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Abstract

This paper describes a formal optimization procedure for helicopter rotor blade designs which minimizes hover horsepower while assuring satisfactory forward flight performance. The approach is to couple hover and forward flight analysis programs with a general purpose optimization procedure. The resulting optimization system provides a systematic evaluation of the rotor blade design variables and their interaction, thus reducing the time and cost of designing advanced rotor blades. The paper discusses the basis for and details of the overall procedure, describes the generation of advanced blade designs for representative Army helicopters, and compares designs and design effort with those from the conventional approach which is based on parametric studies and extensive cross-plots.

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Introduction

One of the goals in helicopter design is to improve the aerodynamic performance of rotor blades in both hover and forward flight. To accomplish this goal, designers are examining the influences of rotor blade design parameters such as twist, blade radius, tip speed (or RPM), blade root chord, chord distribution, taper ratio, point of taper initiation, sweep, point of sweep initiation, and airfoil sections on the aerodynamic performance of the rotor blade.

Designers investigated the advantages of nonrectangular blades with variations in twist and airfoils in the late 1940's (references 1-5), but the cost of manufacturing nonrectangular blades was prohibitive for the small percentage improvement in performance over that of rectangular blades. Also, the development of the aluminum extrusion process influenced designers toward rectangular planforms. Thus, the blades on most current helicopters have a rectangular planform - some with swept rectangular tips. However, with the development of improved airfoil sections and the use of composites in rotor blades which make it practical to fabricate nonrectangular rotor blades with varying twist and airfoil sections, designers are again looking at nonrectangular planforms to improve the aerodynamic performance of rotor blades.

Analytical and experimental work on rotor blade design by the Army Structures Laboratory at the NASA Langley Research Center is reported in references 6-8. The research indicates that the required horsepower for both hover and forward flight may be reduced by using new airfoils, tapering the rotor blades, and adjusting the twist, blade root chord and chord distribution for rotor blades with a fixed radius and tip speed. Reference 6 describes an analytical procedure for designing rotor blades, referred to herein as the conventional approach, which combines a momentum strip theory analysis (based on ref. 5) for the hover analysis and the Rotorcraft Flight Simulation computer program, C-81 (ref. 9), for the forward flight analysis. Although this conventional approach has produced rotor blade designs with improved aerodynamic performance, it is a tedious and time-consuming procedure. A designer typically spends several weeks manipulating the rotor blade design parameters before reaching a final blade configuration. Using this approach, the designer is required to have significant experience and data at hand. Any lack of experience and data tends to increase the design time.

To avoid the time-consuming aspects of the conventional approach, formal optimization techniques are being applied to this design problem. Optimization techniques have been previously applied (refs. 10-13) to helicopter rotor blade design to improve aeroelastic and dynamic behavior.

For example, in reference 13 optimization techniques were applied to the aerodynamic design of rotor blades to find the twist distribution which minimizes hover horsepower. The procedure described in the present paper involves coupling the hover and forward flight analyses used in reference 6 with a general purpose optimization procedure CONMIN (ref. 14). This approach, which will be referred to herein as the mathematical programing approach, systematically searches for a blade design which minimizes hover horsepower while assuring adequate forward flight performance by satisfying explicit design requirements. This paper describes the application of formal optimization techniques to design advanced helicopter rotor blades, and compares the resulting configurations and design effort with the corresponding configurations and design effort of the conventional approach.

Symbols

c_d	airfoil section drag coefficient
$c_{d,all}$	allowable value of drag coefficient
$c_{d,max}$	maximum drag coefficient
c_r	chord at point of taper initiation, also root blade chord
c_t	tip chord
g_i	i^{th} constraint
HP_a	horsepower available

HP_r	horsepower required
r	point of taper initiation (fig. 2)
R	rotor blade radius (fig. 2)
TR	taper ratio, c_r/c_t
V_H	horizontal (forward flight) velocity
V_{lf}	maneuver velocity
τ_{max}	maximum twist (fig. 2)

Design Considerations

Helicopter performance is expressed in terms of horsepower required as a function of velocity. The horsepower required to drive the main rotor is made up of three components - induced, profile, and parasite power (fig. 1). The parasite power which results from fuselage drag is a function of the cube of the forward flight velocity. Primarily the induced power (due to lift) and the profile power (due to blade drag) are affected by the rotor blade design.

