (1). And generation of reliable analytical models is often very difficult simply because the data needed to create such models are not available. Moreover, the decision process is made more complex by the variety of possible configurations for modern rotorcraft. It is fair to say that today's optimization processes are not ready to provide automated selection of the best configuration out of all possible candidates; instead it is more realistic to use design-optimization methods to identify the best candidate for each possible configuration provided by the engineers.

The first paper for applications of mathematical programming methods to preliminary and conceptual design problems was written by Szumanski of Poland (ref. 20). Influenced by Stepniewski and Kalmbach (ref. 3), he extended basic design optimization techniques to both the conceptual and preliminary design of helicopters. The primary subject of Szumanski's paper was the optimization of the geometric parameters of helicopter lifting systems in the form of rotor and wing units. Obviously limited by available computational facilities and software, not all the design problems described were solved by applications of optimization methods. However, Szumanski perceived correctly that relatively ambitious tasks, even by today's technology standards, such as the design of lifting devices, including maneuvering flight conditions and aircraft handling qualities, could be studied with formal optimization methods. It was one of his conclusions that the addition of wings was not desirable unless they were required to meet increased speed requirements. Rotor parameters, such as radius, solidity, rotation speed, blade airfoil, and engine performance, might be adjusted by optimization to eliminate the need for wings up to certain speeds. If wings still had to be added, optimization methods could be used to reduce the unfavorable effects of wings.

Ramos and Taylor published a comprehensive report on the preliminary design of helicopters in 1981 (ref. 21) . The program, named HELISOTON, was developed at the University of Southampton. It appeared to provide comprehensive coverage for the analysis of conventional helicopters and to do so in a form amenable to automated design optimization. Avoiding excessive computational effort was the primary consideration in selecting analytical methods, hence relatively simple methods were used, such as semiempirical statistical relations for empty weight estimation, and an uncoupled equation of motion for trim, static and dynamic stability analyses. Based on the description given in ref. 21, HELISOTON worked as a helicopter sizing program, as well as a design optimization with respect to the following parameters: main-rotor solidity, blade mass, and hinge offset; control sensitivity in roll and pitch; and tail plane area. Although multivariable search capability was not adopted because of the excessive computational effort it could have required, HELISOTON is readily coupled with modern mathematical programming software to carry out multivariable design optimization, if necessary.

Stepniewski and Sloan attempted the formulation of the optimal design of transport helicopters (ref. 22). Their purpose was to come up with a sensible formulation to achieve the lowest total operating cost per revenue seat and per nautical mile. This was probably the first attempt to integrate helicopter performance analysis and cost models specifically for the purpose of helicopter design optimization. Stepniewski and Sloan do not present numerical results, but there is a table in reference 22 that describes the fundamental elements of transport helicopter design; as the summary of the inputs of experienced design engineers, the table is very useful.

It is expected that conceptual and preliminary design-optimization programs will be developed further in the years to come simply because of their practical importance both for manufacturers and users of rotorcraft. Significant improvements in computer capabilities in recent years will relax requirements imposed previously by limited amount of data processing and computer memory capacity; consequently, it will be possible to bring in more comprehensive analysis techniques in the framework of preliminary design. This will allow the users to investigate the performances of given designs in far greater detail. Also, the availability of modern data-base management systems will change the data structure for design-optimization programs so that designers will be provided with more flexible means to build consistent data to describe a design of rotorcraft.

4. ROTOR DESIGN OPTIMIZATION

Applications of optimization methods to rotor design problems may be divided into three areas: (1) rotor global performance, (2) blade structural design, and (3) aerodynamics and accoustic design. Reflecting the current urgent needs to reduce vibration and external noise, recent activities are focused on these two problems. But what is becomming increasingly clear is the fact that all these areas are closely coupled and should really be considered simultaneously. Furthermore, it is frequently necessary to take much wider range of activities into consideration. There are various approaches that may be promising for working the integration of the various disciplines that are involved. They include considering large-scale design programs, adopting multilevel design schemes, incorporating human judgment capabilities through advanced man-machine communication interfaces, and taking advantage of emerging artificial intelligence technology.

