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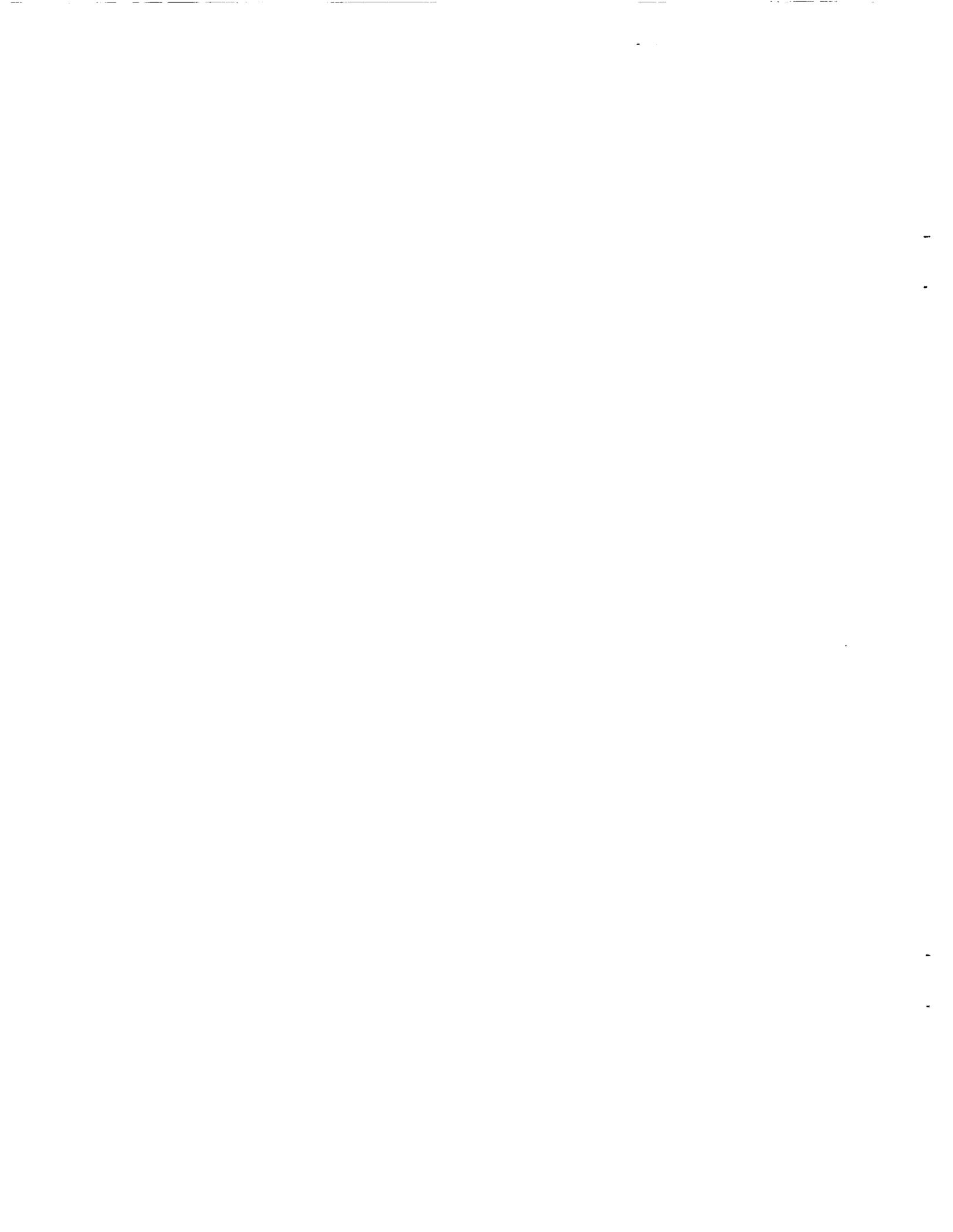# PERFORMANCE OPTIMIZATION OF HELICOPTER ROTOR BLADES

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Performance Optimization of Helicopter Rotor Blades

by

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Abstract

As part of a center-wide activity at NASA Langley Research Center to develop multidisciplinary design procedures by accounting for discipline interactions, a performance design optimization procedure is developed. The procedure optimizes the aerodynamic performance of rotor blades by selecting the point of taper initiation, root chord, taper ratio, and maximum twist which minimize hover horsepower while not degrading forward flight performance. Satisfactory aerodynamic performance is defined by the following requirements which must hold for any flight condition: the required horsepower must be less than the available horsepower; the section drag divergence Mach number on the advancing side of the rotor disc must be avoided, the maximum section lift coefficient on the retreating side of the rotor disc must be avoided, the high nose down pitching moments on either side of the rotor disc must be avoided; and the rotor blade must be trimmed. The procedure uses HOVT (a strip theory momentum analysis) to compute the horsepower required for hover and the comprehensive helicopter analysis program CAMRAD to compute the horsepower required for forward flight and maneuver. The optimization algorithm consists of the general purpose optimization program CONMIN and approximate analyses. Sensitivity analyses consisting of derivatives of the objective function and constraints are carried out by forward finite differences. The procedure is applied to a test problem which is an analytical model of a wind tunnel model of a utility rotor blade. The hover analysis is performed using nonuniform inflow without a wake model. The forward flight analysis is performed with and without wake models.

Introduction

Over the last two decades, work has been done in developing and applying techniques for the optimum design of aircraft structures (refs. 1 and 2). These techniques have only recently been applied to rotorcraft problems (refs. 3-13) due to the multidisciplinary nature of the helicopter rotor blade design process which requires a merging of several disciplines, such as aerodynamics, dynamics, structures, and acoustics. Recently, techniques and strategies for merging appropriate disciplines to obtain an integrated design procedure have been emerging. Currently at NASA Langley Research Center, there is an effort to integrate various disciplines in the rotor blade design process (ref. 14). The present work is part of that effort and deals with the performance aspect of rotor blade design.

One of the goals in the overall design activity is to improve the aerodynamic performance of rotor blades in both hover and forward flight by optimally selecting certain blade design parameters such as twist, chord distribution, taper, sweep, and airfoil sections. The rotor blade aerodynamic design process is complicated by conflicting performance requirements - for example, between hover and forward flight. In refs. 15 and 16, the trade-offs between hover and forward flight performance for various design parameters were investigated. As pointed out in ref. 15 for a tilt rotor, the "best" twist for hover produces negative lift on inboard airfoil

sections in forward flight, while the "best" twist for forward flight causes the blade to stall inboard in hover. Similarly, the best choice of blade chord and airfoil sections are conflicting between hover and forward flight. In order to obtain a high level of performance in both hover and forward flight, it is necessary to balance the design requirements. This can be a tedious process if a designer has to do the trade studies parametrically.

Reference 16 describes an analytical procedure for designing rotor blades, referred to herein as the conventional approach, which combines a strip theory momentum analysis (based on ref. 17) for the hover analysis and the Rotorcraft Flight Simulation computer program C-81 (ref. 18) for the forward flight analysis. This conventional approach has produced rotor blade designs with improved aerodynamic performance, but 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.

