# Design of a Slowed-Rotor Compound Helicopter for Future Joint Service Missions

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**Abstract**
A slowed-rotor compound helicopter has been synthesized using the NASA Design and Analysis of Rotorcraft (NDARC) conceptual design software. An overview of the design process and the capabilities of NDARC are presented. The benefits of trading rotor speed, wing-rotor lift share, and trim strategies are presented for an example set of sizing conditions and missions.

## NOMENCLATURE

**Acronyms**

| | |
|---|---|
| DGW | Design Gross Weight |
| GW | Gross Weight |
| HOGE | Hover out of Ground Effect |
| IRP | Intermediate rated power |
| ISA | International Standard Atmosphere |
| MCP | Maximum continuous power |
| MRP | Maximum rated power |
| MTOW | Maximum Takeoff Weight |
| NDARC | NASA Design and Analysis of Rotorcraft |
| SFC | Specific fuel consumption |
| SRC | Slowed-Rotor Compound |

**Symbols**

| | |
|---|---|
| $\sigma$ | Rotor solidity (geometric) |
| $C_D$ | Drag coefficient |
| $C_L$ | Lift Coefficient |
| $C_T$ | Rotor thrust coefficient |
| $C_W$ | Weight coefficient |
| k | 1,000 feet of elevation |

## INTRODUCTION

A compound helicopter is a helicopter that incorporates an auxiliary propulsor for forward thrust and/or a wing for auxiliary lift. By compounding the rotor, the rotor may be offloaded at higher speeds, with advantages in reduced power and potentially reduced loading on the rotor dynamic components. A compound helicopter typically achieves higher speed, better cruise efficiency, and can operate at higher altitudes. The wing can also provide a convenient mounting location for external stores and improve the maneuver performance in forward flight. Typically, compound helicopters pay penalties in hover performance due to increased download and power losses associated with the auxiliary propulsor, plus the extra weight of the propulsor and main wing. Operationally, the wing can be an issue for storage and transport, and can impede the egress of passengers in some circumstances.

For attack helicopter missions, compound helicopters such as the AH-56A Cheyenne (propulsor and wing) and S-67 Blackhawk (wing) have been developed in response to the perceived need for greater speed and range. For utility and troop transport missions, compounds such as the X-49A Speedhawk (propulsor and wing) have been developed. Other recent studies, such as Sikorsky's X2 demo (propulsor) have also centered on the compound helicopter configuration as potentially desirable.

For traditional helicopters, as true airspeed increases, advancing tip mach numbers become large and retreating blade stall occurs, leading to performance degradation and increased vibration. Slowing the rotor speed can alleviate this, albeit at the cost of reduced lifting capability and retreating blade stall. By unloading the rotor with a wing, the loss of rotor lifting capability is mitigated.

A study was undertaken to explore the factors affecting design of a slowed-rotor compound helicopter using a new rotorcraft design code, NASA Design and Analysis of Rotorcraft (NDARC, Ref. 1). A single main-rotor layout, with an anti-torque rotor, a pusher propeller and a wing, was synthesized and sized against a design mission and four design conditions.

*Presented at the American Helicopter Society Aeromechanics Specialist's Conference, San Francisco, CA, January 20-22, 2010.* 

Following the initial sizing of the aircraft with the simplified aerodynamic models of NDARC, main rotor analysis was performed with CAMRAD II, a comprehensive rotorcraft analysis tool. The comprehensive analysis results were used to find a compromise between hover and high speed flight performance and provide better estimates for rotor performance than the initial NDARC inputs. NDARC sizing was then repeated with the new parameters.

Off-design performance analyses were performed using NDARC to generate some fallout aircraft capability curves and to explore aircraft trim and performance characteristics. Using fallout hover ceiling capability calculated by NDARC and a separate climate modeling tool, hover performance was examined. A simple comparison was performed to examine how the slowed-rotor compound configuration fares when compared to historical transportation efficiency for helicopters and fixed wing aircraft.

## APPROACH

### NDARC

NDARC is a conceptual/preliminary design and analysis code for rapidly sizing and conducting performance analysis of new rotorcraft concepts, with frameworks for introducing multiple levels of fidelity. NDARC is written in Fortran 90/95 and has a modular code base, facilitating its extension to new concepts and the implementation of new computational procedures. NDARC version 1.1 was used in this design activity.

NDARC has extensive documentation, both in a theory manual and in an input manual. There is an NDARC Serious Users Group (SUG), members of which test and periodically suggest modifications and improvements to the code. The SUG maintains a web-based Wiki, hosted by NASA, with reference documentation, tutorials, bug fixes, release notes, and some ancillary utility programs. The Wiki also serves as a location for hosting documents pertaining to the development of ancillary tools for NDARC.

A typical NDARC run consists of a sizing task, followed by off-design performance analysis. During the sizing process, point condition and mission performance are calculated and the aircraft is resized both geometrically and mechanically until the convergence criteria are met. NDARC runs, including sizing and performance analysis, typically are completed on the order of minutes on a desktop computer. Once a sizing task has been performed, further analysis of the configuration can be performed by taking the sized aircraft as input to NDARC in either another case (or cases) within the same job, or as input to a case in a new job.

NDARC provides default configurations and trim strategies for several common rotary wing configurations, including single main-rotor helicopters, tandem helicopters, coaxial helicopters, and tilt-rotors. In each of these default examples, trim strategies have been defined, providing a set of starting points for a design study. In the case of the compound, especially when rotor speed is also varied, there are many indeterminate trim strategies that can be developed, and it is up to the designer to develop trim strategies that will best use the various control effectors to achieve trimmed flight. NDARC performs trim analysis in each flight condition or mission segment. A variety of control effectors can be used to achieve trim. NDARC allows different control states (connections of pilot controls to component controls) to be defined and adjusted during trimming; further, a wide variety of parameters, such as gear ratios, rotor speeds, rotor diameter, etc., can be varied based upon pre-defined schedules. For indeterminate systems, such as a compound with redundant effectors, a strategy external to NDARC is needed to select a schedule for the redundant effectors. In this study, the schedules were selected to achieve minimum weight while retaining control margins.

NDARC is programmed with a large amount of run-time flexibility, including options to allow the designer to select solution procedures and specify starting point trim estimates. An example is the freedom to select secant, Golden Section, or some other user-coded solution procedure for finding maximum effort speeds, such as best range speed. For each flight condition or mission segment, the initial trim estimates may be input, or the case solution may be set to have all initial trim estimates use the last known trim state as the starting estimate. NDARC also provides the facility to output various solution parameters to a file during the run, allowing the user to trace convergence in sizing and trim. These diagnostic capabilities have proven to be valuable in exposing the underlying sources of convergence problems.

### CAMRAD II

NDARC implements simplified aerodynamic models for rotors and lifting surfaces. CAMRAD II is a tool for aeromechanical analysis of rotorcraft that incorporates a combination of advanced analytical and numerical methods, including multibody dynamics, nonlinear finite elements, and rotorcraft aerodynamics. The CAMRAD II aerodynamic model for the rotor blade is based on lifting-line theory using steady two-dimensional airfoil characteristics and a vortex wake model and capable of computational fluid dynamics/computational structural dynamics coupling. CAMRAD II wake analysis calculates the rotor nonuniform induced velocities using rigid, prescribed, or free wake geometry.

CAMRAD II was used to provide more accurate estimates of main-rotor performance, and to explore the design variables in the rotor geometry. The CAMRAD II estimates were then entered into NDARC for another round of sizing.

**Design Process**

In order to achieve an optimal and balanced design, a considerable amount of the designer's judgment must be used in the iterations. The flowchart in Figure 1 illustrates an overview of the design process. The dotted line encompasses the portions of the process that are performed during an NDARC execution. The thick solid box encompasses the changes that were made to the design between runs, in order to improve the overall aircraft, based upon the design objectives and constraints that NDARC does not consider. The list shown in the flowchart is not exclusive; other parameters were also modified, such as number of blades on each rotor to keep blade aspect ratios from becoming too low.

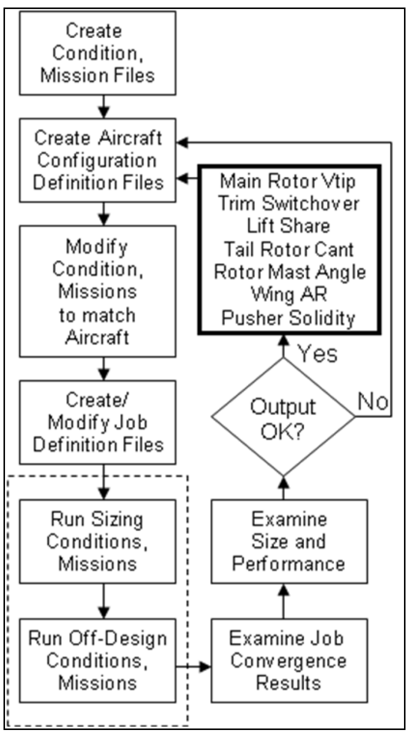


**Figure 1. Flow of the NDARC sizing activity**

**Design Goals**

The design goals for this study are to explore a specific aircraft configuration, a slowed-rotor compound helicopter, for a representative set of requirements, so the limitations and possibilities available with the configuration can be delineated. Because no single set of specific operational scenarios have been defined, a rather generic mission has been selected such that the final sized aircraft can perform many different missions and tasks, but is not optimized for any one type of mission. The sized aircraft, however, does perform many tasks and the model can be quickly converted to size an aircraft that is optimized for a specific mission or mission sets. Many of the processes and trades have been explored and documented for future studies.

