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APPLICATION OF NUMERICAL OPTIMIZATION METHODS IN HELICOPTER INDUSTRY

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Abstract

This paper presents a review of the application of numerical optimization methods for helicopter design at McDonnell Douglas Helicopter Company and in the rest of the helicopter industry. In helicopter optimization a multilevel approach, which consists of a global level and a local level, is used to achieve an overall optimum helicopter configuration. At the global level the overall configuration of the helicopter is optimized to meet the mission requirements. At the local level the primary components are optimized to meet their specific design requirements. Application of numerical optimization methods presented are the overall configuration optimization at the global level using the preliminary design analysis methods and the primary component optimization at the local level using the component specific analysis methods in the optimization process. Optimization of the primary components presented are: (l) the blade airfoil profile optimized to improve performance in the rotory wing environment, (2) the rotor blade geometry to improve performance both in hover and forward flight, (3) the rotor blade structural properties aeroelastically tailored to improve performance ("compliant" rotor), or minimize blade loads or hub vibratory loads, (4) the fuselage structure to minimize weight and also to reduce vibration levels, and (5) the bearingless rotor hub structurally tailored for minimal stresses with dynamics constraints. Numerical results for the overall configuration optimization and the component level optimization show a 3% to 5% improvement in performance, a 5% to 15% reduction in the vibration levels, a similar percentage reduction in the fuselage structure weight, and a 70% reduction in the combined peak normal stresses together with improved rotor dynamics for the optimized bearingless rotor hub design. In addition, the method provides a rational design tool which results in significant savings in man-hours compared to the conventional parametric studies approach. The beneficial impact on the design scheduling due to the savings in man-hours will result in considerable cost and schedule reduction to the project.

1. Overview

Technologists rely on their analysis tool to verify and analyze a design for performance, dynamics, handling qualities, acoustics or structural integrity. Until a few years ago, if a design was unacceptable, a few design parameters were modified based on past experience and the design was re-analyzed, and the procedure was repeated until a satisfactory design was achieved. The major drawbacks of this iterative procedure are:

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1. Designers and technologists did not consolidate their efforts during design development.
2. The iteration process led to significant delays and unproductive effort.
3. The number of design parameters modified were limited to a few.
4. There was no systematic plan to "optimize" a design.

McDonnell Douglas Helicopter Company has established a procedure to overcome the above deficiencies through integration of optimization analysis in various phases of design development of a helicopter.

A review of the pertinent literature indicates that modern optimization methods have found increased application in the helicopter industry only in the recent past. In a recent survey paper, Miura [1]* pointed out that although applications of optimization methods to rotorcraft design were first suggested in the early 1970's [2,3] the helicopter community started to recognize the practical importance of this technology more seriously only in the last four or five years. The main reason for this late start by the helicopter industry to adopt optimization technique as a design tool can be attributed to the complexity of the helicopter design problem and the lack of reliable analytical tools. Although many of the crucial problems, such as dynamic air load predictions, are still subjects of research, the more efficient optimization methods using mathematical programming approaches that are now available [4,5] has made this technique applicable to helicopter design with reasonable success.

In the traditional design process the overall configuration of the helicopter is arrived at through a series of preliminary design studies. This process involves minimization of the airframe/propulsion system weight required to support a prescribed mission payload and profile. The airframe/propulsion system weight is an interrelated function dependent on the requirements of several disciplines such as aerodynamics, dynamics, structures, propulsion, and mission payload (Figure 1). Because of the sometimes conflicting nature of the different disciplines involved, to arrive at a near optimum overall configuration based on parametric studies is time consuming, costly, and imprecise. Numerical optimization methods provide a rational way of meeting these conflicting requirements and, in addition, provide solution in a fraction of the time needed for conventional studies. This time saving can substantially influence the design scheduling of the project.

In the helicopter design process, numerical optimization methods have the potential for application starting from the preliminary design stage to solving problems that often arise during the design phase (such as local vibration reduction on the fuselage) and to the detailed sizing of structural components to minimize weight or to obtain an optimum shape. Optimization techniques can be applied at two distinct levels (using the multilevel approach): i) global level and ii) component level. At the global level, the overall configuration of the helicopter is optimized; at the component level, the primary components of the helicopter, such as the airfoil, rotor geometry, blade cross section, fuselage structure, and bearingless rotor hub, are optimized. This multilevel optimization approach is shown

* Numbers in [ ] indicate references listed at the end.

schematically in Figure 2. The optimization at the global level and at the component level are iterated upon untill the deisred objectives are achieved.

The airfoil of the rotor blade is an important component of the helicopter. A rotating airfoil operates over a wide range of conditions; at high angles of lift coefficients at medium subsonic Mach numbers and at low C_l values at transonic mach numbers. For an optimum performance of the airfoil, low drag is required at high angle of attack and Mach numbers, good stall characteristics are required at the low to moderate Mach numbers of the retreating blade, and finally a high critical Mach number is required at the low angle of attack of the advancing blade in forward flight. In the past helicopter companies have developed airfoils through extensive wind tunnel testing to meet these needs. Recently numerical optimization methods have been applied to develop airfoil sections to reduce drag at transonic speeds [6]. These methods extended to the design of rotating airfoils can reduce the cost of wind tunnel testing in the airfoil development program.

Improved rotor performance in terms of reduced rotor horsepower and reduced vibration levels can be achieved by using tapered blades with nonlinear twists and sweptback parabolic tips [3,7]. The advances made in composite material technology in the recent years have given the designer the freedom to explore the effects of unconventional blade geometries on rotor performance. Numerical optimization methods lend themselves well to accomplish this [8,9,10,11]. Results presented in these references show 1.5% to 5% improvement in performance in addition to cost savings in man-hours.

Rotor performance improvements can be achieved not only with tailoring of rotor geometry, but also structural properties of the rotor blades. These are referred to as "compliant" or "aeroelastically conformable" rotor. Both analytical and experimental studies have shown considerable promise in this effort [12,13,14,15]. Performance improvements between 2 and 6 percent have been shown in high-speed cruise. Of course, such an approach has to balance the requirements of reduced dynamic loads and vibrations, and improved performance.

In rotorcraft structural optimization the rotor blade cross section and the structural members of the fuselage can be optimized to minimize weight and to reduce vibration levels. The demanding requirements on helicopter performance make gross weight reduction and vibration levels and their alleviation in helicopter design important problems that need to be approached in a consistent and rational manner. In helicopter design, minimum weight and reduced vibration levels are equally important. The optimization procedure should therefore be capable of handling these two requirements. In the numerical optimization procedure, this problem can be approached in three ways: i) to form a compound objective function of the weight and the vibration levels, ii) use weight as the objective function and reflect the vibration level requirements as additional behavior constraints, or iii) use vibration levels as objective function and introduce the weight as an upper bound constraint. The last two methods are more practical approaches to solving the problem. Also, it may be appropriate to use both methods in different phases depending on the design phase requirement and the payoff expected. For example, as a first phase use method (ii) to minimize weight and as a second phase use method (iii) to reduce vibration levels.

Structural optimization methods have been successfully applied for fixed wing aircraft [16,17] but such applications to rotory wing aircraft are only beginning to appear in the recent years [1]. A comprehensive review of the recent developments in the application of modern structural optimization methods for vibration reduction in helicopters was presented by Friedmann [18]. Results for rotor blade design, reported in Ref. [19], indicate that 15% to 40% reduction in vibratory force amplitudes, together with 9% to 20% reduction in blade weight, can be realized through only minor changes in the blade cross section in the outboard 20% of the blade. In Ref. [19], the method (iii) described above is used for rotor design.

Application of structural optimization methods to large scale structures like the fuselage necessitate extensive use of the approximation concepts for efficient structural synthesis developed in [4] to make the procedure cost effective. The design sensitivity analysis available in NASTRAN [20] has made it possible to couple this information with existing optimization codes to produce an optimization package. The commercially available codes such as MSC/OPTIM and ADS/NASOPT are based on this coupling procedure. Recently, a procedure for structural sizing optimization procedure using an external finite element program was presented in Ref. [21]. Given the specific requirements of the fuselage in the helicopter design, such an optimization package needs to be developed by the helicopter industry.

An overall approach to aeroelastic/aerodynamic optimization of high speed helicopter/ compound rotor was discussed in Ref. [22] with promising results. Such an approach to helicopter design can minimize the developmental cost of the project.

In this paper, the application of numerical optimization method used as a multilevel approach in the helicopter design at McDonnell Douglas Helicopter Company are described. The global level optimization of the overall configuration and the component level optimization of the rotor blade airfoil, rotor geometry, blade cross section, fuselage structural properties, and bearingless rotor hub design, are presented.

2. Numerical Optimization Methods

The optimization problem posed as the standard mathematical programming problem can be stated in the following form:

Find the vector of design variables $\vec{D}$ such that

$$g_q(\vec{D}) \leq 0 \; ; \; q = 1, 2........Q$$

$$D_i^L \leq D_i \leq D_i^U \; ; \; i = 1, 2.......N$$

and

$$J(\vec{D}) \rightarrow Minimum \; (or \; Maximum) \tag{1}$$

where $g_q(\vec{D})$ is the q-th constraint function in terms of the vector of design variables $\vec{D}$, Q is the number of constraints, D_i is i-th design variable, superscripts L and U denote lower and upper bounds respectively, N is the number of design variables, and $J(\vec{D})$ is the objective function in terms of the design variables.

Various numerical solutions for the problems expressed in the form in Equation (1) that are available in the literature are reviewed in Ref. [1]. Traditionally solution methods of optimization problem (particularly structural optimization problems) have been dictated by the size of the problem in terms of the number of design variables and constraints used to define the problem in order to make it computationally cost effective. In helicopter applications it is dictated more by the cost of function evaluation used for the analysis programs, such as aerodynamic performance, rotor blade aeroelastic loads, stability and response in forward flight, which are computationally expensive even with today's fast computers. When applying mathematical programming methods to practical problems, it is important to recognize that any optimizer must evaluate the objective and constraint functions as many as 50 t0 200 times before the design process converges.

The approximation concepts for efficient structural optimization procedures developed in Ref. [4] provide valuable means of overcoming this barrier. In an optimization process the information needed to guide the design into the neighborhood of a practical optimal design can be obtained from an approximate analysis scheme; accurate evaluation of the system response is not necessarily required for this purpose. However, the final design needs to be evaluated accurately using a comprehensive analysis.

Various approximation schemes that are available to improve the computational efficiency of the procedure include the following [1]:

1. Use of simplified analytical models within the boundary where analysis provides sufficiently accurate trends for design changes.
2. Fast reanalysis of systems with perturbed design 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 constraints to reduce the number of constraints that are handled by an optimization program.
5. Generation of approximate functions which are explicit function of the design variables for the implicit function in Equation (1) and periodic updating of approximate function based on accurate reliable data.

Approximate functions, $f_a(\vec{D})$, for the constraints and objective function ($g(\vec{D})$ and $J(\vec{D})$) can be constructed by means of a Taylor series approximation in the neighborhood of $\vec{D}_0$ as follows:

$$f_a(\vec{D}) = f(\vec{D}_0) + \sum_{i=1}^{N} \frac{\partial f(\vec{D}_0)}{\partial D_i}(\vec{D}_i - \vec{D}_0) \tag{2}$$

Where

$$\frac{\partial f(\vec{D}_0)}{\partial D_i} = \left\{ \frac{\partial f}{\partial D_1}, \frac{\partial f}{\partial D_2}, \dots\dots\dots\dots \frac{\partial f}{\partial D_N} \right\}$$

are the sensitivity imformation. For nonlinear constraints and objective function a second order Taylor series expansion may be adequate. The sensitivity information required to construct Equation (2) may be obtained using finite difference schemes. For some optimization problems the sensitivity information can be generated within the analysis program [4,23] and thus improve the computational efficiency of the process.

The basic architecture of the design optimization program at the component level, which makes use of the above mentioned approximation concepts, is shown in Figure 3. In this approach, the approximate problem generated based on the Taylor series approximation is solved exactly to obtain a sequence of improved designs. These improved designs are evaluated using the analysis programs. The process is terminated when the desired objectives are achieved.

Numerical optimization programs available to solve Equation (1) include CONMIN [24], NEWSUMT [23], and ADS [5]. These optimizers have been successfully used for a wide class of problems ranging from automotive component designs [21] to helicopter vibration reductions [8,19] and to control the coupling of vibration modes in flexible space structures [26].

In the following sections, application of numerical optimization to helicopter optimization problems are presented. The optimization problems addressed here are: configuration optimization, rotor airfoil optimization, rotor aerodynamic performance optimization, aeroelastic tailoring of rotor blade, structural optimization of fuselage, and structural tailoring of bearingless main rotor hub.

