MULTI-MISSION AIRCRAFT

RC2

RECONFIGURABLE **C**OMPOUND **R**OTOR **C**RAFT

INDIAN INSTITUTE OF TECHNOLOGY

KANPUR

Signature Page

This is to certify that this proposal is the bonafide work of the following students to be submitted as an entry for the AHS Student Design Competition 2011:

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Acknowledgements

The semester long course on Helicopter Theory had made us aware of the potential of this vehicle and the underlying complexity. The credit completely belongs to Dr. C. Venkatesan, who inspired and motivated us to appreciate the basic scientific principles that govern a helicopter. His patience in answering questions, his wealth of knowledge and sincere dedication to the subject overawed us.

Most students remain under the impression that the aerospace field is confined to fixed wing vehicles. However, under Dr. Venkatesan's teaching we have seen the stark difference in the dynamics of the helicopter. The challenges that are built into the design of the helicopter have become apparent with our frequent discussions and debates. This project has been enlightening for us and made our theory work in our courses became much more real and important. At several times we were ready to give up and claim that the mission requirements were impossible to meet with one vehicle. But we had the will to atleast submit a proposal with a vehicle which would be the nearest to the demands of the competition. We were intimidated by the standards of the regular participants of the competition, and at times where we were in doubt, we motivated ourselves by the fact that if we weren't able to find a solution to the design problem, then they too would find it hard.

We would like to thank Mr. Angel Moore for permitting us to use his Google Sketchup Black Hawk Helicopter model as a baseline for the 3D designs and graphics. We used the Sketchup Warehouse extensively to salvage components and fit them to meet our final design. We appreciate the efforts put in by the designers.

Lastly, we chose to complete this project without any faculty guidance. In fact we did not even disclose our intention to participate in the competition with anyone. This was an insistence and belief that doing things on your own and making mistakes is a far better way to learn than to going upto someone with a problem. The first helicopter designers did not have anyone else to go upto and they learnt with their experience and research. With the wealth knowledge available from books and papers, we took it upon us as an additional challenge to complete the whole proposal on our own. However, we did take the help of Mr. Rohin, a PhD student, who in his calm and composed way, solved one of the problems we were facing. We thank him wholeheartedly for his help.

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Nomenclature

A: Disk Area
A_b: Blade Area
AR: Aspect RAtio
c: Chord
CG: Center of Gravity
D_v: Vertical Drag
e: Hinge Offset
GW: Gross Weight
H: Height
$HOGE$: Hover out of ground effect
i: Shaft Incidence
I_b: Blade Flapping Inertia
IR: Infrared
J: Polar Moment of Inertia
L: Length
N: Number of Blades
R: Radius
S_W: Wetted Area
$VTOL$: Vertical Take Off and Landing
W: Width
V: Volume
V_mcp: Velocity at maximum continous power
Z_h: Height of Main Rotor above CG

β: Blade Flap Angle
γ: Lock Number
Ω: Rotor angular rate of rotation
σ: Solidity
θ: Blade Pitch Input
μ: Advance Ratio
ρ: Height

Subscripts

F: Fuselage
M: Main Rotor
S: Stabilizer
T: Tail Rotor

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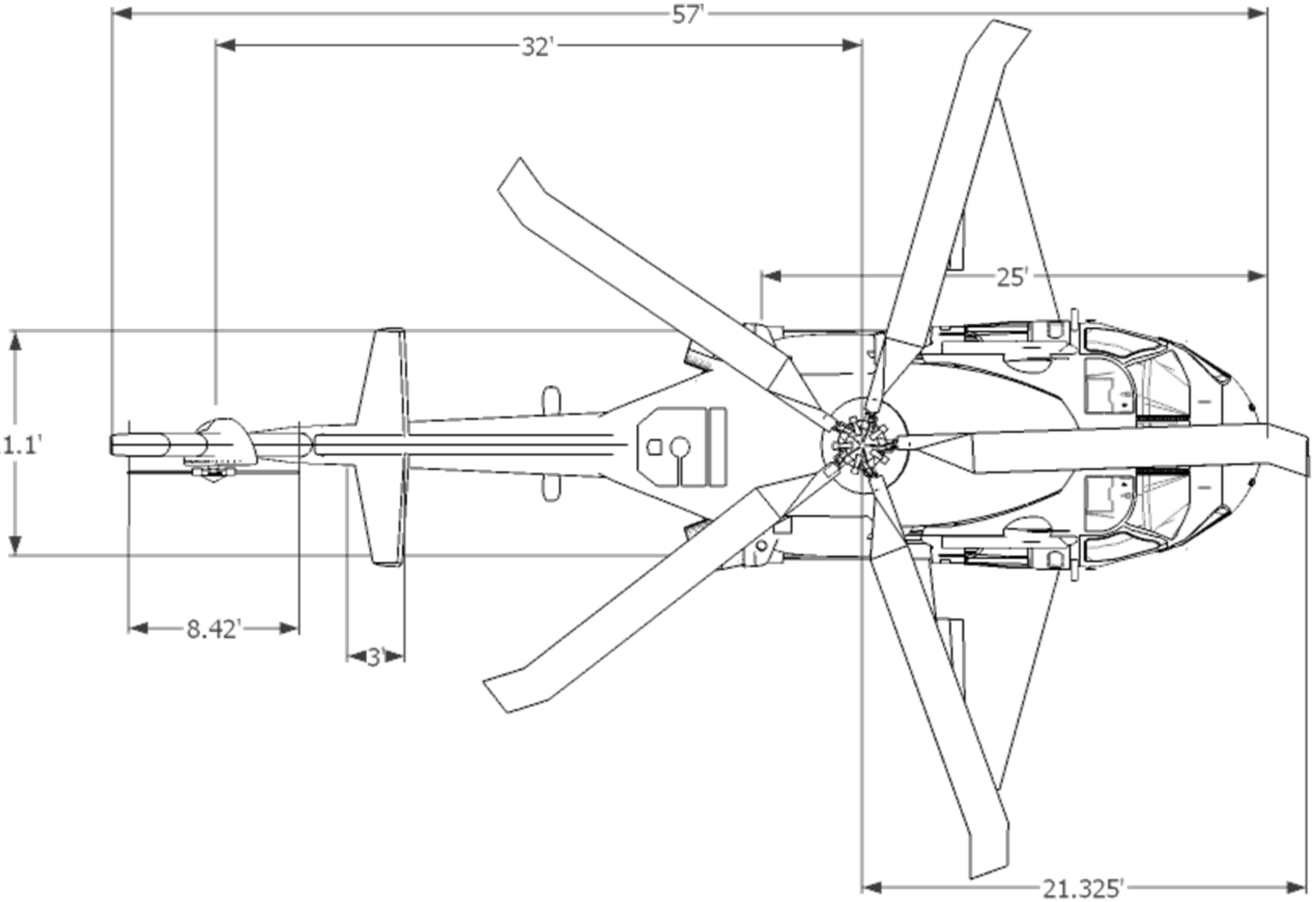
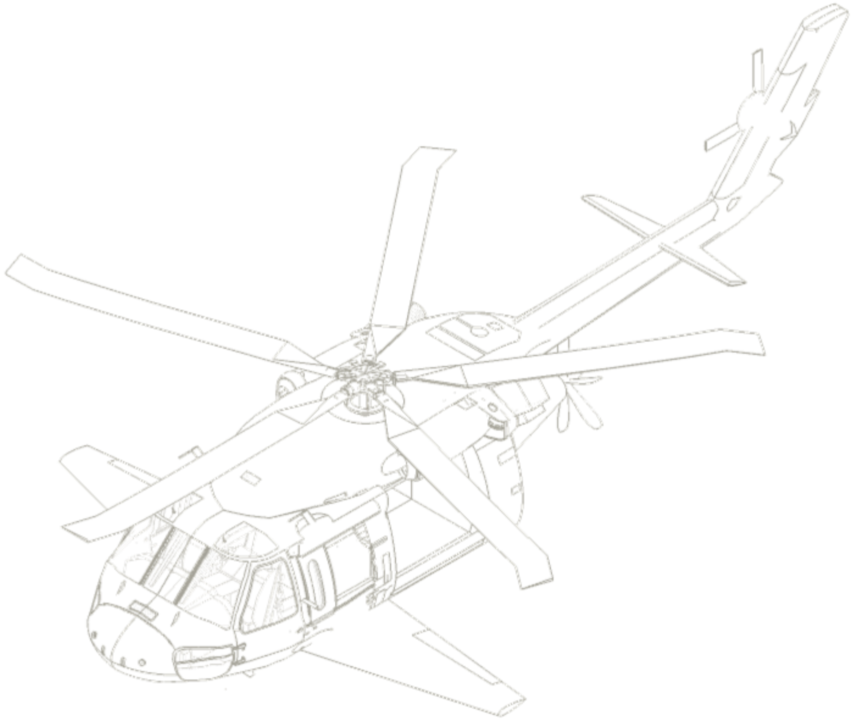
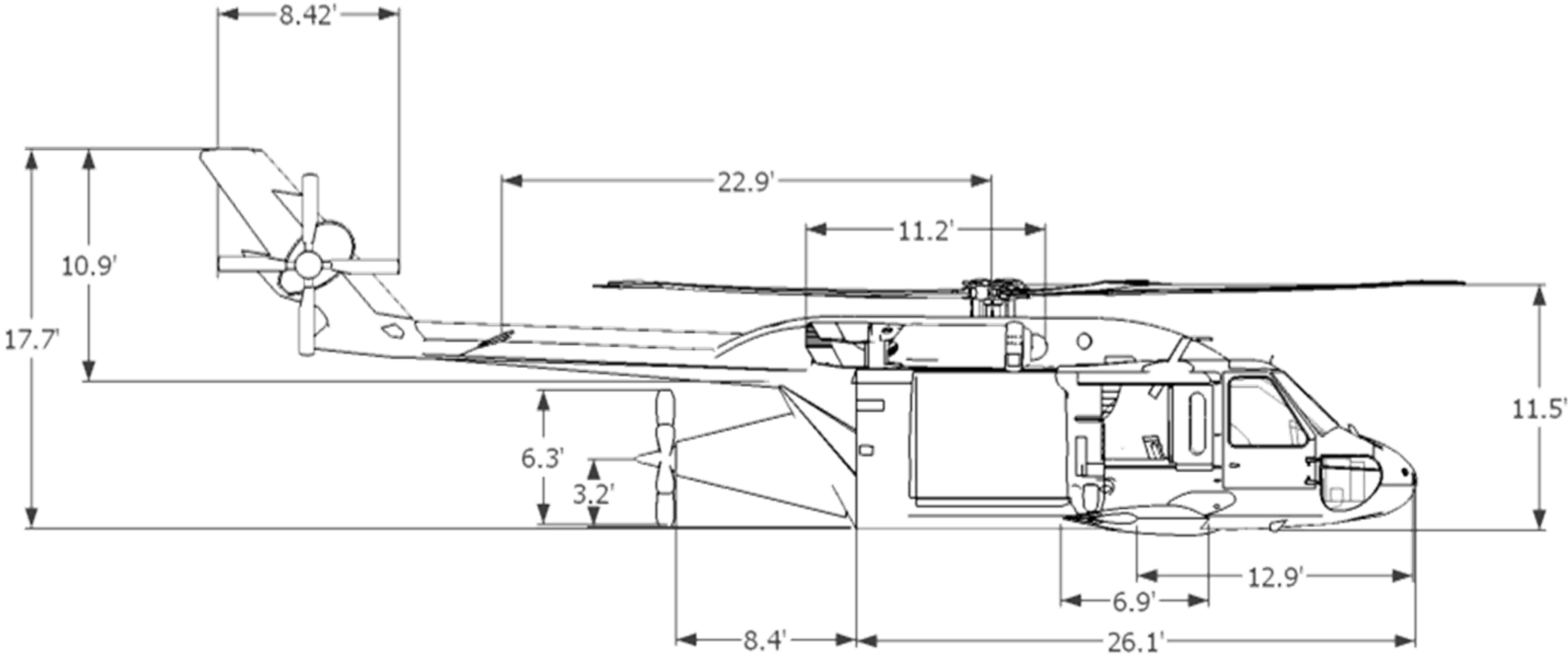
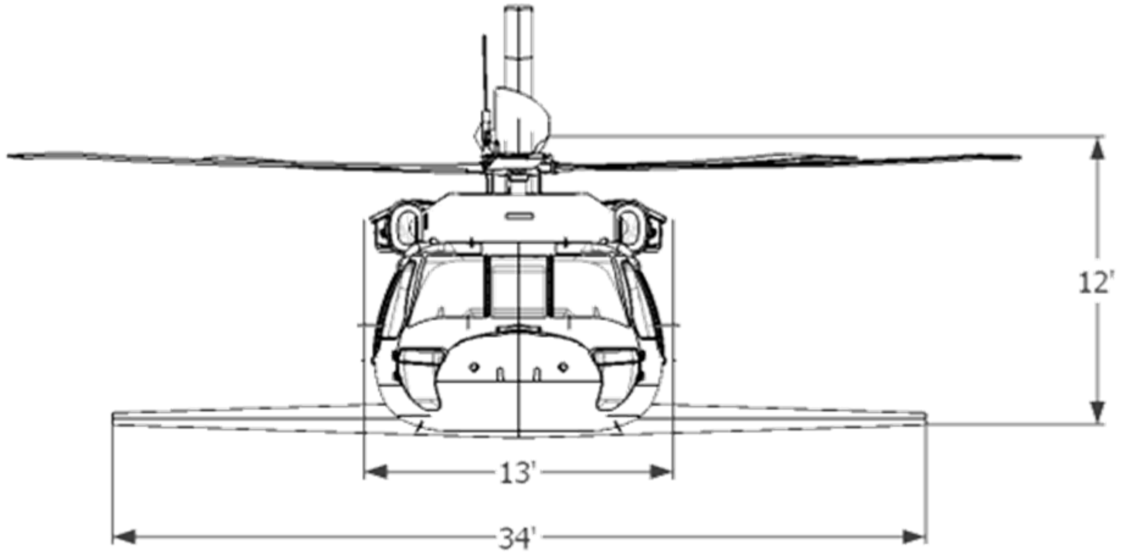








Proposal Summary

Table 1 summarises some important features of the vehicle. A three view drawing of the model is also presented here.

Vehicle	
Design Gross weight	14000lbs
Minimum Operating Weight	8000lbs
Powerplants	two GE CT7-8A T700 turboshafts
Fuel Tank Capacity	3000lbs
Parasite Drag Area, f	14.3ft^2
Vertical Drag Ratio, D_v/G.W.	0.063
Fuselage	
Length, L_F	57ft
Width, W_F	13ft
Height, H_F	9.8ft
Wetted Area, S_{W_F}	280 ft^2
Volume, V_F	3200ft^3
Mass	1072lbs
Material	Composites

Table 1: Overall Vehicle Parameters

The main rotor has been designed according to Table 2.

Main Rotor	
Radius, R	21.325 ft
Disk Area, A	1428ft^2
Tip Speed, ΩR	644ft/s
Chord, c	1.97ft
No. of blades, N	5
Solidity, σ	0.147
Blade Area, A_b	210ft^2
Airfoil	Laminar Flow
Twist	-3^o
Hinge Offset, e/R	0.15
Blade flapping inertia, I_b	462 slug ft^2
Lock no., γ	12
Polar moment of inertia,J	7200 slug ft^2
Shaft incidence, i	0^o
Height above CG, Z_h	9ft
Total Mass	920lbs

Table 2: Main Rotor Parameters

Tail Rotor	
Radius, R_T	4.21 ft
Disk Area, A_T	$55.7ft^2$
Tip Speed, ΩR	644ft/s
Chord, c	0.4ft
No. of blades, N	4
Solidity, σ	0.12
Blade Area, A_b	$7ft^2$
Airfoil	NACA 0012
Twist	-5^o
Lock no., γ	4
Polar moment of inertia,J	10 slug ft^2
Tail rotor moment arm, X_{ht}	32ft
Height above CG, Z_{ht}	9ft
Mass	127lbs
Horizontal Stabilizer	
Area, A_H	31 ft^2
Span, b_H	11.1ft
Aspect Ratio, AR_H	3.96
Taper Ratio, c_T/c_R	0.67
Airfoil	NACA 0012
Moment arm, I_h	33 ft
Height above CG, Z_{hs}	8.5ft
Mass	60lbs
Verticle Stabilizer	
Area, A_V	36 ft^2
Span, b_H	11ft
Aspect Ratio, AR_V	5.3
Moment arm, I_v	34 ft
Height above CG, Z_{hs}	12ft
Mass	88lbs

Table 3: Tail Rotor and Empennage Parameters

Substantiation

A Design

A.1 Critical Requirements

The basic requirements for the vehicle are given in Table 4.
The assumptions made are:
Weight of Adult Human Being = 183lbs [1]
Weight of Patient = 232 lbs.[2]
Weight of Litter = 29lbs [3]

Mission	Max Payload(lbs)	Max Range(nm)
Search and Rescue	1400	450
Insertion	4000	500
Resupply	3000	500

Table 4: Payloads for Missions

A.1.1 Flight Constraints

1. 6K95 HOGE in all missions
2. Maximum Speed = 193 - 270 knots
3. IOCA Level 4 noise requirements
4. IR supression treatments

A.2 Configuration

The required vehicle is to be a vertical lift system. Helicopters and VTOL aircraft are able to meet this requirement. However, most VTOL aircraft are inefficient in hovering flight and cannot compete with the helicopter for the required extreme HOGE requirements. Tiltrotors have a speed benefit, achieved at the expense of payload. The tiltrotor propulsion system is more complex than a conventional helicopter due to the large, moving parts and wings. Tiltrotors have greater cruise altitude capability than helicopters. But a tiltrotor cannot lift heavy payloads when taking off from high altitude.

All conventional helicopters suffer from the limitation of forward speeds. Two factors that dictate this are the retreating blade stall and advancing blade compressibility or Mach Tuck. The world flight airspeed record for helicopters is held by the Westland Lynx, which has gone upto 216.4 knots [4]. This speed barrier has been breached only by compound helicopters. Compound helicopters are defined to have a lifting wing in addition to the main rotor (known as lift compounding) or/and a seperate source of thrust for propulsion (known as thrust compounding). The Sikorsky X2 has recently demonstrated 250 knots capability. It uses coaxial rotors known as the Advancing Blade Concept and propeller-augmented thrust.

A.2.1 Some Compound Helicopters

The Kamov Ka-22 Vintrokryl demonstrated both good forward speed capability and vertical lift capacity and set world records for the same. However it had problems in vibrations, controls, structural failure. Fatal accidents and extreme complexity of the aircraft led to the termination of its development. The McDonnell XV-1 Convertiplane flew extensively and demonstrated successful transitions from helicopter mode to an autogyro mode. But it used the tip jet rotor system whose reliability and complexity caused the cancellation of the programme. The Piasecki Aircraft Corporation pioneered the “Ring Tail” in its Pathfinder compound helicopters and developed several prototypes capable of flying at speeds above 195 knots along with high maneuvrability and efficiency.