The sizing process consisted of first establishing baseline requirements and objectives that could be used to drive a NDARC sizing exercise. The requirements were manifest in a set of performance conditions and a mission, along with targets for disk loadings and control strategies. Once the requirements and objectives were in place, an aircraft was synthesized that would have the features necessary to perform the sizing against. Finally, the aircraft was sized for the design conditions and missions and analyzed for off design performance.

## AIRCRAFT SYNTHESIS

Synthesis of the aircraft in this context means defining the configuration of the aircraft and setting sizing constraints and free variables. Synthesis establishes the number and relative placement of rotors, lifting surfaces, and bodies. The general topology of the drive system and the engine and airframe technology are also established. Operational trim strategies and schedules are also defined.

**General Configuration Synthesis**

The aircraft in this study is a single main-rotor helicopter with a tail (anti-torque) rotor placed at the rear. There is a small separation between the tail-rotor and the main-rotor. For the slowed-rotor compound, an existing helicopter definition was modified to have both a wing and an auxiliary propeller, with appropriate controls defined. A wing is located below and behind the main rotor, and a pusher propeller is located behind the tail rotor. A large fuselage has been accounted for, in order to provide for a substantial cargo or passenger capacity. The fuselage has been sized to seat approximately 9 passengers. For the design mission, an external payload of 5,000lb with 20 square feet of parasite drag area has been assumed to represent the carriage of external stores.

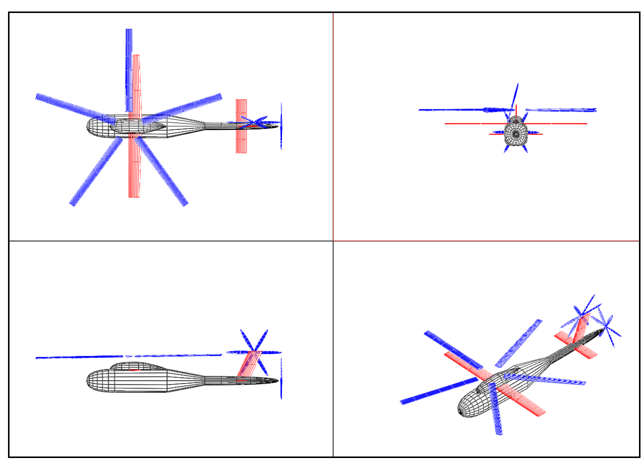

**Figure 2. Sketch of the compound helicopter**

**Component Synthesis**

*Fuselage*

The fuselage was sized to accommodate two crew and 9 passengers.

*Rotors*

The main-rotor dimensions were sized based upon disk loading, tip speed, and $C_W/\sigma$. Disk loading for the main rotor was set based upon experience with similar helicopters, and was also varied slightly between runs to adjust gross weight and rotor diameter. Final maximum disk loading was set to be 9.3lb/ft$^2$. Operational requirements for the helicopter will likely dictate the maximum disk loadings and diameters for various design conditions.

The forward tilt of the mast was varied in the design study, by adjusting the mast angle between runs. A separate control for mast tilt has been implemented in the NDARC aircraft definition, but was not used as a trim control in any point condition or mission segment. Particular attention was paid to the effects on gross weight and maximum speed when determining the mast angle for the main rotor. No lateral tilt has been used.

Main rotor pylon drag was estimated using a typical $C_D$ of 0.04 based on wetted area, with the pylon wetted area scaling with the weight of the drive system to the 2/3 power, which is a standard scaling option in NDARC.

The main rotor hub drag was specified as scaling with a $C_D$ specified as 0.0025 based on disk area. The value of the hub drag was compared to historical helicopter data, partly found in Reference 2. The hub drag is seen to follow the lower trend for hub drag as a function of Gross Weight (Figure 3), and to also trend with the lower drag hubs as a function of rotor diameter (Figure 4). The hub drag estimate could be lowered through the use of higher fidelity analysis/testing for substantiated estimates.

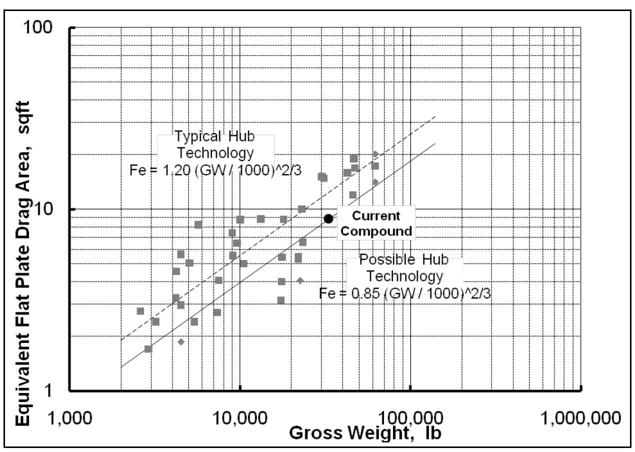


**Figure 3. Hub drag versus gross weight**

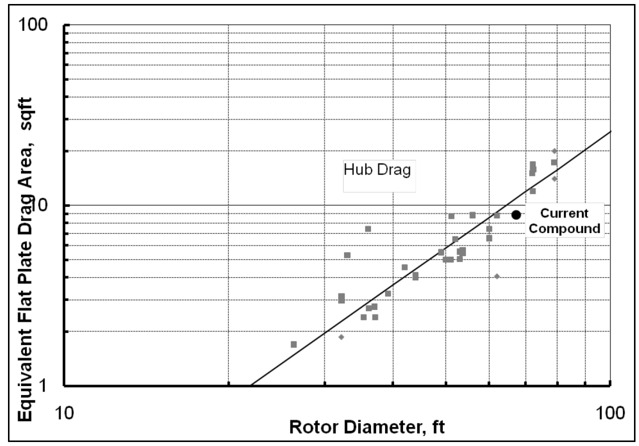


**Figure 4. Hub drag versus diameter**

The number of blades on each of the rotors was varied between runs in order to keep blade aspect ratios high as solidity was increased. An initial linear twist was assumed for each rotor. After an initial, converged NDARC design was found, CAMRAD II was used to optimize main rotor twist for a compromise between hover and cruise performance. A taper of 0.8 was assumed for the main rotor blades, with a root cutout area that extended to 15% radius by designer's choice in absence of a specific design.

NDARC allows the use of rotor tip speed schedules that vary with airspeed, and also direct-input tip speeds for each condition or segment. The gear ratio for each rotor is set by specifying a reference tip speed and using the engine definition rpm. In the case of the slowed-rotor compound in this study, there was only one gear specified, so as the main rotor was slowed to a fraction of its reference tip speed, the engines, tail rotor, and pusher were all slowed by the same fraction of their reference speeds.

The tail rotor is used to both supply a lateral anti-torque force and to provide some additional lift by virtue of its (fixed) cant angle. There is only collective control of the tail rotor. The disk loading for the tail rotor was specified as 13lb/ft$^2$, based upon typical single main rotor helicopter experience and the desire to keep the tail rotor diameter from growing too large. Twist on the tail rotor has not been examined yet, and should be determined as the result of detailed analysis. The hub drag for the tail rotor was specified as a drag coefficient of 0.0100, in line with typical tail rotors. The number of blades on the tail rotor were varied, eventually arriving at 6 blades as solidity was increased during sizing. The speed ratio for the tail rotor was set by setting the hover tip speed to 725ft/s. Solidity was found based upon specification of the design $C_T/\sigma$ = 0.11 for the 12K/ISA hover flight condition. NDARC uses the "design thrust" sizing condition to set solidity.

The tail rotor cant angle was specified for a given sizing execution, with specific attention paid to reducing vehicle weight and keeping the tail rotor diameter from growing too large.

The pusher rotor radius, tip speed and solidity were directly specified. Specifying the values in this way allows the designer to selectively vary the $C_T/\sigma$ for the high speed condition independently.

Pusher rotor hub drag coefficient has been assumed to be 0.0100, the same as the tail rotor. The speed ratio of the pusher relative to the main rotor was fixed manually for each run, in order to keep the tip speed below a helical Mach number of 0.90 to keep the tip airfoils below the drag divergence Mach number at the 200ktas high speed design point, but still high enough that the pusher $C_T/\sigma$ was below blade stall. This process can be made more rigorous by specifying a $C_T/\sigma$ value as a sizing criterion.

A relatively high solidity of 0.2 was selected for the pusher rotor in order to keep tip speeds and rotor diameter lower. The number of blades was set to 6 blades to keep the blade aspect ratio higher. A highly twisted blade should be used for the pusher. Twist on the pusher rotor has not been defined, and should be determined as the result of detailed analysis. Potentially declutching the pusher in hover and compound mode would allow greater twist to be used without a penalty from profile drag in those flight control modes.

*Wing-Rotor Lift Share*

For wing and rotor lift share, a fixed incidence was used in the compound trim state, and a target lift coefficient used for high-speed compound trim state. This allows the designer to see which lift coefficient results in the best aircraft (perhaps lowest DGW), and see what range of incidences are required to achieve that. Then the designer can choose to make the trade between variable incidence and variable flaperon as methods to achieve the desired trim state. A fixed value of the wing lift could also be a target, but lift coefficient was chosen because it is likely to be fixed or nearly fixed for varying speed once the rotor wake is not impinging on it, and the lift coefficient implies a maneuver margin that is available to the wing relative to level un-accelerated flight trim.