To avoid the time-consuming aspects of the conventional approach, formal optimization techniques have been found to be ideally suited to these trade-off procedures and have proven useful in the aerodynamic design of rotor blades. Reference 8 describes a procedure which applies optimization techniques for three flight conditions - hover, forward flight, and maneuver. The procedure involved coupling the hover and forward flight analyses with a general purpose optimization procedure CONMIN (ref. 19). This approach systematically searched for a blade design which minimized hover horsepower while assuring adequate forward flight performance by satisfying explicit design requirements. The mathematical programming approach designs compared favorably with those obtained from the conventional approach (ref. 16). The mathematical programming approach typically obtained results 10 times faster than the conventional approach.

The present work is an extension and modification of the work of ref. 8. The present approach differs in two ways: first, the procedure uses the comprehensive helicopter analysis program CAMRAD (ref. 20) for forward flight and maneuver; second, it incorporates a wake model for forward flight and maneuver performance. The use of CAMRAD is intended as an improvement to the approach of reference 8 which used C-81. An analytical study (ref. 21) of a high speed rotor configuration, using the C81 forward flight analysis indicated that for configurations with the same thrust-weighted solidity, moving the taper initiation point outboard resulted in the lowest horsepower required for the specified cruise and maneuver conditions. This result was contrary to the experimental trends (refs. 22-26) at lower speeds and led to a wind tunnel investigation which confirmed that the analytical trends from C-81 were in error.

Symbols

c_d	airfoil section drag coefficient
$c_{d_{all}}$	allowable airfoil section drag coefficient
$c_{d_{max}}^i$	maximum airfoil section drag coefficient along blade radius at i^{th} azimuth
c_r	root chord
C_T	coefficient of thrust
c_t	tip chord
$c_{t_{min}}$	minimum tip chord
C_X	coefficient of propulsive force
HP_r	horsepower required

HP_a	horsepower available
g_i	i^{th} constraint
ITER	number of trim iterations
$ITER_{MAX}$	maximum trim iterations allowed
R	blade radius
r/R	point of taper initiation
σ	area solidity
τ_{max}	maximum pretwist
ψ	azimuth angle

Rotor Blade Aerodynamic 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 (see figure 1). The parasite power which results from fuselage drag is a function of the cube of the forward flight velocity. The induced power (due to lift) and the profile power (due to blade drag) primarily influence the rotor blade design.

An initial step in the aerodynamic design of a helicopter rotor blade is the selection of the airfoils which could be applied over various regions of 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 rotor disc, exceeding the maximum section lift coefficients on the retreating side of the rotor disc, and high nose-down pitching moments on either side of the rotor disc. 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 the airfoils and an initial airfoil distribution are selected, the induced and profile power components become functions of twist, taper ratio, point of taper initiation, and blade root chord (ref. 16). For hover, over 80 percent of the power is induced power and the remainder is profile power. 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 - both of which tend to increase inboard loading and decrease tip loading.

Satisfactory aerodynamic performance is defined by the following requirements. First, the required horsepower for any flight condition must be less than the available horsepower. Second, airfoil section stall along the retreating side of the rotor blade disc must be avoided and the section drag divergence Mach number on the advancing side of the rotor blade disc must be avoided. These requirements are handled in the present work by requiring that the airfoil sections distributed along the rotor blade 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. The drag coefficients in this reverse flow region are relatively high; however, they are neglected since the velocities in this region are low and the accuracy of two-dimensional drag coefficients for reverse flow conditions is also questionable. Third, the helicopter must be able to trim at each flight condition. 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 a specified tolerance).

Optimization Formulation

In this section of the paper the aerodynamic optimization problem is formulated. The design variables, the constraints, and the objective function are discussed.

Design Variables - The design variables used in the present work are the same as those used in reference 8. The design variables (see figure 2) are the point of taper initiation (r/R), root chord (c_r), taper ratio (c_r/c_t), and maximum pretwist (τ_{max}). The blade is rectangular to the station (r/R) and then tapered linearly to the tip. The twist varies linearly from the root to the tip where the maximum value of occurs. The airfoil distribution is preselected.

Constraints - The aerodynamic design requirements described previously translate into the following constraints (by sign convention, a constraint g is satisfied if it is negative or zero and violated if it is positive).

The first design requirement is that the horsepower required for forward flight and maneuver must be less than the horsepower available

$$g_1 = HP_r/HP_a - 1 \quad \text{for forward flight} \tag{1}$$

$$g_2 = HP_r/HP_a - 1 \quad \text{for maneuver} \tag{2}$$

where HP_r and HP_a are the horsepower required and the horsepower available, respectively.

The second design requirement is that the airfoil sections not stall and that of avoiding the Mach divergence drag number. This requirement translates into constraints on the airfoil section drag coefficient, c_d, which leads to a number of constraints since the c_d's are evaluated at N azimuthal angles for both forward flight and maneuver. At a given azimuthal angle the constraint is formulated as shown below:

$$g_{2+i} = c_{d_{max}}^i/c_{d_{all}} - 1 \qquad i=1,2, \ldots, N \tag{3}$$

where $c_{d_{all}}$ is the allowable drag coefficient and $c_{d_{max}}^i$ is the maximum drag coefficient along the blade radius outside the reverse flow region at the ith azimuthal angle.

The third design requirement that the helicopter must be trimmed for any forward flight condition is somewhat difficult to translate into a continuous mathematical programming constraint. This constraint is implemented by determining from the CAMRAD program whether or not at a specified advance ratio the helicopter can trim. CAMRAD allows the blade $ITER_{MAX}$ iterations to trim. The blade is considered trimmed if the blade trims in $ITER$ iterations and $ITER$ is less than $ITER_{MAX}$. If $ITER$ is greater than $ITER_{MAX}$, the blade is not trimmed. A heuristic constraint having the following form is used for forward flight and maneuver

$$g_{2N+3} = (ITER-ITER_{MAX}+1)\left(\frac{\tau_{max}}{\overline{\tau}_{max}} + \frac{r}{\overline{r}} + \frac{c_r/c_t}{\overline{c_r/c_t}} + \frac{c_r}{\overline{c_r}} \right)$$

$$(4)$$

$$g_{2N+4} = (ITER-ITER_{MAX}+1)\left(\frac{\tau_{max}}{\overline{\tau}_{max}} + \frac{r}{\overline{r}} + \frac{c_r/c_t}{\overline{c_r/c_t}} + \frac{c_r}{\overline{c_r}} \right)$$

where $\overline{\tau}_{max}$, $\overline{r}$, $\overline{c_r/c_t}$ and $\overline{c_r}$ are normalizing factors so each design variable will have equal weight in the constraint.

An additional constraint is used to ensure that the blade tip chord does not become too small. A lower limit of $c_{t_{min}}$ was imposed giving a constraint having the following form

$$g_{2N+5} = 1 - c_t/c_{t_{min}}$$

$$(5)$$

Objective function - The objective function to be minimized is the horsepower required for hover.

Analyses

The hover analysis HOVT (a strip theory momentum analysis, based on ref. 17) is used to compute the hover horsepower and the comprehensive helicopter analysis CAMRAD is used to compute forward flight and maneuver horsepower. Both analyses use tables of experimental two-dimensional airfoil data. The general purpose optimization program CONMIN along with an approximate analysis is used for the optimization. A brief description of the analyses are included in this section of the paper.

