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ROTOR DESIGN FOR MANEUVER PERFORMANCE

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A method of determining the sensitivity of helicopter maneuver performance to changes in basic rotor design parameters is developed. Maneuver performance is measured by the time required, based on a simplified rotor/helicopter performance model, to perform a series of specified maneuvers. This method identifies parameter values which result in minimum time quickly because of the inherent simplicity of the rotor performance model used. For the specific case studied, this method predicts that the minimum time required is obtained with a low disk loading and a relatively high rotor solidity. The method was developed as part of the winning design effort for the American Helicopter Society student design competition for 1984/1985.

1. Introduction:

The driving question asked during the preliminary design of a rotorcraft is: "How well will a design perform the required mission?" To answer this question the designer must identify a measure of the success of the mission. This measure must be predicted during preliminary design to determine the relative merit of one proposed design when compared to another. The configuration of a new rotorcraft is determined by some method of optimizing the predicted measure of success. The predictive method must be sensitive to changes in the basic parameters controlled by the designer.

In the fall of 1984 the American Helicopter Society released the requirements for its annual Student Design Competition; a one man rotary wing racer. This study was developed as a part of the response to that competition (reference 1). The design requirement from that competition will be used as an illustrative example, however, the concept is more general and can be applied to any maneuvering requirement.

The obvious implication of designing a "racing" rotorcraft is that it must win a race by completing the required course in a minimum amount of time. This is then the objective to be met in the design process. The race course must be included in the analysis procedure to insure that the design is influenced not only by top speed, but by all phases of the race. The course specified in the AHS requirements consisted of a triangular course totaling 5 kilometers in length (figure 1). The race was to be started from a hover (out of ground effect), followed by twenty laps of the course, to be flown in the counter-clockwise direction. Although weight of the vehicle was constrained to be less than 500 Kilograms, the design process was more than strictly an exercise in weight minimization. The lightest design did not necessarily insure a racer that would finish first. The use of a compound or variable geometry (tilt wing) helicopter may result in a higher top speed rotorcraft, but it is not clear that a higher top speed rotorcraft will be able to finish

the race before a conventional single main rotor, single tail rotor helicopter. To answer this question a method of predicting the time required to complete the course was needed. Time required became the critical measure of the performance of this design:

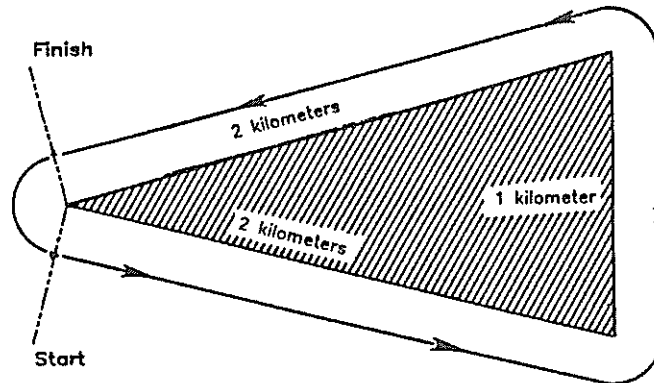


Figure 1. Course specified in AHS/Vertol competition

2. Method:

To compute the time required to fly the specified race, the entire course sequence must be analysed. Since the course starts from hover, hovering capability is required, but the duration of hover is unspecified. For design purposes, the ability to hover was only used as a constraint in the process. From the start of the race the craft must be able to accelerate from hover to a stable forward flight, and then to turn through three corners for each of twenty laps. The ability of a rotorcraft to change its speed and direction is related directly to the ability of the rotor to produce accelerations and is referred to as maneuver ability. The ability of a rotor to produce accelerations and decelerations must be related to design parameters. The rotor design parameters for the present study are: gross weight; rotor disk loading (related through gross weight to rotor radius); rotor solidity (related to blade chord, radius, and number of blades); fuselage equivalent flat plate drag area; horsepower available to the rotor; and tip speed. When rotor thrust and forward velocity are specified, these design parameters determine the rotor torque.

