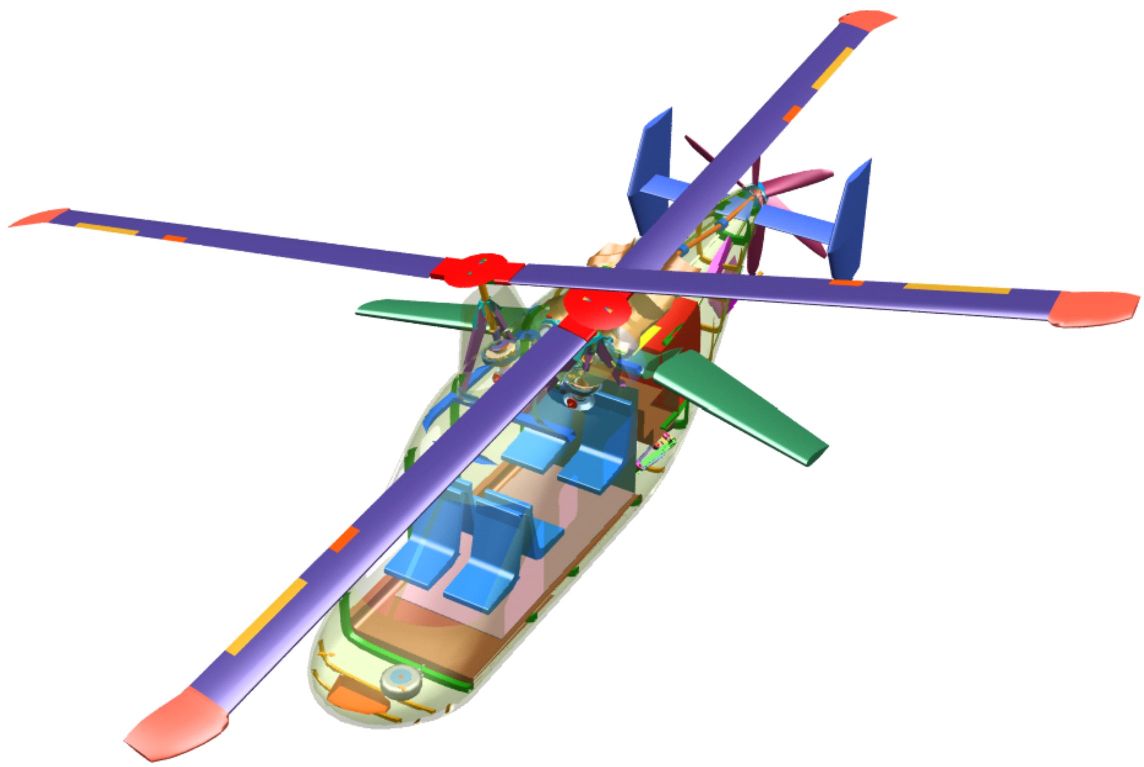
CalVert High-Speed V/STOL Personal Transport



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CalVert High-Speed V/STOL Personal Transport

In response to the 1999 Annual American Helicopter Society
Student Design Competition - Graduate Category
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Contents

List of Figures

List of Tables

Abbreviations and Symbols

Symbol	*Description*
AEO	All engines operative
AI	Autorotation Index
BERP	British Experimental Rotor Program
BVI	Blade vortex interaction
CAE	Computer aided engineering
CADAM	Computer aided design and manufacturing
DL	Disk loading
EPNL	Effective perceived noise level
FAR	Federal aviation regulations
FADEC	Full authority digital engine control
HHC	Higher harmonic control
HOGE	Hover out of ground effect
HVACAI	Heating, ventilation, air conditioning, and anti-ice
ISA	International standard atmosphere
IC	Initial Cost
IBC	Individual Blade Control
LRU	Line replaceable units
LCC	Life cycle cost
L/D	Lift to drag ratio
MEMS	Micro electro mechanical systems
MFD	Multi-function display
MCP	Maximum continuous power
MPT	Magnetic particulate trap
NE	Normalized energy
NC	Numerically controlled
NTSB	National transportation safety board
OEI	One engine inoperative
OEM	Original equipment manufacturer
RTL	Research and technology labs
RI	Rentability index
SMA	Shape memory alloys
UMARC	University of Maryland Advanced Rotor Code

Symbol	*Description*
C_{P}	constant pressure specific heat
I_Ω	polar moment of inertia
q	Power dissipated
$T_{h_{in}}$	Engine inlet temperature
$T_{h_{out}}$	Engine outlet temperature
$\frac{C_T}{\sigma}$	blade loading
V_b	Effective flight speed
W	Aircraft weight
W_c	Weight of component
$\dot{m}$	fuel mass flow rate
ΔT_d	differential driving torque
ΔT_r	differential reacting torque
Ω	rotor speed

Proposal Requirements Matrix

Design Issue	**Requirement**	**CALVERT's capability**	**Chap./Sec./Pg.**
Cruise Speed	180 kts	180 kts in 4 passenger mode 160 kts in 6 passenger mode	Sec. 6.3
Range	540 nm	548 nm in 4 passenger mode 552 nm in 6 passenger mode	Sec. 6.3 Sec. 6.3
Cost	current costs	Meets this requirement	Sec. 8.1 (Table 8.1) Sec. 8.2 (Table 8.5) Sec. 9.5 (Table 9.1)
Number of Passengers	4-6	4-6	Sec. 4.13.1
Cruise Altitude	< 10000 ft	Cruise at 4000 ft	Sec. 6.3
Regulations	FAR 27	Meets FAR 27 requirements	Throughout
Report	**Requirement**	**CALVERT REPORT**	**Chap./Sec./Pg.**
Executive Summary	< 4 pages	Meets requirement	Pg. 1-4
Table of Physical Data Listing	Specified	Meets requirement	Chap. 3 (Table 3.1)
MIL-STD-1374 Weight Statement	Specified	Meets requirement	Pg. 96-99
Recurring Cost Breakdown	Specified	Meets requirement	Sec. 8.2 (Table 8.3)
Performance Charts	Specified	HOGE altitude vs. gross weight Payload vs. Range Altitude vs. max. cont. speed	Sec. 6.3 (Fig. 6.8) Sec. 6.3 (Fig. 6.12) Sec. 6.3 (Fig. 6.10)
Drawings	Specified	Arrangement (major dimensions) Inboard profile fold-out Drive system schematic	Chap. 3 (Fig. 3.1) Chap. 4 (Fig. 4.1) Chap. 4 (Fig. 4.20)
Description of design process	Specified	Trade study Design highlights Detailed design Performance analysis Manufacturing processes Weight and cost	Chap. 2 Chap. 3 Chap. 4 Chap. 6 Chap. 7 Chap. 5 & 8

Executive Summary

Introduction

The Calvert, a high-speed multirole personal transport helicopter, has been designed in response to the 1999 American Helicopter Society Student Design Competition (sponsored by Bell Helicopter). The Request For Proposal (RFP) identified the need for a small civil transport aircraft to replace existing "general aviation" helicopters and small turbine-engined helicopters. The primary goal for this design is to produce an aircraft capable of vertical flight that provides significant gains in performance (in terms of speed and range) over existing helicopters in its class, at a minimal increase in cost over these aircraft. To meet this goal, special attention was to be paid to aspects of cost-effective manufacturing, ease of maintenance and overall value. The RFP stipulated a production run of 300 aircraft at a rate of 60 aircraft per year.

Mission requirements and design objectives

The RFP specified a cruise speed of 180 knots and a range of 540 nautical miles while carrying 4 to 6 people and their baggage. The Calvert exceeds the requirements with a cruise speed of 180 knots and a range (dry-tank) of 548 nm while carrying 4 passengers at 4000 ft ISA. Significantly, it also provides the capacity to carry 6 people at a reduced cruise speed of 160 knots, and with a range of 552 nm. At the production rate stipulated in the RFP, a preliminary cost analysis indicated a purchase price of the Calvert at US$ 1.84 Million. In comparison, BO-105, a twin-engined helicopter in the same weight category, is priced at US$1.9M (1993). The Calvert achieves a significant increase in cruise speed (60%) and range (70%) at a similar price to the BO-105 by synergizing technological advancement with cost-effectiveness and mission adaptability. The compounding features in the Calvert (the wing and pusher propeller) are simple in construction, have weights comparable to a standard helicopter (tail rotor group), are inexpensive, and are proven technologies, and thus provide the Calvert with superior performance with little cost penalty. These factors make the Calvert a potent solution to fulfill the requirements indicated by the market study.

Aircraft configuration trade-off study

An extensive study of various aircraft configurations was conducted. The compound helicopter and tilt rotor/wing emerged as feasible candidates, whereas the coaxial-ABC helicopter, Verticraft, and Autogyro, among others, were eliminated due to their technological risk and poor overall value for the specified mission. Trade studies indicated that a compound helicopter with both thrust and lift compounding offered a considerably less expensive solution than a tilt rotor/tilt wing for the selected mission profile and an enhanced mission flexibility to replace conventional helicopters in low-speed missions. A detailed trade-off study incorporating performance, weights and cost resulted in the choice of a lift compounding of 40% of aircraft gross weight using a high-wing, and a thrust compounding of 80% of aircraft drag using a pusher propeller. Trade-offs involving the rotor and anti-torque device also resulted in the choice of an intermeshing rotor for a compact design. The final configuration selected had several advantages: the capability for high speed flight without encountering stall or compressibility limits, a compact fuselage, a low equivalent drag area, minimized transmission losses, a low apron footprint, low vibration levels (meets ADS-27 limit) and low noise signatures due to reduced tip speed in cruise.

Calvert: design features

The Calvert is a compound helicopter with a wing, a pusher propeller and intermeshing main rotors. The design of the entire aircraft was propelled towards maximizing value to the customer. The high-speed and long range capability of the aircraft are offered while paying special attention to reduced manufacturing, material and operational costs.

• The Calvert uses lift compounding by a wing to offload the rotor, delaying the onset of stall. The offloading factor of 40% was chosen to minimize the weight and hover download penalty while providing the rotor with enough control authority to operate well within stall limits at a cruise speed of 180 knots.

• A variable pitch pusher propeller is used to provide 80% of the forward thrust required by the aircraft in cruise so as to minimize the shaft tilt and fuselage angle of attack variation. The propeller was designed to provide the required thrust with the smallest diameter and weight penalty and with a relatively high propulsive efficiency of 82%.

• A variable RPM configuration is used for the main rotors. The rotational speed of the main rotor is 400 RPM in hover, and is reduced to 346 RPM in cruise. This reduction ensures the advantages of maintaining good autorotation and stall characteristics at low speeds, while avoiding compressibility effects on the advancing rotor at cruise speeds. The choice of RPM was also motivated by the dynamic properties of the rotor to ensure aeroelastic stability in the entire operating range of the aircraft.

• The Calvert is powered by two scalable IHPTET engines (for safe OEI operation capability) that will be developed in parallel with the aircraft. The engines will be equipped with capability to maintain a good fuel efficiency over a range of RPM, and a FADEC system to ensure optimum engine settings. The FADEC also regulates the output shaft speed of the engine with forward speed.

• The transmission of the Calvert is designed to operate over the range of RPM prescribed while minimizing weight. It accepts inputs from the two engines through a spring clutch, and distributes power to the two main rotor shafts and the propeller shaft at varying RPMs and power requirements. To minimize fatigue loads on the transmission housing, the rotor loads are transferred into the fuselage through a unique independent truss support referred to as a standpipe.

• An intermeshing rotor configuration is used for the main rotors. This maximizes the lifting efficiency of the main rotors while providing a compact fuselage without the use of an anti-torque device. Care was taken to minimize the drag penalty for this configuration.

• A compact teetering door-hinge hub design is used for the main rotors. The hub is enclosed in a hub cap to reduce drag. The pitch links, swashplate and upper controls are enclosed inside pylons with fairings cambered outboard to prevent drag buildup

• The design of this high-speed aircraft includes several drag reduction features such as a compact fuselage and cabin space optimized for drag reduction, a compact retractable landing gear design, engine and transmission deck enclosed in an aerodynamic fairing, and compact hub design.

• Several advanced active technologies are proposed for the Calvert, including a piezostack driven servo-flap for vibration suppression, an SMA-activated inflight tracking tab, active interior noise control with a trim panel for noise cancellation, an advanced, fully integrated prognostics and health management (PHM) system for condition monitoring, and a FADEC system to monitor engine settings with forward velocity.

• Manufacturing and maintainability issues were some of the primary drivers for the design of the Calvert. The airframe uses a composite-over-metal-frame construction for reduced parts count and manufacturing costs, enhanced crashworthiness, repairability, and inspectability. A unique assembly process involving three jigs that double as construction and assembly jigs will be used. The materials and construction techniques for each of the components reflect an enhanced manufacturability.

• An integrated solid modeling of the entire aircraft was conducted. This ensures ease of data transfer from design to production stages in the virtual factory and incorporating maintenance, manufacturing, and materials into the preliminary design process, thus reducing the cycle time for production.

• The enhanced marketability of the Calvert comes from its adaptability for use in different missions. The aircraft is capable of flying at 180 knots over a range of 548 nm with 4 passengers, or at 160 knots over a range of 552 nm with 6 people. The Calvert, with only slight modifications, is also highly suitable for search and rescue, surveillance, and short-haul heavy lift operation. This adaptability is likely to increase production rates and reduce aircraft cost.

Methodology and approach

The design of the Calvert was conducted in conjunction with the spring 1999 Helicopter Design Course in the Aerospace Engineering Department. The course was aimed at providing students a fundamental understanding of design issues in engineering and particularly aircraft design. To this end, no commercial codes were used for the primary design. In contrast, the entire design and analysis of this aircraft was conducted using codes developed in-house. The analysis was conducted at varying levels of complexity, the first order models being adapted from Dr. Tishchenko's lecture notes [TNC99] for simplicity and insight. The performance analysis was based on a rigid blade model with a uniform inflow, and successfully captured the interdependent effects of the wing, propeller and intermeshing rotor. The modeling of the aircraft was conducted using IDEAS, and the key aspects of aircraft operation such as spinning of the rotors, blade flapping, propeller, and drivetrain operation were simulated to ensure safety.

