Conceptual Design Tradeoffs for Future Single Main Rotor Compound Helicopters

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Abstract

A compound helicopter is defined as a helicopter with an auxiliary propulsion system which provides thrust in excess of that which the rotor(s) alone could produce, thereby permitting increased forward speeds; wings are usually provided to reduce the lift requirement from the rotor system. While there are a variety of different main rotor configurations for compound helicopters, such as single main rotor, coaxial rotor and tandem rotor, we will restrict this generic study to Single Main Rotor Compound (SMRC) Helicopters. A "Sensitivity" Tradeoff Studies approach will be utilized. The Advanced Vehicle Design Synthesis used in Georgia Tech vertical flight design classes is used for Configuration Solution and "Sensitivity" Tradeoffs for potential SMRC helicopter configuration solutions

1. INTRODUCTION

1.1. The Advanced Vehicle Design Synthesis Process

For most aircraft initial sizing of the conceptual aircraft is based on achieving a fuel balance as illustrated for fixed wing aircraft in Figure 1. The Fuel Required is obtained from Aerodynamics data and the Thrust to Weight (T/W) and Specific Fuel Consumption (SFC) is obtained from Propulsion. The Fuel Weight Available comes from the Weight Control, where the Payload, Crew Weight, and Empty Weight are subtracted from the Mission Gross Weight to provide the Fuel Weight Available. The Fuel Balance is then plotted as a Constraint Curve with T/W vs Wing Loading.

For rotary wing aircraft, rotorcraft, a similar approach is followed and is illustrated in Figure 2. The Performance Requirements (hover, forward flight and maneuver) and Mission Requirements (Payload, Range, Hover Time, Endurance) must first be identified. Next System Models for calculating the Engine Power Available and Vehicle Power Required, to achieve the critical Vehicle Power Loading, as a function of the Disk Loading, w, for Hover, and the Equivalent Flat Plate Drag Area, A_π, for Forward Flight. In a similar manner, models for calculating Fuel Weight Ratio Available and Fuel Weight Required must be identified for achieving a Fuel Balance and the Vehicle Mission Gross Weight. Once the critical Vehicle Power Loading and the Vehicle Mission Gross Weight (MGW) are obtained Synthesis is achieved. A balance between these items results in the required Installed Power and a Configuration Solution. [1]

1.2. Compound Helicopter and Helicopter

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Limitations

A compound helicopter can provide a balance of forces and moments to calculate the total horsepower required (THP), as illustrated in the level flight equilibrium diagram and THP equation in Figure 3. For the pure helicopter, $K_L = 0$, i.e., no wing, and all lift is carried by the rotor, and the THP consists of the first term, *parasite power*, and the last term, *rotor induced power and profile power*. A breakdown of helicopter power required is illustrated in Figure 4. Typical helicopter THP versus airspeed is illustrated in Figure 5, which illustrates how profile power, retreating blade stall and/or compressibility, and parasite power limit the forward speeds of helicopters to approximately 140 to 160 kts. This is caused by the asymmetric airspeed experienced by the main rotor blades in forward flight, as illustrated in Figure 6. Helicopter level flight performance is illustrated in Figure 7, where power available is introduced, with the maximum flight speed determined by the intersection of power available with power required. Increases over time in gross weight and parasite drag are typical of all helicopters, and their influence on power required and power available are illustrated in Figures 8 and 9. Mission performance includes Range and Endurance, which are illustrated in Figure 10. To achieve higher forward airspeeds than the pure helicopter requires compounding, usually with the incorporation of a wing and an auxiliary propulsion device as illustrated in Figure 11. With this compounding, the power required curve is flattened for the SMRC helicopter as the wing picks up most of the lift, approximately 80%, and auxiliary propulsion from a propeller provides thrust to overcome the parasite drag. These strongly reduce the power required by the main rotor; in addition, the rotor rotational speed can be reduced to limit the advancing blade tip Mach number to less than the drag divergence number, further reducing the rotor power required (and also minimizing rotor vibratory loads). Examples of compound helicopters that have been built and flight tested are pictured in Figure 12. While no SMRC helicopter, military or commercial, has gone into series production, we believe that the time is right for their introduction, with the application of an appropriate set of emerging technologies.

