Optimization of Helicopter Airframe Structures for Vibration Reduction—Considerations, Formulations, and Applications

T. Sreekanta Murthy*
Lockheed Engineering and Sciences Company, Hampton, Virginia 23666

The paper addresses several key issues involved in the application of formal optimization techniques to helicopter airframe structures for vibration reduction. Several important considerations necessary in the optimization of airframe structures are discussed. An optimization methodology is presented for minimization of vibration in airframe structures during the design process. Considerations to be made in the formulation and solution of optimization problems during the conceptual, preliminary, detailed, and ground and flight test phases of the airframe design process are discussed. The formulation of optimization problems for helicopter airframes is described and pertinent expressions for objective and constraint functions and their sensitivity derivatives are derived. The application of the optimization methodology is demonstrated using a Bell AH-1G helicopter airframe structure. Numerical results are presented for both a preliminary and detailed design model of the helicopter airframe. The systematic application of a formal optimization technique is shown to be useful in attaining the specified optimization objectives to reduce airframe vibrations.

Introduction

VIBRATION reduction is an important consideration in the design of helicopters. The problem of vibration reduction has been well-recognized and many approaches to the solution of the problem have been proposed and studied. The most common approaches employed to reduce helicopter airframe vibrations include the modification of the main rotor system,[1–3] the use of vibration-control devices,[4,5] and the tuning of the natural frequencies of the airframe structure.[6,7] The use of an optimization-based approach for vibration reduction in helicopter airframe structures is the focus of this paper.

Past research work on the problem of vibration reduction in helicopter airframe structures is reported primarily in Refs. 8–15. References 8–12 address the vibration-reduction problem by way of airframe structural modifications to tune the natural frequencies of the structure and/or reducing the responses under dynamic loads. Although, the word "optimization" is used in these references, the research work described there pertains to ad hoc methods for structural modifications without the use of any formal optimization techniques. The work reported in these references pertains to the development of methods for computing necessary structural modification based on considerations such as Vincent circle trace and/or strain energy in a member. The use of nonlinear mathematical programming methods to tune airframe frequencies has only recently gained attention, and Refs. 13–15 describe what are apparently the first applications of that method to simple elastic-line finite element models of airframes. Clearly, there is a need for further research to explore more fully the potential of optimization approaches for vibration reduction in helicopter airframes.

The objective of this paper is to address several key issues involved in the application of optimization techniques to helicopter airframe structures and to discuss considerations necessary in the formulation of vibration reduction as an optimization problem. The paper presents an optimization methodology for vibration reduction and discusses the considerations required for its application during the airframe design process. The methodology is demonstrated by application to a helicopter airframe structure.

Airframe Design for Vibration Reduction

Among the many conflicting requirements encountered in the helicopter airframe design process, vibration requirements are commonly addressed by tuning the airframe structure. The primary objectives of airframe tuning are 1) to ensure that none of the major airframe natural frequencies are close to the predominant rotor excitation frequencies to avoid resonance, and 2) to reduce the dynamic responses of the airframe under rotor-induced loads at the frequencies of interest. In practice, airframe tuning requires extensive vibration analyses and modifications to the design of the structure. These are complex design tasks that typically involve large finite element analyses and multidimensional searches in design space to determine optimum modifications to the structural members. The airframe tuning is primarily based on engineering judgment and involves a tedious trial-and-error modification process. Therefore, there is a need for a systematic procedure for satisfying vibration requirements during the design process by properly accounting for the various multidisciplinary interactions that influence the design modifications.

Considerations in Formulating Airframe Optimization Problems

The basic idea in airframe structural optimization for vibration reduction is to design the airframe in a way that minimizes the vibratory responses in the areas of interest. Formal optimization techniques based on the nonlinear programming method can be used to determine the optimum sizes of structural members.

A key task in the successful application of optimization techniques to helicopter airframes is the formulation of the optimization problem, and includes the establishment of a relevant set of design variables, objective function, and constraints. In the application of optimization to the vibration-reduction problem, it is possible to formulate the problem in several different ways depending on the definition of the design variables, their numbers, the objective functions, and constraints. Because different formulations will yield different solutions to a given minimization problem, a careful examina-

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*Staff Engineer.

tion of the considerations required in the formulation of optimization problems is needed.

An optimization problem is generally expressed in the form:

Minimize the objection function:

$$F(b) \tag{1}$$

Subject to the constraints:

$$G(b) \leq 0 \tag{2}$$

Bounds on design variables:

$$b_l \leq b \leq b_u \tag{3}$$

The objective function and constraints in the formulation of an optimization problem for vibration reduction will typically include functions representing the natural frequencies, the steady-state forced responses, and the weight of the airframe structure. The design variables include such quantities as the cross-sectional sizes of the structural members in the airframe.

The structural optimization approach for vibration reduction can be used in two ways: 1) for determination of optimum modifications to an existing airframe to achieve lower vibrations; and 2) as an integral part of the design process for a new airframe. Considerations for the formulation of the optimization problem in each of these two ways are addressed and discussed below.

Considerations for Existing and New Airframes

Considerations needed in the formulation of an optimization problem for an existing airframe are different from those needed in the design of new airframes. In the case of an existing airframe structure, it is important to note that major modifications to the airframe structure are generally not permissible and only small modifications to a few structural members can probably be made. In the formulation of the optimization problem, this restriction in the allowable structural modifications needs to be considered by imposing narrow bounds on the structural design variables which could severely constrain the desired alteration of the airframe vibration characteristics.

Before proceeding to the detailed discussion of the various considerations needed in the formulation for new airframes, it is necessary to identify and briefly mention the nature of work in the different phases of airframe design. "Conceptual design," "preliminary design," "detailed design," and "ground and flight test" denote the various phases of design. In the conceptual design phase, the overall configurations of an airframe are evaluated through tradeoff studies on weight, aerodynamics, mission, performance, and stability. In the preliminary design phase, the configurations are worked out in greater detail, including layout of major structural members and selection of materials. In the detailed design phase, airframe members are sized based on strength, vibration, weight, and crash-worthiness requirements and the structural integrity is checked for various load cases within the flight envelope. In the ground and flight test phase, necessary modifications are made to the airframe to enable the helicopter to satisfy the design requirements.