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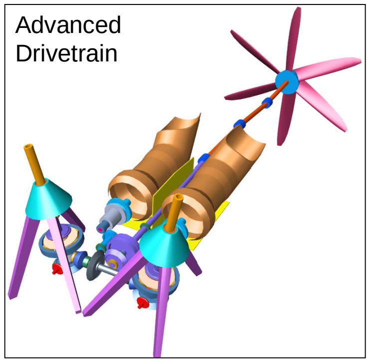

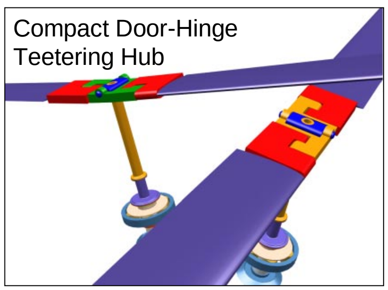

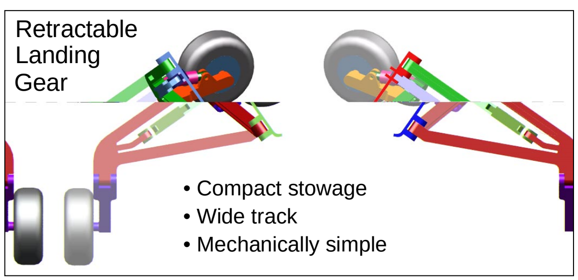

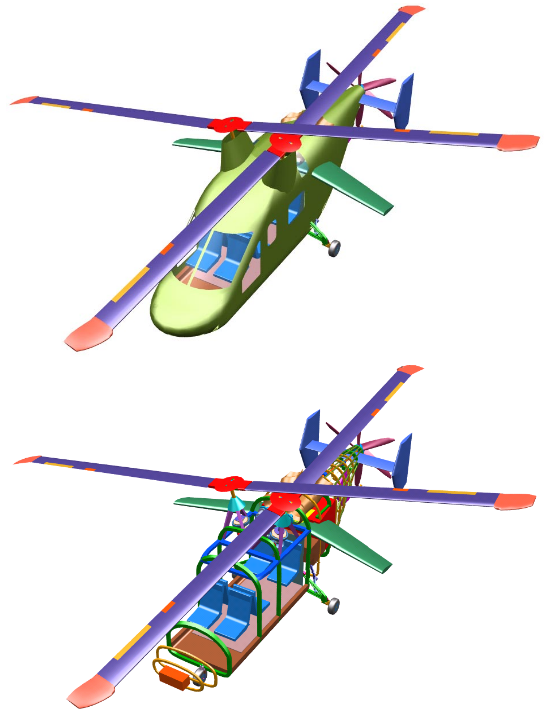

THE CALVERT

Parameter	Units	4 Passengers	6 Passengers
PERFORMANCE			
Max. Cruise Speed	*kt*	***180***	*160*
Range@ Max. Cruise Speed	*nm*	***548***	*552*
Speed for Best Range	kt	140	142
Max. Range	nm	584	580
Cruise Altitude	ft	4000	4000
Never Exceed Speed	kt	210	190
WEIGHTS			
Take-off Weight	lb	5067.7	5486.4
Empty Weight	lb	2926.6	same
Payload	lb	2141.1	2559.8
Maximum Fuel Weight (Usable)	lb	1233.8	same
COST			
Purchase Cost	*US $(1999)*	***1.84 M***	*same*
DOC/air-seat mile	US $(1999)/mi	0.604	0.39
POWERPLANT			
# of Engines		2	same
Max. Continuous Power (MCP)	hp(each engine)	525	same
Take-off Power	hp(each engine)	656	same
TRANSMISSION			
Max. Continuous	hp	1070	same
Contingency (2min)	hp	1320	same
Intermediate (30 min)	hp	678	same
MAJOR DIMENSIONS			
Main Rotor Diameter	ft	34.43	same
Main Rotor Blade Chord	ft	1.04	same
Main Rotor Disk Loading	lb/ft^2	2.72	2.95
Wing Span	ft	14.93	same
Propeller Diameter	ft	6.23	same

- Thrust and lift compounded synchropter
- 540 nm range at 180 kts
- Multi-mission adaptability
- Variable RPM engine and main rotor
- Low vibration and noise signatures
- Low Manufacturing and purchase cost
- Low drag hub and fuselage
- Advanced active systems

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Figure 0.1: Calvert Highlights 4

Figure 0.1: Calvert highlights.

1 Introduction

This proposal presents the design of the Calvert – a helicopter designed from the outset to offer the best value to the customer. The Calvert takes its name from Charles Benedict Calvert, founder of the Maryland Agricultural College (which later became the University of Maryland), and descendent of George Calvert, the first Lord Baltimore and founder of the State of Maryland. Throughout the design of the Calvert, careful attention has been paid to maximizing end-user value through performance, economy, ease of use, and safety. It is believed that, by offering customers a large increase in performance and capability with only a minor cost premium, the Calvert will be positioned to capture a large part of the market to replace existing fleets of older aircraft.

The Calvert was designed in response to a request for proposal (RFP) from AHS International and Bell Helicopter as part of the 1999 AHS Student Design Competition. This RFP for a High-Speed VSTOL Personal Transport specifies a 4-6 seat aircraft that can cruise at 180 knots with a range of 540 nautical miles (dry tanks). These specifications require a substantial performance increase over existing light helicopters with little or no increase in price. Most current light turbine helicopters, such as the MD-500 and EC-120, are limited to a cruise speed of approximately 135 knots and mission range of 350 nautical miles. Technical barriers to achieving a 180 knot cruise speed include compressibility effects, retreating blade stall, poor cruise efficiency and high levels of vibration and noise. The Calvert is designed to overcome these limitations with little or no increase in cost over existing fleets of 4-6 place helicopters. The RFP also requires the designers to pay special attention to producing a machine that is easy and inexpensive to manufacture. In meeting all of these requirements, attention should be paid to the target market – the general aviation marketplace. Specifically, the design should be focused towards current owners and operators of aging light helicopters.

Ultimately, the secret to producing an item inexpensively is to engender enough customer demand to merit the large production quantities necessary to realize substantial reductions in unit cost. The benefits of mass production and large production runs are widely known.

Engineering a product for *inexpensive mass production* requires special attention to manufacturing details. Engineering a product to *generate a high demand* requires attention to customer requirements. Additionally, a successful product must offer high quality in terms of ease of use along with traditional metrics for performance, manufacturability and safety. Any vehicle designed to replace existing fleets should not impose significant retraining requirements on the customer, and the ability to win new customers can be strongly influenced by the ease of learning to use and service the product.

These considerations have guided the design of the Calvert which not only fulfills all the requirements of the RFP but also provides the mission flexibility required to promote mass production of one platform that fulfills many missions.

2 Aircraft Configuration Trade Study

2.1 Candidate configurations

The requirements of the RFP can be met by a number of different configurations. The most important design requirements are the capability for high speed cruise (180 knots) and long range (540 nm). At the very beginning of the design process a brainstorming session was conducted. Every member of the design team was asked to propose a concept and justify his configuration. At this stage, even the most radical and technologically risky configurations were retained for further analysis. The goal was to encourage creativity and original thinking. The following candidate configurations were proposed:

a) Conventional helicopter. The conventional helicopter consists of a single main rotor along with an anti-torque device such as conventional tail rotor, fenestron or notar system. Without modification, most conventional light helicopters have a cruise speed less than 135 knots.

b) Co-axial. A co-axial helicopter (like the Kamov115) consists of two main rotor systems mounted co-axially on a singe axis. This scheme does not require an anti-torque device resulting in very small footprint. In order to prevent the possibility of the blades striking each other, sufficient separation must be maintained between the rotor systems resulting in a very tall rotor hub. This results in significant drag penalties and poor cruise efficiency in high speed forward flight.

c) Tandem. The tandem helicopter consists of two main rotor systems situated at the front and rear ends of the fuselage, as on the Boeing Chinook. The tandem helicopter does not need an anti-torque system. This type of design is well suited for heavy-lift helicopters that may experience large CG travel.

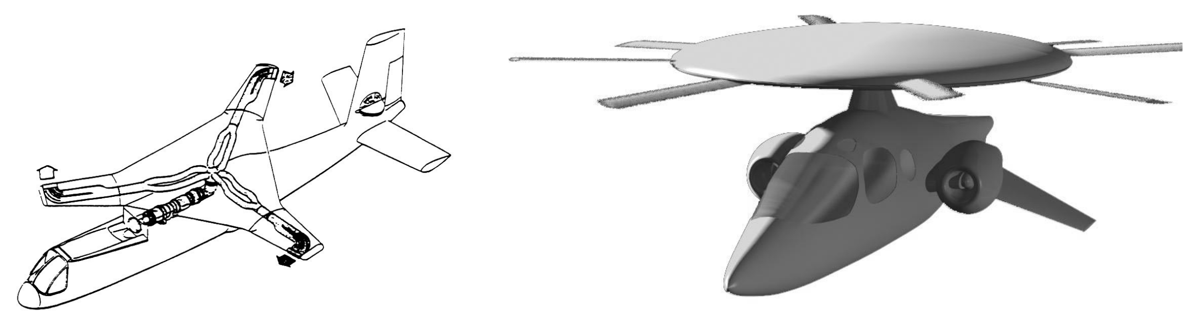
d) Synchropter. A synchropter such as the K-MAX (Kaman Helicopter) uses the intermeshing rotor concept. The synchropter does not require an anti-torque device. The K-MAX has an included angle of 25° between the two rotor shafts to provide sufficient clearance and prevent the blades from striking each other. The intermeshing rotor concept (K-MAX) has a proven track-record for its lifting efficiency, safety and low maintenance requirements. However, intermeshing rotors suffer from the same limitations as conventional helicopter rotors in high-speed cruise.

e) Compound. A conventional helicopter, co-axial, tandem or synchropter with some type of thrust and/or lift compounding results in a compound configuration. The Lockheed Cheyenne and Fairey Rotodyne are examples of compound helicopters. The compound helicopter offers an attractive increase in cruise speed into the 170-220 knot region, compared to the conventional helicopter. However, the increased empty weight fraction and complexity of thrust and lift compounding, if not paid close attention to, can negate the speed advantage in terms of decreased cost effectiveness.

f) Advancing Blade Concept (ABC). The ABC concept rotor system, with a pair of counter-rotating, co-axial, rigid rotors, represents a significant departure from previous helicopter rotor systems. It derives its name from the fact that the predominant lift load at high forward speeds is carried by the advancing blades on both sides of the aircraft. Since the retreating blades are not required to carry a significant fraction of the total lift load at forward speed, the speed and load factor limitations of the conventional helicopter due to retreating blade stall are eliminated. The disadvantages of the ABC rotor are high profile drag, hub drag, vibration, and power requirements.

g) Tilt rotor/wing. The tilt rotor and tilt wing concepts use a set of highly loaded main rotors as propellers in cruise (Examples, V-22 and Bell Agusta-609). Compared to the conventional helicopter the tilt rotor/tilt wing has much better cruise efficiency at cruise speeds higher than 180 knots, at the cost of poor weight efficiency, autorotation, and efficient low speed and hovering capabilities.

h) Stopped rotor. This high speed rotorcraft concept typically consists of a reaction-drive rotor that is stopped after reaching conversion speed for high speed cruise flight [RB93]. The aircraft operates in the helicopter mode in the 0 to 80 knot range. In the 80 to 170 knot range it operates as an autogyro with propulsion provided by turbofans. Above 170 knots the rotors are stopped and locked to provide lift as wings (see Figure 2.1(a)). Transition to the airplane mode is then complete.



(a) Stopped rotor. (b) Verticraft.

Figure 2.1: Two candidate aircraft configurations.

i) Verticraft. The Verticraft employs two counter-rotating circular disks. Four blades are connected to each disk. The blades are used to generate lift in hover. In forward flight, the blades are completely retracted into the circular disks. The disks together behave as a low aspect ratio circular wing with propulsion being provided by a ducted fan or turbojet engine (see Figure 2.1(b)).

j) Cruisefan (Sadleir VTOL concept). The cruisefan utilizes the fan-in-wing concept. In operation, the lift fan draws air from the top of the wing, deflecting it into four primary lift ducts and four smaller control ducts. The control ducts provide vertical lift, initial forward thrust and braking control during hover and low speed forward flight. Inlets and exhausts of the fan-in-wing are closed for high speed flight. A rear fan (conventional turbofan) provides thrust for high speed forward flight. The estimated cruise speeds are over 400 knots. Development of this concept is being carried out by Sadleir Corporation.

k) Autogyro. In cruise, the rotor of the autogyro is not powered directly. Under these conditions, the power to drive the rotor and produce lift comes from the airflow through the rotor. Collective pitch control is used to achieve "jump" take-offs. This is accomplished by overspeeding the rotor on the ground with the blades seat at a low pitch. Subsequently, the rotor is de-clutched, and the energy stored in the rotor is used to lift the aircraft into the air through a sudden increase in blade pitch. An autogyro is incapable of hovering and must autorotate to perform a vertical landing, both of which are major limitations for VTOL civil transport operations.

2.2 Preliminary downselection

In order to qualitatively compare the candidate configurations, a comparison matrix was formulated (see Tables 2.1, 2.2). The first column of the matrix lists the evaluation criteria. The second column indicates the maximum points that can be awarded for each criterion based on its relative importance. The comparison matrix emphasizes high speed and range (200 pts) in order to meet the performance requirements in the RFP. Other desirable characteristics are good efficiency in cruise and hover, low cost and weight, and good maintainability, safety, reliability and manufacturability. Low vibration and noise characteristics are also important.