Hover Analysis

The Langley-developed hover analysis HOVT based on strip theory momentum analysis is used to predict the horsepower required for hover. The nonuniform inflow option is used but there is no wake model in the analysis. The hover performance trends predicted by HOVT have been verified by model tests (refs. 22-26) of both advanced and baseline designs for the UH-1, AH-64, and UH-60 helicopters.

Forward Flight and Maneuver Analysis

The CAMRAD computer program is used to define the trim condition and to compute the horsepower required and the airfoil section drag coefficients for the forward flight and maneuver conditions. The analyses are performed with both the uniform and nonuniform inflow (prescribed wake) models.

Optimization Procedure

The flow chart for the optimization procedure is shown in figure 3. For the present procedure, an optimization cycle is defined to be a full analysis, sensitivity analyses, approximate analysis, and optimization. First, preassigned parameters such as the blade radius, number of blades and blade stiffnesses are set. An optimization cycle is initiated. The

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aerodynamic and structural properties such as twist and chord distributions, radial station locations, and solidity are then calculated using the current values for the design variables. The HOVT analysis is then performed to obtain the horsepower required for hover. Two CAMRAD analyses (forward flight and maneuver) are then performed to obtain the horsepower required, trim information, and c_d's for the stall constraints. Sensitivity analyses are performed to obtain finite difference derivatives of the objective function and constraints with respect to the design variables. Then the optimization is performed to update the design variables. Convergence is obtained if the objective functions from three consecutive cycles are the same within a tolerance of 0.5×10^{-5}.

Test Problem and Model

The method has been applied to an analytical model of a utility rotor blade shown in figure 4. The baseline blade which is a wind tunnel model has a rectangular planform to 80 percent radius and then tapers to the tip with a 3-to-1 taper ratio. The blade has a radius of 56 inches and a root chord of 5.4 inches. Three sets of advanced airfoils are used along the blade. The RC(4)-10 airfoil is used to 85 percent radius. Then the RC(3)-10 airfoil is used to 92 percent radius, and the RC(3)-08 airfoil is used for the remainder. Details of the blade can be found in ref. 27. This blade will be referred to as the reference blade.

The analytical model of the blade consists of 38 structural segments and 18 aerodynamic segments for CAMRAD and 19 aerodynamic segments for HOVT. The hover analysis uses nonuniform inflow (no wake). For the CAMRAD analysis, the wind tunnel option is used which trims the isolated blade to constant C_T/σ, C_X/σ and flapping angles using collective, lateral cyclic and longitudinal cyclic pitch and the shaft angle where C_T, C_X, and σ are the coefficient of thrust, the coefficient of propulsive force, and the area solidity, respectively. The blade is trimmed for a constant thrust C_T. This is accomplished by specifying a constant value of C_T, calculating the value of σ based on the current planform and then calculating C_T/σ and C_X/σ for CAMRAD. The coefficient of drag c_d is evaluated at 24 azimuthal angles around the rotor disc. This results in a total of 48 constraints (24 per flight condition) on c_d (see eqn. 3). Thus there are a total of 53 constraints (see eqns 1-5). The CAMRAD analysis is performed using both uniform and nonuniform inflow models. The nonuniform inflow model is performed using a prescribed (rigid) wake based on Landgrebe's wake model.

Results

First, results will be presented for nonuniform inflow hover analysis and uniform (no wake) forward flight and maneuver analyses. Then results will be presented for nonuniform inflow hover analysis and nonuniform forward flight and maneuver analyses (with wake). Both sets of results contain optimum designs using the reference blade as a starting point and then using a rectangular blade (having the same properties as the reference blade except for a pretwist of -9.0 degrees and taper ratio of 1.0) as a starting point. All the results are for a constant thrust of 279 pounds (C_T=0.0069), propulsive force of -23 pounds (C_X= -0.00056), and an advance ratio of 0.3 for the forward flight condition and a constant thrust of 335 pounds (C_T=0.0082), a propulsive force of -23 pounds (C_X=-0.00056), and an advance ratio of 0.3 for the maneuver flight condition. The maneuver flight condition is for a load factor of 1.2. The values for $c_{t_{min}}$, $c_{d_{all}}$, and HP_a are 1.0 inch, 0.2 and 20 hp, respectively.

Table 1 presents results for the case of nonuniform inflow analysis for hover and uniform (no wake) inflow analysis for forward flight and maneuver. The first column lists the four design variables and the performance measures. Column 2 presents the values of the design variables for the initial design based on the reference blade. With these values for the design variables the model requires 11.98 hp for hover, 9.17 hp for forward flight , and 10.07 hp for maneuver (based on HOVT and CAMRAD analyses). The optimum blade obtained from this starting point is presented in column 3. The optimum blade does not have as much pretwist (-14.6 degrees) as the reference blade. The point of taper initiation is further inboard (27 inches). The optimum blade is tapered slightly less than the reference blade and the root chord is smaller. With this planform, the area solidity of the blade is reduced from 0.11408 to 0.08158. This optimum blade requires 7 percent less horsepower for hover, 12 percent less for forward flight, and an increase of 5 percent for maneuver. The reference blade was originally designed for more stringent flight requirements (higher C_T, C_X and advance ratios) than those chosen in this study. Thus, it is expected that the optimum blade should perform better than the reference blade at these advance ratios, C_T and C_X values.

As a check to see if this result was a local minimum, the design process was started from a rectangular blade which has a pretwist of -9.0 degrees and the same root chord of 5.4 inches. The analytical predictions for this design are given in column 4. For this design, the horsepower required for hover, forward flight, and maneuver are 12.56 hp, 9.41 hp, and 10.36 hp, respectively. The optimum design obtained from this starting point is given in column 5 and has an area solidity σ of 0.07225. This design requires nearly the same horsepower for hover and forward flight , but more horsepower for the maneuver than the optimum design starting from the reference blade (column 3). This blade has slightly more pretwist, similar point of taper initiation, less taper, and a smaller blade root chord than the first design.

As mentioned previously, this study obtained blade designs for minimum hover horsepower. It was of interest to see how these blades performed in forward flight at several advance ratios. Figure 5 shows a plot of the horsepower required versus advance ratio for the blade design obtained from the reference blade starting point. Although not included here, the other optimum blade (starting from the rectangular blade) has a similar trend. As shown in the figure, the optimized blade requires less horsepower than the reference blade over the flight speed range shown (advance ratios of 0.0 to 0.4). The primary reason for this is that the optimized blade has less area solidity (σ = 0.08158) than the reference blade (σ = 0.11408). The reference blade was originally designed for more stringent flight requirements (higher C_T and advance ratios) than those chosen in this study. Thus, it is expected that the new blade should perform better than the reference blade at advance ratios and C_T values less than or equal to the chosen values. However, at higher advance ratios the reference blade should have better performance. This is true in this case since both optimized blades are closer to stall than the reference blade. Both optimized blades have active stall constraints ($c_{d_{max}}^i$ approximately equal to $c_{d_{all}}$ on the retreating side of the rotor disc). The reference blade does not have active stall constraints. In addition, the optimized blades were more difficult to trim at the higher advance ratios (0.35-0.4) for the maneuver flight condition.