3. Configuration Optimization

In the development of a new helicopter, the preliminary concept studies where the overall configuration of the helicopter is determined plays an important role. In the conventional approach, a series of parametric studies are conducted to arrive at a near optimum overall configuration. This approach is time consuming and labor-intensive. Application of optimization techniques at the preliminary design stage can result in considerable cost savings and substantially influence the design schedule of the project.

At McDonnell Douglas Helicopter Company, a helicopter configuration is optimized using a program called CASH (Computer Aided Sizing of Helicopters) [27]. This program was written and has been updated over the past ten years and was an important part of the preliminary design process of the Army's advanced attack helicopter, AH-64. In CASH, as a first step, measures of effectiveness are supplied to define the mission characteristics of the helicopter to be designed. Then CASH allows to rapidly and automatically develop the basic size of the helicopter (or other rotorcraft) for the given mission (Figure 4). This enables the designer to assess the various tradeoffs and to quickly determine the optimum configuration.

The inputs to CASH loosely bound the helicopter design problem by defining mission characteristics such as payload, range, load factor, maneuver, and gross weight. These items can be defined to any detail or allowed to float and become essentially outputs. Given inputs, the CASH program iterates among the physical design constraints to produce the optimum helicopter. The flow chart of the CASH program is shown in Figure 5.

The design constraints include rotor performance, rotor dynamic stability, required rotor blade geometries, and engine characteristics. CASH searches for the particular mission segment that dominates the aircraft design. Depending on the mission, this might be hover performance, maneuver, high speed dash capability, or a combination of these. Once the key design constraints and mission segments are identified, CASH iterates to the optimum geometry to maximize the payload/gross weight fraction.

Gross weight and disc loading are CASH parameters that are generally varied to achieve the minimum size helicopter capable of meeting the payload required (Figure 6). With the gross weight and disc loading determined, the rotor diameter is sized, after which the load factor subroutine sizes the solidity to meet the critical maneuverability requirements.

Then, if an existing engine is to be used, the disc loading is adjusted (along with diameter and solidity) to meet the performance requirements. If an arbitrary engine is to be used, it is sized to meet the performance requirements for the input disc loading. The resulting engine characteristics then become the inputs to an engine development program to support the given helicopter design.

Once CASH has defined the optimum configuration, the various components of the helicopter can be optimized for their specific performance needs using other optimization routines such as OPT, AESOP, CONMIN, NEWSUMT, or ADS. This approach can be looked at as a multilevel optimization; the configuration optimization being the global level and the component optimization as the local level. As examples of the component optimization, rotor airfoil optimization, rotor performance optimization, aeroelastic tailoring of rotor blade, structural optimization of fuselage, and structural tailoring of bearingless rotor hub, are presented in the following sections.

4. Rotor Airfoil Optimization

Design of high speed helicopters necessitates the use of improved airfoil profile characteristics. At these speeds special airfoils are required at the blade tip because of the higher tip speeds. Figure 7 [27] shows a typical aerodynamic environment for the blade tip of a helicopter at 140 Knots. It is important to note that the blade is exposed to high lift coefficients at medium subsonic Mach numbers and to low C_l values at high Mach numbers. These are the two critical design quantities for rotor sections in the helicopter use. With increased flight speed these two operating regions become still more extreme. The two limiting lines describe the maximum dynamic lift capacity and the region where the drag divergence Mach number is exceeded. For different flight conditions and for airfoils at other locations on the blade the airfoil operating environment could be quite different.

Figure 7 illustrates the basic concerns in selecting an airfoil for the helicopter rotor blade. The rotor blade section operates over a wide range of conditions. Low drag is required at the working condition of the rotor in hover, namely moderately high angles of attack and Mach numbers. Good stall characteristics, including high maximum lift coefficient, are required at the low to moderate Mach numbers of the retreating blade in forward flight. Finally a high critical Mach number is required at the low angle of attack of the advancing blade in forward flight. In addition, the airfoil should have a small pitching moment. A low pitching moment about the aerodynamic center is required of the blade airfoil if excessive control system loads are to be avoided, particularly in forward flight where there is a large periodic variation in angle of attack and aerodynamic pressure.

Numerical optimization methods are best suited to select an airfoil meeting these conflicting requirements. McDonnell Douglas has sucessfully used an airfoil optimization routine developed at NASA/Ames [6] to generate a family of airfoils. In using this code, the basic airfoil contour is defined and the code optimally changes that contour to achieve a specified design condition. An example is to maintain lift (C_l) and drag (C_d) at a certain angle-of-attack but minimize the section pitching moment (C_m). The code develops a series of influence coefficients that represent the impact of geometry changes on the airfoil aerodynamic characteristics. The geometry is then varied locally to meet the requirements. Figure 8 shows the changed pressure distribution and airfoil contour for a typical airfoil in the numerical optimization process.

The optimized airfoils were fabricated and tested to verify the results. Tests were conducted at the Lockheed transonic, two-dimensional wind tunnel in August 1983. The test results indicated a significant improvement over the current state-of-the-art boundary as illustrated in Figure 9 [28]. The boundary was defined by plotting the low speed lift coefficient and drag divergence Mach number of all available two-dimensional data after normalization to remove different tunnel effects. (for the purpose of this comparison, the low speed maximum lift coefficient is defined at a Mach number of 0.4, and the drag divergence Mach number is that at which the drag at zero lift increases sharply).

The results of this optimization application clearly show the potential benifits of optimization techniques.

The optimized airfoils, when available at the configuration optimization stage, are used in the CASH program described in the previous section.

5. Rotor Performance Optimization

5.1 Overview

The configuration optimization using the CASH program, discussed in Section 3, provides with a rotor that is optimized at the global level. This rotor can now be optimized at the component level to improve the aerodynamic performance of the rotor in both hover and forward flight. To accomplish this goal, the influence of rotor blade design parameters such as twist, blade root chord, chord distribution, taper ratio, point of taper initiation, tip sweep, and airfoil sections, on the aerodynamic performance of the rotor blade are examined. The rotor parameters such as number of blades, blade radius, rotor solidity, tip speed (or RPM), and gross weight, obtained from CASH, are treated as pre-assigned parameters. The development of improved airfoils sections and the design flexibility and cost effectiveness of composite materials have offered the designers a great potential to investigate the influence of the blade design parameters on rotor performance using optimization techniques.

A review of the pertinent literature shows that numerical optimization methods were applied for rotor performance optimization in the early 1970's [2 and 3]. Both these references used the optimization program AESOP (Automated Engineering and Scientific Optimization Program developed by the Boeing company). After more than a decade later, there is renewed interest in this area in the helicopter industry. This renewed interest could be attributed to three main reasons: i) the advances in composite material technology, ii) the advances in computer technology, and iii) the refined optimization methods and rotor aerodynamic analyses tools available today.

Bennet [8] optimized rotor shaft horsepower for hover performance treating the blade twist distribution as design variables. He showed a 1.55% reduction in the hover horsepower due to the optimum twist compared to a linear twist. In Ref. [9], the FRANOP (Frame Work for Analysis and Optimization Problems) program developed by NASA/LRC was used to optimize the rotor. The rotor was optimized for hover, sustained maneuver and high speed cruise. The design variables used were: linear twist, blade radius, tip speed, equivalent chord, linear taper ratio, radial station at which taper begins, local twist, local chord and local airfoil. Engine size, rotor L/D, dynamic system weight and fuel weight were treated as the objective function and stall criteria and engine size as constraints. Numerical results presented showed subtantial reduction in the objective function compared to their baseline configuration.

Walsh, Bingham and Riley [10] applied the optimization procedure to helicopter blade design which minimized hover horsepower while maintaining satisfactory forward flight performance. They used the C-81 program for forward flight performance and a hover program based on strip theory analysis. These analysis programs were coupled with CONMIN [24] for the optimization process. The design variables used were: point of taper initiation, root chord, taper ratio and maximum twist. Numerical results presented in this paper demonstrated the cost savings that can be achieved in the design process using optimization techniques when compared to the conventional lobor-intensive parametric studies.

McDonnell Douglas has developed a rotor optimization procedure by combining in-house performance analysis programs for hover and forward flight with the ADS [5] optimization package. The optimization procedure has been applied to optimize the main rotor geometries for an advanced rotor system and for a future light helicopter. The problem formulation, design variables, performance analysis programs, optimization procedure, and results of the rotor performance optimization as applied to a future light helicopter rotor design, are presented next.

5.2 Problem Formulation

The main objective of this rotor optimization study was to minimize the rotor horsepower both in hover and forward flight. Minimizing the rotor horsepower in forward flight results in maximizing the rotor $(L/D)_e$ based on the relationship given below:

$$(L/D)_e = \frac{T_V}{\frac{550\ HP}{V} - \frac{1}{2}\rho V^2 f} \tag{3}$$

where T_V is the vertical thrust force, HP is the shaft horsepower, V is the forward velocity, ρ is the mass density of air, and f is the equivalent flat-plate drag area.

The rotor performance optimization analysis developed has a provision for using a linear combination of rotor horsepower in hover and in forward flight as the objective function. The combined objective function is defined as:

$$J = \eta J_f + (1 - \eta) J_h \tag{4}$$

where J is the combined objective function, J_h is the rotor horsepower in hover, J_f is the rotor horsepower in forward flight, and η is a weighting variable ranging from 0 to 1. When $\eta = 1$, the rotor is optimized for forward flight performance only and when $\eta = 0$, the rotor is optimized for hover performance only. For values of $0 \leq \eta \leq 1$, the rotor performance is optimized for a combination of hover and forward flight performance.

In Equation (4), the forward flight objective function, J_f, is chosen as the rotor horsepower at a forward speed, altitude, and temperature, while the hover objective function, J_h, is chosen as the hover horsepower at an altitude and temperature based on the design requirements. These objective functions, J_f and J_h, can be at two different altitude/temperature conditions. Therefore, the final optimized design is analyzed at both these altitude/temperature conditions for all forward speeds of interest to ensure overall improved performance when compared to the baseline design.

The following design constraints were used in the optimization process: The total twist was required to be within a certain upper bound to keep the blade loads and pitch link loads within limits. The rotor solidity was maintained within a narrow range ($\pm 3\%$) of the initial value. The root chord, tip chord, and tip sweep angle are constrained to be within certain specified upper/lower bound limits. Additionally, the design variables, described in the next section, have lower and upper bounds imposed upon them.

5.3 Design Variables

The main parameters affecting the aerodynamics of the rotor are solidity, linear or nonlinear twist and taper, tip sweep, and position of change in taper, twist or sweep. The tip sweep is also a powerful means of improving the acoustic performance of the rotor [29] and modifying the vibratory response of the blade [7]. In addition, earlier studies have shown that most beneficial effects were obtained by modifying the tip region of the blade (outboard of 0.8 R). Therefore the blade was divided in to three sections for defining the chord and twist distributions and into two sections for the sweep distributions. The definition of the sections for chord, twist, and sweep are treated independent. In the tip section, the chord, twist and sweep were represented by a quadratic equation; in the inboard sections a linear representation was used. Based on these considerations, the design variables chosen are (shown in Figure 10):

D1 - Root chord
D2 - Taper ratio in section 1
D3 - Taper ratio in section 2

D4, D5 - Coefficients of quadratic chord distribution in section 3
D6 - Length of section 1 for chord
D7 - Length of section 2 for chord

D8 - Blade root twist
D9 - Rate of twist in section 1
D10 - Rate of twist in section 2
D11,D12 - Coefficients of quadratic twist distribution in section 3
D13 - Length of section 1 for twist
D14 - Length of section 2 for twist

D15 - Sweep initiation (length of region 1)
D16 - Sweep at D15
D17,D18 - Coefficients of quadratic sweep distribution in section 2.

Upper bound and lower bound constraints are imposed on all the design variables. In addition, from practical consideration, the following constraints are imposed:

$$D6 - D7 \leq 0.0$$
$$D13 - D14 \leq 0.0 \quad (5)$$

5.4 Performance Analysis Programs

The rotor horsepower in hover and in forward flight were calculated using the performance analysis programs developed at McDonnell Douglas. Hover performance was calculated using the HOVERSM (Hover Strip Momentum) program. HOVERSM is based on blade strip momentum theory [30]. In this program helicopter equilibrium is calculated iteratively to obtain the collective pitch, rotor horsepower, and hover figure of merit.

For forward flight performance analysis, McDonnell Douglas has developed two trim programs: one for the isolated blade trim RALP (Rotor Air Load Prediction) and the other for the total helicopter BETRIM (Blade Element Trim). The RALP program trims the rotor for a given thrust and propulsive force using two rotor control (or trim) variables: the collective pitch and the longitudinal cyclic pitch. The BETRIM program trims the six forces and moments on the entire aircraft using six control variables: the main rotor collective pitch, longitudinal cyclic pitch, and lateral cyclic pitch, the tail rotor collective pitch and the helicopter pitch and roll angles relative to the flight path.