Optimization in Phases—A Methodology

As indicated above, the work involved in the various phases of a new airframe design encompasses many disciplinary areas. Vibration requirements are considered along with other design requirements in each of the phases of airframe design. In such a multidisciplinary and multiphase design environment, the formulation of a single optimization problem applicable to all phases of design would be an extremely complex and difficult task. Therefore, a simpler approach to both the formulation and solution of the optimization problem is needed. In an attempt to meet this need, an optimization methodology was developed that provides a unique way of applying formal optimization techniques during the various phases of the airframe design process. The methodology basically involves the formulation and solution of separate optimization problems, one corresponding to each of the phases of the airframe design process: conceptual design, preliminary design, detail design, and ground and flight test, as depicted in Fig. 1. In the methodology, the necessary optimization analyses required for the different phases are sequentially organized as depicted in the figure. The optimization tasks, such as the formulation of the problem, structural analysis, sensitivity analysis, and design-change computations, are independently performed in each phase as indicated by the flow diagram in each block of the figure. The optimization formulation in each block includes a set of design variables, objective function, and constraints that are appropriate to a particular phase and the formulation differs from one design phase to another. In a design phase, necessary analyses are performed to evaluate the objective function and constraints, and the sensitivity derivatives required for the solution of the optimization problem at that particular stage of design. These results are used in a nonlinear programming algorithm for determining the design changes necessary to solve the optimization problem. The optimum design solution determined in one phase is used as an initial design in the subsequent phase. Additional and/or redefined design variables and constraints are included as required in each subsequent phase. In this process, the airframe design obtained from the last phase is the "best" or optimum one. The assumption implied here (which is probably reasonable in a practical design situation) is that the design obtained from each phase is successively improved in subsequent phases to obtain an optimum design in the final phase. The sequential and independent organization of optimization computations in this methodology eliminates the need for complex numerical procedures to link the computations from the different phases. Considerations required to formulate an optimization problem in each of the phases of design are discussed below.

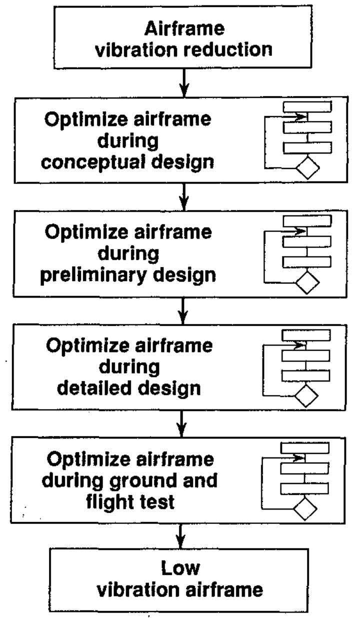

Fig. 1 Airframe optimization methodology.

Conceptual Design

Although vibration considerations are generally not addressed in the conceptual design phase, the present optimization methodology includes it because there is a high potential for optimization to influence the design in this phase for

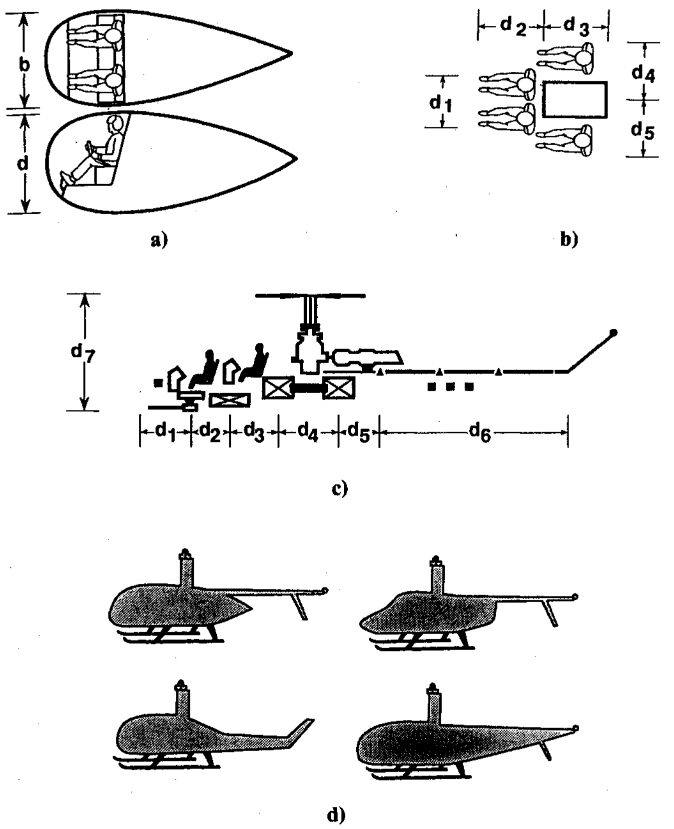

Fig. 2 Design variables in the conceptual design phase: a) aerodynamics; b) cabin layout; c) nonstructural components layout; and d) configuration.