Table 2 presents results for the case of nonuniform inflow (no wake) analysis for hover and nonuniform inflow analysis (prescribed wake) for forward flight and maneuver. Column 2 presents the values of the design variables for the initial design based on the reference blade. With these values for the design variables, the reference blade (based on HOVT and CAMRAD analyses) requires 11.98 hp for hover, 9.74 hp for forward flight, and 10.89 hp for maneuver. The optimum blade obtained from this starting point is presented in column 3. The

optimum blade has less pretwist (-15.2 degrees) than the reference blade. The point of taper initiation is further outboard (48.3 inches). The optimum blade is tapered slightly less (2.4) than the reference blade. and the root chord is smaller (3.7 inches). With this design, the horsepower required for hover is reduced 7 percent from 11.98 to 11.42 hp, the horsepower required for forward flight is reduced 11 percent from 9.74 to 8.79 hp, and the horsepower required for the maneuver is decreased 1 percent from 10.89 to 10.82 hp.

To see if this result is a local minimum, the design process is started from a rectangular blade which has a pretwist of -9.0 degrees and the same root chord of 5.4 inches. The analytical predictions for this design are given in column 4. For this design, the horsepower required for hover, forward flight, and maneuver are 12.56 hp, 9.66 hp, and 10.57 hp, respectively. The optimum blade obtained from this starting point is given in column 5. This optimum blade required about the same horsepower for hover (11.43 hp), slightly more horsepower for forward flight (8.95 hp), and about the same horsepower for the maneuver (10.8 hp) as the optimum blade obtained from the reference blade starting point (column 3). This optimum blade has more pretwist than either the reference blade or the optimum blade (column 3), has the point of taper initiation more inboard (30.4 inches) than either blade, has less taper (taper ratio of 1.33) and has more blade root chord (3.84 inches) than the other optimum design.

It was of interest to see how the optimized blade performed in forward flight. Figure 6 shows a plot of the horsepower required versus advance ratio for the optimum blade which has a blade root chord of 3.7 inches, a pretwist of -15.2 degrees, is rectangular out to 48.3 inches and then tapered 2.4 to 1 out to the tip (Column 3, Table 2). As shown in the figure, the optimized blade requires less horsepower than the reference blade over the flight speed range of interest (advance ratio of 0.0 to 0.4). The reason for this is that the optimized blade has less area solidity (σ = 0.08102) than the reference blade (σ = 0.11408). As in the earlier case (Table 1), the optimum blades are closer to stall than the reference blade. The optimum blades have several stall constraints which are active on the retreating blade side of the rotor disc. The reference blade is further from stall than the optimized blade.

Effect of Forward Flight Wake

It was of interest to investigate the effect of including a wake model in the forward flight analysis on the optimum blade design. Thus a study was done to compare the optimum blade designs obtained with and without a wake model in the forward flight analysis. The Landgrebe prescribed wake model in CAMRAD was used. It was found that including a wake in the forward flight analysis has an effect on the optimum blade design and the effect depends on the initial design.

Figure 7 compares optimum blade designs obtained when the reference blade was used as the starting point. The major effect is on the point of taper initiation. The optimum design obtained using a wake model in the analysis moves the point of taper initiation further outboard (48.3 in) than the optimum design obtained without a wake model in the forward flight analysis which moves the point of taper initiation inboard of the reference blade (27.0 in). Inclusion of a wake analysis increases the predicted horsepower required by the blade. For example, with uniform inflow the reference blade requires 9.17 hp and 10.07 hp for forward flight and maneuver, respectively. With nonuniform inflow, the reference blade requires 9.74 hp and 10.89 hp, respectively.

Figure 8 compares optimum blade designs obtained when the rectangular blade was used as the starting point. Including a wake results in designs with larger pretwist, less taper, and a slightly larger root chord. The point of taper initiation is about the same. From these results, it

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is seen that wake sensitivity cannot be neglected in the design process. It is also apparent from the above results that there is a need to further investigate the effects of including wakes to account for the different trends based on initial starting points for the designs.

Concluding Remarks

As part of a center-wide activity at NASA Langley Research Center to develop multidisciplinary design procedures by accounting for discipline interactions, a performance design optimization procedure was developed. The procedure optimized the aerodynamic performance of rotor blades by selecting the point of taper initiation, root chord, taper ratio, and maximum twist which minimize hover horsepower while not degrading forward flight performance. Satisfactory aerodynamic performance was defined by the following requirements which must hold for any flight condition: the required horsepower must be less than the available horsepower; avoid exceeding the section drag divergence Mach number on the advancing side of the rotor disc, avoid exceeding the maximum section lift coefficient on the retreating side of the rotor disc, the rotor blade must be trimmed, and a lower limit on the blade tip chord is imposed. The procedure used HOVT (a strip theory momentum analysis) to compute the horsepower required for hover and the comprehensive helicopter analysis program CAMRAD to compute the horsepower required for forward flight and maneuver. The hover analysis was performed using nonuniform inflow without a wake model. The forward flight analysis was performed using both uniform and nonuniform inflow models. The optimization algorithm consisted of the general purpose optimization program CONMIN and approximate analyses. Sensitivity analyses consisting of derivatives of the objective function and constraints were carried out by forward finite differences.

The procedure was applied to a test problem which is a CAMRAD model of a wind tunnel model of a utility rotor blade. The procedure was able to obtain designs requiring less hover horsepower than the reference blade for the given flight conditions (this was to be expected since the given flight conditions were less strigent than those to which the reference blade was originally designed). However, the optimum blade was closer to blade stall than the reference blade. A study was performed to assess the effect of including a wake in the forward flight analysis on the optimum design. This effect depended on which starting point was used for the optimization process. When the reference blade was used as the starting point, the major effect was on the point of taper initiation. The optimum design based on wake analysis moved the point of taper initiation further outboard than the optimum design with no wake which moves the point of taper initiation inboard of the reference blade. Inclusion of a wake analysis increased the predicted horsepower required by the blade. When the rectangular blade was used as the starting point, including a wake resulted in larger pretwist, less taper, and a slightly larger root chord. The point of taper initiation was about the same. From these results it was seen that wakes could not be neglected in the design process. It was also apparent from the above results that there is a need for further investigations into the effects of including wakes to account for the different trends based on initial starting points for the designs.