An initial step in the aerodynamic design of a helicopter rotor blade is the selection and distribution of the airfoils along the blade radius. The choice of airfoils is controlled by the need to avoid exceeding the section drag divergence Mach number on the advancing side of the blade (against the wind in forward flight) and the maximum section lift coefficients on the retreating side (with the wind in forward flight). Since airfoils with high maximum lift coefficients are advantageous in high speed forward flight and pull-up maneuvers, high lift sections are used from the rotor blade root out to the radial station where the advancing side drag divergence Mach number precludes the use of the section. From that station outward, other airfoil sections which have higher drag rise Mach numbers are selected.

Once airfoils and airfoil distribution are selected, the induced and profile power components are functions of twist, taper ratio, point of taper initiation, and root blade chord. For the hover condition, over 80 percent of the power is induced power and the remainder is profile power. As forward flight begins, the induced power decreases. The profile power curve increases at higher speeds as the airfoil section approaches stall conditions and/or exceeds the airfoil section drag divergence Mach number. Rotor blade designs which minimize both induced and profile power are desirable. The induced power is a function of blade radius, chord and lift coefficient. The profile power is a function of blade radius, chord, and drag coefficient. The induced and profile power can be reduced (provided the aerodynamics of all retreating blade airfoils are within linear theory) by increasing taper ratio and/or by changing blade twist - all of which tend to increase inboard loading and decrease tip loading.

Definition of the Rotor Blade Aerodynamic Design Problem

The rotor blade aerodynamic design problem can be stated in terms of a design goal and a set of design requirements. The design goal is to reduce the hover horsepower for a given helicopter with a specified design gross weight operating at a specified altitude and temperature. Satisfactory forward flight performance is defined by the following three requirements. First, the required horsepower must be less than the available horsepower. Second, airfoil section stall along the rotor blade must be avoided, i.e. the airfoil sections distributed along the rotor blade must operate at section drag coefficients less than a specified value neglecting the large drag coefficients in the reverse flow region which occurs inboard from the tip at a given azimuthal angle. In order to maintain lift on the rotor blade, the drag coefficients in this reverse flow region are relatively high, however these drag coefficients can be neglected since the velocities in this region are low. Only the drag coefficients corresponding to velocities greater than a preselected velocity are considered. Third, the helicopter must be able to sustain a specified simulated pull-up maneuver, i.e., the aircraft must operate trimmed at a gross weight equal to a specified multiple (load factor) of the design gross weight for a second specified horizontal velocity V_{1f}. The first two requirements must also be satisfied during the simulated pull-up manuever.

Rotor Blade Design Parameters

The design parameters - point of taper initiation, root chord, taper ratio, and maximum twist - are illustrated in figure 2. The point of taper initiation, r, is the radial station where taper begins. The blade is rectangular up to this station and then tapered linearly to the tip. The taper ratio, TR, is c_r/c_t where c_r is the chord (same as the root chord) at the point of taper initiation and c_t is the tip chord. The twist varies linearly from the root to the tip where the maximum value τ_{max} occurs.

Analyses

Two analysis computer programs are used to predict rotor performance. The hover analysis HOVT (a strip theory momentum analysis, based on reference 5) is used to compute hover horsepower. The Rotorcraft Flight Simulation computer program, C-81 (ref. 9), (quasi-static trim option) is used to define the trim condition, the horsepower required and the airfoil section drag coefficients for both forward flight and maneuver conditions. Both analyses use experimental two-dimensional airfoil data. Advanced (tapered) and baseline (rectangular) blade designs based on these analyses for the UH-1, UH-60, and AH-64 helicopters have been experimentally evaluated at the Langley 4-X 7-meter wind tunnel (refs. 6-8, respectively). The theoretical hover performance predictions have been verified for both advanced and baseline designs for all three helicopters. Theoretical forward flight performance predictions have been verified for the advanced and baseline rotor blade designs for the UH-1 and AH-64 helicopters (refs. 7 and 8, respectively).

The analytical model of the rotor blade is shown in figure 3. The blade is segmented into twenty radial stations. One airfoil section is located at each station. Up to five different airfoil sections can be used. For example, in figure 3 three airfoils are used.