The wing aspect ratio was fixed for each run, and adjusted to yield the lowest design gross weight. In a more detailed analysis, the effect of wing lift on rotor loads can be used to potentially reduce rotor component weights. NDARC does not have that level of fidelity, and this trade was not examined in the current design study.

Wing loading is defined by assuming a fraction of gross weight and then calculating the required planform area of the wing. For a compound, where the trim settings determine the lift carried by the rotor, the wing lift fraction must be iteratively converged to make the design wing loading meaningful. In absence of this iterative process, the actual wing loading must be calculated manually, based on the trim condition. The lift fraction for the compound was adjusted by setting a target lift coefficient for the main wing in high-speed compound trim mode. The wing incidence is scheduled to be driven by a target lift coefficient in high speed cruise mode, and is fixed otherwise.

The wing has full span flaperons. The flaperons have not been used in this study, and have always been left undeflected in all analysis. It may be beneficial, depending on the mission set and structural design, to use flaperons rather than variable wing incidence for trim, and the flaperons acting as ailerons can also be used to maintain level roll attitude, whereas the current trim strategy uses roll attitude to balance out the rotor hub moment, tail rotor offset torque, and pusher torque about the longitudinal axis.

*Propulsion*

The compound helicopter uses two identical engines in a single engine group. NDARC has, as part of its base package, a referred parameter turboshaft engine model. The engine in this study was a nominal 3,000 shaft horsepower turboshaft that represents notional 2015 year performance, based upon funded research and development plans. For the current design study, the engines were never operated above 100% of their reference speed.

The transmission takes input from the two engines and distributes power to the main rotor, tail rotor, and pusher. A constant accessory power of 60hp is also taken out at the transmission.

The topology of the propulsion group is shown schematically in Figure 5. Shaft power limits are established for the engines and rotors based upon the sizing conditions and missions, and are checked when performing off-design analysis. Based upon the reference tip speed ratios for the various rotors, the gear ratios are calculated for each rotor and engine.

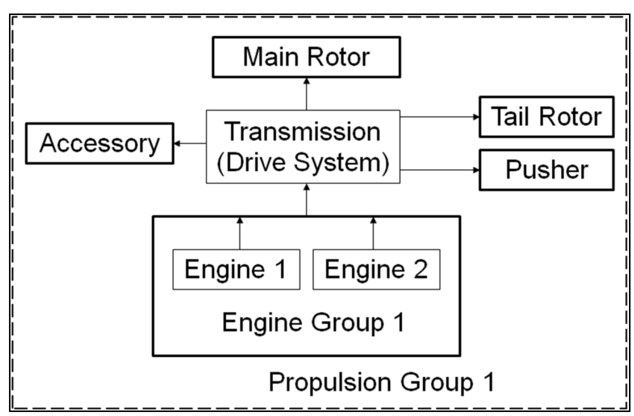


**Figure 5. Propulsion group topology**

Technology factors for the aircraft weights have been assumed. These tech factors are derived from a metal-skinned fuselage utility helicopter.

*Controls and Control Schemes*
NDARC uses a system for setting up controls whereby control variables are identified by name. These trim variables generally correspond to pilot inputs, but can be any definition. For each trim state, the control variables are mapped to a trim quantity. The trim quantities are free body forces, moments, and component forces or coefficients. For each control effector, a matrix is defined for each control state, mapping control variable input to effector output.

By using multiple trim states, an aircraft may vary control effectors used for different flight configurations. In the present design, trim states are used to vary the effectors used for trimming the vehicle, and varied by condition and mission segment.

By using multiple control states, the mapping of control variables may be varied as the aircraft configuration changes. For example, a tilt-rotor might use control states to change the mapping of rudder control variable input from the empennage rudder to the opposing longitudinal cyclic of the prop rotors as the nacelles tilt upwards.

The standard control schemes in NDARC for a helicopter configuration do not address the control effectors that are available in this compound configuration. Additionally, there is another degree of freedom allowed by the engine RPM, which can be used to slow the main rotor and delay compressibility effects, but which also slows the pusher propeller, increasing its $C_T/\sigma$ and bringing it closer to stall. Thus, a minimum power trim strategy may be a goal that is sought, beyond the force- and moment- balance trim of a typical helicopter. The referred parameter turboshaft engine model in NDARC accounts for RPM-dependent engine performance variation

A total of 12 control variables were defined, although not all of them were used. There were three trim states defined, identified as follows: Hover, Compound, and High-Speed Compound.

Table 1 lists the trim quantities that were used in the present compound helicopter. The “X” entries in the table denote quantities that were solved for each trim state. Entries marked “Specified” were solved to a target value for each flight condition or mission segment. Table 2 lists the trim variables that were free to adjust (marked with “X”) for each trim state.

**Table 1. Trim quantities**

| Trim Quantity | Hover | Compound | High Speed Compound |
|---|---|---|---|
| Force X | | X | X |
| Force Y | | X | X |
| Force Z | X | X | X |
| Moment X | | X | X |
| Moment Y | | X | X |
| Moment Z | X | X | X |
| $C_L$ Wing 1 | | | Specified |
| Pusher Thrust | | Specified | |

**Table 2. Trim variables**

| Trim Variable | Hover | Compound | High Speed Compound |
|---|---|---|---|
| Roll | | X | X |
| Pitch | | X | |
| Yaw | | | |
| MR collective | X | X | X |
| MR long. cyclic | | X | |
| MR lat. cyclic | | X | X |
| Pedal (TR coll.) | X | X | X |
| Hor. tail inc. | | | X |
| Wing inc. | | | X |
| Pusher coll. | | X | X |

*Tech Factors and Assumed Component Attributes*
In developing parametric weight estimates, it is often necessary to assume a tech factor to account for a design decision that has a tangible advantage or disadvantage relative to the historical database. The tech factors used in this study represent limited new technology insertion, and are primarily manifest in the engines.

## AIRCRAFT SIZING

A set of 4 point-design conditions and a sizing mission were selected, with the design targets for each condition and mission specified. NDARC allows multiple design conditions to be defined. Each design condition was used to set a specific aircraft parameter, as outlined in Table 3.

**Table 3. Point-design conditions**

| Condition Number | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Name | HOGE-ISA | HOGE-3k/ 91.5 | WMTO | 6k95-200kt |
| Atmosphere | 12k/ ISA | 3k/ 91.5F | Sea Level ISA | 6k/ 95F |
| Weight | DGW | DGW | <Max> | DGW |
| Power | 95% MRP | 95% MRP | 95% MRP | 100% MCP |
| Trim State | Hover | Hover | Hover | High-Speed |
| Sizing | Tail Rotor Radius | Trans-mission | WMTO Tail Rotor Radius | Engine and/or Trans-mission |

A simple design mission was used to size the engine and fuel tank requirements, shown in Table 4 and Figure 6. Multiple design missions may be used for sizing the aircraft. The design mission is performed with a fixed external payload with 20ft$^2$ of drag area and weighing 5,000lb. The entire mission is flown in a 6k/95 atmosphere, although climb segments can be defined and atmospheric conditions can be varied on a per-segment basis. The design mission's first segment is a taxi at maximum continuous power for 3 minutes to burn a representative amount of fuel. The weight at the beginning of the first segment defines design gross weight. The second segment is a hover out of ground effect for 2 minutes. All hovers are performed with the Hover trim state. The third segment is a best-range cruise for 229nm, which represents the diagonal across a 300km x 300km area of operation. The trim state for the best range segments is set as high-speed compound, based on the expectation that this yields the higher best range speed of the compound trims. Best range speed in this case is 99% best range speed, on the high side, sometimes referred to as high speed cruise. The fourth segment is loitering flight at best endurance speed for 30 minutes, representing a mission loiter. The trim for best endurance may be found to be either compound or high-speed compound trim state, depending on the aircraft's exact configuration and the external drag of the payload. The fifth segment is a 1 minute HOGE, representing either landing and taking off again or observing a target. The sixth segment is a 229nm return cruise at best range speed. The seventh segment is a 1 minute HOGE for landing. A reserve segment is placed at the end, and will consist of the longer of 30 minutes of fuel burn or 10% of mission fuel burn. Fuel burn conservatism has been used for the current study, with a value of 5% assumed.

**Table 4. Design mission**

| | Segment | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8* |
| Alt | 6k | 6k | 6k | 6k | 6k | 6k | 6k | 6k |
| Temp | 95 | 95 | 95 | 95 | 95 | 95 | 95 | 95 |
| Power | 100% MCP | 95% MRP | 100% MCP | 100% MCP | 95% MRP | 100% MCP | 95% MRP | 100% MCP |
| GW | DGW | | | | | | | |
| Trim State | power | hover | hs-comp | hs-comp/ comp | hover | hs-comp | hover | hs-comp/ comp |
| Wing CL | | | 1.0 | 1.0 | | 1.0 | | 1.0 |

* Reserve Segment

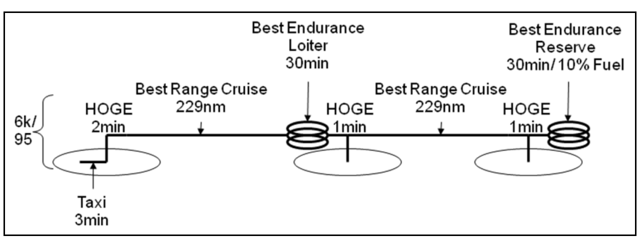


**Figure 6. Design mission stick figure**

The trim state shift point was found iteratively and the appropriate trim state was applied to both the best endurance and best range segments of the missions. The procedure for finding optimal trim state shift speed was to plot power versus airspeed for both modes, Compound trim from hover to about 140KTAS, and High Speed Compound state from about 70KTAS to 210KTAS. Where lines cross, the aircraft should make a shift. Note that the fuselage trim angle goes from free to fixed as the aircraft transitions from Compound to High Speed Compound states, and this discontinuity must be checked. There is not presently a way to perform sweeps in NDARC where the trim state varies, meaning that each point on the curve would need to be manually input when building a performance sweep schedule. In the final designed aircraft, other trades are considered and the optimal schedule is incorporated into the flight control system. The designer could alternatively choose maximum maneuver margin or control authority or minimum vibration (as the AH-56 was flown for much of its life) instead of minimum power as the objective for choosing trim state shift conditions. Vibration suppression could also be implemented with higher fidelity analysis, and the vibration suppression power levels could be fed into NDARC. Rotor resonance crossings will also affect the operating and transition envelope.