The Bell Helicopter Company experimented with various different combinations of rotors (2 - 3 bladed), wings (swept back, straight), thrust (different turbo jet engines) and control riggings.
The Kaman UH-2 Compound Seasprite, Lockheed XH-51A Compound, Sikorsky S-61F were also similar as they used small span wings with auxillary jets for propulsion. Sikorsky also tested the Rotoprop, which swivelled to funciton both as a tail rotor and pusher propeller. The S-72 X-Wing was a stop rotor system that used a ‘circulation control rotor’ instead of a swash plate mechanism. It was never tested for vertical flight because of technological problems. [5]

A.2.2 Sikorsky X2

The Sikorsky X2 is a revisit of the 1970’s S-69 Advancing Blade Concept. The idea to use a coaxial rotor for fast forward speeds is that the symmetric roll moments produced on the two rotors will compensate each other. The S-69 was only able to achieve 160knots but with the addition of two jet engines, it was able to go upto 236 knots. This requirement of auxillary thrust comes from the fact that at high forward speeds, the rotor must act both as a lifting device as well as propelling the craft. The auxillary thrust unloads the rotor from its propelling duty, and the forward flight retreating blade stall speed limit is raised.

Another problem that is faced at high forward speeds is on the advancing blade. The relative air speed at the tip can reach very close to the speed of sound and compressibility effects take over. There is a sudden change in pitching moment on the blade known as Mach tuck.

The Sikorsky X2 uses a propeller instead of a turbojet. According to a study [45], the Sikorsky X2 without any auxillary thrust and only a single 900hp engine, can go upto a maximum speed of 180 knots at an altitude of 10,000ft. However, with a powerful engines and a propeller, it is possible to reach the higher design speeds. This raises the cost of the vehicle. With a single powerful engine, the helicopter will be running at partial power for all flight conditions except for high forward speed. This is fuel inefficient. Two less powerful engines could be used so that the low speed requirement could be met only by one engine and high speed requirements when both are operating.
The ABC also uses very stiff rotor blades to prevent them from flapping into each other. It predecessor, the XH-59A reported the folowing problems:

- High Loads: The high loads and moments on both rotors worked against each other and created damaging stresses in the hub andshaft
- High Drag: The two hubs and shaft (including an instrumentation slip-ring assembly) had as much drag as the rest of the fuselage. The thickness required for the stiff blades also influenced the drag.
- High vibration
- High Weight : (Empty Weight/Gross Weight = 0.775)
- Control: The yaw control was obtained from differential collective at low speeds and rudders on vertical surfaces at high speeds. This was not suitable for autorotation and increased pilot’s workload tremendously.

A.3 Selected Configuration

Considering the above historical and experiential discussions the following helicopter configuration is chosen:

- Single Main Rotor: For thrust and control
- Single Tail Rotor: For torque balancing and yaw control
- Single Main Transmission
- Wing and Propeller for high speed mission

Disadvantages

- Power is absorbed by Tail Rotor, but it does not increase useful weight
- Range of C.G. Travel is limited because of the sensitive trim equilibrium of the helicopter (But it can be increased a little more if hingeless/bearingless rotors are used)
- Tail Rotor operates in an adverse aerodynamic environment and hence has a reduced efficiency. Also there are increased loads and vibration
- Tail Rotor is a hazard for ground personnel

A.3.1 Trade Off with Coaxial Rotors

- There is no need for an anti torque device in the coaxial configuration, so all available power is used for the purpose of thrust
- There are losses due to rotor fuselage aerodynamic interference
- There is greater mechanical complexity in the dual swash plate mechanism as well as coaxial shafts
- The weight of control system and transmissions are higher although the rotor radius will be smaller in comparison to a single rotor
- The hub drag of the coaxial rotors is very large and is the most significant penalty in forward flight. It is of the same order of magnitude as the rest of the vehicle fuselage.

A.3.2 Trade Off with Other Configurations

Tandem Rotors
These helicopters allow a large range of C.G. travel. But these vehicles have a very high inertia and the aerodynamic characteristics of the fuselage are poor. This has an adverse effect on handling qualities.

Side by Side
In this configuration there is lateral separation of the two rotors. The large frontal area causes high drag in forward flight.

Jet Rotors

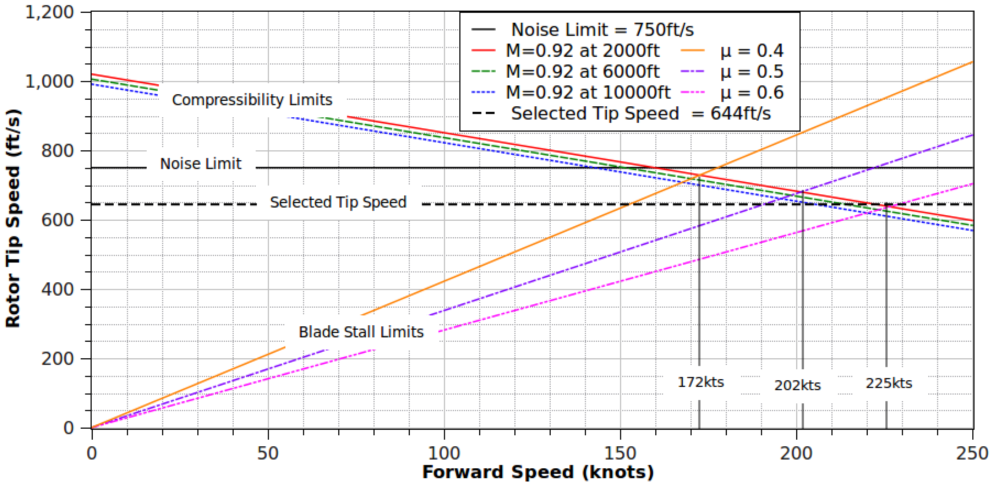


Figure 1: Constraints on tip speeds for forward flight

In this configuration there is no mechanical drive shaft, as the rotation is brought about by jets exiting from the tips of the blades. Hence there is no need for an anti torque device. Yaw control at low speeds is a problem in this configuration. At high forward speeds however, rudders can be effectively used.

A.4 Rotor

A.4.1 Tip Speed

The designed tip speed is a compromise between advancing tip mach number and retreating blade stall. Low tip speeds are beneficial for low noise but problematic due to increased angle of attack at the retreating blade leading to increased profile drag,control loads, and vibration due to stall. High tip speeds allow reduced weight for rotor and drive system, have high stored energy for autorotation but have disadvantages due to compressibility effects and increased noise, profile power,loads and vibration. It is generally accepted that the advancing blade tip mach number must be below 0.92. Higher mach values produce high blade torsional loads due to the Mach Tuck phenomenon. At maximum speed, the advance ratio should not exceed 0.5 to avoid retreating blade stall for conventional helicopters. For a helicopter to be designed such that it can rescue and deliver patients within the golden hour, the advancing tip mach tup constraint gives:

$$\Omega R + V_{mcp} < 0.92 V_{sound} \tag{1}$$

At an altitude of 2000ft this can be written as:

$$\frac{1}{\mu} + 1 < 2.68 \tag{2}$$

This dictates our advance ratio to be nearly 0.6. What the design must ensure is that the retreating blade stall margin is raised significantly. Figure 1 completely depicts the margins that set the design tip speed.

A.4.2 Number of Blades

A 5 bladed rotor has been chosen for our configuration. The number of blades influences mainly the solidity of the rotor. Having less number of blades is advantageous because of low rotor weight, lower cost and ease of folding for storage. There is also lower vulnerability in combat which is not an essential requirement for any of our missions. The BVI (blade vortex interaction) is reduced during hover. But the pulsating wake left by rotors with lower number of blades increases the induced power of the rotor. The advantages of rotors with higher number of blades is decreased vibration and less distinctive noise. In forward flight, low number of blades decrease hub drag. But fewer blades create a pulsating wave which consume more induced power. A rotor with more blades in contrast leaves a smooth wake region behind it. [7]

A.4.3 Radius

The radius of the rotor has been fixed as 21.325 ft. Large rotor radius provides good hover performance and autorotation capability. The disk loading is less and so are the local induced velocities, and also induced power. Using blade element theory we can write the hover power as a function of rotor radius as follows:

$$P = \left(\frac{\kappa W^{1.5}}{\sqrt{2\pi\rho}}\right)\frac{1}{R} + \left(\frac{\rho\sigma C_{Do}\pi(\Omega R)^3}{8}\right)R^2 \tag{3}$$

Figure 2 plots this power assuming 6000 ft 95^{o}F condition, gross weight of 11000lbs, tip speed of 644ft/s and profile drag coefficient C_{Do} equal to 0.015. As visible from the plot, the rotor radius for minimum power decreases with increase in solidity. The same effect will also be seen on increasing the profile drag coefficient. We anticipate the solidity of our rotor to be high as we would like to decrease our disk loading. Hence a low rotor radius value has been chosen keeping in mind the requirement of less available power at high altitudes.

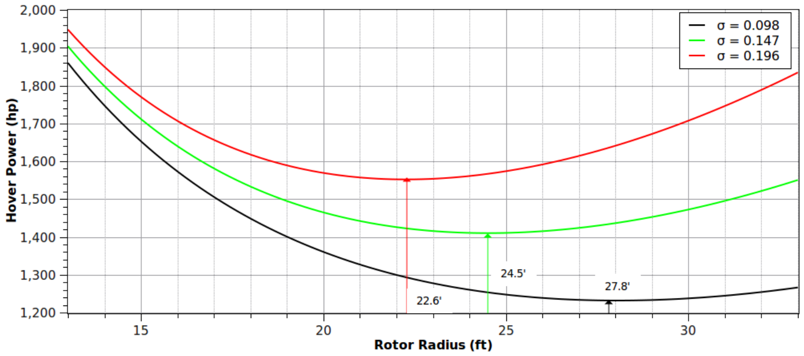


Figure 2: Effect of rotor radius on hover power for different solidities

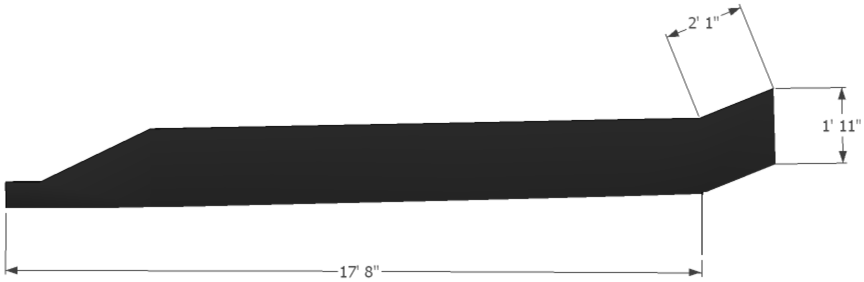


Figure 3: Rotor Blade (from root offset to tip)

A.4.4 Chord

The chord of the main rotor blade is fixed at 1.97 ft. This makes the aspect ratio of the blade 10.825. Designers usually limit maximum aspect ratio of the blade (outboard of flap hinge) to 12. This value of aspect ratio ensures that the natural frequency of the second flapping mode will be below 3/rev.

A.4.5 Twist

Blade twist creates uniform blade loading (equal areas of rotor support equal thrust). High values of twist provide good hovering performance and delay blade stall at forward speeds. Blade twist is detrimental in autorotation. In forward flight it is a major cause of vibration. Twisting the blade reduces the induced torque on the rotor. Generally a linear twist is used. Most helicopter rotors are built with a twist between -8^o and -14^o. In the linear twist:

$$\theta = \theta_{root} + \theta_{twist}\bar{r} \tag{4}$$

Ideal twist is given by:

$$\theta = \frac{\theta_{tip}}{\bar{r}} \tag{5}$$

In comparison with the ideal twist, the linear twist has less profile drag and hence less torque. It has been observed that most of the benefit realised is during the first 10^o of twisting. The optimum twist is different for hover IGE and hover OGE because high twist has poor performance near the ground. Structural limitations also affect twist. During operation of the rotor, the 'Tennis Raquet' effect is seen which reduces the twist of the blade. In some helicopters non linear twist has been tried which has led to improvement in the blade vortex interaction and reduction of negative angel of attack in the reverse flow region.

From previous theoretical analyses carried out [8], it appears that a twist of about -2 deg would represent an acceptable design value for a 250-knot operation of the rotor system studied for a compound helicopter. A negative twist is desirable for hovering and low-speed performance, and -2 deg represents the highest value that can be used without incurring stress or performance difficulties at high speed condition.

A.4.6 Hinge Offset

The hinge offset is kept at 15% keeping in mind the blade chord size and number of blades. Figure 4 shows the dimensions of the hub. Large hinge offsets increase hub drag. Small hinge offsets produce small control power when the rotor is unloaded. In articulated rotors, for satisfying flying quality parameters, the control power during flight at zero load factor shall be no less than "one half" of the control power during level flight. From methods developed in [9] we get:

$$\left(\frac{e}{R}\right)_{req} = 4\bar{Z}_H\beta_o = 0.136 \tag{6}$$

Clearly the hinge offset of 15% is sufficient for the rotor even if the hub was articulated. Our hub is hingeless and hence it meets the safety requirements easily. Generally the equivalent hinge offset for hingeless rotors is 10%.

A.4.7 Hub

The hingeless hub has been chosen for our configuration. The different types available are:

- Articulated: It allows easy analysis, has less control moments, restricts CG travel in the fuselage, and has low lag frequency so an external damper is required to prevent Ground Resonance instability. This system is mechanically complex and requires frequent high level maintenance.

- Teetering: In this, the blade inplane loads must be supported by the root structure. Therefore it requires additional weight. The control moment is entirely due to the rotor thrust tilt and flight at zero or low load factor is not possible. The Lag frequency is greater than 1/rev (stiff inplane), so there is no problem of ground instability.

- Hingeless: This arises from a complex design process on stiffness and mass distribution. The moments are directly transferred to the hub. Therefore it has good control and damping, but has an increased gust response. An external damper is required if the lag frequency goes below 1/rev. The coupling effects play a significant role here.

- Bearingless: This is mechanically simple but has structural dynamic and aeroelastic complexities.

The rigid rotor, offers a clean aerodynamic design with elastomeric hinges and has greater potential for fairing. A drawback of the rigid rotor is that it transmits a greater level of forcing from the blade to the hub than an articulated rotor. This increase in force transference, from blade to hub, can have a detrimental effect on the vibration levels experienced in the airframe. A major advantage of the rigid rotor for application on the compound helicopter is that it can develop significantly more control power than the articulated rotor. Most importantly, this ability is independent of the level of rotor thrust being produced, allowing the rotor to be unloaded without detrimentally affecting the control of the aircraft [10, 11]. This gives the ability to control the aircraft adequately without the provision of ailerons on the wings, an example being the AH-56A Cheyenne, reducing the complexity of the aircraft's control system.

A.4.8 Material

Rotor blades are subjected to extremely harsh conditions, both operational and environmental. Rotational tip velocities of approximately 200 m/s (480mph), and ”flapping” during flight, are coupled with extremes in both humidity and temperature(-40°C to +90°C).A number of specific material properties are required for efficient and effective rotor blades.

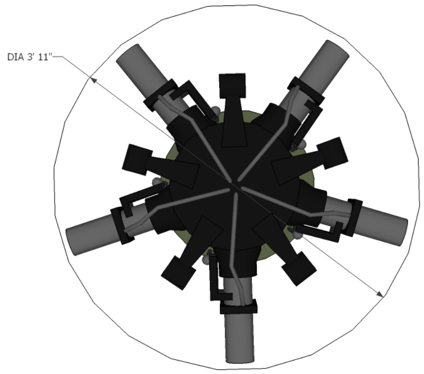


Figure 4: Rotor Hub

Many other desirable properties and characteristics are achieved by the use of composites, including good strength-to-density ratios, which are four to six times greater than those of steel or aluminium. The specific modulus of certain composites is also far greater than those of steel and aluminium, leading to composite blades that are up to 45% lighter than their metal equivalents. In addition, composite blades are much easier to process and manufacture, are joined with adhesives, negating the need for riveting and simplifying assembly and can be produced using much cheaper tooling than for metals. Materials have to be such that noise and vibration is reduced significantly. Radical advancement in rotor blade design was made possible due to the structure and basic ingredients of composite materials, for example, glass fibre reinforced plastics (GFRP).They:

1. Consist of glass fibres dispersed within a polymeric matrix, both of which determine the properties and characteristics of the resulting material.
2. The matrix binds the fibres together, allowing any external stresses to be conveyed and distributed to them. In addition, being ductile, relatively soft and with quite a high plasticity, the matrix is able to play its second role to prevent crack propagation between fibres.
3. The fibres are readily available at low cost. Their strength and chemical inertness also make them highly desirable for use in rotor blades.
4. Composite materials such as GFRPs, offer many advantages over metals, including lightness, ease of manufacture, relative cheapness and strength.

A.4.9 Airfoil

The blade design incorporating the most design features aimed at maximizing the rotor’s potential at high speed is the British Experimental Rotor Programme or BERP blade. This features a tip of increased plan form so that the tip thickness-chord ratio can be reduced, raising the critical Mach number, without compromising the structural integrity of the blade. The blade also uses three different aerofoil sections, optimized for the low speed of the inner blade, the medium velocity of the central blade and the high speed of the tip respectively, the overall blade being also tailored to alleviate retreating-blade stall. To further enhance the tip’s high Mach number capability it is swept, but using a forward notch on the blade so that the pitch instabilities are avoided. The 70^0 angled leading edge outboard of the notch also generates a vortex at high angles of attack, not unlike that of a delta wing, improving the tip’s high angle of attack lifting capability on the retreating side and allowing lower tip speeds and/or higher forward velocities. The vortex generated on the advancing side at lower angles of attack is also beneficial since it truncates the Mach induced shock wave propagating from the thicker inboard sections on to the blade tip. Additionally the increased area of the tip is useful in increasing the lift potential of this most effective part of the blade. Finally, to reduce blade vortex interaction effects, the extreme tip of the blade is given a hedral profile at the tip end that shifts the trailing vortex down away from the following blade in most flight conditions. This is particularly beneficial for hovering flight. Usually there are two airfoil shapes used on a rotor blade - for the tip and for the constant chord portion. The requirements are :

1. High maximum static and dynamic lift coefficient
2. High drag divergence Mach number : But without increase in power or noise
3. Low drag at moderate lift coefficients and Mach numbers
4. Low pitching moment to minimise blade torsional dynamic loads and control system loads
5. Ease of Manufacture
6. Thickness ratio from 10-15% for structural considerations

At low Mach number, the operating condition is dictated by the angle of attack for $C_{L,max}$ or stall limit. For moderate to high Mach number, the angle of attack is dictated by the drag divergence mach number. For high hover and cruise performance, laminar-flow airfoils are best. Their maximum thickness is placed well back from the leading edge. This keeps the flow accelerated for a longer distance and keeps the boundary layer laminar. Their drag bucket indicates that for a small lift coefficient range, the drag is minimum. Thus these airfoils can provide lift for a lesser power penalty to the rotor. However, for high forward speeds, super-critical airfoils are better. These airfoils are able to reach higher angle of atacks on the retreating side before seperation of flow. They have a higher drag divergence Mach number and they develop shock waves farther aft than traditional airfoils. The important factors to design the optimum supercritical airfoil for the rotor have been pointed out in Fig.5.