Rotor Performance Design

In the paper mentioned previously, Stepniewski and Kalmbach (ref. 3) reported a study in which maximization of the figure of merit was carried out successfully by combining the EVIT(explicit vortex interference technique) program with the optimization program AESOP(automated engineering and scientific optimization program). Altogether 10 design variables are prescribed as coefficients to describe blade twist and chord distributions along the span. Stepniewski and Kalmbach proposed to apply a similar approach to designing helicopter rotors for maximum cruise speed at a given power and with imposed bounds on figure of merits and stall flutter margin.

Huber gave a comprehensive review at the 1973 AGARD Lecture indicating his observations of and projections about the future of design optimization (ref. 23). He correctly recognized the importance of the formal applications of optimization techniques as well as their limitations. It is interesting to note that Huber emphasized the importance of analytical methods for predicting rotor performance and transonic profile characteristics in high cruise speed. However, probably owing to the limitations of computer software and hardware in 1973, he kept his reservation in applying formal optimization methods to more comprehensive models, such as those that included stall flutter, maximum lift boundaries, and dynamic blade properties. These are difficult characteristics to handle even with today's technology, but we have begun to understand how to work with these complicated resposes.

Bennett addressed blade-twist distribution to minimize required shaft horsepower for hover, while keeping airfoil, rotor radius, and tip speed unchanged (ref. 24). The result indicated that the optimum twist reduced the hover power by 1.55% compared to a linear twist.

Rotor Blade Design

In 1971, Bielawa presented an excellent pioneering work on rotor-blade design in ref. 25. He derived analytical expressions for eigenvalue sensitivity for linear nonconservative dynamic systems, and applied the method to linearized rotor dynamic equations to achieve minimum blade weight with constraints on bending torsion flutter stability and on natural vibratory frequencies. He used five design variables to describe a blade structure with a uniaxial carbon-epoxy spar and a leading-edge counter weight (fig. 2). The optimization algorithm was the classic Lagrange multiplier method; hence, convergence characteristics were poor with respect to today's standard. Nevertheless, his formulation of the design process was amenable to being combined with modern mathematical programming, and his recognition of the need for sensitivity analyses is still valid.

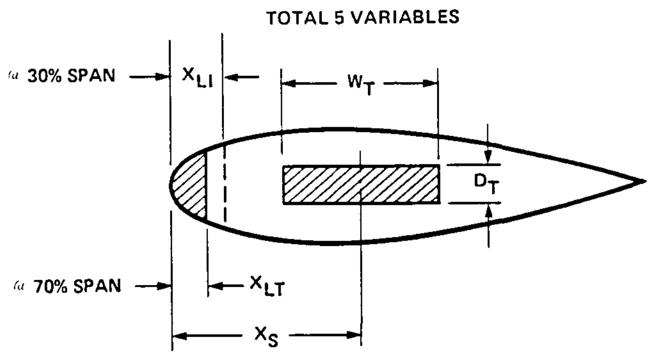

Fig. 2 Design Variables used in Ref. [25]

Little was done for about 10 years following Bielawa's early work, but in the last 3 years there has been a significant renewal of interest in applying optimization methods to rotor-blade design. This is probably the result of the urgent requirement to reduce helicopter vibration (fig. 3). In the past, serious efforts to reduce vibration were begun

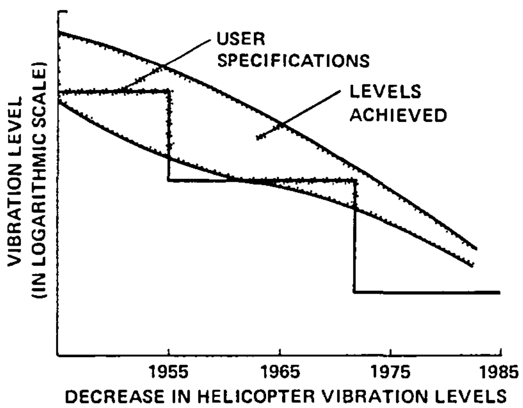

Fig. 3 Decrease in Helicopter Vibration Levels

only after flight tests had started; as a result fixer took the form of local structural modifications, or of adding vibration absorbers or isolation systems. However, as stated previously, it is more effective to work directly on the source of the problem, and for vibration reduction, researchers turned to design techniques applicable to main rotor, which is the primary source of dynamic vibratory forces and moments.