Conventional Approach to Rotor Blade Design

The conventional rotor blade design approach (ref. 6) is a two-step iterative method. The rotor blade is first designed for hover by varying taper ratio (TR) and point of taper initiation (r) to reduce hover horsepower. When no further reduction in hover horsepower is possible, the twist (τ_{max}) is varied and the design process is repeated until the rotor blade configuration with the lowest hover horsepower is obtained. This best hover design is then compromised to meet forward flight and maneuverability requirements by changing the root chord which is primarily influenced by the simulated pull-up maneuver. The root chord and the tip chord must be sufficiently large to avoid retreating blade stall in maneuver and forward flight. It is sometimes necessary to go back and change the first three design quantities (TR, r,

τ_{max}) since the airfoil section lift coefficients required for the maneuver are larger than those required for hover.

As shown in figure 4, the designer using the conventional approach is actively involved in manipulating the design variables and making judgements on design changes. The designer may be thought of as the communications link between the hover and forward flight analyses since the analyses are executed separately. This approach involves time-consuming parametric studies and extensive cross-plots.

Mathematical Programing Approach to Rotor Blade Design

Overview

The mathematical programing approach uses the same rotor blade performance analyses discussed previously and couples a general-purpose optimization program to the analyses. When the designer uses optimization methods, the problem is defined in terms of an objective function (the quantity to be minimized), a set of design variables (the quantities which are changed in order to minimize the objective function), and a set of constraints (design requirements which must be satisfied). Once the problem has been defined in these terms, the designer is no longer as actively involved in manipulating the design variables as he would be using the conventional approach. Instead, as shown in figure 5, the optimization program takes over the role of manipulating the design variables to arrive at the best blade design. With the mathematical programing approach, the objective function (from the hover analysis) and the constraints (from the forward flight analysis) are calculated for each change in design variable. The optimization program used is CONMIN (ref. 14) which is a well-established general purpose optimization program. CONMIN requires the use of derivatives of the objective function and constraints which in this application are calculated internally by CONMIN using finite differences.

Objective Function, Design Variables, and Constraints

The objective function is the required hover horsepower for the main rotor which is evaluated in the hover analysis HOVT. The design variables are maximum twist τ_{max}, point of taper initiation r, taper ratio TR, and blade root chord c_r. The forward flight requirements translate into 27 constraints and are evaluated using information from the forward flight analysis program C-81. By CONMIN sign convention, a constraint g_i is satisfied if it is negative or zero and violated if it is positive. The first design requirement - that horsepower required not exceed the horsepower available - translates into two constraints,

$$g_1 = HP_r / HP_a - 1 \qquad \text{forward flight}$$

$$g_2 = HP_r / HP_a - 1 \qquad \text{pull-up maneuver}$$

where HP_r and HP_a are the total horsepower required (main and tail rotor) and the total horsepower available, respectively.

The second design requirement - that the airfoil sections not stall - translates into constraints on the airfoil section drag coefficient, c_d. This requirement leads to 24 constraints since the c_d's are evaluated at 12 azimuthal angles (every thirty degrees measured from the axis along the fuselage through the tail rotor) by the C-81 program in both forward flight and the simulated pull-up maneuver. These constraints are formulated as

$$g_i = c_{d,max_{i-2}} / c_{d,all} - 1 \qquad i=3,14 \text{ (forward flight)}$$

$$g_i = c_{d,max_{i-14}} / c_{d,all} - 1 \qquad i=15,26 \text{ (pull-up maneuver)}$$

where $c_{d,all}$ is the allowable drag coefficient and $c_{d,max}$ is the maximum drag coefficient along the blade radius outside the reverse flow region at a given azimuthal angle.