Takeaways from this introduction for helicopters and compound helicopters are:

- Mission drives design.
- Induced power is maximum in hover and goes down with increased velocity (mass flow) through the rotor.
- Profile power comes from the torque required to turn the blades and increases with velocity squared, and then velocity to the fourth power when retreating blade stall and advancing blade compressibility comes into play.
- Parasite power overcomes the drag of the entire aircraft and increases with velocity cubed.
- Blade stall and compressibility limit the speed of a pure helicopter to about 140 to 160 knots.
- Adding a wing and/or auxiliary propulsion offloads the rotor and allows higher flight speed for the same installed power.

2. GENERIC COMPOUND HELICOPTER EXAMPLE

2.1. Generic Mission Utilized

The generic mission utilized is based on a Reference Mission [2]. The resulting mission is illustrated in Figure 13.

The selected Single Main Rotor Compound (SMRC) configuration is similar in arrangement to the AH-56A Cheyenne (lifting wing, conventional tail rotor or ducted propeller or fan, and an open propeller aft of the tail rotor), and notionally depicted in Figure 14.

Previously, a Combat Search and Rescue (CSAR) compound helicopter study was conducted at Georgia Tech for the USAF using a similar sizing and performance fuel and power balance method, R_F, as used in this example. The objective of the CSAR study was to parametrically demonstrate the impact of helicopter design and technology variables on the requirement capabilities in a typical CSAR mission. During the CSAR Study confidence in the methodology was gained through calibration and benchmarking, where it was sought to compare CSAR vehicle concepts using the R_F Method and make distinctions, and hopefully eliminations of alternatives. Many combinations were examined, but only five vehicle concepts, as illustrated in Figure 15, are shown here to make the necessary notable distinctions between what was found to be the main alternatives. The five alternatives are depicted in Figure 15; the third concept from the left included a wing, separate tail rotor and an open propeller aft of it, and was the recommended concept configuration.[3]

Also, from this CSAR study, the tradeoff between weight and performance was indistinguishable between the different 'Aux Propulsion Driver' alternatives. Therefore, the AH-56A Cheyenne configuration with an open aux prop was chosen.

Also, from this CSAR study, the tradeoff between weight and performance was indistinguishable between the different 'Aux Propulsion Driver'

alternatives. Therefore, the AH-56A Cheyenne configuration with an open tail rotor and an open propeller is selected as the example compound configuration for this study.

2.2. Simplified Engine Methodology

The engine is based on the Improved Technology Engine (ITE) estimated improvements published by GE for their T-901 engine, as compared to their T-701 engines [4]. These values are then multiplied by the improvement factor from the T-901 engine improvement estimates. For example, their increase in performance goal is an increase in power of 50% over the T-701 series, so we multiplied the sea level standard maximum continuous power specification for the T-701 by 1.5. Engine power for environmental conditions other than sea level standard was calculated from the following equation

$$\boldsymbol{PowerAvailable} = \boldsymbol{Power\ at\ SL\ Standard} * \left(\mathbf{1} - \mathbf{0.195} * \frac{\boldsymbol{hoverAlt}}{\mathbf{10000}}\right) * (\mathbf{1} - \mathbf{0.005} * (\boldsymbol{hoverTemp} - \boldsymbol{ISA_{Temp}@Alt})$$

2.3 Parasite Drag Estimation

Parasite drag is an important consideration for rotorcraft because of its very strong influence on total power required in high speed, level flight. Figure 16 [5] provides historical values for rotorcraft and fixed-wing aircraft parasite drag (gross weight over equivalent flat plate area, F_E), as related to gross weight. Clean airframe design was assumed for this SMRC example; therefore, the “Clean Helicopters” trend line of Figure 16 was adopted for this SMRC example

2.4 Advancing Blade Tip Mach Number Limit

In order to minimize main rotor profile drag rise due to compressibility effects on the rotor blades in high-speed flight, it is useful to slow the rotor rotational speed as a function of atmospheric temperature and flight airspeed, to limit the advancing blade tip Mach number (M_{AT}) to a value below drag divergence (M_{DD}):

$$\Omega R = M_{AT} V_S - V$$

Keeping M_{AT} below M_{DD} also has the important advantage of lower rotor vibratory loads in high speed flight. The sizing methodology for SMRC example incorporates a M_{AT} limit which slows the main rotor rotational speed to keep M_{AT} at or below an input M_{DD} of .81.