The basic trim procedure consists of comparing the current solution for the forces and moments on the helicopter (or rotor trim) with the target values, and incrementing the controls to approach the targets in the next cycle. These steps are repeated until the desired values for the forces and moments on the helicopter are achieved, with in a specified tolerance. The control increments are based on prior evaluations of the derivatives of the helicopter forces with respect to control variables. The main rotor models of both trim programs can use either a simple momentum inflow model or a free-wake inflow model.

Both for hover and forward flight analysis, measured two dimensional airfoil characteristics tabulated as functions of Mach number and angle of attack are used to determine the blade section aerodynamic forces and moments. The effect of tip loss and tip Mach relief are also included in the evaluation of the blade airloads.

5.5 Optimization Procedure

The basic organization of the optimization procedure used for this study is based on the methods discussed in Section 2 (Figure 3). However, the approximation concepts were implemented in chosing a simplified isolated rotor trim procedue for the forward flight analysis rather than the complete helicopter trim. In forward flight, the trim of an isolated rotor (with two degrees of freedom) is realtively simple and can be easily accomplished. However, trimming the six forces and moments of the complete helicopter is more difficult and requires more computer execution time. For this reason, based on the arguments putforth in Section 2 for the advantages of approximation concepts in numerical optimization, the isolated blade trim program was used to calculate the design sensitivity information needed in the optimization procedure. The final optimized design was analysed using the BETRIM program to evaluate the design.

The Automated Design Synthesis (ADS) program developed at NASA/Ames [5] was chosen as the optimizer. Since ADS offers some of the latest algorithms developed, it was chosen over other codes. In addition, ADS allows for the flexibility to choose different combinations within the three basic levels in the optimization process. The three basic levels are the strategy, the optimizer, and the one-dimensional search. The allowable combinations of these three are described in the ADS Users' Guide [5].

5.6 Results and Discussion

At McDonnell Douglas, the rotor performance optimization procedure has been applied to develop the main rotor geometries for an advanced rotor system and for a future light helicopter. The results of the future light helicopter study are discussed in detail in a recent paper [31].

For the future light helicopter study, two optimized rotor designs using the NACA 0015 airfoil were obtained by optimizing the rotor performance for the following two design conditions: i) Hover at 13,000 feet/ISA+20 and ii) Forward flight at 140 knots, sea level/ISA. These two optimized designs were obtained by treating the two flight conditions independently. The baseline design had a rectangular planform with a linear twist of -9 degrees.

The rotor blade planform optimized for hover has two distinct tapers as shown in Figure 11, and a nonlinear twist distribution as shown in Figure 12. The total twist for this design was nearly -12 degrees which was the upper bound specified on the total twist constraint. Tip sweep was not considered as a variable for this design because the hover performance program (HOVERSM) does not include sweep in the analysis. The rotor planform optimized for 140 knots, also shown in Figure 11, has one prominent taper compared to the two distinct tapers seen for the hover optimized design. In addition, the tip is swept at 14 degrees at 87 percent radius. This design also has a nonlinear twist distribution as shown in Figure 12 with a total twist of -6.5 degrees. Both the planform and the total twist for these two designs are similar to what one might expect to arrive at through a series of parametric studies. However, these two designs were obtained in a fraction of the time compared to the parametric studies approach.

The two optimized rotors were analyzed to show the relative performance compared to the baseline design for all flight conditions of interest. At sea level/ISA condition (Figure 13), the design optimized for hover resulted in a significant performance improvement (around 4% reduction in rotor horsepower) in hover and at very low forward speeds over both the baseline and the 140 knots designs. Performance is degraded by 1% to 4% at moderate forward speeds (20 to 80 knots), but for speeds above 80 knots, the hover design showed noticeable performance improvement (by about 2%) over the baseline design. The design optimized for 140 knots provided the best performance for forward speeds of 10 to 140 knots (2% to 5% reduction in rotor horsepower) compared to both the baseline and hover optimized designs. In addition, the rotor $(L/D)_e$ has increased by nearly 9%. At 13,000 feet/ISA+20 condition, both the designs resulted in a similar comparison as shown for the sea level condition in Figure 13.

The reduction in the main rotor horsepower (2% to 5%) obtained can be translated into a similar percentage savings in fuel, or increase in payload or reduction in gross weight.

For high speed rotors, the swept tip geometry of the optimized rotor can be expected to produce additional beneficial effects in terms of reduced tip noise and reduced vibrational levels based on the results for similar rotor geometries reported in Ref. [11] and Ref. [29], respectively.

Independent of the optimization study, McDonnell Douglas designed and developed an advanced rotor blade using more conventional design techniques which are labor-intensive. The optimized rotor design generated in a fraction of the design time matches closely with the design arrived by the conventional means. This emphasizes the design schedule impact optimization can have. The experimental verification of these predictions through wind tunnel and flight tests are under progress at McDonnell Douglas Helicopter Company.

6. Aeroelastic Tailoring of Rotor Blades, Structural Optimization of Fuselage, and Structural Tailoring of Bearingless Rotor Hub

6.1 Overview

The demanding design reqiurements on the present day high speed and high performance helicopters in terms of reduced vibration levels and reduced gross weight has made the modern structural optimization methods a potentially powerful design tool to meet these requirements. For the fixed wing aircraft applications, structural optimization techniques have been successfully used to design minimum weight structures subjected to frequency as well as flutter constraints [16, 17]. Such applications to helicopters are appearing only recently. The dynamic environment of the helicopter complicates the application of the optimization techniques to reduce weight or vibration levels. Any design approach to reduce the weight has to carefully deal with the consequential changes in the vibration levels. Vibration levels and their alleviation will continue to play an important role in the design of helicopters. Therefore, the structural optimization methods applicable to helicopter design has to be able to deal with the dynamic operating environment of the helicopter. The advances made in developing reliable analytical tools to understand the dynamics of the helicopter has made it possible to study optimization techniques as a design tool.

At McDonnell Douglas, structural optimization methods are being developed as a design tool both to meet the weight and the vibration level requirements and also to improve rotor dynamics. The rotor blade, fuselage, and rotor hub are examined in the design process to achieve this goal. The fuselage structure, because of its redundent nature, offers a great potential for weight reduction. In addition the fuselage is examined to reduce vibration levels at specified locations such as the pilot's seat, crew compartment and critical location of weapon platform and other sensitive equipments. The rotor blade being the primary source of vibration is the obvious choice to reduce helicopter vibration at the source. This can be achieved through aeroelastic tailoring of the structural properties of the rotor blade using the optimization method. The optimization procedure being developed at McDonnell Douglas for the aeroelastic tailoring of rotor blades, structural optimization of the fuselage, and structural tailoring of bearingless rotor hub are presented in this section.

6.2 Aeroelastic Tailoring of Rotor Blades

6.2.1 Introduction

In recent years there has been a great deal of research activity in the area of reducing helicopter vibrations by modifying the blade structural properties as indicated in a review paper by Friedmann [18]. Optimization techniques applied to reduce blade weight is not cost effective but their applications to reduce vibration levels can result in substantial benefitial effects. This fact was demonstrated in Ref. [19] where the numerical optimization methods were applied successfully to reduce vibration levels, both in forward flight and hover, by slightly modifying the cross sectional properties in the outboard portion of the blade. Structural optimization methods for vibration reduction can be considered complementary to the other existing methods such as vibration absorbers, isolators, and higher harmonic control devices.

At the Symposium on Recent Experiences in Multidisciplinary Analysis and Optimization (NASA Langley Research Center, April 1984), application of optimization techniques for rotor blade design for reduced vibration was further demonstrated [32,33].

In Ref. [32], a constrained optimization method is applied to design rotor blades for minimum vibration. The performance index minimized is the inner product of the vector of vibration design constraints (Z) and blade weight (W_Z) associated with those constraints ($Z^T W_Z Z$). Numerical results are presented considering six vibration design constraints (three frequency constraints and three modal integrals) and 30 spanwise design variables (10 masses, 10 flatwise stiffnesses, and 10 edgewise stiffnesses). The results showed appreciable overall reduction in the predicted vibratory hub loads, fuselage vibration loads and vibratory blade stresses.

McDonnell Douglas is presently developing a rotor blade deisgn procedure by combining an in-house analysis program called RACAP (Rotor/Airframe Comprehensive Aeroelastic Program) [34] with the ADS [5] optimization package. For the purpose of validation this procedure was first applied to the H-34 blade design. It is currently being applied to the AH-64 and HARP (Helicopter Advanced Rotor Program) rotor for design improvement. A description of the analysis method and the optimization procedure for aeroelastic tailoring of rotor blades are described next.

6.2.2 Analysis Program

McDonnell Douglas has developed a Rotor/Airframe Comprehensive Aeroelastic Program (RACAP) over the past several years. This program is based on the generic approach of the coupled blade-fuselage dynamic response problem presented in Ref. [35]. The analytical formulation used in RACAP are presented in detail in Ref. [34]. RACAP is designed to address a wide range of rotory-wing aeroelastic problem, such as prediction of coupled rotor/ airframe blade and fuselage loads in steady level flight and maneuvers, airframe vibration response, rotor characteristics in free vibration, rotor aeroelastic load prediction, and effects of higher harmonic control inputs on performance and vibrations. For the sake of completeness, a brief description of RACAP and the analytical steps involved are presented here.

In RACAP, the rotor blade representation is based on a coupled flap-lag-torsion formulation of the blade equations of motion. A transfer matrix method is used to discretize the equations of motion for the solution of the rotor blade dynamics problem. The fuselage is represented by means of a hub impedance matrix representing the six hub degrees of freedom. The complex hub impedance matrix is generated via a NASTRAN finite element model of the entire airframe. The dynamics of flexible blade are coupled to the dynamics of the fuselage by matching blade root impedance to fuselage impedance at the rotor head. The resulting coupled model gives the coulpled blade-fuselage dynamic response at a particular speed.

The analytical steps involved in RACAP are listed below [35], and is shown in Figure 14.

1. Rotor trim and initial blade airloads are calculated, assuming rigid blades, in the time domain.
2. A blade structural model is generated using the transfer matrix approach.
3. A fuselage six degree of freedom complex hub impedance matrix is obtained using a dynamic NASTRAN finite element model solved in the frequency domain.
4. Rotor/airframe coupling is performed through impedance matching at the rotor hub in combination with a harmonic balance solution.
5. Structural response is obtained as a superposition of responses due to harmonic loads.
6. The airloads and trim are recomputed to include the effects of blade deformation and the solution process is iterated upon to arrive at converged responses and airloads.

The mixed displacements and forces formulation for coupling a rotor loads model (based on the transfer matrix method) with a finite element airframe model using impedance matching allows for generality in the representation of the fuselage model. For example, one can use either an analytical finite element (NASTRAN) model or one determined experimentally. Further, since the rotor-airframe coupling occurs at only the n-1, n, n+1 per revolution of the blades, the frequency domain solution computation effort is minimized.

RACAP has been successfully applied to model the AH-lG rotor/fuselage and results obtained showed good correlations with flight test results [36].

6.2.3 Fomulation of Optimization problem

The main objective of the blade design is to minimize the vibratory hub loads in both hover and forward flight by modifying the blade structural properties. The objective function chosen is the oscillatory hub vibration obtained as a weighted inner product of the three hub shears and three hub moments.

Design Variables

The design variables chosen are the flapwise stiffness (EI_f), chordwise stiffness (EI_c), torsional stiffness (GJ), and mass (m) along the radius of the blade. The blade along the radius is divided into three regions, as shown in Figure 15. The blade properties in these regions are defined as a function of the chord length as, for example, $EI = (a + br)C^p$, where a and b are the constants of proportionality, r is the radial length, C is the chord, and p is an exponent obtained from a data base representative of several existing helicopters. The design variables are therefore defined as:

Blade Property	$y_0 \rightarrow y_1$	$y_1 \rightarrow y_2$	$y_2 \rightarrow R$
EI_f	$(k_1 + k_2y)C^{p_f}$	$(k_9 + k_{10}y)C^{p_f}$	$(k_{17} + k_{18}y)C^{p_f}$
EI_c	$(k_3 + k_4y)C^{p_c}$	$(k_{11} + k_{12}y)C^{p_c}$	$(k_{19} + k_{20}y)C^{p_c}$
GJ	$(k_5 + k_6y)C^{p_t}$	$(k_{13} + k_{14}y)C^{p_t}$	$(k_{21} + k_{22}y)C^{p_t}$
m	$(k_7 + k_8y)C^{p_m}$	$(k_{15} + k_{16}y)C^{p_m}$	$(k_{23} + k_{24}y)C^{p_m}$

(6)

In the above definition of blade structural properties, the coefficients k_1 through k_{24}, y_0, y_1, and y_2 are treated as the design variables. The blade chord, C, and the exponents p_f, p_c, p_t, and p_m are treated as pre-assigned parameters. In addition, the blade cross sectional offsets $(x_{cg}$, x_{AC}, x_{EA}, and $x_{TC})$ are also treated as pre-assigned parameters.