The third design requirement - that the helicopter must trim in the simulated pull-up maneuver - is somewhat difficult to translate into a continuous mathematical programing constraint. This constraint is implemented by determining from the C-81 program whether or not at a specified velocity V_{lf} the helicopter can trim at a gross weight equal to a load factor multiplied by the design gross weight. If the helicopter is trimmed, it is in an equilibrium flight condition so that the summations of external forces and moments about the center of gravity of the helicopter and the summations of longitudinal and lateral rotor moments acting at the rotor hub are zero (within preassigned limits). For a quasi-static analysis, determining if trim occurs involves an iterative process in C-81. For a given set of design variables, the C-81 program adjusts 11 independent trim parameters so that the summation of the forces and moments will be zero. A modified Newton-Raphson iterative technique is used to solve the system of equations. The user specifies the maximum number of iterations allowed for convergence. If this number (ITERMAX) is reached and the force and moment imbalances are not zero, the C-81 program writes the message "ROTORCRAFT IS NOT TRIMMED". If the force and moment imbalances are zero, the C-81 program writes the message "ROTORCRAFT IS TRIMMED" and gives the number of iterations (ITER) for convergence. These two messages were incorporated into mathematical programing language as a heuristic but effective constraint which is formulated as a continuous expression involving all four design variables as follows:

$$g_{27} = (ITER-ITERMAX+1)(\tau_{max}/\tau_{max}+r/R+TR+c_r/e_r)$$

where τ_{max} and e_r are nondimensionalizing quantities for the twist and root chord, respectively. This constraint is a recovery factor and is not active in the final design. Violation of this constraint occurs infrequently. Table 1 summarizes the 27 constraints used in the mathematical programing approach.

Applications

The conventional and mathematical programing approaches have been used to obtain rotor blade designs for three Army helicopters: the AH-64 (Apache), the UH-1 (Huey), and a conceptual high-speed high-performance helicopter. In each case the goal is to find, for preselected RPM, rotor blade radius, airfoil sections and distribution, the blade configuration which has the lowest hover horsepower for a given design gross weight and a selected pull-up maneuver. Results which are presented in Tables 2-4 include the final design variable values, the main rotor horsepowers required for hover (the objective function), for forward flight, and for the simulated pull-up maneuver conditions, and the active constraints for each approach. In all cases the mathematical programing approach started from a rectangular blade with a twist of -9 degrees and a root blade chord of 1.75 feet. Overall the mathematical programing approach obtained results about ten times faster than the conventional approach.

AH-64 Helicopter

The AH-64 helicopter is a four-bladed attack helicopter with a design gross weight of 14667 pounds and a horizontal forward flight velocity V_H of 160 knots. The simulated pull-up maneuver for this study has a load factor of 1.33 (or 20000 pounds) at a velocity V_{1f} of 100 knots. The AH-64 has a rotor blade radius of 24 feet with a constant rotor speed of 290 RPM. The airfoil distribution along the blade radius is shown in figure 3. RC(4)-10 airfoils are used for radial stations 1-16, RC(3)-10 airfoils (ref. 15) are used for radial stations 17-18, and RC(3)-08 (ref. 15) airfoils are used for radial stations 19 and 20. The maximum allowable drag coefficient ($c_{d,all}$) at any radial station is 0.25. The available horsepower is 2340 hp.

The final AH-64 rotor blade designs obtained using both the conventional and mathematical programing approaches are shown in Table 2. The mathematical programing approach produces a design which had more twist, a point of taper initiation further outboard, and a smaller blade root chord than the conventional approach. The mathematical programing design requires 27 hp less in hover than the conventional design but at the expense of more horsepower required in both the forward flight and maneuver conditions. Constraint 1 (the horsepower required for forward flight) governs the designs obtained by both approaches. In addition, constraint 23 (the section drag coefficient at 240 degrees in maneuver) is active in the final mathematical programing rotor blade design.

UH-1 Helicopter

The UH-1 helicopter is a two-bladed utility helicopter with a rotor blade radius of 24 feet and a constant rotor speed of 324 RPM. The goal is to find the rotor blade design which has the lowest hover horsepower for a helicopter with a design gross weight of 8050 pounds and a horizontal forward flight velocity V_H of 124 knots. The drive system has 1000 horsepower available. The pull-up maneuver is represented by a load factor of 1.5 (or 12075 pounds) at a velocity V_{lf} of 100 knots. For this study the maximum blade segment drag coefficient ($c_{d,all}$) is 0.03. RC(4)-10 airfoils were used for radial stations 1-14, RC(3)-10 airfoils (ref. 15) for radial stations 15-17, and RC(3)-08 airfoils (ref. 15) for radial stations 18-20.