Category	Max. Value	Conventional Hel.	Co-axial	Synchropter/ Tandem	ABC	Tilt Rotor/ Tilt Wing
Speed	200	100	120	150	190	200
Range	200	150	160	160	190	200
Hover Efficiency	100	100	100	100	100	50
Hover Downwash	50	50	50	50	50	20
Gross Weight	100	80	70	60	60	30
Conversion Maneuverability	50	50	50	50	50	40
Cruise Efficiency	100	50	50	50	60	100
New Mission Adaptability	50	50	50	50	50	50
Aeroelasticity	50	30	30	30	50	30
Reliability/Maintainability	150	120	100	100	100	130
Survivability	50	40	40	30	40	40
Purchase Price	100	90	70	70	60	40
DOC	100	60	60	60	50	90
Autorotation	50	50	50	50	50	0
Manufacturability	100	100	90	90	90	100
Technical Maturity	50	50	50	50	30	50
Noise	100	60	50	50	60	90
Total	1600	1230	1190	1200	1280	1260

Table 2.1: Comparison matrix.

Tables 2.1 and 2.2 indicate that the compound helicopter, ABC, tilt rotor/wing, autogyro and the Verticraft were ranked the highest for the present application. The conventional, co-axial and synchropter helicopters were rejected due to inability to meet speed requirements and poor high speed

Category	Max. Value	Compound	Stopped	Autogyro	Verticraft	Cruise Fan
Speed	200	175	200	175	190	190
Range	200	175	200	175	190	190
Hover Efficiency	100	100	80	0	50	20
Hover Downwash	50	50	40	50	10	10
Gross Weight	100	60	50	100	80	60
Conversion Maneuverability	50	50	30	10	30	20
Cruise Efficiency	100	70	90	75	70	90
New Mission Adaptability	50	50	50	10	50	30
Aeroelasticity	50	30	20	30	40	50
Reliability/Maintainability	150	100	20	120	120	80
Survivability	50	30	20	30	40	45
Purchase Price	100	70	40	100	90	40
DOC	100	70	80	100	75	80
Autorotation	50	50	30	50	0	0
Manufacturability	100	90	50	100	80	70
Technical Maturity	50	40	0	40	20	10
Noise	100	50	70	100	90	50
Total	1600	1260	1070	1265	1240	1035

Table 2.2: Comparison matrix (continued).

cruise efficiency. The tandem configuration is more suited for large helicopters because sufficient horizontal and vertical separation is needed between the two rotors. The cruise fan concept was rejected due to poor hover efficiency, large installed power (14349 HP) and substantial technical risks. The stopped rotor was also eliminated. Lack of technical maturity leads to high development costs. Also, for such a configuration, the conversion from helicopter to fixed wing mode occurs at 170 knots [RB93]. Consequently, the stopped rotor is optimized for much higher cruise speeds (400-500 knots), and cannot be considered a cost effective alternative to existing 4-6 seat helicopters.

Though the Verticraft appears very promising, it has numerous potential pitfalls. Preliminary calculations using combined blade element momentum theory indicated high hover downwash and moderate hover efficiency. Inability to autorotate in case of engine failure presents serious safety concerns. Also poor cruise efficiency associated with the low aspect ratio circular wing is another drawback. Due to these reasons the Verticraft was also rejected, however we feel that a more refined analysis is necessary to do full justice to this unique and interesting concept.

The autogyro is the ideal vehicle to replace the automobile as the personal transport vehicle of the future. It is fast, cheap, and relatively low tech. It requires low development and maintenance costs. However, it cannot hover and this is a major limitation for the present design exercise. Also, an autogyro is incapable of aborting a landing once committed. On an open field/runway this is not a concern, but for operation in densely populated areas, the aircraft must demonstrate the capability to abort a landing. In addition, the poor safety record and high accident rates of autogyros are a major cause of concern (source: National Transportation Safety Board (NTSB) database, 1999). Possible reasons for this statistic could be that autogyros are often flown by amateur pilots with poor training and a comparatively poor maintenance infrastructure. In conclusion, to replace existing fleets of 4-6 seat helicopters, this design must demonstrate a wide range of mission capabilities, including adequate hovering capability. Consequently, the autogyro is considered unsuitable for the present design study.

The ABC concept, with co-axial counter-rotating rigid rotors, is a prospect that can meet the RFP speed and range requirements [dBF82]. Thrust compounding enables the fuselage and main rotor system to be kept level in high speed forward flight. In hover, the use of two counter-rotating rotors reduces the energy losses in the slipstream rotation. In 1973, Sikorsky flight tested the ABC rotor system on the XH-59A. However, the rigid counter-rotating co-axial rotor system has its own set of unique technical problems. A conventional rotor operates at very low angles of attack on the advancing side. The ABC rotor, on the other hand, must generate all its lift on the advancing side and hence operates at high angles of attack on the advancing side. This means that the profile power of an ABC rotor is much greater than a conventional rotor. Additionally, the drag associated with the rigid hub is also likely to be substantial. In fact, the XH-59A was equipped with two Pratt and Whitney J60-P-3A turbojet engines for thrust augmentation in high speed forward flight. Each engine provided 3300 lb static thrust at sea level standard conditions. Also, the rigid rotor system used in the ABC configurations typically results in high loads and vibration in high speed forward flight. For these reasons, the ABC rotor will not be competitive compared to advanced compound and tilt rotor/wing designs.

The Cheyenne, a compound helicopter with thrust and lift compounding, was built and flight tested in the late 1960's. It flew at cruise speeds of over 200 knots. Dynamic problems associated with the rigid rotor system (1/2-p hop) were subsequently solved in the 1970's. Such a vehicle presents no significant technological barriers and offers the promise of high speed VTOL capability with minimum penalty in terms of cost and complexity. Recently, there has been renewed interest in the application of compound helicopters as a means of extending the helicopter flight boundary for both civilian and military applications [BB91],[JHB93].

The tilt rotor concept has been demonstrated by Bell-Boeing (V-22 Osprey). Recently Ishida [CS93] has designed a tilt-wing aircraft for civil transport applications. The tilt rotor/wing concept offers some distinct advantages and attractive features: superior vehicle lift to drag ratios compared to helicopters; high speed and range capabilities; and low DOC per air-seat-mile compared to conventional helicopters. However, low weight efficiency and poor hovering capability can offset these advantages, especially if the mission range is less than 200-250 miles. The compound helicopter and tilt rotor/wing appear to be the best solutions for the present RFP. The next section will describe the detailed trade study between these two concepts.

2.3 Compound helicopter *vs.* tilt rotor

For this trade study, the candidate aircraft configurations are a thrust and lift compounded helicopter and a tilt rotor. Considering that this is a first order analysis, the performance differences between a tiltwing and a tiltrotor are expected to be negligible, and these two are considered as a single concept. Furthermore, only a fixed diameter tiltrotor is considered. A variable diameter tiltrotor offers the advantage of a reduced hover disk loading during VTOL and lower tip speed in forward flight. However, these advantages are offset by the added complexity and cost, and reduced efficiency associated with the non-optimal blade twist for the extended rotor blades in hover and reduced rotor diameter for forward flight. Consequently, only a fixed diameter tiltrotor configuration is investigated.

2.3.1 Engine, aerodynamic and weight models

There exist many methods for accurately calculating the performance characteristics of helicopters. However, such methods can be used only when all the details of the helicopter configuration are known. During the preliminary design stage of a helicopter project, the configuration is not known and it is necessary to use approximate methods to proceed with the design. One such method is based on the concept of vehicle lift/drag ratios [TNC99]. It is noteworthy that this idea was used in the mid-30's by Hohenemser, who calculated the lift/drag ratio using the autorotation mode of an autogyro (rotor draws zero power). Later, during the 50's the Russian scientist Dr. Braverman modified and developed the use of this concept. This methodology is now used in the Mil design bureau for conceptual design.

For the present study, forward flight for both compound helicopter and tilt rotor is modeled using the concept of cruise lift/drag ratios. Hover performance is analyzed via momentum theory, taking into account figure of merit, vertical drag and transmission efficiency correction factors. Take-off weight is calculated using assumed weight efficiencies. Take-off weight will include the payload (passengers+baggage) and estimated fuel. These empirical formulae are obtained from curve fits to weight trends of existing VTOL aircraft and are defined separately for conventional helicopters and a wing-borne configuration [TNC99]. This first order model ignores two important features: first, the empty weight fraction is assumed to be a function of only the take-off weight, whereas it is also significantly influenced by the disk loading; second, the empirical cruise performance based on lift/drag ratios fails to capture the effects of the detailed rotor parameters (planform, tip geometry, advanced airfoils) and wing configuration. These effects have been modeled in Chapter 6. The present study uses the engine model specified in the RFP.

2.3.2 Economic model and comparison indices

The helicopter cost analysis uses the cost model specified in the RFP. The aircraft cost effectiveness will be evaluated in terms of four parameters: direct operating cost per air-seat-mile (DOC/asm), initial cost (IC), life cycle cost (LCC) and rentability index (RI).

DOC Calculation	Description
Purchase Price	RFP cost model
Fuel Cost	1.5 $/gallon (Jet A fuel)
Maintenance [Ols93]	0.067/fh/lb (per flight hour per lb empty weight)
Residual Value	10% (with an aircraft life of 10000 flight hours)
Financing [Sco96]	8% per year
Insurance [Sco96], [Ols93]	Compound Helicopter: 5.5% per year, Tilt Rotor : 6% per year
Crew Cost	$62 per flight per crew member

Table 2.3: Cost analysis summary.

The DOC/asm (which includes depreciation, financing, insurance, maintenance, fuel cost, and pilot salary) is a measure of the expenses incurred by the operator per air-seat-mile and does not account for the value of the passenger's time. Scott [Sco96] reports an average maintenance cost of $ 0.067/flight-hour(fh)/pound-empty(lb) for a 40-seat, 600 nm tiltrotor, compared to $ 0.063/fh/lb (empty) for a 40-seat, 400 nm helicopter. These values correlate well with the $0.067/fh/lb (empty) quoted by Olson [Ols93]. For the present trade study, a maintenance cost of $ 0.067/fh/lb (empty) will be used to calculate the DOC/asm for both the helicopter and the tilt rotor. The life cycle cost calculates the total cost of the aircraft over its lifetime (includes IC as well as DOC/asm):

$$LCC = IC + (DOC/asm) \times (\#seats) \times (mission\ distance) \times (total\ \#\ flights\ in\ lifetime) \tag{2.1}$$

The rentability index (RI) is a cost measure that is defined to quantify the premium a passenger is prepared to pay to shorten the effective flight time by a certain percentage. Gmelin *et al.* [GJP+89] indicated that the customer is willing to pay 30% more to double the effective speed and proposed the following definition:

$$RI = \frac{V_b^{0.4}}{DOC/asm} \tag{2.2}$$

where V_b is the effective flight speed, based on the passengers total flight time from boarding to disembarking. The higher the rentability, the more cost effective the aircraft. The best design is one that optimizes the cost drivers identified above: maximizes the cruise speed (RI) and minimizes the cost (LCC, DOC/asm and IC).

2.3.3 Mission profile

Helicopters can be designed for numerous types of missions (conventional civil transport, search and rescue, endurance etc). Our interpretation of the RFP is that the primary mission is long range civil transport. The assumed primary mission profile is shown in Figure 2.2. The nominal and maximum cruise altitude for the compound helicopter is taken as 4000 ft and 8000 ft respectively. The low level cruise offers some distinct advantages. First, traffic conflicts with faster fixed wing commercial air traffic are avoided. Second, the need for aircraft pressurization is eliminated, resulting in a weight and power reduction. The main disadvantage of the low level cruise is that flight operations will be affected if bad weather extends above 8000 ft. The en-route climb rate is limited by the FAR to 1250 ft/min, because the cabin is unpressurized. In contrast, the tilt rotor has to climb to a cruise altitude of 18000 ft to achieve efficient flight at the maximum lift to drag ratio. However, the RFP specifies a maximum cruise altitude of 10000 ft. This will adversely affect the lift/drag ratio of the tiltrotor. For the present study, a cruise altitude of 10000 ft is selected for the tiltrotor.

2.3.4 Trade study methodology

The flowchart for the trade off study is shown in Figure 2.3. The known or fixed inputs are the mission profile, range (540 nm) and number of passengers (four). Since this is a personal transport helicopter the passengers also include the pilot. The cruise speed for the compound helicopter is 180 knots (as

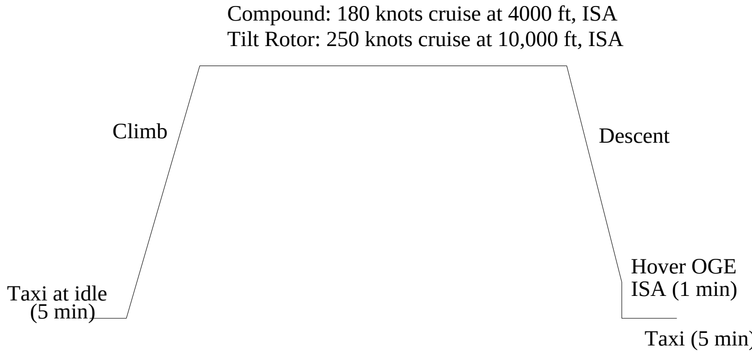


Figure 2.2: Conventional civil transport mission profile.

required by the RFP) and the corresponding value for the tiltrotor is 250 knots (similar to BB-609). Conventional light helicopters have a lift/drag ratio of 4.2 [TNC99] at 130 knots and weight efficiencies around 0.46 [TNC99]. The weight efficiency (Equation 5.2) of an aircraft is defined as the ratio of the total payload (including passengers, crew and fuel) to the gross weight. A compound helicopter has a higher empty weight fraction than a conventional helicopter. Therefore, a weight efficiency of 0.42 is selected for the compound. Also, the cruise lift/drag ratio of a compound helicopter at 180 knots is expected to be lower than a conventional helicopter cruising at 130 knots. Therefore, a cruise lift/drag ratio of 3.7 is selected for the compound helicopter. The tilt rotor is assumed to have a lift/drag ratio of 8.5 [TNC99] and weight efficiency of 0.35 (similar to BB-609). Based on the lift/drag ratio, weight efficiency, and disk loading, the aircraft gross weight is estimated. The gross weight is used to size the rotor and powerplant and estimate the fuel and component weights. This process is repeated until the initial gross weight estimate and the calculated all up mass converge. Subsequently, the initial cost, DOC/asm, life cycle cost and rentability index are calculated for the compound helicopter and tilt rotor. This process is repeated for different values of disk loading.