Constraints

In each region of the blade, shown in Figure 15, the blade properties are constrained to be within certain specified upper and lower bounds in order to keep them from reaching impractical values. These constraints are defined as follows:

$\frac{EI_f}{C^{p_f}}$:

$$\underline{EI}_1 \leq (k_1 + k_2(y - y_0)) \leq \overline{EI}_2$$

$$\underline{EI}_3 \leq (k_9 + k_{10}(y - y_1)) \leq \overline{EI}_4$$

$$\underline{EI}_5 \leq (k_{17} + k_{18}(y - y_2)) \leq \overline{EI}_6 \quad (7)$$

where $\underline{EI}_1$, $\underline{EI}_3$, and $\underline{EI}_5$ are the lower bounds and $\overline{EI}_2$, $\overline{EI}_4$, and $\overline{EI}_6$ are the upper bounds specified on EI_f.

$\frac{EI_c}{C^{p_c}}$:

$$\underline{EI}_7 \leq (k_3 + k_4(y - y_0)) \leq \overline{EI}_8$$

$$\underline{EI}_9 \leq (k_{11} + k_{12}(y - y_1)) \leq \overline{EI}_{10}$$

$$\underline{EI}_{11} \leq (k_{19} + k_{20}(y - y_2)) \leq \overline{EI}_{12} \quad (8)$$

where $\underline{EI}_7$, $\underline{EI}_9$, and $\underline{EI}_{11}$ are the lower bounds and $\overline{EI}_8$, $\overline{EI}_{10}$, and $\overline{EI}_{12}$ are the upper bounds specified on EI_c.

$\frac{GJ}{C^{p_t}}$:

$$\underline{GJ}_1 \leq (k_5 + k_6(y - y_0)) \leq \overline{GJ}_2$$

$$\underline{GJ}_3 \leq (k_{13} + k_{14}(y - y_1)) \leq \overline{GJ}_4$$

$$\underline{GJ}_5 \leq (k_{21} + k_{22}(y - y_2)) \leq \overline{GJ}_6 \quad (9)$$

where $\underline{GJ}_1$, $\underline{GJ}_3$, and $\underline{GJ}_5$ are the lower bounds and $\overline{GJ}_2$, $\overline{GJ}_4$, and $\overline{GJ}_6$ are the upper bounds specified on GJ.

$\frac{m}{C^{p_m}}$:

$$\underline{M}_1 \leq (k_7 + k_8(y - y_0)) \leq \overline{M}_2$$

$$\underline{M}_3 \leq (k_{15} + k_{16}(y - y_1)) \leq \overline{M}_3$$

$$\underline{M}_5 \leq (k_{23} + k_{24}(y - y_2)) \leq \overline{M}_6 \quad (10)$$

where $\underline{M}_1$, $\underline{M}_3$, and $\underline{M}_5$ are the lower bounds and $\overline{M}_2$, $\overline{M}_4$, and $\overline{M}_6$ are the upper bounds specified on m.

Imposing the condition of continuity of blade structural properties at y_1 and y_2 leads to the following additional constraints:

At y_1:

$$k_1 + k_2(y_1 - y_0) = k_9$$

$$k_3 + k_4(y_1 - y_0) = k_{11}$$

$$k_5 + k_6(y_1 - y_0) = k_{13}$$

$$k_7 + k_8(y_1 - y_0) = k_{15} \tag{11}$$

At y_2:

$$k_9 + k_{10}(y_2 - y_1) = k_{17}$$

$$k_{11} + k_{12}(y_2 - y_1) = k_{19}$$

$$k_{13} + k_{14}(y_2 - y_1) = k_{21}$$

$$k_{15} + k_{16}(y_2 - y_1) = k_{23} \tag{12}$$

The behavior constraints considered are:

Total blade weight:

$$M_{BL}^L \leq \int_{y_0}^{R} m dy \leq M_{BL}^U \tag{13}$$

Blade moment of inertia:

$$I_{BL}^L \leq \int_{y_0}^{R} m(y - y_0)^2 dy \leq I_{BL}^U \tag{14}$$

where M_{BL}^L and I_{BL}^L are the lower bounds and M_{BL}^U and I_{BL}^U are the upper bounds on the total blade weight and blade moment of inertia, respectively.

When the blade response is minimized, frequency constraints need not be considered unless convergence problems arise. However, the frequency values should be calculated in the analysis.

<u>Approximate problem</u>

The basic architecture of the optimization procedure shown in Figure (3) , including the approximate problem generator, can be used. To improve the computaional efficiency of the optimization procedure, based on the discussions presented in Section 2 [1], the constraints and the objective function can be represented by a Taylor series approximation.

The second order Taylor series representation of the constraints and the objective function used are, respectively:

$$\tilde{g}(\vec{D}) = g(\vec{D}_0) + (\vec{D} - \vec{D}_0)^T \left\{ \frac{\partial g(\vec{D}_0)}{\partial D_i} \right\} + 1/2(\vec{D} - \vec{D}_0)^T \left[\frac{\partial^2 g(\vec{D}_0)}{\partial D_i \partial D_j} \right] (\vec{D} - \vec{D}_0) \qquad (15)$$

$$\tilde{J}(\vec{D}) = J(\vec{D}_0) + (\vec{D} - \vec{D}_0)^T \left\{ \frac{\partial J(\vec{D}_0)}{\partial D_i} \right\} + 1/2(\vec{D} - \vec{D}_0)^T \left[\frac{\partial^2 J(\vec{D}_0)}{\partial D_i \partial D_j} \right] (\vec{D} - \vec{D}_0) \qquad (16)$$

The gradients required to construct the Taylor series can be generated by a finite difference scheme. This approximate problem can be solved exactly by the optimizer (ADS or CONMIN) to obtain a sequence of improved designs. These improved designs should be evaluated using the comprehensive analysis program. This process can be terminated when the desired objectives are achieved.

6.3 Structural Optimization of Fuselage

6.3.1 Introduction

Structural optimization techniques used as a design tool in the design of a helicopter fuselage will ensure a minimum weight structure as well as reduced vibration levels. This approach can considerably reduce the need for local vibration reduction that often arise during the design cycle of a helicopter. Most of the published literature on helicopter fuselage deal with local vibration reductions in a fuselage that has already been designed [18]. The optimization problem can be formulated with the total weight of the fuselage as the objective function and the requirement of reduced vibration levels at selected locations on the fuselage can be reflected as additional behavior constraints. These fuselage locations can be selected based on past experiences on similar helicopters (for example: pilot's seat, passenger cabin, locations of mission equipment or any other critical area). At McDonnell Douglas, a fuselage optimization program using NASTRAN finite element analysis is being developed. The formulation of the optimization problem, design variables, and optimization procedure used in this program are described below.

6.3.2 Formulation of the Optimization Problem

McDonnell Douglas uses NASTRAN extensively for the finite element analysis of the fuselage model of the helicopter. Therefore it was logical to think of coupling the Design Sensitivity Analysis (DSA) available in NASTRAN [20] to an optimizer to accomplish the reduction of weight and vibration levels of the fuselage.

Commercially available codes such as MSC/OPTIM and ADS/NASOPT which use the NASTRAN generated design sensitivity analysis deal with the minimum weight design problem but do not address the vibration reduction problem. Therefore McDonnell Douglas has developed an interface between NASTRAN/DSA to accomplish both.

In the optimization process, the total weight of the fuselage was chosen as the objective function to be minimized because a greater payoff in weight was expected. However, any one of the constrained quantities can be chosen as the objective function, instead of the total weight, to meet the design reqirements. The total weight then is included as one of the constraints. The vibration levels at the selected locations on the fuselage were constrained to be below certain specified upper bound values as:

$$\mathbf{a}_i \leq \mathbf{a}_i^U \tag{17}$$

where $\mathbf{a}_i$ is the acceleration and $\mathbf{a}_i^U$ is the upper bound on the acceleration specified at the i-th location. The first few natural frequencies of the fuselage were constrained to be within certain upper and lower bounds as:

$$\omega_i^L \leq \omega_i \leq \omega_i^U \tag{18}$$

where ω_i is the natural frequency of the i-th mode and ω_i^L and ω_i^U are the lower and upper limits of the i-th frequency. In addition, the dynamic displacements at selected locations and the element dynamic stresses are constrained to be below the specified upper bound values.

6.3.3 Design Variables

A complete finite element model of the fuselage typically has 10,000 degrees of freedom. Obviously it will not be practical to treat the cross section properties of each one of these elements as independent design variable. Therefore a very carefully chosen design variable linking scheme is needed to reduce the size of the problems. In the present study, two finite element models were chosen: i) an elastic line model (shown in Figure 16) and ii) a coarse finite element model (shown in Figure 17). The elastic line model was chosen to keep the size of the problem small during the developmental stage of this procedure. The coarse finite element model will be a good representation of the complete model and therefore can be expected to bring out any problems that might exist in dealing with a complete fuselage model. For both the models, the design variable linking scheme is used to further reduce the size of the problem.

Elastic Line Model

The elastic line mathematical model of the McDonnell Douglas/U.S Army attack helicopter, AH-64, (Figure 16) consists of a total of 79 elements (37 elements along the fuselage, 16 elelments of the wing, 12 elements each on the vertical tail and stabilator and two elements on the mast). A linear beam element representation (NASTRAN/CBAR element [37]) is used for these elements. In the CBAR element, the cross sectional properties are defined in terms of cross sectional area, area moment of inertia, and torsional constant. To keep the design variable tractable in the optimization process, a rectangular beam cross section with breadth b and height h was used to represent the linear beam element. Within each element b and h are treated as the design variables.

In order to reduce the number of design variables, the following design variable linking scheme was used: The fuselage is divided into four sections:- i) forward fuselage (0 to 176 frame), ii) mid fuselage (176 to 370 frame), iii) aft fuselage (370 to 450 frame), and iv) tail boom (450 to 547 frame). These four sections were chosen to accommodate the stiffness variations of the fuselage in these sections. The wing, vertical tail and stabilator each were divided into two sections (inboard -0 to 75% span and outboard - 75% to tip). Within each one of these sections the design variables were linked. The mast was assigned one independent design variable. This design variable linking scheme resulted in a total of 22 independent design variables for the elastic line model of the fuselage.

Coarse Finite Element Model

The coarse finite model used is shown in Figure 17. The fuselage, wing, vertical tail and stabilator were all divided in to the same number of sections as described for the elastic line model to provide a basis for comparison. Also, the design variables in each one of these sections were linked in a similar manner to produce 22 independent design variables. The number of independent design variables can be increased as a refinement to the design model to obtain a greater payoff in the optimization process.

6.3.4 Optimization Pocedure

The basic organization of the optimization process and the second order Taylor series approximation of the constraints and the objective function used for the aeroelastic tailoring of rotor blade are applied for the fuselage optimization as well. In addition, dynamic deletion of inactive constraints are also considered to further improve the computaional efficiency of the optimization procedure.

6.4 Structural Tailoring of Bearingless Rotor Hub

In recent years bearingless rotors are being developed to simplify rotor design. Examples of such hubs are Boeing-Vertol's BO-105/BMR [38], Bell's model 680 [39] and McDonnell Douglas's Helicopter Advanced Rotor Program (HARP) [40]. The key element in its design is the structurally flexible element generally referred to as the flexbeam. A schematic of the HARP rotor hub is shown in Figure 18. The flex beam deforms elastically to accomodate the flap, lead-lag, and feathering motion of the rotor blades. The flexbeam is generally made with non-isotropic composite material and is designed to a balance of structural, dynamics, performance, and handling qualities requirements of the rotor. Traditionally, at McDonnell Douglas Helicopter Company, such a design was achieved through judicious tailoring which was very time consuming and often, non "optimal". An optimization procedure was established to automate the design process. A schematic of the model boundary conditions and applied loads are shown in Figure 19. The applied loads (F_X, F_Y, F_Z, M_X, M_Y, M_Z) are adjusted for the design limit and fatigue flap (β), lead-lag (ς), and feathering (θ) motions.

6.4.1 Problem Formulation

As shown in Figure 19, the flexbeam is defined by a finite element model. The pitchcase and "snubber-damper" are also included in the model for accurate loading of the flexbeam. The design variables are chosen to be the width (b_i) and thickness (t_i) of each element of the flexbeam.

Objective Function

The objective was to minimize the maximum (peak) *combined stresses along the* flexbeam length for conditions of limit, maximum fatigue, and endurance loads (or motions). Another formulation was to maximize the first inplane damping (damper motion per degree lag) while constraining the peak stresses to be within allowables for the endurance, maximum fatigue and limit loads.