The first indication of significant interest in rotor blade design by optimization techniques appeared at the 1982 Annual National Forum of the American Helicopter Society. At that meeting, Bennett presented an important paper, in which he described four examples related to rotor design-optimization problems that were solved with mathematical programming methods (ref. 25). The particular contribution of his paper was its demonstraton of the effectiveness of numerical optimization methods when applied to problems of interest to helicopter manufacturers and users.

Taylor also made an important contribution at the same meeting with a paper that presented a blade design modification technique for vibratory root force reduction (ref. 26). He pointed out that controlling flatwise mode shapes was an effective approach and proposed to use a "modal shaping parameter" as a measure of blade modal vibration susceptibility in the blade design process. He pointed out that physical blade design parameters, especially mass distributions, had a strong influence on the modal shaping parameter through mode-shape alteration. Thus, these parameters could be used to desensitize certain blade modes to a selected harmonic of the dynamic air load. Even though Taylor did not use numerical optimization to modify the design, his paper is significant, because his formuation is directly usable in formulating the standard blade-optimization problem taking a modal shaping parameter as an objective or constraint function.

At a conference in 1983, Friedmann and Shanthakumaran presented an ambitious and original paper (ref. 27). Their papar was significant in two major respects:

1. Approximation schemes developed for structural optimization as the results of difficult experiences were applied innovatively to rotor-blade design problems, so that comprehensive analytical capabilities could be brought into the design process without incurring unrealistically large computational power requirements,
2. Dynamic force reduction was treated directly as the objective of the design process, without taking recourse to intermediate properties, such as modal frequencies or mode shapes. Adequate placement of these quantities, as well as weight reduction, was obtained as the consequence of the design optimization and, if necessary, could be added to the constraint set.

Based on the assumption that the external geometry of a blade is unchanged in this design phase, the design variables were selected to be the four cross-sectional properties shown in figure 4, specified at seven spanwise stations. In addition, nonstructural masses at three outboard stations were also considered as design variables. Constraints were imposed on aeroelastic stability and rotating natural frequencies in the flap, lead-lag, and torsional degrees of freedom. The blade dynamic response and stability analysis is based on a fully coupled, flap-lag-torsional analysis. The numerical results presented by Friedmann and

Shanthakumaran indicated a 15% to 40% reduction in vibratory force amplitudes and appeared to support significance of automated optimization methods in the design of complex systems such as helicopter rotor blades. The convergence characteristics of the overall design scheme, the significance of aeroelastic stability constraints, and the selection of soft in-plane design will be of interest to design engineers.

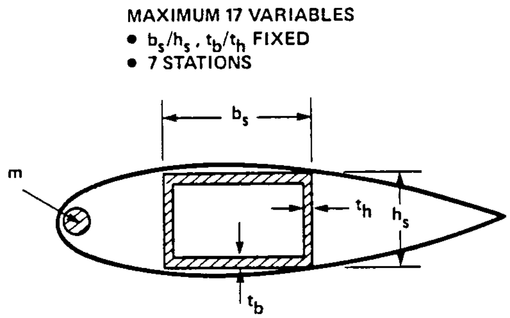

Fig. 4 Design Variables Used in Ref. [27]

Peters et al. reported their efforts to apply design-optimization techniques to helicopter rotor-blade design in 1983 (ref. 28). This was a report of a part of an ongoing effort, including the procedure to exploit the broad range of applications of optimization methods to rotor-blade design. Although the examples presented in reference 28 were based on relatively simple analytical techniques, the approach taken in considering applications of optimization methods within the context of traditional engineering and design practice will provide helpful insight for future work.

More recently (1982, 1983), two reports were written by McIntosh under two separate contracts with U. S. Army (refs. 29 and 30). In ref. 29, McIntosh described a bearingless rotor, flexbeam design to minimize various combinations of bending and axial stresses for a given oscillatory excitation force distribution. In reference 30, he presented an ambitious effort to combine a linear rotor-airframe-coupled vibration analysis code with a general optimization code, to reduce fuselage vibration by modifying the rotor-system design parameters. Both of the studies by McIntosh were preliminary in nature and suggested the need for further work, although some of the results he obtained were encouraging.