2.3.5 Trade study results

To check the numerical accuracy of the simulation, the code was validated for the MD-500E and the BB-609. For the MD-500E, a lift/drag ratio of 4.2 at a cruise speed of 134 knots was selected [TNC99]. For the BB-609, a lift/drag ratio of 8.5 at a cruise speed of 257 knots was chosen [TNC99]. Table 2.3 shows a comparison of the results obtained from the present method with the published values for the MD-500E and the BB-609.

Table 2.4 indicates that the preliminary first order analysis shows good agreement with existing VTOL configurations. The actual purchase price of the MD-500E ($ 0.67 million) is much lower than the value given in the simulation ($ 1.7 million). This is because the simulation assumes a production quantity of 300 aircraft and a production rate of 60 per year as specified in the RFP. However, the MD-500 has been produced in much larger numbers, and hence has a lower purchase price. Having developed sufficient confidence in the simulation, we now apply the algorithm to the compound helicopter and the tilt rotor. In this preliminary study, the disk loading was selected as the primary input parameter. Figures 2.4-2.6 show the take-off weight, fuel weight, nominal engine power, IC, DOC/asm and RI as a function of disk loading.

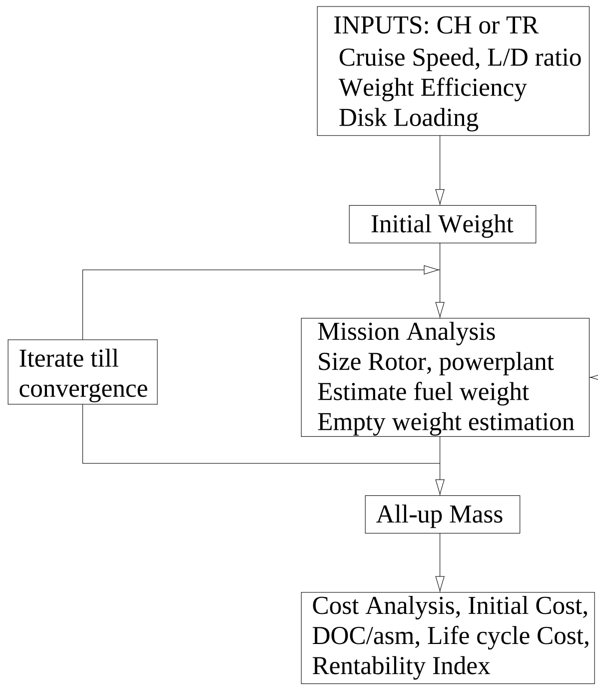
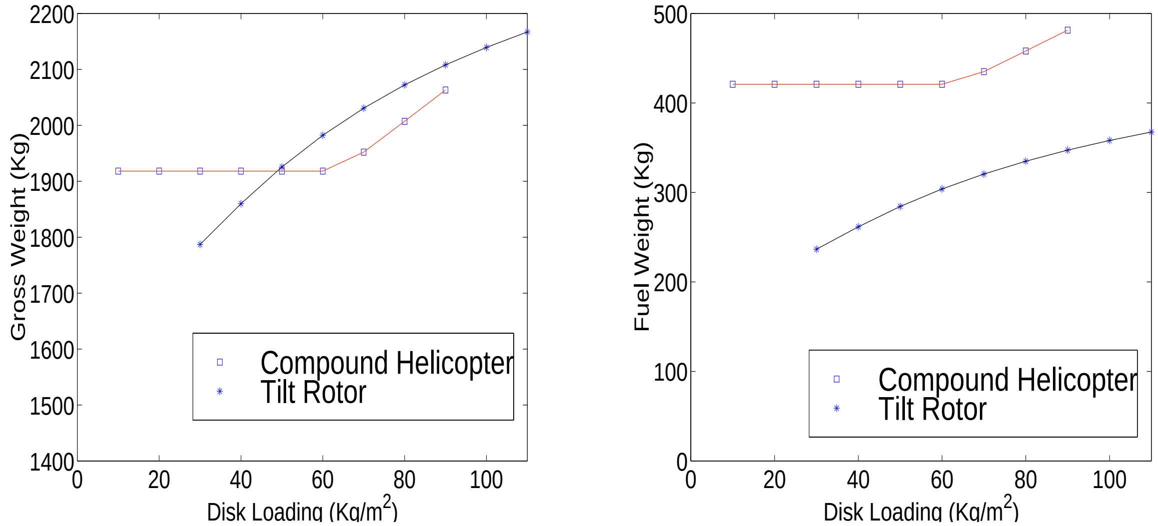


Figure 2.3: Trade study methodology.

Figure 2.4 indicates that the take-off-mass (1918 kg) and fuel weight (420.9 kg) of the compound helicopter is nearly constant in the 10 to 60 kg/m^2 disk loading range. The tilt rotor on the other hand shows a monotonically increasing trend for take-off weight and fuel weight in the 30-110 kg/m^2 disk loading range. For a disk loading of 50 kg/m^2 the tilt rotor and compound helicopters have the same gross take-off weight. Figure 2.4 also indicates that the tilt rotor needs to carry less fuel compared to the compound configuration due to its superior cruise lift/drag ratio. Figure 2.5 shows that the compound helicopter has greater installed power compared to the tilt rotor for disk loadings below 50 kg/m^2. Above 50 kg/m^2, the tilt rotor has greater installed power requirements. Figure 2.5 also shows that the purchase price of the compound helicopter is considerably less than that of the tilt rotor over a wide range of disk loadings. Figure 2.6 indicates that the compound helicopter has a lower DOC/asm compared to the tilt rotor. This is because the lower purchase price and empty weight of the compound helicopter offsets the lower fuel consumption of the tilt rotor, resulting in reduced operating costs. Figure 2.6 also shows that the rentability index has a cross-over point at a disk loading of 50 kg/m^2. For disk loadings below 50 kg/m^2 the tilt rotor has a superior rentability. This trend is reversed above 50 kg/m^2.

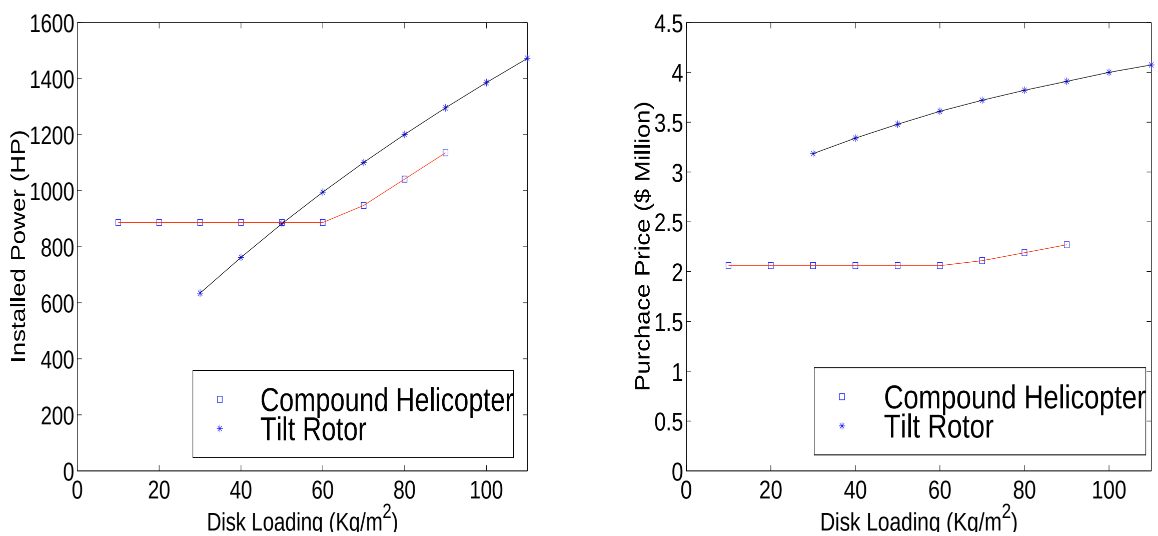
For the cost comparison, a disk loading of 30 kg/m^2 is used for the compound helicopter. This is representative of existing light helicopters such as the MD 500E and the EC120. For the tilt rotor, lower disk loadings improve the performance (Figures 2.4-2.6). As a compromise between low disk loading and reasonable rotor diameter, a disk loading of 50 kg/m^2 was selected for the tilt rotor. The estimated empty weight, fuel weight and initial cost from Figures 2.4-2.6 is used to calculate the Direct Operating Cost per air-seat-mile (DOC/asm) and Life Cycle Cost (LCC). The DOC/asm includes both Cash DOC (fuel, lubricants, maintenance and flight crew salary) as well as Ownership DOC (depreciation, hull insurance and financing). The life cycle cost is calculated using equation 2.1 (section 2.3.2). Table



(a) Take-off mass *vs.* disk loading.

(b) Fuel weight *vs.* disk loading.

Figure 2.4: Take-off mass and fuel weight *vs.* disk loading.



(a) Installed power *vs.* disk loading.

(b) Purchase price *vs.* disk loading.

Figure 2.5: Installed power and purchase price *vs.* disk loading.

Property	Units	MD-500E		BB-609	
		Simulation	**Actual**	**Simulation**	**Actual**
Gross Weight	lb (kg)	3219 (1460)	3003 (1362)	15611 (7081)	16032 (7272)
Fuel Weight	lb (kg)	410.83 (186.35)	396.99 (180.07)	2714 (1231)	3135 (1422)
Installed Power	hp (kW)	457.84 (341.41)	420 (313)	3905 (2912)	3693 (2754)
Main Rotor Diameter	ft (m)	27.92 (8.51)	26.38 (8.04)	25.66 (7.82)	25.98 (7.92)
Main Rotor Chord	ft (m)	0.486 (0.148)	0.568 (0.173)	–	–
Tail Rotor Diameter	ft (m)	5.05 (1.54)	4.56 (1.39)	–	–
Tail Rotor Chord	ft (m)	0.492 (0.15)	0.439 (0.134)	–	–
Cost	US$	1.7M	0.67M (1993 $)	9.9M	8-10M

Table 2.4: Code validation.

2.5 gives the performance summary for the compound helicopter and the tilt rotor. The performance summary lists the disk loading, cruise speed, travel time, rotor diameter, take-off mass, fuel capacity, nominal power, initial cost, DOC/asm, life cycle cost and the rentability index.

Description	Units	Compound Helicopter	Tilt Rotor
Disk Loading	lb/ft^2 (kg/m^2)	5.77 (30)	9.62 (50)
Cruise Speed	knots	180	250
Travel Time	hours	3	2.15
Rotor Diameter	ft (m)	29.59 (9.02)	15.06 (4.95)
Take-off weight	lb (kg)	4229.22 (1918.34)	4245.38 (1925.67)
Fuel Weight	lb (kg)	927.9 (420.9)	626.88 (284.35)
Nominal Power	hp (kW)	886.45 (661.03)	882.24 (657.89)
Initial Cost (Purchase Price)	US$	2.06M	3.48M
DOC/asm	US$	0.6385	0.729
LCC	US$	7.31M	11.76M
Rentability Index	-	15.75	15.64

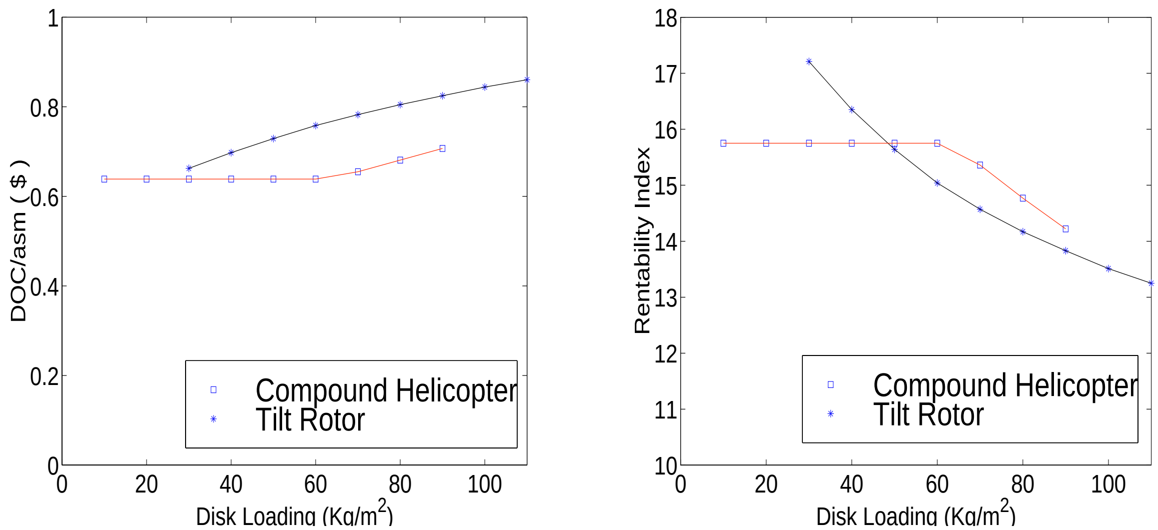
Table 2.5: Trade study performance summary.