minimization of vibrations in the airframe. In the conceptual design phase, a rough estimate of the vibration characteristics of the airframe can be made based on the knowledge of the past vibration history of a similar class of helicopters and also based on the configuration details such as the number of blades, rotor speed, flight loads/speed, gross weight, and layout of large nonstructural masses such as the engine, fuel, payload, and transmission. It is expected that even with a rough estimate of the vibration characteristics, potential vibration problems can be identified and modifications to the airframe configuration can be suggested early enough to be incorporated into the airframe design. Considerations in formulating an optimization problem in this phase should, therefore, be based on those configuration aspects that directly or indirectly influence airframe vibrations. The use of configuration design variables for vibration minimization necessitates consideration of the multidisciplinary aspects of airframe design involving aerodynamics, layout of components, airframe shape and dimensions, weight, and stability. Consideration of airframe aerodynamics, for example, involves inclusion of the airframe drag in the optimization problem. The minimization of airframe drag often requires modification to the airframe configuration which is specified in terms of overall shape and dimensions of the airframe. The modification of configuration has a direct influence on airframe vibrations because the configuration is directly associated with the distribution of airframe structural stiffness and mass, which affects the vibration characteristics. Hence, the configuration has a significant influence on both aerodynamics and vibrations to be included in the formulation of the optimization problem. Helicopter stability can be used as another example to describe the multidisciplinary aspect of the airframe optimization problem. Helicopter-stability considerations involve the imposition of limits on the changes in the center-of-gravity location in the airframe due to the design changes in the weight and the location of the components such as the engine, fuel tanks, transmission, cabin seating, and payload. Vibration characteristics will change significantly with any such changes in the location of large mass components in the airframe. Therefore, constraints on the airframe center of gravity must be included in the formulation of the problem. A possible set of design variables that can be used in the formulation of the optimization problem in the conceptual design phase is depicted in the Fig. 2.

Preliminary Design

In the preliminary design phase, the primary load paths in the airframe are determined, the arrangements of major load carrying members are established, and the materials are selected. Simple "stick" or "elastic-line" models of the airframe are usually developed for vibration analysis based on approximate distributions of stiffness and mass of the airframe. Airframe-vibration characteristics obtained from such simplified models are much better than those estimated during the conceptual phase of design. Therefore, it is possible to include more detailed vibration considerations in the formulation of an optimization problem in this phase of airframe design. For example, constraints can be placed on the frequencies of the predominant modes of the airframe that are in the vicinity of the rotor-induced excitation frequencies, and on the steady-state forced response amplitudes of the airframe under rotor-induced loads. Candidate design variables in the preliminary design phase could include the following: 1) the layout of major structural members such as bulkheads and stringers; 2) material properties of the primary structural members; and 3) overall cross-sectional geometry of the primary structure defined by the distribution of the breadth and depth of the built-up-structural members that carry the major loads of the helicopter (Fig. 3). It is judged that the use of optimization in this phase of design has good potential to influence the airframe design for minimum vibrations.

Detailed Design

The formulation of an optimization problem in the detailed design phase allows for the consideration of constraints evaluated from more detailed discipline-oriented analyses of vibrations, strength, and weight of the airframe. In this phase, the details of thousands of structural members comprising the airframe and their layout are available. Three-dimensional finite element models having better representation of the structural, material, and geometric properties of an airframe can be developed and used to compute much improved estimate of the structural strength, vibration responses, and weight of the airframe. Candidate design variables in this phase are the cross-sectional dimensions of structural members such as the width and the thickness of stringer sections, the depth of beams, and the thickness of panels (Fig. 4). The modification of such design variables is often bounded by minimum-gauge constraints, and producibility and cost considerations. A large number of design variables and con-

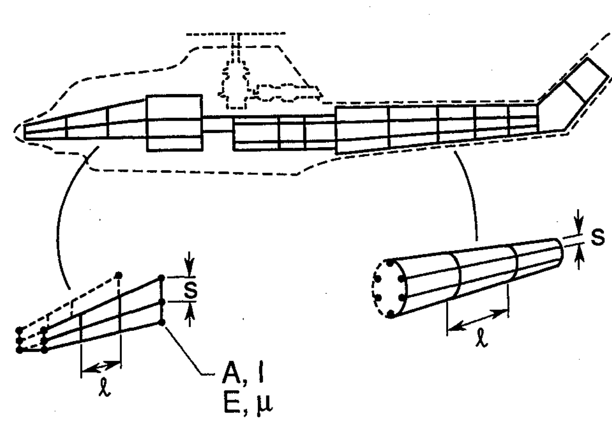

Fig. 3 Design variables in the preliminary design phase.

straints would have to be considered to optimize the cross-sectional sizes of all of the airframe members. For example, imposing constraints on the structural strength would involve stress and deformation constraints on each of the structural members for several load cases. Numerical evaluation of stress and displacement constraints and their gradients may require significant computational effort. On the other hand, the inclusion of vibration constraints in the detailed design stage does not appear to be as computationally demanding as it is for strength constraints. This is because frequency constraints usually need to be imposed only on a few of the lower modes of the airframe. Also, only a relatively small number of forced response constraints, representing responses at important locations in the airframe, would be sufficient. The optimization in this phase is expected to have satisfactory influence on airframe design for minimum vibration.

Ground and Flight Test

In practice, any serious attempt to address airframe vibrations usually begins late in the helicopter design process—after actual vibration problems are identified during ground and flight test. Severe vibrations in specific areas of the helicopter such as tail, landing gear, and engine supports could possibly be identified in the ground and flight test phase. Vibration alleviation in such local areas needs to be addressed through limited structural modifications of the airframe. Considerations to formulate the optimization problem for the ground and flight test phase should be based on the specific vibration problems identified in this phase. Because of the limited choice of design variables, and also because of the narrow allowable bounds on design variables, it would generally be difficult to attain a feasible solution to the vibration-minimization problem. Therefore, the use of optimization in this phase of design would probably have only a limited potential to influence the design for vibration reduction.

Formulation of Functions and Gradients for Airframe Optimization

In view of the foregoing discussion on the considerations required in the formulation of the airframe optimization problem, the formulation of equations for a few pertinent objective/constraint functions and their sensitivity derivatives are presented and discussed here. In particular, the functions selected for discussion are the airframe natural frequency and the steady-state forced responses to rotor-induced loads.