Constraints

As mentioned above, the constraints on stresses are stated as:

$$\frac{\sigma_{y_i}}{\sigma_{allow}} \leq 1.0$$
$$\frac{\tau_{y_i}}{\tau_{allow}} \leq 1.0 \tag{19}$$

where σ_y is the normal stress and τ_y is the shear stress.

Geometric constraints are imposed as:

$$b_i \leq \bar{b},\ i = 1, 2, ...N$$
$$t_i \leq \bar{t},\ i = 1, 2, ...N$$
$$b_i t_i \leq \bar{A},\ i = 1, 2, ...N \tag{20}$$

where $\bar{b}, \bar{t}$, and $\bar{A}$ are the upper bounds on width, thickness, and area, respectively.

Rotor dynamics constraints are imposed as limits on effective flap and lag hinge offsets as:

$$\mathbf{e}_{\beta_{eff}} \leq \bar{\mathbf{e}}_{\beta}$$
$$\mathbf{e}_{\varsigma_{eff}} \leq \bar{\mathbf{e}}_{\varsigma} \tag{21}$$

where $\bar{\mathbf{e}}_{\beta}$ and $\bar{\mathbf{e}}_{\varsigma}$ are the upper bounds on flap and lag hinge offsets, respectively.

Results

Results of the optimization analysis and the resulting flexbeam are compared with the analysis of the existing HARP flexbeam (Figure 20). The optimized flexbeam shows a 70 percent reduction of the combined peak normal stresses. The effective flap hinge offset was reduced from 5.3 percent to 4.2 percent, while maintaining the required lead-lag damping. These changes resulted in a substantial improvement in the rotor dynamics.

7. Concluding Remarks

Application of structural optimization methods to helicopter design provide a rational design tool to improve the performance of the helicopter in a cost effective manner. The availability of efficient structural synthesis methods and refined optimization algorithms have made it possible to apply numerical optimization methods with reasonable success. The beneficial effects of this design approach, applied at the global level and the component level, are listed below:

1. The configuration optimization of the helicopter, treated as a global level optimization, has provided an efficient method to arrive at the overall optimum configuration at the preliminary design phase.
2. The airfoil profile optimization procedure used has successfully dealt with the conflicting requirements of the airfoil operating under the extreme environment of the rotor blade to produce an optimum airfoil profile. This method has significantly reduced the wind tunnel testing required for airfoil development.
3. Rotor geometry optimization has made it possible to take complete advantage of the design flexibility and cost effectiveness the composite materials have offered. The optimized rotor resulted in a 2% to 5% reduction in the rotor horsepower. This savings in rotor horsepower can be translated in to a similar percentage savings in fuel, or an increase in pay load or a reduction in gross weight. In addition, the optimized balde tip geometry can be expected to result in beneficial effects such as reduced blade tip noise.
4. Based on the results reported in Ref. [19], structural optimization of the blade cross section to reduce vibration levels can potentially result in 10% to 20% reduction in the vibration levels, together with a 5% to 10% reduction in the blade weight, through only minor changes in the outboard 20% span of the blade. This method can be treated complementary to the other existing methods such as vibration absorbers, isolators, and higher harmonic control devices.
5. The optimized flexbeam shows a 70% reduction of the combined peak normal stresses. The effective flap hinge offset was reduced from 5.3% to 4.2%, while maintaining the required lead-lag damping. These changes resulted in improved rotor dynamics.

The systematic application of the numerical optimization methods has made it possible to achieve significantly improved design performance at a fraction of the time needed for conventional approach. The time savings realized has a beneficial impact on the design scheduling. In addition, this approach has minimized the problems that often arise during the design phase. These beneficial effects result in the overall cost savings of the project.

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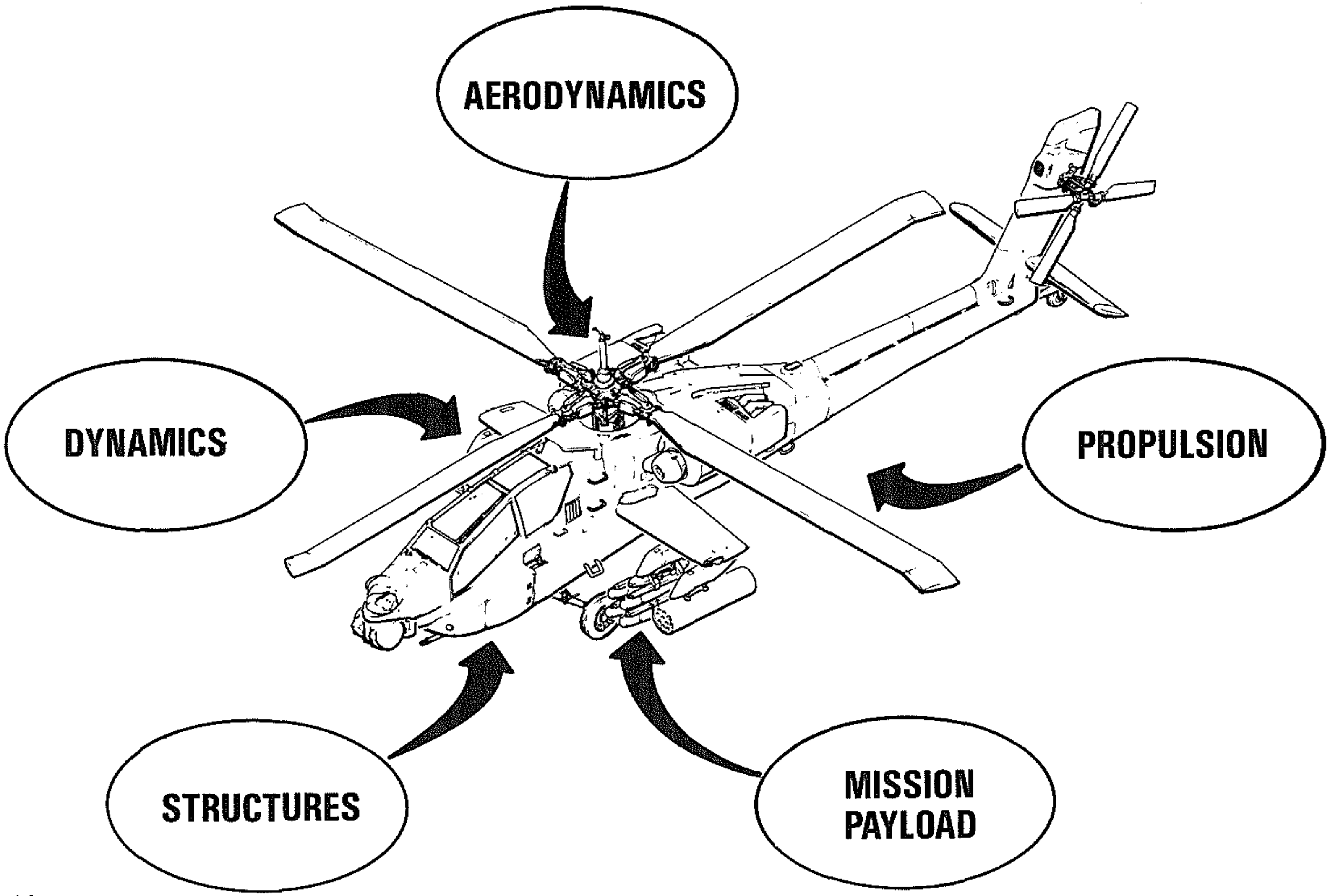

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Figure 1. Helicopter Mission Requirement

