

Excalibur

The Cutting Edge in Tiltrotor Technology

Flying Further, Higher, Faster



Alfred Gessow Rotorcraft Center
Department of Aerospace Engineering
University of Maryland, College Park
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EXCALIBUR

In response to the 2011 Annual AHS International
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RFP Requirements and Compliance

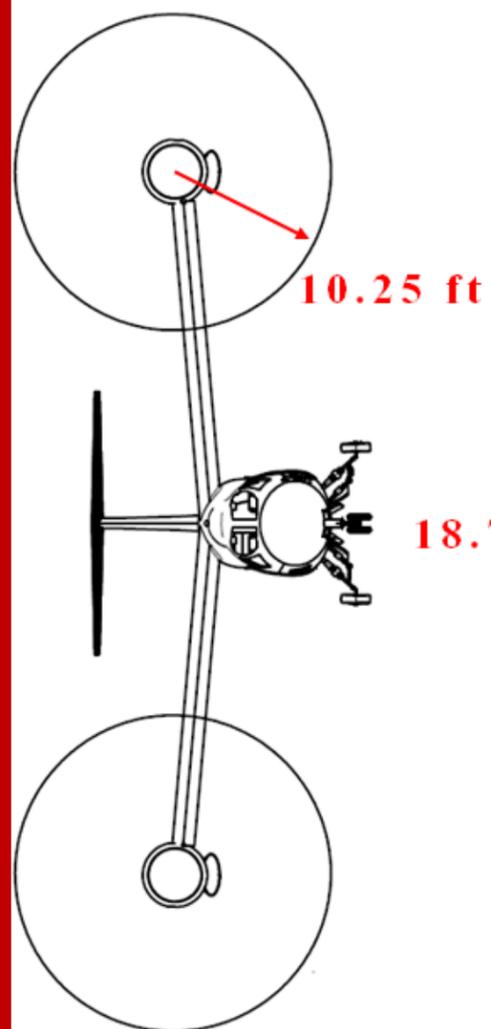
General Capabilities

Requirement	Design	Section
Vtol capable	Tiltrotor	2
Multi-mission capable, reconfigurable within 1 hr	Reconfigurable anterior, universal attachment fittings	10,12,14
4 Crew members for all missions	4 Crew stations	3,10
Passenger or cargo transportation	Removable seats, sliding door, universal attachment fittings	7,10,14
Rubber engine based on CT7-8A characteristics	UMD engine model	3,6
ICAO Level 4 noise requirements	Low disk loading, subsonic tip mach no.	3,13
Para-military	MIL-spec design	11
Ir suppression considered	Engine exhaust cooling, use of composites	7,14
Unload/load (Hot) 6 persons and equipment: 10 minutes, 3,000lbs cargo: 20 minutes	Large sliding door, fuel tanks, run on ground single engine	10,12
Cost analysis	Low operating costs, project development timeline	4,15

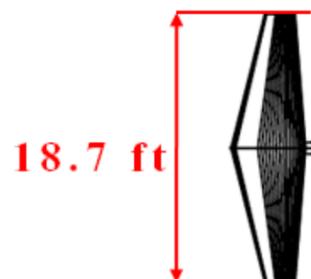
Mission Profile Requirements

Requirement	Design	Section
Start-up/warm up within 5 min	Checklist automation	12
6K95 HOGE for 5 minutes @ MGTOW	Low disk loading, low blade loading, variable diameter rotors	12.3
225 nm at MCP for 50-70 minutes (190-270 kts), "Golden hour"	Cruise speed 275 kts, max speed 298 kts	3, 12.4
Loiter for 30 minutes at V_{end}	Good hovering efficiency	12.3
6 passengers or 2 litters + 2 medics	Removable/reconfigurable seats, 2 litters and additional med equipment	3, 4, 10, 12, 14
500 nm range @ V_{br} with 3,000 lbs internal payload	Low drag, propeller and hover optimized rotors, fuel tanks	3,4,5,10,12.4
250 nm range with 4,000 lbs internal	Low drag, fuel tanks, propeller and hover optimized rotors	3,4,5,10,12.4

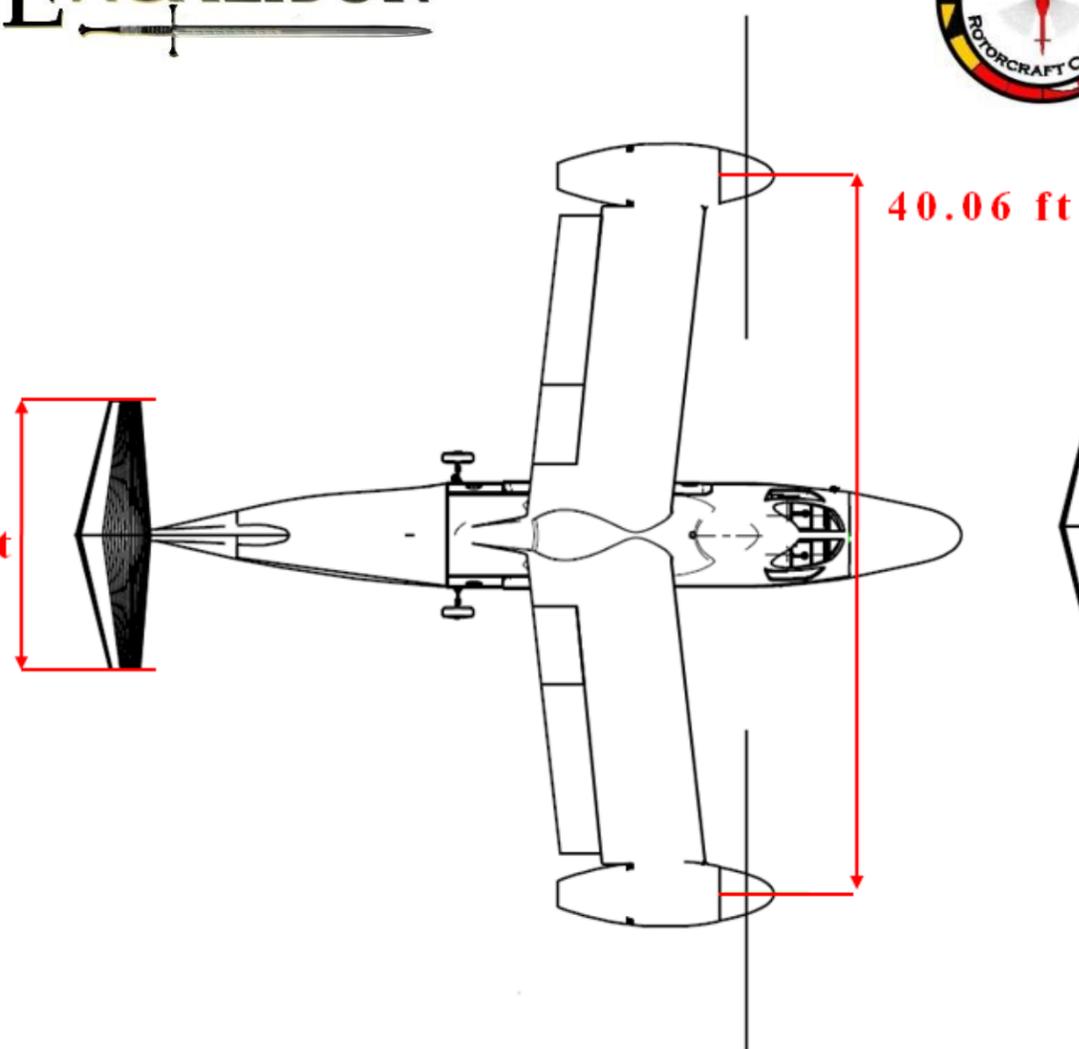
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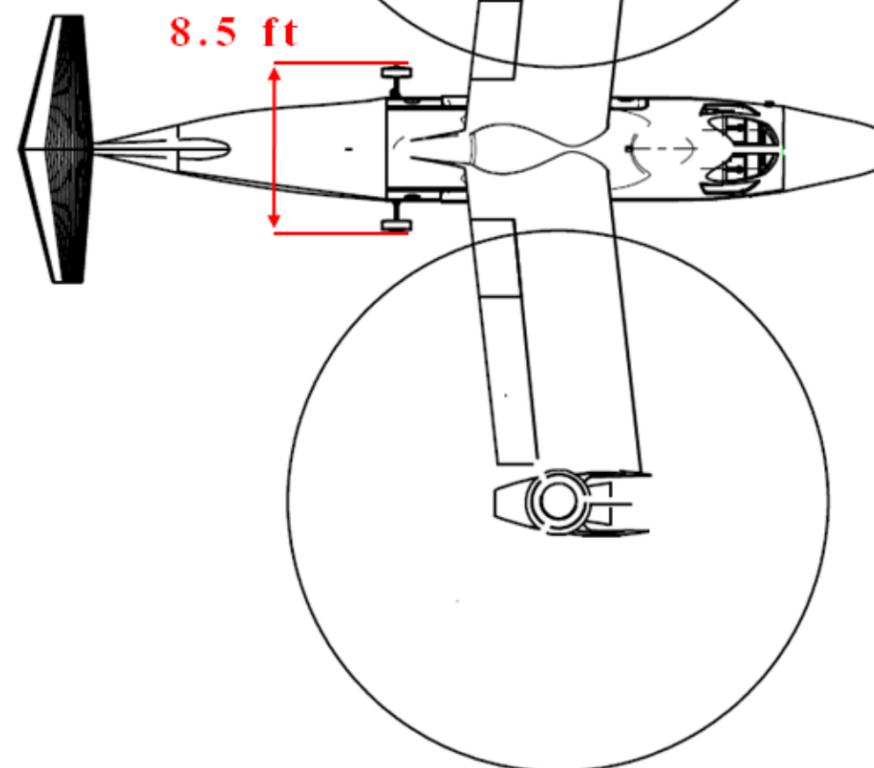
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18.7 ft

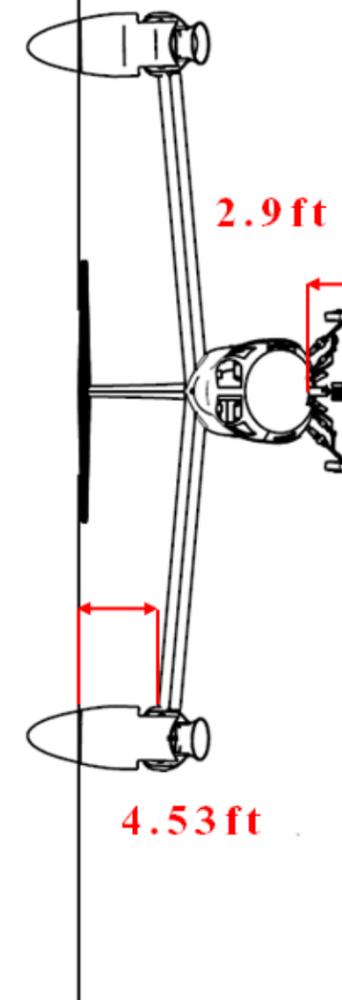


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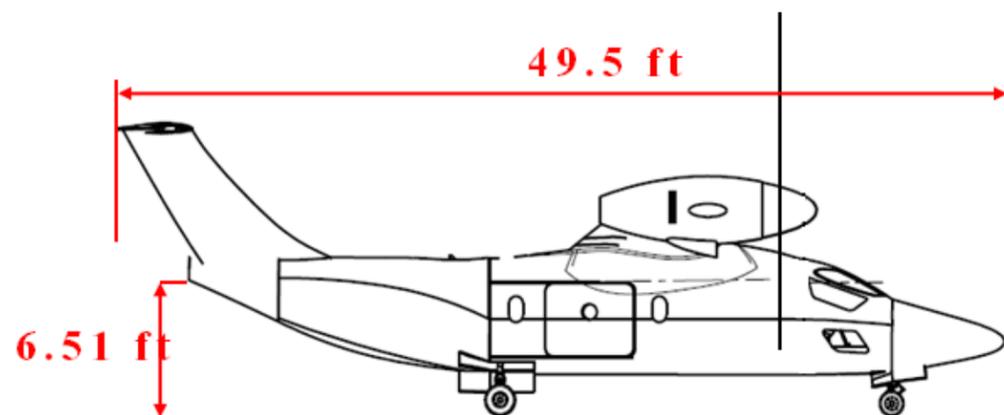
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8.5 ft



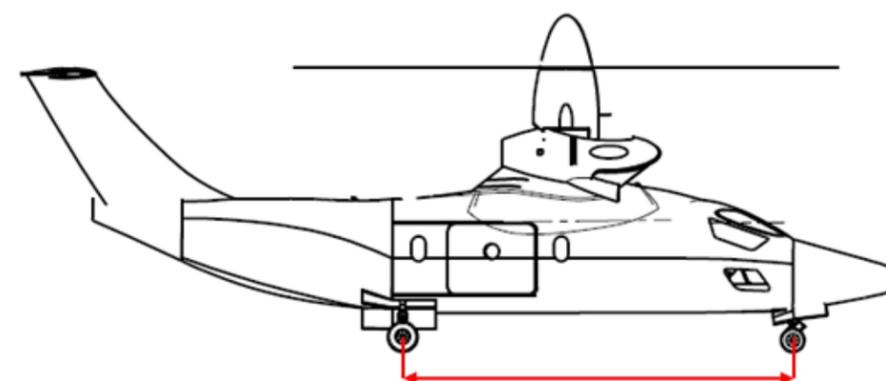
2.9 ft

4.53 ft

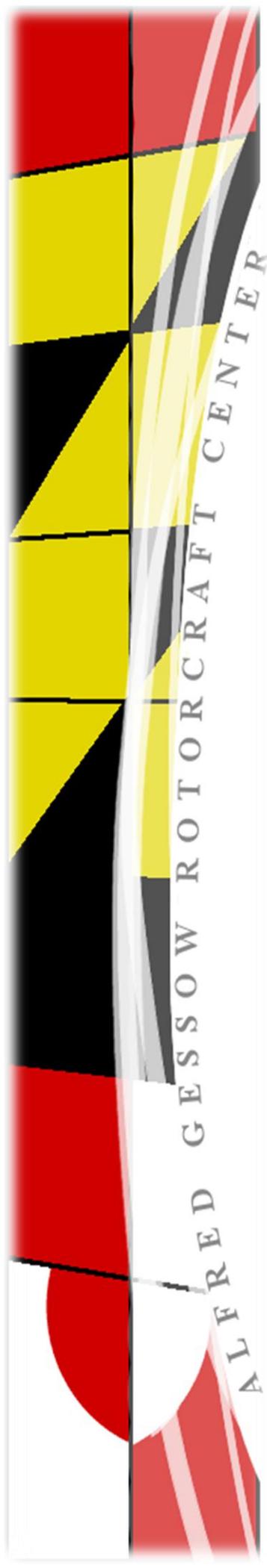


49.5 ft

6.51 ft



20.5 ft



Proposal Summary

Concept Design

In response to the 2011 AHS Student Design Competition Request for Proposal (RFP) for a multi-mission aircraft, co-sponsored by Bell Helicopter Textron, the University of Maryland graduate student team presents *Excalibur*, a multi-role tiltrotor. The graduate team was assembled to take on this challenge of designing a new multi-mission, VTOL aircraft. The team consisted of five students with specialties in aeromechanics, computational fluid dynamics, simulation, and one of the students is also a certificated pilot. *Excalibur* was designed as a variable diameter tiltrotor to meet the requirements of the RFP by providing excellent hover and forward flight performance. All sizing and rotor optimization codes were developed and extensively validated in-house and were applied within the project timeframe. Custom software developed at UMD was utilized to provide all aerodynamic, acoustic, and performance analysis. Computer aided design, component design, and solid modeling conceptual images were developed using a variety of solid design tools including CATIA, SolidWorks, and the Modo 501 Design Tool.

The Request for Proposals

The RFP specifies the need for a new vertical lift aircraft with increased versatility that is capable of multiple missions. Having one rotorcraft that can be widely deployed and used for many different missions reduces inventory and maintenance costs by increased commonality of parts. The goal of the multi-mission design is to optimally blend the competing requirements of three very different missions, which are motivated by the needs of current events. To satisfy these requirements the team proposes the design of a tiltrotor. A description of these three missions along with the proposed capabilities of the design include:

Mission 1: Search and Rescue

Excalibur's Search and Rescue Capabilities

- 4 Crew 800 lbs
- 2 medics + 2 litters 1,000 lbs
- or 6 Passengers 1,200 lbs
- Fuel 1,383 lbs
- GTOW 13,442 lbs

Cruise to Destination

- Cruise Speed: 220 kts
- Flight Time: 61 min
- Range: 225 nmi

Loiter at Best Endurance

- Loiter Speed: 160 kts
- Flight Time: 30 min

Take-off

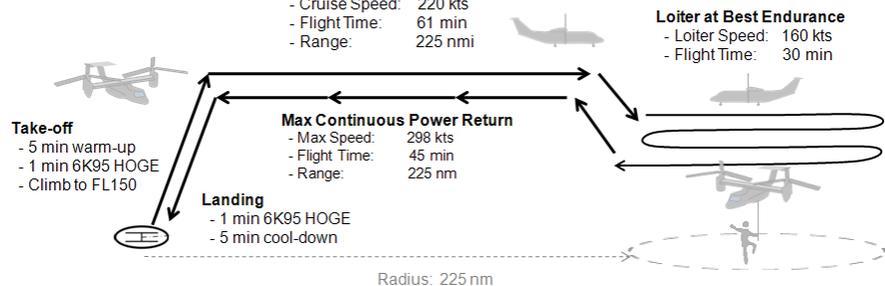
- 5 min warm-up
- 1 min 6K95 HOGE
- Climb to FL150

Max Continuous Power Return

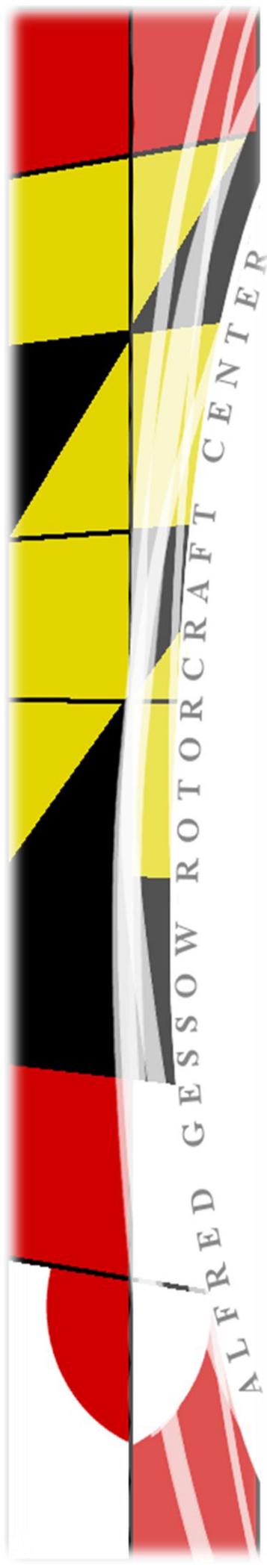
- Max Speed: 298 kts
- Flight Time: 45 min
- Range: 225 nm

Landing

- 1 min 6K95 HOGE
- 5 min cool-down



Radius: 225 nm

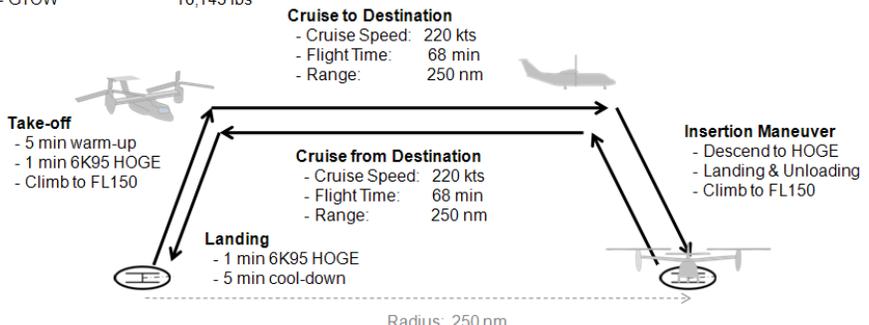


ion requires the aircraft to carry a crew of four on the outbound leg, effect a rescue, and return home carrying two litters and two medical personnel or an additional six passengers. Critically injured passengers are best served if they reach the medical facility in the “golden hour,” a window which is defined in the RFP as 50 to 70 minutes on the return flight. This mission, therefore, requires the vehicle to be capable of flying between 190 kts and 270 kts to satisfy the “golden hour” requirement. *Excalibur* is capable of a 220 kts cruise speed, a 298 kts maximum speed, and a 330 kts dash speed ensuring that rescued persons are returned within this critical timeframe.

Mission 2: Insertion

Excalibur's Insertion Capabilities

- 4 Crew 800 lbs
- 6 Passengers + Eqpt. 4,000 lbs
- Fuel 1,185 lbs
- GTOW 16,143 lbs

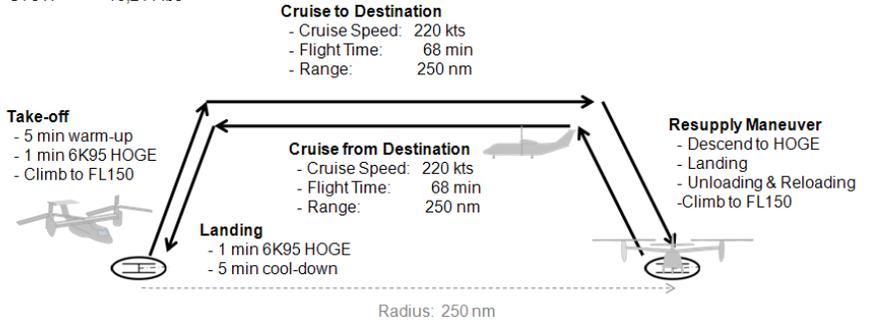


This mission requires the aircraft to carry a crew of four and six additional persons plus equipment, totaling a minimum payload of 4,000 lbs internal for a minimum distance of 250 nm.

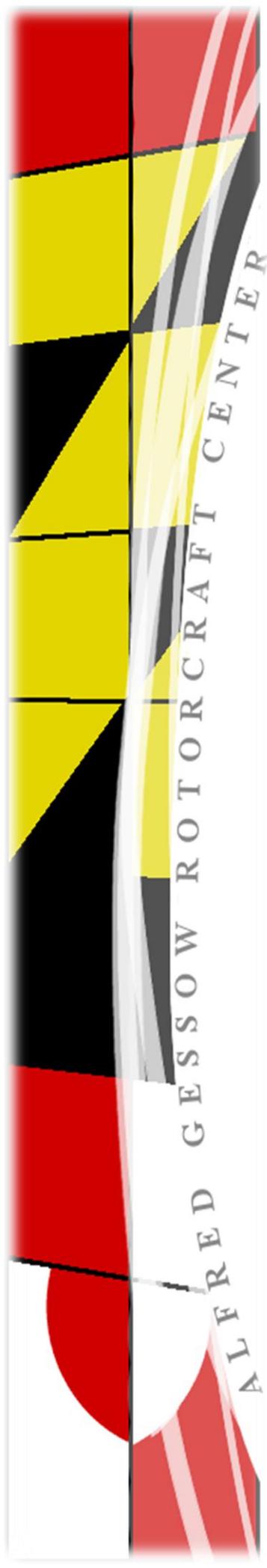
Mission 3: Resupply

Excalibur's Resupply Capabilities

- 4 Crew 800 lbs
- Internal Load 3,000 lbs
- Fuel 1,285 lbs
- GTOW 15,244 lbs



This mission requires the aircraft to carry a crew of four and a payload of at least 3,000 lbs internal for a minimum distance of 250 nm, and then return to the starting point with an alternate payload of 3,000 lbs internal. Common to all missions is the need for hover out-of-ground-effect



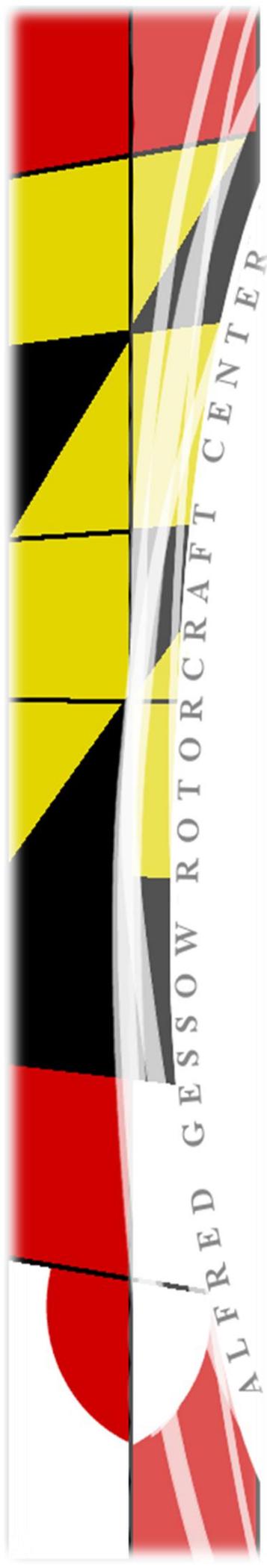
(HOGE) at 6000 ft and 95°F (6K95). This is equivalent to a density altitude of near 9,800 ft.

The *Excalibur* tiltrotor was developed to meet, and in many cases exceed, the requirements of the multi-mission focused RFP emphasizing the requirements of medium lift, long range, and high speed. This design, is capable of being reconfigured quickly for any mission, and is designed to effectively carry out search and rescue (SAR), military insertion, or re-supply missions.

Multi-Mission Design

These three missions, based on the needs of current events, have diverse performance requirements, necessitating the use of both proven and cutting edge technologies to simultaneously achieve the objectives that have traditionally been believed as conflicting ones. Each of these missions has its own impact on sizing the aircraft. The common requirement for HOGE at 6K95 at maximum gross takeoff weight (MGTOW) demands a proprotor with a large diameter to give high efficiency and low power requirements. Mission 1 requires that the aircraft be able to carry out a search and rescue mission with a mission radius of 225 nm and return the rescued persons within the “golden hour.” This mission demands high speed capability of the order of 200 kts. A smaller diameter proprotor with a lower tip speed is required to maintain low helical tip Mach numbers and high propulsive efficiencies during high-speed cruise. The aircraft must also be capable of carrying internal payloads upwards of 4,800 lbs over a range of 250 nm, and then return without the need to refuel. The insertion mission determines the sizing for the aircraft, through the demands imposed on performance for payload and range.

Motivated by the needs of current events, an accelerated development timeline of 8–9 years is important for this rotorcraft. The team decided that this requires the use of viable, proven technologies. An analytical hierarchy process (AHP) was used to evaluate different helicopter configurations. This AHP is mathematically-based multi-criteria evaluation scheme ranks the relative importance of various design criteria against each other based upon the voice of the customer, leading to the determination of different feasible configurations that are capable of meeting the RFP requirements. The different configurations examined included the conventional single main rotor, compound, tandem, and tiltrotor. Conventional helicopters cannot reach the minimum speed requirements set in the SAR mission. However, they offer a high reliability and excellent hover capability. Compound configurations have the potential to meet the speed requirements set by the RFP but the issue of empty weight fraction and fuel burn are considerations. The tandem rotor design was also considered, but was once again limited in its capabilities by the inability to meet the speed requirements. A tiltrotor was, therefore, decided to be the best way to simultaneously satisfy the requirements for payload, range, and speed because it



has the capability to hover and then transition to high speed forward flight, while still being able to meet the payload and range requirements.

A tiltrotor configuration presents its own set of challenges. Influenced by the need to hover at 6K95, to have a low downwash that will not hamper rescue, and have low susceptibility to brownout, it was decided that a disk loading of around 10 lbs/ft² was required. This decision led to a large diameter rotor that proved inefficient in airplane mode. Conflicting forward flight requirements are what makes designing a tiltrotor so challenging. Thus, the team decided upon a variable diameter tiltrotor (VDTR) concept that has a larger diameter in hover and a lower diameter in propeller mode. Variable diameter rotors have been studied, and in many cases considered for other tiltrotor designs because the concept provides the necessary performance in hover without compromising forward flight efficiency. The VDTR has also been successfully wind tunnel tested, demonstrating its feasibility for use on an aircraft within the project development timeline.

Sizing the tiltrotor was performed using a modified Tischenko methodology, where helicopter parameters and weights associated with the tail rotor were removed and wing related terms were added. The modified sizing code uses statistical data to estimate the various component weights. Certain component weights were estimated by using the NASA Design and Analysis of Rotorcraft (NDARC) code. To ensure the confidence in the prediction of the team's sizing code, it was validated using the NDARC. Using the same initial values, the UMD and NDARC codes converged within 6% in their empty weight calculation

The resulting tiltrotor is shown in Foldout 1 where the overall vehicle dimensions are illustrated.

Variable Diameter Rotor Design

Excalibur is different from traditional tiltrotors because it is has been developed from the beginning with emphasis on the variable diameter concept. This makes the aircraft not just a tiltrotor but a true convertible rotor aircraft. Such an innovative rotor system offers numerous advantages.

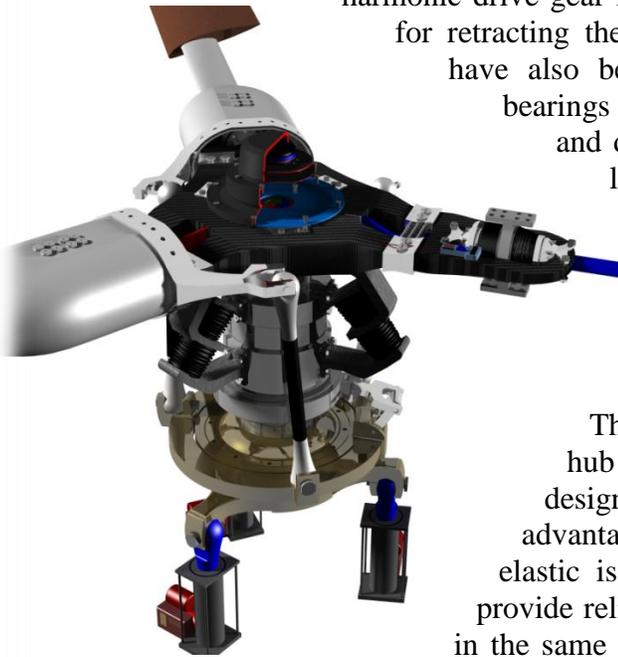
Hover efficiency is greatly improved, with a power loading of 7.5 lb/hp and a disk loading of only 11 lb/ft², comparable to conventional helicopters. In forward flight, decreasing the proprotor diameter resulted in a significant increase in propulsive efficiency.

An added advantage of the VDTR concept is the ability to take off and land on runways like fixed-wing aircraft when the rotor is fully retracted. This feature significantly increases the payload capacity, compared to a tiltrotor without retracting rotor blades, allowing the vehicle to take off with 50% more payload compared to helicopter mode. Not only does this increase operational capability, but also increases survivability as the aircraft can now safely land as an airplane

in the event of engine failure in forward flight or in the event that the nacelle tilting mechanism fails.

Innovative Rotor and Hub Design

Excalibur's innovative hub design contains a spooling motor, coupled with a harmonic drive gear reduction to reel in the tension strap for retracting the rotor blades. Elastomeric bearings have also been used in place of conventional bearings as they provide vibration damping and do not require lubrication, leading to lower maintenance. The design allows the tension strap to pass through to the center of the hub to minimize strap redirection and reduce complexity of the blade retraction system.



The use of a homo-kinetic gimbale hub was also incorporated into the design. Gimbale hubs have distinct advantages that alleviate structural and aero-elastic issues. The gimbale hub is used to provide relief for the 1/rev blade flapping loads in the same manner as for a teetering rotor. The ability of the entire hub to rotate, therefore, virtually eliminates the Coriolis forces that are induced by blade flapping, and thus reduces in-plane bending moments and lead-lag forces.

Rotor Tilting Mechanism

Another key feature of the *Excalibur* is its stationary engine rotor tilting mechanism, where the engine always remains horizontal, and only the rotor system and secondary transmission are tilted. This design offers a significant advantage as it is both simpler and safer. Accessories attached to the engine, including fuel, electric, and hydraulic lines, no longer need to be designed to rotate at the nacelle, resulting in a more elegant design. From a safety standpoint, this system also ensures that hot engine exhaust gasses are continuously directed rearward and, therefore, do not burn to takeoff surfaces or injure persons that might be under the vehicle while in hover.

Exceptional Performance

Excalibur offers many significant performance advantages over other vertical lift aircraft. In particular, its high speed cruise capability. The *Excalibur* provides strategic advantages when it comes to performing missions in a timely manner,

with greater range and endurance while requiring less fuel. This leads to a more economical aircraft. Key features of the aircraft include:

Increased Speed: The RFP requirement is for a max continuous speed of 190–270 kts. The ability to cruise at 225 kts over distances of 500 nm, with a dash speed of 330 kts, ensures that the mission is completed quickly and efficiently.

Longer Range: *Excalibur* satisfies the RFP requirement of 500nm. Because of its higher cruise efficiency, it has a combat radius 52% further than the UH-60A Black Hawk, a helicopter with a similar empty weight.

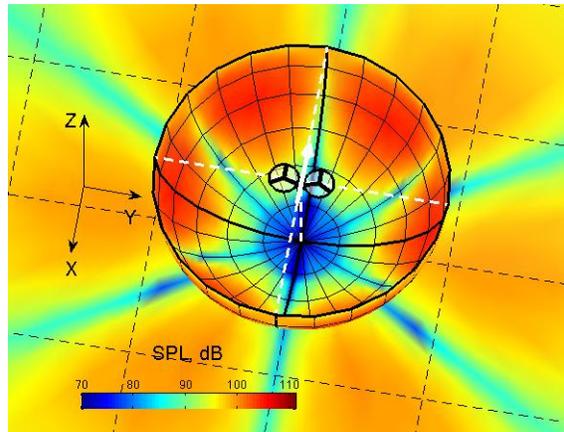
Fuel Efficient: With its ability to fly further and faster, *Excalibur* offers a great increase in its fuel efficiency over all previous helicopter or tiltrotors

Optimized Rotor Design: The ability to change rotor diameter results in a propulsive efficiency of 85% while maintaining a hover power loading of only 7.4 lb/hp, greater than many utility helicopters.

Survivability: Low rotor disk loading, high tip speeds, and high rotor inertia provides good autorotational capability. Also, the reduced diameter rotors in forward flight make conventional airplane landings possible without compromising operational safety.

HOGE Capability: HOGE at MGTOW is ensured at the RFP-required 6K95 with a good thrust/operating margin for maneuvers. This capability is currently unmatched by today’s current tiltrotor aircraft.

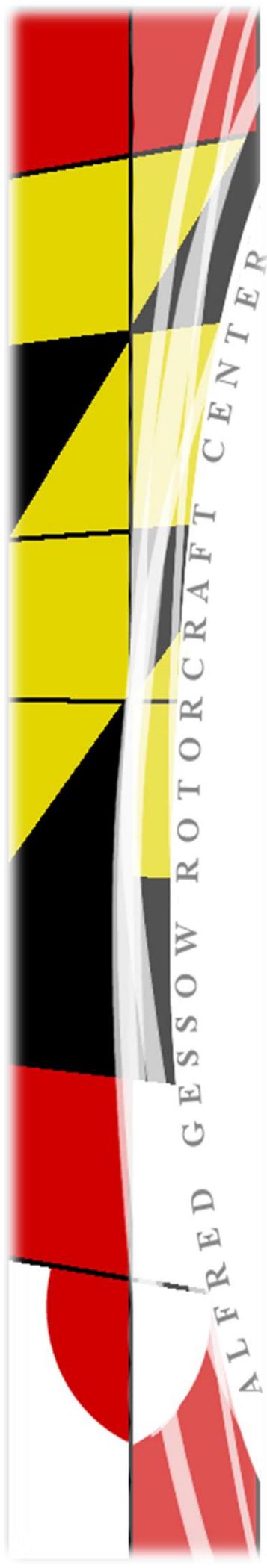
Quieter: The low disk loading and high aspect ratio blades means *Excalibur* is much quieter than current tiltrotors and meets ICAO Level 4 noise requirements.



Acoustic Signature of *Excalibur* in Hover

Engine and Transmission

Excalibur utilizes an innovative engine and transmission configuration unlike other tiltrotor aircraft, which have full tilting engine/transmission assemblies. These designs present significant technical challenges, because lubrication



systems, generators, cooling systems, and hydraulics must operate over a wide range of nacelle angles. *Excalibur* has engines that remain horizontal in all flight modes and only the rotor hub and second stage transmission need to be tilted. The engines also operate at a lower SFC than many other engines with similar power ratings, enabling rotor speed to be decreased by up to 10% through engine speed variations.

Mechanically simple design eliminates the redesign of generators, cooling systems, and other engine mounted accessories

Rearward directed exhaust gasses eliminate danger to personnel during search and rescue.

Avionics

The *Excalibur* utilizes the state-of-the art flight controls and avionics. The system is capable of displaying any and all necessary information to the pilot while minimizing his/her workload. *Excalibur* employs an all Rockwell Collins avionics system that is triply redundant through the use of an air data altitude and heading reference system as well as traditional analog instruments as emergency backups. The all-glass cockpit has five flight displays that can be used interchangeably and provide state-of-the-art features such as traffic collision avoidance system, terrain awareness warning system, and NEXRAD weather radar overlay for all terrain and navigation maps.



The advanced automatic flight control system also ensures that operational limitations are not exceeded by preventing the pilots from performing maneuvers that could cause structural, transmission, or engine damage. The pilot/co-pilot controls also make use of force feedback from the control surfaces to enable precision control.

Mission Capable

The features of *Excalibur* are driven to ensure true multi-mission capability. State-of-the-art tiltrotor design, including variable diameter rotors, stationary engine rotor tilting, bend-twist coupled composite wing structure, and enlarged load volume, ensure that *Excalibur* can complete all missions more effectively than any other VTOL aircraft.

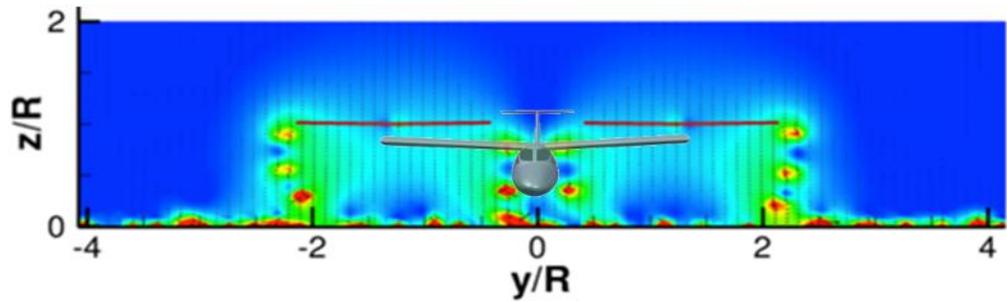
High cruise speed and high maximum level flight speed make the *Excalibur* ideally suited to search and rescue missions.



Large cabin interior provides room for two stretchers while comfortably accommodating two medical personnel and medical equipment.

The easily reconfigurable design seats 6 fully-equipped troops with equipment, and the large door and low floor level allow unhindered ingress and egress.

Benign Brownout Signature compared to contemporary tiltrotors from the low disk loading and low downwash velocities.



Low noise levels from the retracted rotor blades in forward flight ensure a quieter ride and lower noise signature.

Ability to take off and land in airplane mode means that even larger payloads can be carried than taking off in helicopter mode.

Conclusion

Excalibur's design is optimized to ensure the greatest multi-mission flexibility making it the ideal vehicle for completing search and rescue, insertion, and resupply missions. The *Excalibur* VDTR expands upon a new direction in VTOL development. Design parameters are custom tailored to ensure that RFP requirements are not only met, but well exceeded. *Excalibur* offers cutting-edge performance and safety, while exceeding the RFP requirements for payload, range, and speed. *Excalibur* heralds a new generation of multirole fast-response/SAR/medium-lift rotorcraft.

Excalibur – The cutting edge of tiltrotor technology, flying further, higher, and faster.

1 Introduction

Tiltrotors have historically been associated with levels of performance that are not as good as helicopters for what helicopters normally do (i.e., hover and fly at low speeds with great efficiency) and inferior to airplanes for what they do (i.e., fly fast over long ranges with good payloads). The challenges in the design of a single aircraft that can operate in both flight regimes has led to concepts that have many compromises in performance and other capabilities, to the point that they are usually operationally substantially inferior to both helicopters and to airplanes. Through the process of this design, the team recognizes that a tiltrotor is always a mix of trade-offs and fully understands these challenges. The proposed *Excalibur* tiltrotor design with its variable diameter rotor concept attempts to take such a class of aircraft into the next generation, creating an aircraft that truly deserves the reputation of one that has the full capabilities of a helicopter and also most of the capabilities of airplane. The current design takes the next step towards eliminating many of the compromises that have historically plagued tiltrotor designs. The demands being placed on VTOL aircraft will require increasingly new and innovative solutions, as demonstrated by the release of the Army's Joint-Multi-Role (JMR) initiative. The requirements pointing towards the need for quantum advances in the state-of-the-art for vertical lift technologies. The *Excalibur* tiltrotor is designed to fulfill these requirements and bring VTOL flight to the cutting edge of performance.

2 Vehicle Configuration and Selection

In this section, an outline of the considerations that went into the design of the vehicle discussed. The main design philosophy taken was focused towards the multi-mission capability of the aircraft. The RFP made it clear that the vehicle to be designed must be able to be configured easily and quickly for a wide variety of missions. This goal inevitably led to a careful consideration of several different vehicle configurations. A tiltrotor configuration was subsequently chosen that would meet all requirements established in the RFP, as well as having the technology readiness to be developed and deployed in a relatively short period of time.

2.1 Mission Requirements

The RFP proposed three missions that the vehicle to be designed must successfully perform. The different attributes of the three missions are described as follows:

Search and Rescue – Some of the major conditions that affect the ability of the vehicle to perform this mission include: the ability to carry four crew with two medical litters and two medical personnel plus equipment, a hover out of ground effect (HOGE) at 6K95, a radius of action of 225 nm, and a return flight of 225 nm at maximum continuous power within 50–70 minutes. This requirement means that the aircraft must be capable of reaching speeds between and 190 kts and 270 kts. This range of forward speed is difficult for conventional helicopters because they can only reach max speeds around 170 kts.

Insertion – The insertion mission is different from the search and rescue mission. This mission requires that the vehicle be able to carry 4 crew plus 6 passengers and equipment totaling 4,000

lbs a total of 250 nm, and then return to base with the 4 crew members. This is the main sizing mission for the vehicle as it has the highest payload requirements and has a significant radius of action. The internal payload of 4,000 lbs consequently results in the overall size of the being increased to accommodate the payload, range, and fuel to satisfy the mission requirements.

Resupply – This mission is a variation of the insertion mission. It requires that the vehicle be able to carry 3,000 lbs of internal payload to a range of 250 nm, and then return with 3,000 lbs of alternate internal payload. This mission initially appears to be the most difficult mission to accomplish because the internal payload is transported a total distance of 500 nm. However, the total internal payload is actually 1,000 lbs less than that of the insertion mission.