By evaluating simplified relations based on momentum equations and linear aerodynamics, these rotor design parameters are used to predict a relation between thrust and power required. Additional relations are needed to relate accelerations to thrust and power at different forward speeds. A basic concern in using the momentum prediction methods is that of rotor behavior at limit thrust. As a rotor system approaches limiting thrust (excessive power required to maintain RPM), significant portions of the rotor disk area operate near or beyond stall. Prediction methods based on momentum theory and linear aerodynamics do not predict this behavior well, and it is necessary to use empirical relations or use a much more sophisticated aerodynamic theory. A maximum value of thrust coefficient over solidity is related to rotor forward speed ratio in references 2 and 3. Both of these references indicate a loss of maximum thrust with increasing forward speed.

The method used here assumes that during a maneuvering course the rotorcraft will be constantly using its excess power to accelerate, decelerate, or turn. The major variable during negotiation of the course will be the current speed of the rotorcraft. The method first establishes an internal table of maximum possible accelerations for the entire speed range of the rotorcraft. Three accelerations are computed for each speed; forward (limited by maximum thrust coefficient over solidity, or limit horsepower); rearward (limited only by maximum thrust coefficient over solidity); and lateral (limited also by maximum thrust coefficient over solidity). In this table the times required to accelerate from hover to the current speed and decelerate from the current speed are stored. The distances required for the acceleration from hover and deceleration to hover are also stored in this table.

Once the values for accelerations, times, and distances are stored, this information is applied to the specific mission profile (race course). The profile of the flight path must be specified to make the analysis of the mission complete and to compute the required flight time. This specification may seem arbitrary, but, if the pilot chooses to turn sharply he must reduce his turn entry speed. If the speed into the turn is not reduced, wide turns result. In applying the maneuvering characteristics of the specific design to the mission in this study one flight path variable, turning speed/radius, was chosen. This variable became a design parameter.

The flight profile used in the maneuver prediction method is shown in figure 1. The assumptions made for the flight profile are: (1) the flight is level (no altitude variations); (2) turns are made at a constant rate (only lateral acceleration during the turn, constant speed); (3) at the midpoint of the turn, the rotorcraft will be directly over the corner of the course; (4) the rotorcraft will accelerate out of each turn until beginning its deceleration for next turn. Although this may not be the fastest profile for the course, it evaluates the effect of design parameter variation. Faster methods of negotiating the course may involve variable rate turns; or altitude variations which are not allowed in the flight profile used in this study. The design optimized for this course profile is provided to a clever pilot to find the best flight path.

The method was coded to take the table of accelerations, times, and distances computed from the design parameters and to compute the required course times based on a desired turn velocity. From the turn velocity the turning acceleration is obtained (from the internal table) and from the turn acceleration, the turn radius is computed. Knowing the turn radius and the geometry of the course, the lengths of the straight portions of the course are computed. In the straight portion of the course the rotorcraft is required to accelerate to the point where deceleration must begin to allow entrance into the subsequent turn at the required turn velocity. By starting with the speed through the turn, the acceleration lengths stored in the table are used to compute the distances required for the acceleration/deceleration along the straight portion. This combined acceleration/deceleration length is adjusted by finding the highest speed above the turn speed where the combined length fits between the turns.

For the specific course used in this study, nineteen of the laps around the course are identical. The times in each of the turns and

acceleration/deceleration portions of one complete lap were summed and weighted by nineteen. There only remains a two turn, short straight leg portion with the beginning and ending long straight portions to compute. The two turns and the short straight leg portion time is known from the similar laps. The start and end portions are computed in a straightforward manner. If the length required in the starting leg is not sufficient for the rotorcraft to reach the desired turning velocity (determined by table lookup), then this portion of the code returns for a new turning velocity. If the length required in the starting leg is more than that required to reach the turning velocity, the difference in lengths is handled like an acceleration/deceleration leg. For the final segment the rotorcraft is accelerated across the finish line. Times for all legs are summed up and the required time is returned from the course specific routine.

The method is constructed in loops to allow interactive modification of the design parameters. A diagram of the method is shown in figure 2. The code is assembled in modules to allow modification and testing. The inclusion of a more sophisticated aerodynamic model, perhaps based on combined blade element and momentum, would be a logical extension, but such an extension would require more computation time.