Final rotor blade designs for the UH-1 using both the conventional and mathematical programing approaches are shown in Table 3. The two designs requires about the same hover horsepower. The mathematical programing approach obtains a design with slightly more twist, a point of taper initiation further inboard, a smaller taper ratio, and a slightly smaller chord than that obtained using the conventional approach. The hover horsepower is 1 horsepower lower than the horsepower of the conventional design at the expense 25 more horsepower in forward flight and 17 more horsepower in the simulated pull-up maneuver. Constraints 6, 23, 24 (the section drag coefficients on the advancing blade side at 90 degrees and on the retreating blade side at 240 and 270 degrees for the forward flight and the pull-up maneuver, respectively) govern the design obtained by both approaches. In addition, constraint 22 (the section drag coefficient at 210 degrees for the pull-up manuever) is also active for the final mathematical programing design.

Conceptual High Speed Helicopter

Both the conventional and mathematical programing approaches have been applied to design a rotor blade for a four-bladed conceptual high speed helicopter with a design gross weight of 8000 pounds and a horizontal forward flight velocity V_H of 180 knots. The drive system is assumed to have 2340 horsepower available. The simulated pull-up manuever is represented by a load factor of 2.25 (or 18,000 pounds at a velocity V_{lf} of 150 knots). The helicopter has a rotor blade radius of 20.6 feet with RC(4)-10 airfoils at radial stations 1-14, RC(3)-10 airfoils (ref. 15) at radial stations 15-18, and RC(3)-08 airfoils (ref. 15) at radial stations 19 and 20. The maximum section drag coefficient ($c_{d,all}$) is 0.16.

Results obtained using both the conventional and mathematical programing approaches are shown in Table 4. Both designs required about the same hover horsepower. The mathematical programing design required 32 more horsepower for forward flight and 58 more horsepower for the pull-up maneuver than the conventional approach. The design obtained by the mathematical programing approach has more twist, a point of taper initiation further inboard, a smaller taper ratio, and a smaller chord than the design obtained by the conventional approach. Constraint 24 (the manuever section drag constraint at 270 degrees) was active in both the conventional and mathematical programing designs.

Observations on the Methods

Although the mathematical programing approach is significantly faster than the conventional procedure, some of the differences in the designs produced by the two methods have raised questions which need further investigation. In two of the three cases, the final rotor blade designs from the two approaches require similar hover horsepower but have different active constraints. The most noticeable differences are in the horsepower required for forward flight and the simulated maneuver. The mathematical programing design requires more horsepower than the conventional design. This occurrence could result from the manner in which the reverse flow region is handled. At the present time this region is excluded by considering only the drag coefficients corresponding to velocities greater than a preselected velocity. A better criterion for excluding this region needs to be incorporated into the mathematical programing approach. Further, this difference in the horsepower suggests that some considerations implicitly included by the designer in the conventional approach have not yet been identified for inclusion in the mathematical programing approach. The conventional approach involves much intuitive judgement by the designer and needs to be explicitly identified and translated into the mathematical programing formulation.

Concluding Remarks

This paper describes the application of formal optimization techniques to the aerodynamic design of rotor blades. The approach is to couple hover and forward flight analysis programs with the general purpose optimization program CONMIN to determine the blade taper ratio, point of taper initiation, twist distribution, and root chord which minimize the horsepower required at hover while meeting the following performance constraints: the required horsepower must be less than the available horsepower; the airfoil sections distributed along the rotor blade must operate at section drag coefficients (or pitching moment coefficients) less than a specified value; and the helicopter must be able to sustain a specified simulated pull-up maneuver. Designs obtained from the mathematical programing approach for the blades of representative Army helicopters compare favorably with those obtained from a conventional approach involving labor-intensive parametric studies. Results from the present method can typically be obtained ten times faster and less laboriously than those obtained by the conventional procedure. Also the systematic manipulation of the design variables by the optimization procedure minimizes the need for a designer to have a vast amount of past experience and data in determining the influence of a design change on the performance.