To put these three missions into proper perspective, it is important to determine the key design drivers for each mission and how they may impact the overall design of the vehicle. The search and rescue mission, for example, places an emphasis on speed. The vehicle will need to have the capability to return the injured person/persons within the “Golden Hour,” which is defined as 50 to 70 minutes on the return flight of 225 nm. Both the insertion and resupply mission require a relatively large payload be carried a long distance. This requires that the vehicle have good cruise efficiency. None of the missions requires any extended periods of hover, and more than 90% of all the missions are in cruise flight. All the missions had to meet the very stringent design constraint of hovering for 10 min at 6K95 OGE. Analysis of the RFP showed that the final design vehicle should have the following attributes: The vehicle should have a wing with high L/D , low drag fuselage, large internal storage area, high maximum speed, good hovering efficiency, ability to quickly load and unload passengers, and be easily reconfigured between missions. Accomplishing all of these objectives in one vehicle is a significant challenge as some of these capabilities are conflicting. For example, increasing internal cabin storage volume will increase the fuselage dimensions and so increase parasite drag. The issues related to these types of design trades is represented throughout the remainder of this report.

2.2 Examination of Different Configurations

As with the design of any aircraft, it is important to determine what vehicle configurations provide the capability to perform the desired mission profiles. The team, therefore, decided to examine and compare the capabilities of the conventional helicopter against, compound helicopters, tandem rotor helicopters, and various types of convertible rotor vehicles, e.g. the conventional tiltrotor.

2.2.1 Conventional Helicopters

The first design examined was the conventional single main rotor helicopter with a tail rotor. This design is extremely reliable with low production and maintenance costs. The conventional helicopter design offers many advantages, because they have good endurance, low empty weight fraction, as well as low risk in their design. Conventional helicopters are the most widely used configuration, and there are much historical and experimental data to aide in the design of new aircraft. However, conventional helicopter configurations have some major disadvantages that often result in trade-offs in their design. For example, they tend to have poor range efficiency and low cruise and maximum speed capabilities. This outcome is mainly a consequence of the difficulty in designing a rotor system that is efficient for both hover and cruise. Rotors experience asymmetric lift as they fly faster and eventually encounter retreating blade stall and drag divergence of the advancing blade. For the current requirements, a conventional helicopter would be limited to the lower speeds and the ability to perform the search and rescue mission and return within the “Golden Hour” would be all but impossible.

2.2.2 Compound Helicopters

Compound helicopters can increase both the range efficiency and speed capabilities over conventional designs. There are traditionally three ways to compound a helicopter: by the addition of a lift-augmenting wing, by the addition of a propulsive thruster, or by combined lift and thrust augmentation. Technology demonstrators such as the Sikorsky X2 and the Eurocopter X³ are shown in Figure 2.1 to illustrate two different methods of compounding.



Figure 2.1: a) Sikorsky X-2 and b) Eurocopter X³ compound helicopter technology demonstrators

Lift and/or thrust compounding allows the helicopter to fly faster and further but at the cost of a higher empty weight fraction and increased power requirements. A lift compounded helicopter utilizes a small wing to offload the lift the main rotor. This lift augmentation alleviates some of the effects of retreating blade stall. However, drag divergence of the advancing blades still becomes a hurdle to flying faster. Therefore, thrust compounding is often incorporated but at the expensive of increased power and fuel requirements. This design leads to lower endurance efficiencies and lower payload capabilities. A compound design would allow the vehicle to achieve the necessary speed and range requirements, but would add a significant amount of complexity to the overall design. This added complexity would reduce reliability while increasing manufacturing costs. In addition, a compound design would add a significant amount of empty weight, increasing the empty weight fraction. However the added lift generated in forward flight from compounding would most likely counter the losses and payload might not be greatly affected.

The confidence level in the design of these vehicles is relatively low and there are no compound helicopters currently in production for either the military or civilian markets. However, there is no shortage of historical or experimental data for these aircraft. Also, with the success of the Sikorsky X2 and the Eurocopter X³ (shown in Figure 2.1), there has been renewed interest in such designs and a closer look at their capabilities is required^{1,2}.

2.2.3 Tandem Rotor Helicopters

The tandem rotor helicopter configuration utilizes two rotors situated one in front of the other. Generally, these designs are used for carrying large payloads because two rotors allow for a wider range of center of gravity travel and unbalanced loads on the vehicle. Such vehicles have low downwash, a low empty weight fraction, and a considerable amount of interior volume. However, the tandem configuration suffers shortcomings that hinder it as a viable design candidate for the present RFP. Tandems have a high parasitic drag that inevitably leads to low fuel economy and low cruise speeds. Because the mission profiles in the RFP demand a delicate

balance between range, speed, and payload capacity, the tandem cannot deliver the desired spectrum of performance. In particular, they cannot achieve the speeds close to the minimum required speed the RFP dictates for the Search and Rescue mission of 190 kts. Tandem rotor helicopters are also traditionally larger than what is required for the RFP, e.g. both the CH-46 and CH-47 (Figure 2.2) can carry more than 25 passengers. The cost of production is also considerably higher than the equivalent single main rotor tail rotor design. The cost of such a platform, however, is lower than that of the compound helicopter and of the tiltrotor. Ultimately the tandem does not offer an innovative or effective solution to the requirements of this RFP.



Figure 2.2: CH-47 tandem rotor helicopter

2.2.4 Convertible Rotor Aircraft

The main advantage of using a tiltrotor or tiltwing design, often termed convertible rotor aircraft, is the ability to takeoff vertically (like a helicopter) and transition to forward flight (and fly like an airplane). This capability allows the tiltrotor to achieve much higher forward flight speeds than for a conventional helicopter. The main drawbacks of a tiltrotor design are a higher empty weight fraction, cost of production, and complexity of the design. The increased empty weight fraction, coupled with the negative download produced from the wing in the rotor wake, yields a reduction of total payload or degradation in rotor hovering performance. There has been a great deal of research into tiltwing aircraft that can tilt the wing along with the rotors to eliminate the issues of download. However, these designs tend to be complex and carry a significant amount of weight in the tilting actuation systems. There have been nearly a dozen successful research programs on convertible rotor systems, mainly the XV-15, which led to the development of both the V-22 *Osprey* and the BA-609 civilian tiltrotor³. Many scientists and engineers agree that tiltrotors fill a unique niche as they are neither helicopter nor airplane but have certain advantages of both. Dr. Leishman⁴ agrees that "...clearly any aircraft that removes or otherwise limits a dependency on concrete runways gives any operator, military or civil, an unparalleled operational capability and flexibility."

2.3 Analytical Hierarchy Process and House of Quality

When presented with a decision on a specific configuration, it is important to make a choice based on an explicit evaluation of the criteria for the desired configuration. Establishing the evaluation criteria is, therefore, the first step, which came about through the analysis of the RFP requirements. Each of these requirements must be evaluated then on their relative importance against each other, the fundamental question is: What concepts meet the objectives of the top-level requirements? This question is answered by determining the feasible concepts through the analysis of different vehicle configurations.

To evaluate the different concepts and determine how they meet the objectives set forth by the RFP, an Analytical Hierarchy Process (AHP) was used. This is a mathematical technique for multi-criteria decision making and is based on pair-wise comparisons between competing alternatives. This process allows for the consideration of both objective and subjective opinions about various designs and the results from the AHP provide relative weights that can be used in a house of quality. Seven different design criteria were chosen that represent the objectives of the RFP: speed, payload, range, cost, vehicle reconfigurability, noise, and reliability. These figures of merit (FOM) are ranked with their relative importance, based upon the voice of the customer through a prioritization matrix and pair wise comparisons, as shown in Table 2.1.

Table 2.1: Representative FOM Prioritization Matrix

	Speed	Payload	Range	Cost	Reconfigurability	Noise	Reliability	RANKING
Speed	0.100	0.063	0.105	0.113	0.116	0.125	0.133	0.108
Payload	0.300	0.189	0.211	0.151	0.145	0.250	0.178	0.203
Range	0.200	0.189	0.211	0.226	0.232	0.250	0.178	0.212
Cost	0.100	0.142	0.105	0.113	0.116	0.063	0.133	0.110
Reconfigurable	0.150	0.227	0.158	0.170	0.174	0.125	0.178	0.169
Noise	0.050	0.047	0.053	0.113	0.087	0.063	0.067	0.068
Reliability	0.100	0.142	0.158	0.113	0.130	0.125	0.133	0.129

This prioritization matrix is used to generate and establish the qualities that will be used to take a decision by ranking each parameter with a relative importance against another. These columns are then normalized and the rankings averaged across the rows. This outcome represents the relative importance between parameters but does not necessarily reflect that any one of the parameters is not important. These rankings are more easily seen through the use of a spider diagram where each FOM is placed on an axis and outward position of any criteria ranking is favorable, as shown in Figure 2.3.

This prioritization matrix was also used to compare the effectiveness of the various feasible designs against each other in descending order for each of the different FOM metrics. A relative weighting of each of the different vehicle designs was then obtained by applying the prioritization matrix of the FOM for the various designs, as shown in Figure 2.4. Once again, the outward on the spider diagram represents a favorable trait. Such results were used to determine which vehicle configuration was the most viable option. The diagram shows that a conventional helicopter offers the greatest benefits in cost and reliability, while the tandem offers benefits in reconfigurability and payload. However, the tiltrotor demonstrates exceptional speed and range capabilities while maintaining the benefits of increased payload. The tiltrotor was, therefore,

chosen to meet the requirements of the RFP because it most closely matched the prioritization diagram shown in Figure 2.3. Although the figures shown do not convey every step in the analytical hierarchy process, they are representative of the steps that were taken to determine the most feasible vehicle design.

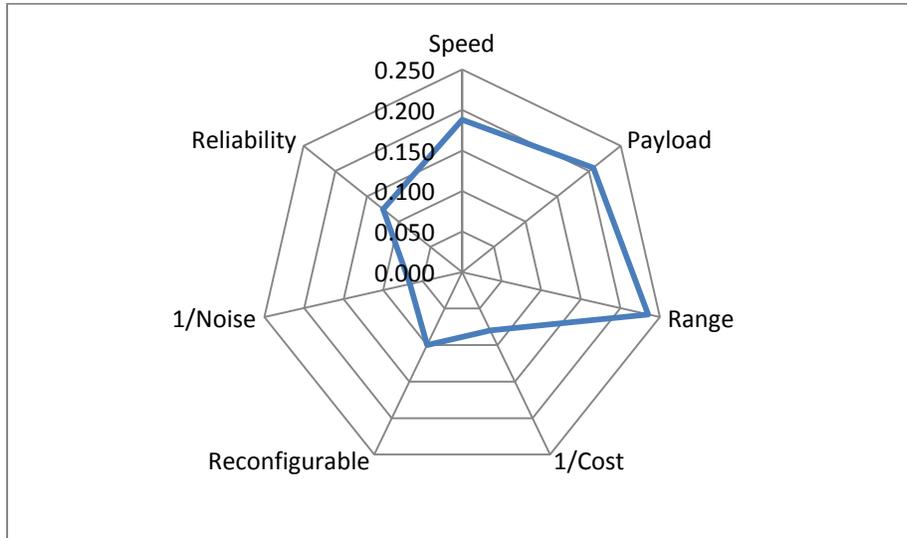


Figure 2.3: Relative Importance of customer evaluation criteria

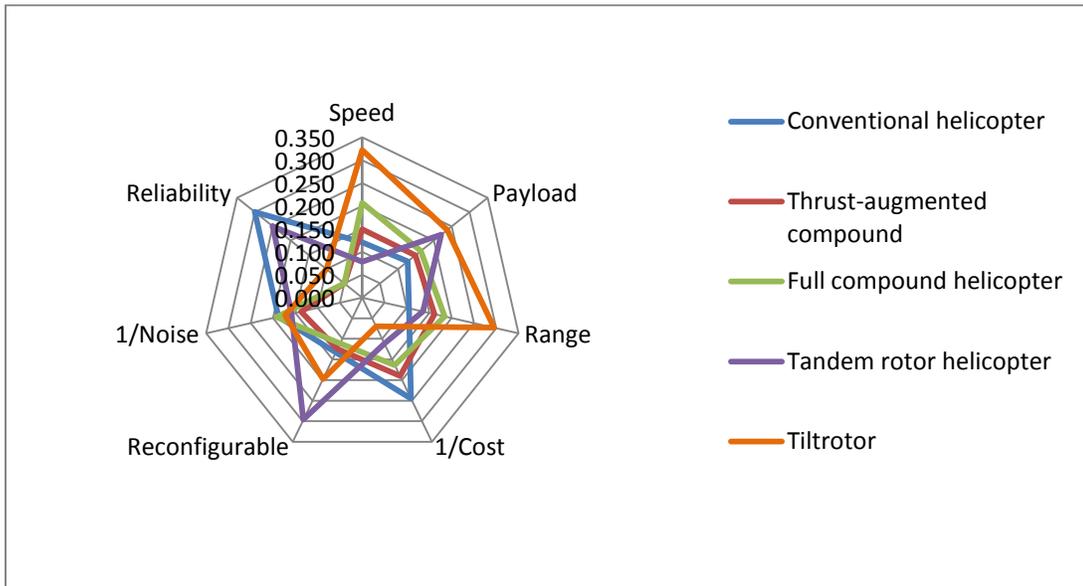


Figure 2.4: Spider diagram representing the relative benefits of one configuration of rotorcraft over another

Once the vehicle configuration was selected, a house of quality (see Table 2.2) was completed to best determine the engineering requirements that would require the most focus as they related to the requirements of the RFP. This house of quality showed that parameters such as engine configuration/location, power loading, and wing aspect ratio would prove to be three most important aspects that would influence the design.

Table 2.2: House of quality

		ENGINEERING REQUIREMENTS																							
		Aerodynamics								Mechanical Design						Safety		Fuselage Design							
		Empty weight fraction	Hub drag	Disk loading	Power loading	Cl/b	Autorotative index	Propulsive efficiency	Tip speed	Wing AR	Engine SFC	Tilting mechanism	Engine location/configuration	Transmission design	Avionics	Material selection	Manufacturability	Flight control system	Health and usage monitoring	Internal fuselage area	Parasite drag	Negative downwash/ download	Ballistic tolerance	Active noise suppression	
		Weights (1-5)																							
Operational Requirements	Range 500nm	5	2	2	2	3	2	0	3	1	3	3	1	1	1	0	0	0	0	1	2	1	1	0	
	Hover OGE 6K95 @ MGTOW	5	2	1	3	3	3	2	1	3	1	1	1	2	1	0	0	0	0	1	0	3	1	0	
	Cruise speed 250 kts	3	1	2	2	3	1	0	3	1	3	2	1	2	1	0	0	0	0	1	2	0	1	0	
	225 nm @ Max continuous power	5	1	2	2	3	1	0	3	1	3	2	1	2	2	0	0	0	1	0	1	3	0	1	0
	4 crew + 6 pax + eqpt = 4700 lbs internal	5	3	0	2	3	2	2	2	2	3	1	1	1	0	0	0	0	0	3	0	0	0	0	0
	Multi-mission capable	4	1	0	0	1	1	0	1	0	1	1	2	1	0	1	0	0	1	0	3	1	1	2	0
Search and rescue capable	5	1	0	2	2	2	1	2	1	2	2	2	1	0	1	0	0	1	0	2	1	1	1	0	
Design Requirement	Level 4 noise requirments	4	0	1	2	2	2	0	0	3	1	1	0	1	1	0	0	0	0	0	0	1	0	3	
	inter-changeability of parts	3	0	0	0	0	0	0	0	0	0	0	2	2	1	1	3	0	0	2	0	0	1	0	
	Reconfigurability	3	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	3	0	0	1	0	
	IR supression treatment	3	0	0	0	0	0	0	0	0	0	1	0	3	0	0	2	0	0	1	0	0	0	0	
	Rubber CT7-8A engine	4	1	0	1	1	1	1	1	1	1	3	1	3	1	0	0	0	0	1	0	0	0	0	
Cost and Development	Baseline vehicle selling price	3	2	0	2	2	1	1	2	1	1	2	2	2	2	3	2	2	1	2	1	1	2	1	
	Hourly operating cost	3	1	0	1	1	0	0	2	0	0	3	1	1	1	0	1	1	0	0	1	0	0	0	
	Hover fuel efficiency	2	1	1	3	3	2	2	1	1	2	3	1	2	1	0	0	0	0	1	0	3	1	0	
	Airplane mode fuel efficiency	3	1	2	1	3	1	1	3	1	3	3	1	2	1	0	0	0	0	1	3	0	1	0	
	Maintenance costs	4	0	0	0	0	0	0	0	0	0	0	3	3	2	1	2	2	1	2	1	0	0	2	1
	Pollution	2	0	0	0	1	0	0	1	0	1	2	0	2	0	0	2	1	0	0	1	1	0	0	
	Total life-cycle costs	4	0	0	0	0	0	0	1	1	1	2	2	2	1	1	2	2	1	1	0	0	1	1	
Safety Requirements	Autorotation capability	2	1	1	3	2	3	3	1	2	2	0	1	1	0	0	0	0	1	0	0	1	2	0	
	Mean time between failure/repair	4	0	0	0	0	0	0	0	0	0	0	3	2	1	1	2	1	1	3	0	0	0	1	
	Crashworthiness	4	0	0	1	0	0	2	0	0	1	0	1	1	0	0	3	0	0	1	0	0	2	0	
	Complexity	2	0	0	0	0	0	0	0	0	1	0	3	3	2	2	3	1	1	1	0	0	1	1	
	Survivability	4	0	0	1	1	2	3	0	0	1	0	1	1	0	1	3	0	1	1	1	0	0	3	1
	Detectability	1	0	0	1	0	1	0	0	1	1	0	0	1	0	0	2	0	0	0	1	0	0	2	3
Raw Score		75	45	106	129	94	65	103	76	118	116	113	144	68	38	88	37	40	33	107	59	48	79	36	
Scaled		0.52	0.31	0.74	0.90	0.65	0.45	0.72	0.53	0.82	0.81	0.78	1.00	0.47	0.26	0.61	0.26	0.28	0.23	0.74	0.41	0.33	0.55	0.25	
Relative Weight		4%	2%	6%	7%	5%	4%	6%	4%	6%	6%	6%	8%	4%	2%	5%	2%	2%	2%	6%	3%	3%	4%	2%	

3 Preliminary Tiltrotor Sizing

The RFP defined three very specific missions, each playing a part in the sizing of *Excalibur*. The first mission (search and rescue) requires the vehicle to rescue injured persons and return 225 nm within 50–70 minutes, defined as the “golden hour.” The second and third missions, insertion and resupply, require a payload of 4,000 lbs and 3,000 lbs, respectively, to be carried. Considering the requirements of all three missions, *Excalibur* is designed to be capable of high forward flight speeds, good hover efficiency at hot and high conditions (6K95), unprecedented cruise efficiency, and with a good acoustic signature. Because a tiltrotor is a hybrid of a fixed-wing aircraft and a helicopter, a new method was developed for sizing the aircraft. This method included changes to the estimation of the mission weights and weight fractions, which incorporates the empty takeoff weight, payload, the power requirements and the fuel weight. This new sizing method was conducted for each of the three missions specified in the RFP. The rigorous process of initial sizing seeks to determine the most difficult mission in terms of the gross takeoff weight. The limiting mission provided the best estimates of the initial size of the aircraft and was defined as the most difficult of the three RFP defined missions.

3.1 Description of the Algorithm

A preliminary design code, based on Tishchenko’s methodology¹, was developed for the initial sizing of tiltrotors. The Tishchenko method constitutes basic methodologies and algorithms that have validated accuracy for determining the size and weight of a rotorcraft. To make Tishchenko’s method applicable for tiltrotor designs, it was necessary to institute several changes. The initial modification to the method involved the removal of the tail rotor related terms, which included the tail rotor power, tail rotor shaft and tail gear box weight, etc. It was also necessary to account for the change in power required for a proprotor in forward flight as compared to a conventional rotor. The weight formulae in Tishchenko’s method were modified using the equations from the NASA Design and Analysis of Rotorcraft² (NDARC) code to account for the wing and spinner weights. The NDARC code was also used to account for the addition of wing-related terms, which included the wing contributions to lift and drag and the addition of a download force during hovering flight. Modifications were also made to add the spinner weight, which is used to minimize hub drag during forward flight. Because the RFP specifies a rubber engine (based on the CT7-8A), the engine characteristics were defined based on the NDARC engine model. Further refinements were made to account for the weight of additional tiltrotor design features such as the interconnecting drive shaft and rotor system (see Section 6).

The algorithm used is presented schematically in Figure 3.1. The design code performs an iterative process that begins with the specification of the required payload, range, and cruise speed. The user inputs a number of initial parameters that are not given explicitly in the mission requirements, such as the estimated proprotor figure of merit, propulsive efficiency, transmission efficiency, proprotor disk loading, blade and wing aspect ratios, tip speed, and number of blades. These parameters are refined to have precise values through optimization of the requirements for efficient forward flight and hover, explained in greater detail in Section 12.

The following steps were used in the iterative procedure of the sizing methodology:

1. Disk loading, number of blades, and proprotor blade aspect ratio in hover are taken as inputs. Other inputs include the figure of merit in hover, wing download, wing aspect ratio, propulsive efficiency and transmission efficiency.
2. An initial estimate for the gross takeoff weight (GTOW) is determined based upon historical data.
3. With the initial GTOW and disk loading, the proprotor diameter required to hover is calculated.
4. With the known blade aspect ratio, and calculated proprotor diameter, the blade chord is calculated in helicopter mode. This completes the proprotor sizing.
5. Power required to hover is calculated based upon GTOW, disk loading, figure of merit, and wing download.
6. Wing span is calculated based on geometrical constraints. With a given wing aspect ratio, the wing chord is then calculated. Using the NDARC equations, these factors give the wing weight.
7. The calculated flat plate drag area results (see Section 12) in conjunction with the wing dimensions, gives the cruise power requirements.
8. With the hover and cruise power requirements known, the fuel weight is calculated.
9. Tischenko's equations, modified for tiltrotor applications, are then used to calculate the component weights, which ultimately gives the empty weight of aircraft.
10. At the end of the first iteration a new GTOW is obtained, and this new value is used as an input to calculate the proprotor diameter in the next iteration.

This procedure is repeated until the code converges based on the relative error between the initial value and the final value of GTOW. This procedure was carried out for the three mission profiles to identify the most critical mission, which determines the sizing of the aircraft.

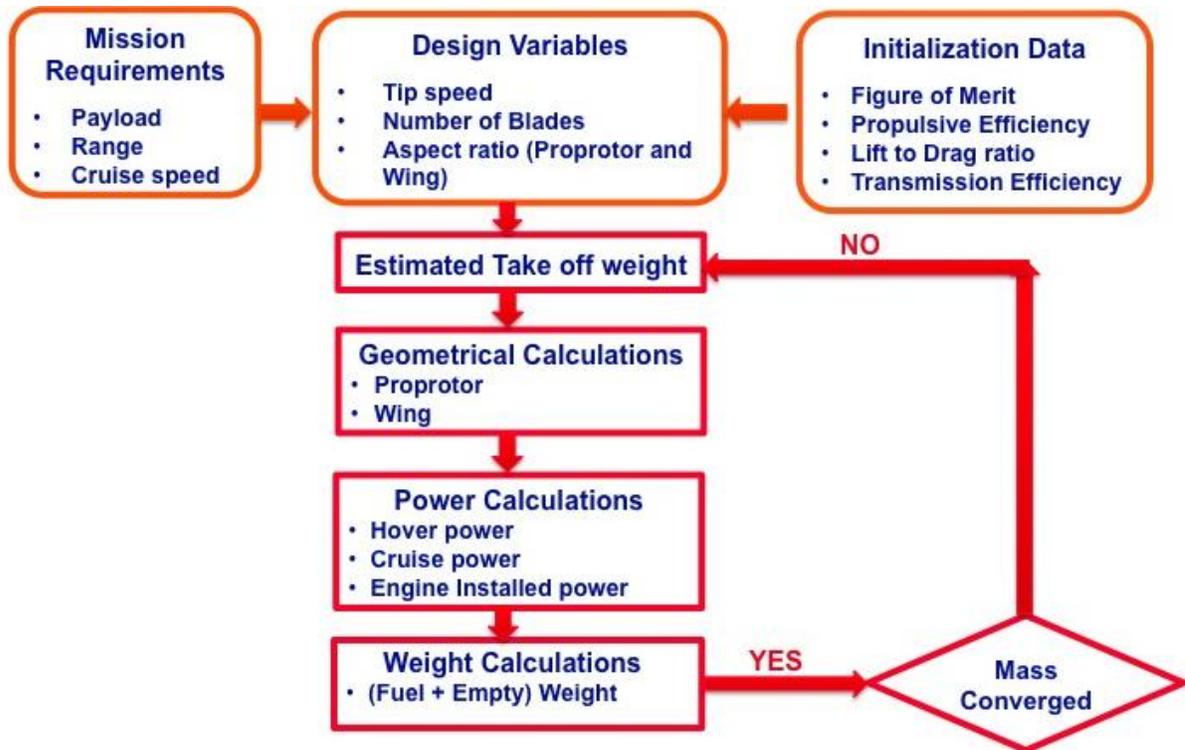


Figure 3.1: Block diagram of initial sizing code

To validate the sizing methodology, the results of the empty weight were compared to the results from the NDARC code.

Common elements of all sizing codes are the calculation of the empty weight and the fuel weight. The empty weight is calculated as the sum of the component weights and the fuel weight is obtained from the mission profile and the engine characteristics.

The sizing code was validated by comparing the predictions of the component weights with those of NDARC. The formulae of the component weights of the proprotor blades, proprotor hubs and the wing were modified to give the same weights as those calculated from the NDARC weight formulae.

The Mission 2 outputs from the UMD code such as MGTOW, rotor and geometrical data, were passed to NDARC. Table 3.1 shows a comparison of the weights predicted by the two codes. While there are differences in the group weights, the difference in the empty weights is about 7%. The percentage difference is defined as

$$= (\text{Empty Weight}^{(\text{NDARC})} - \text{Empty weight}^{(\text{UMD sizing code})}) / (\text{Empty weight}^{(\text{NDARC})})$$

This outcome validates the sizing results obtained from the UMD code, and confirms that outcomes for both codes will generally be in good agreement.

Table 3.1: Comparison of major component weights between NDARC and UMD sizing code

Major component groups	NDARC, lbs	UMD sizing code, lbs	Percentage difference
Rotor group	1,171.1	1,148.6	1.9 %
Wing group	1,037.4	1,224.4	18.0%
Fuselage group	1,649.0	1,715.4	4.0%
Propulsion group	2,107.9	1,860.9	14.7%
Total empty weight	10,888.2	10,159.9	6.7 %

3.2 Identification of the Sizing Mission

Before the parametric studies were performed, an analysis was conducted to determine the most demanding mission profile. The most demanding mission is defined in terms of the fuel and payload required because these factors dictate the takeoff weight and the geometric sizing of the vehicle. Each mission was evaluated individually at 6K95 operating conditions, and the values of initially assumed disk loading, number of blades ($N_b = 3$) and tip speed ($V_{tip} = 689$ ft/s) were fixed. As shown in Figure 3.2, shows the maximum takeoff weight for a disk loading of 12lb/ft² and a range of blades aspect ratios from 10 to 16.

Figure 3.2 also shows that for the same disk loading the insertion mission has the highest maximum takeoff weight and power required for all values of blade aspect ratio. This result shows that the insertion mission is the most crucial in determining the maximum takeoff weight and geometrical sizing of the vehicle. This outcome is further verified in Figure 3.3, where the rotor diameter required for the insertion mission is the largest. The insertion mission was, therefore, chosen as the limiting mission in the aircraft sizing and parametric studies, as described next.

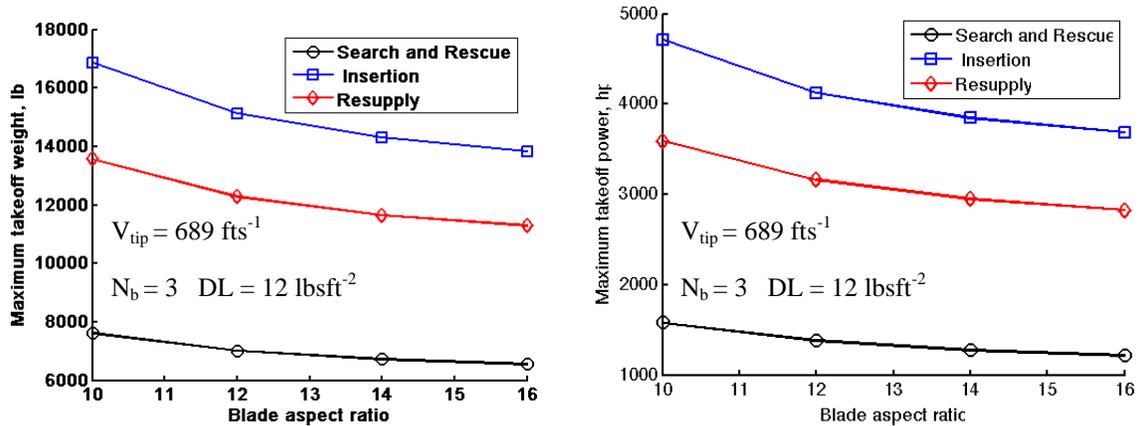


Figure 3.2: Blade aspect ratio versus a) maximum takeoff weight b) maximum takeoff power for the three missions

3.3 Parametric Studies

Based on the previous study, the final configuration of *Excalibur* was decided on the basis of a comprehensive parametric study using the insertion mission. The blade aspect ratio, number of proprotor blades, disk loading and the hovering tip speed were chosen as primary design variables. These parameters were varied to better understand their affect on the sizing of the aircraft.

To achieve lower downwash velocities in hover, the goal was to maintain a low disk loading, which requires a large proprotor diameter. This is at variance with the forward flight operating condition, where the proprotor requires a much smaller diameter to maintain good propulsive efficiency. Another goal is to have an acceptable stall margin for maneuverability, operations in inclement weather, and operations at high altitudes.

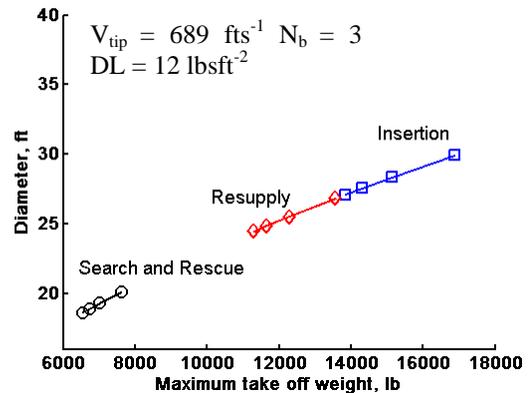


Figure 3.3: Rotor diameter vs maximum take-off weight

A parametric study was conducted using four different values disk loading ranging from 10 to 13 lb/ft². Similarly, the aspect ratio of the proprotor blades was varied from 10 to 16, while the tip speed and number of blades was fixed at 689 ft/s and 3 blades, respectively. The final values of disk loading, aspect ratio, number of blades, and tip speed was decided by examining the blade loading coefficient values and requires sufficient stall margin for maneuvers in helicopter mode.

3.3.1 Selection of Disk Loading (Hover)

Traditional tiltrotor concepts have employed high disk loadings, typically varying from 18 to 24 lb/ft². These values are almost twice those of conventional helicopters of similar weight. High disk loadings lead to excessive downwash velocities, resulting in unsafe operations during search and rescue missions. Moreover, high downwash velocities can cause brownout conditions, resulting in severe visual obscurations for pilots. Evaluation of the brownout signature will be

discussed in a greater detail in Section 12. Hence, for good hovering efficiency, safe working conditions for search and rescue personnel and safe operation when hovering in ground effect, a tiltrotor ideally requires a lower disk loading. In addition, a lower disk loading in hover allows for operation at a reduced tip speed for a constant blade loading, resulting in a reduced acoustic signature for the aircraft. A lower disk loading in conjunction with a larger rotor diameter also provides beneficial autorotational characteristics. An increase in disk loading results in an increase of the power required by the rotors which, adversely affects the fuel, engine, and transmission weights. A parametric study to understand the effect of varying disk loading in hover is shown in Figure 3.4.

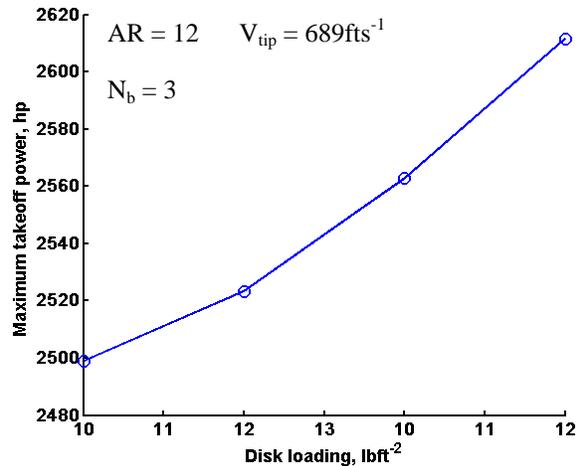


Figure 3.4: Maximum take-off power vs disk loading

to understand the effect of varying disk loading in hover is shown in Figure 3.4. It was observed that increasing the disk loading for a fixed aspect ratio, tip speed, and number of blades, increases the maximum take off power at 6K95. Although the benefits of a low disk loading are significant, a very low disk loading results in a large proprotor diameter, this outcome is also undesirable because it will give rise to a larger aircraft of higher weight and higher costs.

An optimized performance between the two flight regimes was obtained through the use of the Variable Diameter Rotor (VDR) concept. For *Excalibur's* design the final value of disk loading in hover is a trade off between the required stall margin, safe autorotational characteristics, rotor downwash, brownout concerns, and hovering efficiency. Other constraints imposed by the VDR system, and finally weight and cost limitations. The optimized value of disk loading 11 lb/ft.

3.3.2 Selection of Blade Aspect Ratio (Hover)

A higher aspect ratio blade achieves the benefits of reduced noise, lowers vibrations, and better fuel consumption through a reduction in solidity. The use of the VDR system means that a compromise has to be made between performance in hover and cruise. The majority of the time during missions is spent in is in forward flight, as specified by the RFP. A higher aspect ratio proprotor blade would result in decreased solidity for a fixed number of blades. Although a lower solidity is preferred for lower profile power losses, hover performance can be compromised in lieu of other benefits. A lower aspect ratio, for a given disk loading, tip speed, and C_T would result in a higher blade loading coefficient. This outcome is undesirable because it will reduce the stall margin. Because of the requirement to operate at 6K95, it is difficult to reduce C_T/σ . In the trade study, varying aspect ratio from 10 to 16 showed that an increased aspect ratio is beneficial for saving fuel weight and reducing the maximum takeoff weight, as shown in Figure 3.5. The final choice of blade aspect ratio is set by the disk loading and C_T/σ for a fixed tip speed and number of blades.

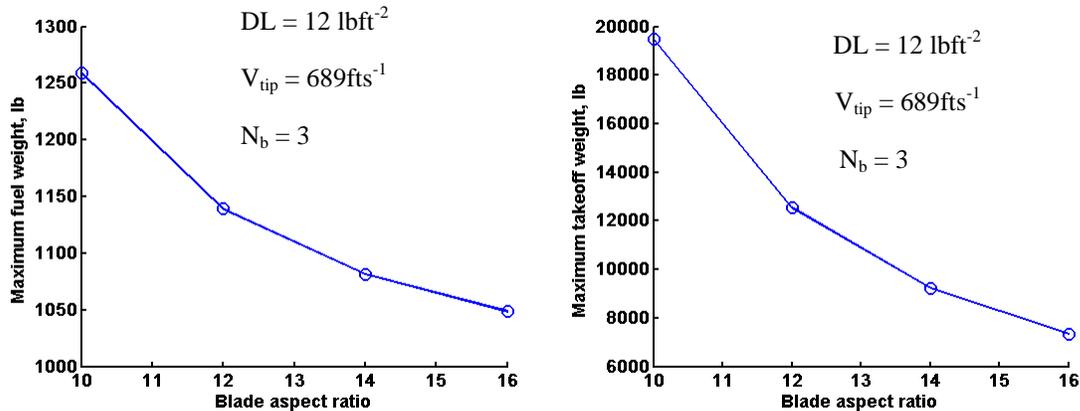


Figure 3.5: Effect of aspect ratio on a) fuel weight and b) max take-off weight

3.3.3 Selection of Number of Blades

Initial trade studies showed that increasing the number of blades increased the fuel weight and takeoff power requirements at 6K95, as shown in Figure 3.6. These results are obtained at a fixed $DL = 12 \text{ lb/ft}^2$, $AR = 12$ and tip speed (689 ft/s).

For a constant C_T , a superior stall margin is achieved by increasing the solidity of the proprotor. This dictates either increasing the number of blades or decreasing blade aspect ratio. Therefore, for a fixed aspect ratio, disk loading, and tip speed, the effect of increasing number of blades was studied.

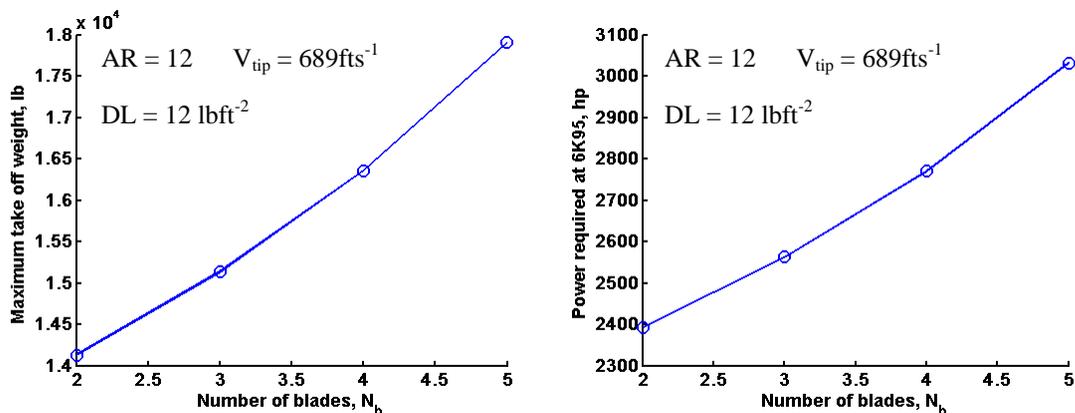


Figure 3.6: Variation of a) maximum take-off weight and b) power required versus number of blades

As shown in Figure 3.6, the fuel weight, power required, and maximum takeoff weight are affected adversely by an increase in the number of blades. Additionally, for a fixed aspect ratio and C_T , a higher number of blades will increase the acoustic signature of a tiltrotor. Acoustic studies performed in Section 13 using the Ffowcs-Williams Hawkins equation showed that the pressure variation using three blades falls within the constraints of RFP's noise requirements. The mechanical complexity of the retraction system and the motor driving the system also increases with increasing number of blades. Using more than four blades is therefore, undesirable for a variable diameter system because of the significant increase in complexity and hub weight. However, using a two-bladed rotor would not provide the necessary stall margin. A three-bladed

rotor would aid in reducing vibration, allow for a reasonable stall margin, and keep the acoustic signature low, while minimizing the complexity of the blade retraction system. A three-bladed rotor also adds to the reliability of the aircraft with the experience of past tiltrotors starting from XV-15 to the V-22 and then BA-609.

3.3.4 Selection of Tip Speed (Hover)

A higher tip speed in hover is beneficial in lowering the blade loading coefficient (C_T/σ) providing a higher stall margin for maneuvering. Additionally, higher tip speeds benefit the design by providing good autorotational performance, thus increasing the kinetic energy stored in the rotor system. However, for the same level of thrust, increasing tip speed will adversely affect the profile power and rotor noise. In forward flight, high tip speeds on a proprotor are constrained by the helical tip Mach number, which can result in compressibility effects and a reduction in propulsive efficiency. The hot-and-high conditions effectively lower the tip Mach number, helping to lower the Mach number on the proprotor in both hover and forward flight.

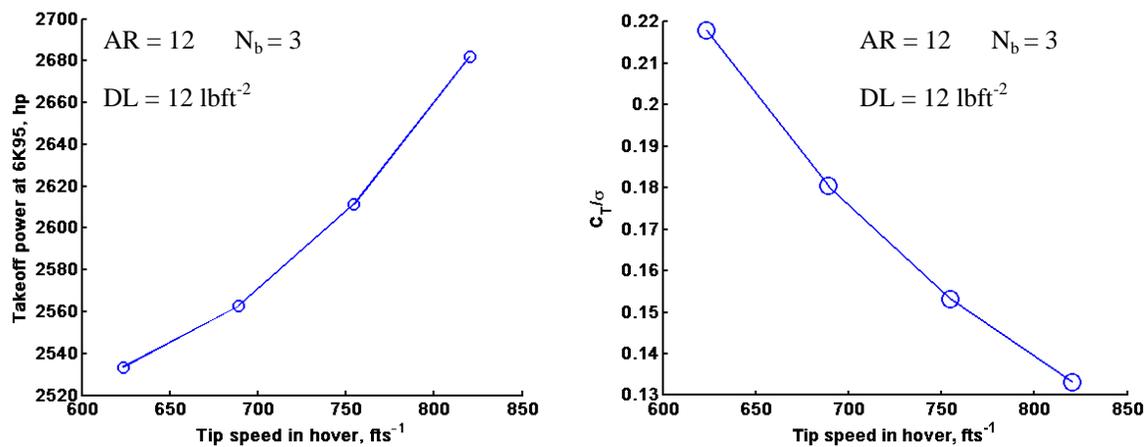


Figure 3.7: Variations in a) takeoff power and b) blade loading with tip speed

Reducing in power requirements will reduce the fuel required for the same payload and range. However, this outcome also results in an increase in torque required. Thus, increasing the tip speed lowers the gearbox torque required. As shown in Figure 3.7, increases in takeoff power and proprotor diameter do not significantly change for increases in tip speed. *Excalibur* can, therefore, afford to operate at higher tip speeds in hover because the VDR system lowers the tip speed in forward flight thus maintaining forward flight efficiency. This issue will be discussed in detail in Section 5.

3.3.5 Selection of Blade Loading (BL), C_T/σ

Blade loading is directly proportional to density altitude therefore, increasing density altitude reduces stall margins. This outcome directly translates into poor maneuver capability. A reasonable stall margin at 6K95 hover conditions is a compromise between the selection of disk loading, aspect ratio, number of blades, and hover tip speed. Parametric variations of different values of disk loading and aspect ratio for a fixed tip speed (807 ft/s) and a 3-bladed proprotor are given in Figure 3.8.

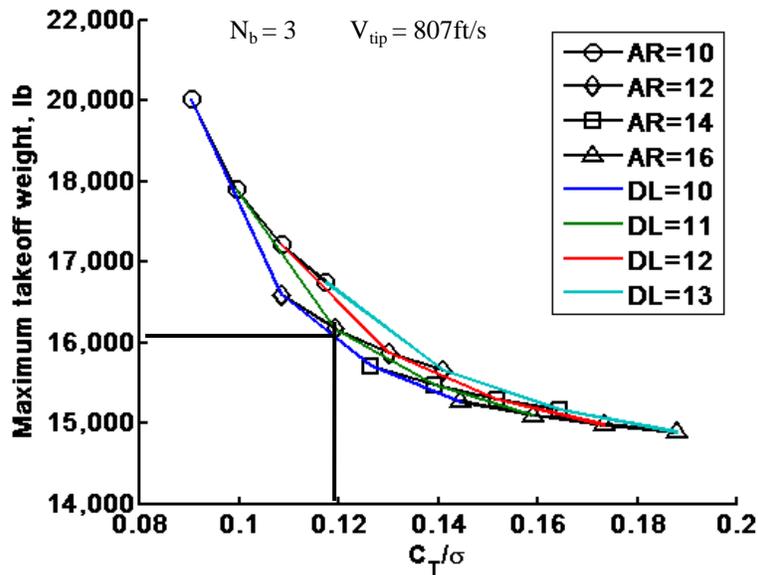


Figure 3.8: Final selection

As can be seen in Figure 3.8, a $C_T/\sigma = 12$ corresponds to a disk loading of 11 lb/ft² and an aspect ratio near 12. This combination ensures that there is a sufficient stall margin to not only hover at 6K95 but also maneuver aggressively in helicopter mode. This design choice also minimized the disk loading, the downwash velocities, and provided a blade aspect ratio that kept the maximum takeoff weight as low as possible. These design choices give *Excalibur* an unprecedented advantage over the current generation of tiltrotors.