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Table 1 - Results for optimization of model rotor blade:
       HOVT - nonuniform inflow;
       CAMRAD - uniform inflow

	Reference blade as initial design		Rectangular blade as initial design	
	INITIAL	OPTIMUM	INITIAL	OPTIMUM
Twist (deg)	-16.0	-14.6	-9.0	-15.0
Taper initiation (in)	45.0	27.0	-	29.2
Taper ratio	3.0	2.8	1.0	1.7
Root chord (in)	5.4	4.3	5.4	3.6
Hover Hp	11.98	11.20	12.56	11.21
Forward flight HP	9.17	8.16	9.41	8.21
Maneuver HP	10.07	10.59	10.36	11.24

Table 2 - Results for optimization of model rotor blade:
       HOVT - Nonuniform inflow;
       CAMRAD - nonuniform inflow (rigid wake)

	Reference blade as starting point		Rectangular blade as starting point	
	INITIAL	OPTIMUM	INITIAL	OPTIMUM
Twist (deg)	-16.0	-15.2	-9.0	-17.2
Taper initiation (in)	45.0	48.3	-	30.4
Taper ratio	3.0	2.4	1.0	1.33
Root chord (in)	5.4	3.7	5.4	3.84
Hover HP	11.98	11.42	12.56	11.43
Forward flight HP	9.74	8.79	9.66	8.95
Maneuver HP	10.89	10.82	10.57	10.8

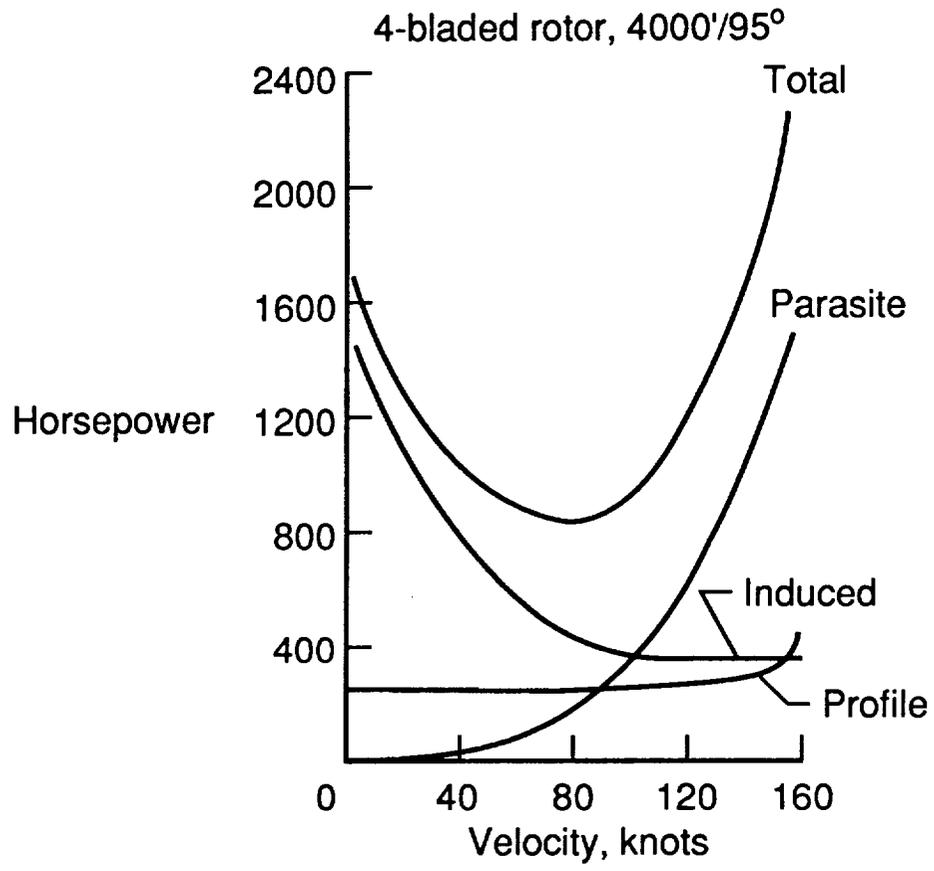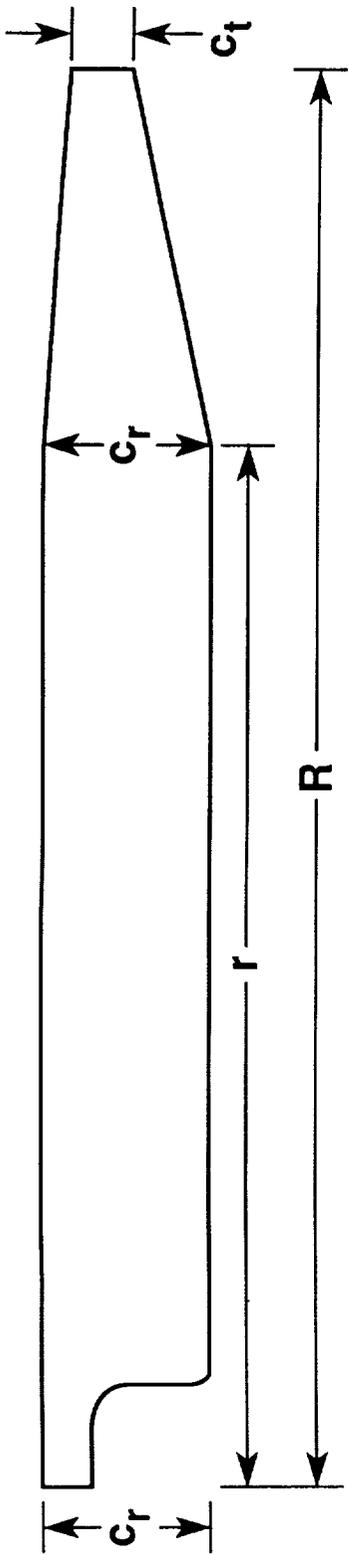**Figure 1. Power required as a function of velocity.**