Natural Frequency Constraints

As discussed earlier, constraints on airframe natural frequencies are required to ensure that the frequencies are well-separated from the main rotor excitation frequencies to avoid resonance. The rotor-induced forcing frequencies are discrete frequencies $nN\Omega$ (where n is an integer, N is the number of blades, and Ω is the rotor speed). The natural frequency constraints can be written as

$$\lambda - \lambda_a \leq 0 \tag{4}$$

where λ and λ_a are the actual and allowable natural frequencies of the airframe, respectively. The airframe natural frequencies are determined by solving the eigenvalue equation

$$[K - \lambda M]\Phi = 0 \tag{5}$$

where K and M are the stiffness and mass matrices of the structure, λ is the eigenvalue and is equal to the square of the frequency ω, and Φ is the mode shape vector. The sensitivity derivatives of the frequency constraints are obtained by differentiating Eq. (5) with respect to the design variables b. After simplifying the differentiated terms by making use of the symmetry and orthogonality of matrices K and M, the resultant expression for the sensitivity derivative is given by

$$\frac{\partial \lambda}{\partial b} = \frac{\partial}{\partial b}[\Phi^T K(b)\Phi] - \lambda \frac{\partial}{\partial b}[\Phi^T M(b)\Phi] \tag{6}$$

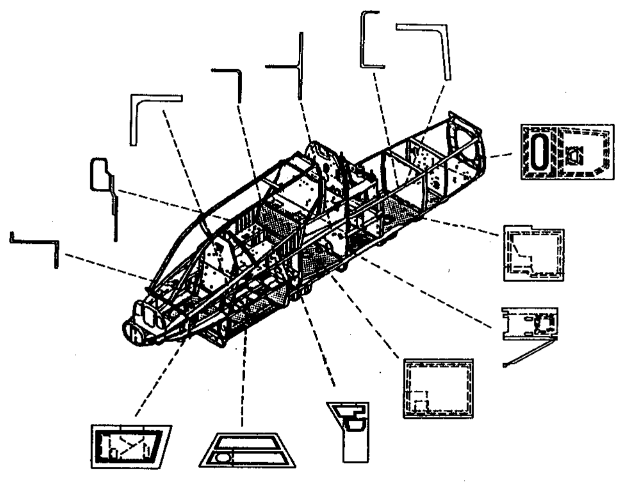

Fig. 4 Design variables in the detailed design phase.

Steady-State Forced Response Constraints

In addition to natural frequency constraints, constraints are required on the forced response amplitudes of the airframe to ensure that the dynamic responses in the airframe are within the allowable limits. The harmonic response in the airframe structure is a result of the periodic airloads acting on the rotor blades that are transmitted from the rotor to the airframe through the main rotor shaft. The forced response displacements are obtained by solving the force equilibrium equation:

$$M(b)\ddot{X}(b) + C(b)\dot{X}(b) + K(b)X(b) = F(t) \tag{7}$$

where M, C, and K are the mass, damping, and stiffness matrices; b is a vector of design variables; F is a vector of steady-state harmonic forces acting on the main rotor shaft, and X is a vector of harmonic response displacements.

The forced response constraints can be written as

$$x - x_a \leq 0 \tag{8}$$

where x is the maximum response displacement at a specified location in the airframe and x_a is the allowable value. The sensitivities of the forced responses are obtained by differentiating Eq. (7) with respect to the design variables b, which leads to the expression

$$[-\Omega^2 M(b) + i\Omega C(b) + K(b)]\frac{\partial x}{\partial b} = \left[-\Omega^2 \frac{\partial}{\partial b}M(b) + i\Omega \frac{\partial}{\partial b}C(b) + \frac{\partial}{\partial b}K(b)\right]x^0 \tag{9}$$

where x^0 is the response vector at the initial design b^0. The partial derivatives of the matrices M, C, and K with respect to the design variables b are determined using either explicit analytical differentiation or finite-difference techniques.

Application to a Helicopter Airframe

This section summarizes the application of the optimization methodology to a helicopter airframe structure. First, the features and the organization of a recently developed optimization computer program are described. Then the numerical results obtained from the application of the program to a Bell AH-1G helicopter airframe structure are discussed to illustrate some of the essential computational tasks involved

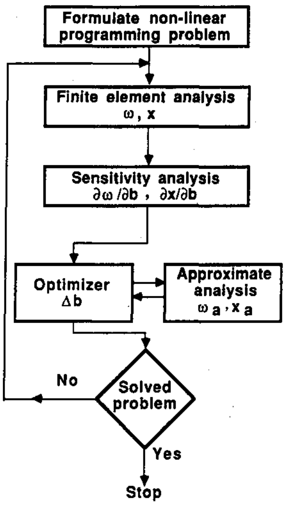

Fig. 5 DYNOPT optimization program.

a)

b)

c)

d)