3.3.6 Selection of Wing Parameters

A larger wing aspect ratio produces lower induced drag in forward flight (in airplane mode) resulting in reduced fuel consumption. Higher aspect ratio necessitates a reduced wing chord for a given wing span. Wing span is primarily fixed by the proprotor diameter, fuselage width, and the necessary clearances. Once the wing span and aspect ratio are known, the wing chord can be determined.

The additional weight at the wing tips from the tilting mechanisms and engine requires a large root chord to resist the increased bending moments that occur in hover and forward flight. *Excalibur* operates at a relatively low cruise speed of 225 kts compared to turboprops of similar MGTOW, so the benefit of using a larger aspect ratio would be offset by an increase in wing weight. The design trade calculations were performed by assuming a rectangular wing at the initial stage of design.

Table 3.2: Proprotor parameters

Number of blades	Blade loading C_T/σ	Solidity	Blade aspect ratio	Blade tip speed (ft/s)	Rotor diameter (ft)	Blade chord (ft)	GTOW (lb)
3	0.12	0.0783	12.2	807	30.5	1.25	16,144

Table 3.3: Wing parameters

Tip-to-tip wing span (ft)	Wing chord (ft)	Wing area (sq. ft)	Wing aspect ratio
40.06	6.67	267.2	6.0

3.3.8 High Lift Devices and Download Control

Flaps occupy the inboard portion of the wing on *Excalibur* and flaperons are deployed on the outboard portions. In airplane mode, the application of flaps and flaperons is similar to those used in a fixed-wing aircraft, i.e., to generate additional lift coefficients and slow the aircraft down. Furthermore, an improvement in hover performance is achieved by deflecting the outboard flaperons and inboard flaps to their maximum extent. These deflections reduce the download from the proprotor wake impingement on the wing. For *Excalibur*, it results in an 9.5% download as will be discussed in Section 12. Additionally, wing flaps can help to alleviate BVI noise, as will be discussed in Section 13.

Table 3.4: High lift devices

Surface	Flap	Flaperons
Area (ft ²)	5.5	10.1
Span (ft)	4.25	7.86
Chord (ft)	1.66	1.66

3.3.9 Empennage Sizing (Horizontal and Vertical Tail Sizing)

The horizontal and vertical tail, referred to as the stabilizer and the fin, are surfaces that provide the lateral and longitudinal stability in pitch and yaw attitude respectively. A T-tail was selected for *Excalibur* to keep the tail in the undisturbed flow, free from the effects of the wake and trailing vortices created by the wing and the proprotors. This configuration allows the horizontal tail to encounter the free stream at the designated angle of attack thus, reducing the tail size, structural requirements and pilot workload. The empennage size was calculated using historical data given in Raymer³. Tail volume coefficients were used to calculate the total area of the horizontal and vertical tail.

Table 3.5: Empennage sizing

Surface	Horizontal tail	Vertical tail	Elevator	Rudder
Area (sq. ft)	69.9	43.9	18.1	6.5
Span (ft)	18.7	8.8	18.8	5.2
Mean chord (ft)	3.2	5	0.96	1.25
Chord aft hinge %	N/A	N/A	0.30	0.25
Aspect ratio	5	1.75	19.6	4.16

A tail volume coefficient of 0.9 was used for the horizontal tail and a coefficient of 0.08 for the vertical tail. The vertical tail has a symmetric airfoil with sufficient thickness to chord ratio (t/c) to stiffen the horizontal tail under dynamic loading. The airfoils selected for the vertical and

horizontal tail the NACA 0012 and NACA64A015, respectively. Historical data for twin turboprop aircraft were utilized to determine the taper ratio and sweep angles of the horizontal and vertical tail. The performance and effectiveness of these surfaces is discussed in the stability and control analysis (Section 9.)

3.3.10 Engine Sizing

The RFP allows the use of a “rubber” engine based on the CT7-8A. The installed power was calculated at sea level ISA using the power required to hover at. The power required at 6K95 was determined using the UMD sizing code.

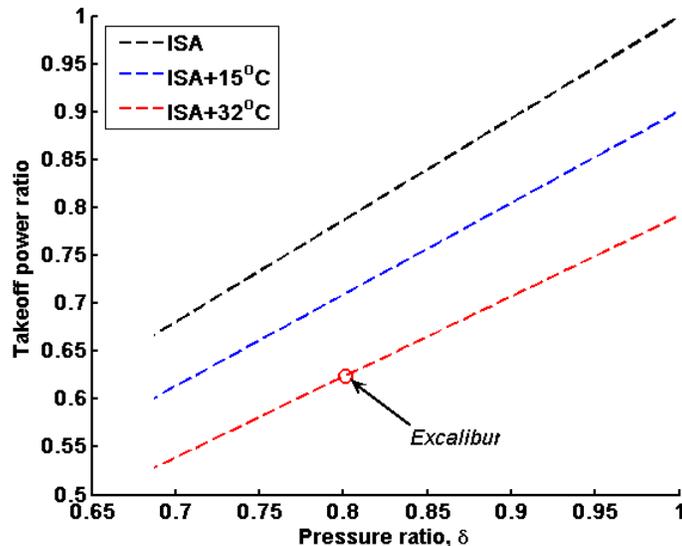


Figure 3.9: Engine takeoff power ratio for different pressure ratio values

Figure 3.9 shows the takeoff power ratio as a function of pressure ratio available from the engine for three different ambient temperature conditions (ISA, ISA + 15°C, ISA + 32°C). In this figure, the available takeoff power ratio is defined as the takeoff power at ambient temperature to the takeoff power at sea level temperature. The pressure ratio is defined as the ratio of ambient pressure to sea level pressure. At sea level ISA conditions, the ambient pressure ratio and power ratios are equal to unity.

Increasing altitude and temperature significantly reduces the takeoff power ratio from unity at sea level to 60% at 6K95, as shown in Figure 3.9. the point. To achieve the power required to HOGE, the installed power at sea level ISA must be 140% of the power required to HOGE at 6K95. It is interesting to note that if the RFP required HOGE at 6K ISA, the take off power ratio increases drastically from 60% to about 80 %. The corresponding installed power would be drastically lower, producing a significantly lighter vehicle design.

The engine weight was derived from a modification to the engine model given in 2007 AHS RFP and includes the effects of possible improvements from the incorporation of advanced technologies, and is referred to as the UMD Model 2011. The 2011 RFP engine was based on advanced technologies available in 2020.

Figure 3.9 shows the specific power given by NDARC for existing engines, the 2011 RFP engine model and the UMD Model 2011.

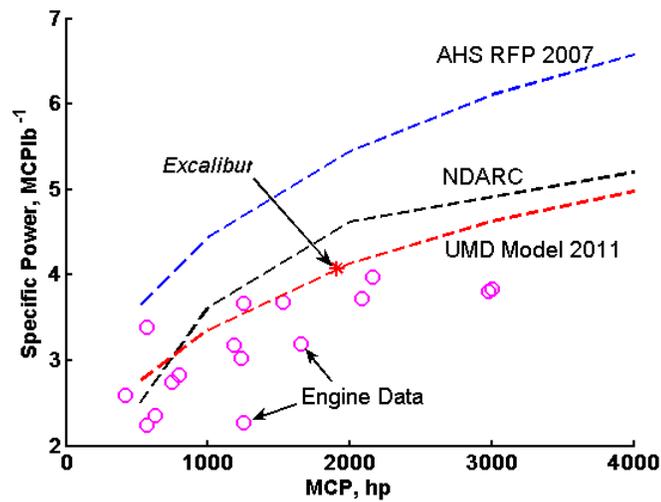


Figure 3.10: Specific power against maximum continuous power for different engines

The AHS RFP 2007 engine⁴ gives overly optimistic values for the specific power. NDARC gives an envelope of the specific power for the best engines at the given power required. The UMD model is the most conservative of the three models. Because of this outcome, the empty weight of *Excalibur* should be lower than predicted. The engine dimensions were calculated using the RFP 2007 modified by Rosenfeld.

4 Excalibur Design Features/ Performance Summary

Excalibur Details	
Type	Twin turboshaft tiltrotor
Accommodation	4 crew / 6 passengers
Acquisition cost	US \$ 8.60 million
Direct operating cost ¹	US \$ 2,030 per flight hour

Weights & Loadings	
Design gross weight	16,144.7 lb (7,323 kg)
Maximum takeoff weight	16,144.7 lb (7,323 kg)
Empty weight	10,159.9 lb (4,608.5 kg)
Fuel weight	1,400 lb (635.0 kg)
Payload weight	4,000 lb (1,814.4 kg)
Alternative payload weight	6,000 lb (2,721.5 kg)
Maximum disk loading	11 lb/ft ² (53.7 kg/m ²)
Proprotor Specifications	
Diameter (hover)	30.5 ft (9.3 m)
Diameter (cruise)	20.3 ft (6.2 m)
Number of blades	3
Equivalent chord	1.25 ft (0.38 m)
Tip Speed (hover)	807 ft/s (246 m/s)
Twist (hover)	-32.8° (bi-linear)
Twist (cruise)	-20.3° (bi-linear)
Sweep (leading edge)	22° (from 80% radius)
Root cutout (hover)	15%
Root cutout (cruise)	22.5%
Airfoil sections	JM1 (48 – 69%) JM2 (73 – 85%) JM3 (90% – tip)

Performance Specifications	
Best range speed	201 knots (231 mph)
Maximum cruise speed	298 knots (342 mph)
Dash speed	330 knots (380 mph)
HOGE ceiling	12,500 ft (3810 m)
Maximum range	608 nm (700 miles)
Maximum endurance	3.25 hours
Engine Specifications	
Number of engines	2
Intermediate power	3,816 hp (2845 kW)
Maximum continuous power	3,052 hp (2275 kW)
Transmission limit	3,000 hp (2237 kW)
Dimensions	
Length	46 ft
Height	13 ft
Fuselage width	5.5 ft
Wheelbase	8.5 ft
Wheel track	20.5 ft
Cabin width	5.4 ft
Cabin height	6 ft
Cabin length	34 ft
Cabin door height	4 ft
Cabin door width	5 ft

5 Proprotor and Hub Design

5.1 Variable Diameter Rotor

Designing a high efficiency proprotor requires a large range of angles of blade twist to operate efficiently and a sufficiently low tip speeds to maintain subcritical helical tip Mach numbers at high forward flight speeds. A proprotor must also have low blade areas for good propulsive efficiency. A hovering rotor requires significantly smaller blade twist distributions and a larger diameter for good efficiency. These contradictory design requirements often result in a design that is neither as efficient as a helicopter rotor nor as good as a propeller. However, varying the diameter of the proprotor between hover and cruise conditions greatly reduces the necessary tradeoffs and permits a design that is both efficient in hover and in forward flight. To this end, a variable diameter proprotor concept was selected.

5.1.1 Diameter

For the given takeoff weight, a proprotor diameter of 25 ft was initially chosen. However to reduce the downwash on ground personnel and increase hovering performance, the diameter was increased to 30 ft. Increasing the diameter decreased the disk loading from 16 lb/ft² to 11 lb/ft², which increased the power loading from 6.3 to 7.5 lb/hp. Forward flight efficiency was not compromised because in forward flight the rotor diameter is decreased from 30 ft to 20 ft. Figure 5.1 shows that reducing the diameter from 30 ft to 20 ft resulted in a propulsive efficiency of 85% at 300 kts. This outcome reduced the fuel required to complete the missions, as well as increasing the maximum level flight speed.

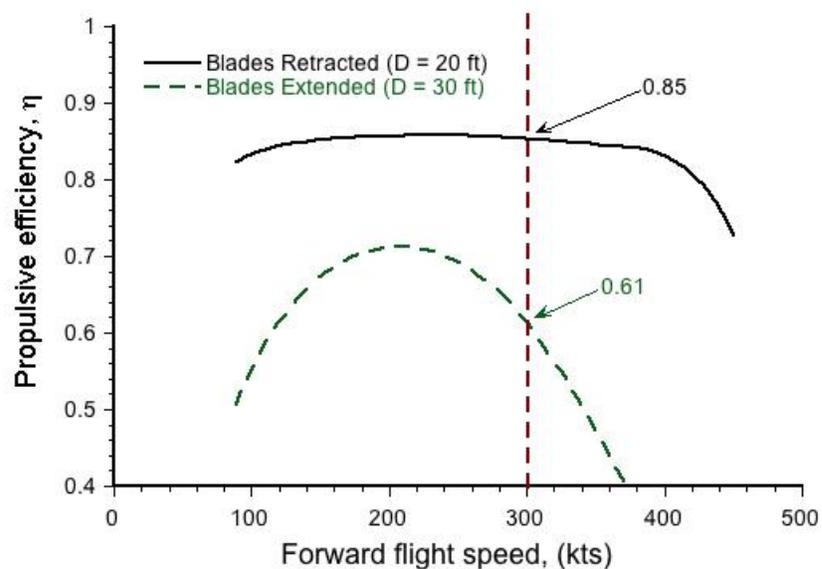


Figure 5.1: Propulsive efficiency versus forward flight speed. A reduction in proprotor diameter greatly increases the propulsive efficiency.

5.1.2 Tip Speed

A tip speed of 807 ft/s was chosen to provide the necessary margin between normal operations and the onset of rotor stall. Figure 5.2 shows historical data trends of the blade loading coefficient in hover versus maximum gross takeoff weight. Most helicopters operate around a blade loading coefficient of 0.08 at sea level. However, tiltrotors generally operate at much

higher values of C_T/σ , and so have smaller stall margins for maneuvers. *Excalibur* operates at a blade loading of 0.12 at 6K95 and 0.09 at sea level ISA.

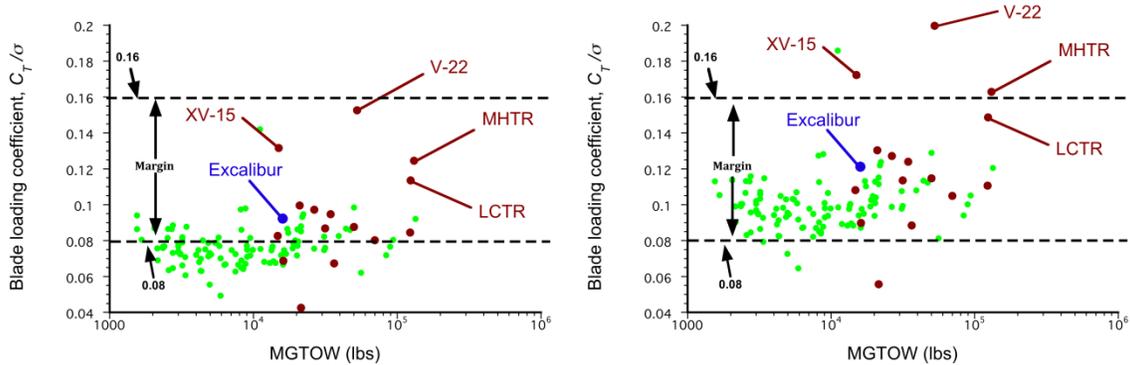


Figure 5.2: Historical results of blade loading coefficient versus MGTOW at sea level (left) and 6000 ft 95° F (right)

This good stall margin allows *Excalibur* to operate in significantly degraded environments (inclement weather), perform evasive flight maneuvers, and hover at higher altitudes (e.g., for mountain search and rescue missions). A high hover tip speed does not adversely affect the forward flight performance because the reduction in proprotor diameter decreases the tip speed from 807 ft/s to 537 ft/s. Additionally the engine rpm can be varied by 10% without a significant degradation in fuel efficiency. The added reduction in engine rpm in forward flight reduces the tip speed further to 483 ft/s. This large reduction in tip speed allows high forward flight efficiency to be maintained up to significantly higher airspeeds than prior tiltrotor designs, while still retaining the necessary proprotor performance levels and stall margins in hover.

5.1.3 Solidity

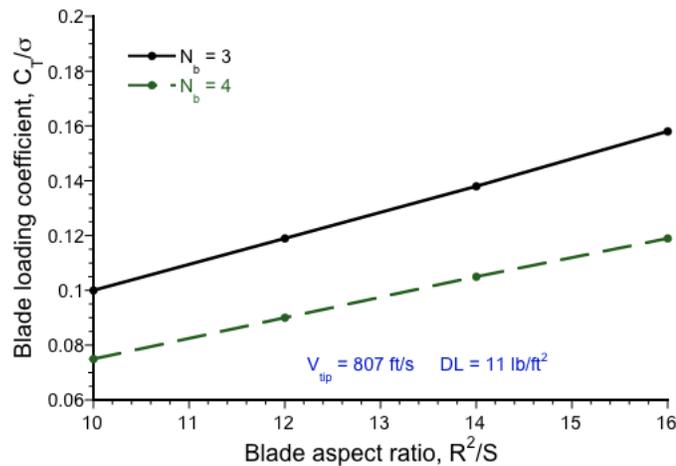


Figure 5.3: Comparison of blade loading coefficient for varying blade aspect ratios and number of proprotor blades.

The solidity was chosen in conjunction with the hover tip speed to give the necessary stall margin when operating at 6K95. The factors affecting solidity selection are the number of blades and the blade aspect ratio. Figure 5.3 shows the effect of aspect ratio and number of blades on the blade

loading coefficient. Increasing the number of blades from three to four can increase the available stall margin. However, such a large stall margin is not required even for a tiltrotor and the added complexity of the variable diameter mechanism prohibits the inclusion of four blades over three, as previously discussed in Section 3.

5.1.4 Blade Twist and Taper

Having selected the proprotor diameter, tip speed, and solidity, to meet the mission requirements, the best blade twist and blade taper were determined through a numerical, multi-objective optimization procedure that sought to find the design that offered the best combination of both cruise and hover performance. The retraction of the outboard blade section over the elliptical inboard section dictated strict constraints on the aerodynamic design and optimization of the blades. For simplicity of the mechanical design, the elliptical inboard section must have the same twist as the portion of the outboard section it retracts into; see Figure 5.4. In addition to restricting the distribution of twist, the retraction of the blade also limited the amount of the blade that could be tapered. These constraints restrict the section of the blade that can be tapered to the outboard 20% and outboard of the point about which the change in bi-linear twist occurs (81% R); see Figure 5.4.

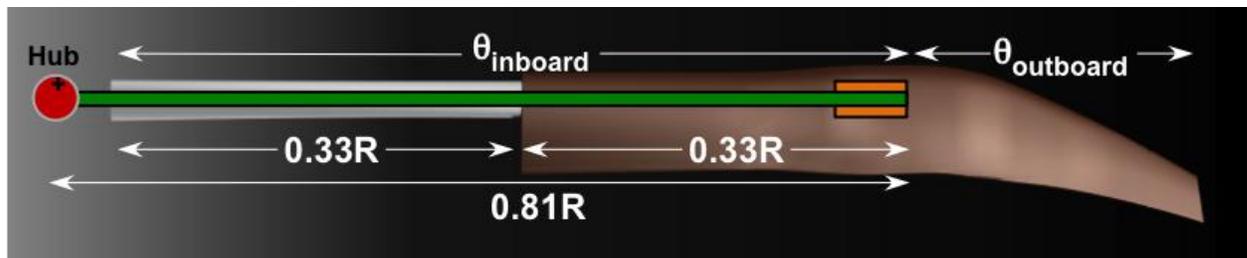


Figure 5.4: Distribution of twist, taper and sweep on the proprotor blade.

The propulsive efficiency in forward flight and the power loading in hover were chosen as objectives to simultaneously maximize the performance in both hover and forward flight. Response surfaces were generated to approximate the objective functions for both the forward flight and hover conditions. Each response surface was generated using a Taylor series expansion that included first-and-second order terms.

To determine the Jacobian and Hessian matrices, an initial complement of potential designs were evaluated for each operating condition. The number of cases required to fully define the Hessian and Jacobian matrices is a function of the number of design variables

In forward flight, the engine rpm was allowed to vary by 10% from the baseline operating condition; adding an additional design variable increased the number of required cases from 10 to 15. The baseline values of twist were chosen to yield a compromise between hover and forward flight. A rectangular, untapered blade was selected for the baseline. The baseline design parameters are given in

Table 5.1.

Table 5.1: Baseline design parameters for cruise and hover operating conditions

Operating Condition	$\theta_{Inboard}$ (deg/ft)	$\theta_{Outboard}$ (deg/ft)	Ω (rpm)	Taper Ratio
Cruise	-3.74	-1.87	550	1
Hover	-3.74	-1.87	550	1

The optimization was performed under the global constraint that the final design parameters could not change by more than 50% from the baseline. Because engine performance is very sensitive to changes in rpm and using a variable speed gearbox added significant weight (as described in Section 6), the engine/rotor rpm was constrained to not change by more than 10%. The optimum designs at each step, as determined from each response surface, were evaluated using a proprotor Blade Element Momentum Theory (BEMT) code and subsequently included in the response surface approximation for the next optimization step. This process was repeated until convergence was achieved for both the cruise and hover conditions. The optimized hover and cruise design parameters are given in Table 5.2.

Table 5.2: Optimized design parameters for cruise and hover operating conditions

Operating Condition	$\theta_{Inboard}$ (deg/ft)	$\theta_{Outboard}$ (deg/ft)	Ω (rpm)	Taper Ratio
Cruise	-4.62	-2.81	495	0.5
Hover	-2.49	-0.935	NA	0.5

As can be seen from Table 5.2, the hover and cruise operating conditions required significantly different design values to reach an optimum, and it was essential to determine the tradeoffs between the two cases. Such tradeoffs can be characterized through the calculation of a Pareto frontier, which is generated by optimizing one of the objective functions (forward flight efficiency) with the constraint that the other objective function (power loading) not decrease by more than a set amount. For the current design three points were evaluated between the hover and cruise optimums as shown in Figure 5.5.

The Pareto frontier clearly shows that a 4% increase in the forward flight efficiency yields a 10% decrease in hovering efficiency. Although the majority of the missions occur in forward flight, the 4% gain in forward flight efficiency was sacrificed for the 10% gain in hovering efficiency. Because the power loading is proportional to the installed power, which dictates the empty weight, there is a bigger weighting given to hover performance. Therefore, increasing the power loading will decrease the vehicle weight, thus reducing the operational cost as well as the manufacturing cost, as discussed in Section 15. In addition, the increase in power loading allows the vehicle to conserve fuel, such as during search and rescue missions.

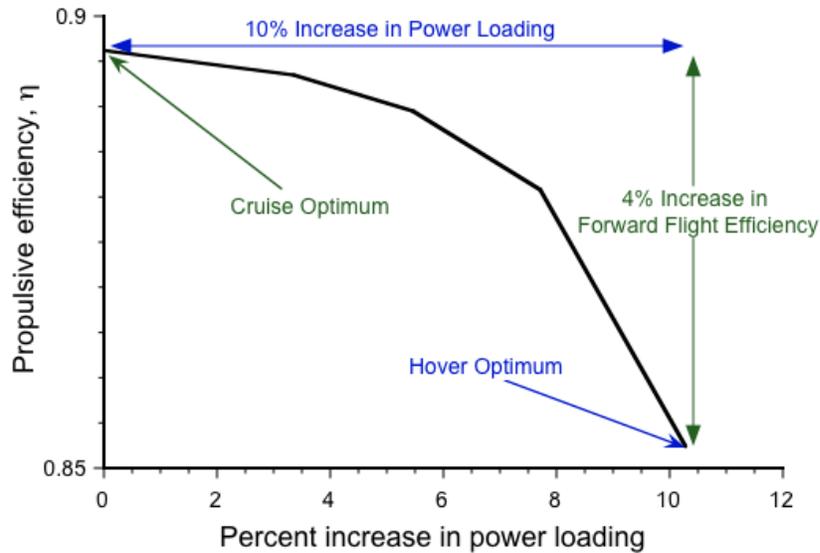


Figure 5.5: Pareto frontier for the current design, showing the tradeoffs between optimization for forward flight and hovering efficiency

5.1.5 Blade Design

The constraints placed on the blade design by the vehicle sizing, the retraction mechanism, and the hovering tip speed (807 ft/s) dictated a 14% thickness-to-chord ratio airfoil be maintained out to a radial position of $0.81R$. The effect of these constraints is that portions of the blade will be operating extremely close to drag divergence.

To avoid drag divergence, the rotor blade was then modified locally to provide sufficient margin between the local Mach number and the drag divergence Mach number. The addition of 2.5 inches to the blade chord between $0.735R$ and $0.85R$ reduced the thickness-to-chord ratio from 14% to 12%, which increased the drag divergence Mach number from 0.65 to between 0.7–0.75 without adding significant weight to the blades. To meet the optimization requirements significant modifications were incorporated to the unconstrained outboard 20% of the blade. To reduce the profile drag and obtain a better lift distribution, the blade tip was tapered to 0.5 of the root chord. To increase the drag divergence Mach number, the thickness-to-chord ratio was also tapered from 12% at the critical region to 6% at the tip. To further increase the margin between the local Mach number and the drag divergence Mach number, blade sweep was added to the outboard 20% of the blade with the angle designed to varying maintain an incident Mach number below 0.7.

5.1.6 Airfoil Sections

The airfoils utilized in the proprotor design are current advanced airfoil designs that were modified to meet the unique operating conditions of the current blade design. The inboard JM1 airfoils operate at local Mach number between 0.3 and 0.5, which allow thicker airfoils with large camber to be utilized. To off load the tip, the inboard airfoils were designed to obtain high values of C_{lmax} at a thickness-to-chord ratio of 14%. Consequently, the GOE-632 airfoil was chosen as a starting point for the JM1 airfoils. Increasing the camber improved the C_{lmax} from 1.5 for the GOE-632 to 1.65 for the JM1. However, this gain in C_{lmax} negatively affected the pitching moments. The unfavorable change in the pitching moments was addressed in the design of the JM3 airfoils. The JM2 airfoil operates in the critical section of the blade were high values of M_{dd}

must be achieved without sacrificing the maximum lift coefficient. To meet these requirements, the camber in the VR-7 airfoil was reduced slightly. This reduction in camber decreased maximum lift coefficient but increased the drag divergence Mach number. The outboard JM3 airfoil was designed to have higher values of maximum lift coefficient and low profile drag. The baseline airfoil chosen was the VR-9. The low thickness to chord ratio (6%) of the VR-9 provided a drag divergence Mach number around 0.95, however, reflex was added to compensate for the large pitching moments of the inboard JM1 airfoils. The use of outboard reflex to compensate for large inboard pitching moments has been discussed for a similar design in Reference 1. The addition of reflex reduced the maximum lift coefficient slightly, however, because the majority of the lift is being produced by the inboard sections, the reduction in maximum lift coefficient will not adversely effect performance. Figure 5.6 shows the airfoil distributions and resulting planform shape.

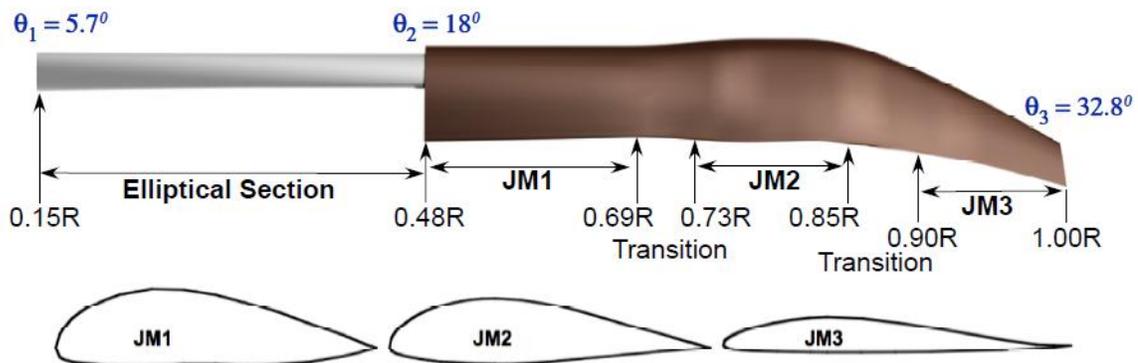


Figure 5.6: Proprotor planform and airfoil selection

5.2 Blade Structural Design

5.2.1 Overview

The *Excalibur* blade assembly consists of an elliptic, linearly-twisted inner segment, and the lift producing outer segment. The twist distribution on the outer blade segment is the same for the length of the inner blade segment.

To ensure that the extension-retraction would be physically feasible with the proposed twist distribution, two blade segments were fabricated using rapid prototyping (see Figure 5.7) to replicate the twist distribution on the proposed blades. This physical model demonstrated the possibility of retraction and extension of the outer segment over the twisted inner segment.

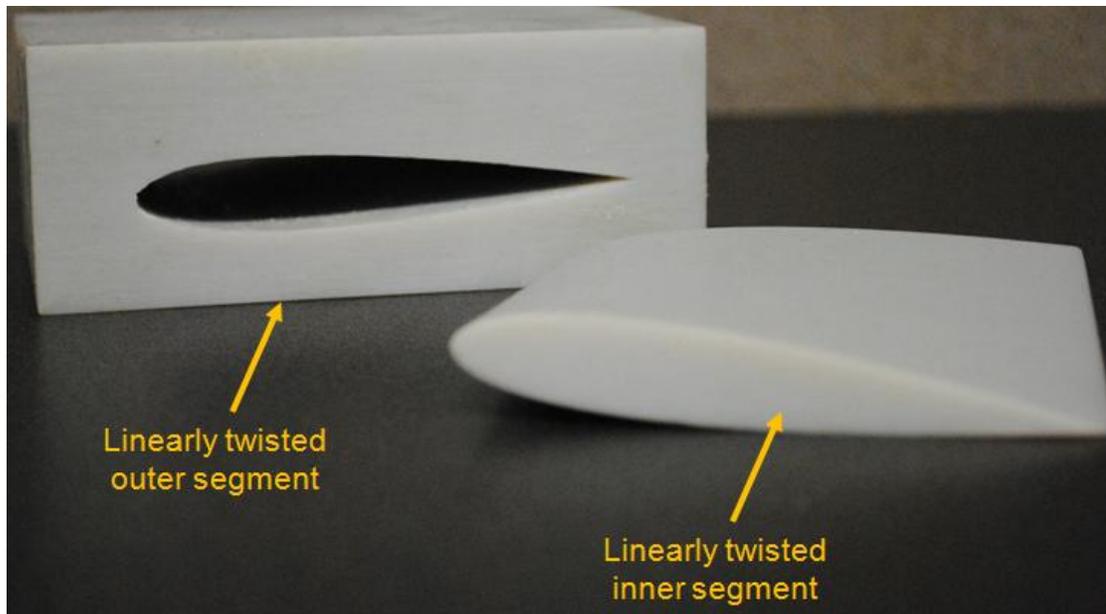


Figure 5.7: Rapid prototyped linear blade twist retraction proof of concept

5.2.2 Inner Segment and Strap

The inner blade houses the strap and is connected to the pitch casing. It must transmit all the torsional, flap and lead-lag forces from the outer blade to the hub. To do this, the blade segment is designed to withstand these loads. As shown in Foldout 2, the inner segment is fabricated from layers of carbon fiber epoxy with a $0^\circ \pm 45^\circ \pm 90^\circ$ fiber layup. Both the interior and exterior of this inner segment have a NYLATRON® film to permit both the strap and the exterior blade to slide with minimum frictional losses¹. The strap travels through the inner segment and is bolted securely to the outer segment over a large area to better distribute and transfer the centrifugal forces.

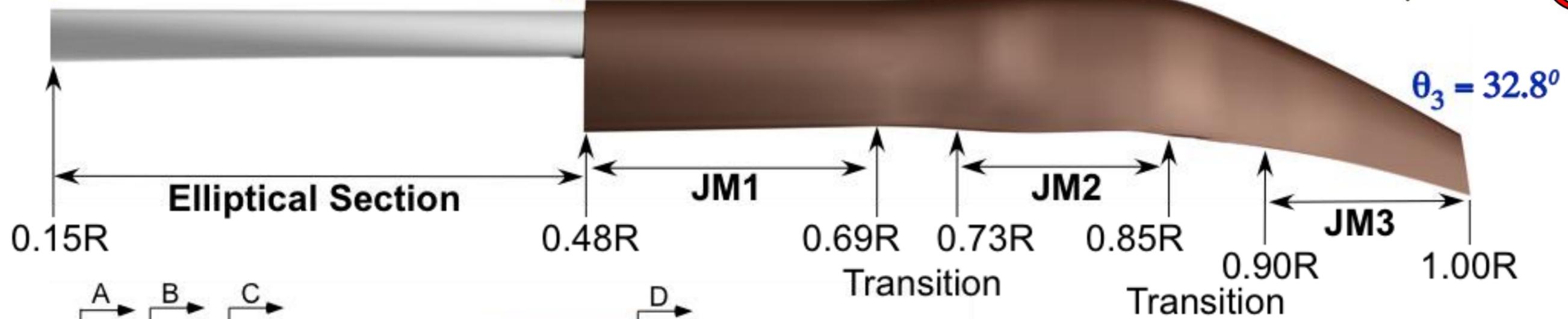
5.2.3 Outer Segment

An exploded view of the outer blade segment is shown in Figure 5.8. The blade is conventional in design, thereby simplifying the manufacturing process. The primary materials utilized are fiber glass and carbon fiber epoxy. All of the elements were designed to ensure that when both the inner segment is retracted or extended, the cross-section center of mass was maintained at the quarter-chord of the outer segment.

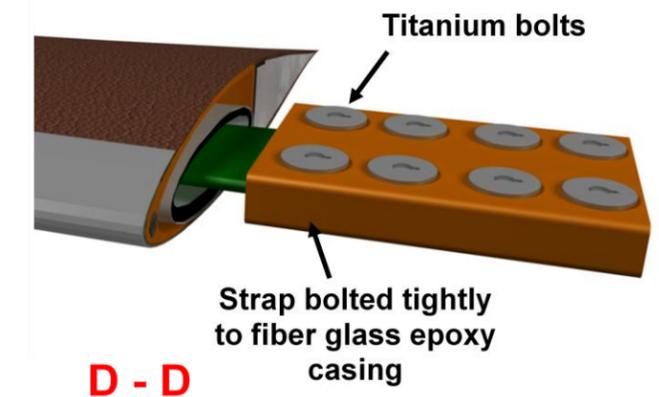
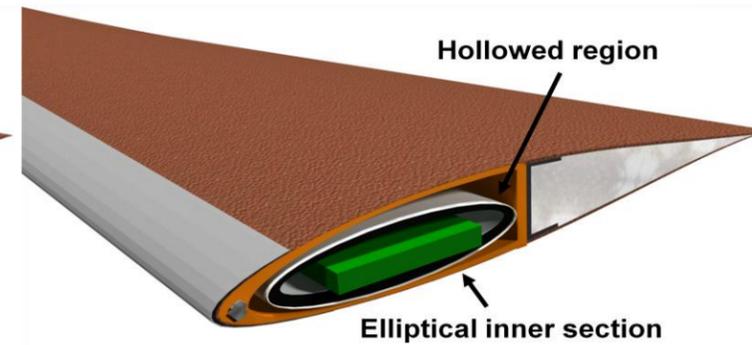
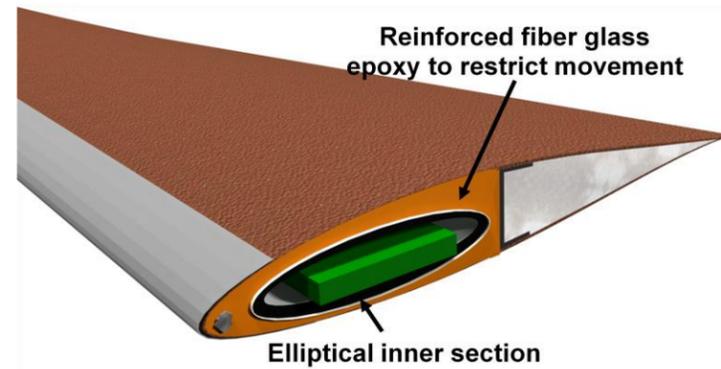
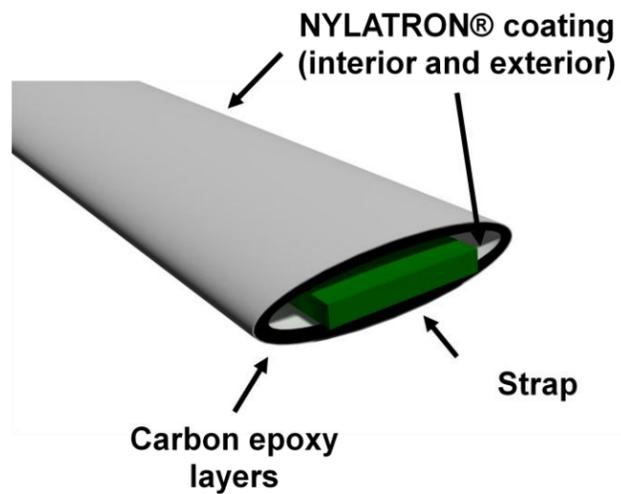
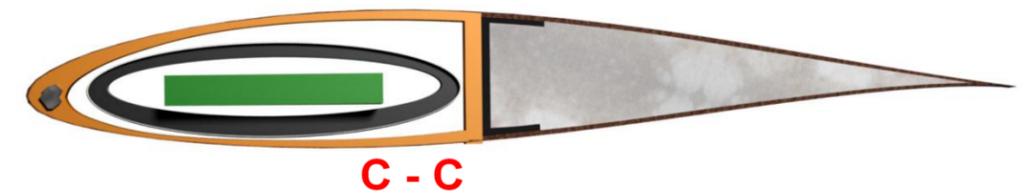
$\theta_1 = 5.7^\circ$

$\theta_2 = 18^\circ$

EXCALIBUR



Notional airfoils shown



* All sections rotated clockwise

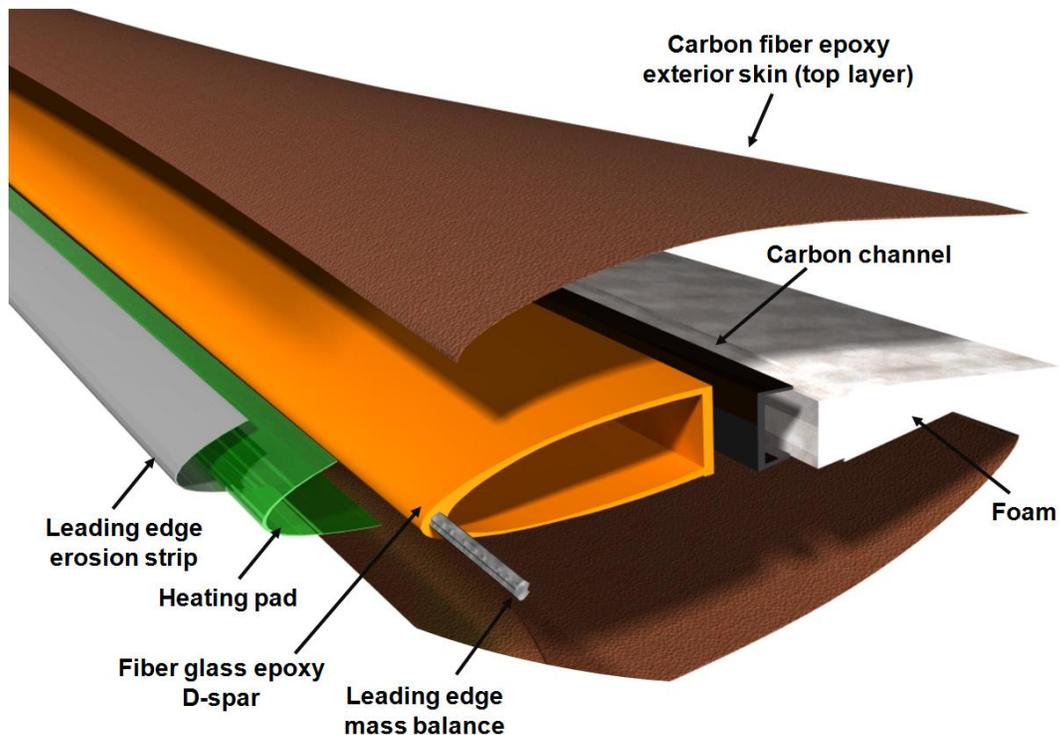


Figure 5.8: Exploded view of the interior design of the blade

5.2.4 Blade Overlap and Locking

To transmit the pitching moments from the pitch links to the outer blade segment, the blades need to be rigidly connected when the extension/retraction is complete. While this does not pose a problem in forward flight (because the outer inner blade is completely housed within the outer segment), in hover there should be sufficient overlapping between the blades. To ensure that the pitching moments are transferred, the *Excalibur* has an overlap of 1ft between the blades. The overlapped section is reinforced with titanium sleeves to diffuse the hoop stresses over the contact area. A locking mechanism rigidly clamps the blades to ensure the transfer of all moments from the hub to the outer blade through the inner blade².

5.2.5 Load Path

It is important to note that throughout flight the strap is always under load from the centrifugal forces. The strap has been designed to sustain these loads with a high fatigue margin. The centrifugal force distribution for the inner segment, the strap and the outer segment are shown schematically in Figure 5.9. Conventional helicopters have large force concentrations at the root, as they are loaded by the centrifugal forces, flap shear, lead-lag shear, flap bending moment, lead-lag bending moment, and torsion. On the *Excalibur*, the centrifugal force is distributed in both tension and compression and over a large area, thereby increasing the fatigue life of all blade sections.