As far as applying numerical optimization methods to helicopter design problems is concerned, this particular subject, that is, rotor design to reduce vibration, is most actively pursued; therefore, it is reasonable to expect that a better understanding of the problems will be forthcoming in the near future. It is interesting to see that the rotor-design procedure itself is being studied and discussed in detail to make the best use of optimization methods. Also, technical integration with other disciplines, such as aerodynamics and materials and structural analysis, will become increasingly important.

Aerodynamics and Accoustics

This survey disclosed little published information about the applications of numerical optimization method to improve helicopter aerodynamic performance. This is probably because the aerodynamic responses of helicopters are very complex phenomena, especially at the boundaries of the flight envelope where critical design conditions are usually set. Also, although helicopter noise is an important problem, the rotor noise-generation mechanisms are just beginning to be understood. Under such circumstances, when reliable analytical techniques are still the subjects of research, it might have been inconceivable to attempt to apply formal optimization methods, particularly because formulation and solution of the design problems requires in-depth knowledge of the physical phenomena.

In the past, attempts were made to transfer technology developed for fixed-wing airfoil optimization to rotary-wing design problems. Hicks and McCroskey reported wind-tunnel test results for a two-dimensional airfoil designed with a program obtained by coupling a transonic analysis code with a general mathematical programming code implementing the modified method of feasible directions (ref. 31). A typical design required 8 hr of CPU time on a CDC 7600 computer. The resultant airfoil section, designated A-1, was found to have certain deficiencies, but the design method was considered valuable, especially because it permitted multiple conditions to be treated simultaneously so that best compromise of conflicting requirements could be found.

Tauber and Hicks reported their attempt to weaken the shock on the advancing side of the blade while reducing leading-edge pressure gradients on the retreating side, using a three-dimensional, invicid, full-potential lifting rotor code (ref. 32). The contour of the basic blade airfoil were modified at selected sections by the addition of specific geometric functions to the original ordinates of the basic airfoil. The airfoil modification process was manual, but appreciable improvements could be achieved.

Most recently, Tauber described his theoretical studies on the effects of tip geometry modifications on shockwave behaviors (ref. 33). His work was aimed at designing a blade with low impulsive noise in high-speed forward flight; ROT22, a full-potential, quasi-steady, transonic analysis code, was used. Tauber modified the tip geometry manually to prevent delocalization, however, his design problems were structured to be amenable to automated design with numerical optimization.

Computational aerodynamic codes coupled with numerical optimization will become increasingly important design tools in the future, but this integration will be by no means straightforward. First, the amount of data processing to carry out even a modest number of analyses may demand an excessively high volume of computation. As a result, the innovative use of approximation schemes in the design process will be critically important to the feasibility of an acceptable design code development. As stated previously, the essence of approximation schemes is to avoid unnecessary data processing while guiding the design towards practical optimal designs. For example, if linear theory will provide reasonable trends, it is not necessary to carry out expensive nonlinear analyses. In this context, aerodynamicists have to develop the boundaries of the valid conditions for their theories and computer codes more rigorously and quantitatively.

Second, it will be important to exploit the posibilty of introducing heuristic decision capabilities or intelligence into the design process. This does not necessarily mean that one should turn immediately to artificial intelligence applications. One of the most interesting ideas for transonic airfoil design was presented by Aidala et al. in reference 34, in which shape modification base functions were generated for specific changes of aerodynamic performance. That paper showed that insight on the part of engineers into the physical problems that are involved could effectively reduce the data processing effort. Third, it is necessary that techniques be developed to provide automated and quantitaive evaluation of the results produced by aerodynamic analytical codes. For example, the graphical presentation of pressure distributions is extremely useful to engineers, but not in the automated design process. If two airfoils produce different pressure distributions, it is necessary to know the quantitative measure by which one is superior to the other.

5. AIRFRAME STRUCTURAL DESIGN

Reflecting current interest and needs for controlling vibrations in helicopters, all the papers reviewed here addressed structural modification to control steady-state vibration levels excited by periodic forces and moments. Typically, these studies aim at reducing cockpit vibration that is excited by main-rotor vibratory forces and moments. Done et al. discussed applications of the Vincent-circle methods to identify candidate elements for modification, then followed with formal optimization to achieve minimum steady-state response at a specified point (refs. 35 - 37). With a two-dimensional, tapered-beam model for the Westland Lynx helicopter, they showed that it was possible to reduce the lateral vibration level at the cockpit almost to zero for the 21.7-Hz oscillatory couple applied at the rotor head, by tuning a relatively small number of element stiffnesses.