2.3.6 Downselection

Based on the performance summary in Table 2.5, the following conclusions are made:

1) For the same payload, the compound helicopter and tilt rotor have nearly the same gross weight and installed power. However, with blades folded, the compound helicopter will require less space than the tilt rotor. The larger apron footprint directly impacts the cost of vertiport development, especially in downtown areas.

2) The compound helicopter has a lower purchase price ($2.06 million) compared to the tilt rotor ($3.48 Million). The RFP stipulates that the purchase price must be comparable to existing fleets of 4-6 seat helicopters. Clearly, the tilt rotor is a very expensive solution, and does not fulfill the stringent



(a) DOC/asm *vs.* disk loading.

(b) Rentability index *vs.* disk loading.

Figure 2.6: DOC/asm and rentability index *vs.* disk loading.

RFP cost requirements.

3) The compound helicopter has a lower DOC/asm ($0.63) as compared to the tilt rotor ($0.72). Note that these numbers are much higher than the typical DOC/asm for conventional fixed wing turboprops ($0.15).

4) The life cycle cost for the compound helicopter is $7.31 million as compared to $11.76 million for the tilt rotor. Ultimately, cost is driven by production quantity. Therefore aircraft that have good mission adaptability characteristics will be sold in larger quantities and hence will be cheaper. The compound helicopter is a very versatile aircraft. It has excellent hovering capability coupled with high speed cruise capability. Hence, it can have numerous applications (search and rescue, long range civil transport, surveillance etc). The tilt rotor, on the other hand, has poor hovering efficiency and is much more restricted in its potential applications. Thus the compound helicopter is the more cost-effective solution.

5) The rentability index for the compound helicopter (15.75) is marginally greater than the tilt rotor(15.64). The primary reason for this is the cruise speed of 250 knots used for the tilt rotor. For a tilt rotor with a cruise speed of 350 knots the present analysis gives a rentability index of 27.27 and DOC/asm of $0.47, thus greatly improving its marketability. However, such a high speed tilt rotor would have to cruise at 18000 ft where its cruise efficiency would be the greatest. Since the RFP stipulates that the maximum cruise altitude is 10000 ft, a cruise speed of 250 knots is more realistic. In conclusion, within the constraints of the RFP, the tilt rotor does not provide a superior rentability index, in spite of its higher cruise speed.

6) FAA certification policies exist for helicopters along with pilot training regulations, safety procedures and other associated infrastructure. On the other hand, no FAR exists for tilt rotors. Therefore, the compound helicopter is more suitable as a personal transport VTOL aircraft at the present time.

7) The main disadvantage of the compound helicopter is that it takes 3 hours to complete a 540 nm trip compared to 2 hours and 9 minutes for the tilt rotor. However, the trade study shows that the reduced passenger flight time for the tilt rotor if offset by the reduced cost and superior mission flexibility of the compound helicopter.

Thus the compound helicopter is the best solution to meet the RFP.

2.4 Compound configuration trade studies

Numerous design decisions must be made before the compound helicopter layout can be frozen. Central to the concept of a compound helicopter is the notion of thrust and lift off-loading of the main rotor. The thrust off-loading enables the fuselage and the rotor disk to be kept nearly level in high speed forward flight, improving the cruise lift/drag ratio. Lift off-loading is beneficial if the rotor is operating close to the stall boundary (Since the rotor lift requirements are reduced, the classical retreating blade stall envelope can be expanded). This section will deal with various design trades associated with compound helicopters.

2.4.1 Thrust compounding mechanism

The objective of this section is to select an appropriate thrust augmentation mechanism. In chapter 6 we show that, for peak efficiency, 80% rotor thrust off-loading is necessary. This corresponds to a static thrust capacity of 660 lbs at 4000 ft, ISA. For the present study, the following thrust generation mechanisms were considered: jet propulsion, variable cycle engine, ducted fan, and the propeller.

1) Jet propulsion. Williams International, in collaboration with NASA Lewis, is developing a high bypass turbofan (FJX-2) for general aviation. This engine can provide up to 700 lbs of thrust and weighs 100 lbs. The engine 41 inches long and 14.5 inches in diameter. For our application, the moderate cruise speed (180 knots) and low cruise altitudes (4000 ft) will adversely affect the fuel efficiency of the FJX-2. Thus jet propulsion is not a cost effective solution to the thrust augmentation problem.

2) Variable cycle engine. Westland Helicopters and Rolls-Royce [BB91], [JHB93] have proposed modifying the RTM322 engines with variable area exhaust nozzles. With the exhaust nozzle in the fully open position, the engine will behave as a conventional turboshaft engine but as the nozzle is progressively closed, back pressure increases and there is a transfer of energy from shaft power to jet thrust. This results in a convertible, variable cycle powerplant that produces high shaft power but very little thrust at one extreme or a high proportion of thrust with some shaft power at the other. The engine may be operated smoothly anywhere between these two extremes.

The variable cycle engine is a simple and readily available option for using a turboshaft engine in a dual mode (shaft power and thrust generation). However this type of design results in a reduction in cruise efficiency and hence is not necessarily the best solution in a transport role [JHB93]. This is particularly true in this case because of the high thrust requirements (660 lbs at 4000 ft, ISA). In fact, Westland's development of the variable cycle engine is directed towards military helicopters (Lynx) where minimizing the DOC/air-seat-mile is not the primary goal. For these reasons, the variable cycle engine was rejected as a possible thrust augmentation mechanism.

3) Ducted fan. This scheme consists of a fan enclosed inside a shroud. The advantage of the ducted fan is that it shields a thrusting propeller from the wake of the main rotor. The ducted fan also results in a smaller fan diameter compared to a conventional propeller. The primary disadvantage of this system is large drag on the duct (shroud) in high speed forward flight (180 knots). For these reasons, the ducted fan was also considered unsuitable for this project.

4) Propeller. The conventional propeller is used on the Cheyenne for thrust augmentation. The propeller is the most efficient solution for generating large thrust (660 lbs) at moderate forward speeds (180 knots). Also, considerable information/test data is available on propeller design. For these reasons, the propeller was selected for the thrust compounding mechanism. An alternative to the conventional propeller is a contra-rotating propeller system which will reduce the swirl velocity in the wake, improving the propeller efficiency. Since limited design data is available on such systems, and due to the increase in the complexity of the transmission, contra-rotating propellers were rejected in favor of a conventional propeller.

2.4.2 High wing *vs.* low wing

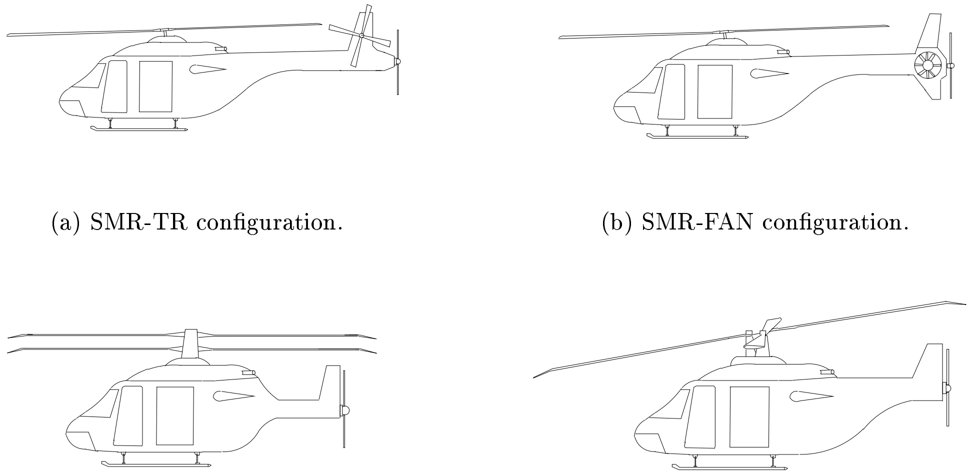
In chapter 6 we show that the optimum lift offloading ($\frac{Wing\ Lift\ at\ Cruise}{Gross\ Weight}$) is 40%. This results in a wing cruise lift requirement of 2025 lbs with associated wing dimensions of 14.93 ft span, 3.32 ft root chord and 1.66 ft tip chord. The wing can either be a high wing (located above the passenger cabin) or a low wing (located below the passenger cabin). The advantages of a low wing are reduced wing-rotor interactional losses in ground effect and lower interference drag between the rotor and the wing in cruise.

However, wake measurements [Bha98] have shown that the induced velocity Out of Ground Effect (OGE) below the rotor disk asymptotes to a value of 1.8 times that at the plane of the rotor disk at a distance of about 0.2 times the rotor radius. Since both the high and low wing configurations were likely to be separated from the rotor disk by more than 0.2R, the influence of the rotor inflow on the wing for both configurations out of ground effect are approximately equal. For normal operating HOGE and cruise conditions, the aerodynamic considerations therefore were not overwhelmingly different for either configuration.

The primary disadvantage of the low wing is the possibility of the wings striking the ground during landing and take-off. The low wing also results in ground interference, especially during cargo/passenger loading and unloading. In contrast the high wing gives sufficient ground clearance margins. A high wing can be given an anhedral angle to eliminate the risk of the blades striking the wings and to improve the aircraft lateral-directional stability characteristics. For these reasons, a high wing was selected for the present design.

2.4.3 Single main rotor *vs.* dual main rotors

In this section the relative merits of single main rotor and dual main rotor compound configurations are compared. The rear propeller and high wing are common to both types of configurations. Figures 2.7(a) and 2.7(b) show the classical single main rotor with tail rotor (SMR-TR) and single main rotor



(a) SMR-TR configuration. (b) SMR-FAN configuration.

(c) Coaxial-ABC configuration. (d) Synchropter configuration.

Figure 2.7: Most competitive configurations.

with fan-in-fin (SMR-FAN) configurations, while Figures 2.7(c) and 2.7(d) depict the coaxial-ABC and synchropter dual main rotor configurations.

A detailed drag estimation was carried out for each of the above concepts using the procedure outlined in Chapter 6. The equivalent flat plate areas for the SMR-TR, SMR-FAN, coaxial-ABC, and synchropter configurations are listed in Table 2.6. These equivalent flat plate areas include the fuselage, tail boom, hub, landing gear, tail rotor/fenestron drag and the wing drag. The rotor blade drag is not included in the flat plate area calculation. The fuselage frontal area is kept the same for all the configurations, while the fuselage length is reduced for the more compact coaxial-ABC and synchropter configurations. Table 2.6 shows that the SMR-TR has the least flat-plate area and the SMR-FAN, synchropter and coaxial-ABC configurations have progressively increasing drag. In the dual main rotor designs the two hubs account for over 50% of the total drag. However, the absence of the tail rotor and reduced fuselage length (less wetted area) compensates for the drag penalty of the extra hub.

Configuration	**Flat Plate Area m^2**
SMR-TR	0.887
SMR-FAN	0.896
Synchropter	0.943
Coaxial-ABC	0.97

Table 2.6: Equivalent flat plate areas of all non lifting surfaces and wing.

A major disadvantage of the SMR-TR and SMR-FAN designs is that the presence of the large propeller (1.9 m diameter) and the tail rotor/fenestron results in a long and heavy tail boom. It is particularly difficult to satisfy the CG balancing requirements on such configurations. The Cheyenne had guns and armaments mounted near the cockpit which helped to bring the vehicle CG close to the main rotor. For civil transport aircraft, this is not possible. In contrast, the coaxial-ABC and synchropter compounds offer more compact and elegant solutions. The ABC rotor generates all its lift on the advancing side and hence operates at high angles of attack on the advancing side. Since the incident velocity is also the highest on the advancing side, this results in large profile losses. Thus the drag penalty on a coaxial-ABC rotor is likely to be higher than a synchropter rotor. This coupled with the fact that the effective flat plate area (non-lifting surfaces and wing) for the synchropter is lower than the coaxial-ABC (Table 2.6), indicates that the synchropter compound has a better cruise efficiency than the coaxial-ABC compound. For these reasons, the synchropter compound was selected.

2.4.4 Landing gear

For the landing gear there are several possibilities : skid, nose-wheeled tricycle and tail-wheeled tricycle. The skid and wheeled tricycle configurations can be either fixed or retractable. The Calvert has a large propeller (diameter 1.9 m(6.23 ft)), located at the rear end of the tail boom. Consequently, a tail wheeled tricycle configuration will result in low ground clearance for the propeller blades. Therefore the tail-wheeled tricycle configuration was rejected. Among the fixed configurations, the fixed nose wheel tricycle configuration has higher drag and cost compared to the fixed skid configuration. Therefore the fixed nose-wheel tricycle configuration was rejected. Among the retractable configurations, the retractable nose-wheel tricycle design provides greater flexibility for ground operations (taxiing, turning etc) compared to the retractable skid. Therefore the fixed skid and retractable nose-wheel tricycle configurations were downselected for further analysis.

Parameter	**Units**	**Fixed-Skid**	**Retractable-Wheeled**
Flat Plate Area	(m^2)	(0.95)	(0.85)
Gross Weight	lb (kg)	5322.2 (2414.1)	5283.4 (2396.5)
Fuel Weight	lb (kg)	1216.1 (551.6)	1128 (512)
Installed Power	hp (kW)	1588 (1184)	1475 (1100)
Purchase Price	US$	2.08M	2.07M

Table 2.7: Skid *vs.* retractable landing gear.