A.4.10 Tip Shape

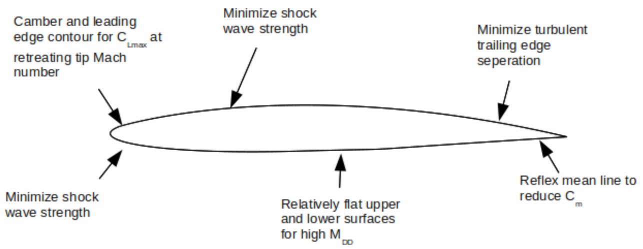


Figure 5: Supercritical Airfoil design parameters

The tip shape is a critical factor for the rotor performance in hover as well as forward flight. We propose the vehicle to have different tip shapes for the different configurations. For the high speed search and rescue mission, the blade tip should follow the same trend as the BERP on the Westland Lynx. Tip sweep helps reduce the compressibility effects at high forwards speeds, high blade torsion and control loads on the advancing blade during Mach Tuck, and generation of noise due to shock wave formations. Dynamic twist is also controlled using a swept back tip. At high speeds, the blade tips create a downward load on the blade due to twist. On a swept back tip, this download pulls up the leading edge of the blade, reduces download and aerodynamic penalty. On the retreating side, there is an upload on the tip which pulls down the leading edge of the blade, reducing the angle of attack and delays retreating blade stall. In other missions a swept tip with rounded edges will be used. This will avoid compressibility effects which cause increased torsional loads, drag and noise due to blade vortec interaction (BVI). Modified tip shapes cause bending-torsion aeroelastic coupling in the blade. They also reduce volume space for keeping the tip weight which is used for improving blade autorotation and dynamical performance. Most blades have rectangular planform with modified tip shape. The cost of designing, testing and building these blades is significantly higher than straight blades with rectangular tip shapes.

A.4.11 Tilt of Shaft

To have a minimum angle of attack of fuselage during forward flight, a shaft tilt is used. In general, a nose down shaft tilt of 5^o is used. However there is an adverse effect on pilot visibility during hover. Horizontal attitude at hover implies 10^o nose down at high forward speed. So 5^o nose up at hover allows 5^o nose down at fast forward speed. While using augmented thrust, this requirement goes away because the fuselage tilt angle can be controlled as the rotor need not tilt to provide a propulsive force. Hence the vehicle will have no tilt in the shaft. For the other configurations, the forward speeds are not critical and hence the augmented thrust using propeller is not present. The vehicle will therefore have a forward tilt.

A.5 Flare Angle

The flare angle is the angle of the fuselage longitudinal axis with respect to ground when the main landing gear and the aft end of the tail boom/skid touch the ground simultaneously. A higher flare angle helps provide good deceleration for landing but there is danger of hitting the ground during flare. In general this angle is from 10^o to 14^o. This designed vehicle has retractable landing gear, and a flare angle of 10^o has been chosen.

A.6 Wings

Most attack helicopters such as the Bell Cobra, Boeing Apache and the Mil Hind, that have wings use them only as convenient places to carry armaments and fuel. The wing interferes with the rotor wake during hover and hence decreases the payload capability by 10%-20%. At high forward speeds, the wing unloads the rotor. This decreases the pitch angle requirement of the rotor and higher advance velocities are possible because retreating blade stall is delayed. However, to counter the drag at high speeds, the helicopter has to tilt nose down and inflow must increase to have more thrust. This results in higher retreating blade angles. For a mission involving high forward speeds, the wing (shown in Fig. 6) is an important factor in the design for relieving retreating blade stall and reducing the thrust requirements of the rotor.

However, it is subject to interference effects with the rotor wake and the fuselage, which causes a large effect on the trim of the aircraft, and the download it causes in hover is detrimental to the payload carrying capability of the aircraft. The wing is subjected to the rotor wake, which is also complicated by the highly uneven distribution of the dynamic velocity, both along span-wise and

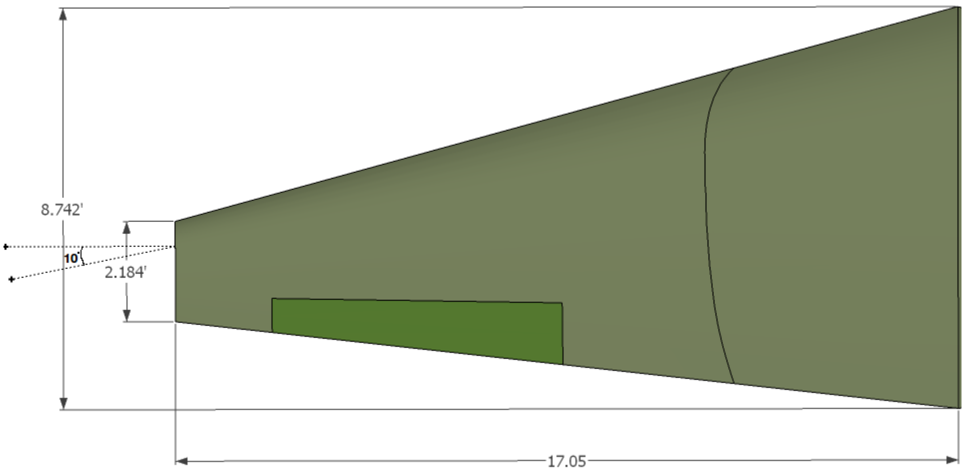


Figure 6: Wing Geometry

azimuth as it operates in forward flight. The fixed wing circulation also has an effect on the rotor. This will aggravate difficulties experienced with the rotor trim, if the wing is placed too far fore or aft of the rotor because of the pitching moment about the centre of gravity which is usually located near the axis of the rotor.

A.6.1 Variable Incidence Wing

As the forward velocity of the compound helicopter increases, the rotor thrust required reduces, due to the increasing lifting capability of a wing , provided the fuselage pitch angle is kept constant. This increasing effectiveness of the wing is such that the ratio of wing-lift to rotor thrust will vary considerably between the forward and return legs of the rescue mission, where forward speeds are different. A wing of variable incidence has the advantage of enabling lift to be controlled by means other than altering the fuselage attitude, which can be discomforting for crew and passengers. The advantages of a variable incidence wing are as follows:

1. It provides the ability to optimize the wing lift ratio, and the flight study of Kaman UH-2 compound helicopter [12] indicates the same.
2. If sufficient freedom is given to enable the wing to be turned perpendicular to the rotor disc, as with Boeing's B-347 lift compound demonstrator, then the wing download can be reduced to negligible proportions.
3. If the actuation mechanism is sufficiently quick, the wing incidence can be used to enhance the maneuverability by increasing wing loading during maneuvers.

With respect to the rescue mission, the first two points hold importance as we would require a optimum wing lift to rotor lift ratio and more importantly desire to reduce the download during

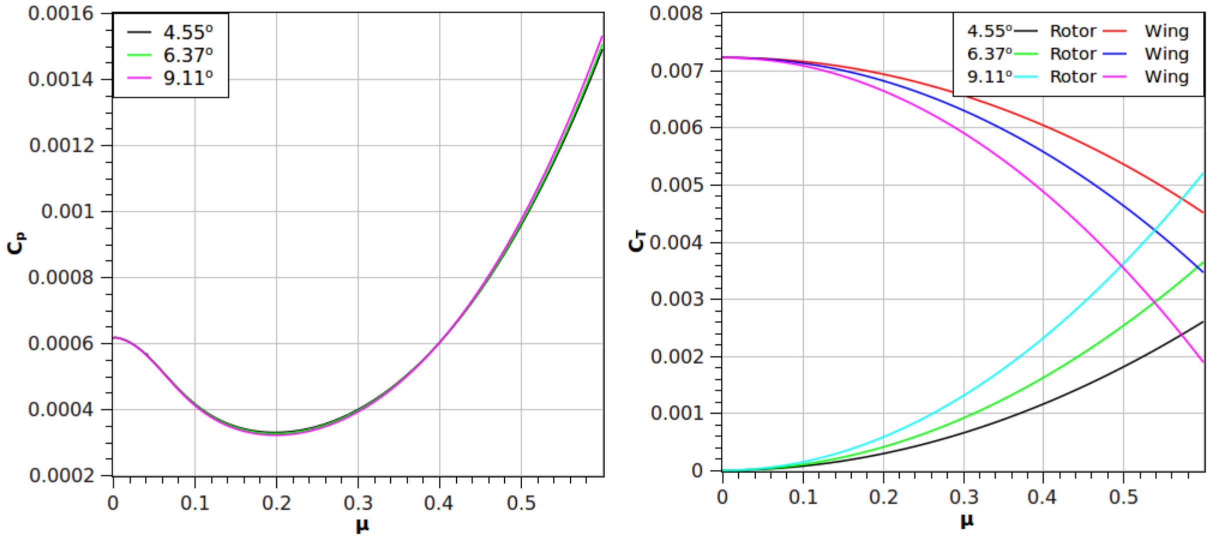


Figure 7: Effect of wing incidence angle on coefficients of power and thrust

hover. Disadvantages of providing variable wing incidence include:

1. Structural complexity of the design, adding to the weight of the aircraft.
2. Inability to build in components such as undercarriage and fuel storage into the wing.

It must be noted that in the Kaman YUH-2 compound helicopter configuration [5], in order to install the wing, the structural tie-in within the fuselage necessitated removal of the aft fuel cells, which normally had a capacity of 176 gallons. Although some fuel capacity was recovered using the fuel tanks in the wings, the total internal fuel capacity were less than that during testing with the auxiliary turbojet only.

A trade study of the effect of wing incidence angle was performed. Its results are shown in Fig. 7. The Cp plot shows that the wing incidence angle has negligible effect on the power consumption of the vehicle. This can be attributed to the fact that the induced power of the rotor is not as significant as the power due to fuselage drag and rotor parasite drag. The Ct plot shows us that at high forward speeds, the wing decreases the loading of the rotor (The wing lift is nondimensionalised with respect to the rotor area, density and square of the tipspeed). A higher incidence angle takes equal lift as the rotor at a smaller advance ratio. This is advantageous since a higher coefficient of thrust requires a higher blade pitch angle increasing chances of retreating blade stall. When the wing is taking most of the weight, the rotor can reach higher forward speeds. Hence, Fig. 7 shows that it is best to operate the wing at a high angle of attack, without a significant power penalty, and with a delayed retreating blade stall.

A.6.2 Flaps

A trade off which allows the wing lift to be controlled to a greater degree is the use of flaps which allows controlled the wing lift to a greater degree while not impairing the structural simplicity. The

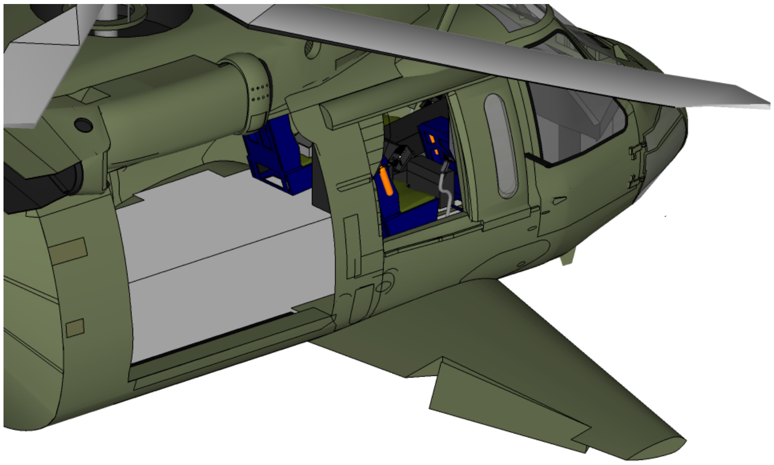


Figure 8: Wing flaps deflected downward to decrease download during hover

experimental work in [13], for example, found that a plain flap of 25% of the wing chord length and with a deflection less than 90^o, to a void flow separation, could reduce the download of a wing by the order of 30%. A similar flap system is employed in our vehicle and is shown in Fig. 8. The swirl in the rotor wake also affects the ability of the flap to reduce the download of the wing, defections of differing degrees being necessary on each side of the wing, as the blade passage is from a different direction on either side of the aircraft.

A.6.3 Spoilers

The addition of supplementary lift to the compound helicopter poses problems when attempting to enter autorotation after engine failure. The difficulty arises due to the lift of the wing, which supports the aircraft after the removal of the engine power, and as such lowers the aircraft sink rate, hence lowering the flow up through the rotor, which is necessary to drive it in autorotation. By this means the lift of the wing is destroyed, increasing the loading of the rotor, and also enhances the aircraft's deceleration capability. A further benefit can be gained though the use of wing spoilers in the reduction of hover download: a reduction of about 20% is possible with a centrally located spoiler at 90^o to the wing surface, the sensitivity to location being low [14]. Previous experiences with compound helicopters have indicated that the autorotative capabilities are not enhanced substantially with spoilers hence they have not been incorporated into our design.

A.6.4 Wing and Planform Geometry

The aircraft velocity, wing section, wing surface area, aspect ratio and the interference effects from the rotor all influence the lift available from the wing. Once the design velocity range is determined, the designers have commonly determined the wing surface area either to provide a certain level of manoeuvrability at a speed [15] or to unload a proportion of the rotor thrust at a set velocity [16].

For hover download considerations a minimum wing area is desirable, but too small a wing and the ${C_L}^2$ or induced drag term can predominate. There are, of course, other influencing factors such as the wing plan form and aspect ratio, which alter the efficiency of this lifting device. With the compound helicopter, the detrimental effect that an excessive aspect ratio will have is due to the protrusion of the wing tip into the high-velocity rotor wake at the outer edge of the rotor disc in hovering flight. As a result of this influence a majority of past compound helicopter designs have utilized a compromised wing aspect ratio of around 6 to create a balance between low induced drag in cruising flight and hover download minimization, an example being the Sikorsky NH-3A (S-61F).

Sweep has been used to a moderate degree on a majority of the past compound aircraft, mainly as a means of correctly positioning the wing aerodynamic centre. It does, however, induce a span wise flow, which can cause tip stall and also reduces the lift coefficient of the whole wing system. The final geometry has been shown in Fig.6.

A.6.5 Airfoil Section

The general thought on the choice of airfoil section for compound helicopters has been to use a section of fairly large thickness, with low drag in cruising flight, a high maximum lift coefficient and gentle stall [15, 16]. The use of camber would promote a high maximum lift coefficient, along with a thick section, which is advocated for its low download characteristics in hover [17]. This is due to the larger radii of curvature, as viewed from above, which should delay the separation of the flow around the wing in hovering flight.

A.6.6 Wing Location

There are practical factors that will affect the choice of wing location other than the interference effects that occur between a rotor and a wing when placed in close proximity. A main consideration will be to place the wing carry-through structure such that it does not restrict the cabin space and allows easy access to the cabin. Another point of regard for the designer in choosing the wing location is ensuring adequate rotor-wing separation to allow for rotor flapping clearance, particularly during manoeuvres and start-up/shut-down, where blade sailing may occur. Similarly, ground clearance must be provided so that the flaps are free from ground impact and the likelihood of debris damage is minimized. The experimental and theoretical consensus on the effect of vertical location is that the interference becomes less with increasing separation for forward flight [16, 18, 19, 20].

In hover, increasing vertical separation between the wing and the rotor has been shown to be beneficial in reducing download, which conveniently complements the requirements for reducing the rotor-wing interference in forward flight. [21, 22] No significant research has been conducted into the effect of altering the fore and aft position of the wing in relation to the rotor on the compound helicopter. The main reason for this is that trim considerations dictate that the wing's aerodynamic centre should be placed slightly behind the rotor hub to give the aircraft good longitudinal stability characteristics, particularly to avoid nose pitch-up in autorotation.

A.7 Tail Rotor

The tail rotor design is usually based on extensive testing and very little theoretical work. In general the main rotor tip speed is same as the tail rotor tip speed. The tail rotor has been shown in Fig. 9.

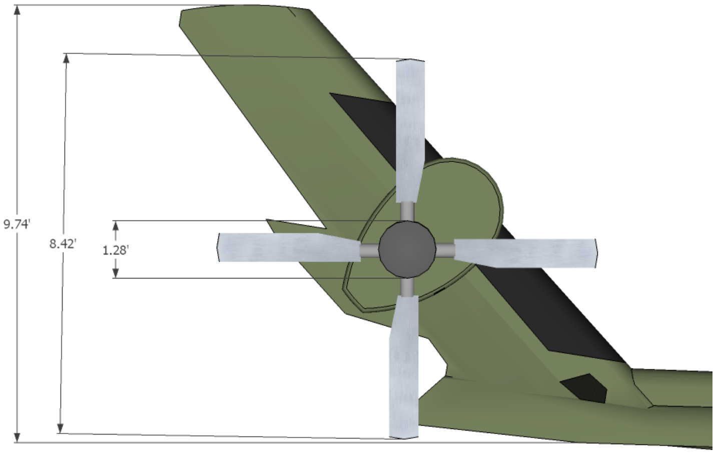


Figure 9: Tail Rotor and Vertical Fin

A.7.1 Location and Type

Test results indicate that a pusher type is more effective than a puller. It has less interference with the vertical fin. However, the puller or tractor configuration is also used, such as in the Sikorsky UH-60. Here the tail rotor shaft was tilted to have some advantage of the upward component of thrust. With a pusher assembly, the shaft would have had to be very long for sufficient clearance. So, due to weight and compactness considerations, the tractor was used.

To prevent interference of the main rotor with the tail rotor, it is usually located as far away as possible. The height of the tail rotor is kept high because the rotor wake is pushed downward and backward during forward flight. Hence in our configuration, the tail rotor hub and main rotor hub are both at the same level. The horizontal displacement has been kept as one and a half times the main rotor radius from its hub. Having a large tail arm reduces thrust requirement of the tail and its power but the penalty due to increased structural weight of a longer tail boom overrides it.