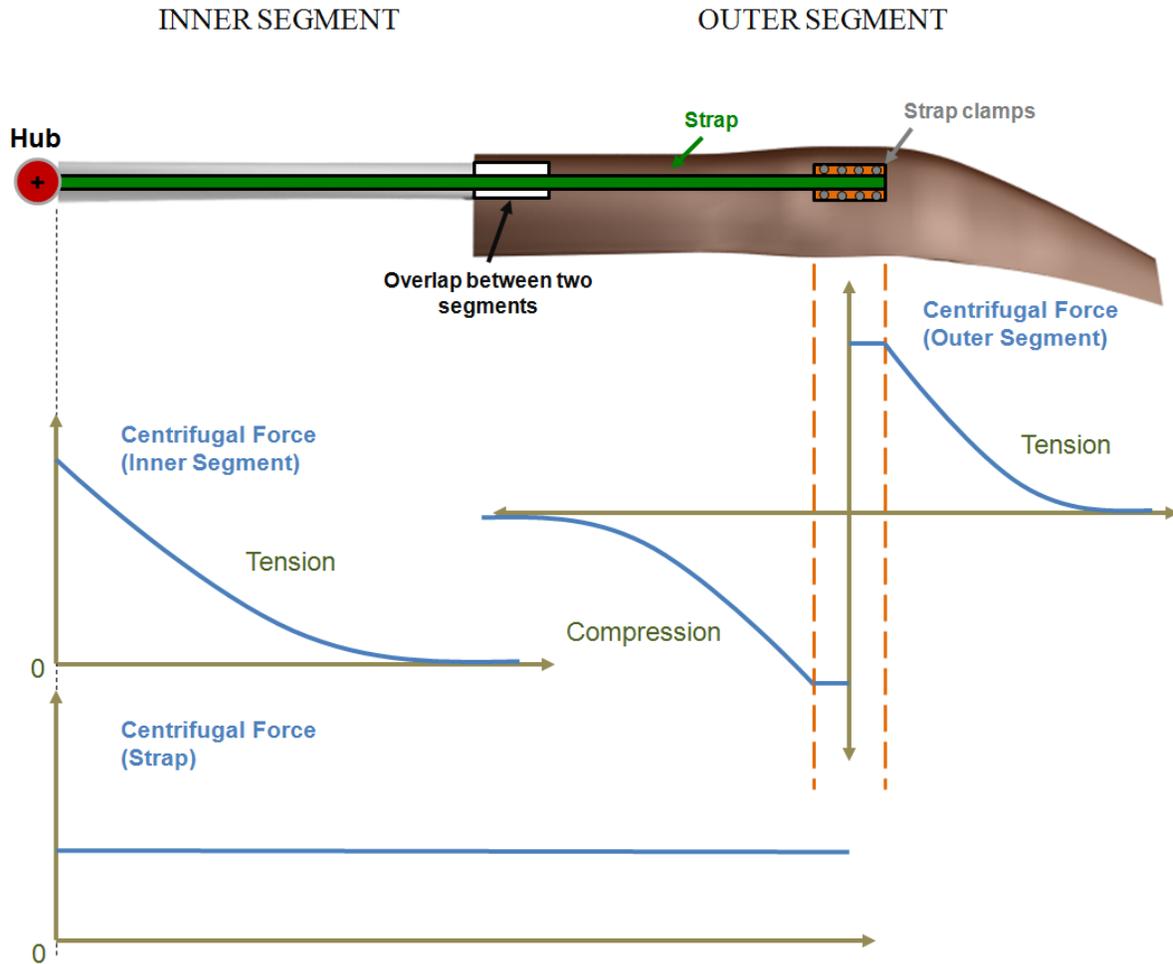


Figure 5.9: Centrifugal force distributions

5.2.6 Methods of Retraction and Extension

Multiple blade retraction mechanisms were evaluated to determine the feasibility and ease of implementation. The mechanisms examined to extend and retract the rotor blades are a series of cables that are driven by electric motors at the base of each blade, a centrifugal force actuated spring, a control shaft that is concentric with the main rotor shaft spinning a spool of composite Kevlar® belts that are attached to outer portions of the blades and, a control shaft that is concentric with the rotor shaft that spins a lead screw.

The centrifugal force actuated spring design keeps the blade from extending until the prop rotor rpm increases past the designated point. The advantage of this design is the simplicity of implementation. However, the inability to control the extension and retraction of the blade, coupled with the added weight of a variable rpm transmission, made this concept impractical for the current application. The lead screw concept was very promising and was the original design choice. However, after further examination it was determined that the required screw size would be too large for the current application and the friction forces present during the retraction would require more power than was feasible. The Kevlar belt concept was chosen because it provided the necessary control over the retraction and extension of the blades while adding less weight and requiring the least amount of power.

The two choices for extending and retracting the blade are individual actuation and co-dependent actuation. Individual actuation moves the blades by using separate mechanisms, whereas, co-dependent actuation uses a linked set of mechanisms to move the blades together. Co-dependent actuation is preferred because it has significantly lower weight than individual actuation mechanisms, however, both methods provide the same failure mode. The failure modes occur if a single proprotor blade retracts/extends unequally creating an imbalance of inertia. A failure using independent actuation would cause a single blade to retract/extend increasing the imbalance in inertia. However, if the mechanism fails on a co-dependent actuation system, none of the blades will retract or extend. Therefore, a co-dependent approach is preferred because of the significant reduction in weight and complexity. Table 5.3 shows the tradeoffs between various variable diameter proprotor designs.

Table 5.3: Trades between several VDR designs

Method of displacement	Co-dependent actuation	Single rotor shaft	No clutch required	Fatigue
Cable driven	✗	✓	✓	✗
Concentric shafts w/ belt	✓	✗	✗	✗
Lead screw	✓	✗	✗	✓
UMD hybrid belt design	✓	✓	✓	✓

The method chosen seeks to combine the benefits of co-dependent actuation without the complexity involved with independently controlled, concentric shafts, or the use of clutch assemblies. The method utilizes a lightweight feedback controlled electric motor that operates in the inertial frame of the hub. The torque required increases proportionately to the speed reduction. The motor provides a high speed/low torque input into a harmonic drive, which reduces that speed by a factor of 1:200.

After the selection of the retraction mechanism the blade configuration was examined. The configurations examined were the DARPA telescoping blade, where the blade sections telescope into each other. The other design evaluated had the outboard lifting section retract over an inboard elliptical section. The telescoping blade design was originally chosen because it provided the largest reduction in diameter between hover and cruise operating conditions. However, the large discontinuities in the thickness and chord between the blade sections produce significant amounts of profile drag, which drastically reduced the performance. Furthermore, there was substantial mechanical complexity involved in retracting and locking the multiple blade sections. Therefore, the retraction of the outboard section over the inboard section was chosen because of the decreased mechanical complexity, as well as having minimal performance losses.

5.2.7 Electric Motor Requirements

An analysis was conducted in the energetic, torsional, inertial, and temporal dimensions. The torque is equal to the angular momentum of the rotor divided by the period in time over which the change occurs. The retraction demands a high torque applied over just several rotations of the spool to release the desire amount of Kevlar belt. High-torque motors are highly undesirable for aircraft applications because the weight of electric motors increases proportionally to their

operating torque. Generally, a low-torque motor can run at a higher operating speed and maintain the same power transfer as for a larger motor. However, a gearing system must be used on the high-speed motor to bring its angular speed down to the appropriate level to turn the spool. This gearing system adds weight and provides a slight decrease in mechanical efficiency. However, if high torque is required over a relatively short angular displacement and weight is a top priority, the ideal solution is a high-speed, low-torque motor connected to a lightweight gearing system. The relationship between actuation time and torque required to retract the proprotors was analyzed to help determine the best motor and gear ratio to use for the actuation system, as shown in Figure 5.10.

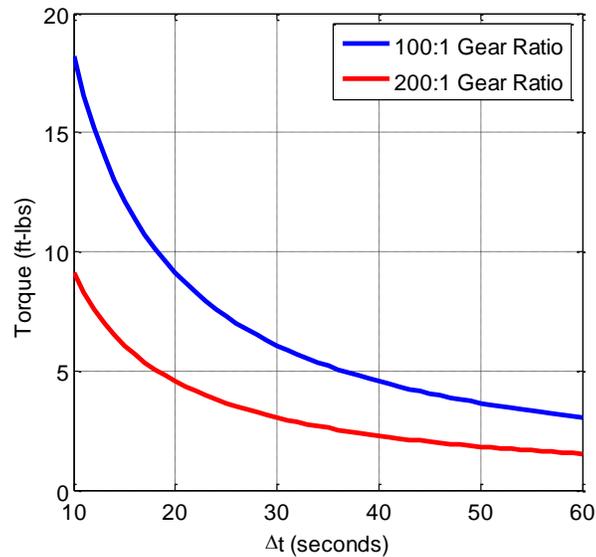


Figure 5.10: Required servo torque for VDR actuation

5.2.8 Strap Sizing

The Kevlar strap that is connected to the outboard blade section must be able to withstand the large centrifugal forces. An accurate estimation of the strap size and strength is of vital importance because the loss of a blade would cause the proprotors to fail catastrophically. A breakdown of the strap dimensions and strengths is shown in Table 5.4. The dimensions of the Kevlar strap also dictated the required size of the elliptical inboard blade section.

Table 5.4: Kevlar strap dimensions and strengths

Ultimate strength	179,846 lb-in ²
Max radius	15.22 ft
Blade mass	80 lbs
V_{tip}	807 ft/s
Ω	505 rpm
Centrifugal forces	105,440 lb
Total force	158,160 lb
Kevlar thickness	0.25 in
Kevlar width	3.5 in

5.3 Hub Design

The *Excalibur* employs a composite flexbeam gimbaled rotor hub design³ as shown in Foldout 3. The two primary reasons for selecting the hub design were the ability to house a variable diameter mechanism and the mitigation of propeller whirl flutter instabilities. This section provides a thorough description of the retraction mechanism, the load paths, and an insight into the various dynamic modes of the hub. The blade section mechanical details will then be discussed in the following section.

5.3.1 Spool Drum

The spool drum houses a mechanism that enables the extension and retraction of the outer blade. A close-up of the spool drum is shown in the foldout. The spool drum in its entirety consists of three straps (shown in red, blue and green) each attached to a blade. Each strap is securely bolted to the telescoping outer blade and the other side is wound around a shaft that is connected to a motor through a harmonic drive gear reduction. As

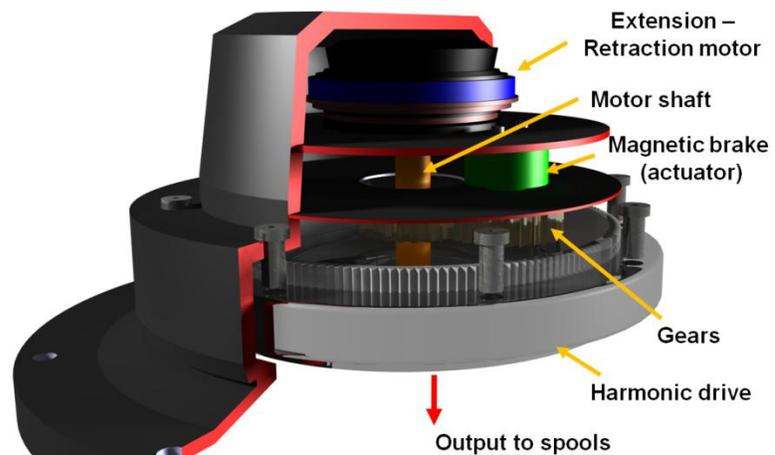


Figure 5.11: Close up of spool drum

viewed from top, rotation of the motor shaft counterclockwise enables the centrifugal force exerting tension on the strap to extend the blade. The outer blade segment then extends, guided by the inner blade segment shown by the white elliptical section. To retract the blades, the motor shaft spins clockwise, causing the straps to be reeled in.^{4,5,6} A detailed figure of the motor assembly is shown in Figure 5.11.

The motor shaft carries a gear that meshes with another gear on an ancillary shaft which is connected to a magnetic actuator (Figure 5.11). This actuator serves as a braking mechanism and locks the spooling mechanism in place, preventing the extension or retraction of the propotor. The actuator works like a brake pad by clamping the ancillary shaft. This prevents the actuator gear from rotating thereby preventing strap movement. The magnetic

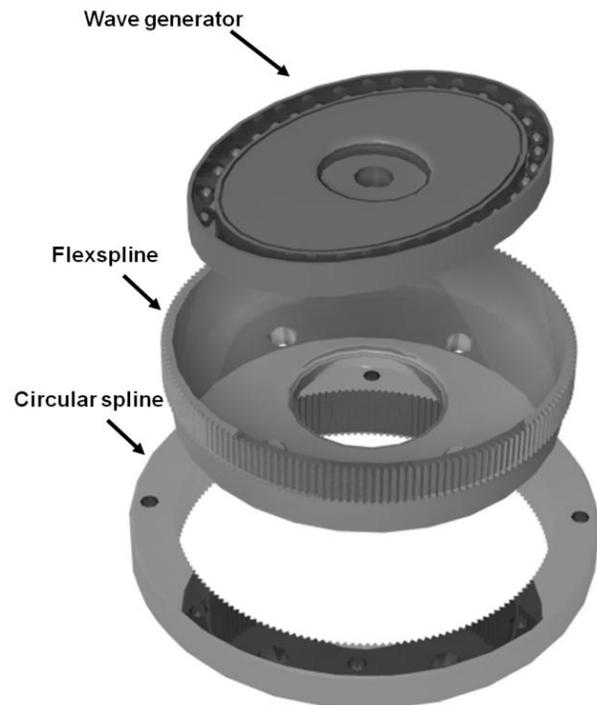


Figure 5.12: Harmonic® Drive

actuator effectively eliminates the induced torque on the extension-retraction motor when the strap and corresponding blade have reached the desired radial extension.

During extension and retraction there is a large amount of torque that the motor has to overcome. Housing a low-speed, high-torque motor on the hub has weight penalties. A high-speed, low-torque motor connected to a harmonic drive gear reduction to minimize weight. The Harmonic Drive housed in the spool drum has a 200:1 gear reduction⁷. The gearing system in its entirety is shown in Figure 5.12. The system consists of three components: a rigid circular spline, an elastic flexspline and an elliptical wave generator. The mechanical novelty of the system is the high gear reduction that occurs because of the apparent eccentricity of the wave generator as it meshes with the elastic spline. This design results in a robust, compact, and lightweight gear reduction that occupies a small area within the hub at the proprotor.

5.3.2 Flexbeam

The hub incorporates a composite flexbeam that is elastically tailored to act as a virtual flap and lag hinge. This tailoring result in a rotating flap and lag frequency of 1.2/rev and 2.18/rev, in rotor mode respectively. The flexbeam, together with the elastomeric bearing assembly, results in a flap-lag-pitch sequence for articulation. In addition to the foregoing components, the flexbeam also houses a set of strap rollers. These rollers, which are positioned at the virtual flap hinge location, serve to flip the strap from its vertical position within the spool drum, to its horizontal position in the blade. After passing through the rollers, the strap goes through the hollow bearing assembly before entering the blade segments.

5.3.3 Bearing Assembly

An exploded view of the bearing assembly is shown in the Foldout 3. Loads from the blades are transferred through a blade clamp to the series of bearings that are bounded on both sides to the flexbeam. The side further from the hub consists of a conical elastomeric bearing whose outer race is connected to the blade clamp on one side, and the inner race is attached to a thrust bearing. The thrust bearing in turn is fastened to a clamp that is rigidly connected to the flex beam. The conical elastomeric bearing is always in compression, and reacts the centrifugal loads. This bearing is also responsible for transferring all the flap and lag shear from the blade root to the flex beam.

The side towards the hub with respect to the blade clamp houses a radial elastomeric bearing and pitch bearing. The function of the radial elastomeric bearing is to provide damping and absorb torsional loads while providing a 15° range for pitch articulation. The radial elastomer also transfers flap and lag shear to the flex beam.

5.3.4 Solenoid Assembly

To operate efficiently in both helicopter and airplane modes, a high collective range is necessary. Aerodynamic analysis showed that for optimal cruise and hover, a collective range of 50° would be required. The bearing assembly has been designed to attain such a high collective pitch range. An exploded close up of the arrangement is shown in Figure 5.13.

The inner race of the pitch bearing has two radial slots located 50° apart. This design permits the solenoid to lock the rotation of the pitch bearing. During a transition from helicopter to forward flight mode, the solenoid pin retracts from the helicopter mode slot (see Figure 5.13) and the pitch bearing is free to rotate. The swashplate moves the pitch links and actuates the entire

bearing assembly, rotating it by 50°. Once this angle is reached, the solenoid pin inserts into airplane mode slot, locking the assembly in place.

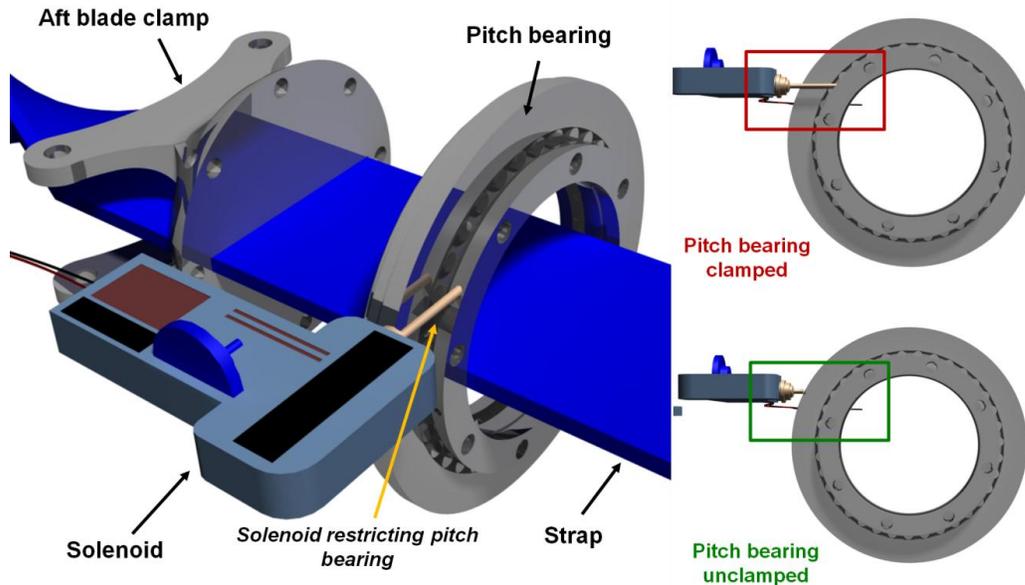


Figure 5.13: Pitch bearing and solenoid assembly

5.3.5 Gimbaled Hub

Traditionally, gimbaled rotors have been used on tiltrotor designs such as the XV-15, BA-609, and V-22. Gimbaled rotors are used to provide relief for the one-per-rev blade flapping air loads and virtually eliminate Coriolis forces induced by blade flapping and so reduce in-plane bending moments from lead-lag. Figure 5.14 shows an exploded view of the hub design.

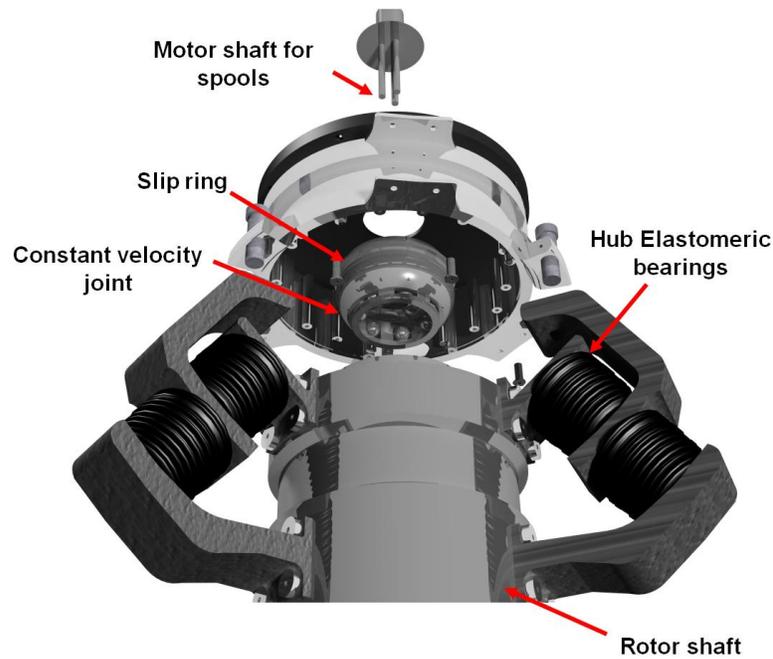
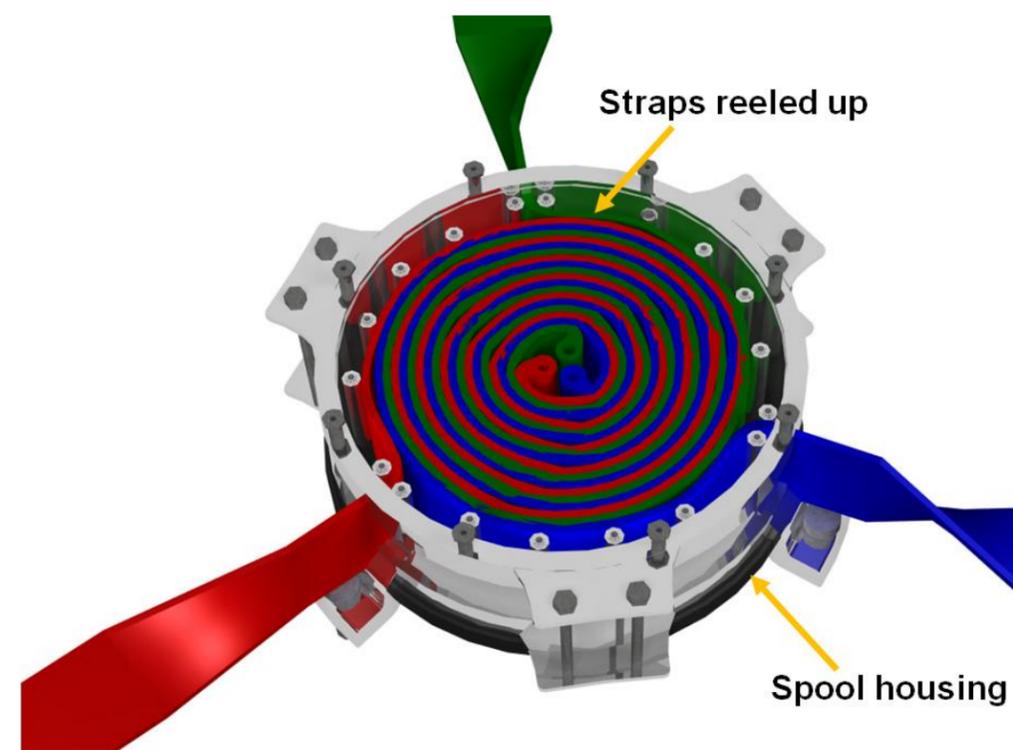
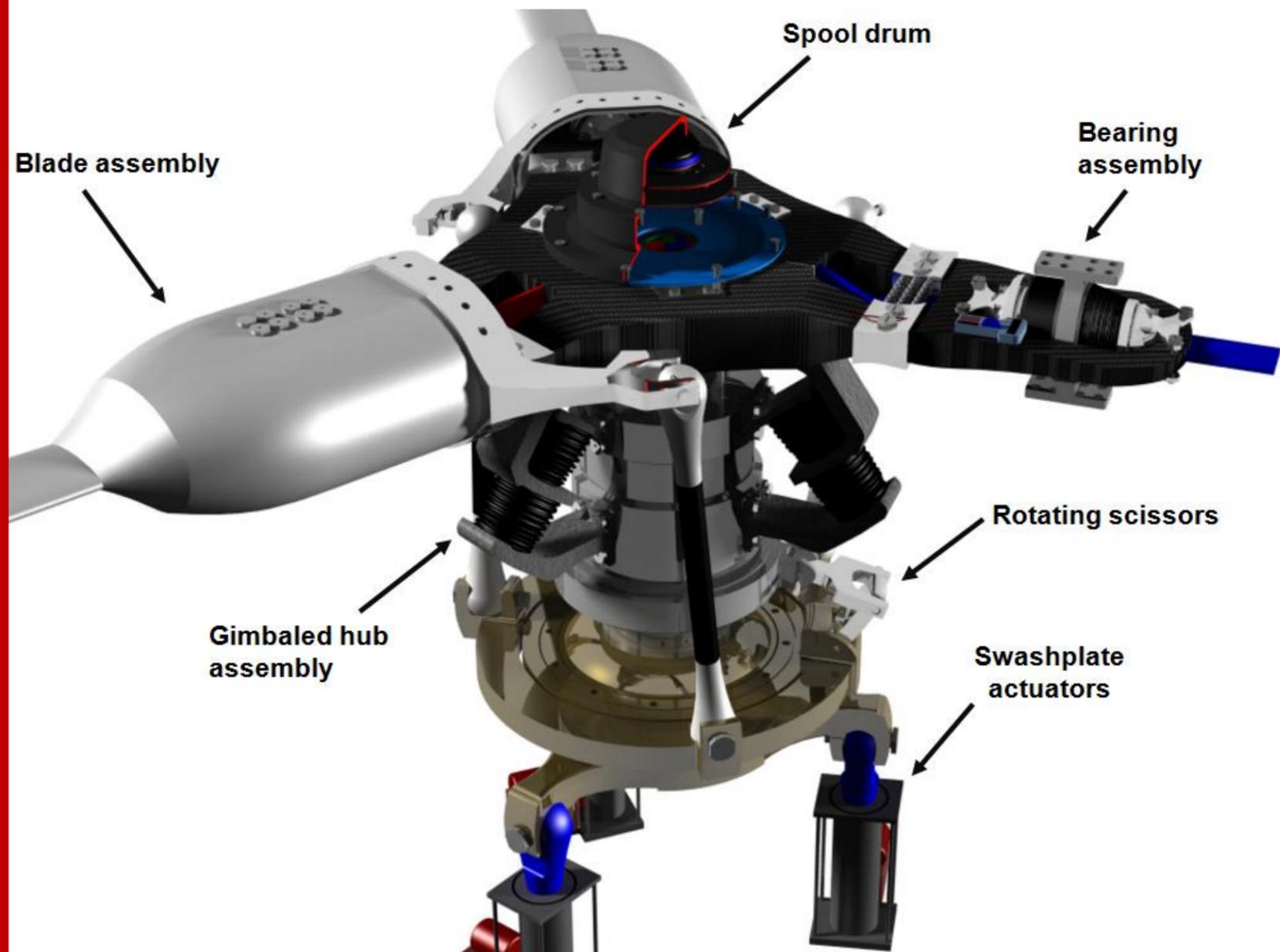
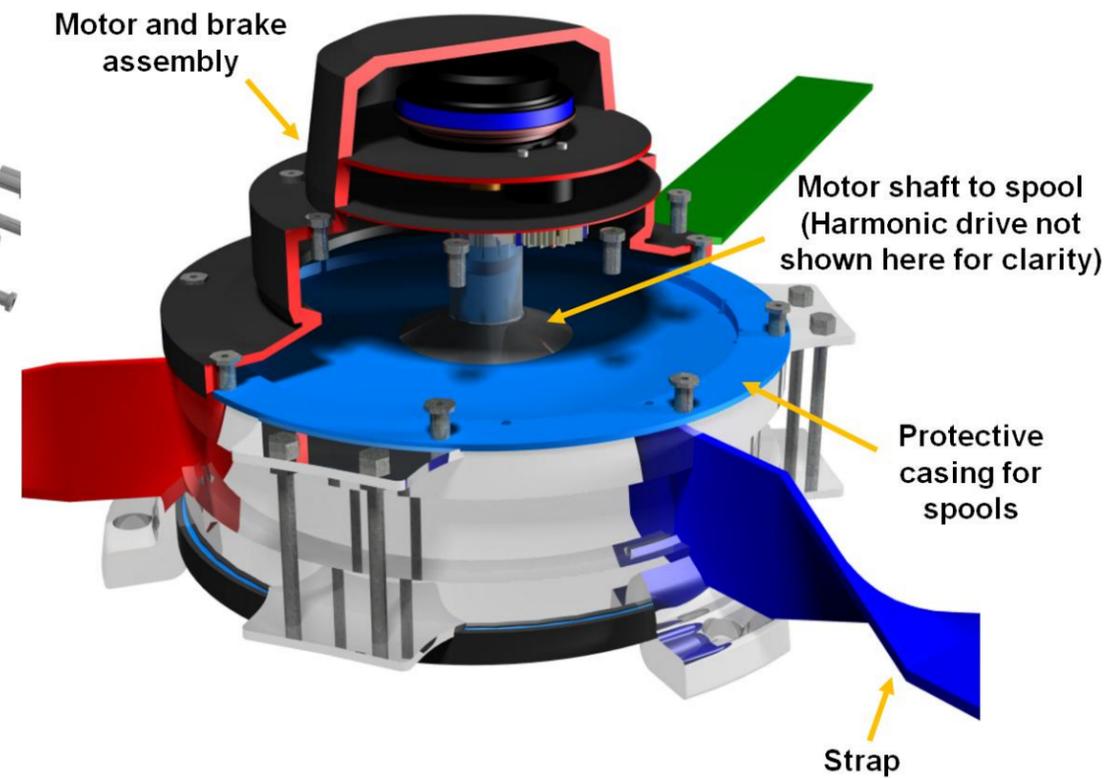
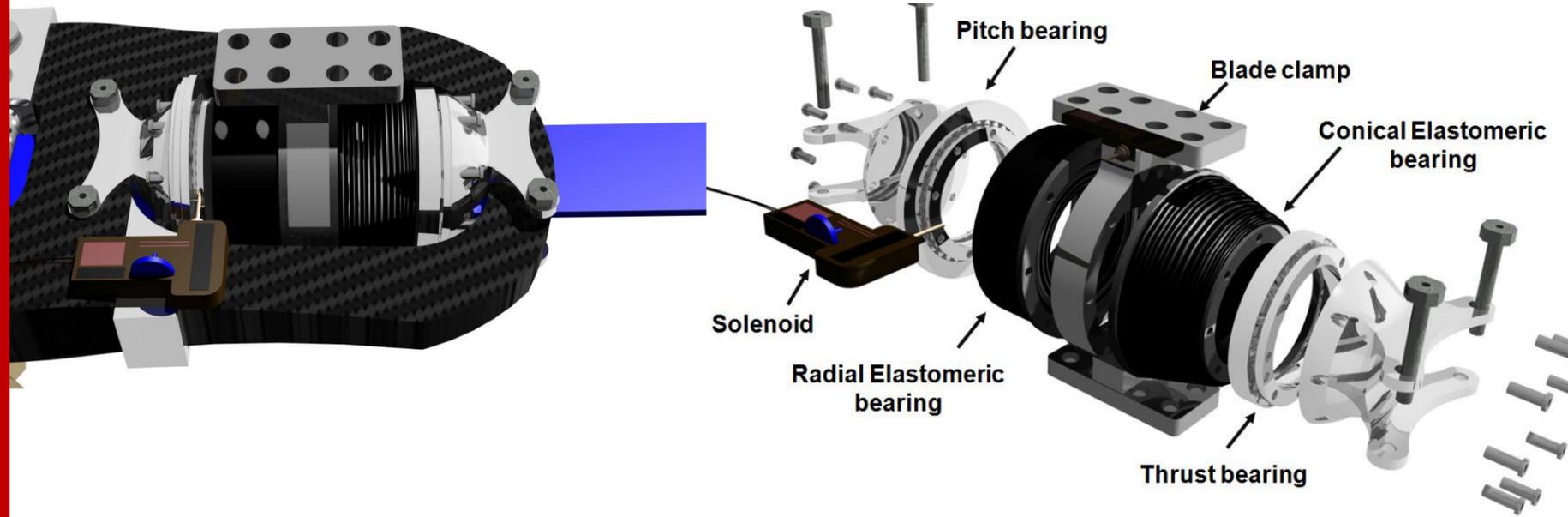


Figure 5.14: Exploded view of homo-kinetic gimbaled hub



Because the rotational axis of the hub can be tilted relative to the rotational axis of the shaft, a constant velocity joint (homo-kinetic) is incorporated to ensure that the hub and rotor shaft are operating at the same speed. This design is also known as a homo-kinetic gimbaled hub. If a constant velocity joint was not used, the shaft torque would experience a 2/rev oscillation which would be transmitted to the wing and would not only be a source of vibration and noise, but would lead to the potential for whirl flutter instabilities.

5.3.6 Aeroelastic Analysis

A variable-diameter proprotor is unique in its flap-lag-torsion characteristics as the natural frequencies in airplane mode are different than in hover. This is because of a decreased radius, increased blade stiffness, and increased spanwise mass distribution that occurs with blade retraction in forward flight. These effects result in an overall increase in the natural frequencies that are beneficial from the standpoint of whirl-flutter stability. However, this makes proper hub design essential because gimbal, flap, lag, and torsion frequencies must be properly placed so they do not intersect the per-rev frequencies of the rotor in these two different regimes.

To obtain the natural frequencies of the proprotor, it must be modeled in both gimbal-free and gimbal-lock modes. The gimbaled proprotor is stiff in-plane and is not fully articulated. It utilizes a flexbeam design with elastomeric bearings that act as gimbal spring, hinge and damper. Elastomeric bearings are used for pitch articulation as well, and are hollow in the middle to allow for the blade retention strap to pass through, as previously described in Section 5.3.3. Whirl flutter stability is ensured by keeping the first four rotor modes (gimbal, flap, lag, and torsion) away from the bending and torsion modes of the wing. The wing has also been designed to ensure that whirl-flutter is avoided as the carbon fiber plies have been oriented to counter the destabilizing bending-torsion inherent with a forward swept wing. This will be discussed further in Section 7.

The elastomeric gimbal bearings act as springs and provide only a marginal stiffness when the proprotors are rotating. The flap and lag frequencies are calculated based upon the stiffness of the flexbeam in respective directions, while the torsional frequency depends upon the effective stiffness of the pitch rod and elastomeric pitch bearings. Table 5.5 indicates the placement of these frequencies in both helicopter and airplane mode as they are illustrated in Figure 5.15.

Table 5.5: Rotating flap, lag, and torsion frequencies in helicopter and airplane mode

Rotating frequency	Helicopter mode	Airplane mode
Gimbal flap	1.05/rev	1.08/rev
1 st flap	1.2/rev	1.4/rev
2 nd flap	4.05/rev	6.25/rev
1 st lag	2.18/rev	3.69/rev
1 st torsion	4.5/rev	5.6/rev

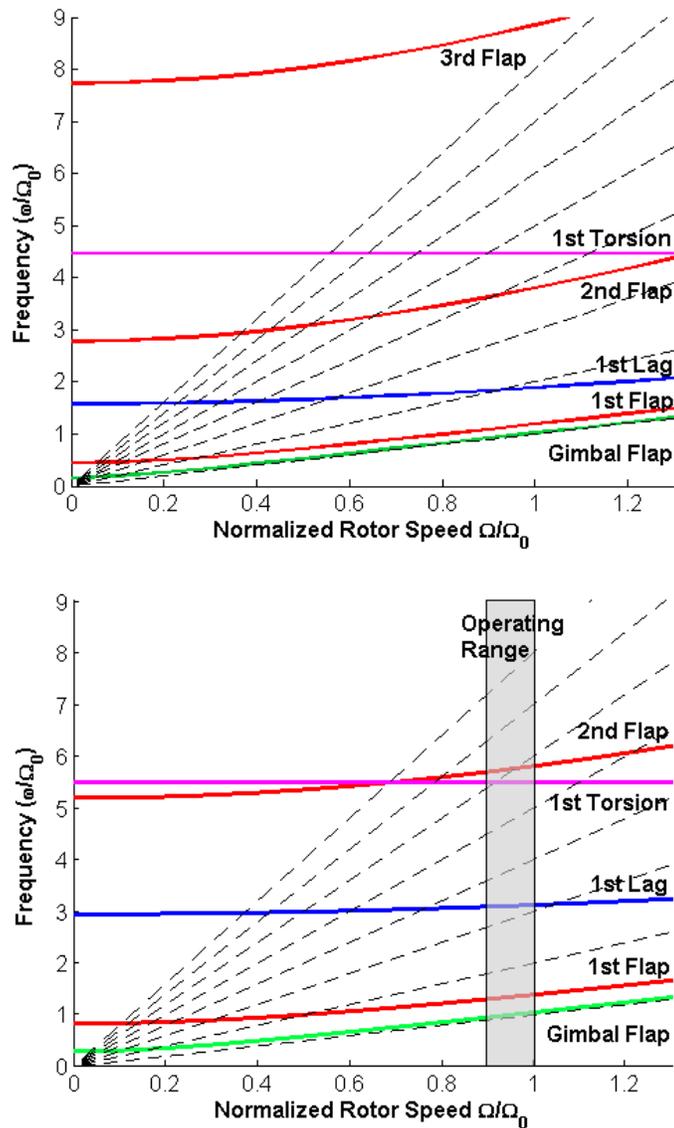


Figure 5.15: Fan plots for the proprotor in a) helicopter mode b) airplane mode

6 Drivetrain

6.1 Existing Drivetrain Designs

The conventional tiltrotor drivetrain configuration has established engines and transmissions placed together in full tilting nacelles at the wing tips (e.g., XV-15, V-22, BA609). Though this configuration has the benefit of being compact, however, there are disadvantages with this design in the rotor mode:

1. The hot exhaust from the turboshafts located at the wingtip adds to the rotor downwash and can hinder the rescue of victims.

2. During takeoff and landing, the high velocity exhaust jets can contribute to brownout conditions.
3. The hot exhaust directly impinges into the landing area and can be potentially damaging to aircraft carrier decks.

A possible alternative configuration involves the engines installed in the fuselage, much like the XV3. However, this configuration also had issues with vibration attributed to having high torque distributed through shafts running down the wings. In the design of the *Excalibur*, two main powertrain configurations were examined: 1. The engines located at the rear of the fuselage; 2. The engines located at the wingtips. Each of these configurations had the potential of increasing the efficiency of the proprotor in forward flight by the use of either a variable speed transmission or a variable diameter rotor (VDR). In addition, a configuration that had the engines at the wingtips, a VDR system, and non-tilting engines was examined. There is also the possibility of utilizing the VDR rotor and variable speed through the engines alone.

6.2 Trade Studies

The five different versions of the drivetrain were examined in full detail. The main qualities of each design are the power transfer efficiency, the overall weight, and the Technology Readiness Level (TRL). These parameters have been calculated including all components of the powertrain assembly. It was found early on that using both VST and VDR at the same time is not advantageous because while the system weight increases the drivetrain efficiency decreases, and only small increases are seen in either propulsive or hover efficiency. For this reason, this part of the option was eliminated. Table 6.1 contains the results of the drivetrain trade-study.

Table 6.1: Weight, efficiency, and TRL for drivetrain configurations

Drivetrain configuration	Drivetrain weight (lbs)	Drivetrain efficiency (%)	Drivetrain TRL
Wingtip engines			
With Variable Speed Trans.	880	95.0	6
With VDR	810	95.5	4
With VDR & tiltrotor only	855	95.0	4
Rear fuselage engines			
With Variable Speed Trans.	915	94.4	4
With VDR	875	94.9	3

(VDR: Variable Diameter Rotor)

The qualitative advantages and disadvantages of each configuration are:

Wingtip engines – It is apparent from Table 6.1 that the wingtip mounted engines offers much as far as weight and efficiency are concerned. The configuration, however, suffers from the effect of downward exhaust jets problems with lubrication flow paths within the gearbox housing; this makes implementing the “30-minute loss of lube” requirement more difficult. A conceptual illustration of *Excalibur* with this configuration is shown in Figure 6.1.

Variable Speed Transmission – The main deficiency of this configuration is that a variable speed transmission is needed at each wingtip to allow for variable rotor rpm. This design reduces the efficiency and increases weight. The VST itself could be a 2-or 4-speed dual clutch or a Continuously Variable Transmission (CVT). The advantage of a CVT is that the rotor rpm can be continuously adjusted to match the torque requirement

of the rotor system. For a tiltrotor, this design can also be used to allow for maximum proprotor efficiency in airplane mode at all flight speeds. Unfortunately, CVTs are not technologically ready for operational deployment within the *Excalibur's* development timeline. The use of a dual-clutch at both wingtips creates issues with maintaining synchrony between rotors while changing gears. Further, it requires a sequence of simultaneously disengaging the clutch, adjusting engine speeds engaging the new gears, for both rotors.

VDR – A VDR system can be augmented by a reduction in engine rpm to yield a higher efficiency in forward flight. A modest reduction of about 15% in engine speed can result in improvements in overall propulsive efficiency in airplane mode.

VDR and fixed engine positions – This configuration benefits from the previously mentioned advantages of the wing tip engines and the VDR system. Because the engines remain horizontal, the exhaust is always expelled rearwards and never downwards. Only a portion of the nacelle needs to be tilted, which requires less torque from the tilting mechanism. There are no lubrication issues for the non-tilting portion of the drivetrain.



Figure 6.1: Conceptual configuration of *Excalibur* with wing tip mounted engines

Rear fuselage engines – This configuration benefits from the effect of having stationary engines with rearward exhaust jets. There is also the benefit of having smaller wingtip nacelles that produce less drag, and so require less torque from the tilting mechanism to rotate. Locating the engines at the top or the rear fuselage, as shown in Figure 6.2, allows for engine-related systems (fuel and pneumatic lines) to be collocated. It also has the benefit of offering ballistic tolerance by having the fuselage and internal payload as a defensive shield. However, this design has several disadvantages. Locating the engines and a large portion of the drivetrain at the rear of the fuselage displaces the center of gravity (CG) significantly rearward. This effect moves the location of the wing further back, which reduces the moment aft to the horizontal and vertical tails. This outcome leads to a very large empennage to obtain the required stability of the aircraft.

Variable Speed Transmission – This configuration avoids the problem of having separate VSTs at both wingtips because the engine torques are combined at the rear of the fuselage. A speed change is conducted by a single variable speed transmission and sent down a single driveshaft. This single driveshaft is then split down both wings at the appropriate location. This design still suffers from the added weight and decreased efficiency along with a significant increase in mechanical complexity.

VDR – This configuration benefits from the superior gain in efficiency during cruise and hover. However, the added complexity and weight of overhead cabin shafts, redirection gearboxes, and the addition of the variable diameter mechanism decreases the efficient transfer of power and increases the empty weight.



Figure 6.2: Conceptual configuration with rear mounted engines

It is apparent that best configuration is wingtip mounted engines with a VDR system for improved performance but with engine position fixed. This method provides an increase in reliability and performance for the entire life of the vehicle.

6.3 *Excalibur* Drivetrain Overview

The powertrain starts at the chosen turboshaft engines. The original equipment manufacturer (OEM) gearbox allows a cost-effective, off-the-shelf speed reduction to a level that is manageable to accommodate the interconnecting driveshaft stability and sprag clutch. The output of the OEM gearbox is split between the interconnecting driveshaft, which maintains synchrony between rotors, and the tilt-independent gearbox. The output from this gearbox is transferred into a two stage epicyclic transmission that provides a 11.80:1 gear reduction. The final shaft torque, speed, and tilt are transferred to the main rotor hub.

6.4 Drivetrain Description

6.4.1 UMD Turboshaft Engines

The RFP requires that a “rubber” engine be designed based on the CT7-8A turboshaft engine. Following this, the engine selection has been done using the UMD engine model (see Section 3 for details). This selection was done to meet the project development timeline proposed by the Team (see Section 15). The selected engine had a MSL power of 1,908 hp and weighs 376 pounds. Engine power and rotation rate are maintained by an onboard Full Authority Digital Engine Control (FADEC) system, which tracks engine temperature, manifold pressure, atmospheric conditions, and emissions, and adjusts engine operations accordingly.

The requirement that *Excalibur* meets all performance goals at 6K95 conditions represents a significant challenge for the engine. The available engine power as a function of altitude and temperature is shown in Figure 6.3.

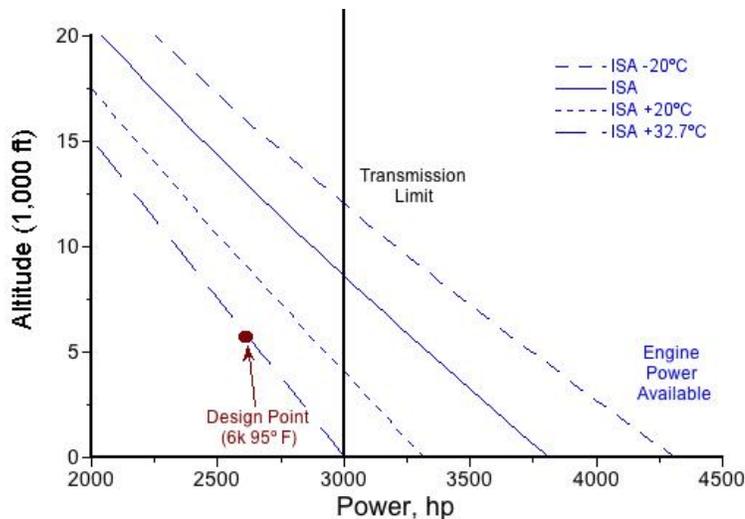


Figure 6.3: Engine power versus pressure altitude

6.4.2 Auxiliary Power Unit

The engines are started by an onboard Auxiliary Power Unit (APU). The APU generates high pressure air that is routed through a triple redundant pneumatic line. This line is used to drive an accumulator that spins the main engines until they reach the self-accelerating rpm. The need for an APU is based on the fact that *Excalibur* will likely be operating in hostile environments. The aircraft must be able to restart engines should they be shut down during the mission. Civil use of the aircraft will also benefit from an increased versatility in operating environment because no external ground power unit (GPU) is needed for operation.