The weights of the landing gear were estimated using the RTL formulae [SS83] described in chapter 5. The retractable nose-wheel tricycle landing gear (93 kg) weighs approximately three times the fixed skid landing gear (34 kg). However, the drag analysis described in the previous section indicates that the retractable landing gear results in a 0.1 square meter reduction in the equivalent flat plate area. Table 2.7 compares a 6-bladed synchropter (two three bladed hubs) with fixed-skid and retractable-wheeled landing gears. Table 2.7 shows that the retractable landing gear results in a 39.6 kg saving in fuel consumption per flight (This is a reflection of the lower flat plate area of the retractable configuration). Over the life time of the helicopter, the reduced fuel consumption amounts to savings of $0.08 million. The retractable configuration also requires lower cruise power and hence lower transmission and engine weight. However the decrease in weight associated with the engine, transmission and fuel is somewhat offset by the increased weight of the retractable landing gear (93 kg compared to 34 kg for the fixed). The purchase prices of the fixed-skid and retractable-wheeled versions are nearly the same since the increased cost of the retractable landing gear is offset by the reduced engine power and gross weight of the retractable configuration.

Since the primary mission is to cruise at 180 knots, the reduction in flat plate area of 0.1 square meters associated with the retractable-wheeled configuration is very attractive because it causes substantial reduction in the installed power (113 HP), fuel weight (39.6 Kg), purchase price ($10,000) and life cycle cost ($80,000). For these reasons the retractable nose-wheeled tricycle landing gear was selected for the present design.

2.4.5 Number of blades

The 4-bladed synchropter (two 2-bladed hubs) is cheaper to manufacture and maintain than the 6-bladed configuration (two 3-bladed hubs). 2-bladed hubs are typically designed as teetering and stiff in-plane (no dampers). 3-bladed hubs on the other hand are typically soft in-plane and require lag dampers to prevent ground/air resonance instabilities. However, high loads and vibration is a very serious problem for stiff in-plane, teetering 2-bladed rotors (especially in high speed forward flight). BVI noise is also a greater concern for 2-bladed rotors as compared to 3-bladed ones (increased strength of tip vortices).

Parameter	**Units**	**4-bladed**	**6-bladed**
Gross Weight	lb (kg)	5162.8 (2341.8)	5283.4 (2396.5)
Hub Weight	lb (kg)	56.4 (25.6)	96.3 (43.7)
Blade Weight	lb (kg)	102.1 (46.3)	150 (68)
Fuel Weight	lb (kg)	1123.7 (509.7)	1128 (512)
Installed Power	hp (kW)	1468 (1095)	1475 (1100)
Purchase Price	(US$)	1.99M	2.07M

Table 2.8: 4-bladed *vs.* 6-bladed synchropter comparison.

Table 2.8 compares the 4-bladed (two 2-bladed rotors) and 6-bladed (two 3-bladed rotors) synchropter configurations. The rotor radius and solidity is kept the same for the 2-bladed and 3-bladed rotors. Therefore the blade chord of the 3-bladed rotor is two-thirds that of the 2-bladed rotor. Table 2.8 indicates that the 4-bladed system results in a marginally lower gross weight, fuel weight and installed power compared to the 6-bladed configuration. These benefits will probably be offset by the increased loads and vibration associated with the stiff in-plane teetering rotor. However, the main advantage of the 4-bladed configuration is the reduced cost of blade manufacture. The rotor blade is one of the more expensive components in a helicopter. Table 2.8 shows that the purchase price of the 4-bladed configuration is $80,000 lower than the 6-bladed configuration. The cost calculations in Table 2.8 are based on the RFP cost formulae. The RFP rotor cost model does not include details of lag damper cost. The 4-bladed configuration with two 2-bladed, stiff in-plane, teetering hubs does not require lag dampers and this will result in a substantial reduction in purchase price as well as maintenance costs. Additionally, the 4-bladed intermeshing rotor allows for improved safety clearances and reduced possibility of the blades striking each other. Problems of high loads and vibration associated with the stiff in-plane rotor system are mitigated due to thrust and lift offloading of the main rotor in high speed forward flight. For these reasons, the 4-bladed synchropter configuration with two 2-bladed stiff in-plane teetering hubs is the best compromise in terms of cost, complexity, safety, performance, maintainability and aesthetics.

2.5 Conclusion

This chapter has presented a large number of design choices. Initially ten concepts were considered: conventional helicopter, tandem/synchropter, co-axial, compound, ABC, tilt rotor/wing, stopped rotor, cruise fan, Verticraft and autogyro. A comparison matrix was prepared to downselect two concepts for detailed analysis (the thrust and lift compounded helicopter and the tilt rotor). The trade-off study revealed that the compound helicopter is the more cost-effective solution to the present RFP. The maximum cruise altitude limitation of 10,000 ft coupled with the stringent RFP cost requirements (purchase price should be comparable to existing fleets of 4-6 seat helicopters) severely limit the tilt rotor. In contrast the compound helicopter offers the promise of improved performance (180 knots, 540 nm) with minimum increase in cost and complexity over existing helicopter designs.

Various options were considered for the thrust compounding mechanism (jet propulsion, variable cycle engine, ducted fan, contra rotating propeller and conventional propeller). It was determined that the conventional propeller is the most efficient mechanism for generating the required thrust at moderate cruise speeds (180 knots). For the wing design, the high wing was selected over the low wing (The high wing gives improved ground clearances).

A comparison of single main rotor and dual main rotor compound configurations revealed that the single main rotor designs are "tail heavy" and not ideally suited to civil transport applications (CG balancing problems). Dual main rotor configurations such as the co-axial ABC and the synchropter compounds offer more compact configurations. However, the large profile power of the ABC rotor reduces its cost effectiveness. Drag estimates indicate that the increased drag penalty associated with two rotor hubs (synchropter) is partially offset by the absence of tail rotor blades, tail rotor hub and reduced fuselage length. However, the synchropter hubs and transmission deck must be carefully designed (with hub caps, fairings etc) to minimize the drag penalty. The synchropter compound emerged as the best compromise for meeting the RFP performance and cost targets.

The retractable-wheeled landing gear gives significant improvement in cruise efficiency at 180 knots compared to a fixed-skid landing gear. Therefore, a retractable nose-wheel tricycle landing gear was selected. Also, a 4-bladed synchropter (two 2-bladed hubs) significantly reduces manufacturing cost as compared to a 6-bladed configuration (two 3-bladed hubs). Therefore, a 4-bladed configuration was selected. All subsequent chapters will describe the detailed design of the 4-bladed compound synchropter.

3 Aircraft Level Description

The Calvert is a thrust and lift compounded synchropter. It utilizes a pair of intermeshing rotors to provide thrust and control in low speed flight. At higher speeds, the main rotors are thrust and lift off-loaded. Figure 3.1 is a four-view of the Calvert. Table 3.1 identifies key parameters and capabilities of the Calvert. These specifications indicate that the Calvert is designed to fulfill the RFP requirements (180 knots, 540 nm) with 4 passengers. However, with 6 passengers (maximum seating capacity), the Calvert can fly 552 nm at 160 knots cruise speed. The 6-passenger mode trades cruise speed for reduced operating costs. The advantages and disadvantages of the 4- and 6-passenger flight modes are discussed in greater detail in chapter 9. The final choice of operation for a specific mission lies in the hands of the user.

Figure 3.2 shows an internal system view of the Calvert. By incorporating parametric modeling into the design process, detail design of the Calvert will benefit from designers being able to share data directly from the preliminary drawings. Additionally, when manufacturing plans are being created, the virtual factory will help to maximize efficiency of space and handling before any reorganization of existing factories begins. It is clear that the Calvert is a unique aircraft. Special design aspects of the Calvert are discussed in the following sections.

Table 3.1: Performance data and specifications.

Parameter	Units	4-passenger mode	6-passenger mode
Weights			
Empty Weight	*lb*	2926.6	same
Take-Off Weight	*lb*	5067.7	5486.4
Payload	*lb*	2141.1	2559.8
Performance			
Cruise Altitude	*ft*	4000	same
V_{cruise}	*kt*	180	160
$V_{bestrange}$	*kt*	140	142
V_{NE} (Based on rotor stall)	*kt*	210	190
V_{loiter} (velocity for max. endurance)	*kt*	75	75
Range @ V_{cruise}	*nm*	548	552
Max. Range	*nm*	584	580
Max. Endurance	*hrs*	4.6	4.4
Max. Rate of Climb	*ft/min*	5360	4818
Rate of Climb at Cruise	*ft/min*	2100	1950
HOGE (ISA +20°C)	*ft*	17000	14700
Engines			
No. of Engines	–	2	same
Max. Continuous Power	*hp*	1050	same
Contingency Power (30 sec)	*hp*	1312	same
Cruise Power	*hp*	1050	same

continued...

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Parameter	Units	4-passenger mode	6-passenger mode
Hover Power	*hp*	780	same
Shaft Speed (Hover - Cruise)	*RPM*	21000 - 18136	same
TRANSMISSION			
Contingency (2 min)	*hp*	1320	same
Intermediate (30 min)	*hp*	1215	same
Max. Continuous	*hp*	1070	same
OEI Emergency (30 sec)	*hp*	845	same
OEI Contingency (2 min)	*hp*	815	same
OEI Intermediate (30 min)	*hp*	678	same
OEI Continuous	*hp*	656	same
MAIN ROTORS			same
No. of Blades	–	2 × 2	same
Diameter (Each Rotor)	*ft*	34.43	same
Chord (Each Rotor)	*ft*	1.04	same
Disk Loading (Each Rotor)	lb/ft^2	2.72	2.95
Solidity (Each Rotor)		0.038	same
Twist (Linear)	*deg*	-8	same
Tip Shape	–	Similar to BERP	same
Shaft Tilt (Forward)	*deg*	5.3	same
Shaft Tilt (Lateral)	*deg*	13	same
Root Cut-Out	%	9.7	same
Rotor Tip Speed Schedule			same
0 - 100 kts (forward speed)	*ft/sec*	722	same
140 - 180 kts (forward speed)	*ft/sec*	623	same
190 - 210 kts (forward speed)	*ft/sec*	607	-NA-
Airfoil Sections			same
0R - 0.55R		RAE 9648	same
0.6R - 0.8R		OA 312	same
0.85R - R		OA 309	same
PROPELLER			same
Diameter	*ft*	6.23	same
No. of Blades	–	6	same
Twist (Linear)	*deg*	40	same
Tip Speed	*ft/sec*	755	same
Airfoil		Clark YM 15	same
FUSELAGE			same
Length	*ft*	24.87	same
Width	*ft*	4.5	same
Cabin Volume	ft^3	127.9	same
WING			same
Airfoil Section		GA(W) - 2	same
Surface Area	ft^2	37.2	same

continued...

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Parameter	Units	4-passenger mode	6-passenger mode
Span	*ft*	14.93	same
Root Chord	*ft*	3.32	same
Tip Chord	*ft*	1.66	same
Aspect Ratio	-	6	same
Forward Sweep	*deg*	10	same
Anhedral	*deg*	5	same

3.1 Thrust and lift compounding

When flying at the velocities required by the RFP, propellers and wings are more efficient than rotors for producing thrust and lift respectively. Hence, the Calvert is equipped with a thrust augmenting propeller (80% of required thrust) and a lift augmenting wing (40% of total lift).

An isolated rotor operating at 180 knots cruise speed has a lift/drag ratio of approximately 4. The Calvert's wing (aspect ratio of 6) has a cruise lift/drag ratio at 180 knots of 10 (this includes the effect of the rotor downwash on the wing). Since the predominant drag at 180 knots is the parasite drag associated with the fuselage and rotor hubs, the wing does not significantly improve the cruise efficiency. However, the wing generates 40% of the required lift in cruise, thus providing sufficient separation between the 180 knots operating condition and the rotor stall boundary. A six-bladed propeller located at the rear end of the tail boom is used to provide thrust augmentation for the Calvert in cruise. This thrust augmentation is important because it helps the fuselage remain level in cruise and allows the rotors to operate with only a slight tilt of their tip path planes. Both of these effects lead to reduced parasite drag. This is significant since, when cruising at 180 knots, parasite drag can represent 70% of the power requirements.

3.2 Variable RPM power plant

Since the Calvert operates over a wide range of flight speeds (from hover to 180 kts), it is necessary for the rotor to operate at different RPMs. If the rotor speed is too high, it will encounter compressibility effects on the advancing side, even at low advance ratios and noise will be a problem throughout the flight envelope. At low rotational speeds, the rotor will experience retreating blade stall at relatively low advance ratios and will have poor autorotative characteristics. Hence, a means of altering the rotor tip speed in conjunction with the compounding features in flight is desirable.

Several high-speed concepts have examined using variable diameter rotors as a means of optimizing rotor performance through a variety of flight modes. The Calvert uses a simpler, variable RPM system. This concept has been proven in flight by the Mitsubishi Heavy Industry's MH2000. During the development of the MH2000, MHI also developed the MG5-100 turboshaft engine, which is capable of operating at two distinct RPM levels. Additionally, NASA Lewis has explored broad-spectrum engines capable of operating with high power and good specific fuel consumption over a wide power turbine RPM range [Tal91].

3.3 Low drag design features

Minimizing the vehicle drag is critical for a high speed compound helicopter. From the very outset the Calvert's fuselage, rotor hubs and sub-systems have been designed with a view to drag minimization. At the same time care has been taken to ensure that the fuselage crashworthiness and pilot visibility requirements are not compromised. The Calvert's low drag design features are given below.