Point of taper initiation r/R
Root chord c_r
Taper ratio c_r/c_t
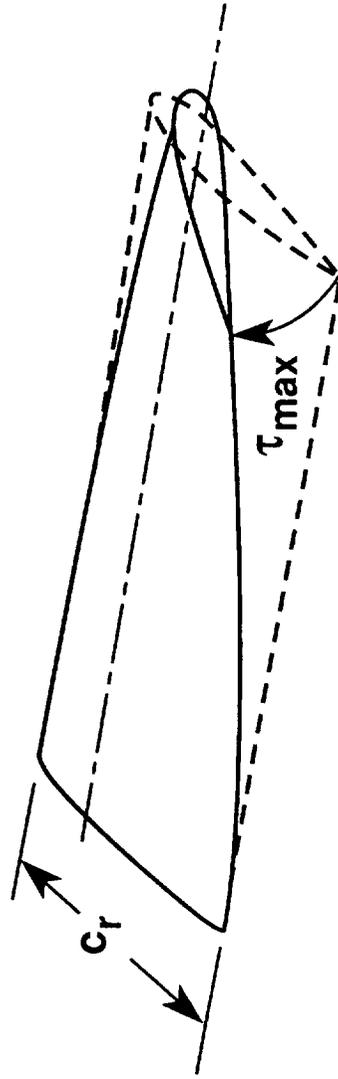Maximum pretwist τ_{max}
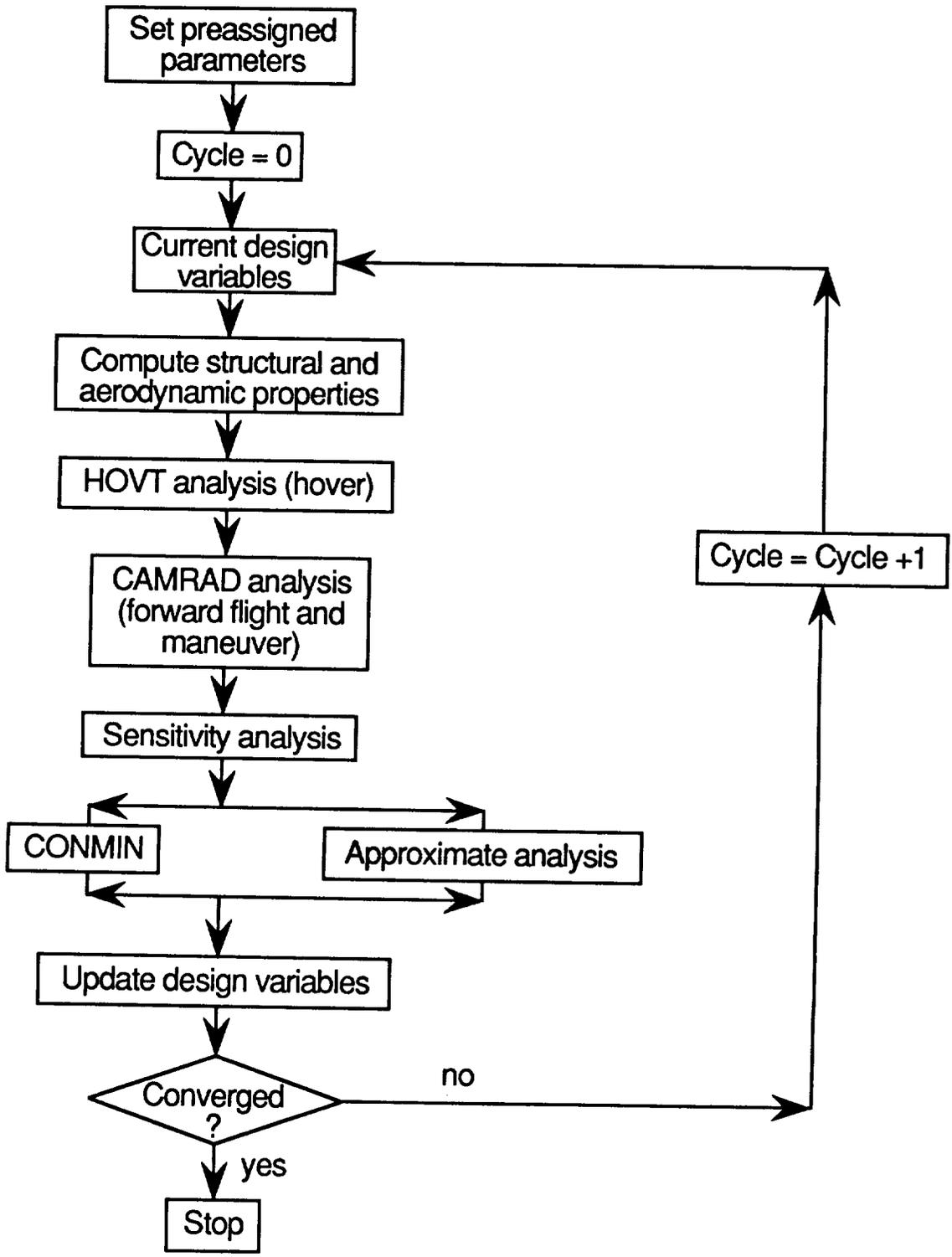
Figure 2. Rotor blade design variables.

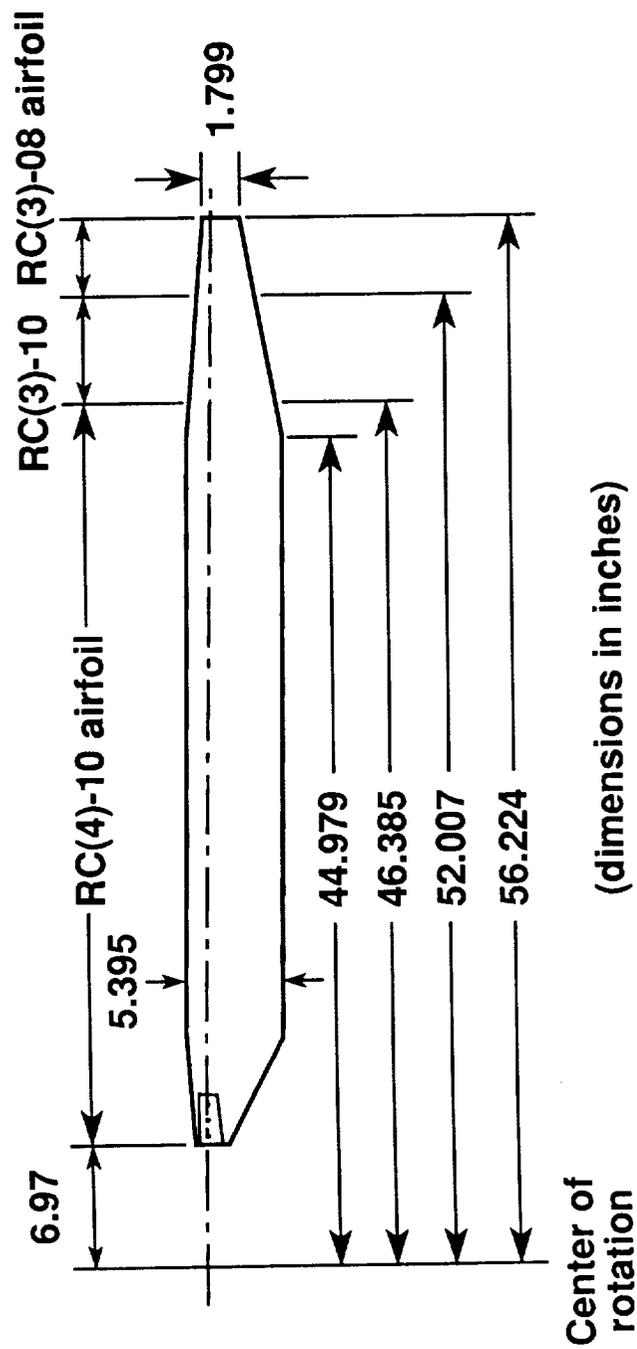**Figure 3.** Optimization procedure flow chart.

Figure 4. Rotor blade model.