2.5. Wing Lift Sharing and Tail Rotor Off Load

In order to be able to trim the rotor and to reduce vibratory loads the main rotor will not be completely unloaded, as illustrated in Figures 17 and 18. It will provide 20% of the lift at the vehicle mission weight at the design cruise speed.

2.6 Empty Weight Estimation

Empty weight fraction was estimated using the Shinn weight equations from the 1981 Advanced Scout Helicopter study [6] and the JVX Technical Assessment (JTA) study[7]. The Shinn weight equations, as do most weight estimating methods, use a multiple linear regression general formula which has the form:

$$W=kA^xB^yC^z\text{....etc}$$

Where W = weight of the respective component (e.g. main rotor blades)

A,B,C = aircraft design parameters that have some effect on the weight of the component (e.g. gross weight, rotor radius, solidity, horsepower, etc.)

k, x, y, z ….= constants determined by the multiple linear regression computer program

2.7. Power Required and Payload Sensitivity Curves: Example

Payload fraction is used to determine the best combination of disk loading, main rotor solidity, and necessary use of maximum rated power (MRP, a10 minute rating) or intermediate rated power (IRP, a 30 minute rating) versus use of maximum continuous power (MCP). Also, the possible use of hybrid electric propulsion (HEP) is initially investigated.

In accordance with the compound helicopter sizing section in AMCP 706-201, Helicopter Engineering, Part One: Preliminary Design [8] rotor geometric solidity, $bc/\pi R$, is determined based on the following rationale:

The broad requirements for the rotor are: to operate efficiently in hover; at moderate speeds, to provide its share of the required maneuvering capability; and, at high speeds, to produce as much lift as possible without producing excessive vibration or loads. Once the disk loading is chosen, either on the basis of using all of the installed power to hover or on the basis of maximum allowable downwash velocity, several other rotor parameters must be defined:

1. Tip speed
2. Solidity
3. Twist
4. Airfoil section

A notional example power required sensitivity analysis plot for a 10,000 lbs aircraft is provided in Figure 19 and a payload sensitivity analysis plot is provided in Figure 20.

Figure 20 can be broken into three regions, from left to right these are the single engine region, the single engine hybrid drive region, and the dual engine region. The left half of the figure shows where the aircraft can meet the performance and mission requirements with a single engine. The engine was assumed to representative of the improved turbine engine (ITE) and was not sized based on gross weight. Thus at extremely low gross weights the single ITE represents a much larger portion of the aircraft's empty weight. As the gross weight increases this percentage shrinks and the empty weight fraction decreases and the payload increases.

At roughly the 9,000 to 15,000 pound range the single ITE can no longer provide the aircraft with sufficient power for the mission. This center region of the figure shows the hybrid power train where an electric motor covers the power deficit between the single ITE power and the power required. This portion of the figure is characterized by slightly increasing empty weight fraction with gross weight and a slight decrease in payload with increasing gross weight.

The final portion of the figure is on the right when two ITEs and the associated drive train weigh less than a single ITE hybrid configuration. Much like the single engine region this portion of the figure is characterized by decreasing empty weight fraction with an increase in gross weight and increased payload with an increase in gross weight.