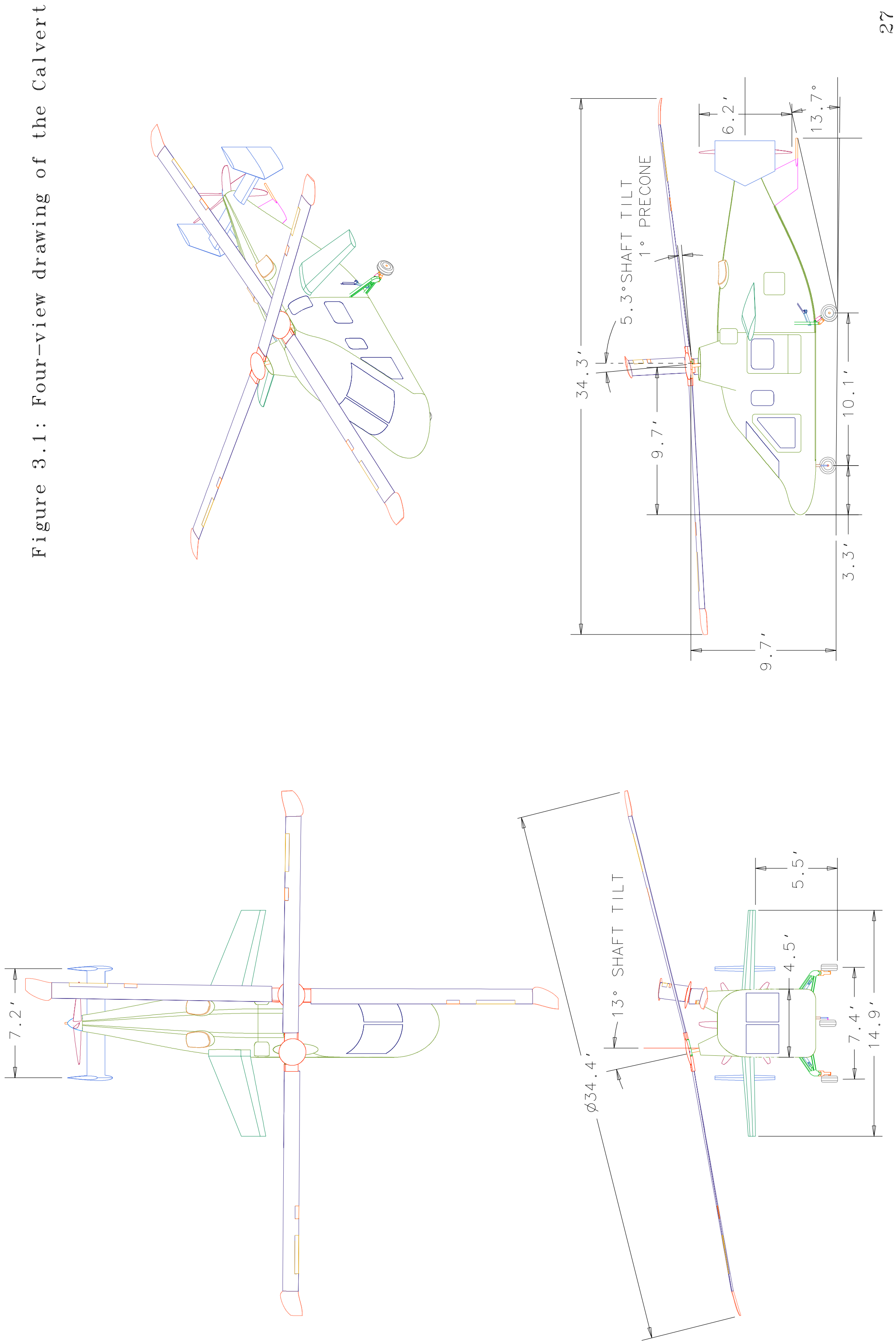

Figure 3.1: Four-view drawing of the Calvert.

Figure 3.2: Internal system view of the Calvert.

- Both engines and the transmission deck are fully enclosed inside an aerodynamic fairing.
- The swashplate and upper controls are all enclosed inside the pylons. To prevent pressure buildup in-between the two pylons, the fairings are cambered towards the outboard side. A flange will be included at the top of the aerodynamic fairing to minimize rotor interference.
- The Calvert has a door-hinge type hub (similar to the AH-1G) with a very thin cross-section resulting in low drag. Additionally, the hub is enclosed inside a specially designed hub cap which further reduces the hub drag.
- The Calvert has retractable landing gear.
- The seating is arranged in three rows of two seats to minimize frontal area.
- The shortened tail boom (synchropter configuration) results in reduced wetted area and hence less drag. Also, the propeller creates a low pressure region upstream of the propeller disk, which reduces flow separation from the aft upswept fuselage.

3.4 Advanced active systems

The Calvert is equipped with several advanced active systems in order to improve aircraft performance, handling, ride-quality, safety, reliability and cost-effectiveness. A discrete piezo-stack driven servo-flap is installed in the rotor blade for individual blade control of helicopter vibration. The flap is controlled using an adaptive, time domain, neural network based control algorithm. Additionally, a shape memory alloy actuated trailing edge trim tab is installed for active rotor blade tracking. Structure borne cabin noise is reduced via a novel hybrid active-passive scheme. The passive treatment (internal trim panel) is most effective for broadband high frequency noise (related to transmission). The active component consists of trim panels with surface bonded piezo-ceramic patches for active cancellation of low frequency noise (related to the rotor). The Calvert is also equipped with an advanced, fully integrated prognostics and health management (PHM) system and a FADEC system is used to control the engine settings, vary the engine speed depending on the flight condition and accelerate the remaining engine to the appropriate setting during an OEI situation.

3.5 Variable payload configurations

One of the main advantages of the Calvert is that it provides users with flexibility. Designed with enough power and fuel capacity to carry four people 548 nautical miles at 180 knots, the Calvert fulfills all of the requirements of the RFP. However, the passenger cabin and baggage space are designed with enough room to accommodate six people. With this increased payload, the Calvert can travel 552 nm at 160 knots or 580 nm at 142 knots.

3.6 Mission adaptability

The Calvert maintains all the capabilities of a conventional helicopter. Hence, the Calvert is a single airframe that can replace existing fleets of helicopters and light aircraft. Additionally, the synchropter configuration and the powerful engines of the Calvert allow it, with only slight modifications, to perform heavy lift operations and with its large fuel capacity, these operations can be carried out in remote areas with large amounts of time on-site.

3.7 Maximum mission readiness

The Calvert is designed for low maintenance. Through advanced health and usage monitoring, the Calvert essentially inspects itself. The Calvert is also designed to provide easy access to components requiring frequent inspection or replacement and the number of parts that are lifetime rated is maximized, thus further reducing inspection time.

4 Calvert: Detailed Design

A thrust and lift compounded synchropter was chosen as the best configuration to fulfill the RFP requirements. Detailed design of major systems is described in this chapter. The chapter concludes with a section on aircraft operation. The inboard profile drawing is shown in Figure 4.1.

4.1 Main rotor and hub design

The design of the main rotor system includes the selection of the hub configuration, number of rotor blades, rotor diameter, tip speed, solidity, airfoil section, planform, and materials. The detailed design of the main rotor is described in this section.

4.1.1 Rotor system

The Calvert has two counter-rotating intermeshing rotors with two separate hubs. Rotor designers are always looking for hub designs that give lower parts count, weight, drag and maintenance costs. Recent trends are towards simpler hub designs. Each of the Calvert's main lifting rotors is a two-bladed teetering rotor. The hub is made out of titanium and the blades are manufactured using composite materials. The rotor blades have a diameter of 34.43 feet (disk loading: 2.72 lb/ft^2) and chord of 1.04 ft. The blades have a linear twist of $-8°$ and the rotor shaft tilt is 5.3°. The solidity of each rotor is 0.038 and the tip speed varies from 220 m/s (hover) to 190 m/s (cruise). The blades have a suitably designed tip (similar to the BERP) which extends the rotor stall boundary to higher speeds and reduces blade-vortex-interaction noise (see Figure 4.2).

4.1.2 Airfoil selection

The performance of the main rotor depends, in large measure, on the aerodynamic characteristics of its airfoil. Unlike a fixed wing, a helicopter blade operates in a time periodic rotating aerodynamic environment. During each rotor revolution, the airfoil sections on helicopter rotors encounter a wide range of operating conditions. The airfoil at a particular section is exposed to diverse aerodynamic environments depending upon whether the helicopter is in hover or forward flight or whether the blade is on the advancing or retreating side. A suitable airfoil distribution for a helicopter rotor blade must have the following properties: (i) high lift coefficient (ii) low drag (all along the blade) (iii) high drag divergence Mach number at the tip (iv) camber to give a high C_{lmax} (v) low control system load (vi) good unsteady stall properties (vii) good lift to drag ratio.

In high speed forward flight, an increasing portion of the retreating side of the rotor disk gets into stall condition. In general, the goal is to balance the advancing blade requirements with those of the retreating blade while maintaining a good overall lift to drag ratio. No single airfoil can satisfy all these requirements. Hence, different airfoils are used along the blade span to achieve optimum aerodynamic performance. For the Calvert, three types of airfoils are used: RAE9648 (inboard 50% of the blade), OA312 (from 50% to 77.5%), OA309 (from 77.5% to the tip) [Sel99]. As shown in Figure 4.2, the planform near the tip is similar to a BERP tip which has

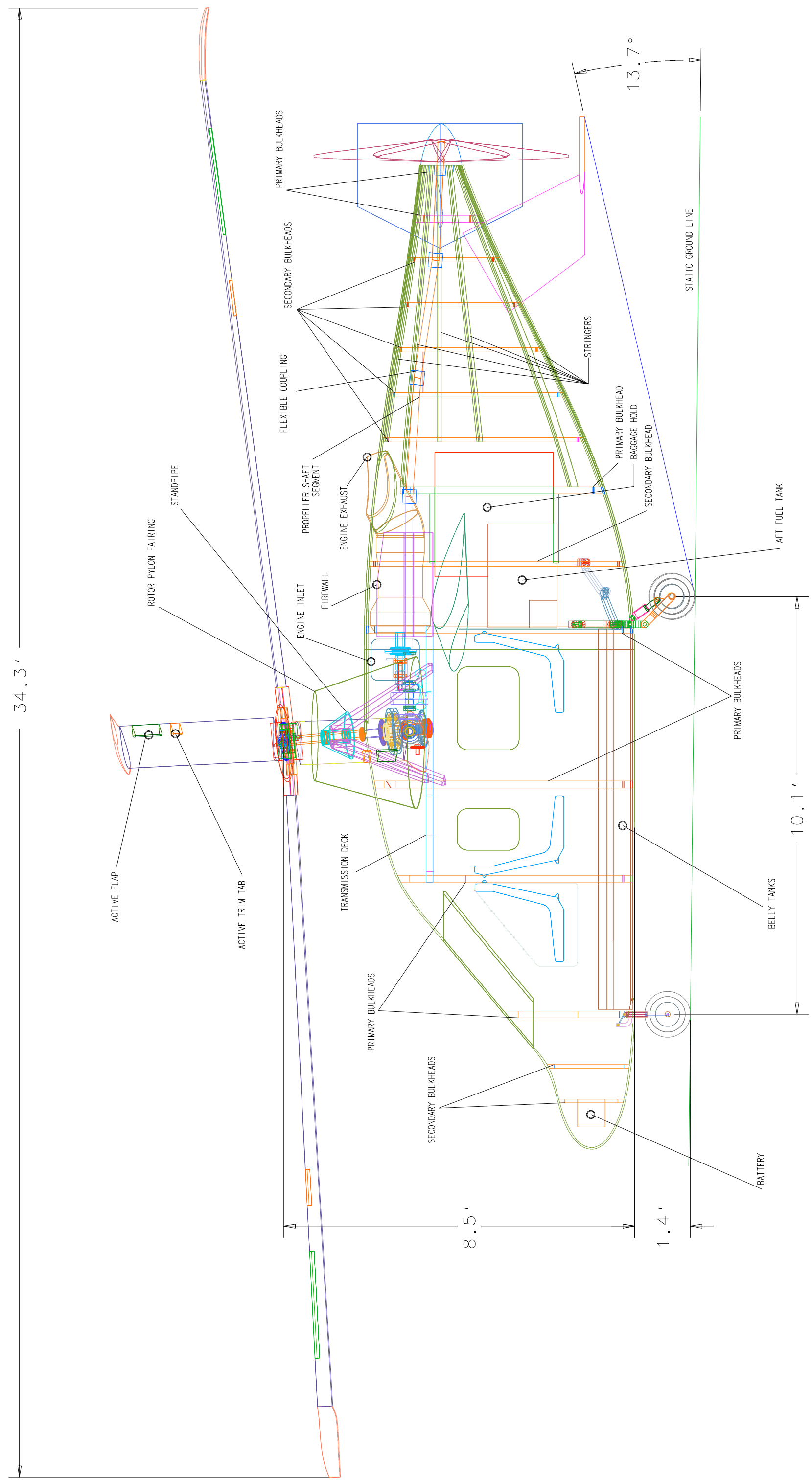

Figure 4.1: Inboard profile view of the Calvert.
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Figure 4.1: Inboard profile view of the Calvert.