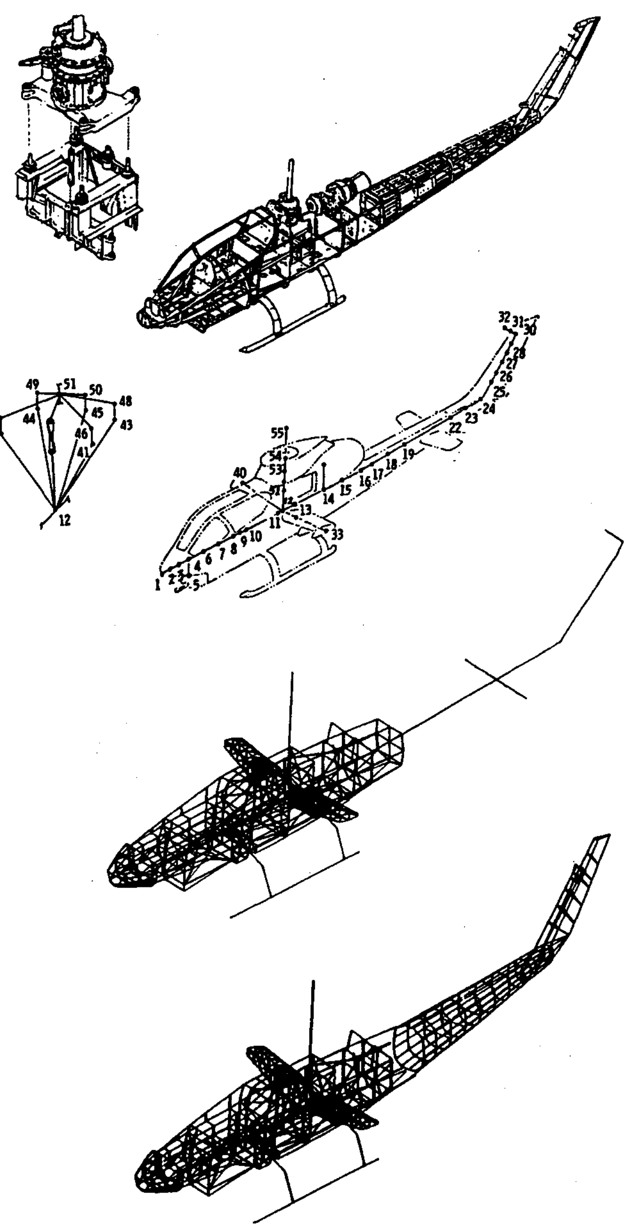

Fig. 6 Bell AH-1G helicopter airframe structure and finite element models: a) airframe structure with skin panels removed; b) elastic-line or stick model; c) built-up fuselage and stick tailboom model; and d) complete built-up model.

in applying the optimization methodology to the preliminary and detailed design phases of airframe design.

DYNOPT Computer Program

A computer program called DYNOPT (dynamics optimization) was developed to carry out the optimization computations based on the nonlinear mathematical programming technique. The DYNOPT code features a unique operational combination of the MSC/NASTRAN finite element structural analysis code[16] extended to include the calculation of steady-state dynamic response sensitivities, with the CONMIN optimizer.[17] The computational steps used in the DYNOPT program are illustrated in Fig. 5. Several modules were developed to perform computational steps indicated in the figure. The modules used in the finite element analysis are 1) assembly of stiffness and mass matrices; 2) static analysis; 3) frequency analysis; and 4) steady-state forced response analysis. The modules used in the sensitivity analysis are 1) static sensitivity; 2) frequency sensitivity; 3) response sensitivity; and 4) weight gradient. For repetitive function evaluations, Taylor series approximation techniques are incorporated into the DYNOPT program. The method of feasible directions available in the CONMIN optimizer program is used for design-change computations.

AH-1G Helicopter Airframe Structure

The structure of the Bell AH-1G helicopter airframe[18] with its skin panels removed is shown in Fig. 6a. The airframe structure is composed of several major components—fuselage, tailboom, vertical fin, landing gear, main rotor pylon, main rotor shaft, and wing and carry-through structure. The fuselage portion of the airframe is built around two main beams that provide the primary vertical bending stiffness in the fuselage structure. The tailboom is of semimonocoque construction having aluminium skins, stringers, and longerons.

The gross weight of the AH-1G helicopter is 8399 lb. This weight is composed of structural weight, nonstructural weight, and useful weight items. The primary structural weight is about 1000 lb. The total empty weight is 5226 lb, which includes both structural and nonstructural weight. Large nonstructural weight items are the engine (585 lb), gun turret (253 lb), main rotor (947 lb), and tail rotor (30 lb). Useful weight totals 3173 lb and includes crew (400 lb), fuel (1600 lb), wing stores (550 lb), and ammunition (323 lb).

Analysis Models of AH-1G Airframe

Three different finite element models of the airframe are available (see Fig. 6). However, in the optimization studies discussed here only two of these models were used: the elastic-line (or "stick") model[11] and the detailed (or "built-up") model.[18]

In the stick model of the airframe, the fuselage, tailboom, wings, and rotor shaft structure were modeled with beam elements. The MSC/NASTRAN finite element model consists of 42 beam elements, 13 scalar spring elements, and 12 rigid-bar elements. There are 56 grid points in the model for a total of 336 degrees of freedom. A consistent mass representation is employed to model the primary structural weight of the airframe. A finite element analysis was carried out to determine the natural frequencies and mode shapes of the elastic-line model of the airframe. The first few natural frequencies and the corresponding mode shapes are shown in Fig. 7.

In the built-up model of the airframe, the fuselage and wing structures were modeled primarily with rods, shear panels, and membrane elements. The tailboom, vertical fin, and tail rotor shaft were modeled with beam elements in the same manner as they were in the stick model. The MSC/NASTRAN finite element model of the airframe consists of a total of 2954 finite elements which includes 2001 rods, 197 beams, 340 shear panels, 243 triangular membranes, 160 quadrilateral

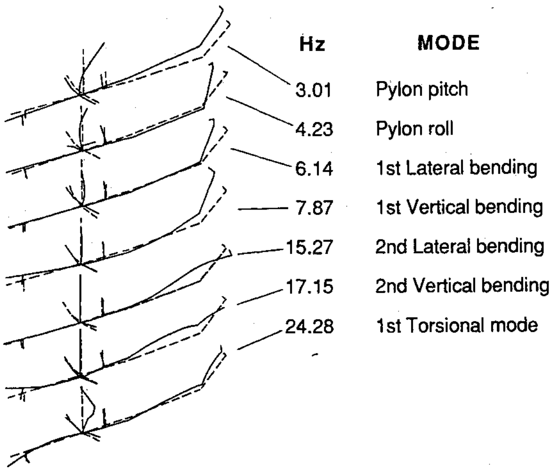

Fig. 7 Natural frequencies and mode shapes of the airframe.