2.8 References

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2. Silva, C., Yeo, H., and Johnson, W., "Design of a Slowed Rotor Compound Helicopter for Future Joint Service Missions", Proceedings of the AHS Aeromechanics Specialist's Conference, San Francisco, CA, January 20-22, 2010.
3. Georgia Tech USAF Combat Search And Rescue (CSAR) Study, 2008
4. Plummer, B., Smith, J., and Carter, C., "Preparing for the U.S. Army's Improved Turbine Engine", Proceedings of the AHS International 73rd Annual Forum & Technology Display", May 9-11, 2017, Fort Worth, TX
5. Wilkerson, J.B., and Smith, R.L., "Aircraft System Analysis of Technology Benefits to Civil Transport Rotorcraft", NASA/CR-2009-214594.
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7. Advanced Joint Vertical Lift Aircraft (JVX) Technology Assessment, Summary Report, Analysis and Preparation Chaired by AVRADCOM, May 1983.
8. AMCP 706-201, Helicopter Engineering: Part 1: Preliminary Design, Section 3-2: Compound Configurations, Subsection: 3.2.2.3 Configuration Parameters, 30 August 1974.

2.9 Biographies

Dr. Daniel P. Schrage is a Professor in the School of AE, Georgia Tech since 1984 and Director of the Vertical Lift Research Center of Excellence (VLRCOE) since 1986. Prior to Georgia Tech he was an engineer, manager and senior executive with the U.S. Army Aviation Systems Command and the U.S. Army Aviation Research and Development Command from 1974-1984. He was an Army Aviator and Nuclear Weapons officer from 1967-1978. He has a BS Engineering, USMA, 1967; MS AE Georgia Tech, 1974; MA BA Webster U., 1975; and D.Sc. ME Washington U. (St. Louis) 1978. He is a retired U.S.Army SES, Level 3 and COL (USAR).

Mr. Bob Walters graduated from the United States Military Academy at West Point in 2007 with a BS in mechanical engineering. He commissioned as an Army Aviation officer. During his military service he flew MEDEVAC missions in the UH72 and commanded a UH60 command and control company. He left active duty in 2015 to pursue is masters degree in aerospace engineering at GA Tech where he built GA Tech's pilot in the loop flight simulator. He received his masters degree in May of 2018 and continues to pursue a Ph.D.

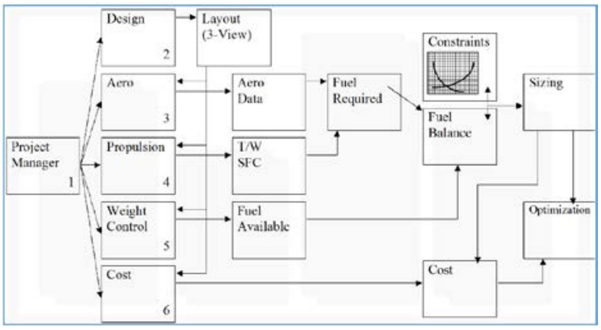


Figure 1. Fixed Wing Aircraft Design Synthesis

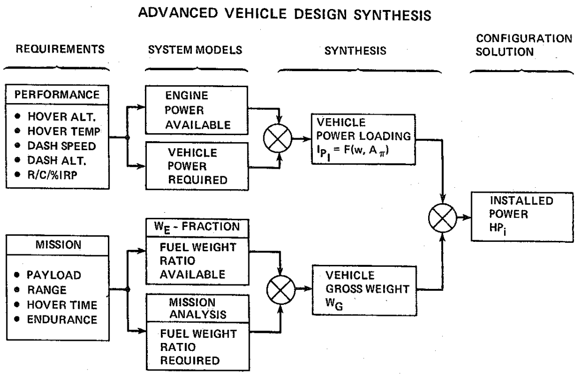
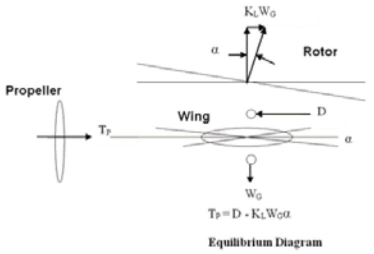