6.4.3 OEM Engine Gearboxes

There is an (OEM) gearbox at the output shaft of each engine. This gearbox allows for a reduction in speed from 24,800 to 6,063 rpm, and has been designed based on the OEM analog of the CT7-8A. Reducing the high engine rpm increases the torque but the advantages of having a reduced speed allows for better stability and control.

6.4.4 Overrunning Clutch

The sprag clutch allows the engine to drive the geartrain but does not allow the geartrain to drive the engine. This feature is important in autorotational flight. The sprag clutch output leads into the interconnecting shaft and then immediately into the tilting bevel gears.

6.4.5 Interconnecting Driveshaft

The interconnecting driveshaft serves as a means of synchronizing the rotor speeds to create inherent stability within the system. It also adds the benefit of using one engine to power both rotors. Careful placement of the OEM gear reduction, the sprag clutch, and the split torque transmission allows for the successful and safe distribution of power from one engine to both rotors. The connections between driveshaft segments must allow for axial and angular displacements by the structural loading displacements of the fuselage and wings. Tilt-Independent Transfer Joint

This joint allows for the engine, OEM speed reduction, sprag clutch, and interconnecting driveshaft to maintain a constant horizontal orientation independent of the tilt angle of the rotor

mast. This goal is accomplished by using tilting bevel gears. The housing is also the primary structure that is lifted by the rotor shaft. The entire drivetrain up until this point is contained in one gear housing with one oil sump.

6.4.6 Planetary Transmission

The two stage planetary transmission elegantly reduces the speed from 6,063 to 514 rpm. A large oil pump operates within the housing of this gearbox. The oil from this pump is ported through the large oil cooler located adjacent to this gearbox. The first stage has a reduction of 92/24 (3.83) and the second stage has 74/24 (3.08). The progression of these gear reductions is shown in Table 6.2

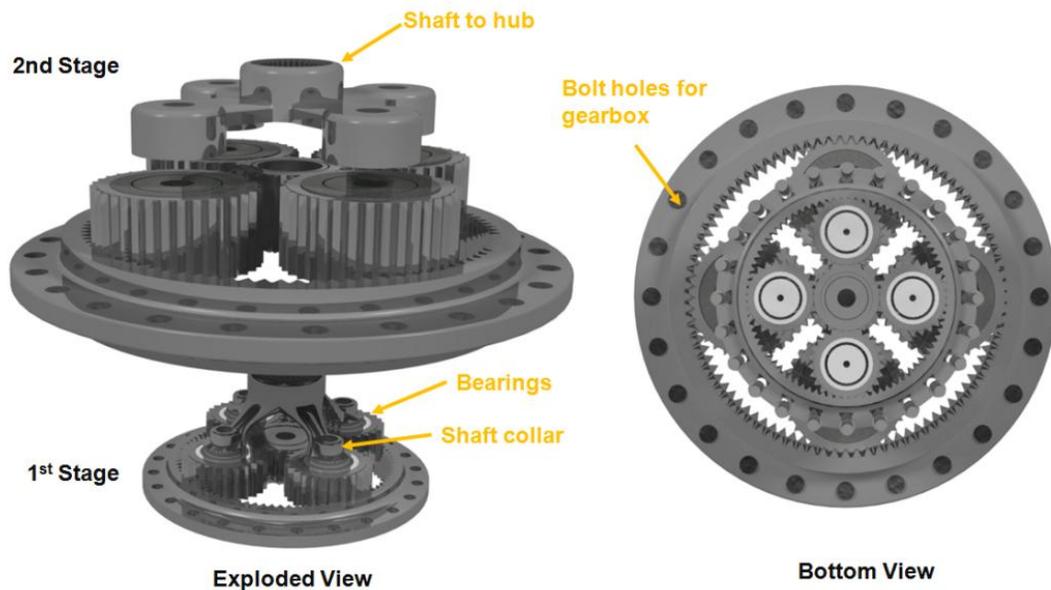


Figure 6.4: Two stage planetary transmission layout

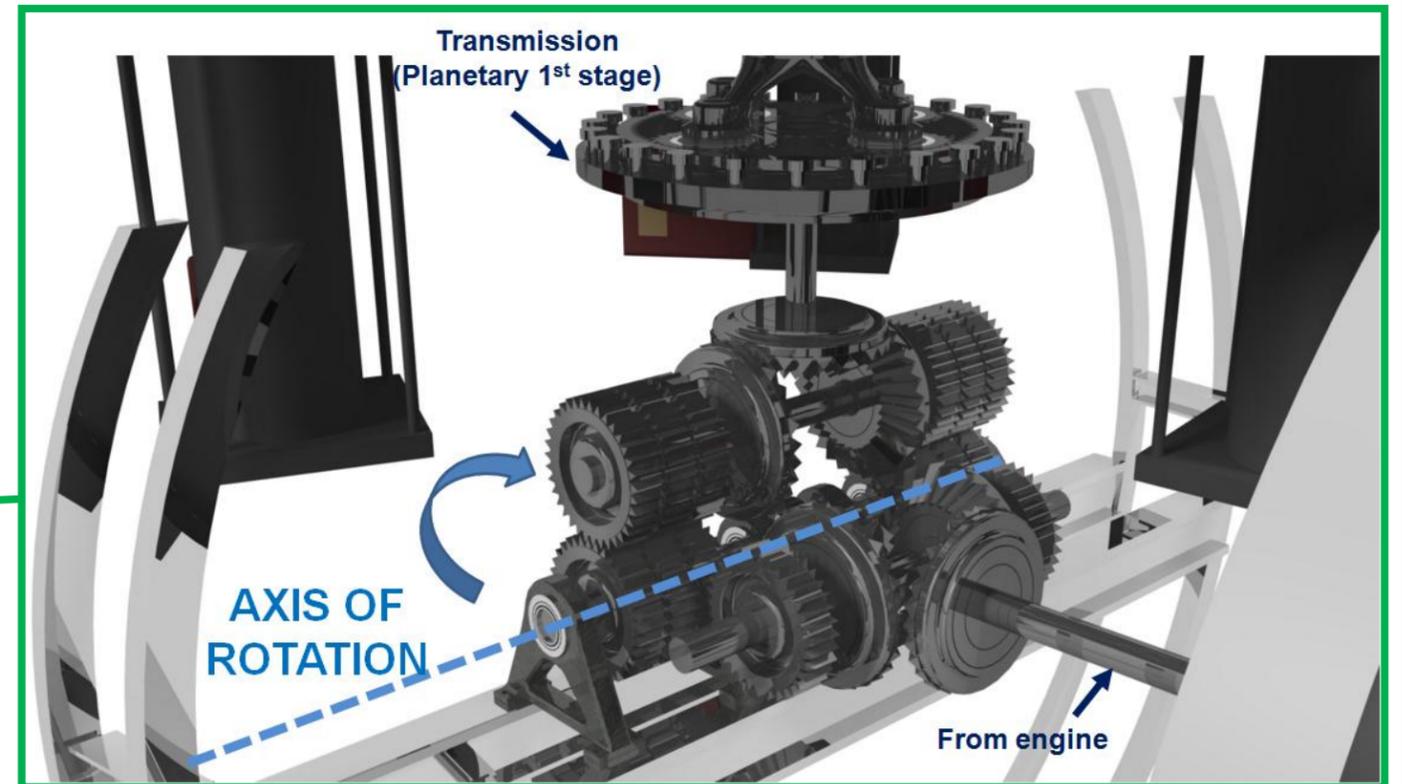
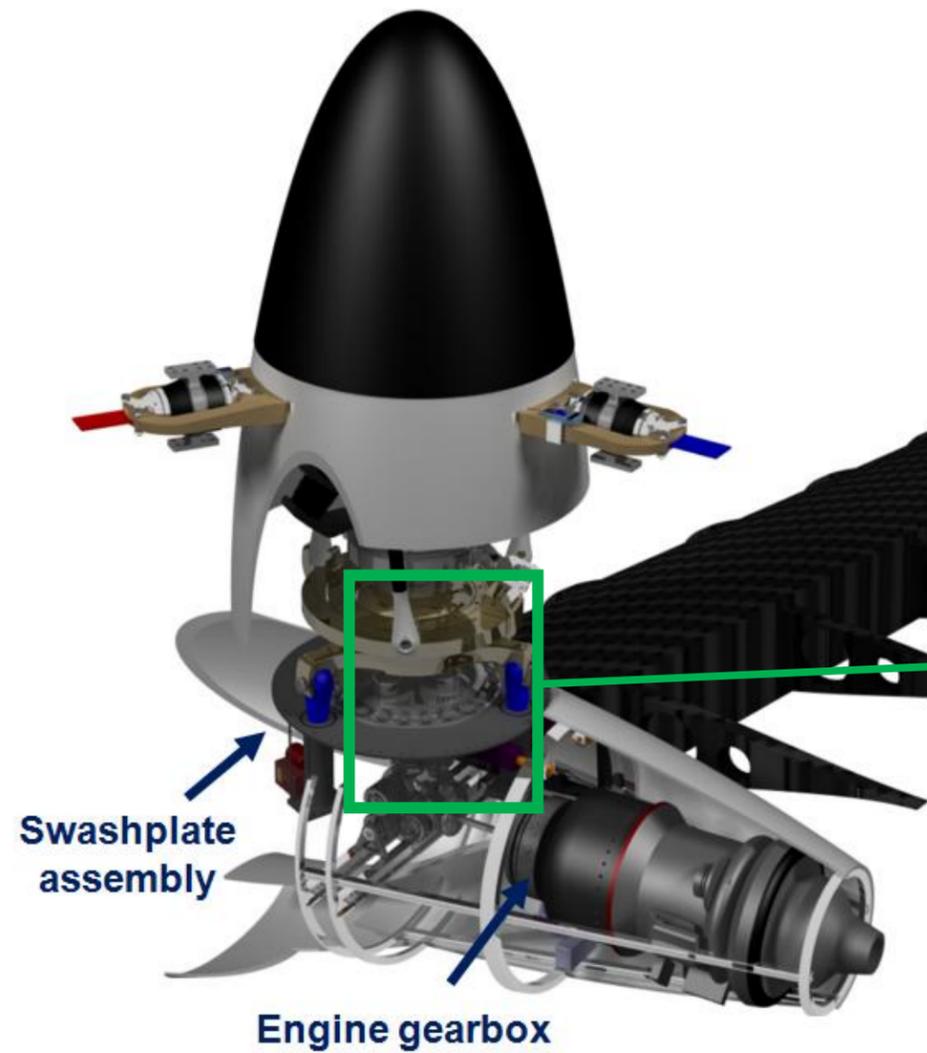
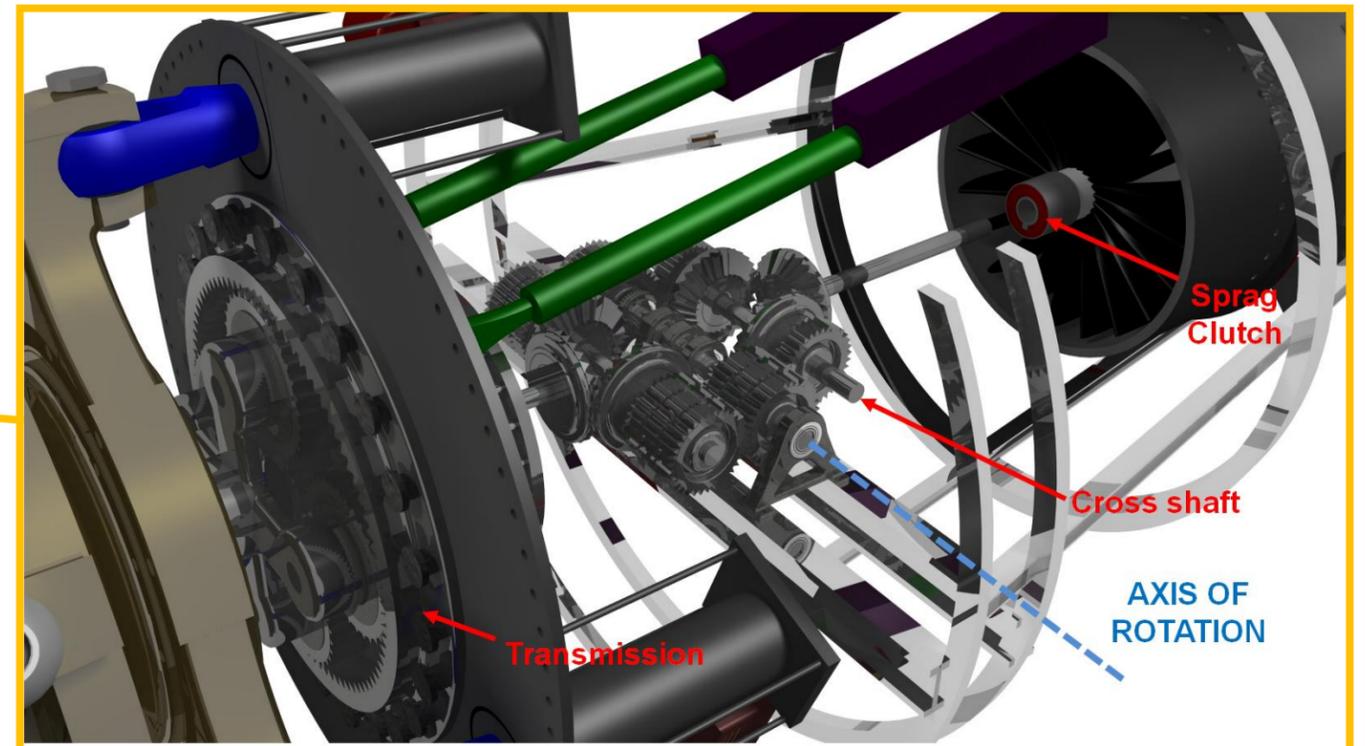
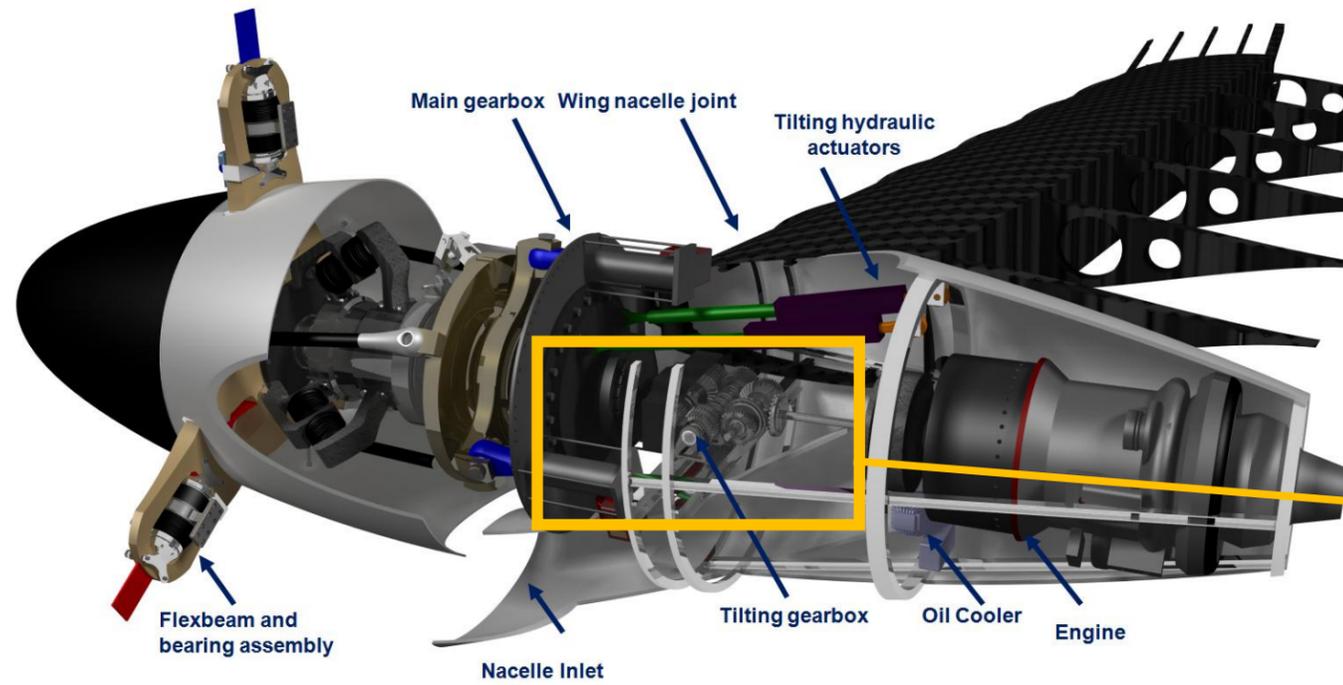
Table 6.2: Drivetrain gear design summary

Drivetrain section	OEM speed reduction		Planetary stage 1		Planetary stage 2	
	Pinion	Gear	Pinion	Gear	Pinion	Gear
Teeth	90	22	92	24	74	24
Gear ratio	4.09		3.83		3.08	
rpm	24,800	6,063	6,063	1,583	1,583	514

6.5 Lubrication and Cooling

The lubrication system has two primary objectives: to lubricate the gears, and to remove the excess heat from the gears. Oil is routed through cored passages in the housing walls, which then lead to nozzles that spray the gears before they contact. The sump at the bottom of the housing draws out the hot oil, where it then pumped through filters and coolers before being sprayed back into the gearbox.

A tiltrotor requires special care to incorporate these functions because a part of the drivetrain tilts through 90 degrees. There are two sumps so that oil can be removed in either of the horizontal and vertical orientations. The remaining tilting portion of the transmission has been designed to



last 30 minutes after the loss of lubrication. Cells have been carved into the internal housing walls to allow for oil to pool after the loss of lubrication. Once this oil is effectively being recycled by the spinning gears, it is only a matter of time before the temperatures in the gearbox begin to degrade not only the gear teeth, but also destroy the effectiveness of lubrication of the oil that makes it useful for lubrication. Verification of the 30 minutes dry running capability must be proved by testing of the *Excalibur's* transmission.

The lubrication cooling system has been designed so that the exit temperature of the oil from any gearbox is no more than 45°F above the entrance temperature. For any of the given gearbox a single drop of oil may cycle through the lubrication system several times per minute. The OEM gear boxes contain approximately 1 gallon of oil, and the two-stage planetary transmission housing contains approximately 2 gallons of oil. Hot oil from either the tilting or non-tilting gearbox is pumped through the multi-input-multi-output (MIMO) oil cooler located at the outer edge of the wingtip nacelle. Redundancy of on oil cooler input and output path allows oil flow in the event of single entrance or exit becoming blocked.

The oil pressure and temperature sensors have been placed in strategic locations throughout the lubrication system. In addition magnetic chip detectors have been placed in the oil flow path. For the portion of the drivetrain that tilts, detectors are located at the settling locations for both horizontal and vertical orientations.

6.6 Alternator

The power converter draws energy off of the powertrain at the intermediate gearbox. The wattage of the alternator must meet the demands of the aircraft during peak power consumption, as well as during normal operation.

7 Airframe Design

The *Excalibur* is designed to handle multiple missions in a military environment. Therefore, *Excalibur* utilizes a compact, crashworthy airframe that is designed to meet the rigors of military operations. The components used in the airframe design provide a modular internal layout, ballistic protection, and a retractable landing gear system.

7.1.1 Wing Structure

The sizing of structural members within the wing was determined based upon calculations of shear force, bending, and torsion moments along the span of the wing. Wing components were sized to ensure a sufficient margin to permit high-speed maneuvering flight. This section discusses the structure of the wing and the reasoning for the configuration and sizes chosen.

The wing composite structure used on the *Excalibur* is shown in Figure 7.1 The wing structure is fabricated from 35 layers of $\pm 45^\circ$ carbon epoxy to provide sufficient stiffness to prevent whirl flutter and to have adequate strength to overcome the bending and torsion loads on the wing. In addition, the torque box has layers of carbon/epoxy oriented at 15° to generate flap bending-twist coupling. This coupling increases aeroelastic stability margins in forward flight.

The torque box is located along the chord from $0.07c$ to $0.45c$. Because the wing has a 20% thickness-to-chord ratio with a maximum thickness at $0.30c$, the torque box has a large flap stiffness and torsional stiffness.

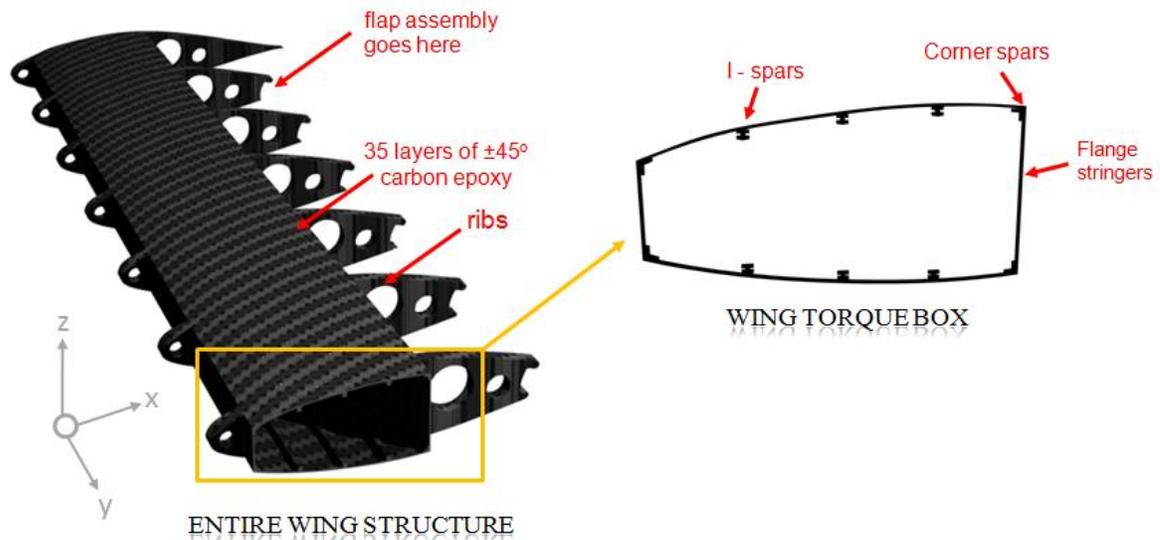


Figure 7.1: Advanced composite wing structure (shown without flaps / flaperons)

The torque box also serves to house the fuel required for all three missions. No cutouts are present within the torque box because this destroys the continuity of shear flow. Cutouts for the interconnecting shaft, electric, and hydraulic lines are located on the ribs.

7.1.2 Fuselage Structure

Excalibur's fuselage is based on a semi-monocoque construction. The cross-section of this structure is based on distributing concentrated loads to utilize the space efficiently. A double ellipsoid was chosen for the cross-section as this shape maximizes the usable space of the fuselage. Primary bulkheads are placed to distribute the major loads throughout the fuselage. A static load analysis helped in determining the placement of these bulkheads. The first bulkhead connects the nose of the fuselage to the main cabin. This bulkhead also transmits loads through the floor and the fuselage roof structure, which houses the cockpit windows.

The second through fifth bulkheads are placed at the main sliding door. These first of these bulkheads supports the landing gear assembly. The fourth and fifth bulkheads are placed between the two spars of the wing. The placement of the fourth and fifth bulkheads between the wing I-beams allows the shape of the torque box to be maintained and provides a rigid attachment point for the main wing spar. This is done through a cross riveted arrangement where the carbon fiber wing is directly riveted to the bulkhead structure of the fuselage. Beyond this point, secondary bulkheads are attached to the T-Tail section. These bulkheads provide the aerodynamic profile and provide closure to the fuselage structure.

7.1.3 Cabin Layout

The cockpit provides crashworthy seating capacity for a pilot and a copilot with full access to the flight control and all systems. Furthermore, the main cabin volume is sufficient to carry two crew and a maximum of six passengers (insertion mission) or hold cargo weighing 4000 lb (resupply mission). The arrangement of seats also permits litters to be accommodated by attachment through universal attachment fittings, as described in Section 10. Finally, with the structural design and all the components placed in the fuselage, the entire layout can be seen in the Foldout 5.

The sliding doors used in *Excalibur* are jettisonable. A sliding design provides an optimized solution between accessibility and maintaining structural integrity. This adds to the versatility of *Excalibur*. The door is attached between the fifth and sixth bulkheads and is large enough for easy loading/unloading of cargo and the maneuver of a rescue basket for search and rescue missions. The overall size of the door is 4 ft by 5 ft.

The cockpit windows present on the cockpit of *Excalibur* offer vision for both the pilots and the copilot. Another window is provided on the floor of *Excalibur* for the pilots to see the landing area when descending in helicopter mode.

7.2 Structural Materials

Selection of a material for aircraft construction depends on several factors specific to their application. Some of the material properties to be considered include the yield and ultimate strength, stiffness, fatigue resistance, corrosion resistance, manufacturability, ease of repair, cost, and availability. More importantly, there has been recent emphasis on the use of environmental friendly materials, reduced energy consumption, and lower life cycle costs.

Excalibur has been designed to have a balance between low cost, manufacturability, maintainability and environmental friendliness. *Excalibur* will perform missions for military applications and, therefore, will be subject to different weather conditions, varied loads, unfriendly airspace, and other unknowns. These concerns lead to the need for a robust and versatile airframe structure. The following section details the material selection and specifics for major components of *Excalibur*.

Aluminum-Lithium (Al-Li) alloys are used for the construction of frames of the cabin of *Excalibur*. Al-Li alloys drive the weight of the system down and can be formed using traditional aluminum manufacturing techniques. Therefore, a commercially available alloy of Al-Li, Weldalite 0409 is used. Weldalite 0409 is comprised of about 2% lithium, resulting in a 7% reduction in density and a 10% increase in elastic modulus. Weldalite has an excellent strength to weight ratio, resistance to chemical corrosion, fatigue resistance, and crack propagation resistance. At the same time, however, this material demonstrates reduced fracture toughness and ductility in the short transverse direction. On *Excalibur*, Weldalite 0409 is used on the primary and secondary bulkheads and longerons. From a manufacturing perspective, it is easily weldable and reduces the number of mechanical fasteners that can contribute to fatigue loads. This brings down the production and maintenance cost of *Excalibur*'s primary structure.

Cabin floors need to be lightweight while maintaining the ability to carry large inertial loads. Kevlar and nomex honeycomb was used for the floor to provide superior stiffness and abrasion resistance.

The empennage structure (horizontal and vertical tail) is constructed using a composite construction that makes it lightweight. The vertical stabilizer, rudder, horizontal stabilizer and elevator use Kevlar/carbon/glass. The top layers of the vertical and horizontal stabilizer are made of Kevlar/epoxy. This reduces the number of components and rivets by a factor of 20 as compared with an equivalent metallic construction.

The rotor blades must be stiff enough to carry high centrifugal loads, and resists the oscillatory flap, lead-lag, and torsional moments. Selecting suitable materials produces favorable structural couplings. The blade for *Excalibur* principally consists of an envelope that ensures aerodynamic

profile and stiffeners to carry the large centrifugal forces. The spar is made of glass/epoxy. Composite materials such as carbon fiber/epoxy are considered for the outer portion of the blades and elliptic parts that are light, possess high stiffness to weight ratio, and good strength-to-weight ratio. In addition, these materials have good damage tolerance properties, good ballistic tolerance, and can be easily constructed and elastically tailored¹. Nomex honeycomb is used as the filler material to give rigidity to the skin. To allow for grounding of any electrical charge, electrical bonding is achieved in the structure using an aluminum mesh.

The rotor hub assembly should allow for different degrees-of-freedom for the rotor blade. The yoke of hub is made by use of balanced multilayer glass/epoxy fabric (0/+45/90) and molding it in an autoclave. Major benefits of using this material are cost high stiffness, reduction, weight reduction and most significantly, ease of maintenance. The elastomeric bearings present in the rotor hub are made of alternating layers of steel and rubber to allow for movement through shear of the rubber. These bearings are then coated with silicon to protect them the effects of oil and ozone.

Two disadvantages of using rubber in the elastomeric bearings are that its stiffness is a function of temperature. As the temperature decreases, its Young's modulus E and torsional rigidity G , increases. This increase in stiffness would require higher forces to change the pitch of the rotor blades on cold days. However, because rubber is a poor conductor of heat, the bearings usually warm up after a few actuations, and the force required for actuation returns to normal levels. Another disadvantage is that rubber deteriorates in the presence of ozone, therefore the bearings are protected by a layer of silicone.

This material selection makes the rotor hub and blades tolerant to damage and to be able to sustain damage for projectiles of less than 20 mm caliber.

Door: The cockpit doors are large sliding doors under the wing. These sliding doors are located on both sides of the fuselage, and are wide enough to facilitate search and rescue operations and litter embarkation. All doors are braced to prevent jamming in the event of airframe warping, and can be jettisoned in emergencies as is required by 14 CFR 29.783.

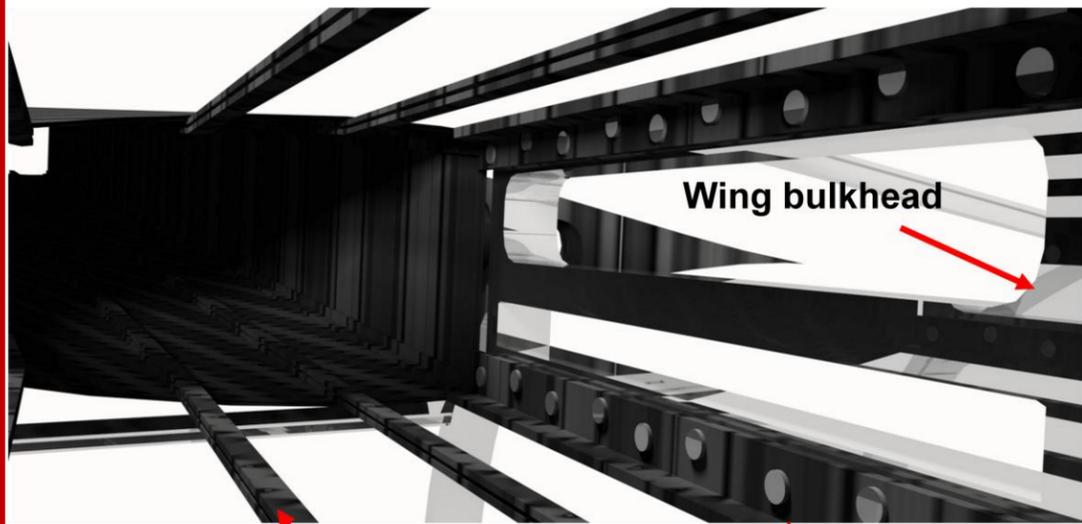
Table 7.1 lists the different materials used during the manufacturing of *Excalibur*. The majority of these materials will be available under our project development timeline.

In addition to strength-to-weight and operative cost benefits of composites, the extensive usage of composite materials in *Excalibur* reduces its radar signature, as required by RFP. In *Excalibur's* design, adequate consideration has been made of the recyclability. Nearly all the Aluminum alloys used in *Excalibur* are recyclable. Similarly a number of non-fatigue components such as avionics, cabin flooring, furnishing equipment, etc. will be available for direct reuse and do not require additional energy at the end of life cycle.

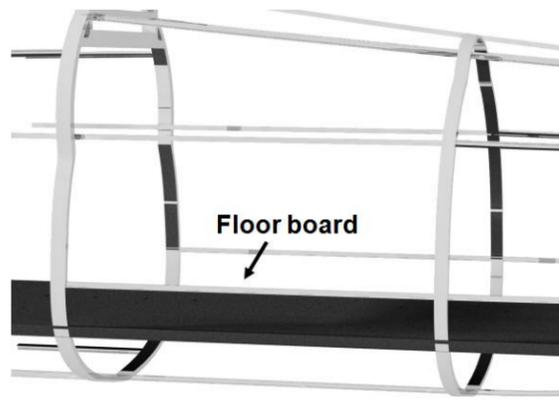
Excalibur's airframe is both lightweight and highly environmentally friendly, and the choice of materials allows the aircraft to be versatile.

WING FUSELAGE MATING

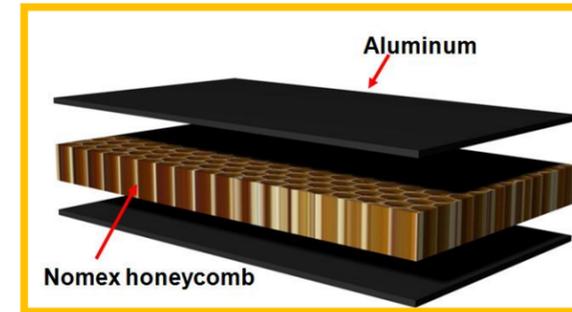
EXCALIBUR



Wing bulkhead



Floor board

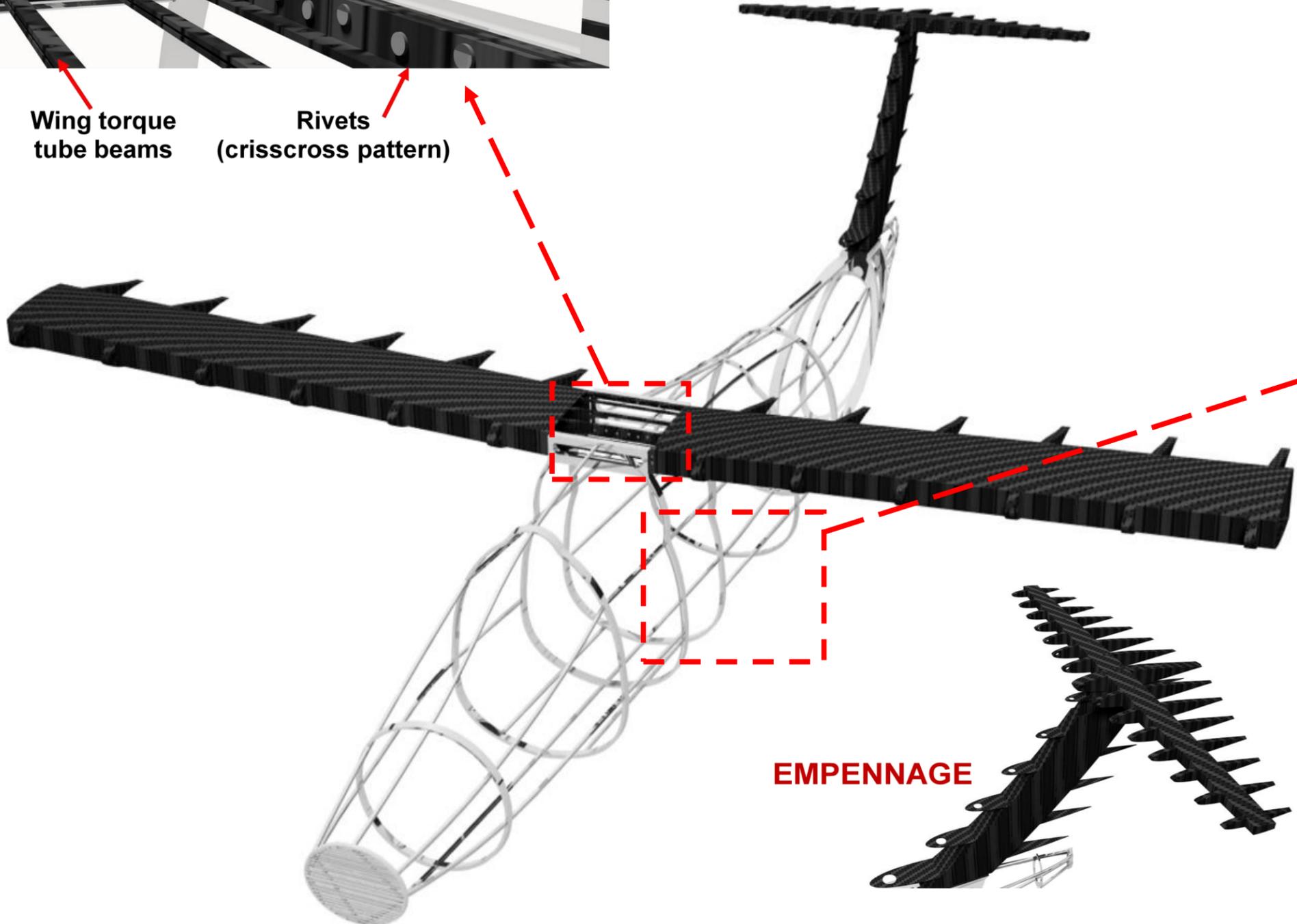


Aluminum

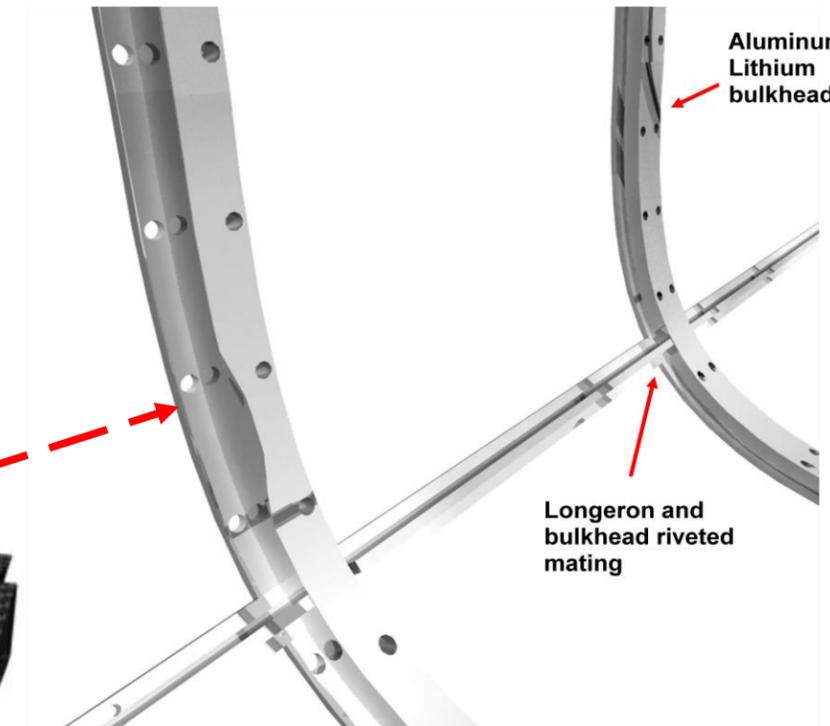
Nomex honeycomb

Wing torque tube beams

Rivets (crisscross pattern)



EMPENNAGE



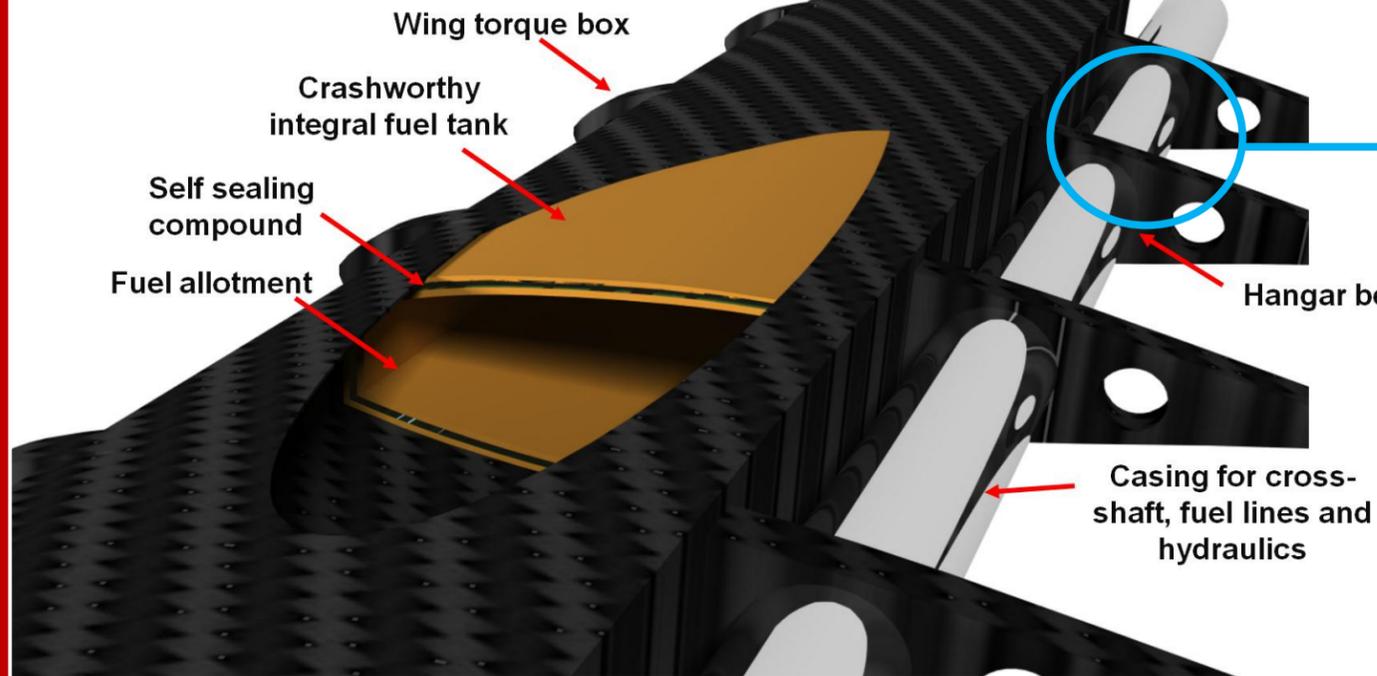
Aluminum Lithium bulkheads

Longeron and bulkhead riveted mating

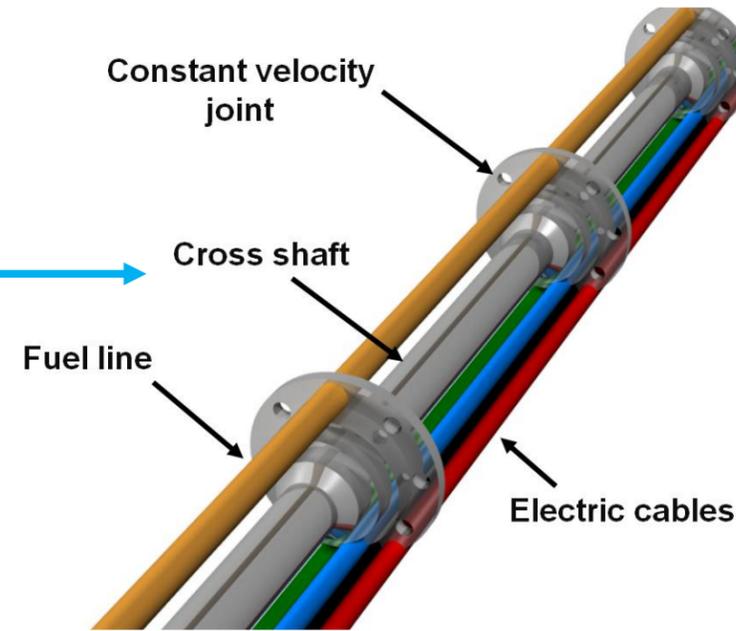
BULKHEAD DESIGN

*Control surfaces not shown for clarity

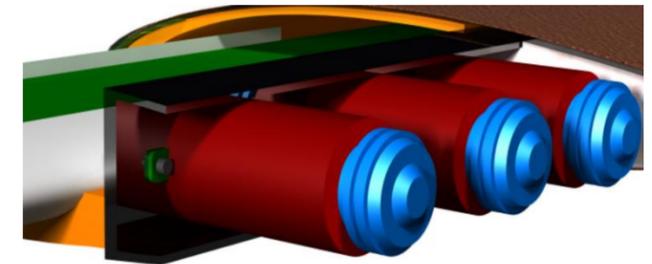
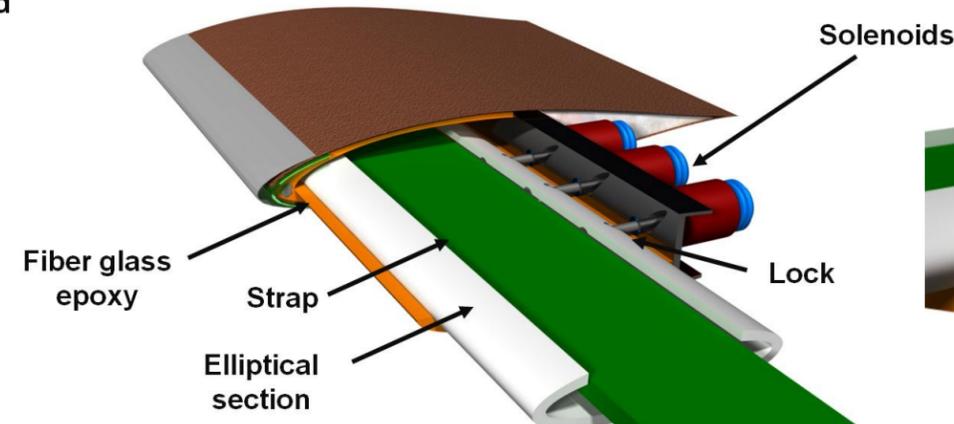
Wing Interior