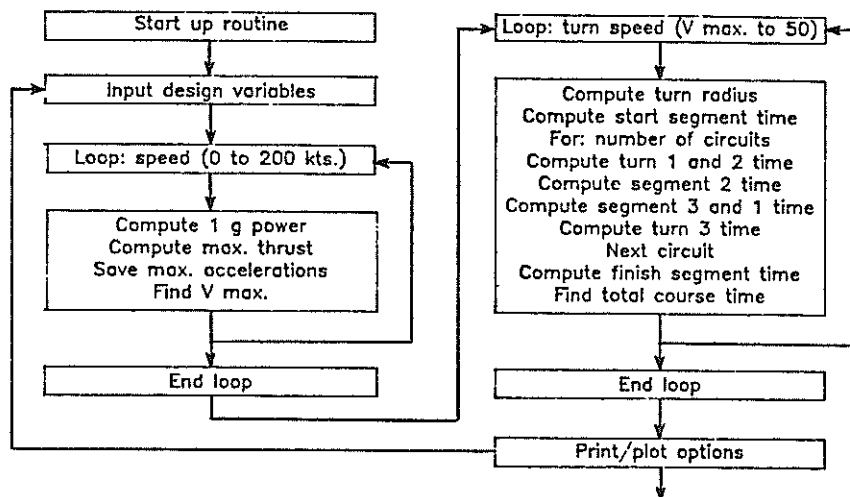


Figure 2. Block diagram of computational method

3. Results:

The computation of the speed table also included the predicted power required for 1-g level flight. For the maneuvering course proposed, this value was used to determine the maximum level speed. Although not checked rigorously against other predictive methods or experimental data, the character of the 1-g curve is reasonable. A representative case is shown in figure 3.

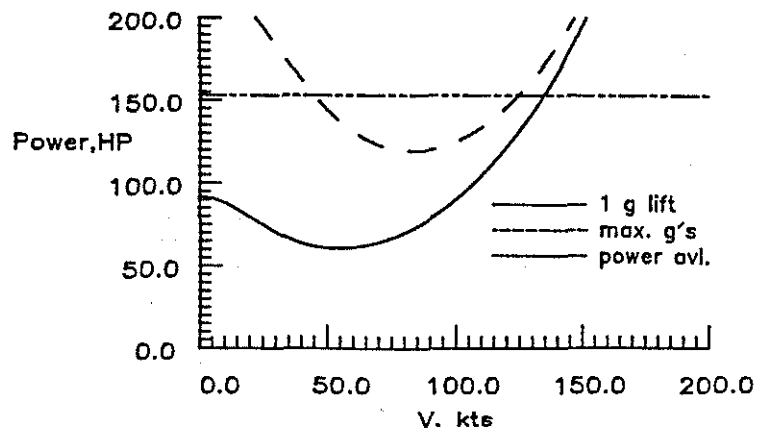


Figure 3. Power required in forward flight.

The method begins by taking the input design and computing the internal table described above. The method then computes course times required for a range of turn speeds. The times resulting from this variation in turn speeds are shown in figure 4. This figure shows a reduction in time required as turn speed is increased up to a value where a sharp rise in course time is experienced. This speed is found to be very close to the speed where there is no longer sufficient power to sustain 1-g level flight.

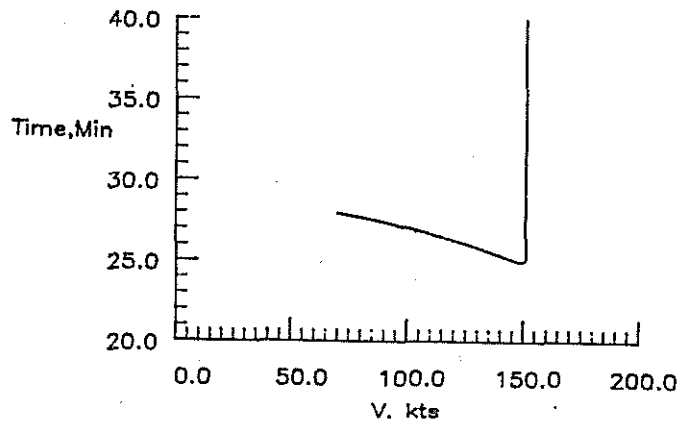


Figure 4. Times required for varying turn speed

The method is set to loop through the turn speed values and find the turn speed for the minimum required time to complete the course. By including this loop in the method, the turn speed variable is eliminated from consideration as a design variable. When the resulting flight path is plotted, figure 5, it is seen that the course path has practically eliminated the short straight segment of the course. This segment has been reduced by increasing the first and second turn radii until these two turns are almost merged. This flight path effectively eliminates one of the three required turns. Further results are all based on the optimum turn speed.