Figure 2. Rotorcraft Advanced Vehicle Design Synthesis



Total Horsepower Required(THP) for Generic Subsonic Fixed Wing and Rotorcraft:

$$THP = \frac{\sigma f V^3}{146000\eta_p} + \frac{0.332}{\sigma e \eta_p}\left[(1-K_L)\frac{W_G}{b}\right]^2 \frac{1}{V} + \frac{1}{\eta_H}\left[K_L^{3/2} K_u \frac{ihp_H}{\sqrt{\sigma}} + K_\mu \sigma rhp_H\right]$$

$$K_u = \frac{U_o}{V}$$

K_L is the ratio of lift on the main rotor to vehicle gross weight

$$K_\mu = 1 + 3\mu^2 + C\mu^4$$

$K_L = 1 - V_o/2.25$, ($K_L = 0$ at 225 MPH)

$$ihp_H = \frac{0.0938\omega^{3/2} R^2}{B\sqrt{\sigma}}$$

$$rhp_H = \frac{\sigma A_B}{1.85} V_{T_o}^{3/2} \delta_m$$

Figure 3. Compound Helicopter Equilibrium Diagram

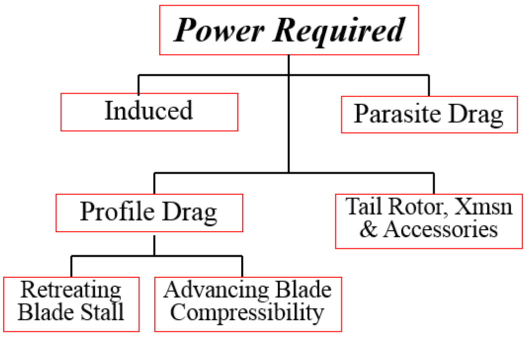


Figure 4. Breakdown of Helicopter Power Required

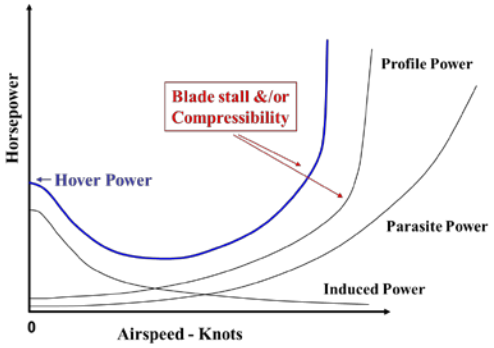