EXCALIBUR

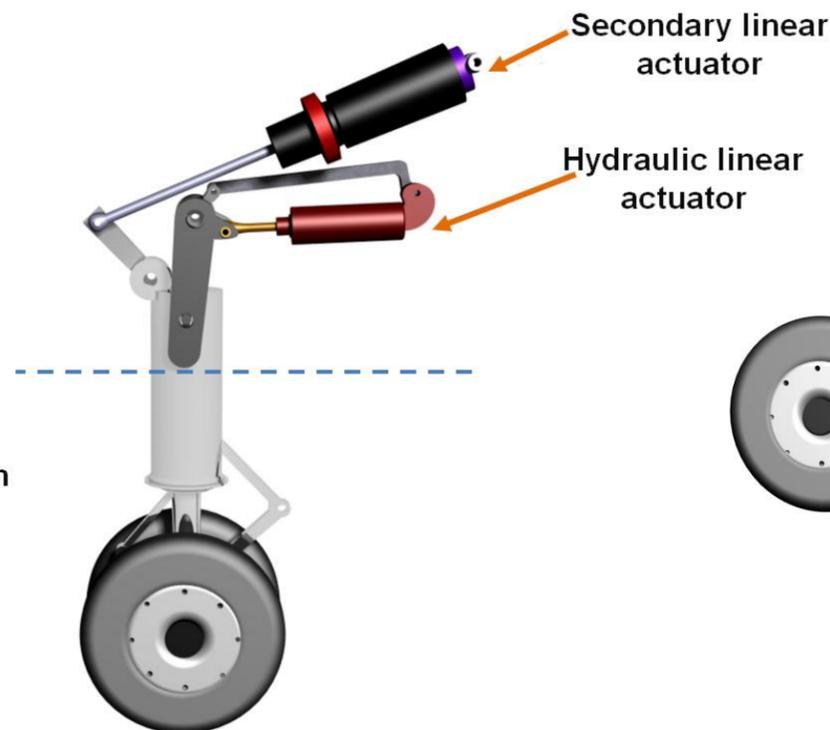
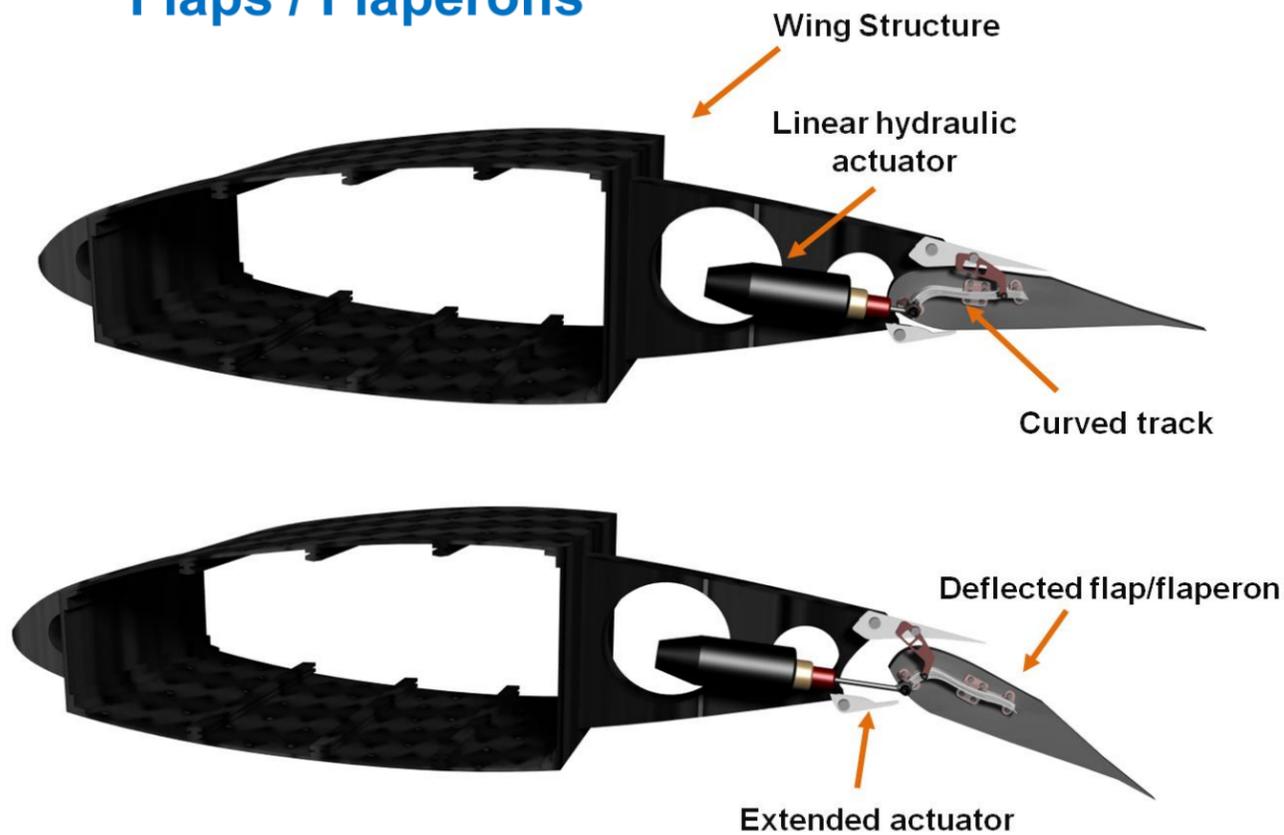


Blade Locking



Solenoids bolted to carbon channel

Flaps / Flaperons



Nose Landing Gear

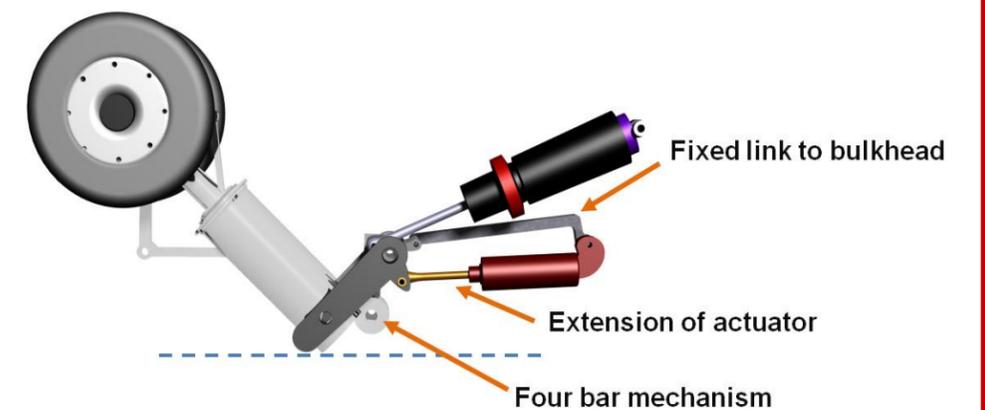


Table 7.1: *Excalibur* material use

Materials	Primary <i>Excalibur</i> uses
Al-Li Alloys	Bulkheads, longerons, stringers
Kevlar and Nomex honeycomb	Cabin floor
Fiber glass	Wings
Carbon fiber	Proprotor blade
Glass/epoxy	Proprotor hub yoke
Rubber	Proprotor hub bearings
Fiber glass	Empennage
Aluminium casting alloy	Main gearbox housing
VASCO X-2M Steel	Transmission gears
Oleo pneumatic type	Landing gear
Rubber	Engine
Natural rubber	Fuel tank
Stainless steel	Fuel lines
Polycarbonate (PC)	Front windshield, windows
Silicon (PFDs)	Avionics
Bio polymer foam	Seat cushions
Epoxy	Paints

7.3 Landing Gear

The landing gear has been designed to ensure safety and handling in both VTOL and conventional fixed-wing takeoff and landing maneuvers. Because *Excalibur* has a cruise speed greater than 225 kts, it was designed with retractable landing gear. To reduce the parasitic drag of the aircraft, retractable tricycle configuration has been employed to allow for a balance between stability, fuselage clearance, weight, and retraction method.

The strut geometry was sized to absorb and dampen the loads incurred during takeoff, landing, and ground maneuvering. The landing gear sizes and lengths were also analyzed to provide ample ground clearance from the rotors when they are in the full forward position. Wheels were selected from the current aircraft-grade selection of Type VII certified civil and military markets.

7.3.1 Longitudinal Tip-Over Criteria

The longitudinal criteria dictate that the center of gravity be situated in a manner that allows for full braking to be applied without any chance of the aircraft tipping over frontwards or backwards. The main gear is situated a minimum of 15° behind and below the most aft center of gravity position ensuring that rearward longitudinal tip-over is avoided.

7.3.2 Lateral Tip-Over Criteria

The lateral tip-over criteria requires main gear separation to prevent the aircraft from tipping over during takeoff and landing. As such, a balance must be achieved between the height of the CG, the distance from the nose gear to the main gear, and the separation between the main landing gear points of contact with the ground. Greater separation between the points of contact of the main gear provides stability when landing on uneven and sloped surfaces.

7.3.3 Ground Clearance Criteria

The ground clearance of the fuselage, wings, and propellers must be maintained to allow for ample distance between the propeller and the landing surface for when the vehicle rolls during landing. Fixed-wing aircraft generate their highest lift coefficients during landing to minimize the landing speed. This necessitates a high angle of attack and an angle of 15° must be allowed between the landing surface and any components behind of the main landing gear.



Figure 7.2. Diagram of Ground Clearance Criteria

8 Avionics

The avionics and control system are the primary interface between the crew and the systems and control of the aircraft. The avionics systems should provide the pilot and co-pilot with all the necessary information needed to effectively and efficiently fly the aircraft while minimizing the pilot workload. The *Excalibur* accomplishes this by utilizing modern digital flight displays and control architecture, as well as sensors, to provide the pilot with enhanced situational awareness and the ability to fully control the aircraft.

8.1 Cockpit Layout

The *Excalibur* is designed for two pilot operation with stations for two additional flight crew or flight engineers. The main panel is organized to minimize pilot workload and all controls and displays are organized in a consistent and task-oriented manner. This architecture ensures that pilots transitioning to the aircraft for the first time will have no difficulty in viewing and operating the aircraft systems and controls. All displays are anti-glare and are compatible with night vision goggles (NVG), which makes them ideal for both day and night search and rescue missions.

8.1.1 Flight Displays/Pilot Interface

The cockpit features dual displays for both the pilot and co-pilot with a total of four 8-by-10 inch Rockwell Collins AFD-3010/3310 Adaptive Flight Displays¹. These four displays are separated into a Primary Flight Display (PFD) and Multi-Function Display (MFD) for each pilot. The displays can be used interchangeably for PFD, MFD. The PFD provides the primary flight instruments, which can optionally be overlaid on synthetic vision that includes terrain and traffic awareness. This architecture allows the pilot to fly the aircraft more effectively in both IFR and brownout landing conditions. The multi-function display shows information such as electronic charts, approach plates, or GPS and navigation/terrain maps, which can all be overlaid with

weather radar, Traffic Collision Avoidance System (TCAS) information, and terrain awareness warning system (TAWS) information.



Figure 8.1: Cockpit Displays and Avionics

There is also a centrally located 10-by-12 inch Rockwell Collins AFD-5220 Adaptive Flight Display for engine and system monitoring. This display utilizes the engine indication and crew alerting system (EICAS) to provide critical engine and system status, as well as data recording to provide health and usage monitoring data (HUMS). This display shows FADEC information for both the left and right engines, as well as turbine temperatures, retractable blade lengths for each of the 6 rotor blades, landing gear up/down, electrical system information, fuel flow and quantity, and hydraulics systems. This display is also coupled with the engine control unit to manage power for maximum hovering and cruising efficiency.

All flight displays offer redundancy in design so that if any one fails, each display is capable of displaying all of the information gathered by the vehicle management system. Each display also employs its own individual backup battery to ensure that all information is displayed in the event of a total or partial electrical failure. In the unlikely event that all displays fail, the pilot is still provided information using the analog backup airspeed indicator, directional gyro, artificial horizon, and barometric altimeter.

8.1.2 Communications System

Communication and navigation is provided through two digital Rockwell Collins RTU-42XX Radio Tuning Units (RTUs). These units provide integrated control of all communication, navigation and surveillance sensors. Each of these units offer complete radio management functionality, and offer a means of selecting frequencies, codes, channels, operating modes and volume control. This unit is integrated with the flight management system so that the tuned

frequency is always displayed on the RTU regardless of the tuning source. The RTU also can display backup horizontal attitude information, and can even display backup engine display data.

The *Excalibur* capitalizes on the complete system integration that Rockwell Collins avionics provide so that the pilot's productivity is maximized for minimal workload, while also providing redundancy for all information provided by the vehicle management system.

In-cockpit communication is accomplished through the use of a David Clark Series 3800 Vehicle Intercom System². This system is capable of providing isolated communication for all crew and passengers with an isolating U3800 master station to separate cockpit and cabin communication at the discretion of the pilot and crew. The crews will utilize David Clark H10-76XL electronic noise canceling headsets capable of actively cancelling ambient noise from engines, rotors, and other vehicle systems. These headset meets MIL-26542/2 specifications for military aircraft, and are standard in many of today's modern military aircraft.

8.1.3 Avionics Sensors

All information presented on the flight displays originates from the vehicle management system. This includes magnetometers, gyroscopes, accelerometers, GPS, pitot and static ports, and FADEC information. A high-fidelity navigation system is crucial to successful mission completion. Therefore, the *Excalibur* employs a Rockwell Collins Athena 611 Integrated Flight Control System, this is a fully integrated inertial navigation system (INS), coupled with GPS, and an air data attitude and heading reference system (ADAHRS). It works by incorporating navigation grade IMU and altimeter data, and uses a Kalman filter to include GPS data to provide the most accurate navigation data to the pilot. The ADAHRS also provides very accurate state estimation data to the primary flight control computer (PFCC) to help maintain constant, safe operation of the aircraft.

8.2 Health and Usage Monitoring

Because of the large number of dynamic components on the *Excalibur*, including most notably the blade retraction mechanism, rotor hub, transmission and engine systems, and nacelle tilting mechanism, it is imperative to diagnose problems quickly and effectively. Health and Usage Monitoring Systems (HUMS) perform much of the work for ground crews as they act as a means of monitoring flight critical components and diagnosing potential system failures³. Life-limited parts are monitored and automatically tracked by cycles or hours. When a part approaches its life limit, the HUMS automatically informs the pilots or ground crew that the part has exceeded its life expectancy. The suite of warning sensors is coupled with software that has knowledge of the physical and temporal limits of the mechanical components to allow for a comprehensive life-cycle analysis to be conducted in real-time. The HUMS can, therefore, monitor various aircraft systems and warn crews of not only when a system fails but when a system *might* fail. The HUMS continually monitors and compares sensor data to its database of potential risks and failure modes that are compiled during the flight testing and certification phase. If the observed sensor data exhibits characteristics similar to data matching a pre-existing template for failure, the system alerts flight crews and creates a diagnostic report to be examined later by maintenance technicians. The capabilities of the HUMS include three main functions; health monitoring, usage monitoring, and maintenance interface.

8.2.1 Health Monitoring

The health monitoring function has four main tasks which ensure all systems are operating at their nominal performance levels. This includes a rotor track and balance, engine performance

assessment, mechanical diagnostic, and flight data recorder. The rotor tracker monitors both of *Excalibur's* variable diameter rotors and employs a suite of accelerometers to ensure continuous rotor track and balance. The engine performance assessment system continually monitors engine torque and temperatures of the inlet, compressor, combustor, turbine, and exhaust to ensure continual safe engine operation. The mechanical diagnostic system monitors other static and dynamic mechanical systems including the rotor and drive shafts as well as gearboxes and nacelle tilting devices. The flight data recorder, is explicitly linked to the main flight computer and communication system. The recorder tracks all control inputs from the cockpit, logs all pilot vocal commands, and aides in the diagnosis of post catastrophe evaluation. The entire health monitoring system also incorporates a condition trending algorithm that takes use of the data collected by the usage monitoring system and analyzes incoming data to help predict potential problems before they arise.

8.2.2 Usage Monitoring

The usage monitoring function acts as a recorder and database for the rest of the HUMS and flight/ground crews. This is the system that provides time tracking and cycle counting for life limited parts. The usage monitor records critical events such as time spent above torque limits and in flight fault and warning system resets to help reduce and prevent the likelihood of catastrophic failures. Also included is an exceedance monitoring system that alerts crew of operational limitation exceedance or pending exceedance when the control limiter has been disengaged by the pilot. This regime recognition actually allows the vehicle to be self aware of its operating limitations as found in the flight manual and uses the pilot input data from the flight computer to 'know' what the limitations are for each mission.

8.2.3 Maintenance Interface

One of the most important aspects of the HUMS system is the maintenance interface. This system allows ground and maintenance crews to diagnose any and all problems associated with the aircraft. All flight data can be downloaded and a ground system check can be performed using the automatic fault information system. Ground crews can examine the trending data in conjunction with the flight data to allow for expert diagnosis. The maintenance interface can also be used for configuration management to allow crews to more heavily monitor particular systems that may have become susceptible to ambiguous problems. All data from the HUMS is also down linked to the ground station unit that archives a complete record system for the aircraft. In doing so it acts as a digital airframe, engine, rotor, stress, fatigue, and system logbook⁴.

9 Flight Control System

9.1 Control Mixing

The *Excalibur's* flight controls must operate like a helicopter's collective, cyclic, and anti-torque controls in hover, yet smoothly transition to throttle, pitch, roll, and yaw controls like an airplane in forward flight. This means that extensive and continuous control mixing must be employed in *Excalibur's* flight control computer. The primary flight controls use a fly-by-wire system, which is described below.

Figure 9.1 describes all control actions of *Excalibur* in both helicopter and airplane mode. In helicopter mode, yaw is achieved through differential longitudinal cyclic of the rotors. In a similar manner, roll is performed through differential collective pitch of the rotors coupled with

symmetric lateral cyclic. Pitch fore-and-aft is achieved through symmetric longitudinal cyclic pitch of the rotors. Finally, thrust/power is applied through simultaneous collective pitch of the rotors and the throttle. In airplane mode, however, these controls maintain traditional fixed-wing (airplane) controls: yaw is induced by rudder movement, roll is accomplished through differential flaperon deflection, pitch is performed through elevator deflection, and thrust/power is applied through engine throttle. The mixing of these controls is pertained through a washout scheduling scheme that varies each of the control functions in such a way as to continually maintain control of the aircraft in all flight regimes. This scheduling is most effectively attained through linear washout of the controls to provide adequate overlap within the transition regions between helicopter and airplane mode¹. Various other functions, such as flap and flaperon control, are set for automatic deflection, but controls in the cockpit also allow the pilot to manually control them for situations such as approach to landing in airplane mode, where the rotor mast will remain nearly horizontal.

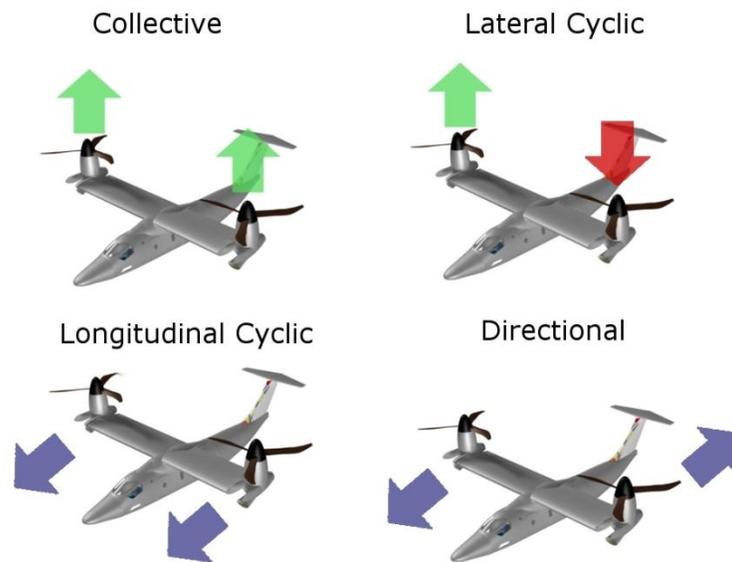


Figure 9.1: Control mixing strategy in hover

Tiltrotors provide a unique challenge to pilots as the perceived throttle/collective control may be intuitive for one pilot yet not the same for another. A pilot who has been primarily trained on a helicopter knows that to increase power the collective stick is pulled upwards. This arm movement is essentially a pulling motion and a contraction of the arm through bending at the elbow. However, airplane pilots use an opposite physical movement to increase power; the throttle lever is pushed forward with a pushing/extending arm movement. FAR Part §25.779² describes the “Motion and Effect of the Cockpit Controls” as standardized for airplane powerplant controls and FAR Part §29.779 for rotorcraft flight controls, but there is no FAR describing standards for tiltrotor aircraft. Reflecting this lack in standardization is further demonstrated by the differences between the BA-609 civilian tiltrotor and the Marine’s MV-22 *Osprey*. The BA-609 civilian tiltrotor utilizes a collective style throttle much like those found in conventional helicopter designs. In the V-22 *Osprey*, however, the throttle interface mimics those found in fixed wing aircraft, requiring the pilot to push the throttle forward to increase power in airplane mode or increase collective in helicopter mode. This *perceived* control reversal was the result of a V-22 accident in 1991 where a pilot trained as a CH-47 pilot crashed the aircraft while attempting to land by inadvertently pushing the throttle lever fully forward once the vehicle had

touched down³. This would have been an appropriate response in his CH-47 helicopter but it was a pilot-caused control-reversal in the MV-22 which subsequently led to a mishap (Dugan 1998). In high stress situations, pilots revert back to their training and this was exactly the case with the V-22 pilot. This is a cause for problems for pilots who are not primary trained on tiltrotors.

To eliminate this issue, the *Excalibur* uses a novel rotational throttle interface illustrated in Figure 9.2. This throttle interface is a two degree-of-freedom interface that transitions along with the nacelles to provide throttle-like movement when the rotors are facing forward in airplane mode and collective like movement when the rotors are horizontal in helicopter mode. The base of the RTI moves via a servo control and automatically orients itself to the same angle as the proprotor shaft. This effect is shown in Figure 9.2 below.

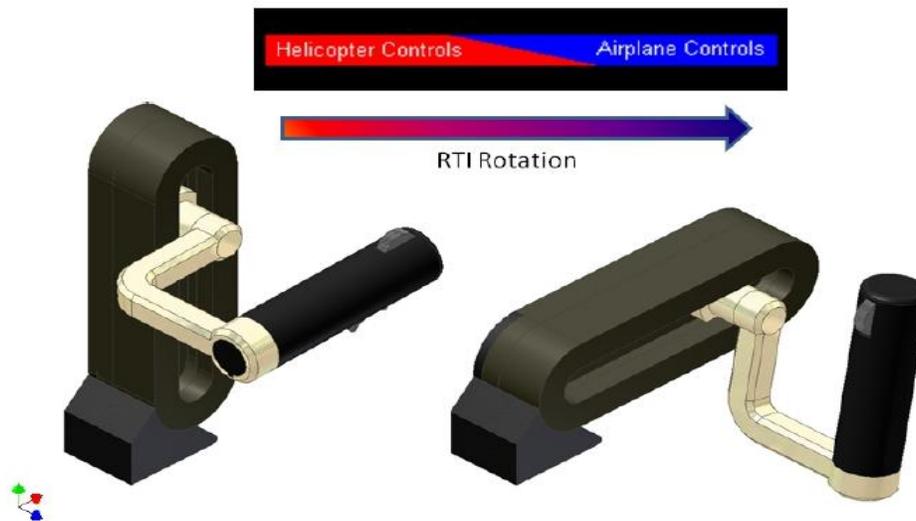


Figure 9.2: Rotational Throttle Interface shown in 90° helicopter and 0° fixed wing configuration (Rozovski, 2008)⁴

9.2 Dynamics and Stability

The ability of the pilot to control the aircraft is directly affected by the complexity of the action, by his/her training, and by any external disturbing factors. In modern military and commercial aircraft, advances in avionics and flight controls have increased the complexity of the aircraft and, therefore, increases the pilot's workload. Poor handling qualities can then make it difficult for the pilot to maintain control over the aircraft. This affect is noted most when workloads increase such as during a search and rescue mission, where flight operations are often in instrument metrological conditions. During the conceptual design of an aircraft, simple linearized models are used to predict the open-loop stability of the aircraft. These analyses do not model the full non-linear dynamics of these vehicles and, therefore, may not be representative of the transitional states of the aircraft between helicopter and airplane modes, but do provide insight into steady, stick-fixed flight regimes such as hover and level, forward flight. A simplified linear flight model was, therefore, utilized to carry out the stability and control analysis for *Excalibur*. This model was developed for both helicopter mode and airplane mode through the use of a tiltrotor trim analysis code RaPID⁵. The linear model was then used with each trim point as defined by the equation $AX=Bu$. This is a classical flight mechanics equation where X is the state vector and u is the control input vector. The matrices A and B correspond to the stability derivative matrix and control derivative matrix respectively.

9.2.1 Stability in Helicopter Mode

The key longitudinal and lateral modes were examined in helicopter mode to determine the stability of *Excalibur* in hover. It is well known that helicopters are inherently unstable so it is no surprise that some of *Excalibur*'s poles are positive or zero, indicating they are non-stable modes. These three modes include a neutrally stable heading mode, an unstable phugoid, and unstable sideslip/roll mode. These non-stable modes however have long enough time constants to be easily controlled by the pilot. These hover stability modes were also compared to two other VTOL aircraft, including the UH-1H *Huey* and the XV-15 tiltrotor⁶. The XV-15 exhibits two oscillatory unstable modes in hover while both the *Huey* and *Excalibur* exhibit mainly stable oscillatory modes. *Excalibur*'s stable modes include a short period mode and a Dutch roll mode. A pole-zero diagram illustrates these six modes, as shown in Figure 9.3.

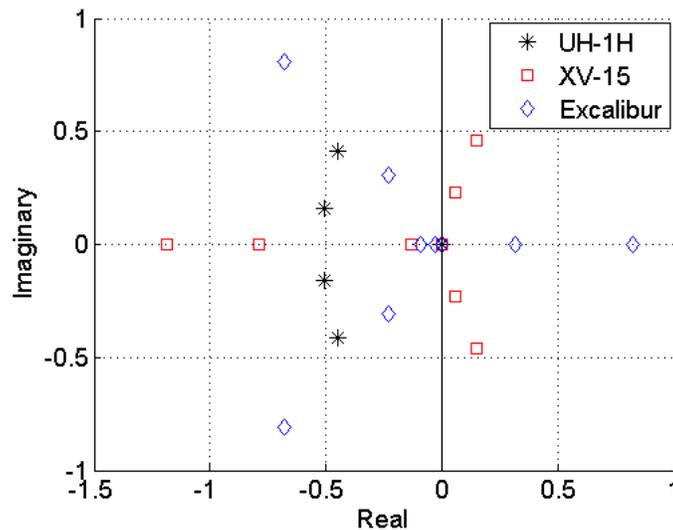


Figure 9.3: Pole Diagram Characterizing Hover Stability Modes

9.2.2 Stability in Airplane Mode

The forward flight trim analysis was performed at two key flight speeds corresponding to the climb out speed (110 kts) and cruise speed (225 kts). Through evaluation of the *A* matrix, key stability modes of the aircraft were identified as in Figure 9.4. This allows for the prediction of the open-loop stability of the aircraft without the addition of digital stability augmentation system to providing the stability.

Six of *Excalibur*'s stability modes were identified as heading hold, wing rocking, spiral, Dutch roll, short period, and the phugoid mode. Of these modes, the heading hold mode was found to be neutrally stable and the spiral mode was found to be unstable, while all other modes were determined to be stable. These two non-stable modes are related. The spiral/heading mode takes a very long time to induce and is characterized by a yawing motion with rolling that generates a sideslip. If not controlled by the pilot, this mode will result in an ever tightening downward spiral with increasing bank angles. Nearly all aircraft exhibit this mode, including the XV-15, which also has two non-stable poles, as shown in Figure 9.4. However, both of *Excalibur*'s non-stable modes demonstrated long enough time constants to be easily controlled by the pilot. Because of *Excalibur*'s wing dihedral, the wing rocking mode is self-stabilizing. The phugoid and short period mode are also self-stabilizing as characteristic of proper selection of the distance and

surface area of *Excalibur's* horizontal stabilizer. The Dutch roll mode is characterized by damped oscillations in yaw that couples out of phase with roll.

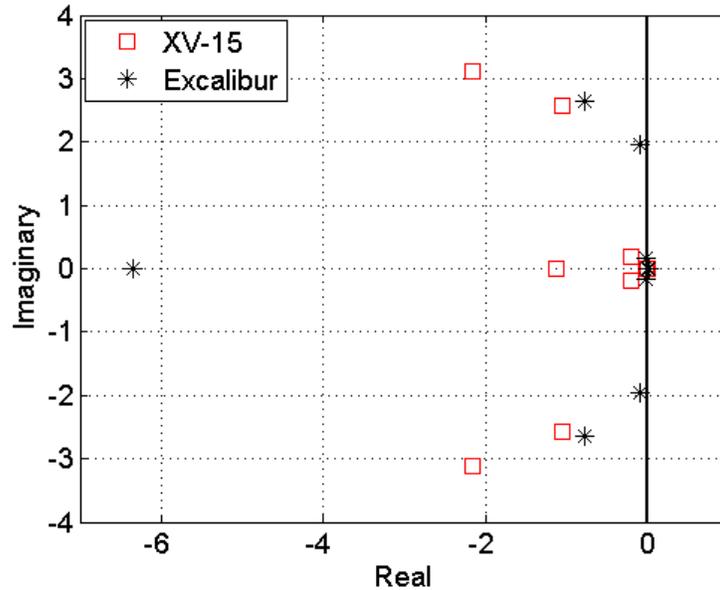


Figure 9.4: Pole Diagram Characterizing Forward Flight Stability Modes

Table 9.1: Stability Derivatives in hover and 225 kt cruise

Derivative	Hover	Cruise	Unit	Derivative	Hover	Cruise	Unit
X_u	-0.124	-0.045	1/sec	R_u	.035E-5	-0.0002	m/rad-sec
X_v	0.25E-6	-0.0005	1/sec	R_v	0.200	0.24	m/rad-sec
X_w	0.21E-4	-0.068	1/sec	R_w	-0.3E-9	-0.0001	m/rad-sec
X_p	0.0001	-0.493	m/rad-sec	R_p	-0.427	-6.18	1/sec
X_q	-0.248	-2.920	m/rad-sec	R_q	.74E-5	-0.0025	1/sec
X_r	0.829	-0.453	m/rad-sec	R_r	0.307	-2.86	1/sec
Y_u	0.7E-9	0.0012	1/sec	M_u	-0.010	0.001	m/rad-sec
Y_v	-0.124	-0.178	1/sec	M_v	0.15E-7	-0.000	m/rad-sec
Y_w	0.35E-7	0.0001	1/sec	M_w	0.75E-6	-0.066	m/rad-sec
Y_p	0.248	3.17	m/rad-sec	M_p	0.5E-5	-0.043	1/sec
Y_q	0.24E-6	0.0018	m/rad-sec	M_q	-0.022	-0.337	1/sec
Y_r	-0.15E-4	-109.0	m/rad-sec	M_r	0.691	0.0077	1/sec
Z_u	0.33E-4	0.301	1/sec	N_u	0.3E-7	-0.0022	m/rad-sec
Z_v	0.64E-6	-0.0002	1/sec	N_v	0.53E-5	0.033	m/rad-sec
Z_w	-0.029	-1.22	1/sec	N_w	0.44E-7	0.0000	m/rad-sec
Z_p	-0.195	-1.07	m/rad-sec	N_p	0.0049	-0.023	1/sec
Z_q	-0.88E-4	109	m/rad-sec	N_q	-0.2E-7	-0.0003	1/sec
Z_r	-0.18E-3	-1.16	m/rad-sec	N_r	-0.079	-0.16	1/sec

9.3 Handling Qualities

The ADS-33E “Handling Qualities Requirements for Military Rotorcraft^{8b}” outlines the required control sensitivity and damping characteristics that are important in establishing the handling qualities of the aircraft. Pilots desire a vehicle that is not only responsive to their inputs, but also

stable and forgiving. These attributes are often conflicting as a vehicle that has good stability characteristics may not be very agile. This is why many of today's fighter aircraft are designed to be inherently unstable and then stability is augmented using a sophisticated fly-by-wire flight control computer. *Excalibur*, not being an attack vehicle, does not require this extremely high level of agility and, therefore, it boasts features that make the aircraft stable and easy to fly. Examination of the stability derivatives alone does not provide the designer with the vehicle's handling qualities, but it does give clues as to how easy the vehicle will be to fly. Through the aforementioned examination of the aircraft's stability in hover and forward flight, and inspection of the stability derivatives, it is safe to assume in this stage of the design, that *Excalibur* will exhibit exceptional handling qualities. Nearly all the roots are negative indicating stability and the roots that are unstable have long enough time constants to prove controllable. This, and the addition of a digital fly-by-wire control system, will ensure the pilot and copilot can easily control the vehicle.

To more accurately determine the handling qualities of a conceptual aircraft like *Excalibur* it would be prudent to develop and test a wind tunnel model. This would allow for correlation of the hover and forward flight stability derivatives. The dynamics of the vehicle during transition from hover to forward flight and back may also be determined through such wind tunnel tests. However, it must be noted that such an experiment would not be easy because aerodynamic phenomenon such as stall, BVI, and fountain effects may lead to unrepresentative data at smaller scales from Reynolds number distortion.

9.4 Fly-by-Wire Architecture

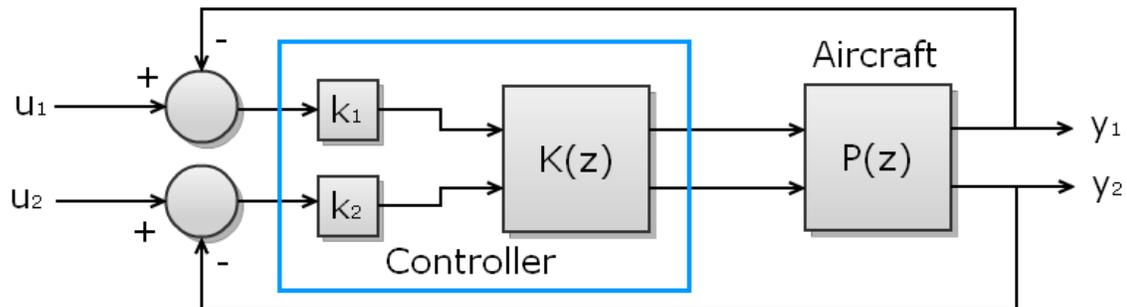


Figure 9.5: Simplified Representation of MIMO Controller

The fly-by-wire control is a set of stabilization and control enhancement control laws that use pilot inputs and aircraft states to improve the stability and controllability of the aircraft. *Excalibur* uses a quadruplex fly-by-wire system, which uses four separate channels to send data from sensors to the main FCS. This system ensures that the computer receives all control signals. The aircraft states are taken from a combination of the navigational equipment and GPS and are combined within the altitude and heading reference system (see Section 8). These states are then fed into the air data computer, which are subsequently fed into the flight control computer. The flight control computer (FCC) contains all control laws and gains that have been obtained through flight tests and system identification techniques. The FCC uses a multi-input multi-output (MIMO) control system with gain scheduling where the desired states of the vehicle, obtained through either direct pilot input or the flight director/autopilot, are fed to the control system and the corresponding control of the aircraft is then performed⁹.

MIMO control strategies have been successfully used for flight controls in other aircraft and are already FAA certified for use on aircraft. A MIMO control system was chosen knowing that the vehicle development timeline was already chosen to be an accelerated 8–9 year development. More exotic control systems, such as model predictive control strategies, may offer performance benefits but may have difficulty, within the development timeframe, in satisfying the FAA requirements set forth in FAR Part 25.1329² for “Flight Guidance Systems.” MIMO control strategies that employ automatic gain scheduling are an effective means to ensure consistent control over the vehicle in all flight regimes. This attribute is important for a tiltrotor type aircraft because the vehicle dynamics are different in helicopter mode than in airplane mode. This form of control uses changing gains and calculates the correct flight control movements. This control system is also coupled with the HUMS system’s exceedance monitoring system (see Section 8) to apply violation constraints to prevent the pilot from performing maneuvers that could structurally damage the vehicle. This integrated system is known as flight envelope protection, which prevents the pilot from making giving commands that would force the aircraft to exceed its structural and aerodynamic operating limits. A comprehensive overview of *Excalibur*’s fly-by-wire and control system architecture is illustrated in Figure 9.6.