A.7.2 Direction of Rotation

The direction of rotor has a significant effect on the performance of the tail rotor. The wake of the main rotor influences the aerodynamic environment of the tail rotor. Various helicopter projects have indicated that the bottom-forward motion (when the tail rotor blade is closest to the main rotor it should move up) is best [23]. This provides steadiness in sideward flight. Another benefit with this direction of rotation is reduction in noise. Westland have reported that noise in forward flight is lower as the top blade does not slice through the main rotor wake violently [9].

A.7.3 Diameter

- Large Diameter: low power, good directional control, high stability
- Small Diameter: lower weight, lower hub drag

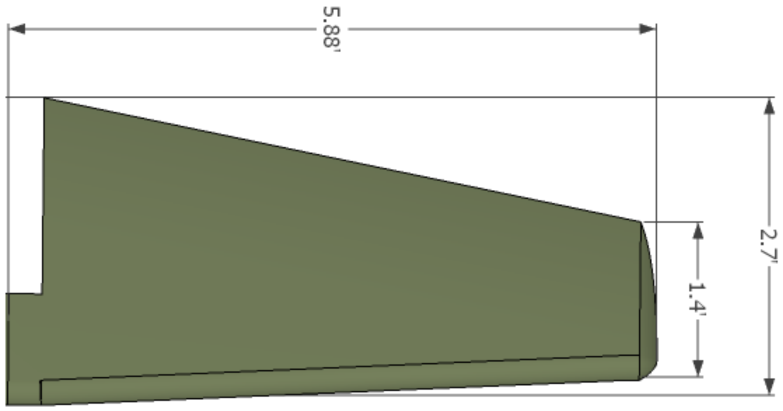


Figure 10: Horizontal Stabilizer

Existing helicopters :

$$\frac{D_t}{D_m} = \frac{1}{7.15 - 0.27DL_m}$$

Where DL_m is the disk loading of main rotor = 7.7184 lb/ft2 Hence radius of the tail is 4.21 ft.

A.7.4 Cant

This is the angle of tilt of tail rotor plane with respect to the vertical plane. It helps to put efficient use of tail rotor power since a component of tail rotor thrust is used to support the weight of the vehicle. Also, one can trim an aft center of gravity position (which is important for our reconfiguration change in center of gravity). But there is a disadvantage due to the coupling of longitudinal motion with yaw control and increases the necessity of an AFCS. As explained earlier, the ability to 'cant' decided the tractor tail rotor for the UH-60A.

A.7.5 Horizontal Stabilizer

The stabilizer used for our vehicle has been shown in Fig. 10. The horizontal stabilizer provides significant improvement in flying qualities during forward flight. It creates good static and dynamic longitudinal stability characteristics with the helicopter. But there are often erratic longitudinal trim shifts when transitioning from hover to forward flight due to the main rotor wake interacting with stabilizer. To avoid this, one can have the stabilizer move forward, so it is under the wake even during hover. Another way is to use adjustable incidence 'stabilator', that can be aligned with the local flow in a pre-programmed manner. For example, the AH-64 stabilator incidence is programmed as a funciton of airspeed, collective pitch and pitch rate. The horizontal stabilizer played an important role in the Kaman YUH-2 compound helicopter. For the initial tests with the additional wing and turbojet engine, the stabilizer was fixed at a 3 degree nose up angle. In the next phase, it was modifed to to allow the pilot change it during flight from 12 degrees trailing edge up to 16 degrees trailing edge down. Now the helicopter was able to operate at various trim angles. The wing/rotor lift sharing ratio was in the control of the pilot. At high speeds the Kaman YUH-2, was sharing its weight equally between the rotor and the wing. This configuration enabled more maneuvrability to the aircraft and it reached a maximum speed of 225 mph. [5] Therefore the variable incidence stabilator is being used in our vehicle.

A.8 Augmented Propulsion

The factors involved in selecting an efficient auxiliary propulsion system for the compound helicopter are:

1. Cost, with both the initial purchase price and the operating costs, in terms of fuel costs and maintenance, to be considered.
2. In an effort to maintain a good payload fraction and to have a high productivity, the weight of both the propulsion system itself and the required fuel must be kept to a minimum.

A.8.1 Turbojet

The advantages of using turbojet in a compound helicopter for thrust augmentation are:

- Ease of installation to minimise interference, both on the wing and the rotor.
- Due to its relative light weight, the turbojet can compensate for its high fuel consumption on shorter-range missions, as the aircraft should have a lower empty weight.
- It causes lower wake blockage in hover than when using other propulsion devices.

The turbojet has been utilized as a separate supplementary propulsion device for many of the experimental compound helicopters, simply because it expedited their development. Therefore are many factors that weigh against its use in a production aircraft. They are:

- The efficiency of turbojet is particularly poor at the relatively low speed likely to be obtained by compound helicopters.
- Fuel represents a high proportion of the direct operating costs, which will be important for any civil deployment of the compound helicopter, and will also influence the payload-range capability of the aircraft.
- The high-momentum airflow of the turbojet also produces difficulties in limiting the noise of the aircraft to levels acceptable for civil use in built-up areas, and may cause problems in acoustic detection for military versions.
- Another major disadvantage of the pure jet is the expense incurred by the addition of separate propulsive engines to the aircraft, although the lack of the transmission necessary for the other systems will offset this drawback to a certain extent.

A.8.2 Turbofan

The turbofan offers improvements in both performance attributes and noise characteristics.

- In comparison to the turbojet, the turbofan is weightier and its increased bulk increases the likelihood of negative interference with the rotor and wings.

- It was, however, mainly for improvements in the fuel consumption over the turbojet and the resultant gross weight reductions enabling it to be used for long high-speed missions that led to the selection of a turbofan by Bell [24] in their design study for the Rotor Systems Research Aircraft.

The major disadvantage of the turbofan, as with the turbojet, is that it represents an additional propulsion system on the aircraft, increasing costs, and it will also result in a power redundancy on the aircraft as the power from the turbofan cannot be used during hovering flight.

A.8.3 Propeller

Because of the moderate cruising speed of the compound helicopter in relation to fixed-wing aircraft, the propeller offers an efficient method of providing forward propulsion.

- As the propeller gives a small velocity increment to a large amount of air, its efficiency has the potential of being far superior to either turbo jet or turbofan.
- While not being of insignificant weight, the efficiency of the propeller nevertheless offers improved acceleration and extended range for a set fuel load, particularly if a majority of the flight time is to be spent in cruising flight.
- The use of the propeller in the 'windmill' state has four important advantages for the compound helicopter.
    1. The first is that by using reverse pitch it acts as an extremely effective braking device to slow the aircraft or hold the speed steady in a dive, as was found with the Lockheed AH-56A Cheyenne [25].
    2. This application of reverse pitch allows the elimination of the 'hop' that occurs when attempting to slow the conventional helicopter quickly.
    3. Not only does the propeller in the 'windmill' state enable the aircraft to be braked to a safe autorotation speed after power failure but it potentially can also feed in 'negative'power into the transmission system.
    4. If it were connected to the rotor, as with the Cheyenne [26], torque can be fed into the rotor from the propeller so that the rate of rotor speed decay is safe, even at high speed, eliminating much of the pilot workload in this critical condition.

Some of the issues in installing propeller as the mechanism for providing auxiliary thrust are :

1. Placing a propeller in close proximity to the rotor can affect the rotor flapping and bending moments when the blades pass through the propeller pressure fields [20].
2. Care has to be taken regarding the bending moments that the rotor wake induces on the propeller blades, which is not a significant factor with other devices, such as the ducted fan, since these are generally shielded from the direct influence of the rotor wake.
3. Apart from the safety of ground personnel, which is likely to be a problem for a transport, the exposed propeller also poses problems in terms of noise for civil uses. A design study [27] found that if the internal cabin noise and external sound footprint was to be maintained at acceptable civil levels, then the weight penalty of the sound-proofing and low propeller rotation necessary would detract significantly from the benefits of the efficiency of the propeller.

4. A final, yet possibly significant, problem with the use of propellers for a military compound helicopter is their radar reflectivity, which being in the vertical plane may make the compound helicopter even less receptive to the adaptation of stealth technology than the conventional helicopter.

The interactions between the rotor wake and propeller present an unknown factor, although effects similar to the tail rotor-main rotor wake blade vortex interaction effect must be expected, but only for certain portions of the flight envelope. The past propeller-driven compound helicopter programmes have not reported any severely adverse problems with rotor interference.
In terms of location, the favoured choice has been a tail mounted pusher, an example being the Lockheed Cheyenne maximizing the rotor-propeller clearance, although the Rotodyne notably used wing mounted propellers. Experiments [20] showed this latter configuration to have less bending stresses imposed on the propellers, but with the tail-mounted pusher the rotor interference effects were diminished.
The study [27] noted that if higher noise limits were accepted, then the use of the propeller could significantly lower the direct operating costs. However, it was also stated that public acceptance was unlikely for an aircraft designed outside the constraints of an external maximum of 95 PNdB at 150m and an internal speech interference level of 75 dB PSIL.

A.8.4 Ducted Fan

The ducted fan is in a way a compromise between the propeller and the turbofan, attempting to maintain the efficiency of a propeller while using less disc area, through the effect of the duct formed by the shroud.The difficulties with this device lie with:

- The shroud incurs a weight penalty for the aircraft and particularly if it is wing mounted, it may induce significant blockage effects in hovering flight and has interference with the wing and rotor in cruising flight.
- In the case of the configuration favoured by Piasecki with a tail-mounted ducted fan, it was necessary for the detected airflow to have a sufficient moment arm, and the weight and position of this device created trimming problems for the aircraft.

Based on all the above arguments, the propulsion is being augmented with a propeller which is shown in Fig. 11. For the given mission profile, and taking into account the nature of various missions and reconfigurations, the propeller complied with most of the mission requirements and provided a lighter, less noisy and a reliable source of auxiliary thrust for a sustained flight. The arguments favouring the inclusion of propeller are:

1. Ease of Installation and removal during reconfiguration, as augmented thrust wouldn't be required in Insertion and Resupply missions.
2. It has greater fuel efficiency as compared to turbofan and turbojet engines, which is critical in missions involving high power requirements.
3. It reduces mechanical complexity and separation losses as compared to the fan-in-fin ducted fan concept. When auxiliary thrust is not required in Insertion and Resupply missions, ducted fan concept poses problems in reconfiguring the helicopter.

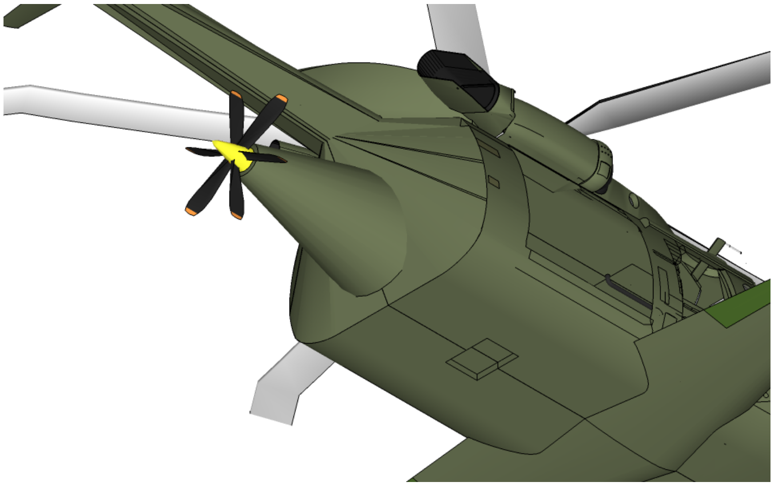


Figure 11: Augmented Propeller Thrust unit

A.9 Transmission

One of the main difficulties for the compound helicopter concerns providing power effectively to both the rotor and the auxiliary propulsion and also varying the power transmission ratio between them. The various transmission mechanisms are installing separate engines, using a mechanical or pneumatic drive system, variable-cycle engines and the use of electric drives.

A.9.1 Mechanical

The mechanical drive has the benefit of being a proven and mature technology, and as such can be used with confidence in an otherwise advanced configuration. Its drawback is that to ensure an adequate fatigue life it generally results in a system of significant weight, which is a critical issue for the compound helicopter design, since it must already overcome the payload penalties of the wing structure and download. Since the rotor will be unloaded in forward flight to a major extent, the fatigue loading will be less severe [49] than a conventional helicopter so that some savings in transmission weight can therefore be made.

A.9.2 Variable Cycle

In an attempt to avoid power redundancy and reduce the weight penalty of the transmission, one technique promoted has been the variable-cycle engine. This type of gas turbine engine is modified from the standard turbo shaft so that it can be controlled to provide both shaft power and thrust, or two different shaft power outputs where the power can be continuously varied.

There are three main types of variable-cycle engine that have been investigated. These either allow the variation in power distribution through the use of separate free turbines for each of the power outputs and variable controlling nozzles/vanes, or a common power turbine connected to the rotor and a variable pitch fan, or simply a variable-area final nozzle.

1. In the first type of variable-cycle engine [28], the use of separate free turbines for driving the two propulsion systems has the advantage of allowing the rotor and propeller speeds to be

easily and independently controlled. The difficulty with this cycle is that even with careful nozzle design and sealing, the efficiency of the system will be somewhat down on that of a fixed geometry system at its design point.

2. Seery promoted the use of a single power shaft connected to a variable pitch fan, the fan pitch determining how much shaft power is available for the rotor shaft. This has the benefit of leaving the engine core essentially unchanged, apart from optimizing the geometry, and minimizes the mechanical complexity.
3. The third variable-cycle system, with a variable nozzle area, is the mechanically least complex. By simply reducing the nozzle area a backpressure is formed, which transfers energy from the shaft to jet thrust, as a result full expansion is no longer possible through the turbine. Having a nozzle of variable area allows the thrust to shaft power to be simply and continuously varied, which is of significant advantage [29]. The main disadvantage is that the jet contains the same inefficiency as the turbojet since it produces high momentum jet flow.

A.10 Rotor Characteristics

A.10.1 Disk Loading

The usual range of disk loadings is between 0.0145psi - 0.0725psi. For this vehicle the loading is 0.0536 psi. A low value of disk loading implies low induced velocity for hover, low induced power in hover and low autorotation descent velocity. High disk loading helps the vehicle to have compact size, reduced weight and drag of rotor system and hub. The Vertol Model 76 and Ling-Temco-Vought XC-142 were vehicles with high disk loadings and their operation was only satisfactory grass lawns and asphalt. Over gravel and sand, the rotor wake created such a disturbance that pilot visibility was impaired and nearby equipment also tumbled. The autorotation rate of descent is extremely dependent on the disk loading. For multi engine helicopters, a rate of descent of 3500ft/min is nearly the maximum allowable limit.

A.10.2 Solidity

For Hover Figure of Merit, the solidity must be as as low as possible For Maximum forward speed, retreating blade stall is prevented by having a high solidity. However, rotor weight and profile increase with the blade chord. Selecting the smallest blade area helps maintain adequate stall margin. General range of solidities is between 0.05 and 0.08. The lowest is 0.03 (for the Robinson R22) while the highest is 0.138 . As can be seen in Fig. 2, the lowest solidity plotted corresponds to the general trend of conventional helicopters. Hence the rotor radii of those helicopters is also much higher.

A.10.3 Download

The interference of the rotor wake with the fuselage and wings increases the amount of thrust required, because of the download it produces. This drag is given by:

$$D = C_D q S \tag{7}$$

Here S is the projected area of the affected components. Usually this $C_D = 0.3$. We can write equivalently:

$$\frac{D_V}{GW} = 0.3\frac{Projected\ Area}{Disk\ Area} \tag{8}$$

and

$$T = \left(1 + \frac{D_V}{GW}\right) GW \tag{9}$$

For our helicopter, the download ratio $\frac{D_V}{GW}$ is 0.062

A.11 Powerplant

A.11.1 Engine Overview

The selected engine has Full Authority Digital Electrical Control (FADEC) for better cockpit information and reduced pilot workload, plus advanced, commercially-proven components for added durability. Its modular design combines with superior erosion/corrosion resistance features to help ensure easy maintenance and lower life cycle costs.

- Compressor Stages: 6
- Low-Pressure Turbine/High-Pressure Turbine Stages: 2/2
- Max Diameter (Inches): 26
- Length (Inches): 48.8
- Dry Weight (Lb.): 542
- Specific Fuel Consumption at Takeoff Rating: 0.452

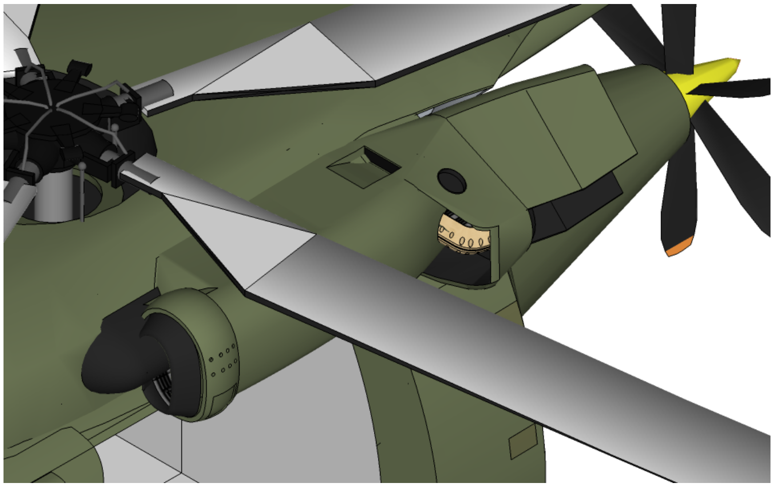


Figure 12: Installed Engine

CT7-8A	
Maximum Continous Power	2043 hp at 21945 RPM
Take off power (5 min)	2520 hp at 21945 RPM
30 minute AEO	2336 hp at 21945 RPM
Continous OEI	2498 hp at 21945 RPM
2 minute OEI	2520 hp at 20900 RPM
30 second OEI	2740 hp at 20900 RPM

Table 5: Engine Ratings at Sea Level

Two engines are installed in a side by side arrangement. The engine can be seen in Fig. 12. The installation is important for C.G. location and for efficient power train transmission. Helicopters are equipped with an overrunning clutch between transmission and engine so that the rotor does not have to drive a "dead" engine during autorotation. The power ratings of the engine are given in Table A.11.1. Here OEI = One Engine Inoperative and AEO = All Engines Operating.

A.11.2 Cowling

The cowling for the engine needs to be:

1. Aerodynamically clean
2. Easily removable for maintenance
3. Ventilated to prevent accumulation of gases
4. Accessible for fire extinguishing

A.11.3 Mounting

1. Withstand loads from engine torque, thrust and gyroscopic couple + ground flight and inertial loads
2. Withstand Crash load conditions
3. Must allow accurate alignment with Main Gear Box

A Three Point Mount is used with a Vibration Isolator between mounting and helicopter.