Hanson and Calapodas (ref. 38) and Hanson (ref. 39) compared the Vincent-circle method with the forced-response, strain-energy method proposed by Sciarra (ref. 40) to select a set of elements that were best candidates for modification to control forced response at a specified point. Their experience with AH-1G stick and build-up models indicated that the strain-energy method was more suitable than the Vincent-circle method, because it indicated correct sensitivities of dynamic amplification factors for element-stiffness changes. They exercised optimization based on semiempirical optimality criteria for uniform strain-energy distribution and verified that it was possible to nulify 2/rev vibration at the pilot seat by stiffening tail-boom sections.

In spite of the desirable characteristics of the strain-energy method, it does not provide sensitivity data with respect to changes in mass, damping, or dynamic absorber parameters. It is believed that the forced-response sensitivity data will be computed more effectively by the method used in formal structural optimization method. The procedure is outlined as follows. Let the system equation of motion for steady-state response to sinusoidal excitation of frequency ω be:

$$[\ K + i\omega C - \omega^2 M\ ]\ U = F \tag{5}$$

where both the forcing vector F and response vector U are complex vectors and the stiffness K, damping C, and mass M matrices are all real and symmetric. If equation (5) is differentiated by a design parameter x,

$$[K+i\omega C- \omega^2 M]\frac{\partial U}{\partial x} = - [\frac{\partial K}{\partial x} + i\omega\frac{\partial C}{\partial x} - \omega^2\frac{\partial M}{\partial x}]\ U \tag{6}$$

If equation (5) has already been solved, and the eigenvalues and eigenvectors of the undamped system are known, then the right-hand-side of equation (6) may be computed approximately using the data for the undamped system. If equation (6) is written in the modal coordinates, the right-hand-side will be more involved because eigenvector sensitivity will be required, but technlogy is available to compute all the required quantities. Consequently, solution of equation (6) for sensitivity data is a relatively simple process. For helicopter vibration problems, the number of excitation frequencies to be computed will be limited; therefore, it is not necessary to decompose large, complex matrices many times. Furthermore, this sensitivity data can be used as input to numerical optimization programs directly. This procedure is well known, but has not been used for the design of helicopter airframe structures.

The finite-matrix perturbation technique was used by King to predict changes in eigenvalues and eigenvectors of a linear, undamped system (ref. 41). Although the method predicted correct trends, the nonlinear characteristics of these quantities with respect to design variables caused substantial errors in estimated frequencies, unless the design changes are small. The formulation was not presented in reference 41, but the method was extended to estimate steady-state vibration at the pilot seat as a function of rotor speed or forward flight speed. Estimated results were compared, with fair success, with the results obtained by flight tests.

Kitis et al. described two reanalysis techniques for steady-state responses for local structural modifications and subsequently used them with a nonlinear programming algorithm to design a spring-damper absorber and an attached beam system for simple helicopter airframe models (ref. 42). The first approach is based on the finite-matrix perturbation technique to obtain exact frequency responses of a modified structure at specified frequencies, and the second method uses component mode synthesis to compute the approximate but explicit frequency responses of the modified structure. Based on the first method, reanalyses for five trial designs took less than one half of the CPU time required for the initial, complete structural analysis. This paper by Kitis et al. makes an important contribution, because it presented effective use of efficient reanalysis techniques coupled with a formal optimization method.

Structural weight reduction is probably more important in helicopters than in conventional fixed-wing airplanes; as a result, one would suppose that there must be a number of weight minimization applications in the helicopter industry, but no published documentation of such cases was found in this survey. The critical problem might have been a lack of appropriate software. Disjoint feasible design space problem for minimum weight structural design subject to dynamic response constraints, reported initially by Johnson (ref. 43) and more recently by Mills-Curran and Schmit (ref. 44), has not been reported with respect to helicoter airframe design. However, this problem is likely to be important if weight reduction of airframe structures is studied more seriously.

There is a strong trend toward extensive use of modern composite materials in the primary and secondary load-carrying structures of helicopters. Automated design, such as the one represented by the PASCO program (ref. 44), will be useful as the industry gains more experience and confidence in using such tools in practical applications.