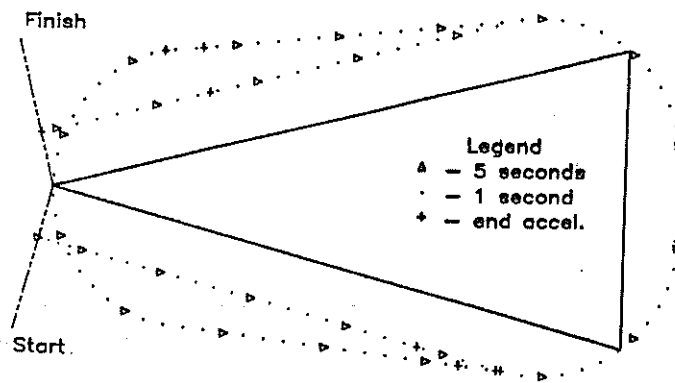


Figure 5. Resulting course path.

The results of evaluating the effect of variation of each of the design parameter inputs on the resulting time required are shown in figure 6. Varying some of the design parameters showed a monotonic relation between the value of the design variable and the time required to complete the course. Other variables are observed to have definite minima over the range studied. The most sensitive of these parameters seems to be rotor solidity.

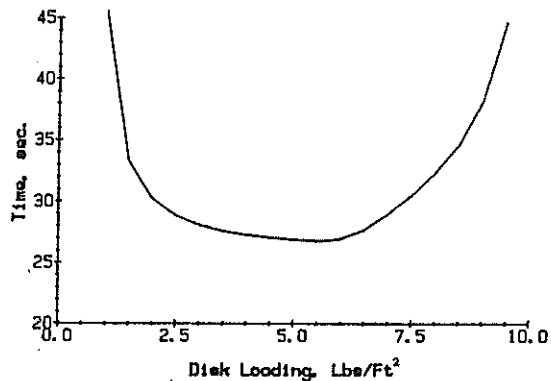


Figure 6. Effect of parametric variation on course time.
(a) Disk loading

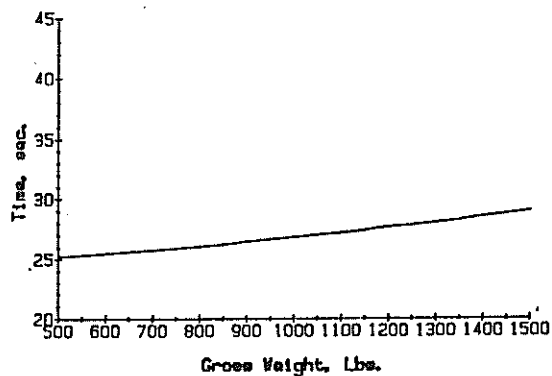


Figure 6 (b) Gross weight

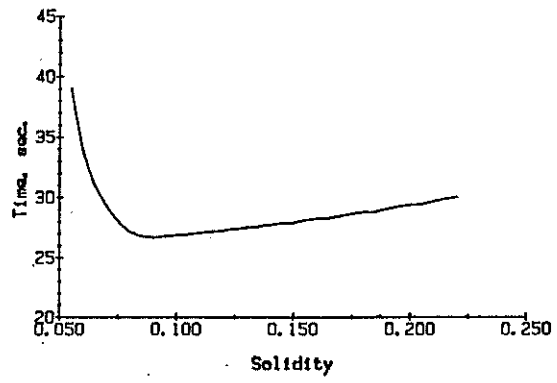


Figure 6 (c) Solidity

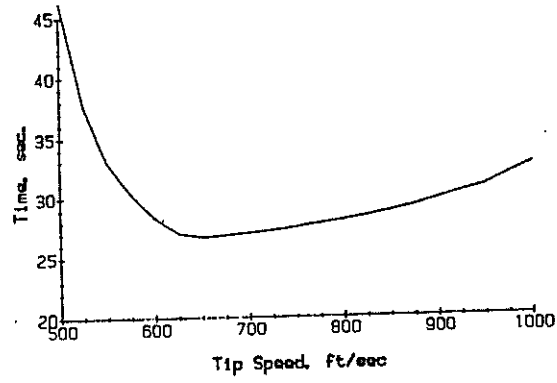


Figure 6 (d) Tip speed

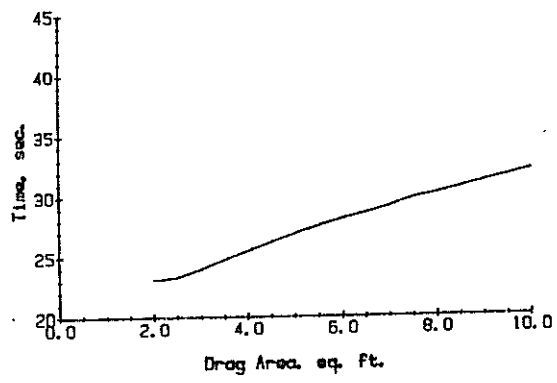


Figure 6 (e) Equivalent drag area

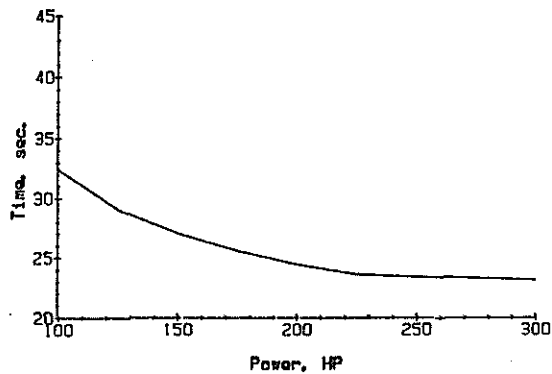


Figure 6 (f) Power available

Monotonic design variables must be established by considerations other than analysis of maneuvering capability. The fuselage equivalent flat plate drag area, for example, is derived by establishing the fuselage configuration and either estimating the component part drags, or by wind tunnel drag measurement. Those variables which result in a monotonic change in required time must be established prior to the actual evaluation of the remaining variables. This condition assures that evaluation of the remaining variables is conducted in the proper range for the other design variables.

Figure 7 shows the loci of solutions to the minimization problem when variation of the rotor disk loading and solidity are varied at a fixed tip speed. There exists a subtle minima in the disk loading variation when coupled with the optimized solidity (between disk loadings of 2.0 and 2.5). Figure 8 shows the loci of solutions to the minimization problem when variation of the rotor tip speed and solidity are varied at a fixed rotor disk loading. The combination of these variations (figure 9) results in the "optimized" solution. The time required seems to vary monotonically with disk loading. The data evaluated by this method show that a low disk loading at a specific solidity result in the most favorable design for maneuverability.