Disk loading is important from an operational perspective as it largely defines the downwash environment near the helicopter. Lower disk loadings also aid in autorotation, but other factors such as blade inertia are also important. Higher disk loadings mean that the rotor diameter is reduced, which has operational benefits in transportation and storage of the helicopter. Some excursions in disk loading were performed, in order to observe its impact on diameter and weight of the sized vehicle.

The tail rotor was sized to provide adequate anti-torque at a hover ceiling of 12K/ISA at DGW, which is 6,000feet above the design altitude of 6,000feet, but in an ISA atmosphere. This corresponds to a similar sizing requirement of 10K/ISA hover for a 4K/95-capable helicopter.

The sizing minimum HOGE ceiling was also set to 12K/ISA at DGW by the same rationale as the tail rotor sizing.

The design mission was set to be a 6K/95 mission with an external payload, based upon the belief that 6K/95 will be the design driver for future rotorcraft. 4K/95 performance is then fallout from the sized aircraft.

Maximum takeoff weight was fallout for the sized aircraft, with the transmission, engines, and rotors fixed by other sizing points. Maximum takeoff weight is the gross weight at 95%MRP engine capability and 100% transmission capability, while respecting rotor $C_T/\sigma$ limits.

A top speed of 200kt at 6K/95 DGW and no external payload was set as a target, based on a slight capability push beyond current helicopter performance.

The transmission is sized to accommodate a top speed of 200kt at 6K/95 DGW and hover at 3K/91.5 DGW. Transmission sizing for these two points guarantees performance capability. Due to the ability to operate at lower tip speeds, the transmission limits are sometimes different than the engine limits, even at the same atmospheric conditions. Also, different parts of the transmission and drive system are sized by the various conditions and segments. For instance, the power to the pusher propeller is sized by the high-speed condition, and the drive system torque happens to be sized by the high speed condition. As can be seen in Table 5, the transmission torque is sized by the high speed requirement. Condition 3 sizes the maximum takeoff weight, in this case by using the maximum torque available from the transmission.

**Table 5. Sizing engines and transmission**

| Sizing Condition/ Segment | Rating | Limit | Actual Engine Fraction | Trans. Torque Fraction |
|---|---|---|---|---|
| Cond. 1 | MRP | 100% | 88% | 88% |
| Cond. 2 | MRP | 95% | 73% | 77% |
| Cond. 3 | MRP | 95% | 77% | 100% |
| Cond. 4 | MCP | 100% | **100%** | **100%** |
| M1 Seg. 1 | MCP | 100% | 100% | 100% |
| M1 Seg. 2 | MRP | 95% | 88% | 93% |
| M1 Seg. 3 | MCP | 100% | 72% | 72% |
| M1 Seg. 4 | MCP | 100% | 49% | 49% |
| M1 Seg. 5 | MRP | 95% | 78% | 82% |
| M1 Seg. 6 | MCP | 100% | 66% | 66% |
| M1 Seg. 7 | MRP | 95% | 70% | 74% |
| M1 Seg. 8 | MCP | 100% | 45% | 45% |

**CAMRAD II Main Rotor Analysis**

The sizing conditions and missions were used with NDARC to establish an initial estimate of the compound helicopter, and the main-rotor dimensions and aircraft speeds were input to CAMRAD II for exploration of the design space and optimizing twist. CAMRAD II results calibrated the NDARC performance model.

A hingeless rotor hub was used for the main-rotor. Blade inertial and structural properties were scaled from the blade developed for the LCTC (Ref. 7). The current compound helicopter has a very stiff rotor. Thus, structural dynamics is not a significant factor in the aerodynamic performance shown in this paper. A stiff hingeless rotor is considered a good design choice, if innovative solutions are found to keep rotor weight reasonable. In any case, it allows this paper to focus on aerodynamic performance. The calculated blade frequencies were very close to those presented in Ref. 8. State-of-the-art rotor airfoils (VR-12 and SSCA09) were used for the main rotor blades.

The blade twist was varied to obtain balanced hover and cruise performance. Four design conditions were used to select the optimum twist; hover at 12K/ISA and 3K/91.5 deg F and 200 knot cruise at 6K/95 deg F, 145 knot best range at 6K/95 deg F. The first hover condition was 725 ft/sec tip speed, $C_T/\sigma$ = 0.1028 and the second hover condition was 725 ft/sec tip speed, $C_T/\sigma$= 0.0843. The cruise condition was 600 ft/sec tip speed, $C_T/\sigma$ = 0.0381, and the best range condition was 610 ft/sec tip speed, $C_T/\sigma$=0.0704. The 600ft/s tip speed is slightly above the 5/rev 1$^{st}$ lag frequency of the main rotor.

An isolated-rotor, axisymmetric solution was used for hover and an isolated-rotor, wind-tunnel trim for a given shaft tilt angle was used for forward flight performance calculations. A free-wake model was used for rotor analyses, computed by the CAMRAD II comprehensive analysis code.

The twist distribution had two linear segments, inboard (0.0R to 0.5R) and outboard (0.5R to 1.0R). Figures 1 and 2 present the results for twist variation. Hover figure of merit was plotted against equivalent rotor drag area (D/q ($ft^2$) = (PI+PO)/(V*q)), where PI is rotor induced power, PO is rotor profile power, V is airspeed, and q is dynamic pressure. For each value of outboard twist (-15, -12, and -9 deg), the inboard twist values are -6, -3, 0, 3, 6 and 9 deg. Solid symbols represent for hover at 12K/ISA and open symbols represent hover at 3K/91.5 deg F. A large negative twist improves hover performance, but the smaller twist gives better forward flight performance. The result shows that figure of merit is larger at 3K/91.5 deg F than at 12K/ISA for larger negative outboard twist, but the difference diminishes as the negative outboard twist gets smaller. Equivalent rotor drag area is larger at 145 knots than at 200 knots due to higher rotor thrust. The design twist of 0 deg inboard and -12 deg outboard was selected based on the hover-cruise compromise. At the design condition, hover figure of merit values at 12K/ISA and 3K/91.5 deg F are 0.766 and 0.773, respectively, and the equivalent rotor drag areas at 200 knot cruise and 145 knot best range conditions are 14.98$ft^2$ and 39.46$ft^2$, respectively. The CAMRAD II profile and induced powers at these conditions were used to calibrate the NDARC main-rotor performance model.

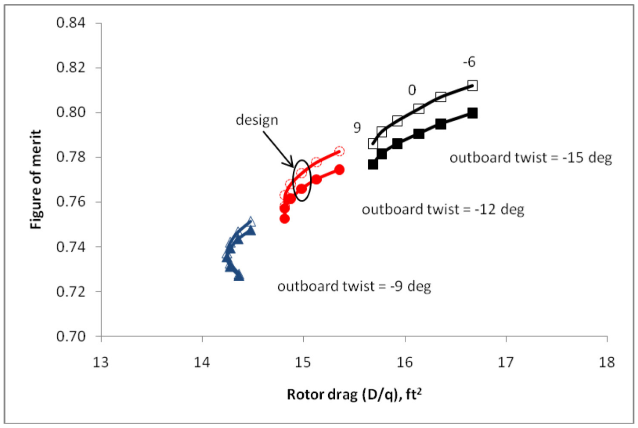


**Figure 7. Effect of blade twist on rotor hover and cruise at 200 knot performance (inboard twist = -6, -3, 0, 3, 6, and 9 deg)**

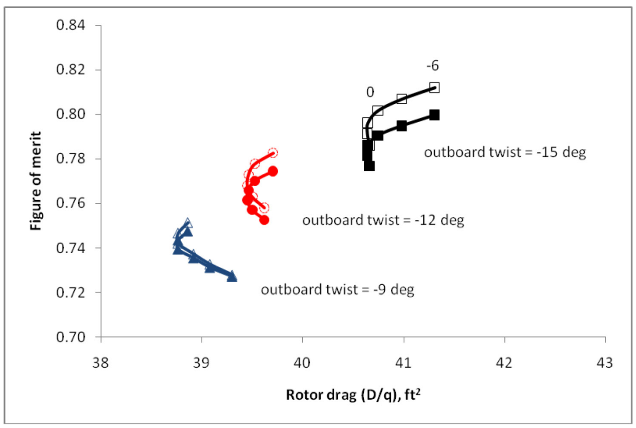


**Figure 8. Effect of blade twist on rotor hover and best range at 145 knot performance (inboard twist = -6, -3, 0, 3, 6, and 9 deg)**

**NDARC Solution Procedures and Diagnostics**

NDARC provides the user with run-time control over many aspects of the solution. The designer may also select various levels of verbosity for the interim solution, allowing a post mortem trace of a solution's convergence to identify the sources of divergence. Sample convergence histories are shown in Figures 9, 10, and 11.