Figure 5. Typical Helicopter Power Required

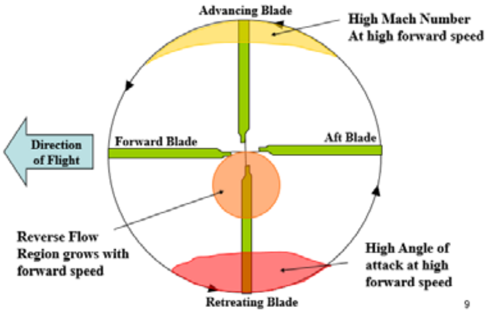


Figure 6.Assymetric Airspeed Experienced by the Main Rotor Blades

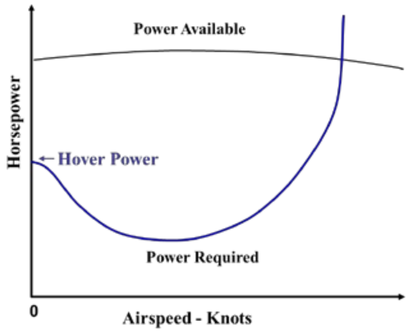


Figure 7. Helicopter Level Flight Performance

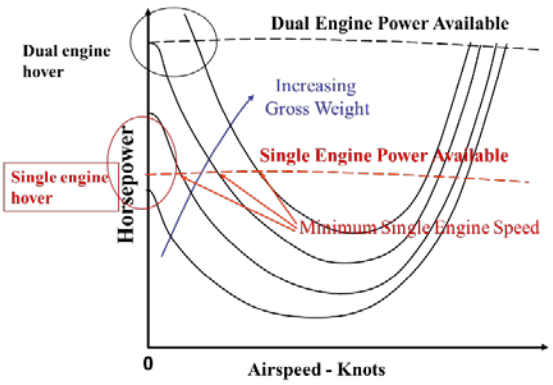


Figure 8. Impact of Increasing MGW on Helicopter Power Required and Available

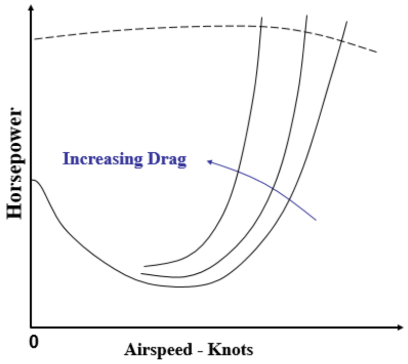


Figure 9. Impact of Increasing Parasite Drag and vPower on Airspeed

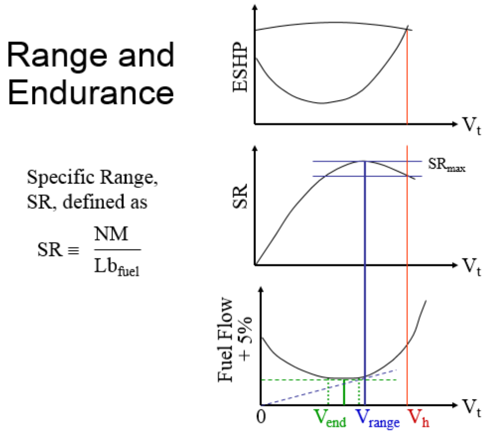


Figure 10. Mission Requirements Drive Range and Endurance

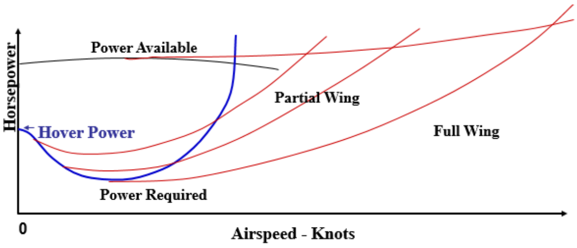


Figure 11. Wing and Aux Propulsion Flattens the Power Required Curve

Figure 12. Compound Helicopter Prototypes: Lockheed AH-56A Cheyenne, Piasecki X-16H3 and Bell X-40

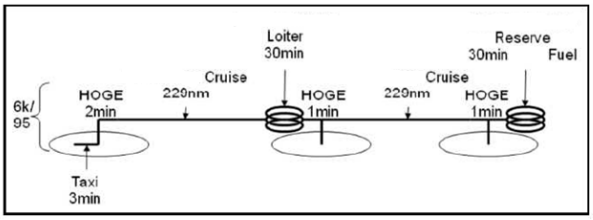


Figure 13. Reference Mission Profile [2]