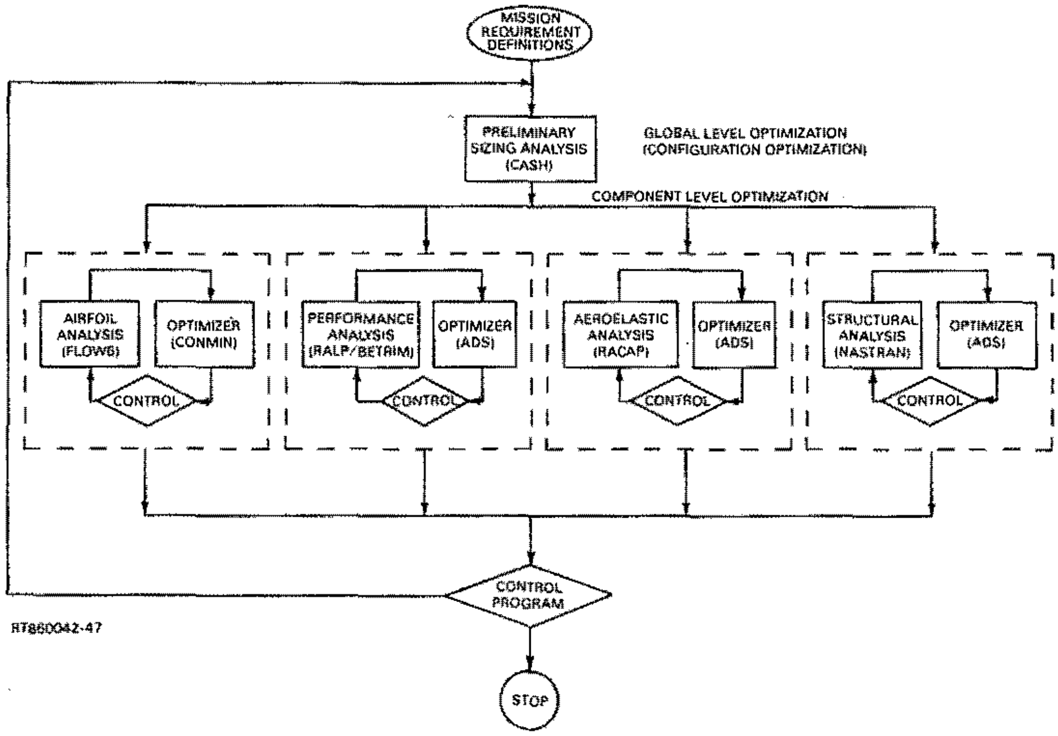

Figure 2. Multilevel Optimization Approach in Helicopter Design

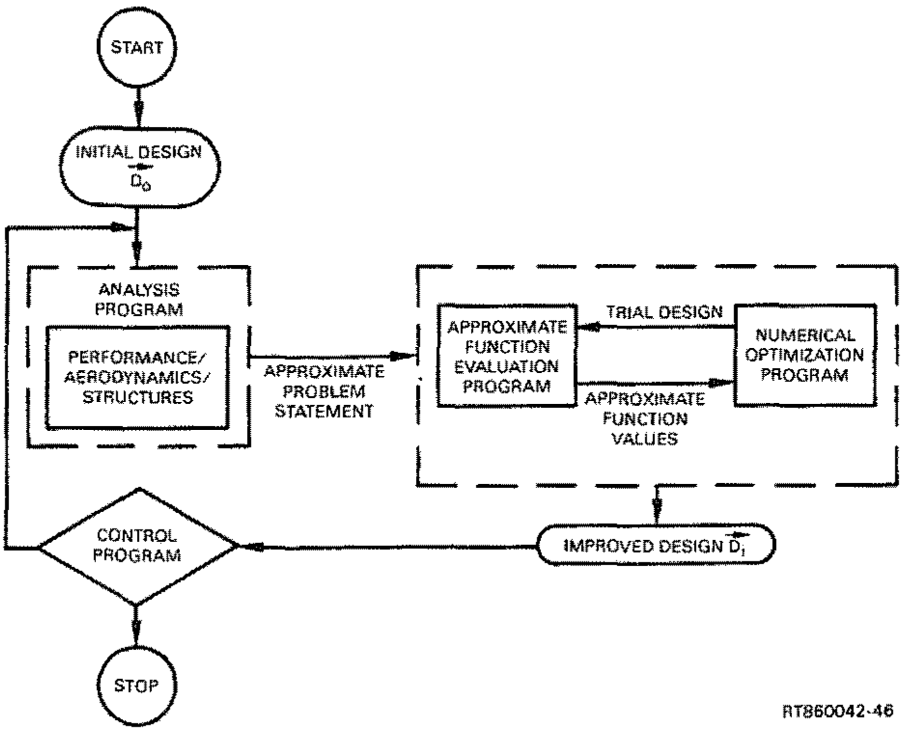

Figure 3. Basic Architecture of the Design Optimization Program

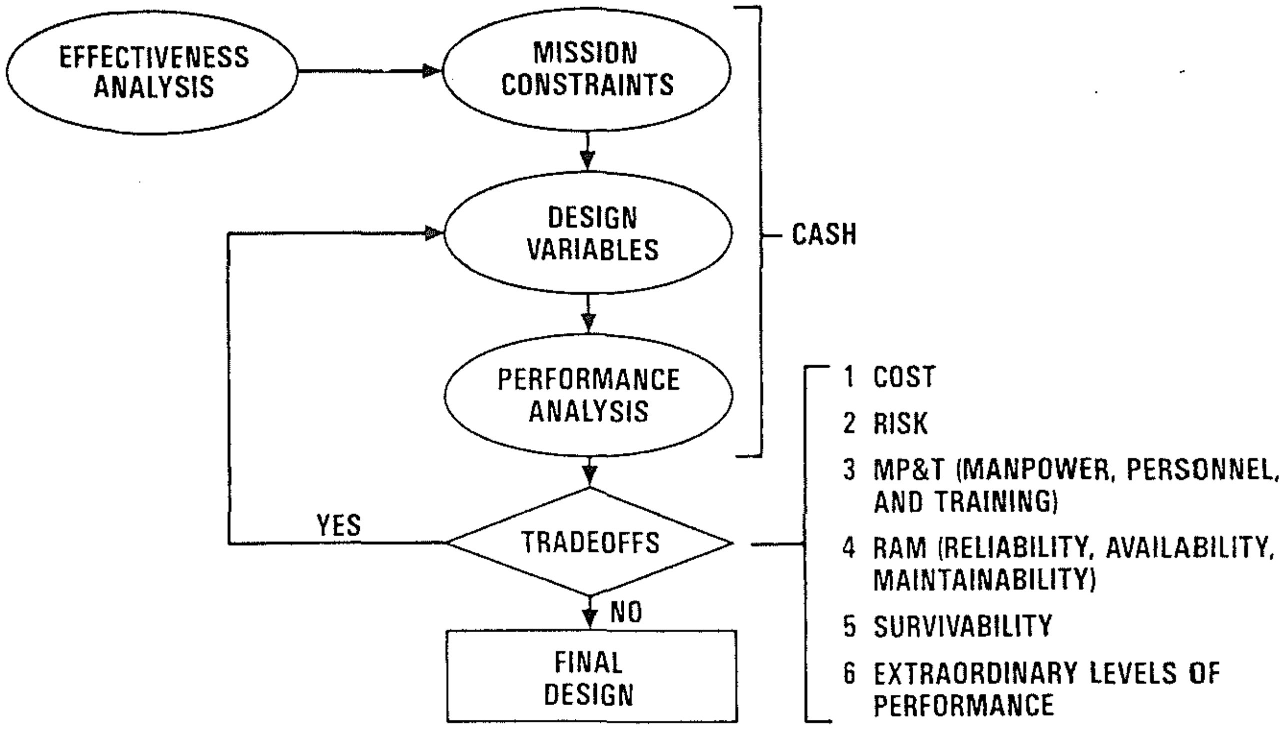

Figure 4. CASH (Computer Aided Sizing of Helicopter) Problem Definition

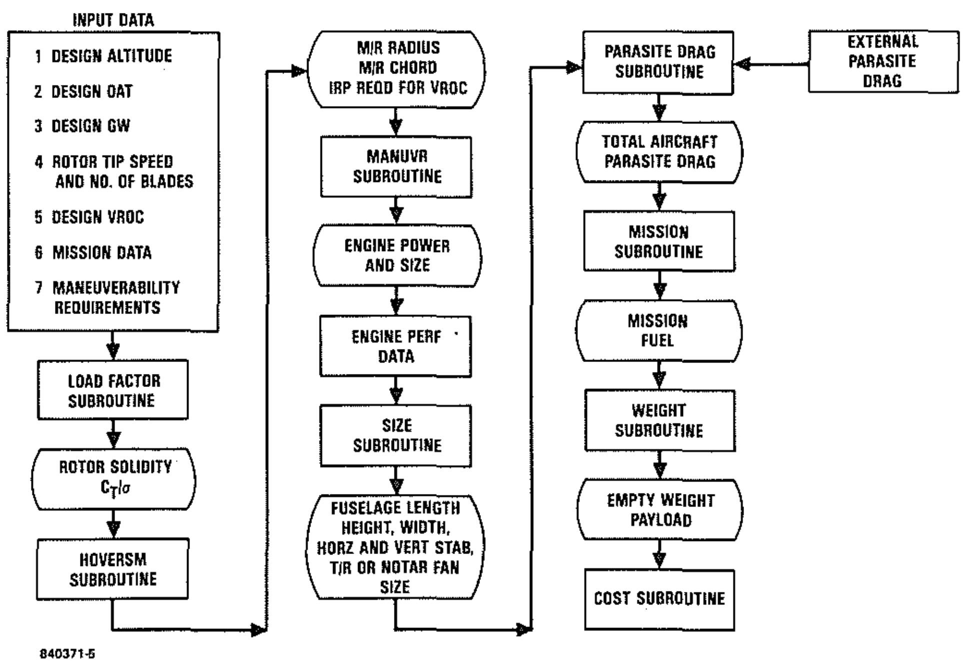

Figure 5. CASH (Computer Aided Sizing of Helicopter) Flow Chart

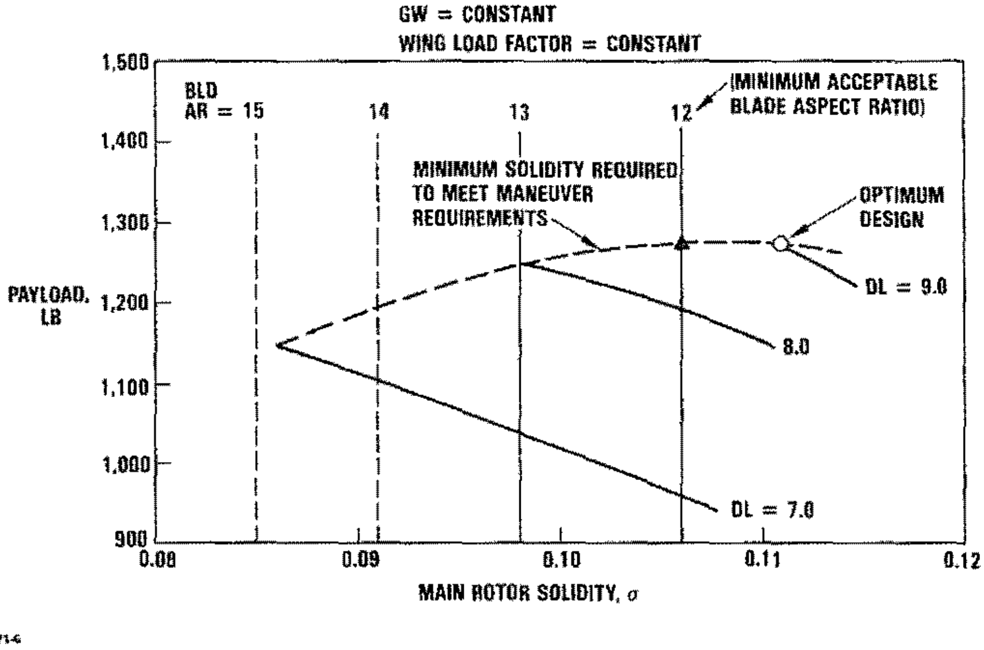

Figure 6. Main Rotor Solidity Vs Payload

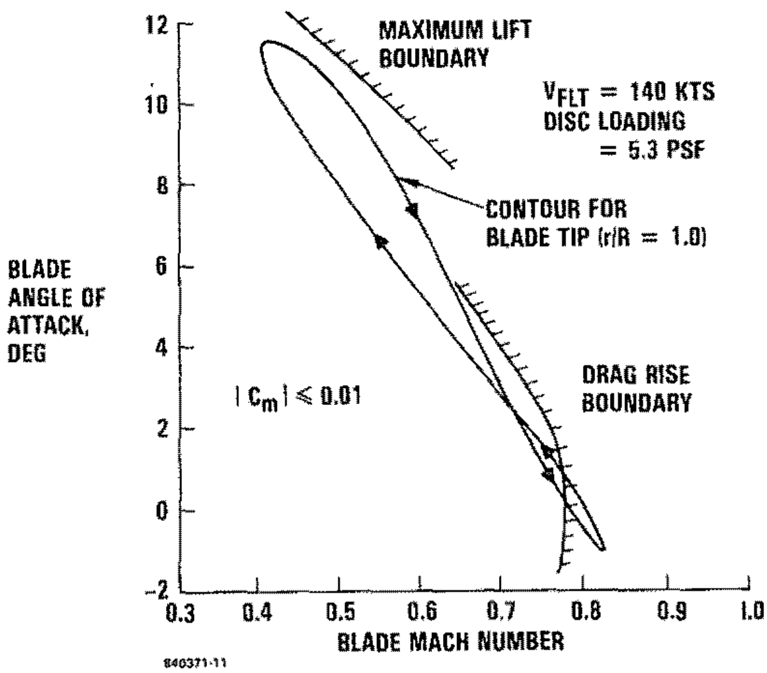

Figure 7. Airfoil Angle of Attack Vs Mach Number

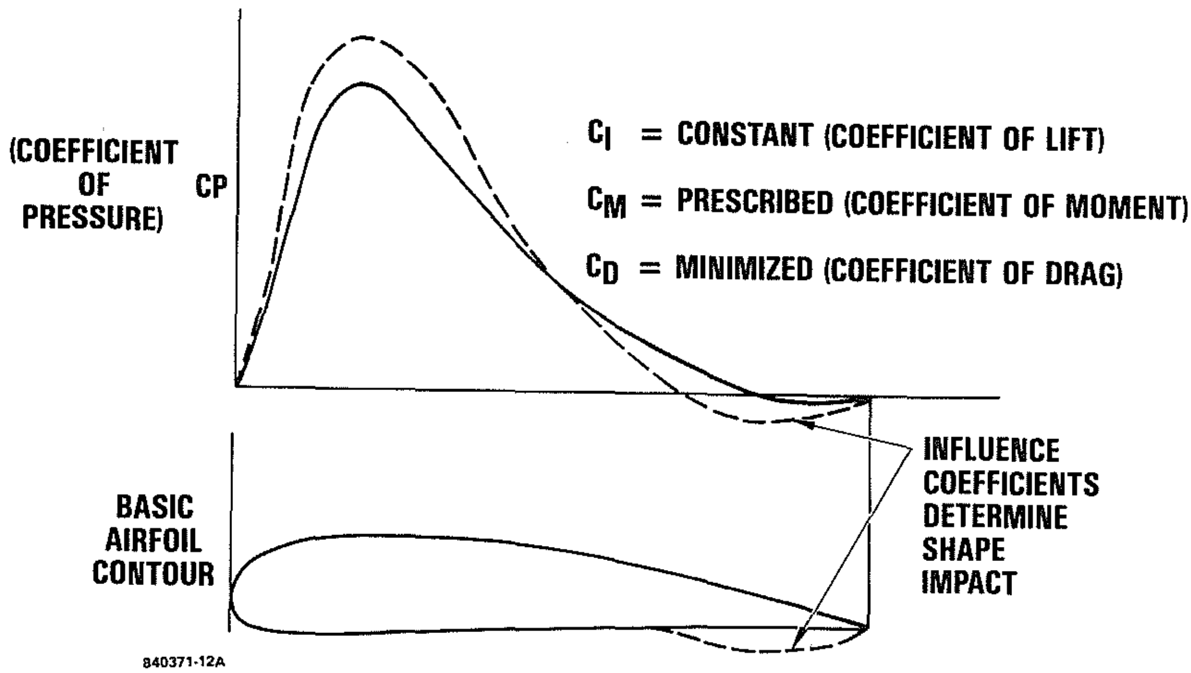

Figure 8. Airfoil Contours and Pressure Distribution