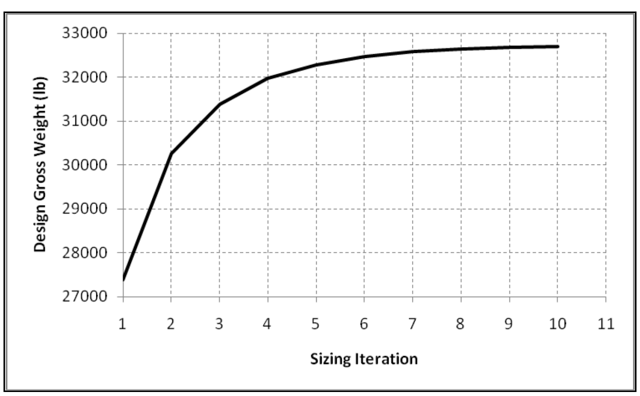


**Figure 9. Design gross weight convergence history**

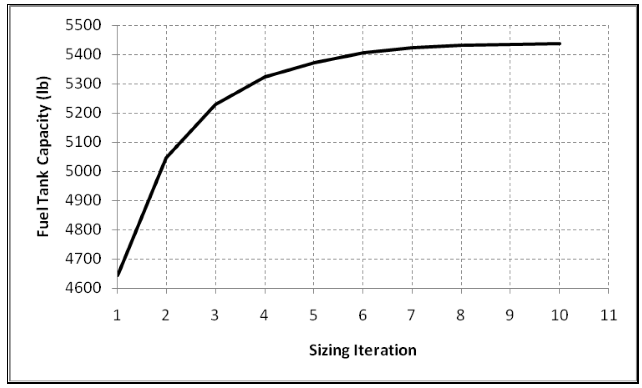


**Figure 10. Fuel tank capacity convergence history**

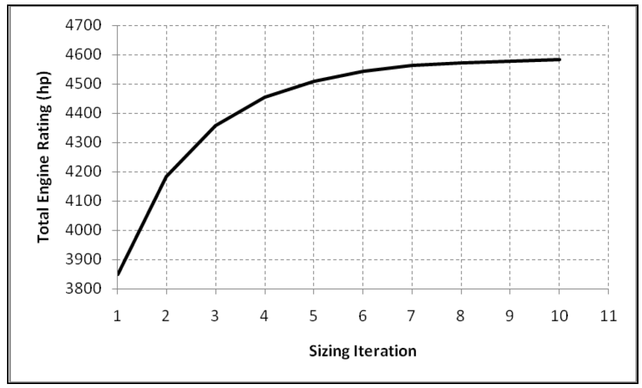


**Figure 11. Engine power convergence history**

A simple text parsing utility has been written, which allows the designer to quickly gage the convergence of design gross weight, maximum takeoff weight, fuel tank capacity, weight empty, engine power, power limit at the engine shaft, power ratio, and power limit of the drive system.

## OFF-DESIGN ANALYSIS DURING SIZING

Some of the off-design analysis, such as the high speed flight tip speed sweep, was used as feedback during the sizing process of Figure 1. Other analysis was performed in order to help place the performance of the sized rotorcraft in context.

**High Speed Flight Tip Speed**

A simple schedule of main rotor tip speeds was selected. The schedule is shown in Figure 12, and consists of a constant 725ft/s from hover to 90kt, then a linear ramp to the high-speed tip speed target of 600ft/s above 150kt. The high-speed target was found iteratively, by choosing a value and monitoring the design gross weight change in the sizing results. Once the design gross weight reached a local minimum, a sweep was performed to find what tip speed resulted in the maximum value for maximum continuous power speed. The tip speed was then adjusted incrementally until the peak maximum continuous power speed coincided with the target tip speed and minimum design gross weight. This sequential optimization can be improved by implementing an optimizer in the loop of operation by extending NDARC or automating the design study parameters.

The tip speed sweep also indicates the sensitivity of tip speed and gives insight to what may be the physics limiting performance in each direction. For instance, in Figure 13 slowing the high-speed cruise tip speed below 590ft/s is seen to have a much steeper drop off in maximum speed than does increasing the tip speed. Higher fidelity analysis in a comprehensive code should be performed to validate this observation.

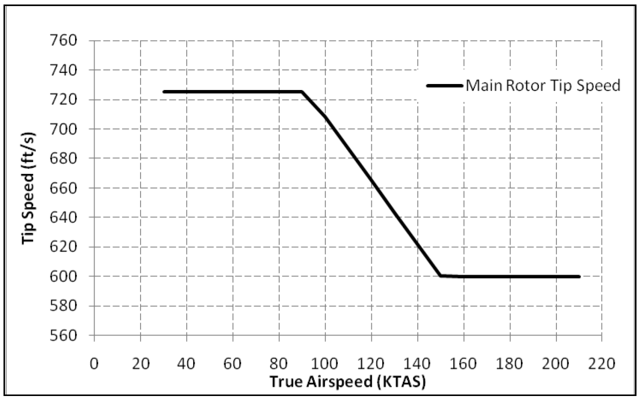


**Figure 12. Current design tip speed schedule**

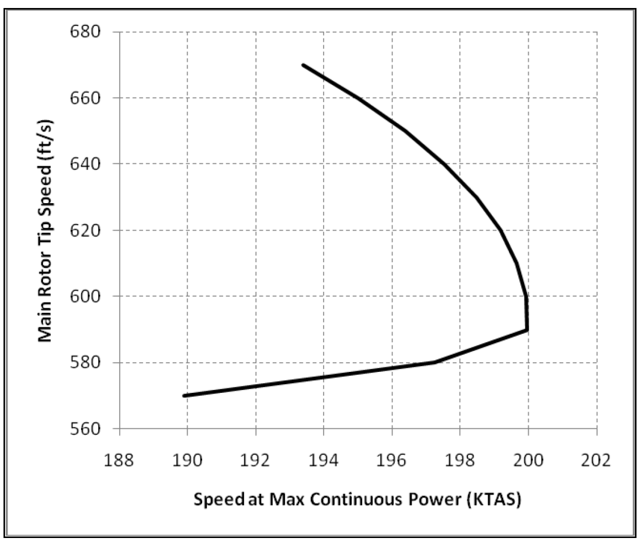


**Figure 13. Sweeping high-speed cruise tip speed, fixed design**

The effect of altitude on maximum speed is shown in Figure 14, with a slight advantage in top speed seen for increasing altitudes up to approximately 11,000ft in an ISA atmosphere.

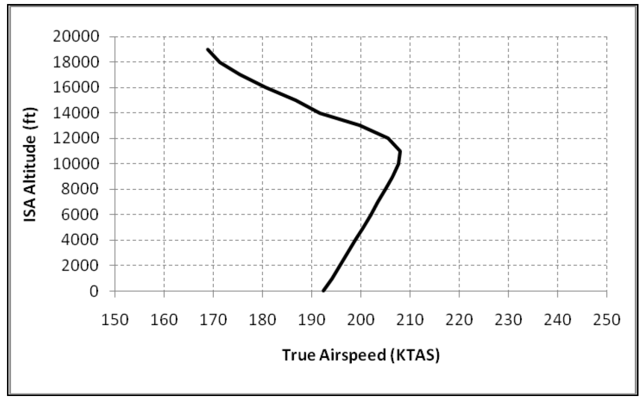


**Figure 14. Maximum speed at DGW**

A plot of HOGE ceiling as weight varies in an ISA atmosphere at 100%MRP is shown in Figure 15, with empty weight indicated by a vertical dashed line. Above 10,000ft ISA, the lifting ability of the compound drops off more significantly. This is due to the power being limited by the transmission limit below 10,000ft and by the engine above that altitude.

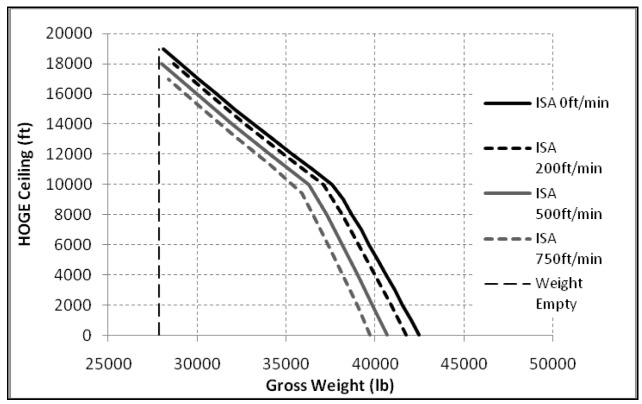


**Figure 15. HOGE ceiling and climb rate**

Best effort speeds with varying altitude and at DGW are shown in Figure 16 (ISA atmosphere) and Figure 17 (constant 95F atmosphere). An interesting observation is that the best endurance speed reaches an altitude in both plots, above which the speed for best endurance changes abruptly. This is due to the rotor speed schedule, which varies with forward speed, and places another degree of freedom in the solution space. In the ISA atmosphere, above 20,000ft altitude, the best endurance speed drops from 130KTAS at approximately 20,000ft altitude to 90KTAS at 21,000ft. The 99% best range speed, high side, was approximately 150KTAS for all altitudes.