A.11.4 Firewalls

The firewall is a fireproof compartment for the engines. The standard firewall must be able to withstand a $2000^o F$ Flame for 15 minutes. For this steel or titanium of a thickness of 0.4mm is be used and it is removable with fireproof seals

A.11.5 Air intake

The intake must provide good airflow at compresser inlet at all operating conditions and altitudes. The minimum pressure loss that can be expected is between 0.5% - 1.0%. A pressure loss of 1% causes 1.5%-2.0% of power loss. The distortion limits must also be acceptable for the engine. This can be calculated using:

$$\omega r = \frac{\frac{r}{R}\nu_i}{\sqrt{\frac{C_t}{2}}}\left[1 - \sqrt{1 - \frac{2C_t}{\left(\frac{r}{R}\right)^2} + \frac{\sigma C_d}{4\frac{\nu_i}{\Omega R}}}\right] \tag{10}$$

which gives the maximum rotational velocity at engine inlet as 70ft/s. An air intake entry lip which has NACA-1 series profile or an elliptical shape is used for this vehicle.

A.11.6 Air Intake Protection

This consists of a mesh to prevent foreign objects entry. Two systems can be used:

1. Inertial Separator: It has a 60-85% efficiency for seperation of bigger and heavier particles
2. Vortex Tube: It is a cylindrical tube with helical swirl vanes. The scavenged air must be pumped out overboard by fan or by an engine bleed air ejector. It has nearly 60-85% efficiency for small particles.

A.11.7 Exhaust

This duct lets out waste gases safely from the helicopter. It is built for maximum diffusion and minimum pressure loss. It can also be used as an ejector to draw ambient air into engine bay for ventilation.

A.11.8 Engine Bay Ventilation

There is an engine manufacturer specified surrounding air temperature limit. The ventilation circulates cooling air between engine and the surrounding structure. The exhaust ejector provides secondary airflow of the order of 6%-7% .

A.11.9 Fire Extinguishing Systems

These sytems need to have low toxicity. Bromotrifluoromethane (CF_3Br) is a known effective agent. The vehicle needs to have a two shot fire extinguishing system: Two bottles and a distribution system. The quantity of extinguisher depends on the empty space in the engine zone and rate of airflow in the compartment.

A.11.10 Fuel System

This consists of:

1. Tanks
2. Refueling/Defueling Features
3. Fuel Feed and Vent lines

4. Fuel pumps, valves
5. Fuel gauging and draining provisions

Some common specifications used for these are MIL-F-38363, MIL-F-8615, MIL-T-5578, MIL-T-6396, MIL-T-27422.

For Crash worthiness, MIL-STD-1290 is followed. The Fuel tank and Fuel system component bays need to be adequately sealed from cabin and properly drained. For maximum reliability the operation of fuel feed system should be independent of the helicopter's electrical, hydraulic and pneumatic system. The feed system must deliver under all design conditions, at pressures specified by the engine model. A suction fuel feed system should be used in place of pressurised system for safety and reliability.

A.11.11 Fuel Tanks

Main Fuel Tanks have bladder type cells interconnected to form a tank of specific capacity. Some Crashworthy Tanks are based on:

1. MIL-T-27422 Type 1 : Self Sealing
2. MIL-T-27422 Type 2 : Non Self Sealing

They are provided with internal/external expansion space of at least 2% of tank capacity. Gravity filler openings are used to prevent overflow. Each tank must have drain plugs to drain out water contaminant.

A.11.12 Fuel Tank Vents

Each tank must be vented to atmosphere. Pressure detrimental to tank/structure is then not felt during climb, descent, or when maximum fuel rate is drawn. The vents are designed to cater for high amount of air discharge during pressure fueling. There is redundancy required. Vent valves are also built in to avoid fuel spillage if helicopter overturns.

A.11.13 Fuel Feed System

The standard followed is MIL-F-38363 for the feed system. General uninterrupted fuel supply must be available without continuous attention of crew. It shoul have normal performance at all altitudes upto service ceiling. There is an independent fuel supply to each engine. The main tanks also have to be interconnected. Each engine has its own independent supply tank. These supply tanks are provided with prime pumps to prime fuel lines before engine start up. Fuel Filters are required as per MIL-F-38363. In a suction fuel feed system, fuel filters are part of engine after LP pump of engine.

A.11.14 Gauging

Fuel Probes are employed along with a Computing and Indicating System. The probes are of capacitance type. Care must be taken so that on crash, they must not puncture tank. The standard followed is the MIL-G-26988. Each supply tank must have its own device independent of the Fuel Gauging System. The Low Fuel warning is set to allow engine to operate for 30 minutes at cruise power.

A.12 Autorotation

The upper limit speed is set by when centrifugal forces in blades and hub reach structural design limit. The lower limit speed is set when each blade element is operating at near stall angle of attack. For a vertical descent, the rule of thumb dictates that the hover induced velocity is half the rate of descent during autorotation. From momentum theory considerations,

$$\lambda_{i,hover} = \sqrt{\frac{C_T}{2}} \tag{11}$$

This gives us an induced velocity of 43.3ft/s which corresponds to a very high rate of descent of 5194 ft/min. From energy considerations as given in [9], we obtain:

$$R/D = \frac{30DL}{\rho V_{be}} + \frac{30\rho V^3 f}{GW} + \frac{33000hp_o}{GW}, ft/min \tag{12}$$

Assuming best range velocity as around 76 knots, we obtain an autorotative descent rate of 2273 ft/min which is well under the limits for multi engined helicopter. These calculations are valid only for the wingless configuration of the helicopter. As explained earlier, the presence of a wing reduces the energy stored in the rotor for autorotation and is detrimental. However, at forward speeds it is generating some lift for the vehicle and helps it to glide.

B Weight Estimates

The following weight estimation is based from [9]. This gives us an upper limit of the weights of the vehicle components because it is based on old helicopters' data with very sparing use of composites. Our final designed vehicle is expected to be built with a major proportion of composites and hence be much lighter.

B.1 Main Rotor Blades

$$W_{b_M} = 0.026N^{0.66}cR^{1.3}(\Omega R)^{0.67} = 603lbs \tag{13}$$

B.2 Main Rotor Hub and Hinge

The polar moment of inertia is taken to be around 4200 slug ft^2

$$W_{b_M h} = 0.0037N^{0.28}R^{1.5}(\Omega R)^{0.43}\left(0.67W_{b_M} + \frac{gJ}{R^2}\right)^{0.54} = 317lbs \tag{14}$$

B.3 Horizontal Stabilizer

$$W_H = 0.72A_H^{1.2}(AR_H)^{0.32} = 60lbs \tag{15}$$

B.4 Fin

$$W_V = 1.05A_V^{0.94}(AR_V)^{0.53}(no.\ of\ tail\ rotor\ gearboxes)^{0.71} = 88lbs \tag{16}$$

B.5 Tail Rotor

$$W_T = 1.4R_T^{0.09}\left(\frac{Transmission\ hp\ rating}{\Omega_M}\right)^{0.9} = 127lbs \tag{17}$$

B.6 Body

$$W_F = 6.9\left(\frac{GW}{1000}\right)^{0.49} L_F^{0.61} S_{wet_F}^{0.25} = 1072lbs \tag{18}$$

B.7 Landing Gear

$$W_{LG} = 1.1 \cdot 40\left(\frac{GW}{1000}\right)^{0.67}(no.\ of\ wheel\ legs)^{0.54} = 398lbs \tag{19}$$

B.8 Nacelles

$$W_N = 0.041(Total\ Engine\ Weight)^{1.1}(no.\ of\ engines)^{0.24} + 0.33S_{wet_N}^{1.3} = 296lbs \tag{20}$$

B.9 Engine Installation

$$W_{eng} = (Installed\ Engine\ Weight)(no.\ of\ engines) = 1084lbs \tag{21}$$

B.10 Propulsion Subsystems

$$W_{Pss} = 2(W_{eng})^{0.59}(no.\ of\ engines)^{0.2} = 142lbs \tag{22}$$

B.11 Fuel system

375 gallons capacity

$$W_{Fs} = 0.43(capacity\ in\ gallons)^{0.77}(no.\ of\ tanks)^{0.59} = 62lbs \tag{23}$$

B.12 Drive System

$$\begin{aligned} W_{DS} = 13.6(transmission\ hp\ rating)^{0.82}\left(\frac{rpm_{eng}}{1000}\right)^{0.037} \\ \times\left[\left(\frac{tailrotor\ hp\ rating}{transmission\ hp\ rating}\right)\left(\frac{\Omega_M}{\Omega_T}\right)\right]^{0.068}\frac{(no.\ of\ gearboxes)^{0.066}}{\Omega_M^{0.64}} = 1288lbs \end{aligned} \tag{24}$$

B.13 Cockpit controls

$$W_{cc} = 11.5\left(\frac{GW}{1000}\right)^{0.4} = 30lbs \tag{25}$$

B.14 Auxillary Power Plant

$$W_{APP} = 150lbs \tag{26}$$

B.15 Instruments

$$W_i = 3.5\left(\frac{GW}{1000}\right)^{1.3} = 79lbs \tag{27}$$

B.16 Hydraulics

$$W_{hyd} = 37N^{0.63}c^{1.3}\left(\frac{\Omega R_M}{1000}\right)^{2.1} = 98lbs \tag{28}$$

B.17 Electrical

$$W_{EL} = \frac{9.6(transmission\ hp\ rating)^{0.65}}{\left(\frac{GW}{1000}\right)^{0.4}} - W_{hyd} = 720lbs \tag{29}$$

B.18 Avionics

$$W_{av} = 50lbs \tag{30}$$

B.19 Furnishings and Equipment

$$W_{fe} = 6\left(\frac{GW}{1000}\right)^{1.3} = 136lbs \tag{31}$$

B.20 Air Conditioning and anti-ice

$$W_{ac,ai} = 8\left(\frac{GW}{1000}\right) = 88lbs \tag{32}$$

B.21 Manufacturing Variation

$$W_M = 4\left(\frac{GW}{1000}\right) = 44lbs \tag{33}$$

B.22 Wing

$$W_{wing} = 2.5S_{wing\ exposed} = 484lbs \tag{34}$$

B.23 Gross Weight

The empty weight of the vehicle is nearly 6930lbs. With the additonal weight of the wing, it goes upto 7416lbs. The vehicle has a fuel capacity of 375 gallons or nearly 2500lbs of fuel. For the search and rescue mission, the additional wing will have built in fuel tanks to increase the capacity to 3000lbs.

B.24 Costs

From [38], the relative price of the helicopter is calculated to be \$5.1million. By factoring in the advanced research and development of technologies, we expect the cost per unit to be \$6 million. Direct Operating Costs are \$350/hour/ton.

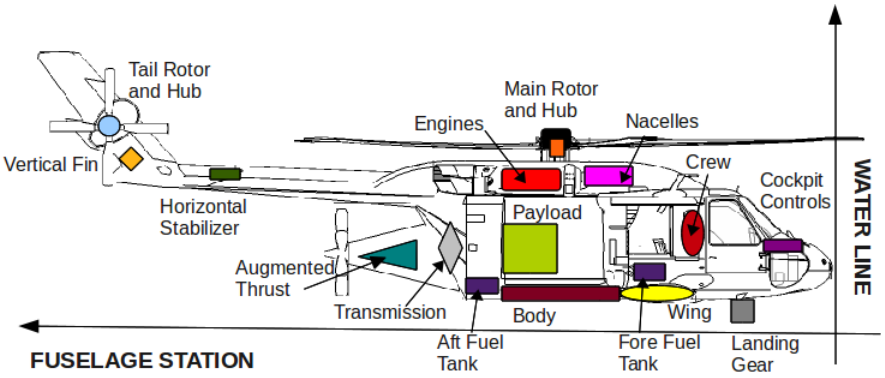


Figure 13: Model to calculate position of center of gravity

B.25 Center of Gravity Position

The vehicle in its thre different configurations is likely to have different positions of its center of gravity. The location has been calculated with simplified techniques according to [9]. Figure 13 shows the location of various components to estimate the net center of gravity of the vehicle. The fuselage nose is taken as a reference for calculating the horizontal location.

The horizontal location of the center of gravity are calculated for the different missions using the moment arms obtained from Table 6 and the results are shown in Table 7. The advantage of having two main fuel tanks, aft and fore of the main rotor, is that with suitable discretion of the pilot and AFCS, the center of gravity can be kept confined to remain within a small space during the complete mission flight. This will improve handling qualities and reduce pilot workload.

C Performance

To justify the use of both wings and augmented the propulsion, the power curves in Fig. 14 are not extended upto the same advance speeds because those high forward speeds are not possible with the helicopter in equilibrium or in trimmed condition without the presence of augmented thrust or a wing.

C.1 Variation with Altitude

For ease of calculations at different altitudes, Fig. 15 shows the variation of different critical parameters. By solving for sea level conditions, the resultant variables can multiplied or divided by the density ratio factors for obtaining the values at that particular altitude. The engine performance has been plotted in Fig. 16 which varies with altitude. The International Standard Atmosphere conditions are assumed for this plot. The power required by the helicopter (in the compunded configuration) at different forward speeds has been plotted in Fig. 17. The curves indicate that the hover power is more at higher altitudes but fast forward speed power is less. This is because the major component of power at high forward speeds is the parasite drag. At lower densities this drag decreases. At low speeds, power is dominated by the induced power of the rotor. At lower densities, the coeffecient of thrust is higher to lift the same weight. This change is seen in the power

Group	Weight (lbs)	Fuselage Station (ft)	Moment (lb ft)
Main Rotor and Hub	920	20	18400
Tail Rotor and Hub	127	52	6604
Body	2445	19	46455
Engines	1226	21.5	26359
Horizontal Stabilizer	60	42.9	2574
Vertical Fin	88	51	4488
Wing	484	12.9	6243.6
Augmented Propulsion	100	30.3	3030
Transmission	1280	27	34560
Aft Fuel Tank	1250	25	31250
Fore Fuel Tank	1250	12.9	16125
Nacelles	296	15	4440
Crew	730	7	5110
Cockpit Controls	30	3	90
Landing Gear	398	10	3980
Payload (Rescue)	1400	24	33600
Payload (Resupply)	3000	24	72000
Payload (Insertion)	4000	24	96000

Table 6: Horizontal weight moment arm estimation

Mission	Fuselage Station (ft)
Search and Rescue	19.69
Resupply	20.42
Insertion (Outbound)	20.68
Insertion (Inbound)	19.35