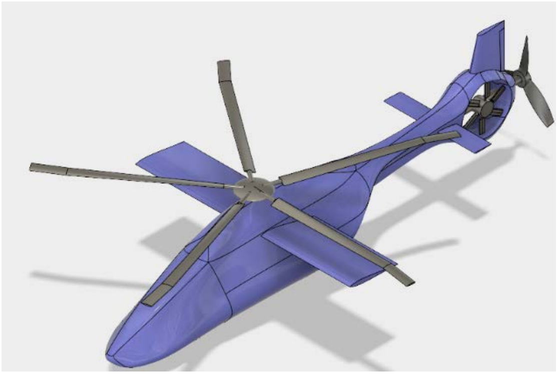


Figure 14. Selected Single Main Rotor Compound Configuration

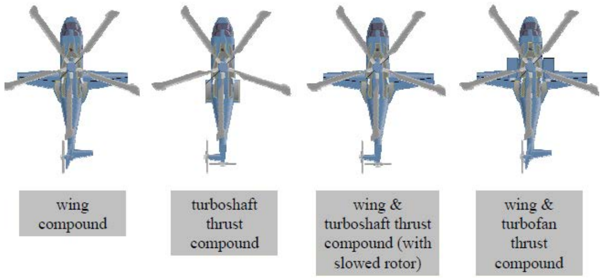


Figure 15. Several of the CSAR Vehicle Concepts Analyzed

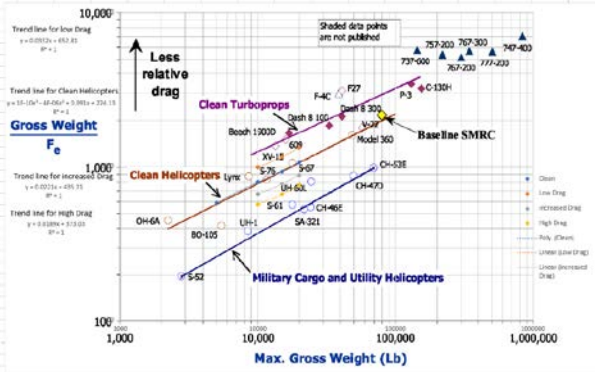


Figure 16. Rotorcraft Parasite Drag vs GW Comparison [4]

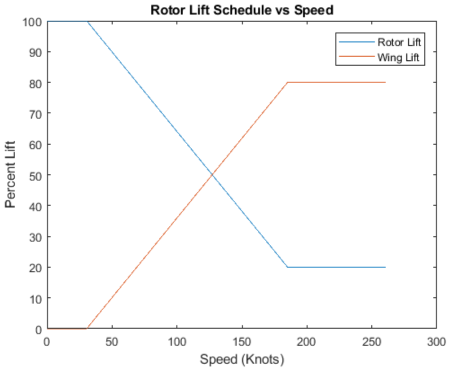


Figure 17. Rotor Lift Share Schedule (Design Airspeed of 185 knots)

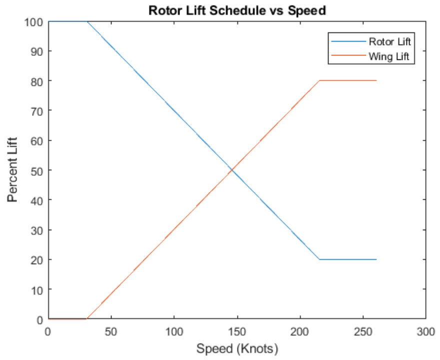


Figure 18. Rotor Lift Share Schedule (Design Airspeed of 215 knots)

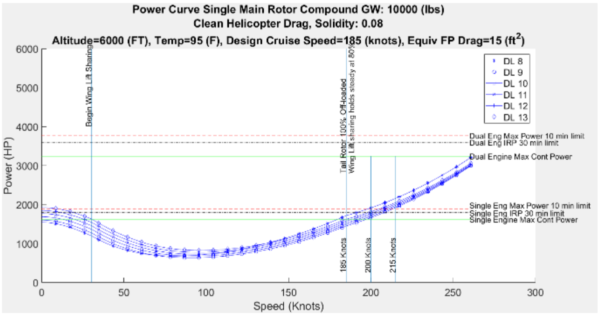


Figure 19. Notional Power Required Sensitivity Analysis for Compound Helicopter

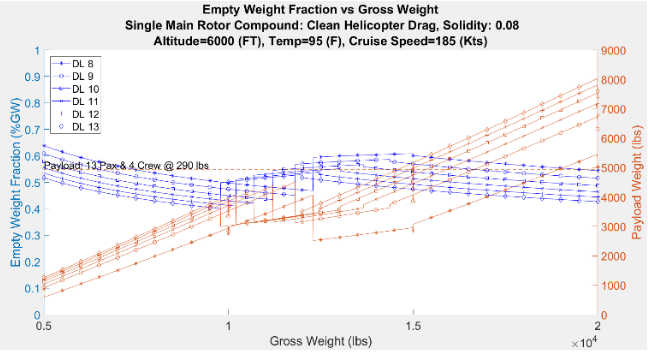


Figure 20. Notional Payload Sensitivity Analysis