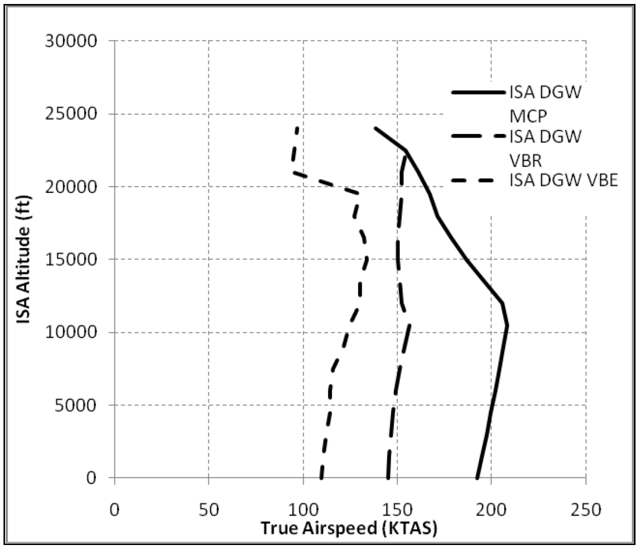


**Figure 16. Maximum effort speeds, DGW ISA**

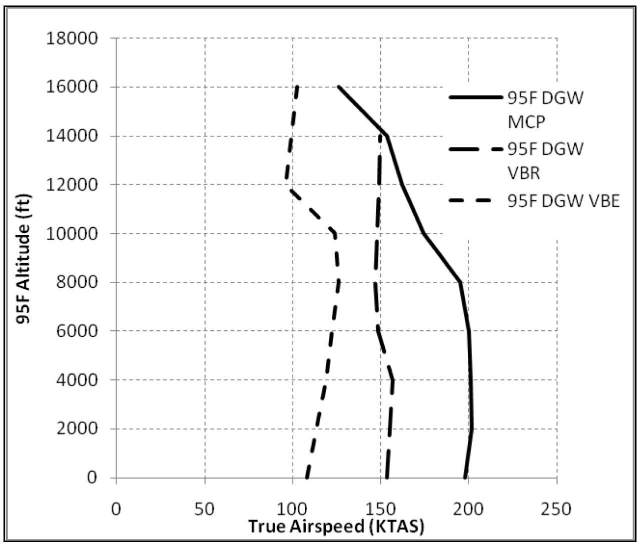


**Figure 17. Maximum effort speeds, DGW 95F**

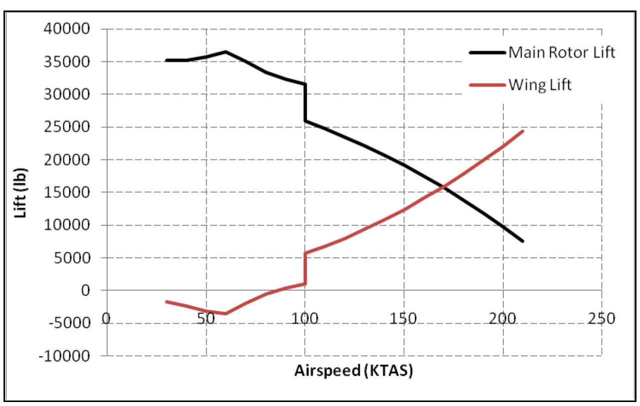


**Figure 18 Wing-Rotor Lift Share**

## THE SIZED AIRCRAFT

NDARC provides formatted summary pages with dimensions and weights for the aircraft at the end of the analysis. The output includes both dimensional data and estimates for weights broken out by Society of Allied Weight Engineers (SAWE) RP-8A weight group.

Table 6. Rotor Dimensions and Propertiespresents some selected rotor dimensions for the three rotors of the current compound helicopter. The twists of the tail and pusher rotors have not been defined as of yet.

**Table 6. Rotor Dimensions and Properties**

| Item | Units | Main | Tail | Pusher |
|---|---|---|---|---|
| Radius | ft | 33.5 | 9.4 | 8.0 |
| Solidity (geometric) | -- | 0.1142 | 0.1354 | 0.2000 |
| # of Blades | -- | 5 | 6 | 6 |
| Twist | deg | 0/-12 | TBD | TBD |
| $V_{tip}$ (hover) | ft/s | 725 | 700 | 953.8 |
| $V_{tip}$ (cruise) | ft/s | 600 | 579 | 789.4 |
| Mast Tilt/Cant (+aft/up) | deg | -1 | 15 | 0 |
| $C_D$ Hub | -- | 0.0025 | 0.0100 | 0.0100 |
| $M_{at}$ @ 200ktas | -- | 0.81 | 0.79 | 0.74 |

Table 7 presents the dimensions of the flying surfaces. The NDARC model calculates interference between the various components and the rotors. For the CAMRAD II analysis, no interaction between components was examined. Therefore, positioning and sizes of the flying surfaces may be varied as more detailed analysis is performed.

**Table 7. Flying surface dimensions**

| Item | Units | Main Wing | Vertical Tail | Horizontal Tail |
|---|---|---|---|---|
| Span | ft | 49.0 | 10.0 | 18.3 |
| Taper | -- | 0.8 | 1.0 | 1.0 |
| Aspect Ratio | -- | 11.0 | 2.0 | 5.0 |
| Thickness | % | 14.0 | 20.0 | 12.0 |
| Sweep | deg | 0.0 | 45.0 | 0.0 |
| Dihedral | deg | 0.0 | 0.0 | 0.0 |

The NDARC summary weight statement showing the highest two levels of weight breakdown is shown in Table 8.

**Table 8 NDARC Weight Summary**

| Aircraft Weight (x=fixed) | | |
|---|---|---|
| | lb | |
| DESIGN GROSS WEIGHT | 32728 | |
| Struct Design GW | 32728 | |
| Weight Max Takeoff | 42307 | |
| | | |
| WEIGHT EMPTY | 21703 | |
| STRUCTURE | 10393 | |
| wing group | 1663 | |
| rotor group | 3199 | |
| empennage group | 717 | |
| fuselage group | 3685 | |
| alighting gear | 737 | |
| engine sect/nac | 300 | |
| air induction | 94 | |
| PROPULSION GROUP | 6599 | |
| engine system | 1874 | |
| prop/fan install | 251 | |
| fuel system | 770 | |
| drive system | 3703 | |
| SYSTEMS AND EQUIP | 4169 | |
| flight controls | 1755 | |
| auxiliary power | 200 | x |
| instruments group | 200 | x |
| hydraulic group | 272 | |
| electrical group | 400 | x |
| avionics (MEQ) | 400 | x |
| furnish & equip | 600 | x |
| environ control | 100 | x |
| anti-icing group | 242 | |
| VIBRATION | 543 | |
| FIXED USEFUL LOAD | 800 | |
| crew | 725 | x |
| fluids | 75 | x |
| OPERATING WEIGHT | 22503 | |
| | | |
| Fuel for DGW | 5426 | |
| Payload for DGW | 4798 | |
| USEFUL LOAD | 11025 | |
| DESIGN GROSS WEIGHT | 32728 | |

A velocity sweep was performed at 6k/95, DGW, clean configuration, with a step transition from compound trim to high-speed compound trim at 100kt. The results of this sweep are shown in the figures below. In Figure 19, the total power curve is seen to be slightly lower for compound trim below about 60kt and more substantially lower for high-speed compound trim above 100kt. The split point for this transition was selected iteratively, by plotting these sweeps and picking an approximate transition point based upon the crossover of the power curves. A transition between the two trim states was selected to be 100kt. The selection of trim crossover speed could also be chosen based on power margins, marginal control authority, maneuver requirements, or operational details as well.