Table 7: Horizontal location of center of gravity

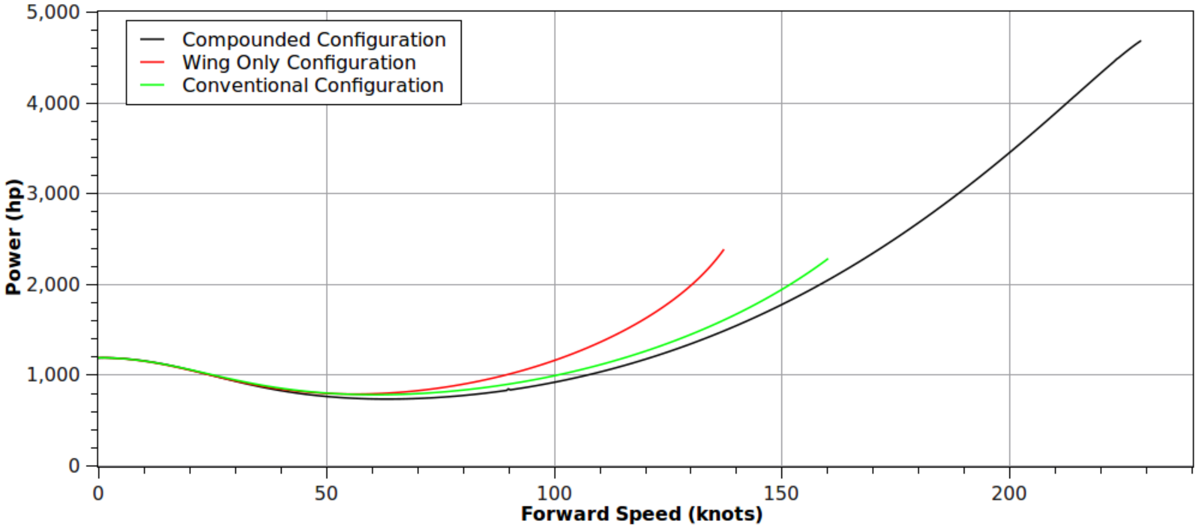


Figure 14: Power comparison of different configurations with forward speeds

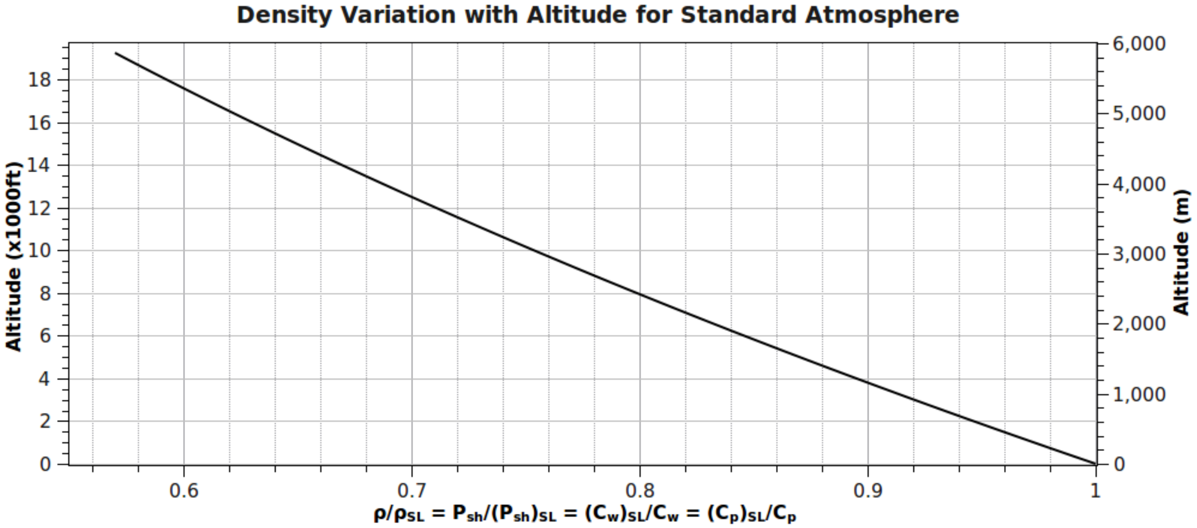


Figure 15: Density variation with altitude

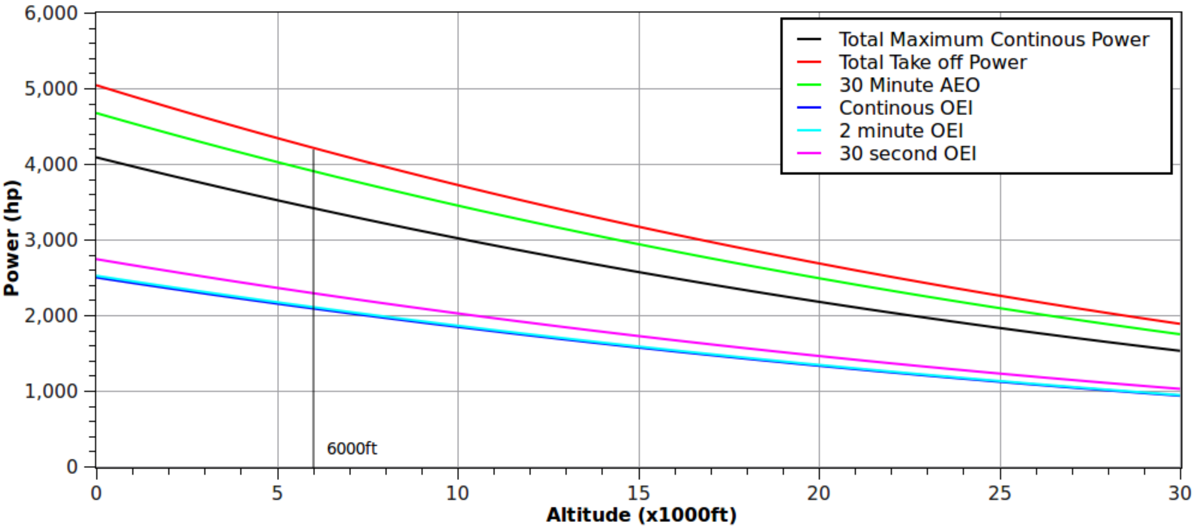


Figure 16: Variation of available engine power or performance with altitude

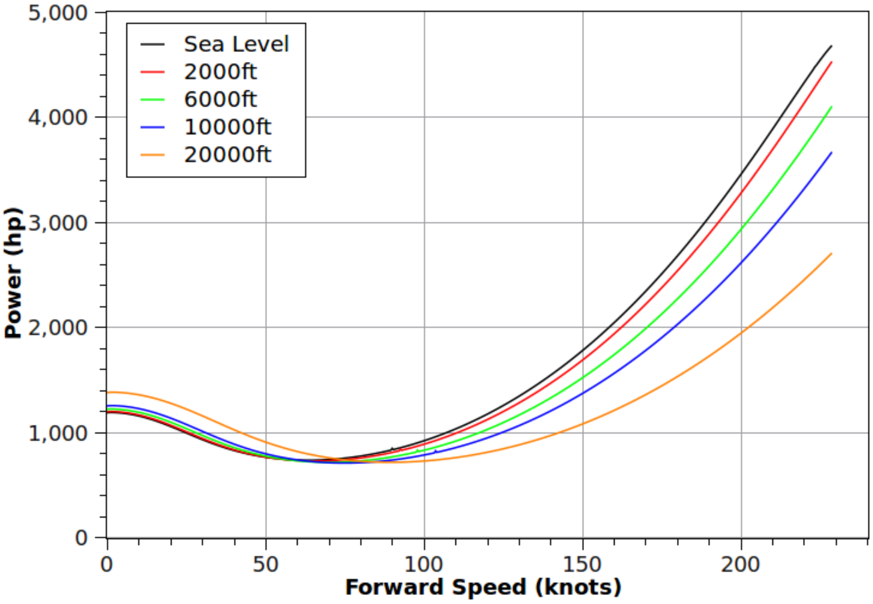


Figure 17: Variation of power with forward speed at different altitudes for compounded configuration

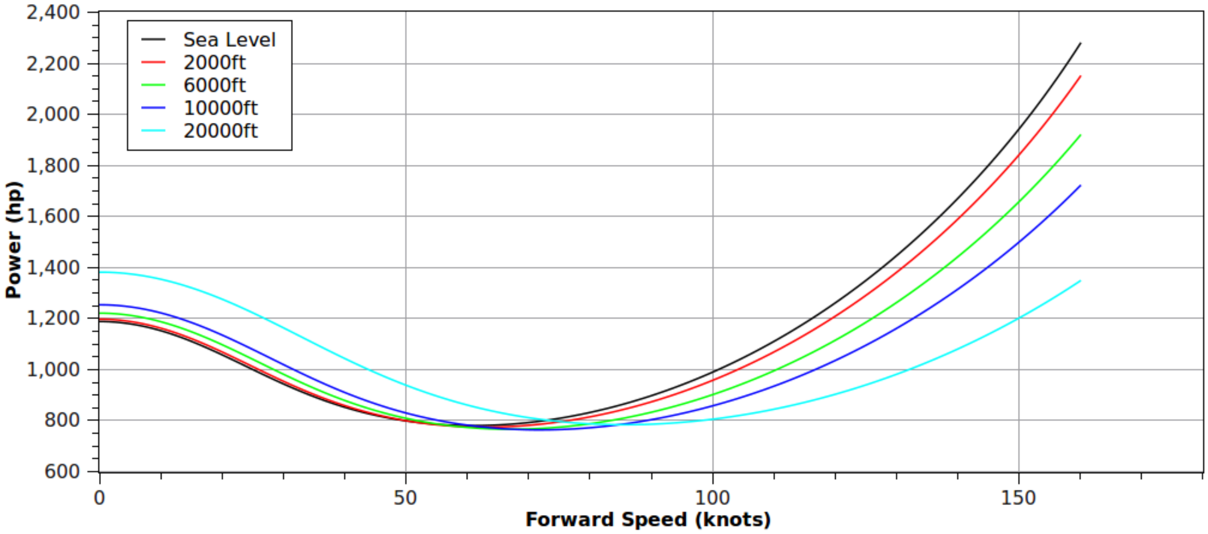


Figure 18: Variation of power with forward speed at different altitudes for insertion and resupply configuration

required by the helicopter. The same trend is also observed for the uncompounded configuration and is plotted in Fig. 18. For a representative altitude of 15000ft, and with total weight depending on mission condition, the following curves in Figs. 19,20, and 21 were plotted to estimate the power required in forward flight.

Based on the above plots, the power was estimated at different altitudes and for different flying conditions and finally the power usage was calculated and is shown in the Tables **??**.

C.2 Angle of Attack Distribution

It is necessary to estimate the angle of attack distribution of the rotor in forward flight to know whether the retreating blade is under stall and to know the area of rotor under reverse flow. For this, the maximum advance ratio of 0.6 when the rescue mission is on its inbound journey, was used and the trim angles for the coning and rotor input gave the angle of attack in Fig. 22. We can notice in this figure that the circular cutout in the center of the disk corresponds to the offset. The larger circular cutout with the center of the circle well within the retreating side is the area with reverse flow. The boundaries of this reverse flow region are stalling which has been represented by 15^o. For a succesful rescue, the minimum speed required for the 'Golden hour' window is 193 knots. The angle of attack for this region is also plotted in Fig. 22

D Limitations

D.1 Reverse Flow Region

The reverse flow region is shaped as a circle whose one point is located at the axis of rotation and the diametrically opposite point on the radial station in the retreating side, where the local speed is zero. At low forward speeds this region is small, and within the blade offset but at high forward

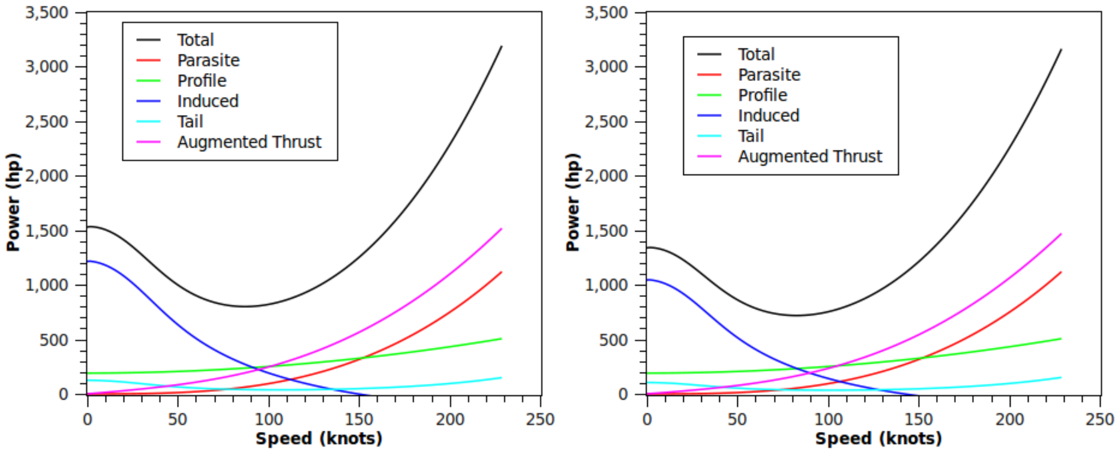


Figure 19: Power required in Search and Rescue Mission during outbound (W = 12,484lbs) and inbound journey (W = 11,284lbs)

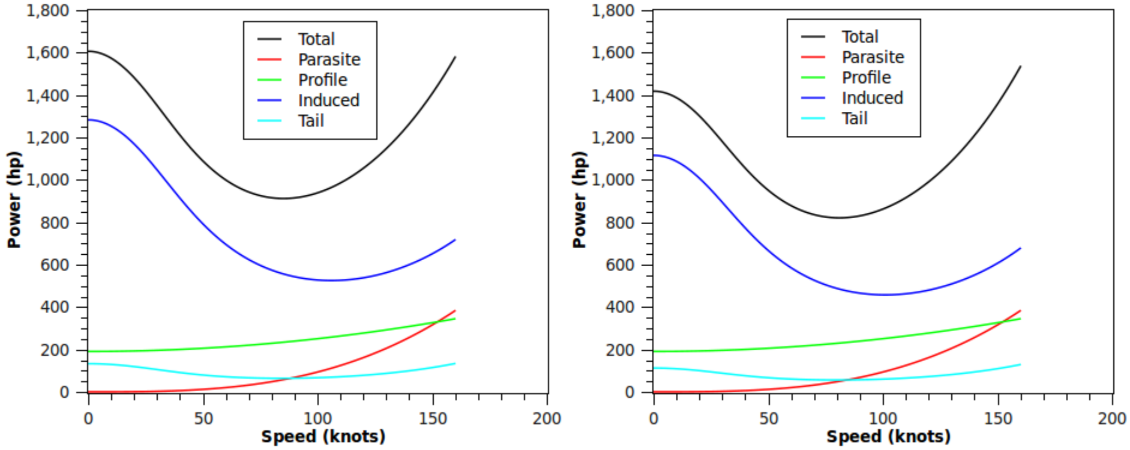


Figure 20: Power required in Resupply Mission during outbound journey (W = 12,900lbs) and inbound journey (W = 11,750lbs)

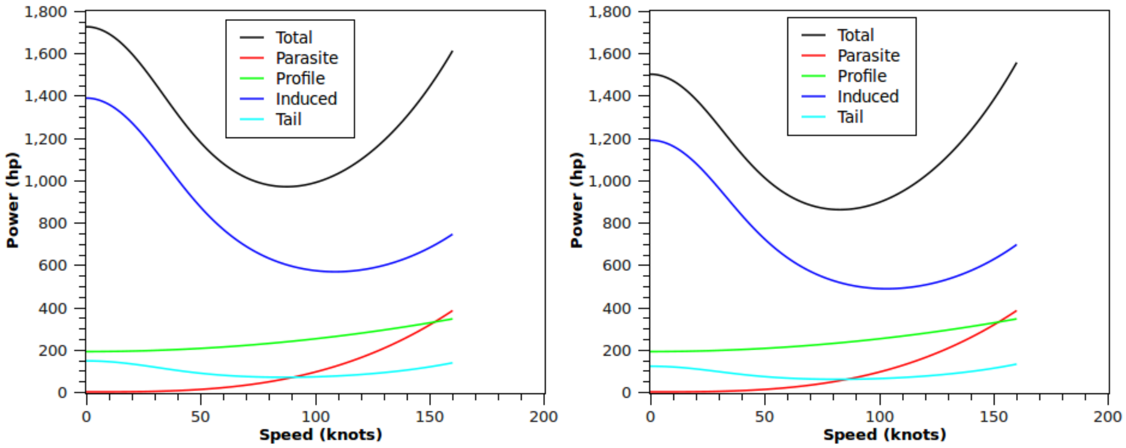


Figure 21: Power required in Insertion Mission during outbound journey (W = 13,600lbs) and inbound journey (W = 12,266lbs)

Title	Time	Power
Startup/Warmup	5 minutes	4200hp
6K95 HOGE	1 minute	1200hp
Climb	5 minutes	3000hp
Outbound	1.829hrs = 1hr 50min	830hp
Loiter	30 minutes	730hp
Descent	5 minutes	500hp
6K95 HOGE	5 minute	1200hp
Climb	5 minutes	3000hp
Inbound	1 hour	3000hp
Descent	5 minutes	500hp
6K95 HOGE	1 minute	1200hp
Landing/Cooling/Shutdown	5 minutes	1500hp

Table 8: Search and Rescue Mission Power Consumption

Title	Time	Power
Startup/Warmup	5 minutes	4200hp
6K95 HOGE	1 minute	1200hp
Climb	10 minutes	2000hp
Outbound	2.27hr = 2hr 16min	850hp
Descent	10 minutes	500hp
6K95 HOGE	5 minute	1200hp
6K95 Landing	1 minute	1500hp
Unload/Load (Hot)	10 minutes	500hp
6K95 HOGE	1 minute	1200hp
Inbound	2hr 16min	850hp
Descent	10 minutes	500hp
6K95 HOGE	1 minute	1200hp
Landing/Cooling/Shutdown	5minutes	1500hp

Table 9: Resupply Mission Power Consumption

Title	Time	Power
Startup/Warmup	5 minutes	4200hp
6K95 HOGE	1 minute	1300hp
Climb	10 minutes	2100hp
Outbound	2.4hr = 2hr 24min	950hp
Descent	10 minutes	500hp
6K95 HOGE	5 minute	1200hp
6K95 Landing	1 minute	1500hp
Unload/Load (Hot)	20 minutes	500hp
6K95 HOGE	1 minute	1100hp
Inbound	2.3hr = 2hr 18min	860hp
Descent	10 minutes	400hp
6K95 HOGE	1 minute	1100hp
Landing/Cooling/Shutdown	5minutes	1500hp

Table 10: Insertion Mission Power Consumption

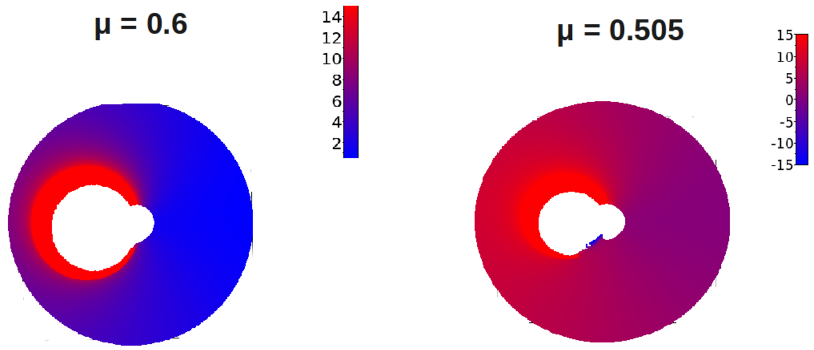


Figure 22: Angle of Attack Distribution on the rotor at 229knots ($\mu = 0.6$) and 193knots ($\mu = 0.505$) in Rescue Mission return flight

speeds this region extends over a sigificant proportion of the retreating side. The local angle of attack is negative with respect to the trailing edge. The negative lift contributes to a download. But most of the blade is stalled in this region because the trailing edge facing the flow is sharp and flow seperation is encountered very early. The download must be compensated with higher thrust, and more power is required for the drag. [31]

D.2 Variable Rotor Speed

For the optimum use of the rotor, it is desirable to operate as many blade elements as possible at an angle of attack with large lift to drag ratios. For rotor blade airfoils, this is in the range of 6 to 9 degrees. The blade loading coefficient (C_t/σ) gives an estimate of the average angle of attack of the disk.

Loiter capability can be compared using Specific Endurance, which is measured as the time of flight per unit weight of fuel. Similarly, the cruise capability is estimated using Specific Range which is given as the distance covered per unit weight of fuel. Maximum speed is limited by either the maximum continous power available or by the retreating blade stall. It is desirable to have high RPM during very fast forward flight. This increases the tip speed and hence decreases the advance ratio. The power consumption is dominated by the cubic variation with advance ratio. Also, the retreating blade stall can be delayed by operating at small angle of attacks. For the same thrust of the rotor in trim, the rotor RPM must increase if the blade pitch input is to decrease. So high speed forward flight demands a faster rotation rate of the blades for both power and stall constraints.

To defer compressibility effects to a higher forward speed it can be beneficial to reduce the rotor speed, which has a secondary benefit in lowering the noise generated by the rotor. While these are important advantages, they have to be balanced against an increase in vibration caused by the lowering of the blade passing frequency. The difficulty here is that vibration is a function of the rotor blade number divided by the rotor revolution speed, so a rotor speed reduction increases the excitation. In addition, any change of rotor speed will subject the structure to a wider range of excitation frequencies, making it harder for the designer to keep the structural resonant frequencies away from the rotor harmonics. These effects can be offset by an increase in the number of rotor blades or the provision of a wing to off-load the rotor. The aircraft must also be designed to accommodate the reduced rotor speed operation, as Lockheed found with the XH-51A, which experienced body hop and rotor tip path oscillations as the rotor forcing frequencies matched rational fractions of the blade in-plane bending mode when the rotor speed was lowered [32]. There is a penalty to be paid in terms of increases in transmission weight due to the increased rotor torque necessary and increased power for hover when using a lower tip speed.

D.3 Vibrations

In [44], the following methods to reduce vibrations are discussed and elaborated upon:

- Higher Harmonic Control (HHC): Originally it was intended to prevent retreating blade stall and allow the helicopter to fly faster. But experiments did not validate the predictions. However, the rotor vibrations were reduced significantly (90% in Sikorsky UH-60A). At high forward speeds, due to greater control loads, the hydraulic pumps could not keep up with the demand and hence the system was ineffective.

- Individual Blade Control (IBC): In this system, each blade pitch horn is replaced by an actuator. Although, the collective and cyclic pitch required is given by the swashplate, small changes by the actuators minimize vibrations. Unlike the HHC, this system is in a rotating frame and is more challenging to design. Experiments on the BO-105 and Sikorsky CH-53G reduced noise and decreased cruise power by 6%.