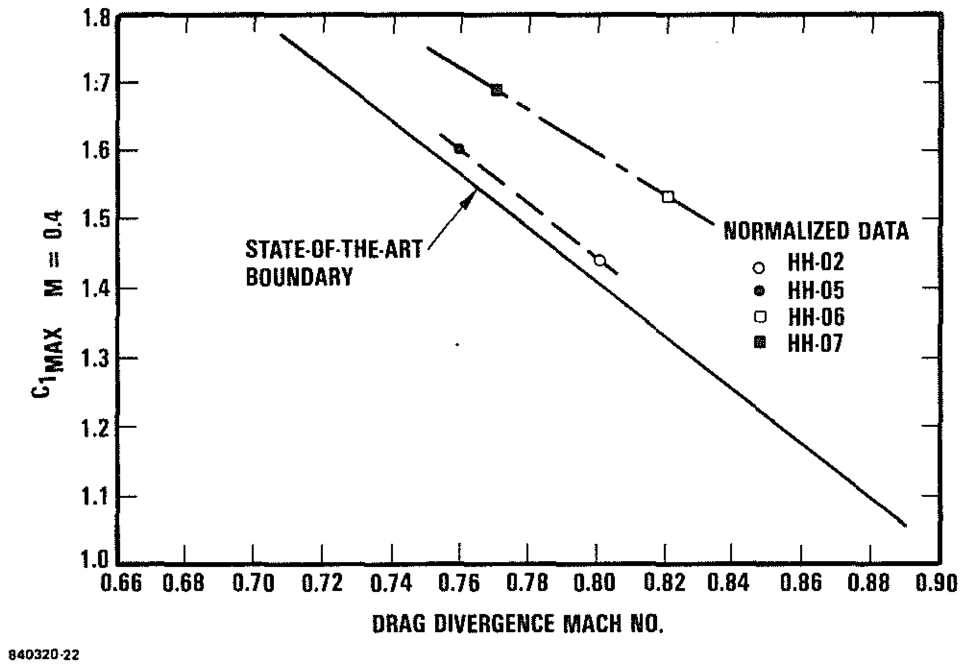

Figure 9. Airfoil $C_{l_{MAX}}$ Vs Drag Divergence Mach Number

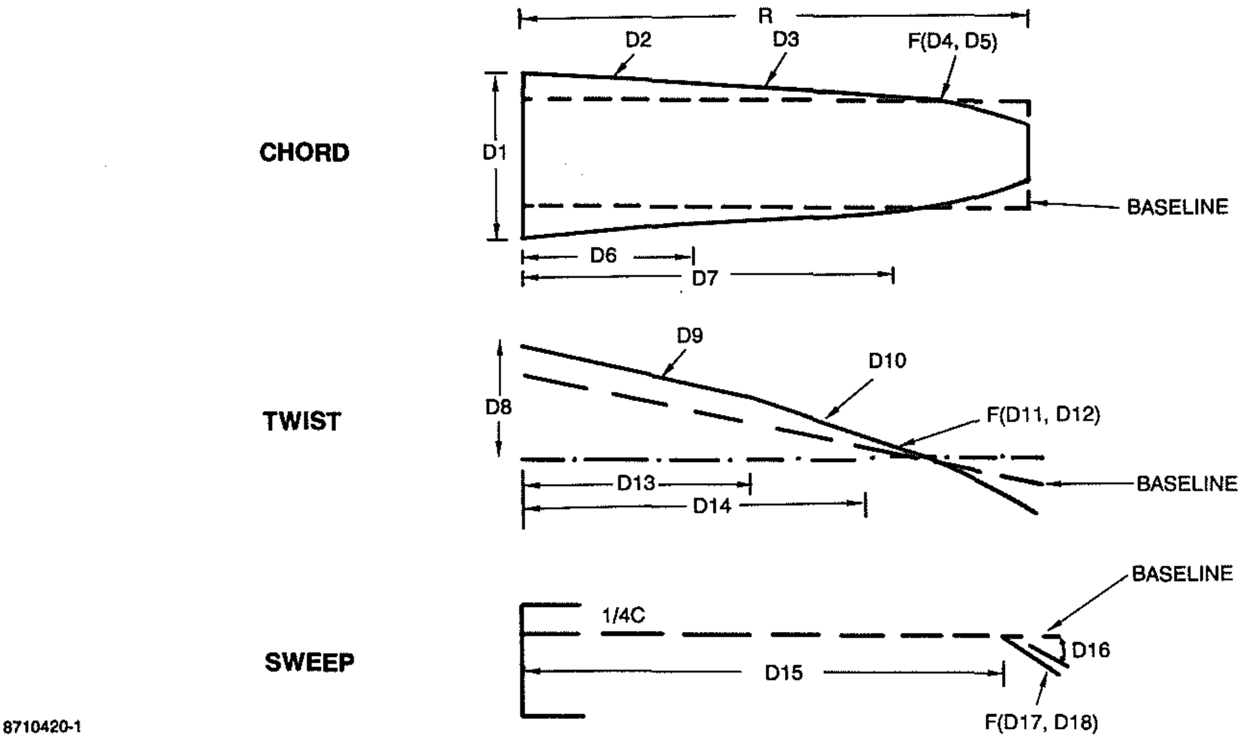

Figure 10. Design Variables for Main Rotor Performance Optimization

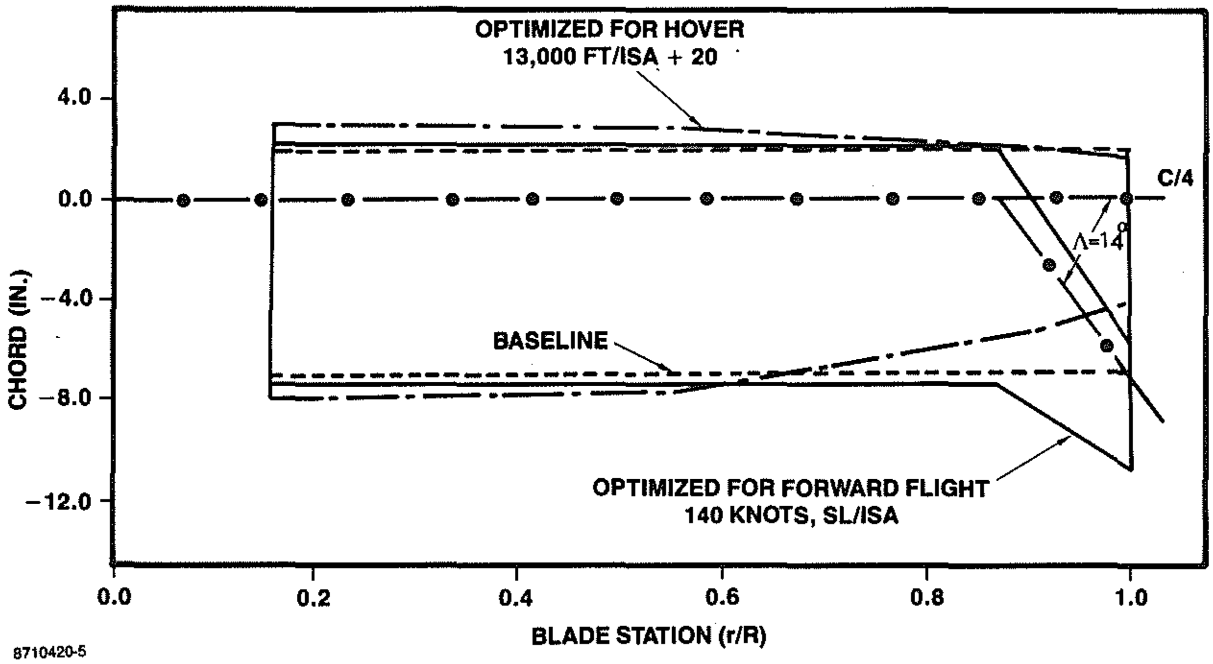

Figure 11. Optimized Main Rotor Blade Planform for a Future Light Helicopter

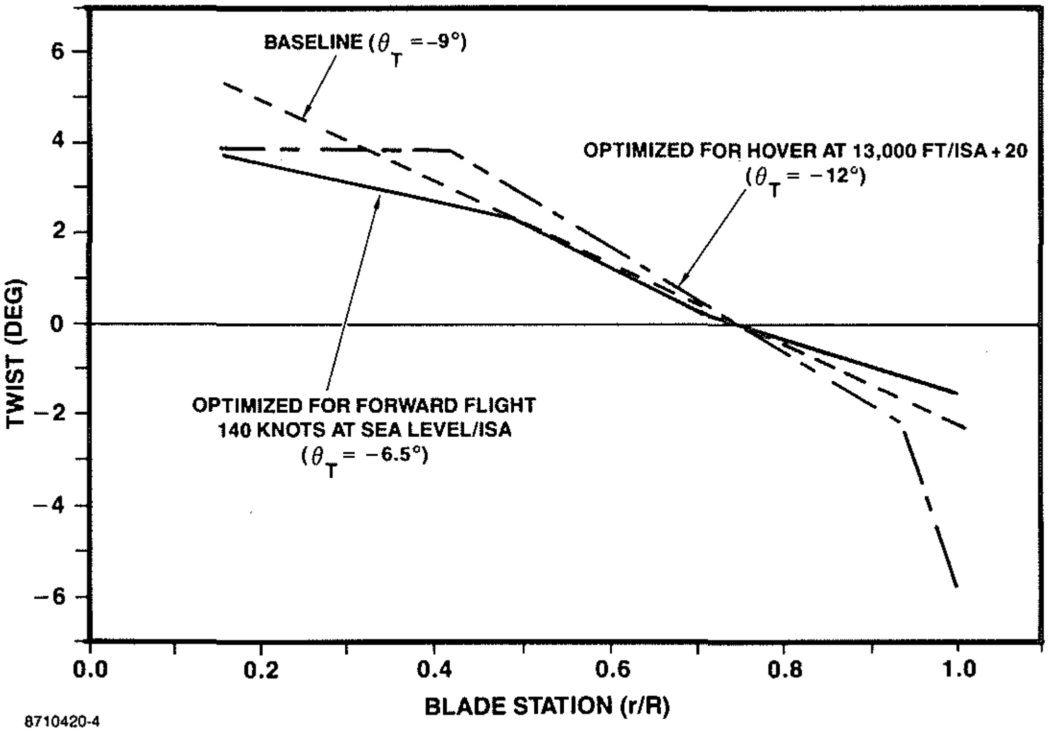

Figure 12. Optimized Main Rotor Blade Twist for a Future Light Helicopter

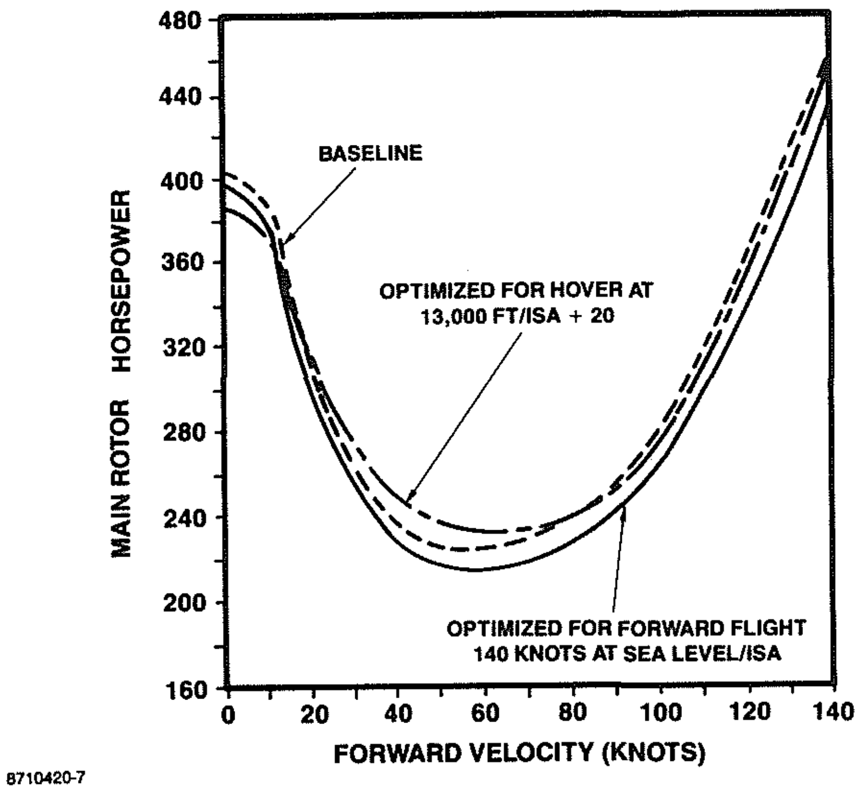

Figure 13. M/R Horsepower Vs Forward Velocity for a Future Light Helicopter

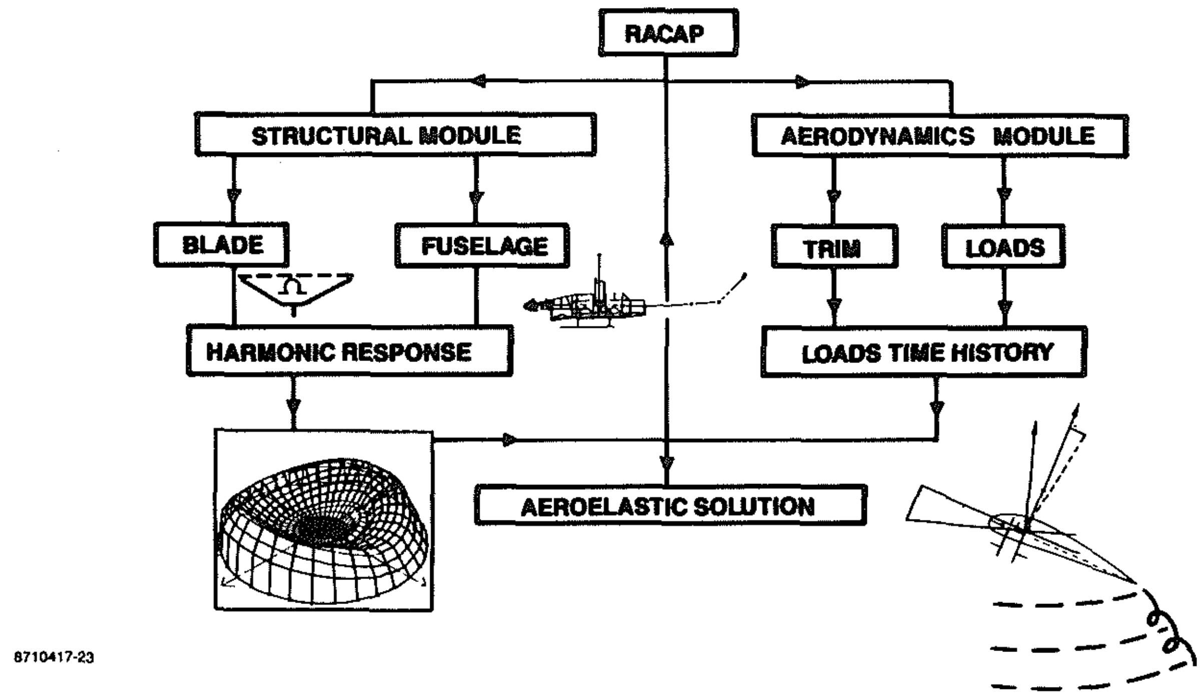

Figure 14. Rotor/Airframe Comprehensive Aeroelastic Program Flow Chart (RACAP)