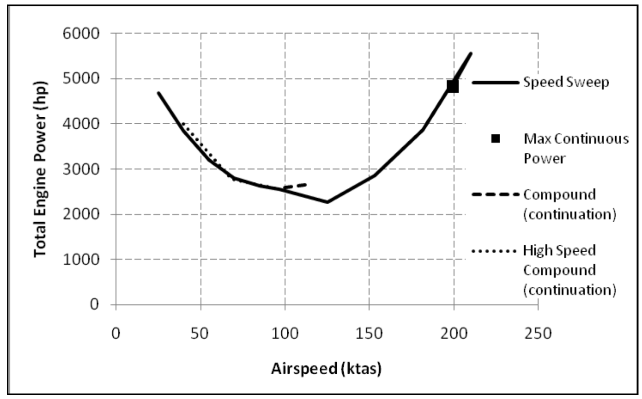


**Figure 19. Total power from velocity sweep**

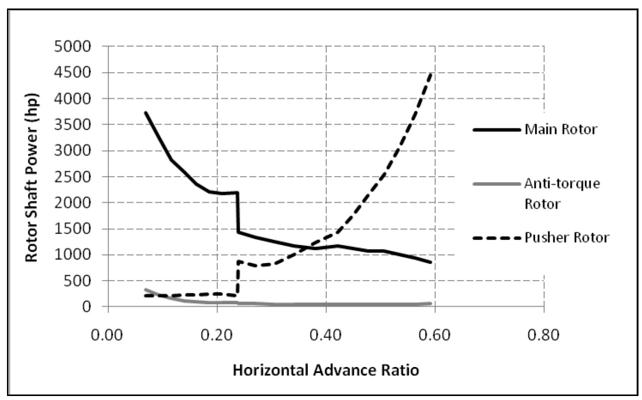


**Figure 20. Power split from velocity sweep**

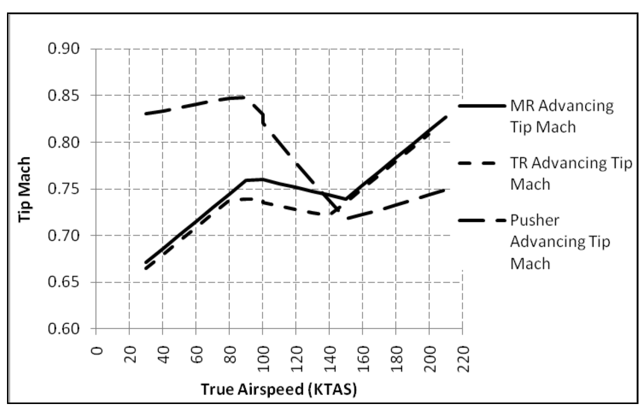


**Figure 21. Advancing tip mach**

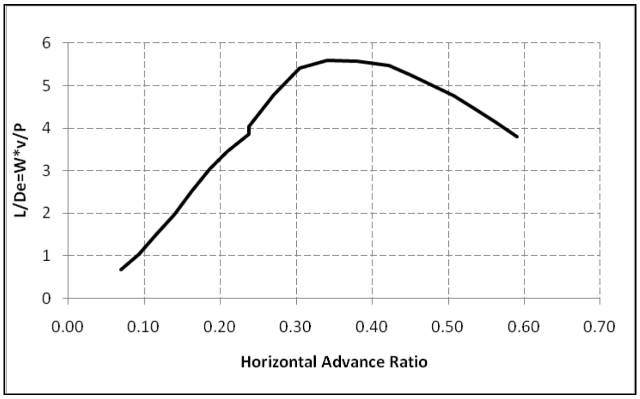


**Figure 22. Equivalent lift/drag from velocity sweep**

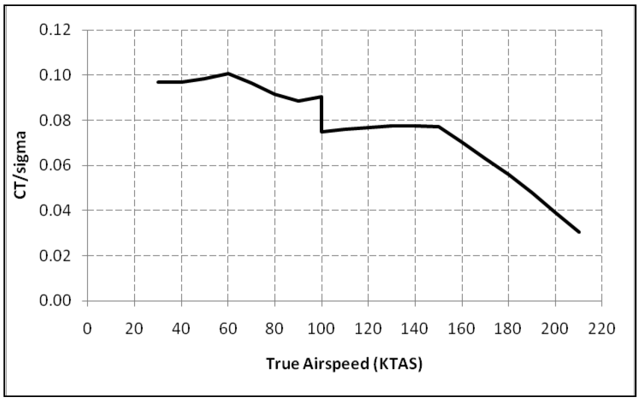


**Figure 23. Main rotor $C_T/\sigma$ from velocity sweep**

The fuselage pitch is free to vary in compound mode trim to balance the pitch moment, but pitch is fixed in high speed compound to free up the pusher for use as a free-body trim effector. The change in trim setting from one control scheme to the other need not be as abrupt in practice, and the indeterminate trim state can be solved differently than is currently done with NDARC. The step change in pitch at transition is 3.6 degrees with the current scheme, which is not exceptionally large, and can be smoothed with little impact on performance and no impact on the vehicle sizing; the sizing method does not account for transition states in evaluating trim or performance.

The plot of fuselage pitch angle as a function of airspeed for the speed sweep is shown in Figure 24.The fuselage pitch angle magnitude was being reduced as speed was increased below the transition, due to the wing taking more of the lift, at a fixed incidence of 12 degrees nose up relative to the fuselage. Use of flaperons could also ease the transition by loading the wing more in compound mode, but this might have an adverse impact on performance, as wing induced and profile drag may increase at a faster rate than main rotor power decreases. The control margin due to reserve wing lift will also be reduced. This trade will need to be made for each mission and scenario that a compound helicopter is eventually expected to perform.

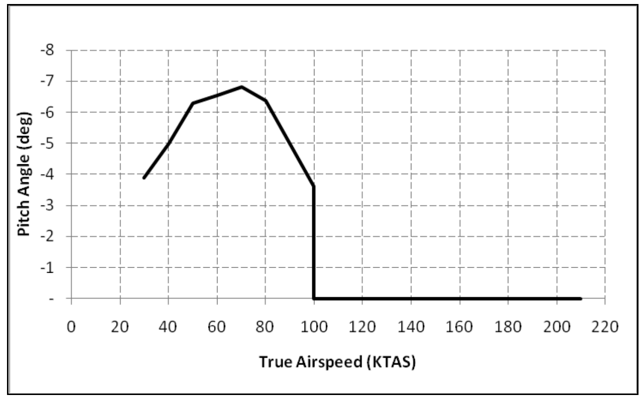


**Figure 24. Fuselage pitch angle from velocity sweep**

Figure 25 shows the roll angle of the aircraft over the speed sweep. Variable engine RPM causes some extra, small variation in the roll angle for trim, affecting the curve between 100kt and 150kt.


**Figure 25. Roll angle from velocity sweep**

**Drag Breakdown**

The drag breakdown is a plot that has a useful role in helping the designer to determine the various controls settings that should be used in various stages of flight. In Figure 26, the drag of the wing is seen as a substantial portion of the overall drag of the aircraft at speeds below 60kt with the current trim schedules. This is due to the wing being stalled at the incidences that NDARC has found as trim solutions. A designer could choose to adjust the incidence of the wing, either by biasing the fixed incidence of the wing, or by pursuing an all-moving wing. Flaperons can also be deflected to allow the wing to operate in a broader range of angles of attack. The ideal solution to the problem may in the end rely on estimates of the usage spectrum to determine the relative importance of low speed performance. Operational limitations, such as geometric constraints on interference with side doors on the fuselage, may also affect the optimal solution for wing incidence. Since these operational requirements are not quantified in NDARC, either designer judgment or some other algorithm is needed to determine how best to address the high drag of the wing at low forward speeds.

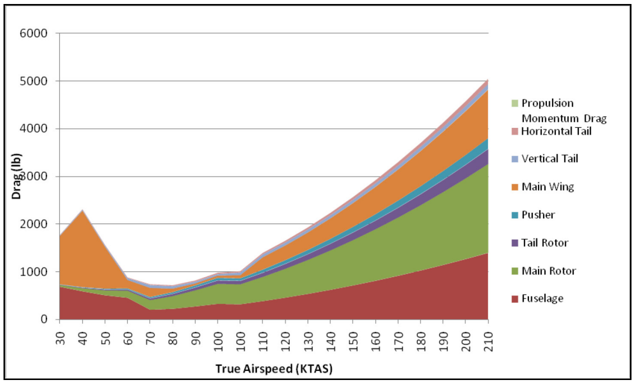


**Figure 26. Drag from Velocity Sweep**

NDARC was used to find off-design mission performance for various payloads, and the results are presented in Figure 27. An external payload with 50ft$^2$ of parasite drag area was examined, with a weight capped at 9,500lb. Clean configuration performance at 6k95 and 4k95 are also shown, showing that maximum lift is higher at the lower altitude, but that maximum distance traveled can be slightly greater at the higher altitude. Two different fixed payloads were examined: one with 9 passengers internally and no external stores, and another case with 9 passengers internally and 5,000lb of external stores having 20ft$^2$ of parasite drag area.

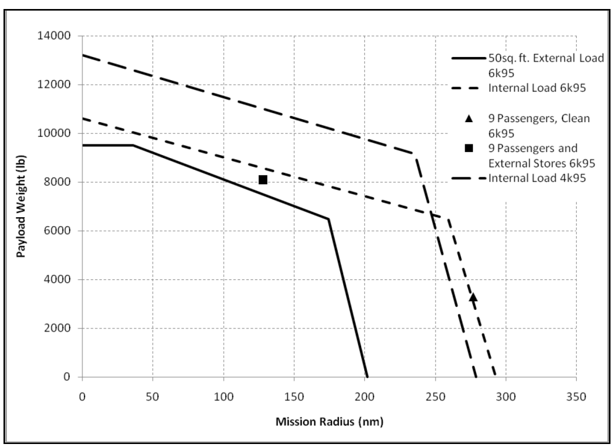


**Figure 27. Payload-Radius for Missions with a 30 Minute Loiter and 1 Minute Hover at the Midpoint**

A plot of HOGE ceiling versus temperature can be generated in NDARC by sweeping temperature and solving for HOGE ceiling at a given gross weight. The curve that is generated by this sweep can then be used to generate probability of hover maps for use in operational performance estimation (Reference 6). A sweep was produced for the current compound at design gross weight, and the overall probability of hover in Colorado for the entire year for the aircraft is estimated to be 96%. Figure 28 is a plot of the HOGE ceiling versus temperature at DGW. Figure 29 is an isopleths plot of the HOGE boundary versus altitude and temperature probabilities for the entire state over an entire year. In the plot, CPHP is the cumulative probability of a pressure altitude occurrence, and CPT is the cumulative probability of a temperature occurrence. The blue line represents the aircraft capability boundary. Horizontal green lines represent the altitude distribution in Colorado, and the red contours represent the temperature distribution in the state. Figure 30 through Figure 32 graphically depict the HOGE probability for regions of the state of Colorado for the months of December, June, and July. The dots on the plot roughly represent the state schematically, forming the rectangular shape of Colorado. December has the highest probability of hover, with greater than 99.78% probability of HOGE at DGW for every point in the state. June and July have the lowest probabilities of HOGE at DGW, yet the lowest probability for any location on the gridded map is 77.38%. The analysis of HOGE probability indicates that the aircraft is probably substantially oversized in hover, as fallout capability due to extra power installed to reach the 200kt design top speed.