6 CONTROL SYSTEM DESIGN

Multivariable, function-minimization techniques have been used in the design of linear control systems. For example, minimization of a quadratic merit function of state variables has been commonly used to obtain the closed-loop gain schedule for linearized models. However, the control-system design process involves a great many heuristic decisions, and its final evaluation may have to depend on pilot evaluations obtained from simulator or flight tests. If future developments permit quantitative evaluation of handling qualities with respect to control-system variables, better possiblities for applying formal optimization methods may be at hand.

Vibration reduction by means of higher harmonics, blade-pitch control has been studied extensively, using optimal estimation and control theory. However, Jacob and Lehmann presented an interesting method for transforming the dynamic blade pitch scheduling problem into a non-time-dependent, static optimization problem (ref. 45). The basic idea was to expand the scheduled pitch-angle variation as the weighted sum of Chebyshev polynomials (spanwise) and Fourier series (azimuthwise). The coefficients of this summation were considered as design variables to be modified by the optimization program. The objective was to minimize the vibratory hub load amplitudes. Even though the mathematical model used was relatively simple, Jacob and Lehmann showed the feasiblity of using such a scheme to let the "static" optimization methods generate basic control scheduling. In addition to the scheduled higher harmonics pitch variations, optimal feedback control schemes will be necessary to respond to unexpected phenomena, such as gusts. Namely, the static optimization of pitch scheduling will not be considered a replacement of an active system; instead, both static design and dynamic control schemes may find appropriate roles in improving overall system performances.

7. FLIGHT TRAJECTORY OPTIMIZATION

Flight-trajectory optimization is obviously not a helicopter design consideration. It addresses the problem of determining the optimal flight path to accomplish a specified mission for a given helicopter with specified payload and weather conditions. The objective can be, for example, minimum fuel, minimum time, maximum distance, minimum cost, maximum payload, or maximum survivability. Previously, these types of problems were solved using optimal control theory, which seeks solutions in the form of time-dependent control inputs (e.g., refs. 47 - 49). However, if a mission can be broken into a relatively small number of segments and if the flight conditions are kept unchanged in each segment, then this problem can be cast into a standard form to be solved by mathematical programming methods. Hoewever, no publications dealing with this application were found. Recent developments in microcomputers indicate rapid growth in the capabilities and memory capacities of on-board computers; in the future, therefore, dynamic optimization of flight trajectories may become routine. A futuristic version of this scenario is to let on-board computers work with autopilot systems to reduce pilot workload while carrying out the optimization of flight-trajectory.

8. CONCLUDING REMARKS

There are a number of helicopter design problems that are well suited to the methods of numerical optimization. A number of excellent response/performance analytical programs have been and are being developed, but their real value will be realized only if their results are reflected in the design of actual flight hardware. Recently developed optimization programs and technical experience with optimization techniques provide opportunities to create powerful design tools by integrating comprehensive analytical programs from many disciplines with optimization programs. It has often been the case that integration into a design program reveals shortcommings of or mistakes in the analytical programs, but in return, high-quality analytical capabilities improve the performance of the design process, and as a consequence, contribute to the design of better products.

In practical applications, it is not necessary to arrive at the theoretical optimal design. What is important will be that the value of product improvements obtained as the results of applying optimization methods exceeds the investment to implement and use such capabilities. It is expected that the payoff to investment ratio is high enough for many of the rotorcraft design applications, so that initiation of such development programs can be justified.

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16 Abstract

This paper presents the results of a survey of applications of mathematical programming methods to improve the design of helicopters and their components. More specifically, applications of multivariable search techniques in the finite dimensional space are considered; optimal control theories and their applications are not included. Five categories of helicopter design problems are considered: conceptual and preliminary design, rotor-system design, airframe structures design, control system design, and flight trajectory planning. In addition, key technical progress in numerical optimization methods relevant to rotorcraft applications are summarized. After publication of the first paper by Stepniewski et al. (Stepniewski, W. Z.; Kalmbac, C. F. Jr.: Multi-variable Search and Its Applications to Aircraft Design Optimization, Aeronaut. J. R. Aeronaut. Soc., vol. 74, no. 713, 1970.) in 1970, which included helicopter design optimization by means of mathematical programming techniques, continued interests in this area had been sustained, and there has been significant research in the last 2 to 3 years. This paper is intended to put these newer activities in a proper perspective from a view of a design optimization engineer.

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