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TABLE 1. SUMMARY OF CONSTRAINTS

Constraint Number	Description
1	Horsepower required[1]
2	Horsepower required[2]
3	c_d @ 0 degrees[1]
4	c_d @ 30 degrees[1]
5	c_d @ 60 degrees[1]
6	c_d @ 90 degrees[1]
7	c_d @ 120 degrees[1]
8	c_d @ 150 degrees[1]
9	c_d @ 180 degrees[1]
10	c_d @ 210 degrees[1]
11	c_d @ 240 degrees[1]
12	c_d @ 270 degrees[1]
13	c_d @ 300 degrees[1]
14	c_d @ 330 degrees[1]
15	c_d @ 0 degrees[2]
16	c_d @ 30 degrees[2]
17	c_d @ 60 degrees[2]
18	c_d @ 90 degrees[2]
19	c_d @ 120 degrees[2]
20	c_d @ 150 degrees[2]
21	c_d @ 180 degrees[2]
22	c_d @ 210 degrees[2]
23	c_d @ 240 degrees[2]
24	c_d @ 270 degrees[2]
25	c_d @ 300 degrees[2]
26	c_d @ 330 degrees[2]
27	Trim[2]

[1]Forward flight
[2]Maneuver

TABLE 2. SUMMARY OF RESULTS FOR AH-64 HELICOPTER

	Conventional approach	Mathematical programing approach
Twist, degrees	-12	-15
Point of taper initiation ratio[a]	0.8	0.91
Taper ratio	3.0	3.1
Blade root chord, ft	2.30	1.78
Main rotor, horsepower required		
Hover, hp[b]	1560	1533
Forward flight, hp	2158	2244
Maneuver, hp	1261	1493
Active constraints[c]	1	1,23

[a] r/R

[b] Objective function

[c] See Table 1

TABLE 3. SUMMARY OF RESULTS FOR UH-1 HELICOPTER

	Conventional approach	Mathematical programing approach
Twist, degrees	-13	-14
Point of taper initiation ratio[a]	0.5	0.44
Taper ratio	3.0	2.0
Blade root chord, ft	2.78	2.49
Main rotor, horsepower required		
Hover, hp[b]	669	668
Forward flight, hp	552	577
Manuever, hp	543	560
Active constraints[c]	6,23,24	6,22,23,24

[a] r/R

[b] Objective function

[c] See Table 1

TABLE 4. SUMMARY OF RESULTS FOR 180 KNOT HELICOPTER

	Conventional approach	Mathematical programing approach
Twist, degrees	-13	-14.8
Point of taper initiation ratio[a]	0.754	0.530
Taper ratio	3.0	1.54
Balde root chord, ft	2.09	1.95
Main rotor, horsepower required		
Hover, hp[b]	750	748
Forward flight, hp	1867	1899
Manuever, hp	1257	1315
Active constraints[c]	24	24

[a] r/R

[b] Objective function

[c] See Table 1

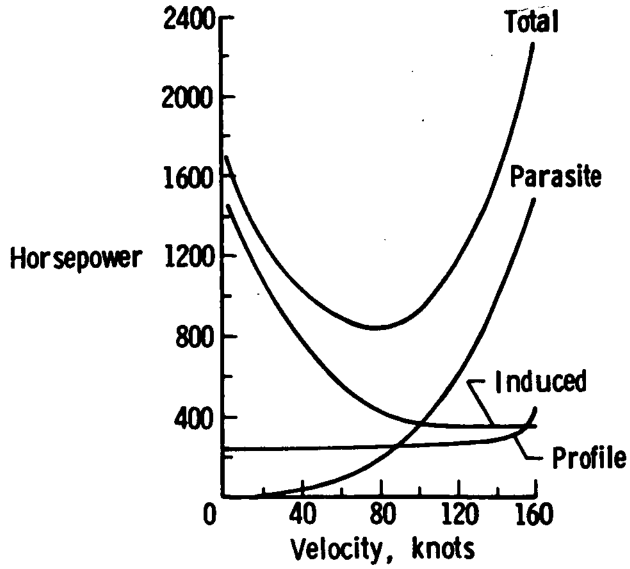


Figure 1 Typical curves of horsepower required as a function of velocity.