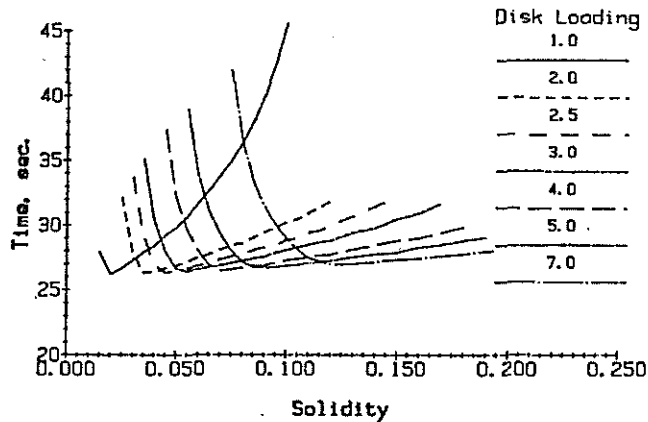


Figure 7. Effect of disk loading and solidity on course time

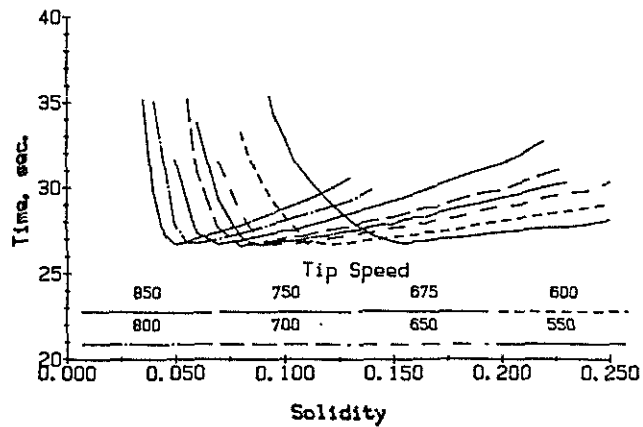


Figure 8. Effect of tip speed and solidity on course time

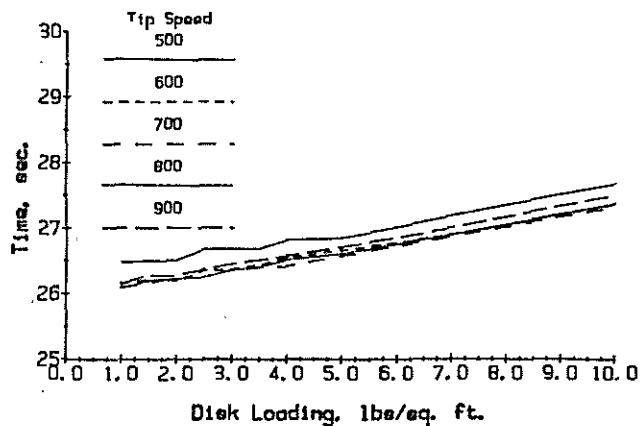


Figure 9. Combined effect of disk loading and tip speed.

The variation of course time with respect to tip speed is, perhaps, misleading. The effect of tip speed on a helicopter cannot be understood through the momentum considerations presented here alone. Mach drag divergence on the advancing side of the disk, and reverse flow on the retreating side of the disk are not modeled by this method. Both are serious considerations, and variation within the scope of this method was restricted to "safe" tip speeds. Safe tip speeds are those which minimize the effects of Mach drag rise and reverse flow, generally between 600 and 800 feet per second.

The values of solidity for optimal course performance can be compared with values of actual helicopters on the basis of disk loading. Data obtained from reference 4 are shown along with the loci from figure 7. For the disk loadings studied, the values of solidity which led to optimal performance in race course time are higher than those used in actual helicopters. This result may occur due to the lack of payload weight in design, and/or the minimal effect of the hovering criteria.

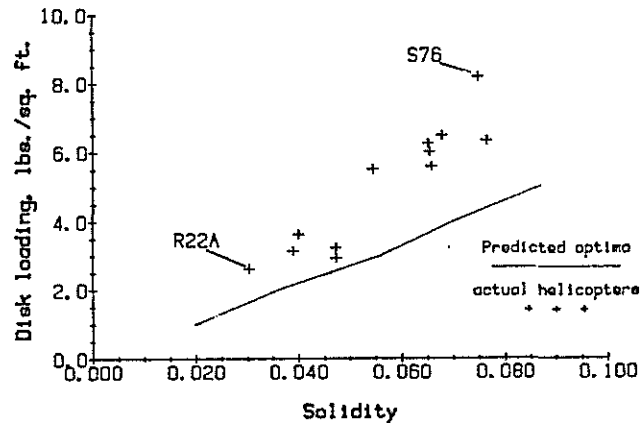


Figure 10. Comparison with actual helicopters

4. Discussion:

The method of predicting the maneuvering performance of rotorcraft based on a momentum/linear aerodynamic model for a single rotor helicopter has been described. Within these limitations the variation of basic rotor parameters such as thrust, tip speed, disk loading, solidity, fuselage drag, and power available was related to the time required to complete a maneuvering course. For a specific set of requirements, a design solution was formed based on minimizing the time required to complete the course.

Other considerations were formulated in determining the design solution. Alternate rotorcraft configurations were considered to determine their effect on the required mission. Configurations eliminating the counter-torque tail rotor in favor of using a thrust producing counter-torque device such as counter-rotating main rotors, or an offset propeller were considered. In the specific case of the AHS requirements, the weight margin available to absorb the added control complexity offset any performance gains. Another consideration was the addition of a fixed aerodynamic lifting surface. The efficiency of a fixed lifting surface can be optimized if its attitude relative to the oncoming flow can be controlled. If this is not possible, then it is significantly less efficient than a lightly loaded rotor. The complexity in controlling a fixed lifting surface through the range of speeds expected in this role, again, violated weight constraints.

5. Conclusions:

The method of relating design parameters to maneuvering performance is based on evaluation of the times required to complete a set of prescribed maneuvers. The time required is directly related to the capability of a vehicle to accelerate. For the course described in this study, the evaluation of the design parameters indicates that a low disk loading and a relatively high solidity will minimize the time required to complete the course. The relationship of disk loading and rotor solidity was found to be critical to minimizing the time.

6. References:

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