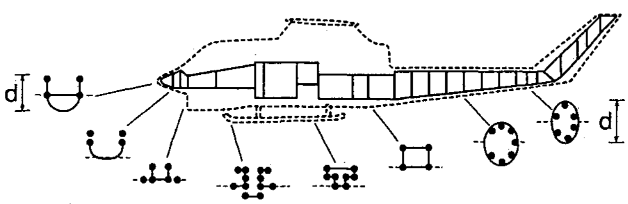

Fig. 8 Preliminary design model for optimization.

membranes, and 13 scalar spring elements. There are 504 grid points for a total of 3024 degrees of freedom. The natural frequencies computed using the built-up model are within 10% of the frequencies of the stick model for the modes of interest here.

Development of Design Models

Two different design models of the airframe (see Figs. 8 and 9) were developed for the optimization studies using the DYNOPT program. One of the models is appropriate for use on preliminary design and the other in the detailed design of the airframe. They are referred to as the preliminary design model and the detailed design model in the discussions that follow.

The preliminary design model takes as design variables the overall depth of the cross section of the primary structure at several stations along the airframe. The design model, which is schematically depicted in Fig. 8, shows several different types of cross sections that comprise the primary structure of the airframe. The locations of structural members acting as stiffeners are indicated by solid dots while the location of flanges, webs, and skins are indicated by solid lines. In the design model, the depth of these sections in the fuselage and the tailboom was allowed to vary while holding fixed the sizes of the stiffeners, flanges, webs, and skins. The design model has a total of 46 independent design variables. An empirical relationship between the design variables of the design model (Fig. 8) and the element sections properties of the stick finite element model (Fig. 6b) was established to update the NASTRAN bulk data deck during optimization iterations. For the numerical studies, the design variables were bounded within 50% of the initial values of the design variables.

The detailed design model (Fig. 9) was developed to optimize the sizes of the many individual structural members comprising the airframe structure. The development of this model required a more detailed consideration of the structure of the fuselage. Figure 9 shows details of some of the fuselage design variables, such as the panels and stiffeners located on either side of the fuselage. The design variables consisted of the thickness of the outer skin of each of the panels and the cross-sectional areas of the stiffeners. A total of 191 design variables were used in this model out of which 108 were independent design variables. The design variables were related to the element properties of the built-up finite element model (Fig. 6c) of the airframe.

Optimization Using the Preliminary Design Model

Using the preliminary design model, an optimization problem was formulated for tuning the natural frequencies of the airframe. The objective function was selected to be the primary structural weight of the airframe. Constraints were imposed on the natural frequencies corresponding to the pylon pitching ω_1, pylon rolling ω_2, first vertical bending ω_3, second vertical bending ω_4, and torsional modes ω_5. The objective function and the constraints are given by Eqs. (10–12):

$$\Psi_0 = \sum \rho_i A_i L_i \tag{10}$$

$$\Psi_{il} = \omega_{il} - \omega_i \le 0, \qquad i = 1,5 \tag{11}$$

$$\Psi_{iu} = \omega_i - \omega_{iu} \le 0, \qquad i = 1,5 \tag{12}$$

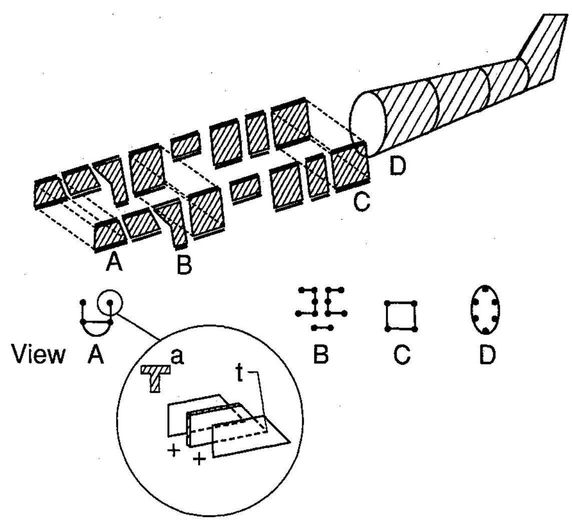

Fig. 9 Detailed design model for optimization.

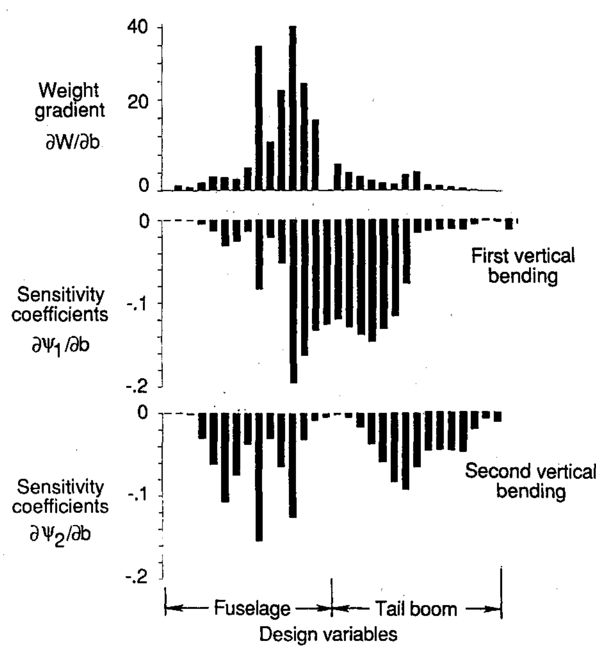

Fig. 10 Sensitivity of weight and natural frequency functions.

where ρ_i is the material density, A_i is the area of the cross sections, and L_i is the length of the beam element. Subscripts l and u indicate lower and upper bounds on the natural frequencies. In Eqs. (11) and (12), the lower bounds on the frequencies are 2.5, 3.5, 5.0, 15.0, and 20 Hz and the upper bounds are 3.5, 4.5, 11.0, 20.0, and 25.0 Hz.