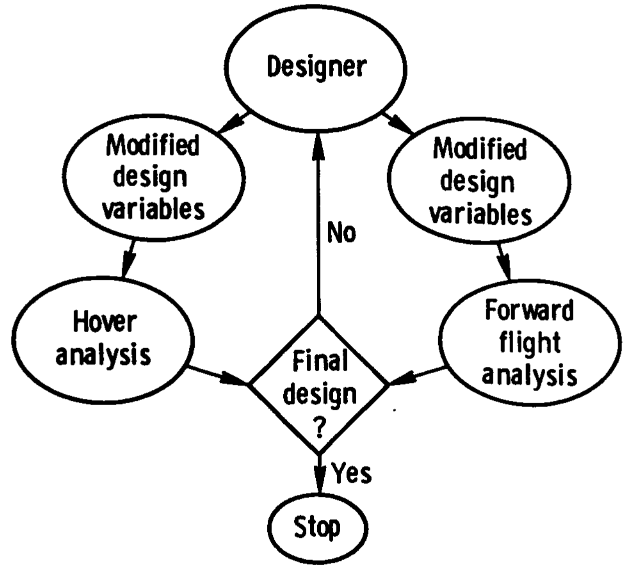


Figure 4 Schematic of the conventional approach to rotor blade design.

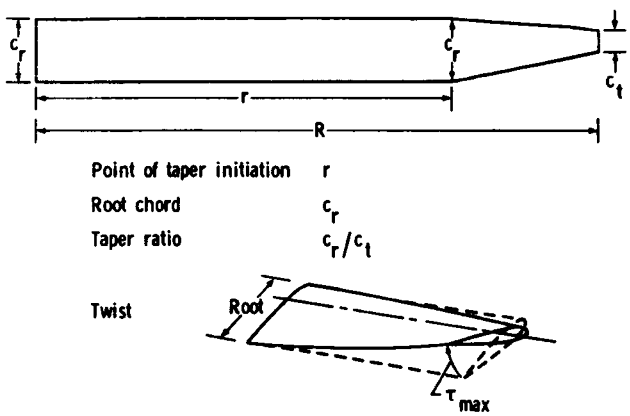


Figure 2 Rotor blade design variables.

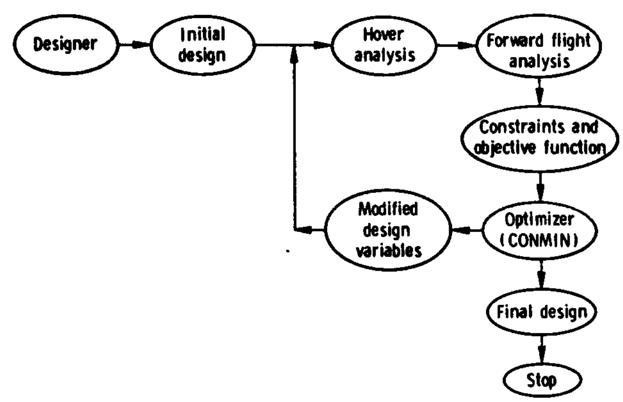
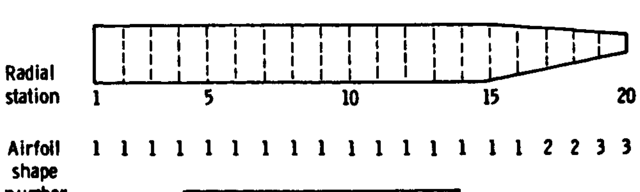


Figure 5 Schematic of mathematical programing approach to rotor blade design.



Number	Airfoil designation
1	RC (4)-10
2	RC (3)-10 (ref. 14)
3	RC (3)-08 (ref. 14)

Figure 3 Typical distribution of airfoil shapes along the rotor blade.

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**PRC Kentron, Hampton, VA
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16. Abstract

This paper describes a formal optimization procedure for helicopter rotor blade design which minimizes hover horsepower while assuring satisfactory forward flight performance. The approach is to couple hover and forward flight analysis programs with a general-purpose optimization procedure. The resulting optimization system provides a systematic evaluation of the rotor blade design variables and their interaction, thus reducing the time and cost of designing advanced rotor blades. The paper discusses the basis for and details of the overall procedure, describes the generation of advanced blade designs for representative Army helicopters, and compares designs and design effort with those from the conventional approach which is based on parametric studies and extensive cross-plots.

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