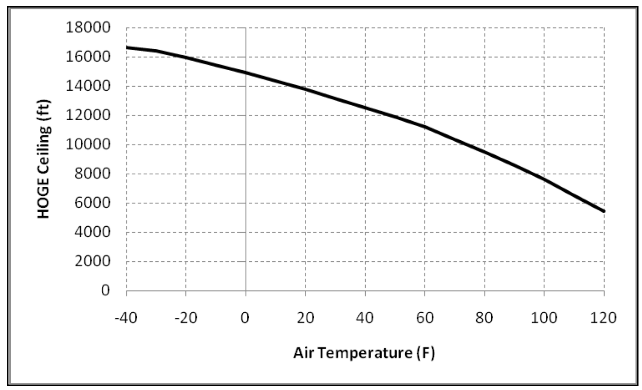


**Figure 28. Temperature effects on HOGE**

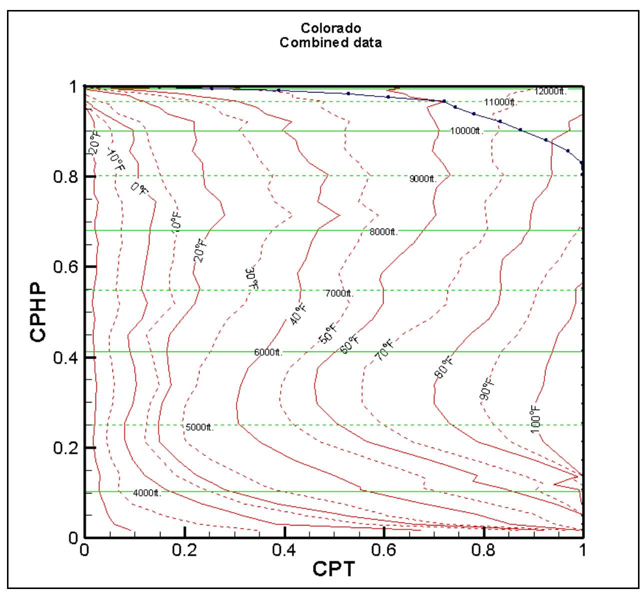


**Figure 29. Cumulative probability of HOGE in Colorado**

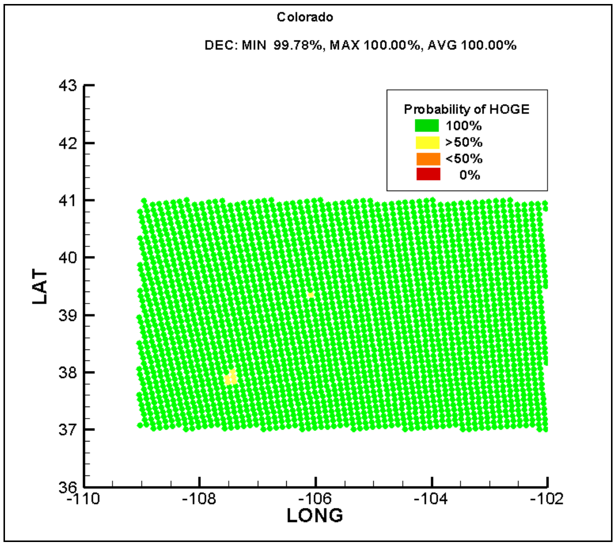


**Figure 30. HOGE probability, Colorado in December**

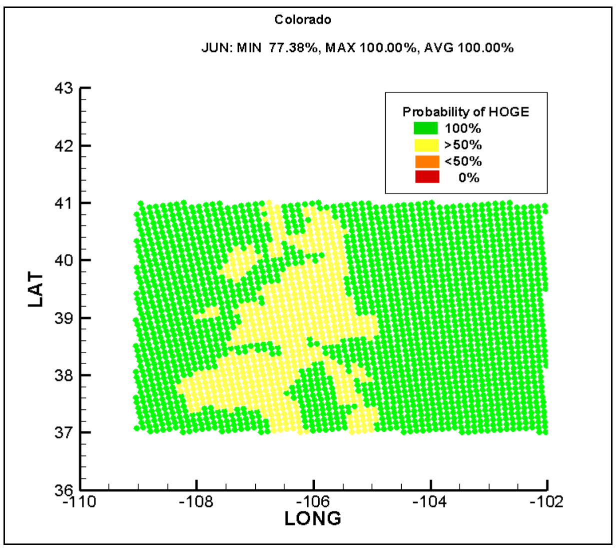


**Figure 31. HOGE probability, Colorado in June**

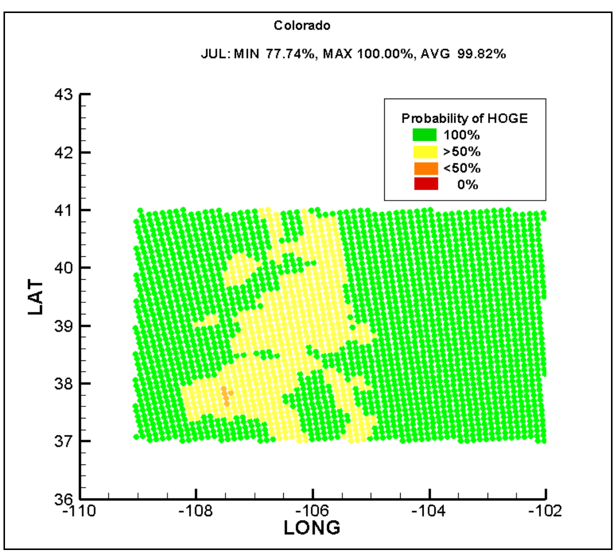


**Figure 32. HOGE probability, Colorado in July**

## COMPARISON TO HISTORICAL DATA

An interesting point of comparison that is always important to make with a compound helicopter is how much like a helicopter is this new aircraft, and how much like an airplane is it.

Designers have identified some metrics that reduce the mission dependence of the comparisons between concepts and provide useful information about what kinds of missions that a design might be well suited for. There are many such metrics, such as L/De, distance traveled per 1% gross weight fuel burn, hover time per 1% gross weight fuel burn, which are commonly used to evaluate efficiency in some mission phase. These metrics are listed in Table 9.

**Table 9. Performance metrics**

| Metric | Value @ 6k/95 DGW |
|---|---|
| Hover time per 1% GW fuel burn | 9.5min |
| Distance per 1% GW fuel burn | 41nm |
| L/De Max | 5.6 |

An interesting metric that looks at speed is horsepower per ton of gross weight versus airspeed, which was plotted by Gabrielli and von Karman (Ref. 4) and updated by Harris (Ref. 5). Figure 33 shows the plot from Harris with the current compound superimposed. The immediate observation is that the current compound is more similar to an airplane than to a helicopter, and has achieved its speed without the large penalty in power that begins to constrict helicopters to a narrowing band at speeds above 100mph. The compound described herein achieves a 208kt top speed at engine MCP and 11,000ft/ISA while having 216hp/ton installed power, based on engine MRP and MTOW.

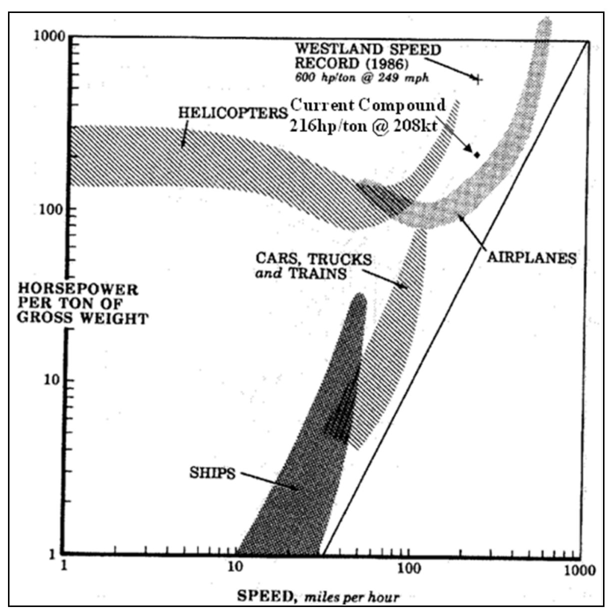


**Figure 33. Transportation efficiency metric**

## FUTURE WORK

Further refinement of trim schedules and a more consistent transition between the flight control modes can be devloped. Based upon operational requirements and performance, it may be desirable to use flaperons for main wing $C_L$ trim and to maintain wings level rolling attitude, and the benefits should be traded. A weight penalty for a variable incidence wing is not currently accounted for, and will need to be added into the trade study. Integration of automation tools for performing sizing iterations on parameters that are currently manually modified between runs can allow the designer to achieve a more optimal design, and an application programming interface for integrating these tools could be of great utility.

## CONCLUSIONS

A slowed-rotor compound helicopter has been synthesized and sized using NDARC and CAMRAD II analysis tools. Some of the capabilities available in NDARC have been demonstrated in the context of a simple design study. A methodology for sizing a compound helicopter for a simple set of design condition and mission requirements has been outlined. Trim strategies and their associated performance trades have been discussed. The effects of varying main-rotor tip speed and wing-rotor lift share have been examined.

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