- Actively Controlled Flap: The servo flap is a small airfoil located at about 75 percent span of the rotor blade, situated on the trailing edge of each rotor blade. Moving the trailing edge of the flap upward moves the leading edge of the main rotor blade up. This increases the rotor pitch. There is some additional stability effect because the servo flap by contributing to additional rotational and flapping inertia, provides the system with angle of attack stability. In the event of an engine failure, the servo flap responds automatically to increased angle of attack caused by the change in airflow through the rotor and decreasing rotor RPM. Although the pilot still has to decrease collective to stabilize the autorotational descent, the servo flap provides the pilot additional reaction time before rotor RPM decays too low. An accompanying advantage is the ability of the system to provide for in-flight rotor blade tracking.

D.4 Noise

There are two groups of sources of noise in Helicopters [34]:

1. Machine Noise: This exists because of mechanical parts such as engine, gears, linkages and transmissions. This noise is typically controlled using balancing of rotating parts, muffling of exhaust, improving accuracy of moving and meshing components and isolation of vibration and damping.

2. Rotor Noise: This is the principal cause of Helicopter noise. The mean lift and drag forces rotate with the blades and produce pressure pulsations. Rotor noise can be classified into three divisions but their differences are not clear cut:

- Rotational
- Blade Slap
- Vortex Generated

The first two are concentrated in harmonics of blade passage frequency $N\Omega$, while the last one has a broad band spectrum of frequencies.

D.4.1 Rotational Noise

At multiples of blade passage frequency, it has discrete lines at harmonics. As the higher harmonic content increase, the blade thump becomes blade slap. Typically it is in the order of 10-20Hz, but higher blade harmonics are important subjectively. The tail rotor has a higher fundamental frequency around 40-120Hz.

D.4.2 Vortex / Broad band Noise

This is a high frequency swishing sound. The variations in amplitude and frequency from the mean of the blade passage frequency create this random sound radiated because of random pressure fluctuations on the blade. The spectrum extends from 150Hz to 1000Hz, with peaks around 300-400Hz. The main sources are: operation of blade in turbulent wake, random blade loads induced by tip vortices, vortex shedding from trailing edge, turbulence in free stream, boundary layer turbulence and seperations.

D.4.3 Blade Slap

This is a sharp cracking, popping or slapping sound, that occurs at:Descent to Landing, Shallow Descents, Decelerating steep turns, High forward speeds. This is caused due to: Blade Vortex Interactions, Thick blades operating at high Mach number, Air compressibility and Stall. It is an extremely important trade off in tandem rotor vehicles due to interaction of the rear rotor with wake from tips of the front rotor.

D.4.4 Noise Reduction Techniques

The most important parameter of rotor noise is tip speed. Vortex Noise can be reduced by lowering rotor thrust or the blade loading. Decreasing the RPM lowers the frequency range of rotor noise. Increasing number of blades decreases magnitude of rotational noise harmonics but it increases the fundamental frequency.

D.5 Control Systems

From a piloting perspective the compound helicopter raises a number of difficult issues for the designer. Current rotorcrafts require the coordination of many separate controls to fly the aircraft, which requires a high level of training to achieve. Given that many helicopter missions, such as military attack and instrument flight rules (IFR) operations, necessitate the pilot's attention to be split to accommodate other tasks as well, it is unreasonable for the designer to expect the pilot to be responsible for further major controls.

Given that a compound helicopter is likely to have additional control functions for the propeller or fan pitch and flaps, some improved form of automatic flight control system (AFCS) may be necessary to bring the control of a compound helicopter within the capabilities of the pilot. To make the aircraft more effective, a control system that reduces the demands on the pilot would be advantageous. Also, because of the aircraft's complexity and interactions, careful balancing of the lift of the wing and the rotor is necessary to realize the full performance potential of the aircraft, a balance possibly best left to an AFCS.

Several common control difficulties were experienced with past compound helicopter programmes, which require different control strategies or piloting techniques compared to the conventional helicopter to overcome them. The most sensitive portion of the compound helicopter's flight envelope appears to be during high speed manoeuvres, where there is a high chance of rotor over-speed. This has been experienced in past flight test programmes [11], as the rotor load factor increases more quickly than that of the wing. This requires significant monitoring on the part of the pilot and in order to allow attention to be otherwise utilized, either a speed and manoeuvre load limitation will have to be placed on the aircraft.

The collective feedback controller has the further advantage of eliminating the natural increase in longitudinal cyclic sensitivity that occurs due to the slower increase of the rotor damping in relation to the increase in blade dynamic pressure, a widespread finding with past flight test programmes.

Lockheed's alternative solution to this problem with their XH-51A aircraft was to shift the centre of gravity to a forward location and to reduce the stick pitch rate [11].

In contrast, the lateral rotor control sensitivity and power is reduced, partially due to the wing roll inertia added to the aircraft, and also because of the reduced lifting capability of the retreating rotor blade at high velocity. This was a common finding for the Sikorsky S-61F [8], the Lockheed XH- 51A [11] and the Kaman UH-2 compound helicopter [12] . Lockheed's solution was again to alter the stick sensitivity, this time increasing it, whereas Kaman and Bell, without the advantage of the control power of the rigid rotor, resorted to the addition of conventional ailerons to the wing. The alteration of the rigid rotor sensitivity did cause difficulties at low forward velocities, yet potentially this could be overcome with an AFCS.

Autorotation entry has not entailed any specific control problems at high-speed programmes, the most thorough investigation, using Lockheed's XH-51A, entering autorotation from a forward velocity of 232 knots [11]. It is of note that, at this velocity, the pilot response time necessary to save the aircraft only just falls within the 2 s limit required by the MIL specification. This indicates that either an external drive to the rotor such as a propeller, extremely high inertia blades, a special AFCS or a combination of all three will be necessary to produce an aircraft that can safely enter autorotation from speeds in excess of 250 knots.

Given that the vehicle has 3 different configurations with different positions of center of gravity, presence/absence of lifting wing and thrust augmentation, and changes in tail rotor cant and horizontal stabilizer, the AFCS of the final helicopter will need to have three different modes ac-

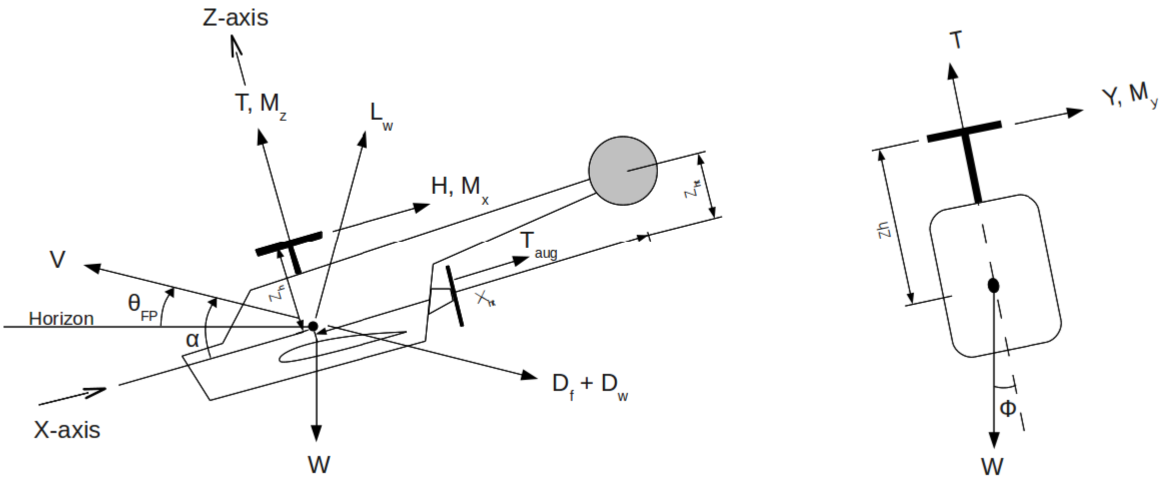


Figure 23: Free Body Diagram of Vehicle

cording to the configuration. These different modes will need to encompass the different gain values of the closed loop system which will also depend on the flight condition. This AFCS will need to incorporate more flexibility and complexity for the vehicle and hence will certainly be more costly.

E Trim Analysis

The equilibrium equations for the system (Fig. 23) are given as:

1. Inflow Equation

$$\lambda = \mu \tan\alpha + \frac{C_T}{2\sqrt{\mu^2+\lambda^2}} \tag{35}$$

2. Thrust Equation

$$T + L_w - W\cos(\alpha - \theta_{FP})\cos\phi + (D + D_w)\sin\alpha = 0 \tag{36}$$

3. Drag Equation

$$H + T_{aug} + (D + D_w)\cos\alpha - W\sin(\alpha - \theta_{FP})\cos\phi = 0 \tag{37}$$

4. Side Force Equation

$$Y + T_t - W\sin\phi = 0 \tag{38}$$

5. Roll Moment Equation

$$M_X - YZ_h - T_tZ_{ht} + TY_h = 0 \tag{39}$$

6. Pitch Moment Equation

$$M_y + HZ_h - M_w = 0 \tag{40}$$

7. Yaw Moment Equation

$$M_z - HY_h + T_t X_{ht} = 0 \tag{41}$$

The pilot input to the rotor was taken to be:

$$\theta = \theta_o + \theta_{1c}\cos\psi + \theta_{1s}\sin\psi \tag{42}$$

Here θ_o is the collective input and θ_{1c}, θ_{1s} are the cyclic longitudanal and lateral inputs respectively. The blade flap is represented only up till the first harmonic for simplification:

$$\beta = \beta_o + \beta_{1c}\cos\psi + \beta_{1s}\sin\psi \tag{43}$$

where ψ is the azimuthal location, taken counterclockwise from the x axis. The relationships between the blade flap angles, control input angles and rotor forces are derived from [37]. These were suitably non dimensionalised and solved using iterations for different advance ratios. For all these calculations, uniform inflow is assumed over the rotor disk.

At high advance ratios, we expect the blade to stall on the retreating side. Hence we need to plot the effective angle of attack at each blade section. For this we use the following equations, with the parameters obtained from the trim equations. At each blade location the perpendicular velocity is given by

$$\frac{U_p}{\Omega R} = \bar{U}_p = \lambda + \bar{r}\dot{\beta}(\psi) + \beta(\psi)\mu\cos(\psi) \tag{44}$$

The tangential velocity is:

$$\frac{U_t}{\Omega R} = \bar{U}_t = \bar{r} + \mu\sin(\psi) \tag{45}$$

Hence the net angle of attack is given by:

$$\alpha = \theta(\psi) - \tan^{-1}\left(\frac{U_p}{U_t}\right) \tag{46}$$

The helicopter trim results are plotted in the accompanying fold out page.

F Reconfiguration

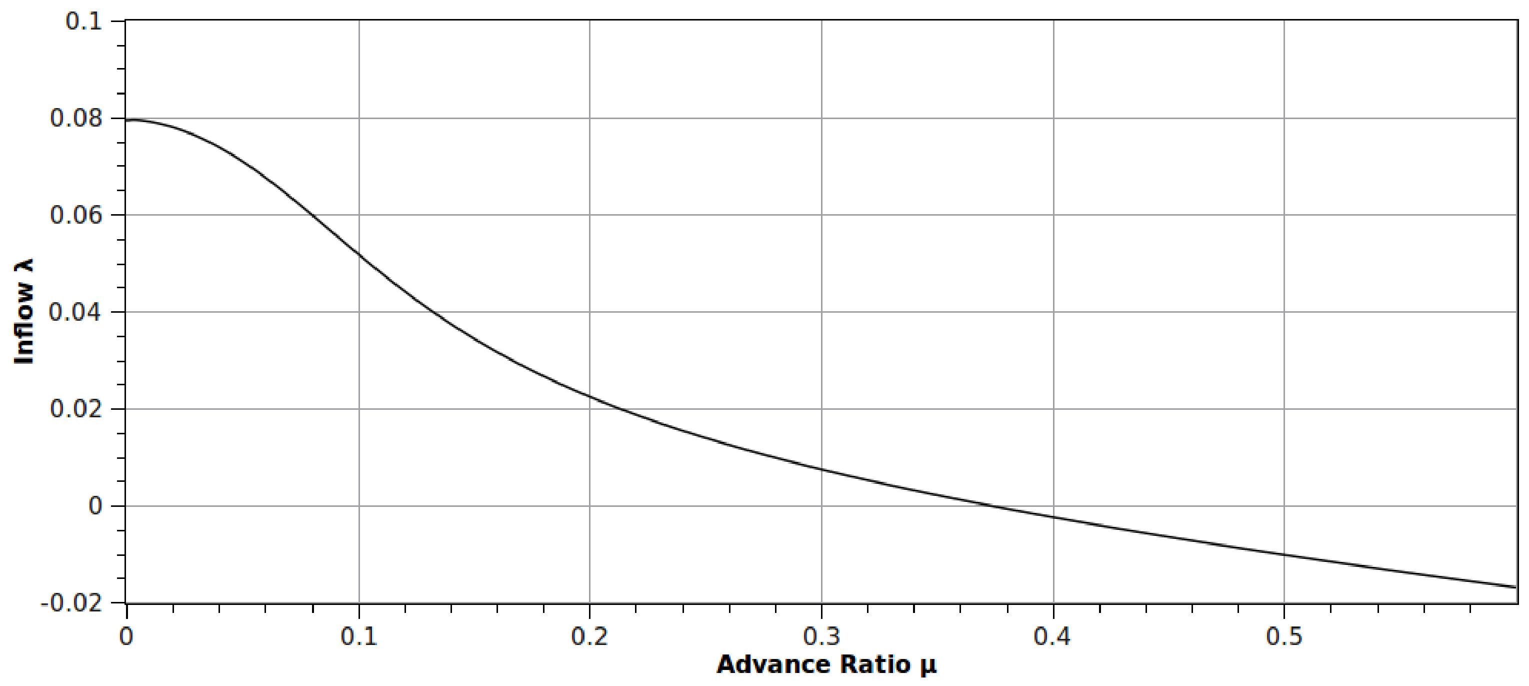
F.1 Search and Rescue

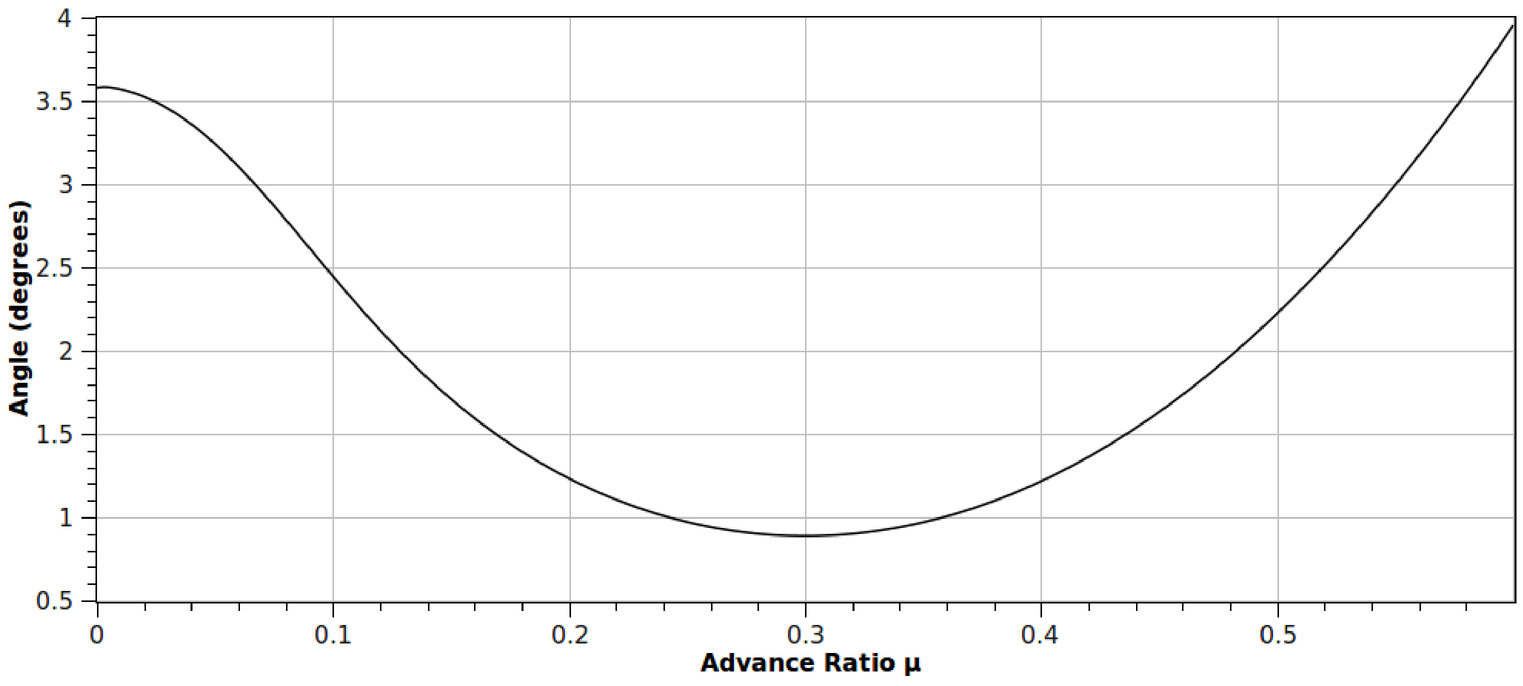
F.1.1 Air Ambulance Standards

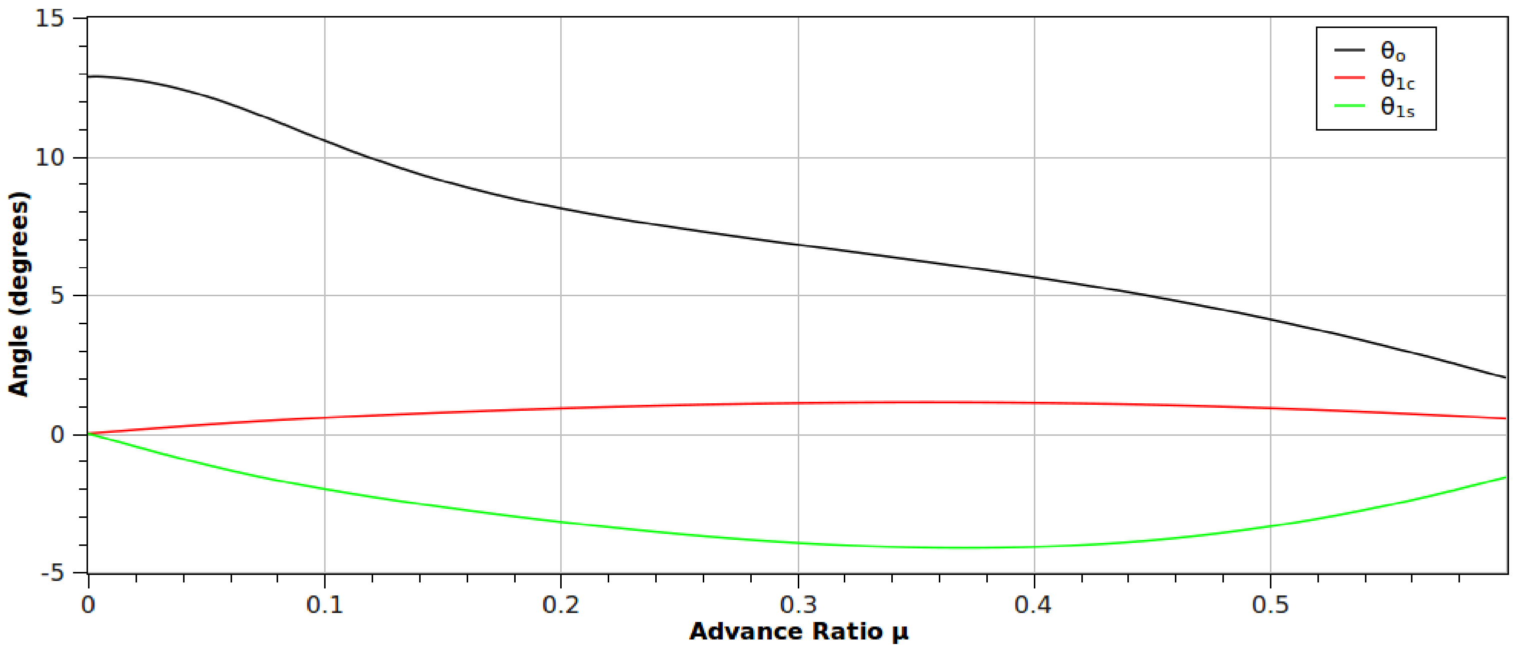
The following points from the 8th Edition Accreditation Standards of the Commission on Accreditation of Medical Transport Systems [35, 2] for air ambulances, have been addressed in this configuration. Figure 24 shows the medical equipment panel that will slide onto the tracks on the floor. Apart from this panel, a ceiling board with IV hooks and overhead grab rails will be installed during reconfiguration. A winch mechanism and a searchlight to affect the rescue will also be clamped at the relevant positions. Figure 25 depicts the final overall interior arrangement in the aircraft. Figure 26 shows the stretcher with its dimensions.