Figure 5. Performance of an rotor blade designed for minimum hover horsepower at various flight speeds (nonuniform inflow for hover and uniform inflow for forward flight).
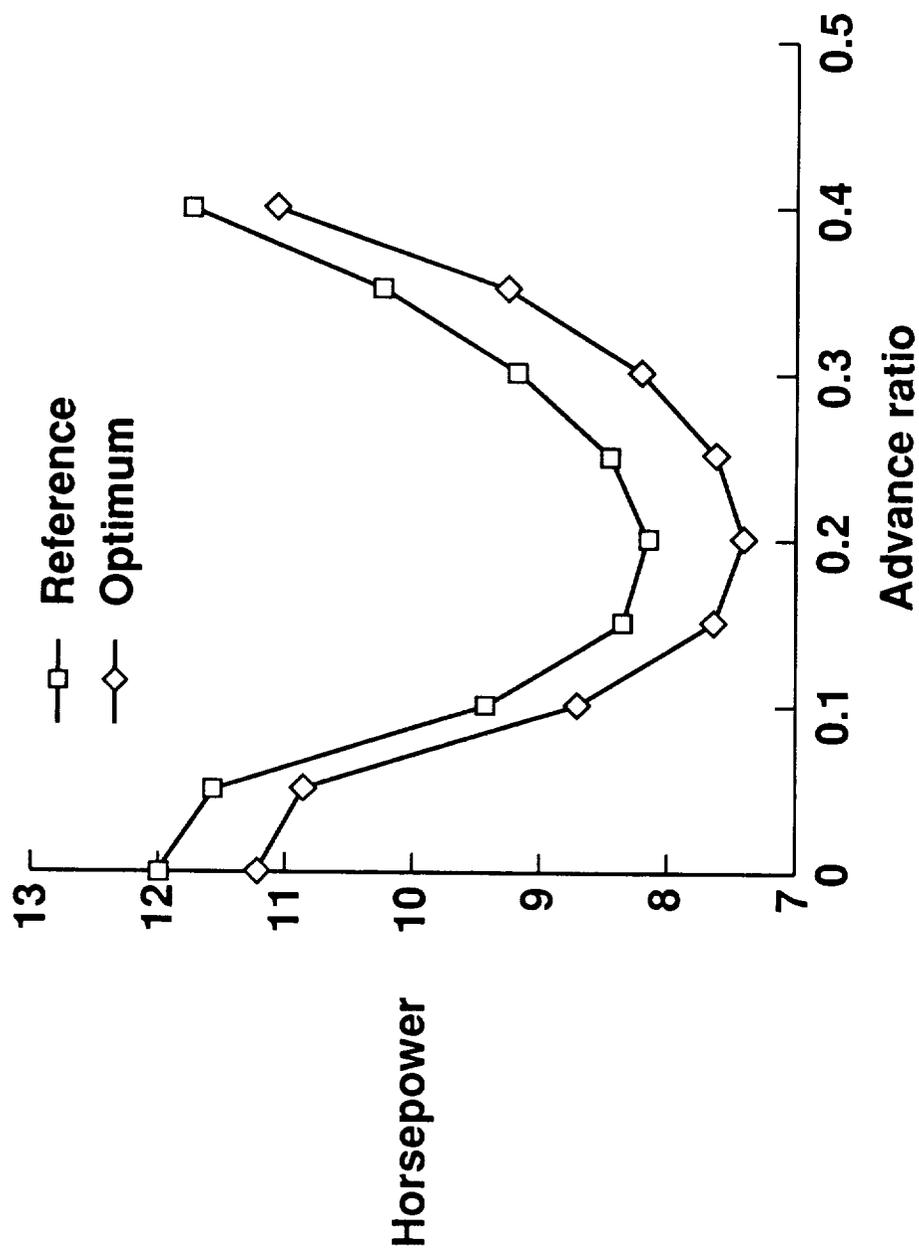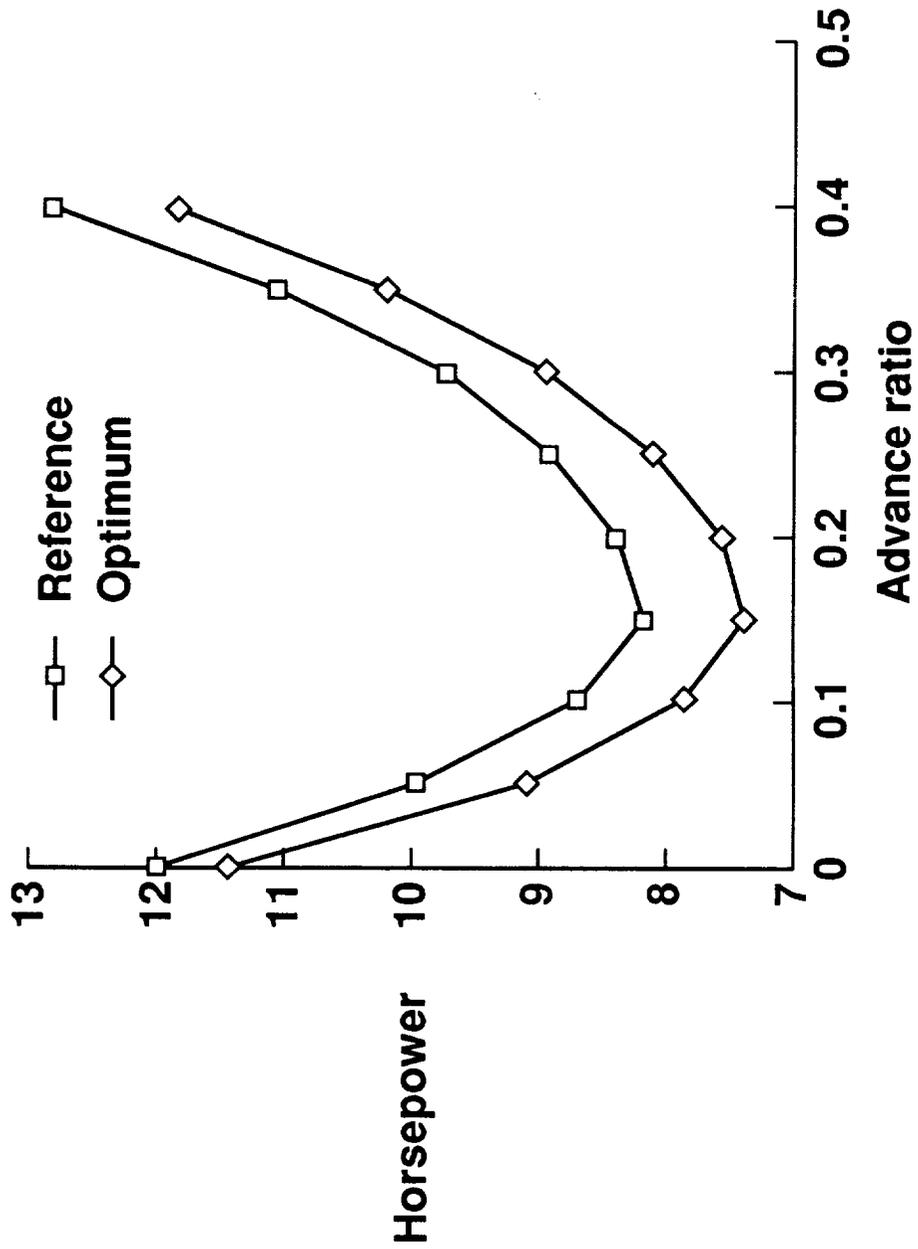
Figure 6. Performance of an rotor blade designed for minimum hover horsepower at various flight speeds (nonuniform inflow for hover and nonuniform inflow for forward flight).