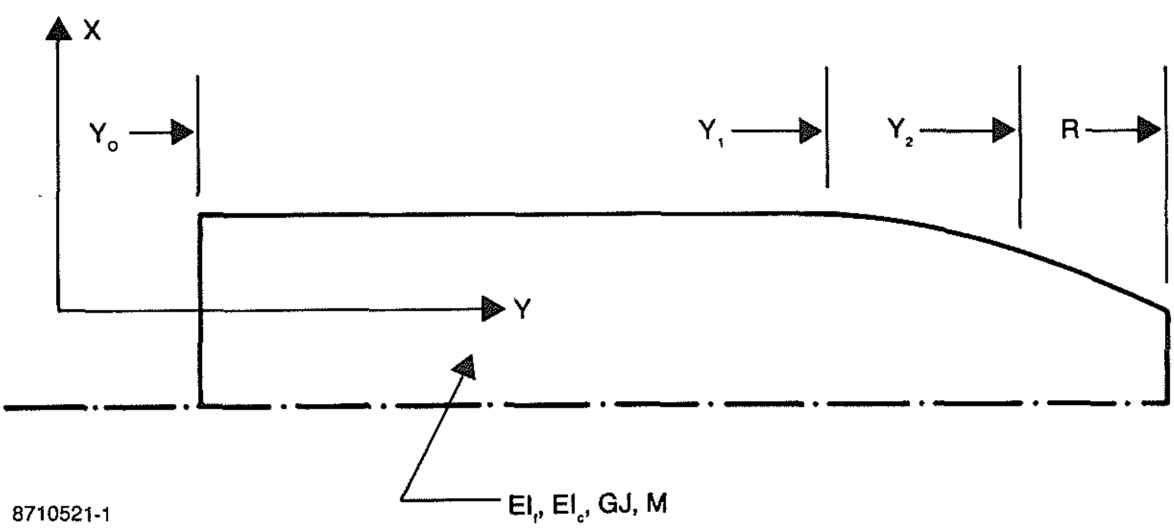

Figure 15. Design Variables for Aeroelastic Tailoring of Rotor Blade

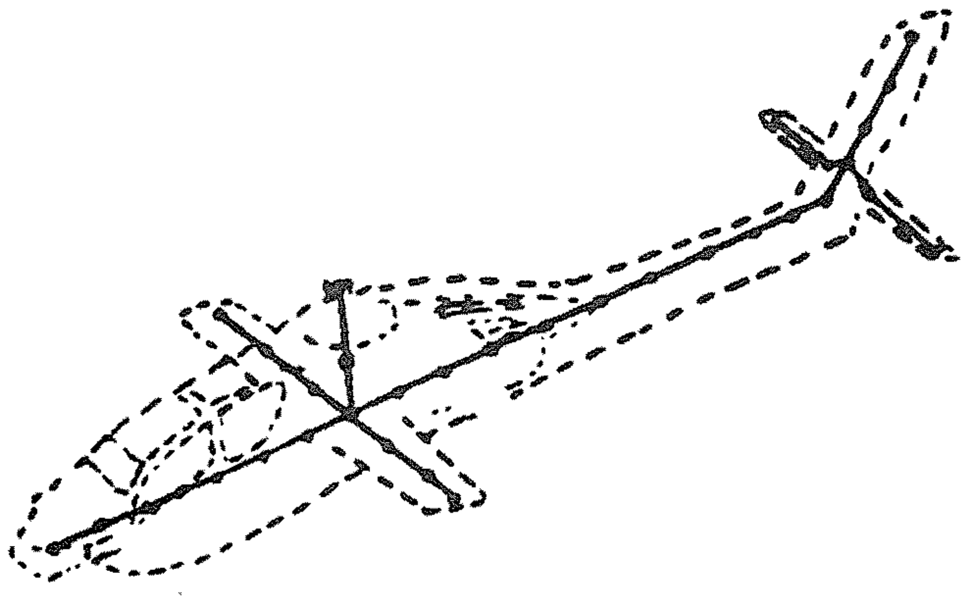

Figure 16. Elastic line Model of AH-64 Fuselage

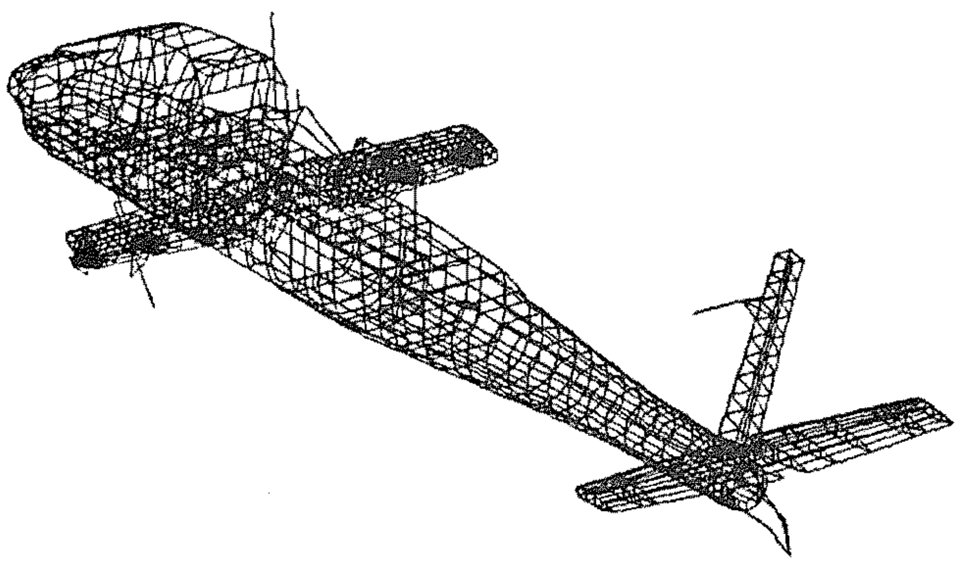

Figure 17. Finite Element Model of AH-64 Fuselage

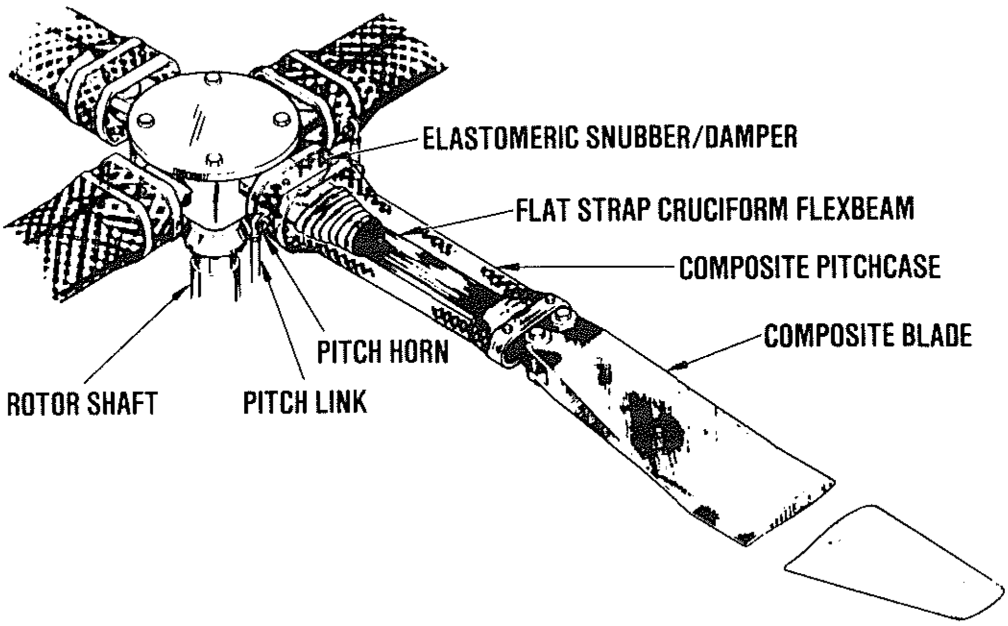

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Figure 18. McDonnell Douglas Helicopter Advanced Rotor Program (HARP) Hub Configuration

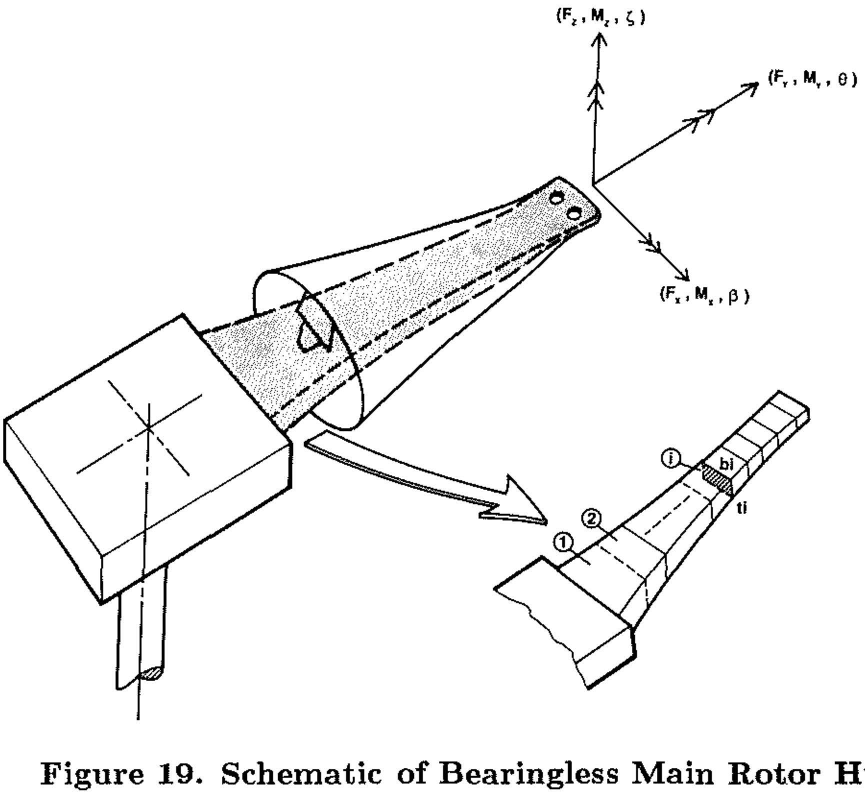

Figure 19. Schematic of Bearingless Main Rotor Hub Model

Parameter	Existing HARP	"Optimized" HARP
Normalized Max Combined Normal Stresses	1.70	1.04
Normalized Max Combined Shear Stresses	0.96	1.03
Damper Motion Per Degree Lag	0.18	0.16
$(\frac{e_\beta}{R}) \times 100$	5.30	4.20
$(\frac{e_\varsigma}{R}) \times 100$	24.80	15.60
$(\frac{\Omega_\beta}{\Omega})$	1.06	1.04
$(\frac{\Omega_\varsigma}{\Omega})$	0.61	0.50
β	6.80	6.80
ς	2.00	2.00
θ	11.50	11.50

Figure 20. Comparison of Structural Properties of the Existing and the "Optimized" HARP Flexbeam