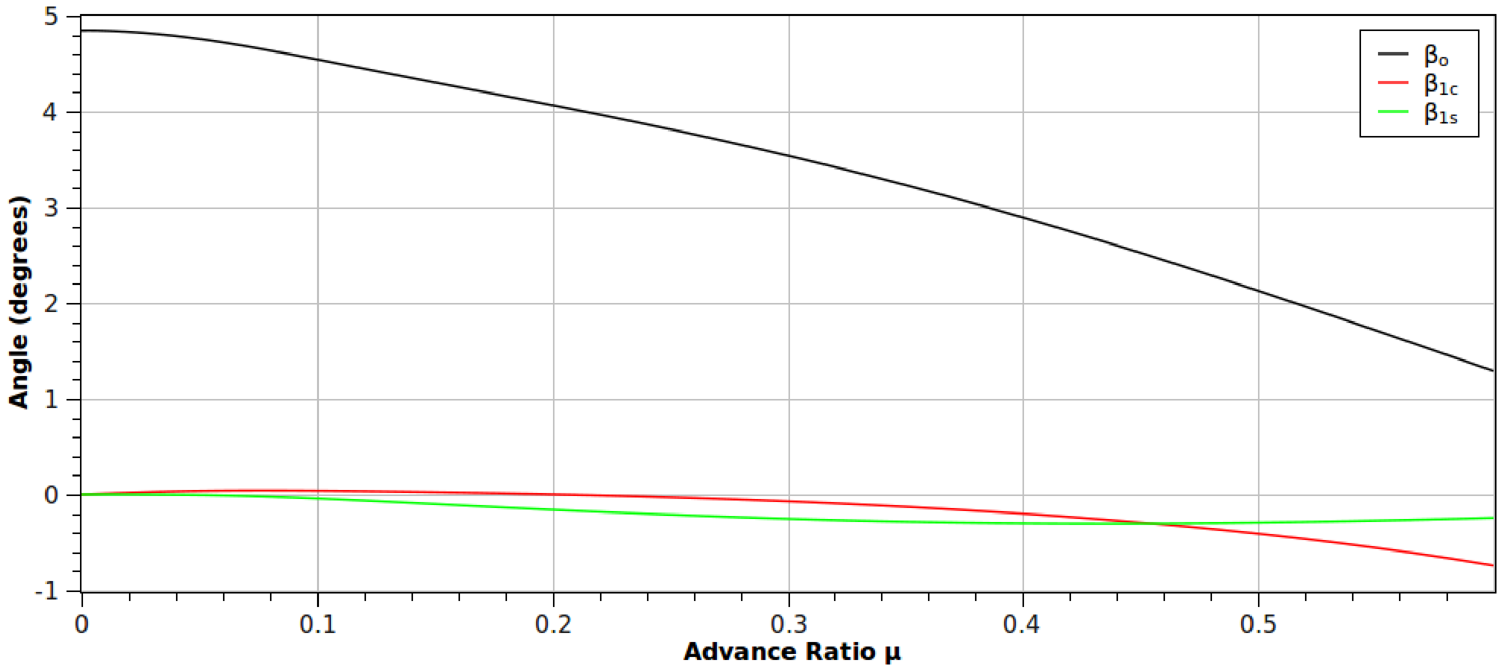
- Medical transport personnel have access to the patient in order to begin and maintain basic and advanced life support treatment.

TRIM ANALYSIS OF COMPOUND HELICOPTER FOR SEARCH AND RESCUE MISSION AT 15000FT


Inflow Ratio


Roll Angle


Collective and Cyclic Input


Coning of Blades

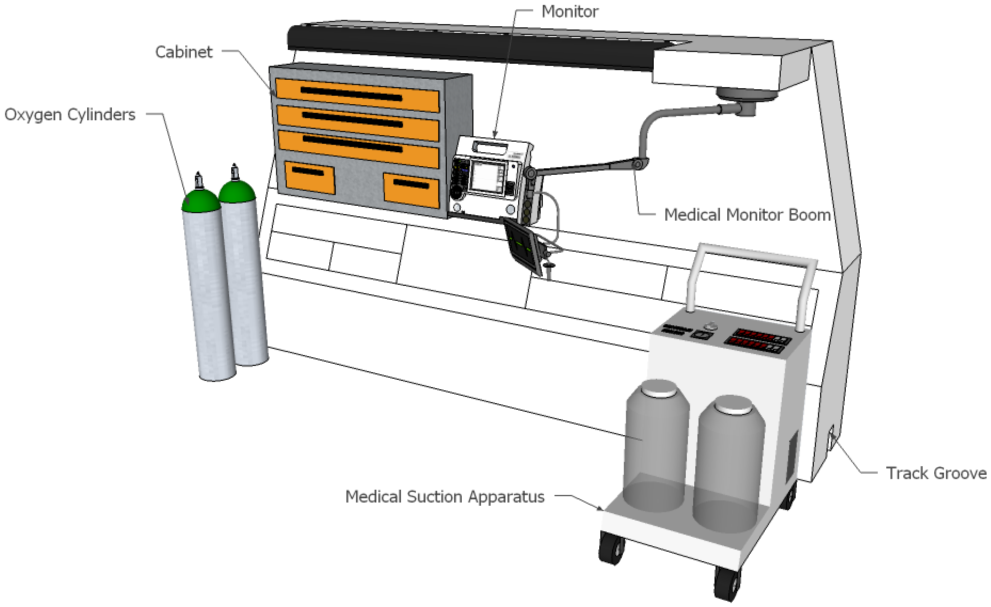


Figure 24: Medical Equipment

- Delivering Oxygen - Oxygen is installed according to national aviation and ground ambulance regulations. A variety of oxygen delivery devices consistent with the service's scope of care must be available. An appropriately secured portable oxygen tank with a delivery device must be carried on the aircraft/ambulance so that oxygen delivery is not disrupted when transferring the patient to a hospital or other receiving facility.

- Hangers/hooks are available that secure IV solutions in place or a mechanism to provide high flow fluids if needed. All IV hooks are padded, flush mounted, or so located to prevent head trauma to the medical transport personnel in the event of a hard landing in the aircraft or emergency stop/maneuver of the ambulance. A minimum of three IV infusion pumps are on the aircraft/ambulance or immediately available for critical care transports and as appropriate to the scope of care.

- Additionally, the following equipment must be on the aircraft/ambulance and available for all Critical Care or ALS Providers.Cardiac monitoring capabilities, Defibrillator,External pacemaker, Advanced airway and vntilatory support equipment: Laryngoscope and tracheal intubation supplies, including laryngoscope blades, bag-valve- mask and oxygen supplies, including PEEP valves; appropriate for ages and potential needs of patients transported

- Two suction units, one of which is portable and both of which must be required to deliver adequate suction

- The aircraft/ambulance design and configuration must not compromise patient stability in loading, unloading or in-flight operations. The aircraft/ambulance must have an entry that allows loading and unloading without excessive maneuvering (no more than 45 degrees about

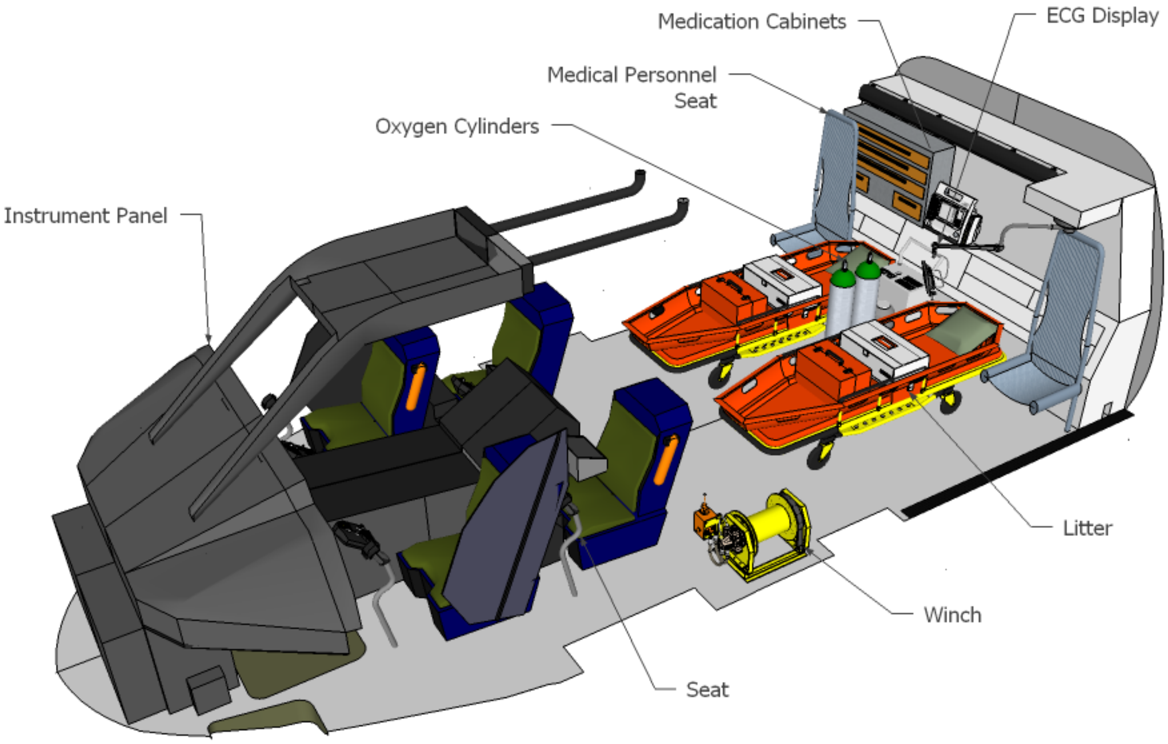


Figure 25: Interior Configuration

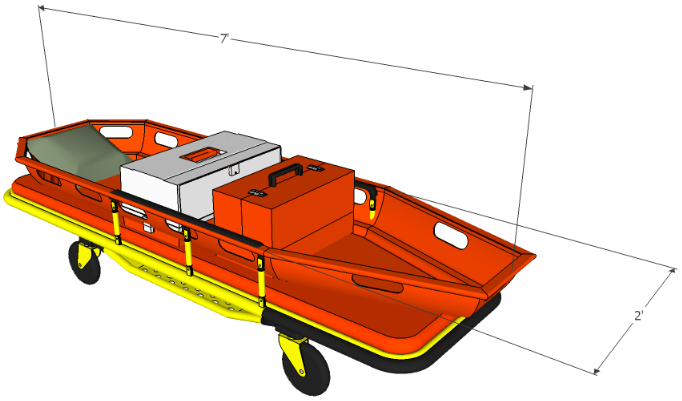


Figure 26: Litter

the lateral axis and 30 degrees about the longitudinal axis) of the patient, and does not compromise functioning of monitoring systems, intravenous lines, and manual or mechanical ventilation.

- Policy indicates the maximum gross weight allowed on the stretcher (inclusive of patient and equipment) as consistent with manufacturer's guidelines. The stretcher should be large enough to carry the 95th percentile adult patient, full length in the supine position. (Estimated 95th percentile adult American male is 6 ft. and 232 lbs.)
- If the ambulance stretcher is floor-supported by its own wheels, there is a mechanism to secure it in position under all conditions. These restraints permit quick attachment and detachment for patient transfer.
- The helicopter must be equipped with a 180 degree controllable searchlight capable of at least 400,000candle power
- The aircraft must either have a 406 MHz emergency locator transmitter (ELT) OR must be monitored at 3 minute intervals or less by a satellite tracking system. If using the satellite tracking system and the aircraft has not been upgraded to a 406 MHz ELT, a 121.5 MHz ELT should not be disarmed because it may be monitored by other aircraft.
- The aircraft must be equipped with a functioning radar altimeter.
- Air medical personnel must be in seat belts (and shoulder harnesses if installed) that are properly worn and secured for all takeoffs and landings according to national aviation regulations. Overhead grab rails must be present in the patient care area.

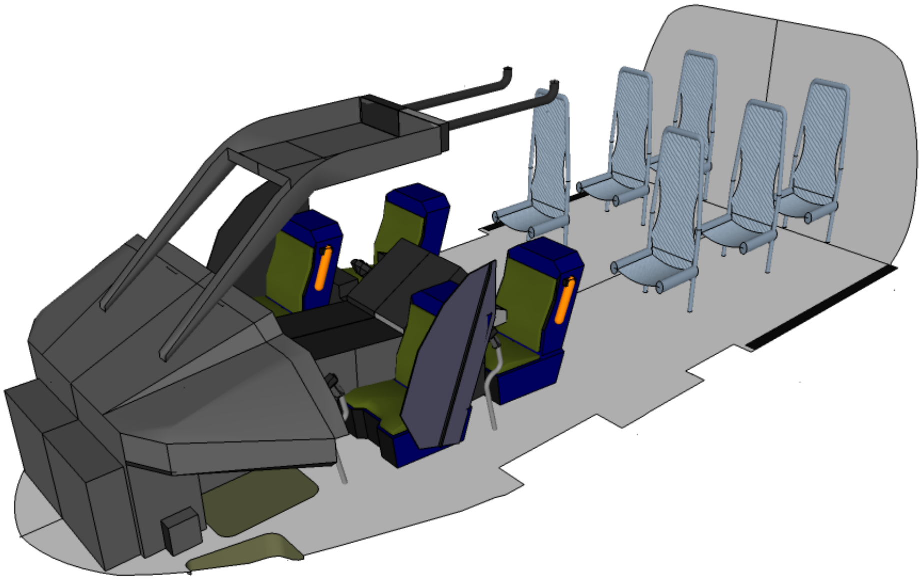


Figure 27: 6 Passenger Interior Configuration

F.2 Resupply

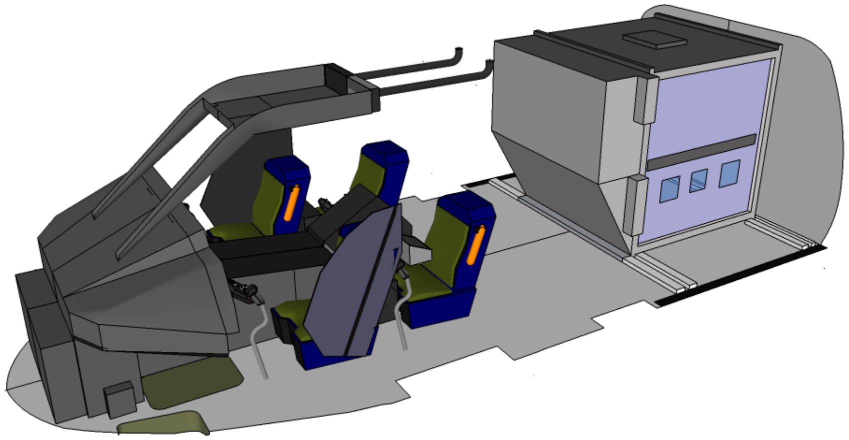


Figure 28: Cargo Configuration

F.2.1 Containers

The International Air Transport Association recommends several standardized cargo containers for use on aircraft. The Type 8 and Type 8D containers shown in Fig. 29 are suitable for the loads required for the mission. The specifications of these two types of containers are given in Table 11. They will be slightly modified by allowing for grooves in the bottom, so they easily slide into the vehicle. The clamps on the floor of the helicopter will restrain further movement. By already pre-packaging the cargo in containers, considerable time could be saved to reconfigure the aircraft.

Model	Maximum Gross Weight	Volume	Tare
Type 8D	2,700 lb	120 ft^3	132 lb
Type 8	3,500 lb	120 ft^3	132 lb

Table 11: IATA Specifications

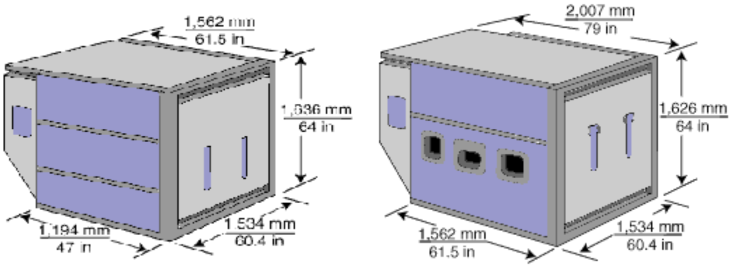


Figure 29: IATA Type 8 and Type 8D containers

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