	Reference blade	Optimum blade design (no forward flight wake)	Optimum blade design (forward flight wake)
Twist (deg)	-16.0	-14.6	-15.2
Taper initiation (in.)	45.0	27.6	48.3
Taper ratio	3.0	2.8	2.4
Root chord (in.)	5.4	4.3	3.7
Hover HP	11.98	11.20	11.42
Forward flight HP	9.17* (9.74)**	8.15	8.79
Maneuver HP	10.07* (10.89)**	10.59	10.82
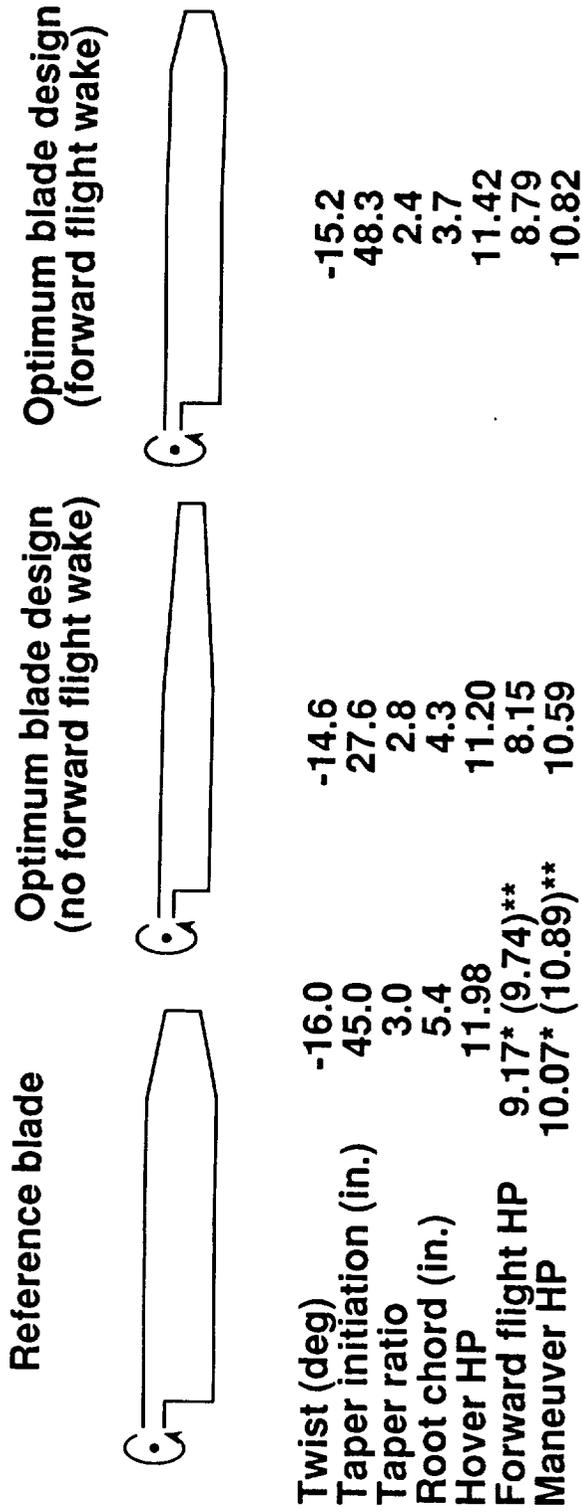
* Uniform inflow calculation
** Rigid wake calculation

Figure 7. Effect of forward flight wake on optimum blade design obtained from reference blade starting point.

	Reference blade	Optimum blade design (no forward flight wake)	Optimum blade design (forward flight wake)
Twist (deg)	-16.0	-15.0	-17.2
Taper initiation (in.)	45.0	29.2	30.4
Taper ratio	3.0	1.70	1.33
Root chord (in.)	5.4	3.6	3.84
Hover HP	11.98	11.21	11.43
Forward flight HP	9.17* (9.74)**	8.21	8.95
Maneuver HP	10.07* (10.89)**	11.24	10.8
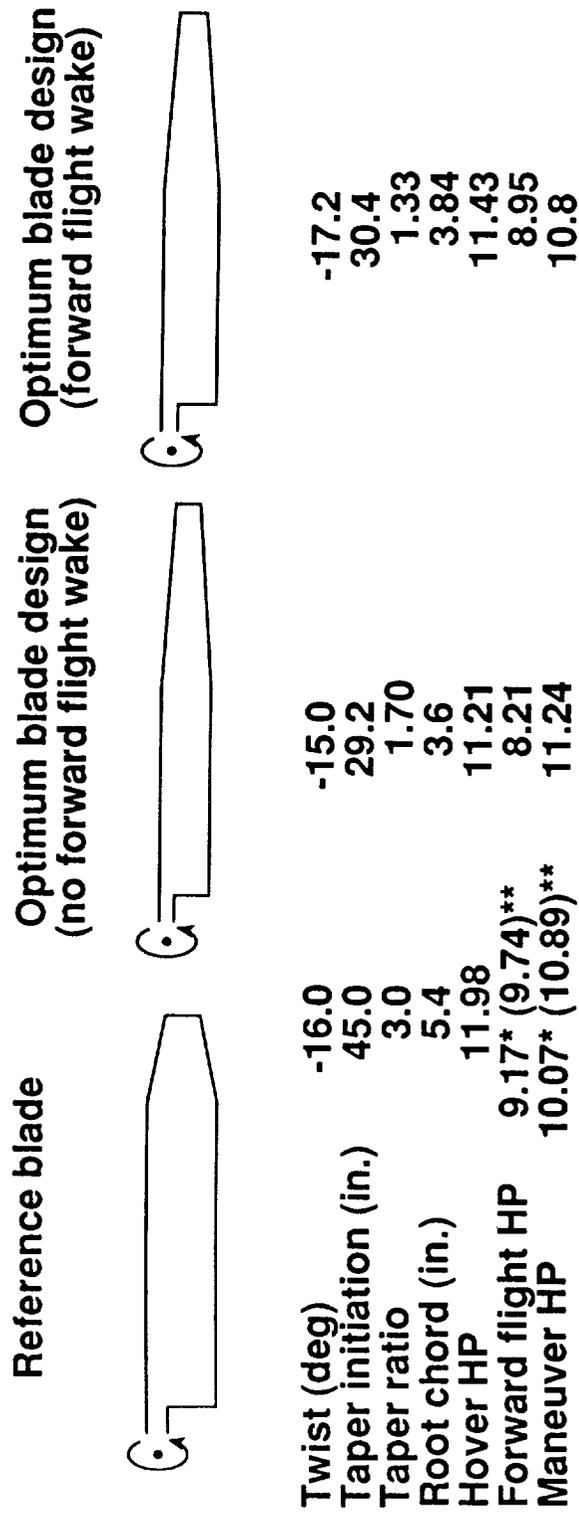
* Uniform inflow calculation
** Rigid wake calculation

Figure 8. Effect of forward flight wake on optimum blade design obtained from rectangular blade starting point.

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16. Abstract

As part of a center-wide activity at NASA Langley Research Center to develop multidisciplinary design procedures by accounting for discipline interactions, a performance design optimization procedure is developed. The procedure optimizes the aerodynamic performance of rotor blades by selecting the point of taper initiation, root chord, taper ratio, and maximum twist which minimize hover horsepower while not degrading forward flight performance. The procedure uses HOVT (a strip theory momentum analysis) to compute the horse power required for hover and the comprehensive helicopter analysis program CAMRAD to compute the horsepower required for forward flight and maneuver. The optimization algorithm consists of the general purpose optimization program CONMIN and approximate analyses. Sensitivity analyses consisting of derivatives of the objective function and constraints are carried out by forward finite differences. The procedure is applied to a test problem which is an analytical model of a wind tunnel model of a utility rotor blade.

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