The sensitivity coefficients for the frequency constraints were computed using the DYNOPT program. Figure 10 shows the distribution of sensitivity coefficients for the constraints on the first and second vertical bending modes. The sensitivity coefficients indicate that the design variables in the rear fuselage and most of the tailboom would be effective in changing the first vertical bending mode. The figure also indicates that the design variables in both the fuselage and tailboom would be effective in changing the second vertical bending mode. The weight gradients of the airframe were also computed and are shown in the figure. The design variables in the central and rear fuselage structures would have a significant effect in changing in the weight of the airframe.

The computed frequency sensitivity coefficients were made available to the optimizer in the DYNOPT program, and the changes in the design variables, objective function, and constraints were determined iteratively to solve the optimization problem. The history of the objective function and constraints is plotted in Fig. 11. In the design, the frequency constraints were within the allowable bounds and the optimizer computed the design changes by reducing the value of the objective function. In the first iteration, the airframe structural weight reduced from 1000 to 987 lb. In the second iteration, the frequency constraints were still within bounds and the airframe weight reduced by a small amount compared to the previous iteration. In the third iteration, the airframe weight was reduced to 937 lb. In this iteration, the constraint on the frequency of the first vertical bending mode reached its lower bound and the constraints on the other frequencies were still within their bounds. The optimization computations were continued further using updated values of the design variables. In the fourth, fifth, and sixth iterations the constraints on pylon pitching, rolling, first and second vertical bending, and the torsion modes became active. Many design variables in the rear fuselage region reached their lower bounds. The weight of the airframe reduced to 900 lb in the sixth iteration. The optimization computations were continued for a few more iterations of which the results are not shown. In the subsequent iterations, there were no significant changes in the airframe weight, frequencies, and design variables and the computations were terminated. A comparison of the initial and optimum values of the design variables is shown in Fig. 12. It can be seen that the design variables were reduced in the rear fuselage and forward tailboom structure, whereas they increased in the forward fuselage and rear tailboom structure.

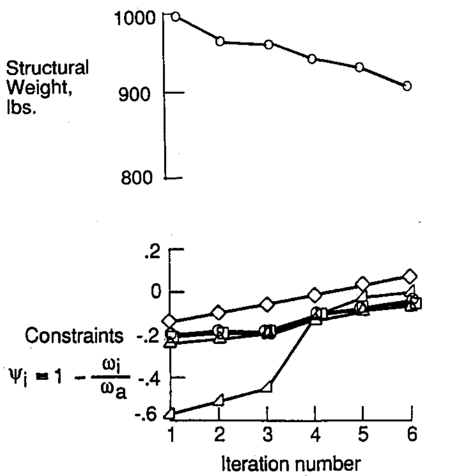

Fig. 11 Optimization history for the preliminary design model.

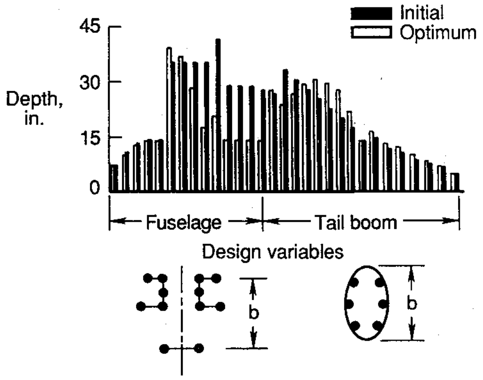

Fig. 12 Initial and optimum design of the primary structure.

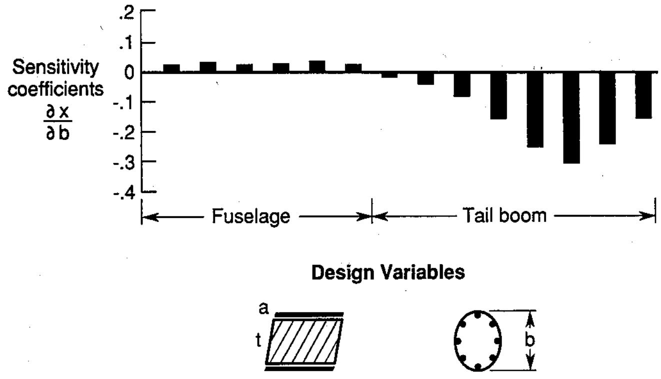

Fig. 13 Sensitivity of forced response displacement constraint.

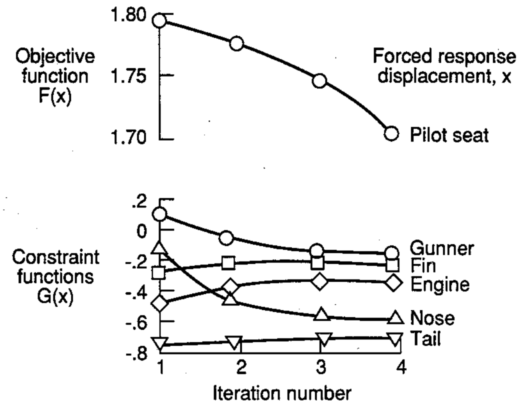

Fig. 14 Optimization history for the detailed design model.

Optimization Using the Detailed Design Model

To illustrate the optimization of the AH-1G helicopter airframe using the detailed design model (Fig. 9), another example problem was formulated. The airframe vibration-reduction problem was formulated with both an objective function and constraints representing the forced response displacements at selected locations on the airframe. The finite element model shown in Fig. 6c was used for the analyses. The forced response displacements at various locations on the airframe were computed for the predominant rotor-induced excitation force of 1000 lb at the frequency of 10.8 Hz (2/rev solution) acting vertically at the top of the main rotor shaft. The objective here was to minimize the forced response displacement at the pilot seat location (whose location in the built-up model of Fig. 6c approximately corresponds to grid point 8 in the stick model of Fig. 6b). Constraints were imposed on forced response displacements at the nose (grid point 2), gunner (grid point 4), engine (grid point 60), tailboom (grid point 24), and fin (grid point 30) locations. The constraint limits at the nose, gunner, and the engine locations were 0.0025 in. and those at the tail and fin locations were 0.005 in.