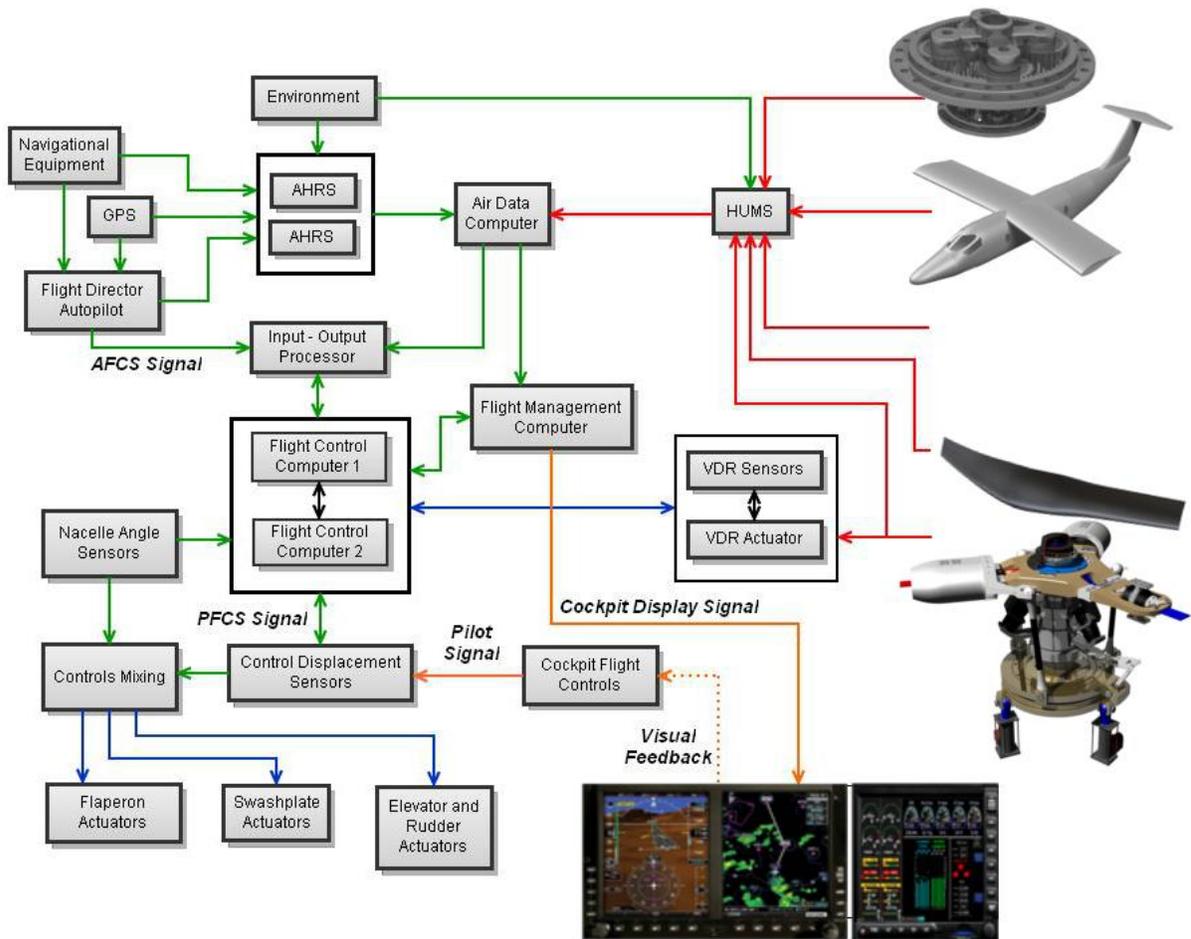
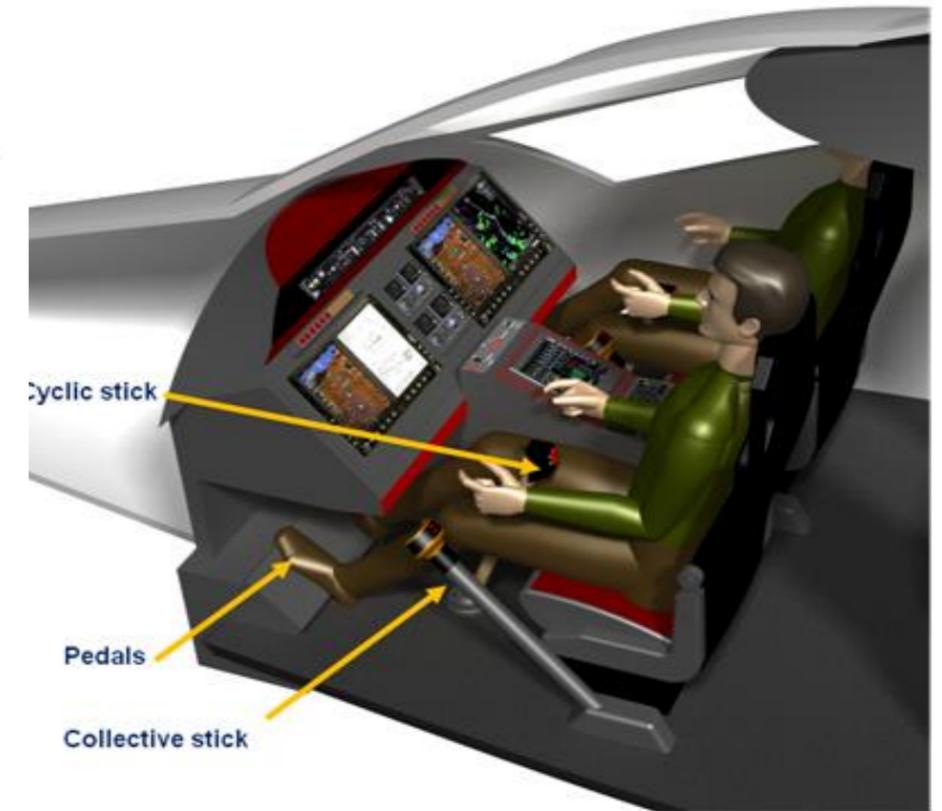
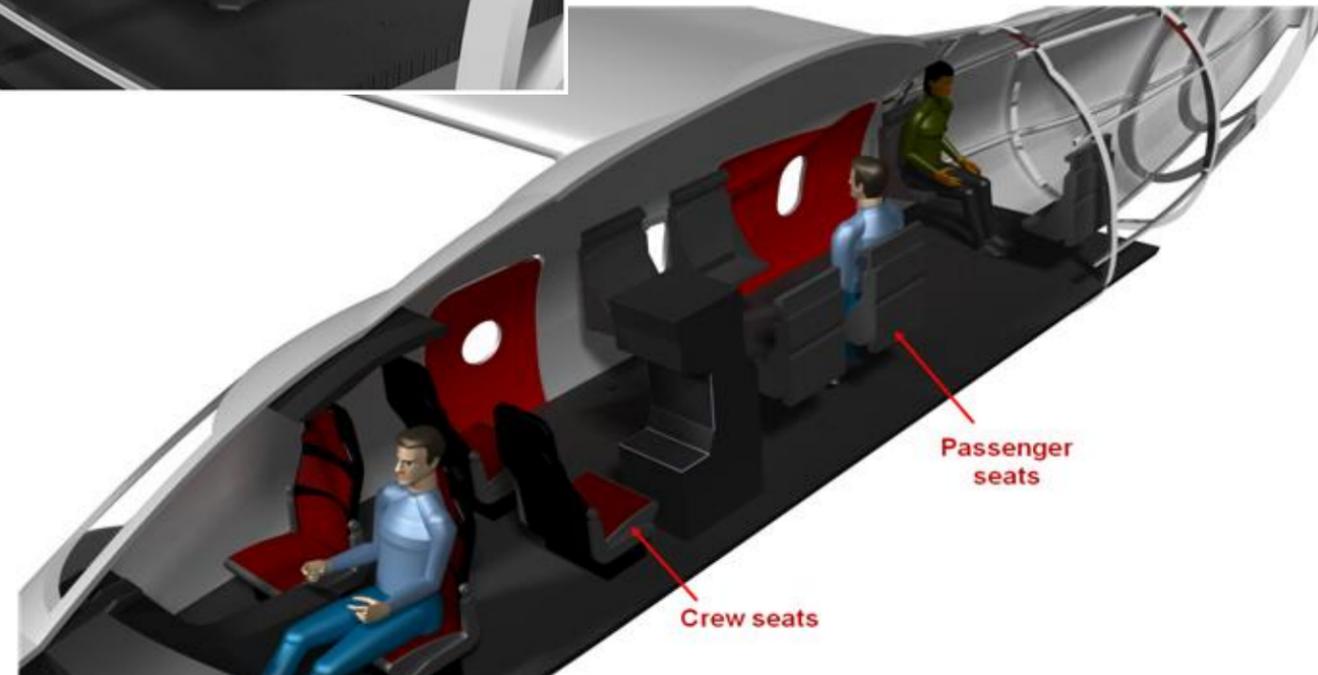
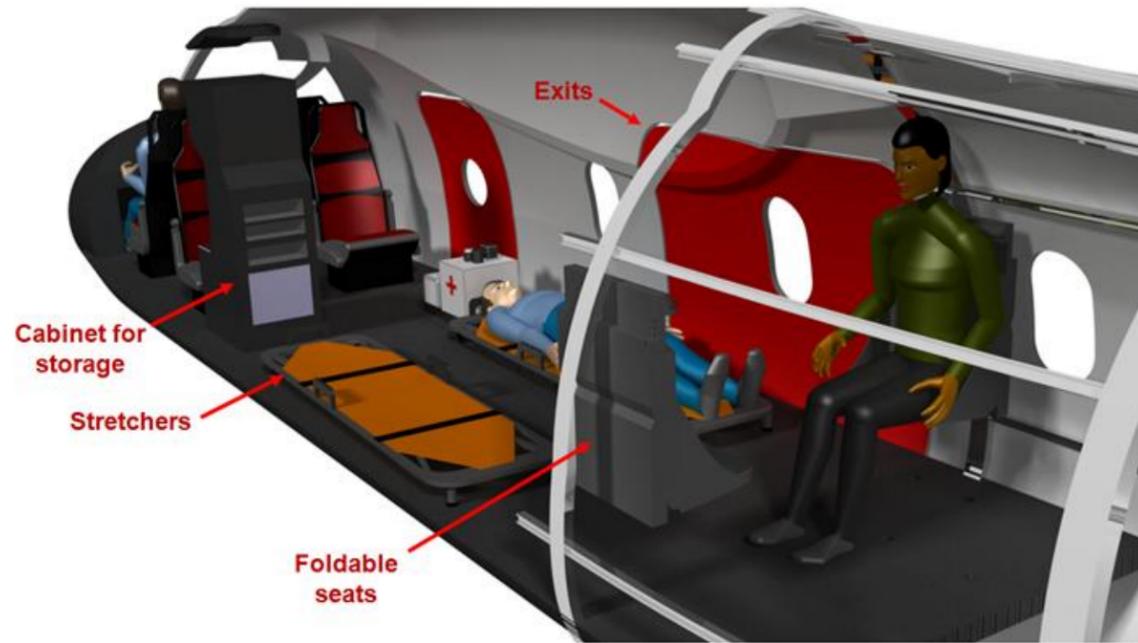


Figure 9.6: Fly-by-wire and control system architecture

FLIGHT CONTROLS



10 Multi-Mission Capability

10.1 Designed for Versatility

A system has been designed on *Excalibur* that effectively allows for the integration of equipment for multiple missions to be affixed to the interior fuselage with relative ease and rapid reconfigurability. Everything from cargo, seats, medical litters, rolling cargo system, winches, and modules can be affixed to the inside of the aircraft via Universal Attachment Fittings (UAF)¹. The UAFs are standard $\frac{3}{4}$ -inch female bolt fittings and snap fittings that can accommodate a number of different screw-in attachments or snap-in attachments. These attachments include tie-down fittings (TDF), seat posts, and other mission specific modules. A UAF is shown in Figure 10.1, utilizing the hook for cargo restraint and snap-in attachment for seat/litter post attachment.

The UAFs integrate with all items that need to attach to the interior of the cabin. The UAFs are equally spaced every 2 feet down the length of the fuselage and vertically every 3 ft up the interior walls. This has been selected to allow for seats, litters, and cargo restraint systems to be easily attached in nearly any configuration desired.



Figure 10.1: Universal attachment fitting (left) cargo restraint (right) seat/litter post attachment

10.2 Search and Rescue Mission

Excalibur's high cruise speed and long range make it ideally suited for SAR missions. The low disk loading in hover ensures that persons being rescued are not encumbered by high downwash velocities. This also minimizes brownout signature ensuring that victims are not hit by dust, dirt, and sand. Fixed horizontal engines also keep hot exhaust gasses away from those being rescued. The easily reconfigurable, spacious internal structure of *Excalibur* also ensures the seamless addition of litters and seats. For SAR, *Excalibur's* cabin must provide the crew with the capability to rapidly store and access rescue equipment such as litters, rescue basket, and other medical equipment. Much of this equipment has been bundled into a SAR module, as shown in Table 10.1.

The cabin area includes a crew chief station, four seats for the crew and medics, two bunked litters, and the rest of the medical equipment. The starboard side of the vehicle is kept clear to facilitate operations of the hoist and ingress of patients and pararescuers. Contained in the cabin is a hover control panel that is used for search assistance and to provide the cabin crew with the capability to position the aircraft during hoist and rescue operations. The hover controller has limited control authority and must be initially activated from the cockpit. The crew control panel is located to the right of the starboard cabin sliding door and includes hoist controls, an ICS trigger switch, cabin light controls, exterior light switch, a hoist shear switch, and radio/ICS controls.

Table 10.1: SAR mission equipment

SAR mission equipment	Weight (lb)
6 Passenger seats	240
Ventilator/respirator	12
Portable cardiac EKG monitor	8
Defibrillator & external pacemakers	14
Wall oxygen, suction and pressurized air ports	4
Intravenous fluid equipment	24
Medical dressing and surgical supply box	8
Portable lab analyzer	16
Intubation equipment and anesthesia bag	6
Blood supplies	24
Two litters with head/neck stabilizer	100
Rescue spotlight	30
Rescue winch	50
Total	536

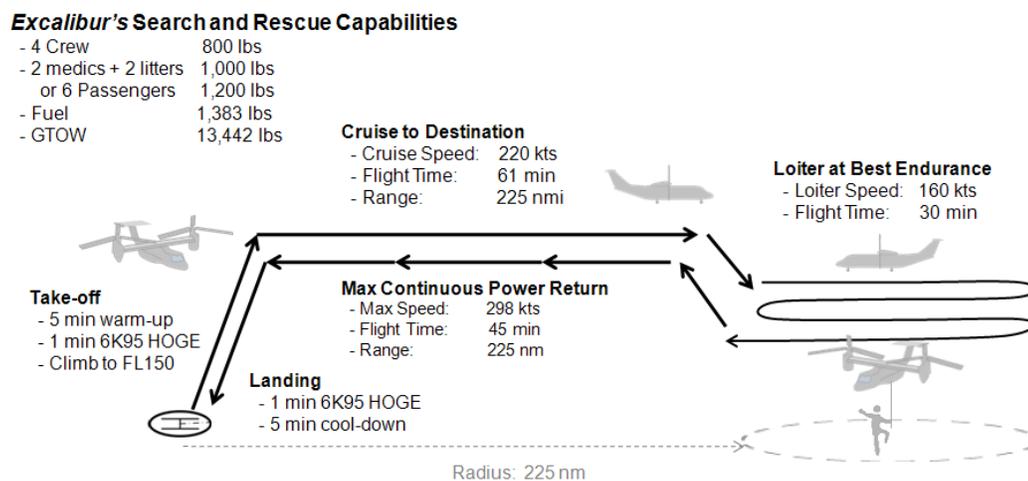


Figure 10.2: Typical search and rescue mission showing Excalibur's speed, flight time, and range capabilities.

Figure 10.2 shows a general SAR mission profile consisting of three distinct operating segments including cruise to the search area at best range, loiter at best endurance while scanning the search area, rescue and hoist operations in hover mode, and a high speed return at maximum

continuous power. *Excalibur's* 220 kts cruise speed enables it to reach the search area faster than traditional helicopters. Once *Excalibur* has reached the search area, it slows to its best endurance speed of 160 kts. The slower speed not only decreases fuel consumption, but also allows for a more thorough search of the area as it is slower than many search airplanes. A larger search area is also achieved as the 160 kts search speed is faster than most rescue helicopters.

Upon reaching the location of those to be rescued, *Excalibur* transitions to helicopter mode and effects the rescue/hoist part of the mission. The ideal time to rescue all injured or stranded persons is five minutes. To do this effectively, *Excalibur* uses a special crew control panel that is located next to the starboard cabin door. This control panel allows the pilot to transfer translational control of the aircraft to the crew member who is operating the hoist. This control panel has a simplified two degree of freedom joystick that feeds into the primary flight control computer and the signals are interpreted to provide precise hover control, while the pilots inputs can still override control inputs by the hoist operator. By giving partial aircraft control to the hoist operator, the pilot is relieved of additional tasks that would require him/her to look out the window and position the winch and rescue basket near the persons to be rescued.

After rescue, *Excalibur's* 298 kts maximum cruise speed ensures that victims reach the medical facility in 45 minutes as critically injured persons are best served if they reach the medical facility in the minimum time possible. Thus, *Excalibur* is capable of exceeding the RFP required 50 minute "golden hour."

10.3 Insertion Mission

The insertion mission requires a large amount of seating and storage of military equipment. *Excalibur* utilizes traditional military seats that affix to the UAFs using a snap-in hook release as shown above in Figure 10.1. *Excalibur's* inherent flexibility and versatility allows it to fulfill the unique role of military insertion. The aircraft's high cruise speed and maneuverability enables it to get in and out of "hot-spots" quickly and efficiently. The two large sliding doors enable troops to exit quickly. *Excalibur's* reduced noise signature in forward flight also makes it ideal for covert insertion missions that would preclude the use of a conventional helicopter. A typical insertion mission profile for *Excalibur* is shown in Figure 10.3.

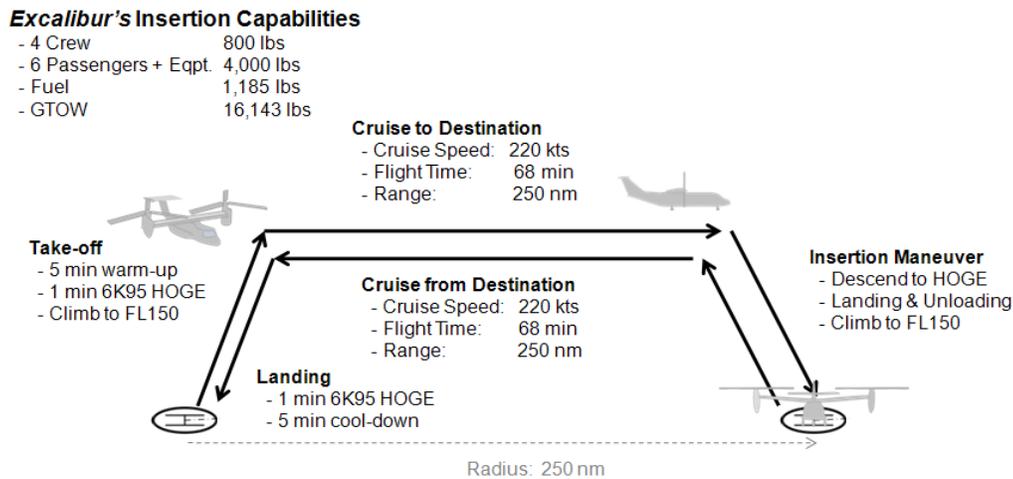


Figure 10.3: Insertion mission profile showing *Excalibur's* speed, flight time, and range capabilities

A typical insertion mission consists of reconfiguring the aircraft to have 6 seats and room for equipment resulting in a combined payload of 4,000 lb. Reconfiguring the aircraft can be accomplished in under an hour as litters are easily removed and seats inserted via the UAF. Equipment in military pelican cases or ATA containers can easily be tied down using cargo restraints and attached via the hooks of the UAFs as previously shown. The estimated totally time to complete the insertion mission, including a hot unload at the landing zone is 150 minutes demonstrating *Excalibur's* unique capability to complete the mission in a relatively short time.

Table 10.2: Insertion equipment and weight breakdown

Insertion mission equipment	Weight (lb)
Cargo restraint TDF	20
Cargo restraint harness	30
6 Passenger seats	240
Removable ramps	80
Total	370

10.4 Resupply Mission

The mission specified for *Excalibur* is resupply. To accomplish this mission, *Excalibur* must deliver a 3,000 lb payload over a 500 nm radius, and return with an alternate 3,000 lb payload. Figure 10.4 shows a general resupply mission profile. *Excalibur* must be capable of loading and unloading typical military cargo containers including pelican and ATA cases; shown in. These cases are durable heavy duty containers typically used by the military to handle anything from sensitive electronic equipment to weapons and come in a variety of sizes and shapes. It is, therefore, important that *Excalibur* offers a flexible system for cargo restraint so that a payload of any size can be handled. The typical cargo restraint system once again makes use of the UAF attachments making it the fastest and most effective way of loading/unloading the aircraft. To expedite the handling of cargo, *Excalibur's* relatively low floor level makes lifting containers up and into the cabin easier. The large sliding doors on either side of the fuselage also makes loading and unloading faster and easier.

Excalibur's Resupply Capabilities

- 4 Crew 800 lbs
- Internal Load 3,000 lbs
- Fuel 1,285 lbs
- GTOW 15,244 lbs



Figure 10.4: Typical resupply mission showing *Excalibur's* speed, flight time, and range capabilities

11 Weight Analysis

Weight estimates are performed by using the most critical mission (Insertion) as explained in greater detail in the sizing section. The longitudinal center is referred from the nose of the aircraft, and the vertical center of gravity is referenced from the ground.

Table 11.1: Excalibur weight estimates

Component number	Component Description	Weight, lbs	% Weight	x.c.g., ft	z.c.g., ft
1.	Wing group	1,148.6	7.11	19.47	9.95
2.	Rotor group	1,224.4	7.58	19.15	16.68
	Blade assembly	476.7	2.95		
	Hub and Hinge	747.7	4.63		
3.	Empennage group	224.1	1.40		
	Horizontal tail	104.0	0.64	46.32	6.4
	Vertical tail	122.1	0.76	44.64	16.18
4.	Fuselage group	1,715.3	10.62	18.16	5.183
5.	Alighting gear group	557.2	3.45	26.75	2.9
6.	Nacelle group	484.3	3.00	17.32	11.329
7.	Propulsion group	865.8	5.36	18.21	16.68
9.	Fuel system	118.5	7.3	17.18	10.02
10.	Drive system group	875.9	5.42	19.54	13.34
11.	Flights control group	1,072.8	6.64	18.78	9.01
12.	Auxiliary power group	123.4	0.77	18.19	9.0
13.	Instrument group	200	1.22	6.3	4.2
14.	Hydraulics group	359.2	2.22	19.67	13.34
15.	Electrical group	201.8	1.25	15.87	16.68
16.	Avionics group	102.8	0.64	10.7	4.73
17.	Furnishing and equipment	400.0	2.48	18.16	5.183
18.	Manufacturing variation	483.8	3.00	18.16	5.83
	Empty weight	10,159.9	62.93	19.31	10.94
	Payload (Outbound)	4000	24.78	18.16	3.88
	2 Pilots + 2 Crew members	800	4.96	10.7	4.73
	Fuel	1,184.8	7.33	17.18	10.02
	Gross weight	16,144.7	100.00	18.44	8.82

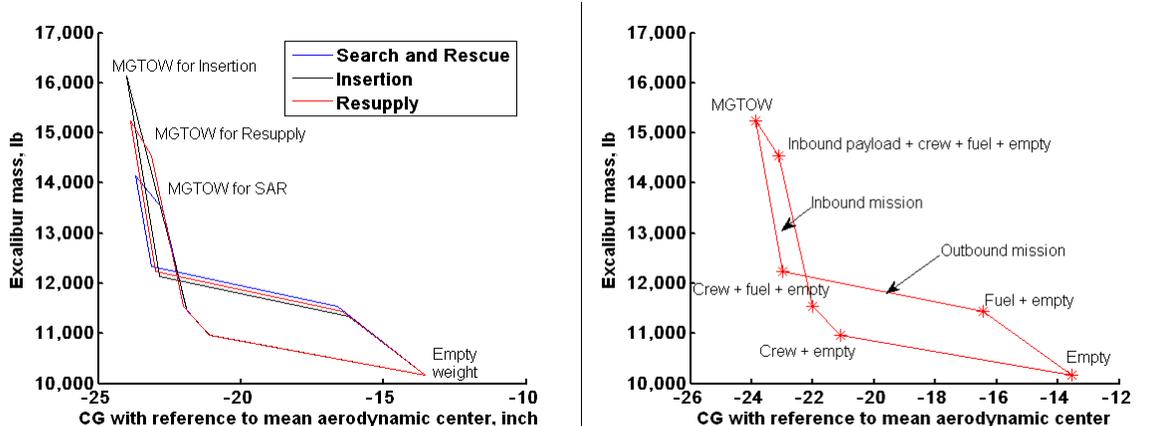


Figure 11.1: Longitudinal CG travel charts for a) all three missions b) resupply mission

The longitudinal center of gravity is referenced from the nose of the aircraft. The vertical center of gravity is referenced from the ground. The values in the table are for "Insertion" mission only. Figure 11.1 shows the longitudinal center of gravity variation for Excalibur's three missions. The resulting range shows that the CG always stays ahead of aerodynamic center of the aircraft. Figure 11.1 shows the different points traversed in during CG travel for one of the missions i.e., "Resupply" mission to have a clear illustration. These results exhibit that the bending moments stay well within the range for stability of the aircraft.

12 Performance Analysis

Excalibur was designed to provide excellent hovering performance while maintaining superb forward flight efficiency. This goal was achieved by retracting the blades of the proprotor in forward flight. The ability to operate essentially as a fixed-wing aircraft in forward flight allowed for effective streamlining of the fuselage, which greatly reduced drag. Increasing the forward flight performance while reducing the drag permits *Excalibur* to reach unprecedented cruise speeds of 298 kts and dash speeds of 330 kts at maximum gross takeoff weight. *Excalibur* was also designed specifically to hover at MGTOW in hot and high conditions (6K95). Performance calculations were completed to determine the hovering ceiling for various gross takeoff weights and ambient conditions. Forward flight performance calculations were carried out for the three RFP-defined missions at varying altitudes. The calculations showed that *Excalibur* has excellent performance capabilities when compared to helicopters and especially to other tiltrotors.

12.1 Drag Estimation

The total drag on the vehicle was decomposed into three parts: profile, parasitic and induced¹. The fuselage zero lift drag coefficient is a function of the wing-fuselage interference factor, flat plate drag area, ratio of fuselage length to maximum diameter, ratio of fuselage wetted area to wing area and the base drag coefficient. The wing-fuselage interference factor and flat plate drag area are determined from known data trends at various Mach and fuselage Reynolds numbers. The Mach and Reynolds numbers were calculated for various forward flight speeds at 15,000 ft.

The wetted area the fuselage was estimated by dividing the fuselage into eight sections, as shown in Figure 12.1.

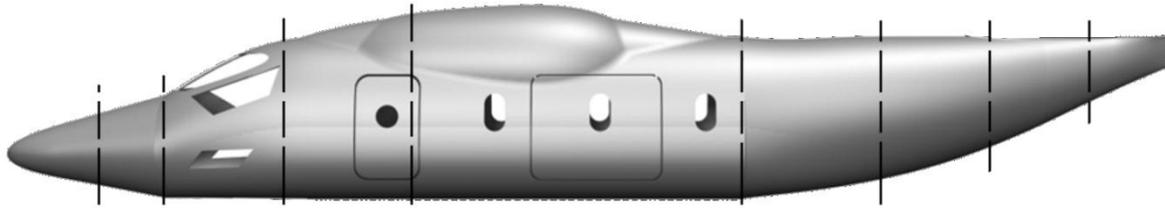


Figure 12.1: Fuselage cross-sectional cuts

The cross-sectional area, equivalent diameter, equivalent circumference and distance from the nose of the fuselage were found using CAD software. Averaging the circumferences between adjacent cross-sections and multiplying by the distance between the cross-sections the equivalent wetted area was determined for each section and the total wetted area was set equal to the sum of the equivalent wetted areas. The fuselage base drag coefficient is a function of the ratio of the equivalent diameter of the base to the equivalent maximum diameter of the fuselage, maximum cross-sectional area of the fuselage to the wing area, and zero lift drag coefficient of the base. The estimated drag was increased by 25% to account for the empennage, nacelle and other miscellaneous drag. This analysis provided a very conservative estimation of the parasitic drag.

Table 12.1: Variation in required lift coefficient and angle of attack with forward speed

Forward flight speed (knots)	Design C_L	Angle of attack (deg)
200	0.51	3.5
250	0.32	2.0
300	0.22	1.0

The profile drag coefficient of the wing is a function of the Reynolds number, Mach number, airfoil characteristics, and the wetted area of the wing¹. As with the fuselage parasitic drag calculations the Mach number and wing Reynolds number was calculated for various forward flight speeds at an altitude of 15,000 ft. The airfoil characteristics are defined by the airfoil selected, which for this application was a NACA 65-220. This airfoil was selected because of its high drag divergence Mach number and its low operating angles of attack in cruise and at maximum speed. Table 12.1 shows the required lift coefficient and angle of attack for various forward flight speeds.

The wetted area of the wing was calculated by multiplying the circumference of the airfoil cross-section by the wingspan. A lift coefficient of 1.05 times the required wing C_L was utilized to account for the lift produced by the canards and horizontal tail surfaces, and the Oswald efficiency factor was determined graphically¹. For a rectangular wing with an aspect ratio of 6 and an untapered planform the Oswald efficiency factor was determined to be 0.87. The drag synthesis for the induced and viscous drag is given versus forward flight speed in Table 12.2, with corresponding parasitic drag area versus forward flight speed being shown in Table 12.3.

Table 12.2: Aircraft drag coefficient breakdown versus forward flight speed

Forward flight speed (ft/s)	C_{Dwo}	C_{Di}	C_{Dof}
200	0.0097	0.0740	0.0252
300	0.0085	0.0150	0.0214
400	0.0087	0.0050	0.0214
500	0.0086	0.0020	0.0202
600	0.0086	0.0010	0.0204
700	0.0086	0.0005	0.0193
800	0.0089	0.0003	0.0187

Table 12.3: Variation in vehicle flat plate area with forward flight speed

Forward flight speed (ft/s)	Parasitic drag area (ft ²)
200	6.4
300	5.4
400	5.4
500	5.1
600	5.2
700	4.9
800	4.7

12.2 Vehicle Download

The impingement of the rotor wake on the wings in hovering flight can create a significant download on the vehicle. To minimize the effect of this download, most tiltrotor designs utilize a trailing-edge flap that deflect downward to reduce the drag and decrease the planform area². Momentum theory can be used to calculate the induced velocity in the fully contracted wake³. The download produced by the wings is directly related to this induced velocity, which is a function of the thrust/weight. Therefore, the download calculations were performed at MGTOW of the vehicle. Drag coefficients for multiple configurations of a wing in the wake of a hovering rotor were also examined². For a non-deflected flap, the drag coefficient will be 1.20, however, for a 44% chord flap deflected to 75°, the drag coefficient is reduced drastically to 0.92. In addition to reducing the drag coefficient, the flap deflection reduces the planform area by 30%. The download results for the undeflected and deflected flaps are shown in Table 12.3. In the flaps deflected configuration, the total download is approximately 9.5% of the total vehicle weight; this is a drastic reduction from the retracted flaps configuration (17.6%). Reducing the download in this manner increases the available payload by 1,226 lb.

Table 12.4: Download for various flap configurations

Flap configuration	Download (lb)
No deflection	2,647
75° deflection	1,421

12.3 Hover Performance

Excalibur's engine was sized to meet the most difficult requirement of the RFP; to HOGE at 6K95 conditions with 4 crewmembers (800 lb) and a 4,000 lb payload (Mission 2). The result was a total installed SL ISA power of 3,850 hp, however a transmission limit of 3,000 hp has been imposed to give a lightweight transmission and a better empty weight fraction. The sizing power required and the power available as a function of altitude and temperature are shown in Figure 12.2. Figure 12.3 shows that sizing *Excalibur* to HOGE at 6K95 conditions provides significant margin, which under ISA conditions allows *Excalibur* to HOGE at MGTOW up to an pressure altitude of 12,500 ft.

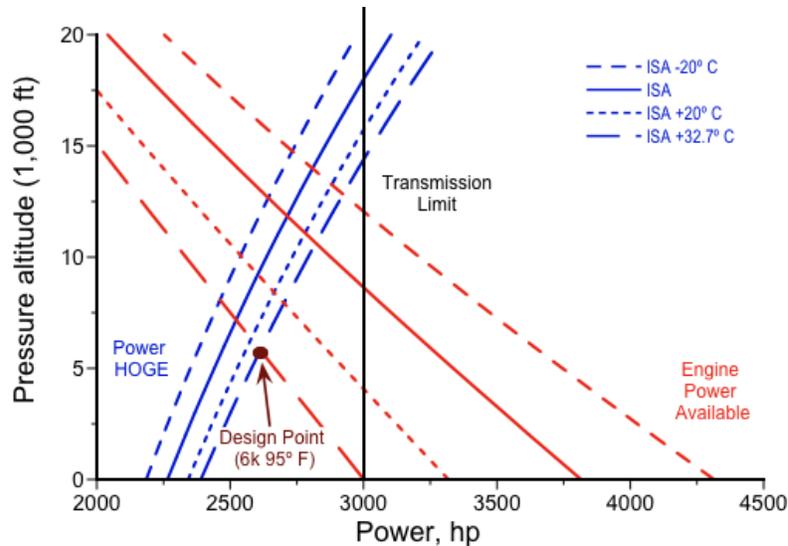


Figure 12.2: HOGE power required and power available at MGTOW versus altitude

As shown in Figure 12.3, at the reduced takeoff weight of Mission 1, *Excalibur* can HOGE up to 18,000 ft pressure altitude. The ability to hover at 18,000 ft allows *Excalibur* to perform missions that were previously impossible for most helicopters and all tiltrotors. This tremendous hot-and-high capability allows *Excalibur* to excel in mountainous terrain, as well as increasing the safety of flight for emergency medical and insertions missions at high altitude. Consequently, *Excalibur* is able to perform missions previously only achievable by standard helicopters but with the speed and efficiency of a fixed-wing aircraft.

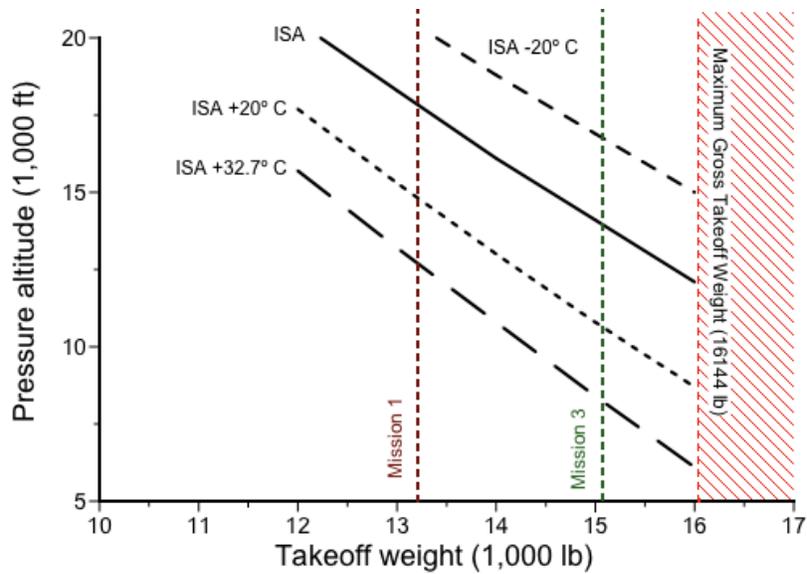


Figure 12.3: Weight - altitude - temperature curves

12.4 Forward Flight Performance

The forward flight performance analysis was conducted using a proprotor blade element momentum theory (BEMT) code, which trimmed the proprotor before calculating the power required. *Excalibur*'s unique feature is the ability to retract the proprotor blades to the necessary collective in forward flight. Reducing the diameter of the proprotor allows considerably higher propulsive efficiencies to be achieved, as shown in Figure 5.1. The ability to maintain high propulsive efficiencies allows *Excalibur* to use significantly less power in forward flight compared to contemporary tiltrotor designs. Figure 12.4 and Figure 12.5 show the variation in power required and fuel flow with forward flight speed for Mission 2.

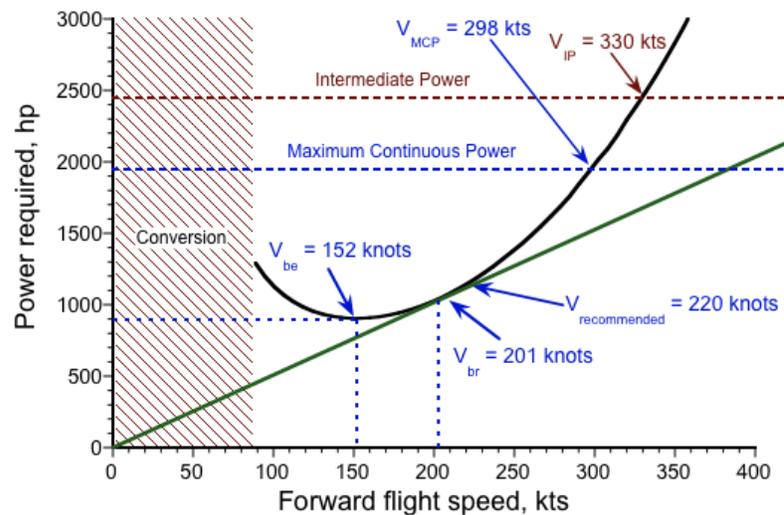


Figure 12.4: Power required versus forward flight speed at MGTOW.

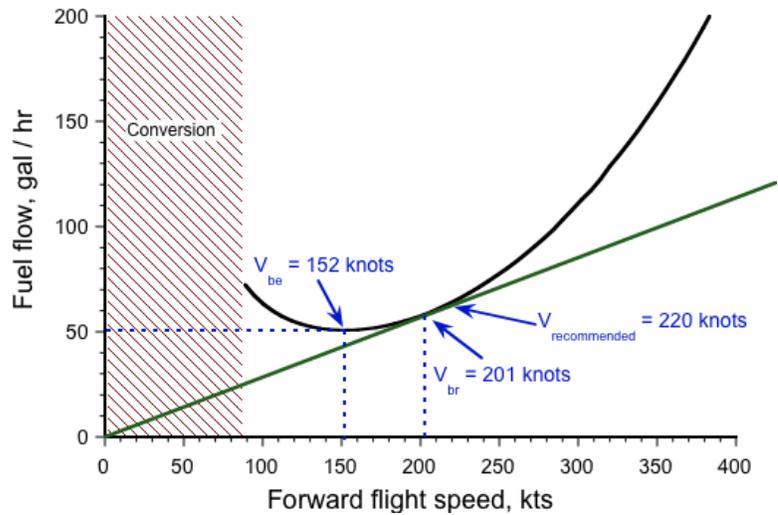


Figure 12.5: Fuel flow versus forward flight speed at MGTOW

Figure 12.4 shows the best range and endurance speed for MGTOW for various altitudes. The recommended cruise altitude is FL150 and the cruise speed chosen was as 99% the velocity for best range. Figure 12. shows that only a 1% reduction in maximum range yielded a significant increase in speed from 201 kts to 220 kts.

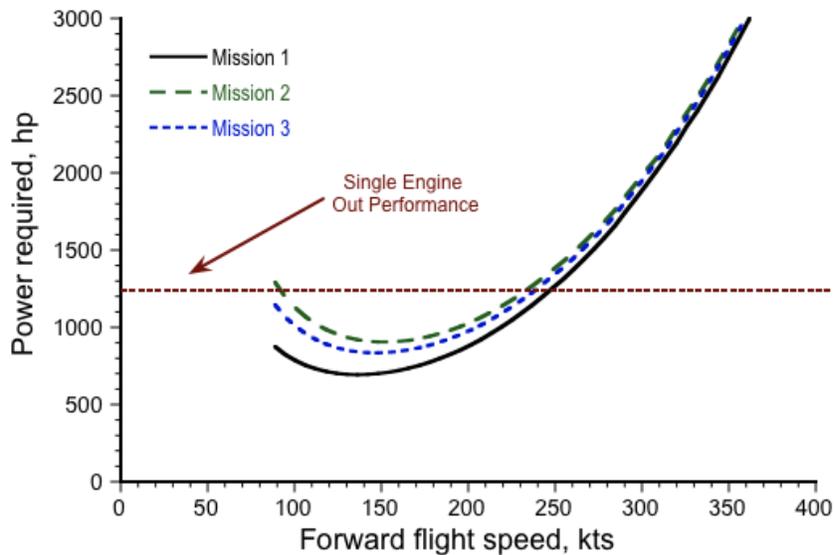


Figure 12.6: Power required versus forward flight speed for Missions 1–3. The high propulsive efficiency also allows *Excalibur* to perform the missions under single engine out conditions.

In addition to requiring less fuel, the added propulsive efficiency allows *Excalibur* to perform all three missions with a single engine out; see Figure 12.6. Compared to current tiltrotor designs, the ability to operate with a single engine out provides *Excalibur* with an unsurpassed level of safety of flight.

Table 12.5: Best endurance and range speed versus altitude.

Altitude (ft)	V_{be} (kts)	V_{br} (kts)
0	130	155
5,000	145	160
10,000	150	175
15,000	160	201
20,000	170	209

The RFP requires the vehicle to travel a distance of 500 nm. After the addition of a 20 minute fuel reserve, the achievable range of *Excalibur* at MGTOW is 555 nm (without reserves the range is 608 nm)²; see Figure 12.6. At the reduced weight of Mission 1 (13,442 lb) the maximum range is 840 nm. Figure 12. shows the maximum endurance of *Excalibur* at MGTOW with 1,184 lb of fuel is 3.25 hours.

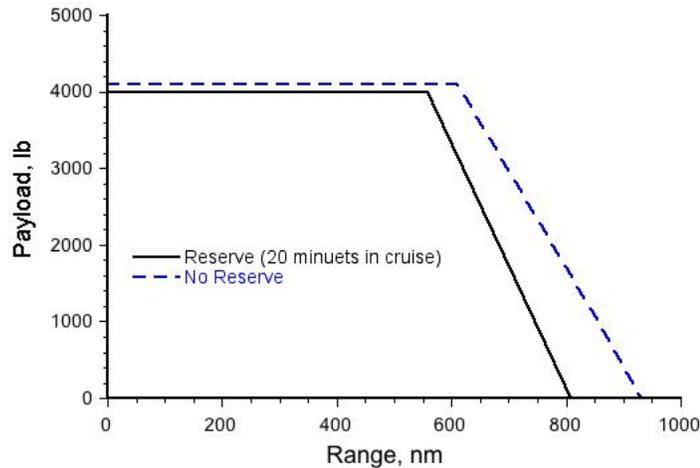


Figure 12.6: Payload – range plot.

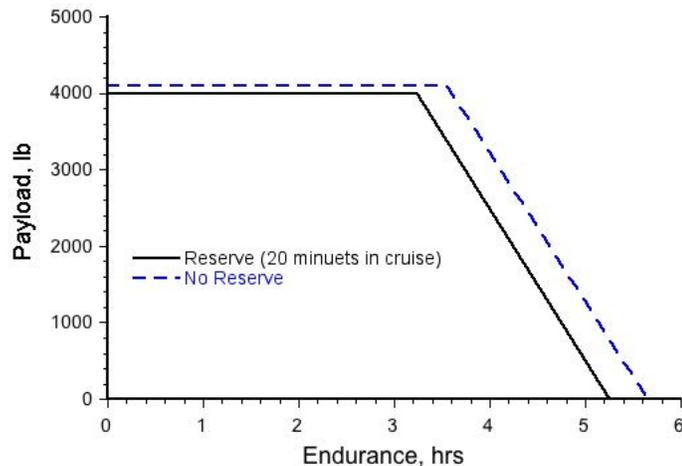


Figure 12.7: Payload – endurance plot.

12.5 Conventional Airplane Takeoff/Landing

The takeoff and landing analysis was performed for MGTOW and an alternative takeoff weight of 1.5 times the MGTOW (24,000 lb). The takeoff and landing was broken down into three sections: ground roll, transition, and climb/descent⁴. Stall speeds of 80 and 96 knots were calculated for the two take off weights based on the achievable C_{Lmax} of the wing with the flaps deflected. The ground roll portion is defined as the distance required to achieve a speed of 1.1 times the wing stall speed. For the current application the runway material was assumed to be concrete/asphalt with a friction coefficient of 0.3. As the vehicle transitions between ground roll and climb the transition speed was set equal to 1.15 times the stall speed. The climb portion is defined as the distance required to clear an obstacle of a fixed height; for the current design an obstacle height of 50 ft was chosen. The breakdown of the required takeoff distance for MGTOW and the alternative weight are shown in Table 12.6. *Excalibur's* ability to takeoff and land as a STOL airplane gives it an unprecedented level of safety for standard tiltrotors with the added benefit of carrying an additional 6,000 lb of payload.

Table 12.6: Takeoff distance for MGTOW and alternative takeoff weight.

	MGTOW	Alternative
Total (ft)	713	812

12.6 Brownout Signature Studies

Brownout is characterized by the rapid onset of a blinding dust cloud when a rotorcraft takes off or lands in a dry and dusty environment. This problem is aggravated during search and rescue operations during typical military operational scenarios. Currently, brownout-related accidents are the leading cause of human factor-related helicopter mishaps. Besides causing severe visual obscurations that affect the pilot's ability to fly safely, the suspended dust particles cause blade erosion and mechanical wear, which can increase operational costs.

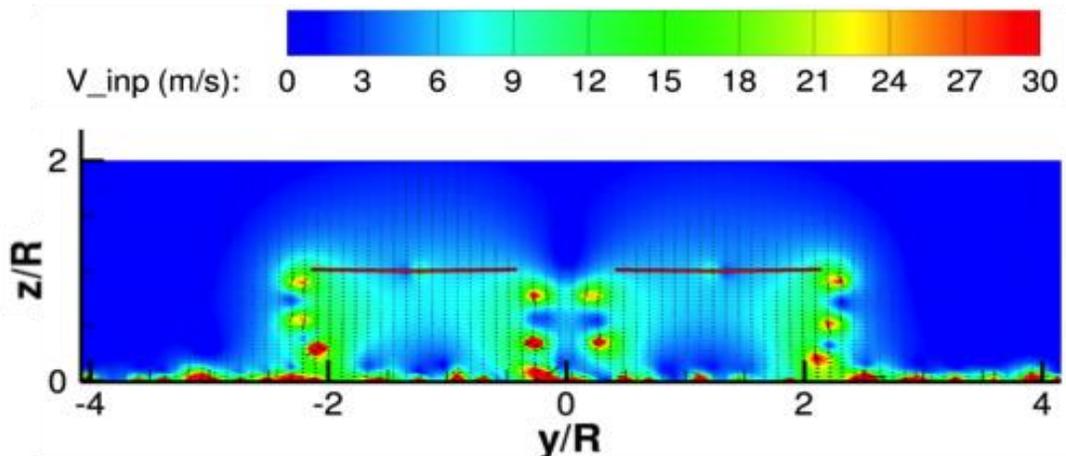


Figure 12.9: Induced velocity contours for *Excalibur* operating at one rotor radius above ground in hover

Although sensor technologies and operational tactics have helped to mitigate brownout problems, they are not permanent solutions to the problem. Because the rotor wake causes the dust particles to be uplifted and develop brownout conditions, the decisions to select both a low disk loading

and low blade loading coefficient results in a much more benign dust cloud for *Excalibur*. Figure 12. shows the predicted induced velocity field for *Excalibur* as it hovers near the ground. The computational methodology employed a free-vortex method. For modeling the brownout cloud, a sediment tracking code was used (Figure 12.). Both of these codes have been developed and successfully tested at UMD. The results shown that *Excalibur* has a relatively benign dust cloud, and would be expected to have a relatively good brownout signature.

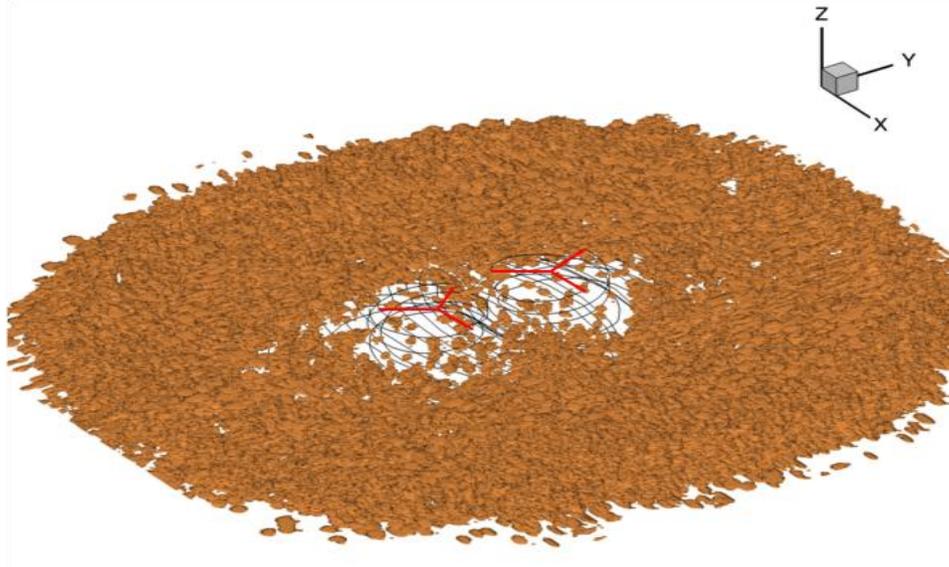


Figure 12.10: Isometric view of *Excalibur*'s brownout cloud evolution

12.7 Autorotative Index

Autorotational capabilities of *Excalibur* in helicopter mode (fully extended rotor) give the vehicle an unprecedented advantage over current tiltrotors. The autorotative index for *Excalibur* is 10. The details of this calculation is given in greater detail in Section 14.

13 Acoustics

To operate in a military environment, and especially to minimize detectability, the acoustic signature of *Excalibur* must remain below the ICAO Level 4 noise requirements. The noise of *Excalibur* was analyzed during the design for both helicopter and airplane modes of flight.

13.1 Internal Noise

Internal noise is primarily caused by the engines and is influenced by clearance between the proprotor blade tips and the fuselage. The engines and main gear boxes are far removed from the cockpit and will have minor influence on the internal noise. The two-thirds reduction in blade diameter in cruise will increase the clearance between the blade tips and the fuselage from 4.75 ft to 9.65 ft. This increase in distance has the effect of moving the noise sources further away from the observer and will reduce noise. The VDTR concept, therefore, provides a fundamental benefit

over non-retractable proprotors by giving much lower internal cabin noise. The reduction in rotor rpm in forward flight mode will further reduce the noise.

13.2 Effective Perceived Noise Level

To accurately determine the ICAO Level 4 noise requirements, certain flight tests must be performed. These tests include measurements of the effective perceived noise levels (EPNL) during approach to landing, takeoff, and a 50 m altitude fly-over. These noise certification tests must be repeated at least six times at the same engine thrust, height, speed and configuration at each of the reference noise measurement positions¹. An analysis was performed using the Ffowcs Williams Hawkins equation to predict *Excalibur's* acoustic signature². This equation solves for the sound pressure levels as an integral of the thickness and loading noise contributions.

The acoustic signatures of the *Excalibur* were analyzed at 6K95 conditions for both hover and airplane mode. In these calculations, an observer was located at 50 m away from the mid-point between rotors with the left rotor rotating clockwise and the right rotating counter clockwise when viewed from above in helicopter mode. *Excalibur's* unique blade design gives it a low thickness-to-chord ratio at the blade tip, thus decreasing the thickness noise. It is important to note that the thickness noise calculations employed an equivalent blade with a constant t/c of 9%, which gives a conservative estimate of the thickness noise levels. The loading on the proprotor was used to obtain an estimate of the loading noise levels. Because the thrust of each rotor causes pressure waves to radiate outward, low disk loadings are generally desirable. *Excalibur* has a low disk loading of 11 lb/ft² in hover and 4.86 lb/ft² in airplane mode at FL150.

Figure 13.1 and Figure 13.2 show the calculated sound pressure levels (SPL) of *Excalibur* in helicopter and airplane mode respectively.

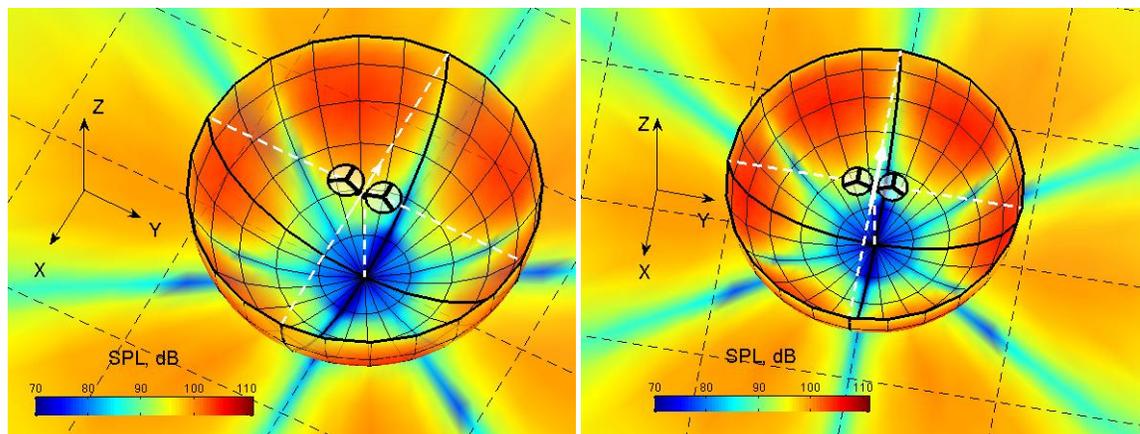


Figure 13.1: Three-dimensional representations of the sound pressure levels in hover

Shown in Figure 13.1 are the sound levels projected onto a hemisphere with a radius of 165 ft, and also onto a ground plane. It is interesting to note that the presence of two proprotors operating adjacent to each other create areas of constructive and destructive interference. When the sound waves of both rotors are in-phase, as indicated by areas of orange or red, rotor noise is amplified to as high as 90 dB at the ground. Areas of blue indicate regions where the sound waves are out of phase and destructively interfere with each other which lowers noise levels to as low as 70 dB. Although in some regions we see high SPL in hover, perceived levels are generally

found to be much lower. This gives the team confidence that *Excalibur* can operate within the permissible ICAO Level 4 noise requirements.

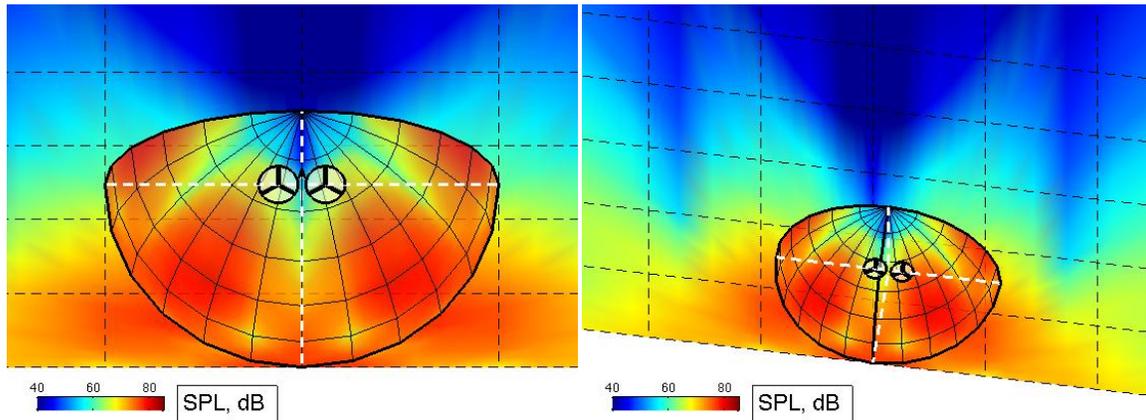


Figure 13.2: Three dimensional representations of the sound pressure levels in airplane mode

Figure 13.2 shows the sound pressure level in airplane mode. In this figure the ground plane is 165 ft below the rotor, with quarter spheres projecting forward and down in front of the tiltrotor. The rotors are now turned 90° and the proprotor diameter reduced as they would be in airplane mode. In airplane mode, *Excalibur's* noise levels are considerably lower. This result is expected because the disk loading is decreased by more than 40%. The figure shows that in front of the tiltrotor, the SPL are very low, as illustrated by the blue region on the ground plane. Because the rotor planes are now perpendicular to the ground, the regions of constructive and destructive interference are more pronounced forward of the aircraft and no longer downwards onto the ground plane as was found in the hover case. In forward flight, the indicated noise levels in front of the aircraft indicate *Excalibur's* signature remains as low as 40dB until the aircraft flies within a few hundred feet of the observer, at which point noise levels only reach near 80dB.

The further analysis does not include the calculation of high speed impulsive (HSI) or blade vortex interaction (BVI) noise. HSI noise is directly related to the proprotor tip Mach number. *Excalibur's* innovative proprotor design incorporates 30° of blade sweep and helps to lower the levels of HSI noise. The retraction of the proprotors in forward flight reduces the helical tip Mach number, further reducing HSI noise. During the transition from airplane to helicopter mode, the most critical region of BVI noise, effective flight path management can lead to a more benign acoustic signature for *Excalibur*. Before this transition, airspeed should be reduced in airplane mode. This reduction in airspeed can be provided by larger wing flap deflections resulting in increasing the percentage of total lift carried by the aircraft. During transition a slow nacelle tilt-rate can avoid large decelerations and small inflow values, therefore, flattening the descent angle during this deceleration and reducing noise. The analysis has shown that *Excalibur's* low disk loading and low blade *t/c*, in addition to its reduced tip Mach number and effective flight path management, will ensure it satisfies the RFP required ICAO Level 4 noise requirements.

14 Survivability

Within the military setting, survivability is defined as the ability to remain mission capable after a single engagement. It is important that, for a military vehicle, survivability is not addressed solely by trying to protect the vehicle itself, but by safeguarding the crew¹. This is accomplished by ensuring occupants are protected not only by the effects of being hit by a projectile, but by decreasing the likelihood of being detected, identified, and hit, as well as by minimizing post-hit effects and increasing damage control.

14.1 Susceptibility

The *Excalibur* significantly reduces the likelihood of being detected, identified, and hit by an enemy fire. The main advantage comes from the performance of the aircraft. The *Excalibur* flies at a higher altitude with a greater range and speed than most other VTOL aircraft. Cruising at 15,000 ft ensures that most weapons fired from the ground, including small weapons, cannon, and RPG fire cannot reach the aircraft. Its ability to fly like an airplane reduces the visual and acoustic signature of the aircraft and increases its maneuverability over traditional helicopter configurations, giving it the ability to evade the enemy more easily.

14.2 Vulnerability

Many features have been built into the *Excalibur* to reduce its vulnerability. The biggest advantage is the ability to operate one engine inoperative (OEI). This is accomplished through an interconnected drive shaft so that during normal operation it ensures that both rotors are turning at the same rate. In an emergency, such a system can be utilized to drive the opposite rotor if that rotor engine has malfunctioned. This shaft has also been designed large enough and strong enough that it can also be pierced by a 50 mm round and continue to function. This redundancy ensures that in the unlikely event that an engine becomes damaged and fails, the *Excalibur* can continue flying long enough to land safely. This capability, coupled with an excellent autorotational capability, ensures that even if *both* engines fail, the aircraft can be landed safely in either airplane mode or helicopter mode, providing an unprecedented capability for a tiltrotor concept. Redundancy in design is built into many of the vehicles systems as many are triple redundant and most of the avionics, sensors, and displays are quadruple redundant.

Fire-protection and suspension are also built in features as all aspects. The vehicle incorporates a dry bay with engine fire-suppression which reduces the likelihood of an engine fire spreading to other parts of the vehicle. The fuel systems are also self-sealing and if the fuel system experiences a break in the line, a fire will not break out. Fuel bladder tanks are also self-sealing and conform to MIL-DTL-27422 specs, which include a crashworthiness requirement.

14.3 Recoverability

The vehicle's recoverability refers to its ability to mitigate the effects of a post-critical event. This means that after an emergency or failure has occurred, the post-crash danger must be minimized. The *Excalibur* does this in much the same way that other military aircraft do. The aircraft utilizes a remote mass design, such as engines and transmission at the wing tips, which ensures that the wing undergoes controlled failure by separating at the cantilever of the fuselage/wing intersection. This design feature alleviates the potential fuselage crushing that might occur if there was transmission or engine mass above the fuselage. The composite

materials in the rotor blades exhibit a “soft” failure mode by ‘broomstrawing’ instead of causing entire blade separation.

In the event of a crash landing, the survivability of *Excalibur* is increased by a number of factors. The fuselage lower surface is contoured to prevent plowing. The aircraft frames and extended landing gear also absorb energy while stroking seats ensure safety for the crew and passengers. All areas of ingress and egress are also maintained in a crash as the frames around doors minimize deformation and all exits are jettisonable.

14.4 Crashworthy Seat Design

The US Army has developed guidelines for the design of all crashworthiness features. These detailed requirements are detailed in mil standard MIL-S-85510(AS)². Civil requirements are also in place and outlined in SAE, AS8049 and are also established in CFR Title 14 Parts 27 and 29³. Because the human body cannot withstand the decelerative “g” loading prescribed in the documents, a method for absorbs or dissipates energy must be employed in crew seat design. Since the 1960s there have been a host of proposed energy absorbing designs proposed including, crushable column, tube and die, wire benders, tube flaring, and hydraulic and pneumatic designs.

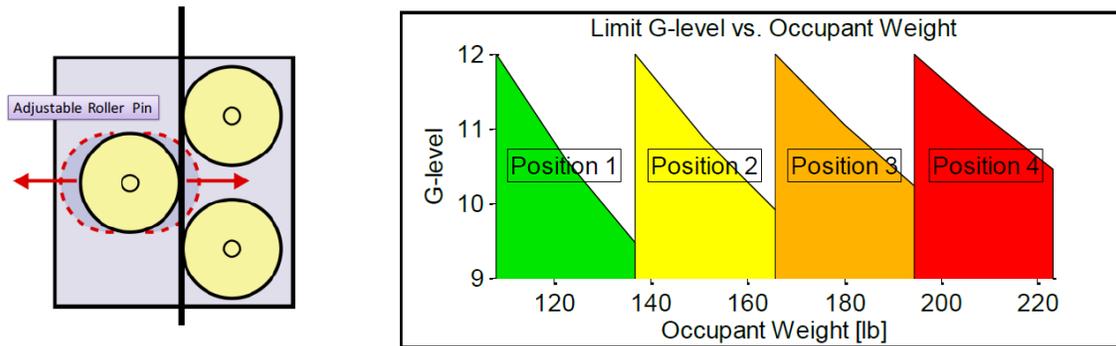


Figure 14.1: Adjustable roller pin and wire bender VLEA and corresponding limit load adjustment setting

14.4.1 Variable Load Energy Absorber

At the University of Maryland, a Variable Load Energy Absorber (VLEA) crashworthy seat has been designed to exceed the current standards as prescribed in the aforementioned standardization documents⁴. This seat design has been designed to minimize compressive lumbar loads to 12 g’s or less. This improved seat design minimizes the risk of spinal injuries in the event of a crash and decreases the spinal injury rate for occupants to only 20%⁵. The VLEA utilizes a wire bending design which is built into the structure of the seat. A schematic of the VLEA system is shown in Figure 14.1. This VLEA seat is adjustable based upon the weight of the occupant so that proper position of the roller pin is attained for maximum occupant safety. This is done through a load cell which senses the occupant weight and subsequently sets the adjustable pin one of four appropriate settings depicted in Figure 14.1. This anthropometric displays the stroking g-level across the weight range from the 5th percentile to the 95th percentile male occupants.

14.4.2 Vibration Isolation

The VLEA seat used incorporates an additional safety feature through the use of a magnetorheological (MR) damper⁶. Helicopter pilots and passengers experience whole body

vibration, which is a major cause of fatigue. This fatigue can lead to issues of discomfort and loss in situational awareness, which reduces reaction time and inhibits the pilot's aeronautical decision making capability. Magnetorheological fluid dampers have been incorporated into the VLEA seat design to provide an effective way to actively isolate vibration transmission from the vehicle to occupants.

This revolutionary seat technology was found to reduce 4/rev rotor induced vibration by 90% for the 50th percentile male⁷. *Excalibur's* four crew seats utilize this technology to provide vibration attenuation and comfort. The MR dampers are integrated in series with the VLEA seats (reference). The load path passes through the VLEA wire bending mechanism to the MR damper and then to the seat. The VLEA will not stroke until the requisite g-level is achieved. In the event of a crash landing, the MR damper will fully stroke to the bottom of the housing and then the VLEA will stroke.

14.5 Autorotative Index

To compare the potential autorotational capabilities of *Excalibur* to other helicopters and tiltrotors, an estimate of the Autorotative Index (AI) was made. The AI depends on the stored kinetic energy of the entire rotor system (i.e., on the blade mass, radius of gyration, and its angular velocity) and the vehicle gross weight. Because *Excalibur* employs relatively high tip speeds in the hover mode, the stored inertia in the rotor is also relatively high. The larger stored inertia coupled with the increased radius and low disk loading in hover allows *Excalibur* to achieve an AI equivalent to multi-engine helicopters of similar MGTOW, as shown in Figure 14.8. The ability to autorotate as good as a helicopter, glide to a landing in airplane mode, and successfully perform all of the missions under single-engine-out conditions gives *Excalibur* an unprecedented level of performance and safety of flight compared to any type of rotary-wing vehicle that is currently flying.

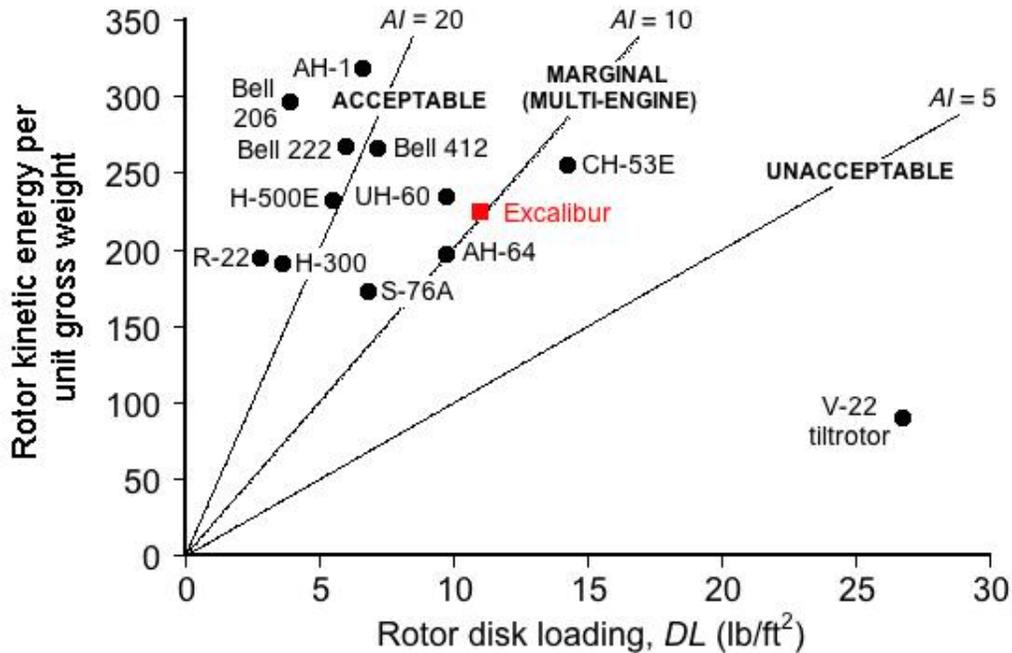


Figure 14.2: Comparison of autorotative index for different rotorcraft

14.6 Assessment of Failure Modes

Excalibur has been designed to ensure safety for various failure modes that could be encountered. The response of the system to the major failure modes is outlined as follows:

Each of *Excalibur's* nacelles is equipped with a tilt sensor. In the event that one of *Excalibur's* nacelles fails to tilt, the health and usage monitoring system detects the difference between the two tilt sensors and sends a warning to the pilot. If this angle exceeds 5°, the HUMS automatically stops further tilting of the nacelles. The difference in thrust between the two rotors can be countered by the pilot through rudder and stick input until the aircraft can be trimmed.

A failure of the blade retraction mechanism on both rotors, or the failure of a single blade or rotor to extend or retract is also detected by the HUMS. If a failure were to occur in the airplane mode, both rotors remain in the previous position and a landing in airplane or STOL mode can be performed at a suitable location. If the failure of the retraction mechanism occurs in helicopter mode, an immediate landing is not necessary, as the vehicle can continue to fly and a landing performed at best possible location.

As previously discussed in Section 5.3.4, the blade collective pitch has two ranges, one for hover and one for forward flight. These collective settings utilize a solenoid mechanism to lock the pitch bearings in their respective range positions. During nacelle tilt, and upon reaching the 45° position, pitch range transitions to the respective position. The solenoid then locks the assembly in this position. If the solenoid fails to lock in the new position, further nacelle tilting is halted. The HUMS will then alert the pilot of the failure and the assembly will attempt to lock in the previous position. If this also results in a locking failure and a return to base or an immediate landing must be performed.

In the case of a single engine failure, the interconnecting shaft between the two rotors will be able to power both the rotors in helicopter and airplane mode. In the case of helicopter mode, the pilot should land in the closest possible location because the power required to hover cannot be sufficed by a single operative engine. However, in airplane mode, *Excalibur* can continue to fly at the best range speed or lowest power required.

In the event of dual engine failure in helicopter mode, *Excalibur* can autorotate as it has an autorotative index of 10. If the dual engines fail in airplane mode, *Excalibur* can glide to the nearest suitable landing location at its best glide speed.

If the landing gear fails to extended, the pilots can utilize a manual gear lever in an attempt to lower it. The weight of the gear should cause it to extend and lock into place while automatically pushing open the gear bay doors. A gear lock indicator on the pilots multi-function display shows green lights or red lights, indicating the gear is in a safe or unsafe position to land.

15 Project Development Timeline

15.1 Life-Cycle Cost Analysis

The cost of a tiltrotor, as with any other aircraft is divided into various categories: development cost, production cost, and operational costs. These categories add up to the total life-cycle cost of the vehicle. Often, the customer will only see two areas of cost for the aircraft, mainly the acquisition cost and the operational costs. Acquisition cost is the sum of the development and

production cost and is also referred to as the base price of the vehicle. For the analysis, the estimation of the cost is based on historical data. All costs are presented in 2010 U.S. dollars. The consumer price index¹ form is used to generate 2008 dollars by application of annual inflation rates.

Harris and Scully² developed an empirical model for estimating helicopter cost based on historical trends from 118 helicopters and 2 tiltrotors. This empirical model proves to be effective at estimating helicopter cost but has yet to be proven for tiltrotors. However, because this is currently the most readily available and widely accepted method for estimating cost, it will be used for cost estimation of the *Excalibur*. Harris and Scully's empirical formula is a function of various parameters given below:

$$\text{Base Price} = \$350 \times H \times N_b^{0.2045} \times W_0^{0.4854} \times P^{0.5843}$$

where H is a product of factors given in the table below, and is computed using

$$H = \text{Engine type} \times \text{No. of Engines} \times \text{Country} \times \text{No. of rotors} \times \text{Landing gear} \times \text{Pressurization}$$

Table 15.1: Product factors for the variable H

Engine type		No. of engines		Country	
Piston	1.000	Single	1.000	US Commercial	1.000
Piston (supercharged)	1.000	Multi	1.352	US Military	0.838
Piston (turbine conversion)	1.180			France/ Germany	0.860
Turbine	1.779			Russia	0.330
No. of main rotors		Landing gear		Pressurization	
Single	1.000	Fixed	1.000	No	1.000
Twin	1.046	Retractable	1.104	Yes	1.135

Using Harris and Scully's formula along with the update from the consumer price index (CPI) the cost of the *Excalibur* can be estimated and compared to the cost of two other tiltrotors.

Table 15.2: Comparison of estimated base price for tiltrotor aircraft

Million \$	V-22 Osprey	BA-609	Excalibur	ERICA
Actual base price	67	8–10 (predicted)	-	16 (predicted)
Calculated base price	42.63	10.1	8.6	15.53
Equipped price (CV-22)	83	8–10	-	16

It can be seen from Table 15.2 that the comparison of estimated base price for various tiltrotors that Harris and Scully's formula does well with predicting the base price of various tiltrotors with the exception of the V-22 *Osprey*³. It is also shown that *Excalibur* has a relatively low base price. This estimated base price of \$8.6 million is representative of the highly optimized design. Installed engine power is closely correlated to the base price of the vehicle. The *Excalibur* has been designed for operations at 6K95 conditions and because available engine power decreases

with altitude and temperature, the installed power is relatively high. If *Excalibur* had been designed to operate at sea level conditions or even 4K95 conditions, the required power would have been much less and, thus, the base price of the vehicle would have been reduced further.

To determine the life cycle costs of the vehicle, two other costs must be considered, the direct operating cost (DOC) and indirect operating cost (IOC). Conklin and de Decker⁴ have developed a detailed financial analysis that allow for the calculation of life cycle costs and budget and residual value data for fixed-wing and rotary-wing aircraft, and include a database of more than 310 aircraft. Analysis using their software helped to determine the DOC and IOC of the current tiltrotor design.

15.1.1 Direct Operating Cost (DOC)

Direct operating costs are defined as the costs that vary in direct proportion to the number of flight hours⁵. These costs include fuel, additives and lubricants, as well as inspection costs, parts and maintenance. *Excalibur* was compared to two other helicopters in the same weight class, as shown below in Table 15.3.

Table 15.3 : Direct operating costs comparison

Direct operating costs	Average \$/FH over 20 years		
	S-76C+	EC-155B1	Excalibur
Takeoff weight	11,700 lbs	10,580 lbs	16,145 lbs
Fuel + additives	736	760	665
Maintenance labor	404	341	405
Inspections	21	113	40
Parts	359	318	360
Engine overhaul	246	273	330
Life limited/overhaul	209	112	230
TOTAL DOC	1,975	1,918	2,030

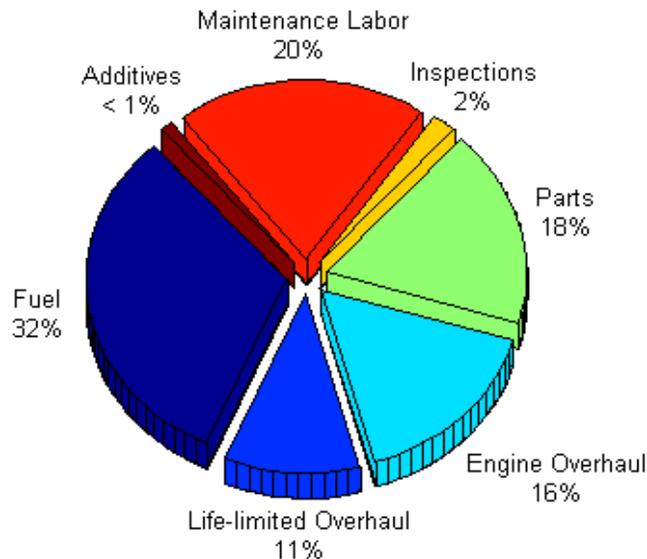


Figure 15.1: Breakdown of direct operating cost

It can be seen that the current tiltrotor design's DOC is comparable to current conventional helicopter designs. The tiltrotor design is much more fuel efficient than other helicopters, which helps keep operating costs low because fuel costs are 32% of the direct operating cost of the vehicle. One reason the tiltrotor has a higher DOC than comparable helicopters is because of the advanced technology, mainly the retractable rotor blades and blade retraction mechanisms, which all increase the cost of maintenance labor, parts, and life-limited overhaul.

15.1.2 Indirect Operating Cost (IOC)

Indirect operating costs (IOC) correspond to the daily operating costs and the fixed costs. These costs include pilot/crew salaries and benefits, day-based maintenance, hangar costs, hull and liability insurance, and training costs. These costs are fixed by day or year, and when incorporated into cost per hour for operating the aircraft, come down by one over flight hours as the aircraft is operated. For example, hangar costs are not dependant on the number of hours flown but if broken down into cost per flight hour, expenditure is reduced as the number of flight hours increase. A breakdown of the indirect operating costs is shown below.

Table 15.4: Indirect operating costs comparison

Indirect operating costs	Average \$/year over 20 years		
	S-76C+	EC-155B1	Excalibur
Takeoff weight	11,700 lbs	10,580 lbs	16,145 lbs
Pilot/crew salary+benefits	257,808	257,808	515,616
Hangar	9,300	9,300	9,300
Hull insurance	142,448	159,516	160,000
Liability insurance	32,746	32,746	32,746
Misc.	96,668	73,789	121,600
TOTAL IOC	538,710	533,161	839,262

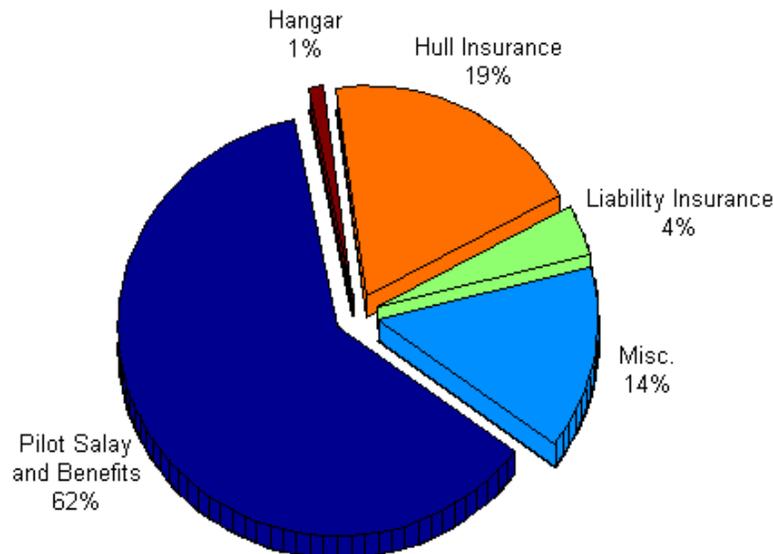


Figure 15.2: Breakdown of indirect operating costs

At first glance, the total indirect operating cost of the tiltrotor appears to be significantly higher than a conventional helicopter. However, the main reason for this is because the RFP stated

requirement of always having four crewmembers on board for all missions flown. Pilot/crew salary and benefits accounts for over 60% of the vehicle IOC. If only two crew members were needed for any given mission, then the total indirect operating cost would reduce to \$581,454/year averaged over 20-years. This cost is comparable to the other helicopters.

It is therefore important that the vehicle be flown an optimal amount of hours per year to minimize the DOC per hour while simultaneously attempting to minimize the IOC per hour. Optimizing of the number of hours shows that the vehicle should be flown 413 hrs/yr for lowest DOC. Although the DOC and IOC for the tiltrotor are greater than that for the helicopter, the costs are comparable and lie within a range of operating costs for other helicopters. This outcome indicates that the development of current and future tiltrotor aircraft will be able to provide cost-effective mission capabilities that the current fleet of conventional rotary-wing aircraft simply cannot provide.

15.2 Technology Development Program

The *Excalibur* incorporates leading advances in tiltrotor research, development, and engineering. Some of the major technologies and their corresponding TRL are shown in Table 15.5. Much of the technology to be utilized on the vehicle represents research that is ready for integration on to a new design. Technology such as the VDR has been proven in wind tunnel tests to be viable, and the systems, subsystems, and components have all been validated in relevant environments. The next step in its development is prototype demonstration in a relevant end-to-end environment. Partial nacelle tilting has also been demonstrated in the wind tunnel and, therefore, also has proven viability. Other design features such as avionics, control system architecture, and sensors are all deployment ready technologies and, therefore, do not require further technology development.

Table 15.5: Current TRL and projected year ready for VDTR technologies

Technology	Stage of development	Estimated TRL level	Projected year ready
Avionics and sensors	Certified	TRL 9	Ready
UMD crash worthy seats	Drop tested/vibration stand	TRL 7	2012
Partial nacelle tilting	Static tested/wind-tunnel-tested	TRL 5	2014
Variable diameter rotor	Wind-tunnel-tested/fatigue Tested	TRL 5	2015
Blade retraction mechanism	Wind-tunnel-tested/fatigue Tested	TRL 5	2015

Excalibur also has an excellent ability for growth. Because it has a large power to weight ratio, low disk loading, and excellent stall margin for maneuvers, fuselage growth is a likely possibility in the future. This would allow *Excalibur* to have an increased payload and gross weight. Ultra hot and high performance is possible because of the already low blade loading at 6K95. Currently *Excalibur* cruises at 15,000 ft but has the capability to go higher. Cabin pressurization would expand the operational capabilities further, making it an attractive option for the civilian market and providing the potential for bio-chemical protection for military application with only a 20% growth in airframe weight.

15.3 Project Development

Development of the *Excalibur* vehicle will be accomplished using an ISO9001/AS9100 quality management system to ensure productivity, quality, and safety are all maximized, costs are minimized, and the needs of the customer and stakeholders are met. Along with the design of the aircraft, progress will be continually examined and current cost, schedule, and completion reports generated. For detailed design, resource allocation and cost management will be prioritized and a dedicated process will be implemented to evaluate and reduce program risks. The development and design of *Excalibur* will be accomplished using:

- ✓ **Customer Focus:** Understanding the RFP and needs of the customer, striving to exceed the needs of the customer
- ✓ **Leadership:** Creating and maintaining an environment that involves achieving the organization objectives
- ✓ **Involvement of People:** Members at all levels of the design are fully involved in project development and decision making
- ✓ **Process Approach:** Design of the aircraft is achieved more efficiently when activities and resources are managed as a process. This will include extensive use of CAD and CAM software
- ✓ **System Approach to Management:** Interrelated processes identified and design managed to increase efficiency
- ✓ **Continual Improvement:** The design team will strive to continually improve understanding of design and process
- ✓ **Factual Approach to Decision Making:** Decisions will be made on sound engineering and analysis of available information and data
- ✓ **Mutually Beneficial Relationships:** Cooperative development and design will be ensured for all stages of design.

A possible program schedule shown in Figure 15.3 defines the plan for development, design, testing, and certification of the *Excalibur* aircraft for future deployment.

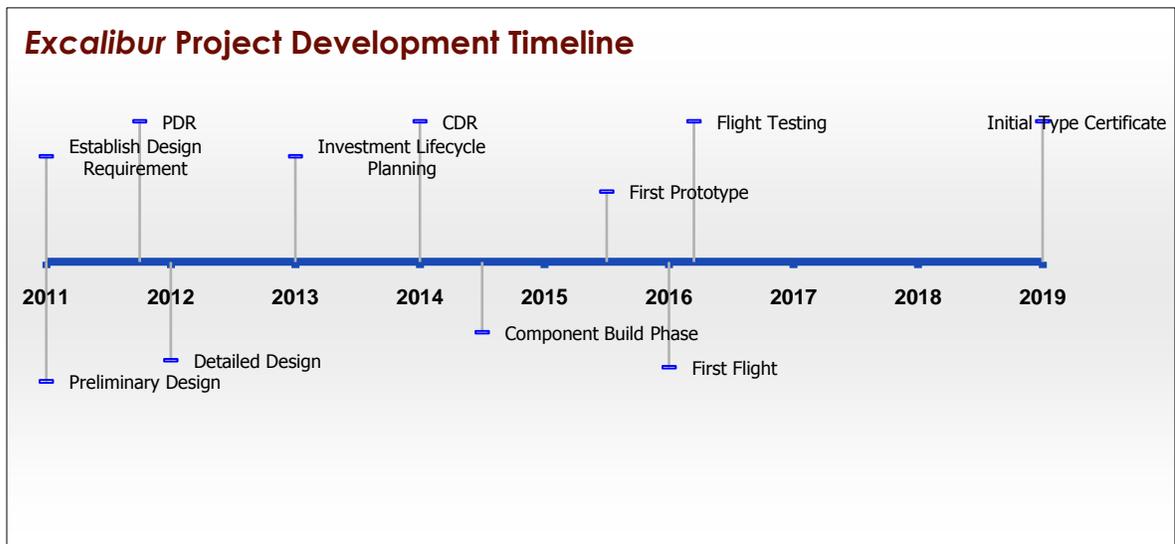
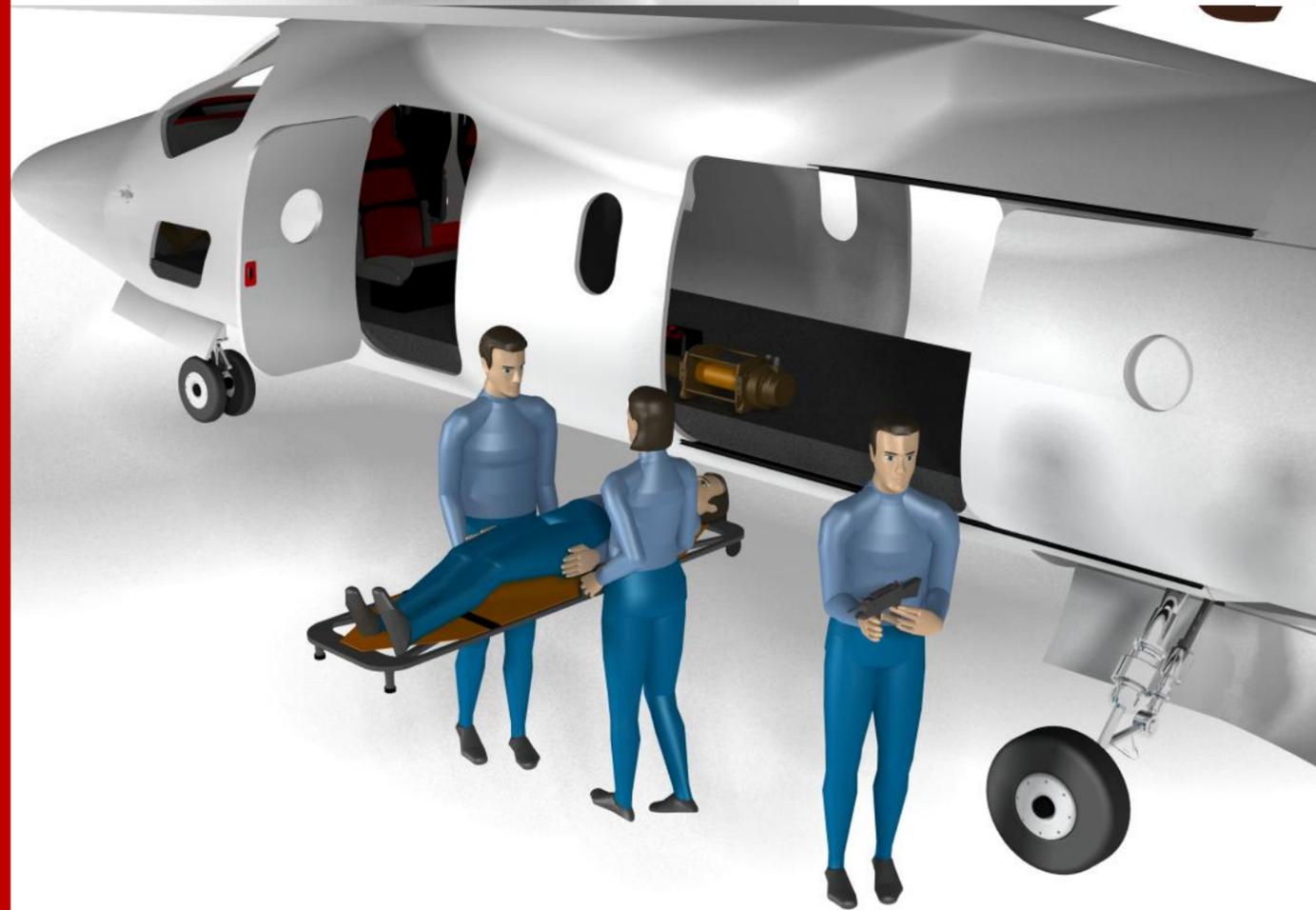


Figure 15.3: Milestones chart



EXCALIBUR



16 Summary

The 2011 Student Design Competition Request for Proposals issued by the American Helicopter Society and Bell Helicopter Textron desired the development of a new multi-mission aircraft. This report has outlined the proposed design of *Excalibur*, a highly innovative, multi-mission variable diameter tiltrotor. *Excalibur's* design has been optimized to ensure the greatest multi-mission flexibility making it the ideal vehicle for completing search and rescue, insertion, and resupply missions. These three missions, based on the needs of current events, have diverse performance requirements. Therefore, the design uses proven, cutting edge technologies to simultaneously achieve both a highly efficient helicopter and an equally efficient airplane. This gives *Excalibur* significant performance advantages over other vertical lift aircraft, with greater range and endurance, while performing the missions in a timely manner. The ability to change rotor diameter provides excellent propulsive efficiency in forward flight without sacrificing hover efficiency.

The RFP specified the need for a new vertical lift aircraft with increased versatility, capable of multiple missions. These missions include search and rescue, military insertion, and resupply. *Excalibur* has also been designed to meet the requirements of hover at 6K95 at MGTOW with sufficient stall margin for maneuvers. To meet these requirements, *Excalibur* has been designed using a combination of cutting edge technologies including:

Variable Diameter Rotors

- Optimized to provide the best hovering efficiency and propulsive efficiency.
 - Power loading = 7 lb/hp (Section 5)
 - Propulsive efficiency = 11 lb/ft² (Section 5)
- *Excalibur* is able to take off and land on runways like fixed-wing aircraft
- Increased payload capacity
 - 4,000 lbs: Vertical Takeoff
 - 6,000 lbs: Airplane Takeoff
- Autorotation Capability as good as multi-engine helicopters $AI = 10$ (Section 14.5)

Innovative Rotor and Hub Design

- Uses maintenance free elastomeric bearings to provide pitch articulation and blade retention
- Contains a spooling motor, coupled with a Harmonic Drive to reel in the tension strap for blade retraction
- Homo-kinetic gimbaled design relieves 1/rev blade flapping loads and virtually eliminates Coriolis forces induced by blade flapping

Rotor Tilting Mechanism

- Engines remain horizontal and only the rotor and secondary transmission are tilted
- Simpler design as engine mounted accessories no longer need to be designed to rotate at the nacelle
- Hot exhaust gasses are directed rearward and, therefore, do not burn takeoff surfaces or injure persons under the vehicle while in hover

Surpasses RFP Mission Requirements

- Mission 1: Search and Rescue
 - Payload = 1,200 lbs
 - Range = 450 nm
 - Speed: $V_{BR} = 220$ kts, $V_{MAX} = 298$ kts
- Mission 2: Insertion
 - Payload = 4,000 lbs
 - Range = 500 nm
 - Speed = 220 kts
- Mission 3: Resupply
 - Payload = 3,000 lbs
 - Range = 500 nm
 - Speed = 220 kts

Excalibur's unmatched performance gives it a strategic advantage. *Excalibur* has high cruise speed with the ability to cruise at 225 kts and dash at speeds of 330 kts with a longer range, extending to distances of 500 nm. This makes it highly fuel efficient as *Excalibur* can fly further and faster. HOGE capability at MGTOW and at 6K95 is unprecedented for current tiltrotor technology. Low disk loadings, optimized blade design, and lower tip speeds ensures that *Excalibur* will meet ICAO Level 4 noise requirements. All of the aircraft's features are driven to ensure true multi-mission capability ensuring it can complete all missions more effectively than any other VTOL aircraft. *Excalibur* represents a paradigm shift and provides a quantum leap forward in tiltrotor utility and performance making it the cutting edge of tiltrotor technology.

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