Figure 13 shows the distribution of the sensitivity coefficients for the forced response displacement at the pilot seat with respect to the fuselage and tailboom design variables. A comparison of the magnitudes of the sensitivity coefficients in the figure indicates that the response is an order of magnitude more sensitive to changes in the design variables in the tailboom portion of the airframe than with respect to changes in the design variables in the fuselage portion of the airframe. This comparison indicates that the design variables in the tailboom would be significantly more effective in reducing the response at the pilot seat location.

The optimization history of the objective and constraint functions in the various iterations of the DYNOPT program are shown in Fig. 14. The objective function was reduced, indicating a trend of decreasing vibration response at the pilot seat. As shown in the figure, the constraints are satisfied at all locations except for iteration 1 at the gunner location. During the iterations, the constraints at the gunner and nose locations were reduced, indicating a reduction of the vibration response at those locations; however, the constraint values at the fin, tail, and engine locations increased gradually.

Summary and Concluding Remarks

The paper addressed several key issues involved in the optimization of helicopter airframe structures for vibration reduction. Several considerations needed in the formulation of airframe optimization problems were described and discussed. Considerations necessary in the formulation of optimization problems for existing airframes as well as for the design of new airframes were discussed. The paper described an optimization methodology that provides a unique way of applying formal optimization techniques during the various phases of an airframe design process. The paper discussed several important multidisciplinary considerations needed in the formulation and solution of the optimization problem. The formulation of optimization problem for helicopter airframe structures was described and expressions for pertinent equations were discussed. The features and organization of the DYNOPT optimization program were described. Numerical results were obtained from the application of the DYNOPT optimization code to the AH-1G helicopter airframe. Studies using the preliminary and detailed design models have been shown to be useful in reducing the primary structural weight, tuning the natural frequencies, and reducing the vibration response at the pilot seat. The results from this initial application of the optimization methodology to a real helicopter airframe are encouraging and more studies are needed to pursue further application of the methodology. In summary, it can be remarked that the systematic application of formal optimization techniques has been shown to be useful in attaining the specified optimization objectives for reducing vibrations in the helicopter airframe.

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References

[1]Taylor, R. B., "Helicopter Vibration Reduction by Rotor Blade Model Shaping," *Proceedings of the 38th Annual Forum of the American Helicopter Society*, AHS, Alexandria, VA, May 1982, pp. 90–101.

[2]Wei, F. S., and Jones, R., "Blade Vibration Reduction Using Minimized Rotor Hub Force Approach," 2nd International Conf. on Basic Rotorcraft Research, AHS, Alexandria, VA, Feb. 1988.

[3]Chattopadhyay, A., and Walsh, J. L., "Minimum-Weight Design of Rectangular and Tapered Helicopter Rotor Blades with Frequency Constraints," 2nd International Conf. on Basic Rotorcraft Research, AHS, Alexandria, VA, Feb. 1988.

[4]Taylor, R. B., and Teare, P. A., "Helicopter Vibration Reduction with Pendulum Absorbers," *Journal of the American Helicopter Society*, Vol. 20, No. 3, 1975.

[5]Desjardins, R. A., and Hooper, W. E., "Antiresonant Isolation for Vibration Reduction," The 38th Annual Forum of the American Helicopter Society, AHS, Alexandria, VA, May 1982.

[6]Shipman, D. P., White, J. A., and Cronkhite, J. D., "Fuselage Nodalization," 28th Annual Forum of the American Helicopter Society, AHS, Alexandria, VA, Paper 611, 1972.

[7]Welge, R. T., "Application of Boron/Epoxy Reinforced Aluminium Stringers For The CH-54B Helicopter Tail Cone," NASA CR-111929, July 1971.

[8]Sciarra, J. J., "Use of the Finite-Element Damped Forced Response Strain-Energy Distribution for Vibration Reduction," Boeing-Vertol Company, Philadelphia, PA, Rept. D210-10819-1, July 1974.

[9]Done, G. T. S., and Hughes, A. D., "Reducing Vibrations by Structural Modification," *Vertica*, Vol. 1, 1976, pp. 31–38.

[10]Sobey, A. J., "Improved Helicopter Airframe Response Through Structural Change," Ninth European Rotorcraft Forum, Paper 59, Stresa, Italy, Sept. 1983.

[11]Hanson, H. W., "Investigation of Vibration Reduction Through Structural Optimization," Bell Helicopter Textron Rept. USAAVRADCOM-TR-80-D-13, July 1980.

[12]King, S. P., "The Modal Approach to Structural Modification," *Journal of the American Helicopter Society*, Vol. 28, No. 2, 1983,

[13]Done, G. T. S., and Rangacharyulu, M. A. V., "Use of Optimization in Helicopter Vibration Control by Structural Modification," *Journal of Sound and Vibration*, Vol. 74, 1981, pp. 507–518.

[14]Miura, H., and Chargin, M., "Automated Tuning of Airframe Vibration by Structural Optimization," *Proceedings of the 42nd Annual Forum of the American Helicopter Society*, AHS, Alexandria, VA, 1986.

[15]Sreekanta Murthy, T., "Design Sensitivity Analysis of Rotorcraft Airframe Structures for Vibration Reduction," Sensitivity Analysis In Engineering, NASA CP-2457, Sept. 1986.

[16]MSC/NASTRAN, *User's Manual Volume I and II*, The McNeal-Schwendler Corp., Los Angeles, CA, Nov. 1985.

[17]Vanderplatts, G. N., "CONMIN—A Fortran Program for Constrained Function Minimization: User's Manual," NASA TMX-62282, Aug. 1973.

[18]Cronkhite, J. D., Berry, V. L., and Brunken, J. E., "A NASTRAN Vibration Model of the AH-1G Helicopter Airframe," Vol. I, U.S. Army Armament Command Rept. R-TR-74-045, June 1974.