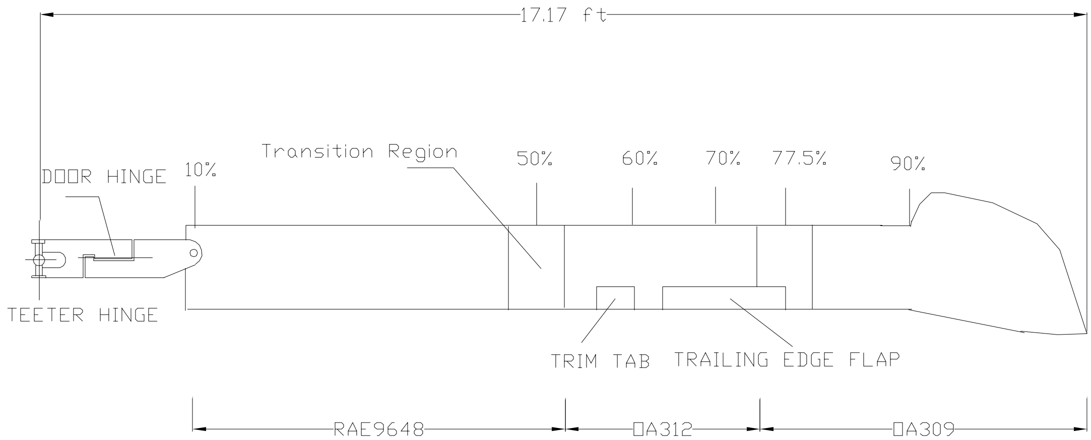


Figure 4.2: Blade and hub schematic (not to scale).

been known to extend the stall boundary beyond those achieved by regular tip shapes. More detailed testing and analysis will subsequently lead to an appropriate tip shape for the Calvert rotor blades. There is a 5% transition region between two adjacent airfoil sections. Figure 4.3 from [Vui90] shows the properties of various airfoils for comparative purposes. The OA312 airfoil provides most of the blade lift and is a 12% thick cambered airfoil with a C_{lmax} of 1.5. The most significant gains offered by the airfoil OA312 are evident in advancing blade conditions and involve a high drag divergence Mach number of 0.78, a drag level decrease prior to divergence and low moment coefficient [Vui90]. The OA309 airfoil is a 9% thin cambered airfoil with good lifting properties, selected primarily for its high Mach-drag-divergence number (0.84). The profiles of the OA312 and OA309 airfoil sections are shown in Figure 4.4. The strong nose down pitching moment of both the outboard cambered profiles is reduced by the reflex cambered airfoil RAE9648 used in the inboard section (where its lower stalling angle is not important).

4.1.3 Hub design

The main functions of a rotor hub are as follows: (i) the rotor lift and moments must be transmitted from the rotating frame to the fixed frame. (ii) the drive system torque must be transmitted to the rotating hub and (iii) the cyclic and collective control inputs must be transmitted from the fixed frame to the blades. The challenge in rotor hub design is to arrive at a configuration that provides the functions mentioned above with the following desired features: low weight, low drag in forward flight, low parts count, high maintainability, long fatigue life, freedom from dynamic problems and adequate control power.

The Calvert uses a stiff in-plane teetering hub. A teetering rotor has two blades that are hinged at the rotational axis, i.e. on the shaft, and usually uses no independent flap or lead-lag offset hinges. The blades are rigidly attached together, so that both blades have a common flapping axis. Thus, when one blade moves up, the other moves down like a see-saw or teeter board. A separate pitch or feathering bearing on each blade allows cyclic and collective pitch change capability. The teetering design has the advantage of being mechanically simple with a lower number of parts, and is easy to maintain. Being stiff in-plane, a two bladed teetering rotor is free from ground and air resonance problems [Yeo99]. A teetering rotor exhibits the characteristics of an articulated rotor for odd harmonics and those of a hingeless rotor for even harmonics (Figure 4.5).

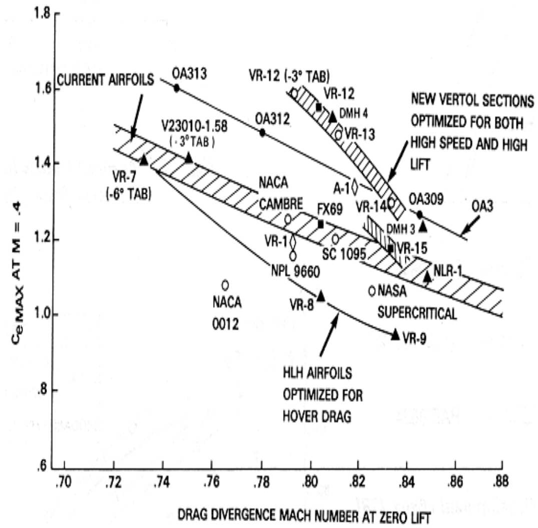
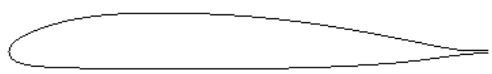
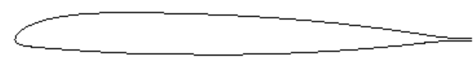


Figure 4.3: Comparison of helicopter rotor airfoils, adapted from [Vui90].



(a) OA312 (Main rotor between 50% and 77.5% of blade radius).



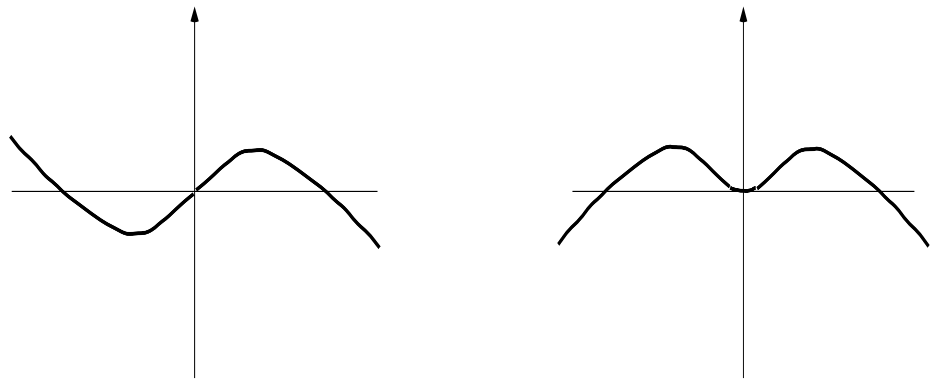
(b) OA309 (Main rotor between 77.5% of blade radius and the blade tip).

Figure 4.4: Airfoil sections used on the Calvert.

The Calvert incorporates a door-hinge hub. Because of its thin cross-section, this hub has a lower drag than that of other designs which use separate bearings for collective and cyclic pitch changes. In this design, both collective and cyclic pitch changes are incorporated about the door hinge. Figure 4.6 shows a detailed drawing of the Calvert's hub. The hub extends 20 inches (9.7% of the rotor radius) from the center of rotation. A common technique utilized in teetering rotor practice is to locate the teetering axis at a specified distance above the main portion of the rotor hub. This design is called the "undersling" and is adopted to reduce Coriolis forces induced by the teetering motion. A smaller undersling distance improves the blade-hub clearance in this synchropter configuration. Also, a larger precone angle will require a larger undersling distance to keep the Coriolis forces low. Hence, the precone angle and the undersling distance will have to be suitably optimized. The calculated blade coning angle due to flap-wise bending is 1° for cruise and 2° for hover. Since the Calvert spends the majority of the mission in cruise, a static hub precone angle of 1° is selected to minimize the blade steady stresses. For a precone angle of 1°, the calculated undersling distance is 1.4 inches. There is no rotor pitch-flap and pitch-lag coupling. The pitch link has a moment arm of 4.5 inches and the pitch horn offset is 10 inches from the center of the shaft. The moment arm has been chosen based on AH-1G hub values and can provide high control moments. The pitch horn offset has been chosen so that the rotor hub can be enclosed with a suitable hub cap resulting in significant drag reduction.

4.2 Rotor blade dynamics and stability

This section presents the dynamic behavior of the Calvert's rotor blades in the rotating condition. One of the critical parameters in blade dynamic analysis is the relationship between blade natural frequencies and blade



(a) Articulated rotor characteristics for odd harmonics.

(b) Hingeless rotor characteristics for even harmonics.

Figure 4.5: Characteristics of a teetering rotor.

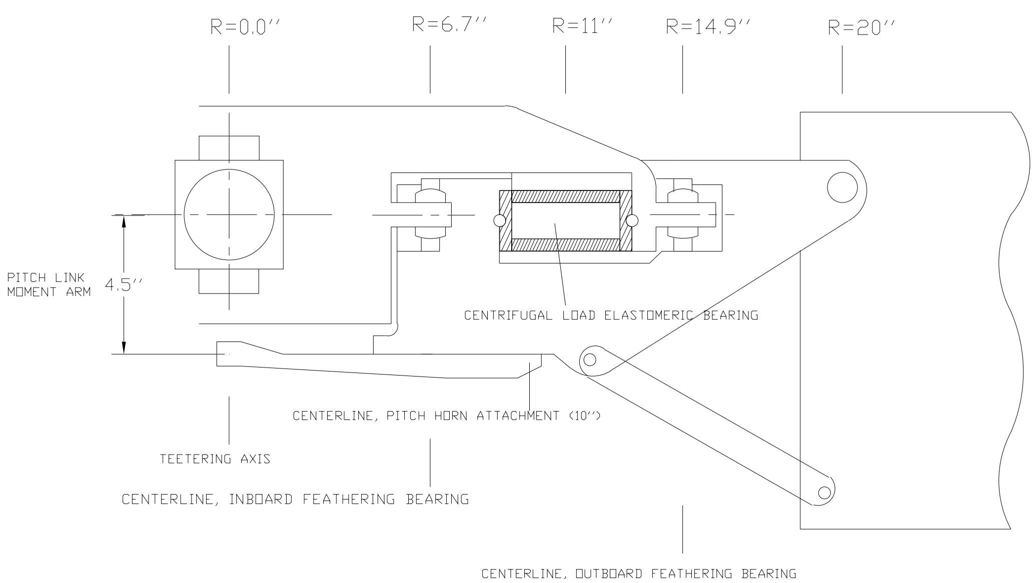
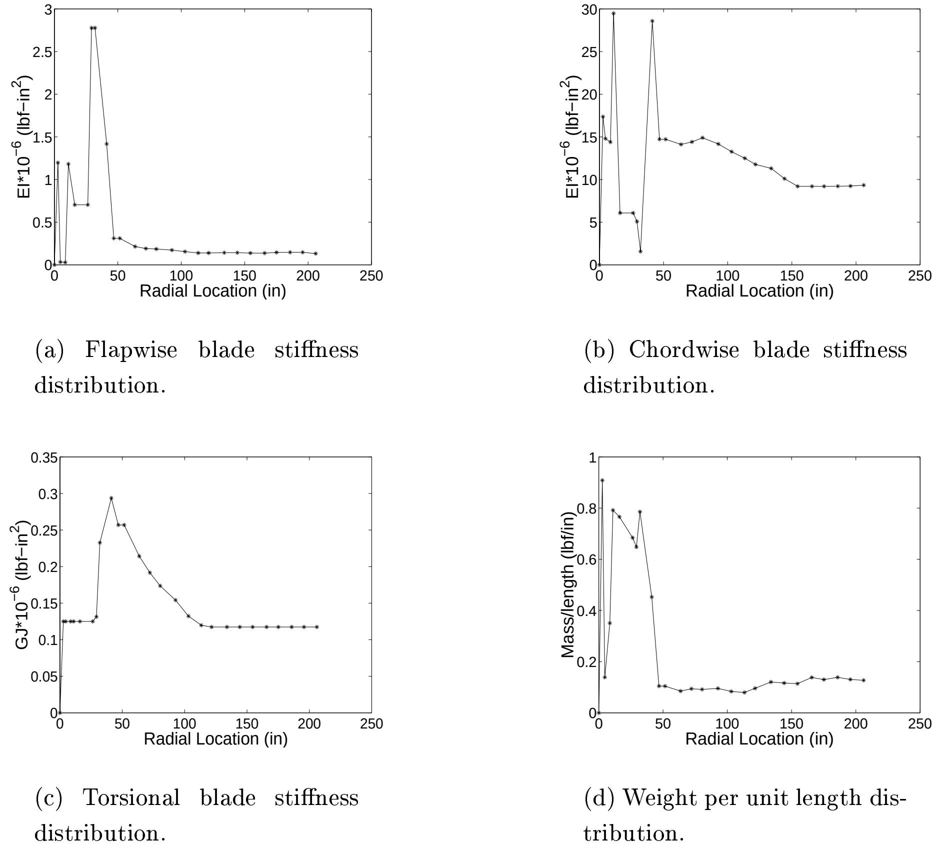


Figure 4.6: Detailed drawing of the Calvert teetering main rotor hub.



(a) Flapwise blade stiffness distribution.

(b) Chordwise blade stiffness distribution.

(c) Torsional blade stiffness distribution.

(d) Weight per unit length distribution.

Figure 4.7: Stiffness and inertia distributions on the rotor blade used for dynamic analysis.

rotational speed. It is important to avoid resonance conditions between the coupled blade frequencies and the rotor harmonics. For the Calvert, the placement of blade frequencies assumes even greater importance because of the variable engine RPM. The operating speed of the main rotor is varied from 400 RPM in hover to 346 RPM in cruise. Therefore, the Calvert's blade frequency placement must be optimized in order to maintain the required separation with the rotor harmonics over the entire range of operating speeds.

For the present analysis, the blade rotating natural frequencies are calculated using UMARC (University of Maryland Advanced Rotorcraft Code). The flapwise, chordwise and torsional stiffness distributions of the blade are shown in Figure 4.7. These values have been chosen based on non-dimensional distributions used on the AH-1G rotor hub. The Calvert hub is discretized into 5 spatial finite elements and the rotor blade is discretized into 8 spatial finite elements. Each spatial element has 15 degrees of freedom (4 flapwise bending, 4 lagwise bending, 3 torsion and 4 axial deflection). Figure 4.8 shows the first three flap, first lag and first torsional frequency of the Calvert rotor blade. Figure 4.8 shows that the Calvert's first torsional frequency (3.57/rev at cruise and 3.48/rev at hover) is lower than conventional helicopters. Low torsional frequency is a characteristic of 2-bladed teetering rotors [Yeo99]. The advantage of low torsional frequency is better loads management and improved control authority for the active vibration control system (servo-flap).

The first flap, lag and torsional blade frequencies at the cruise and hover operating speeds are listed in Table 4.1. The first in-plane frequency is a key parameter in the aeromechanical stability. It has a direct influence on ground and air resonance instabilities. The first lag frequency of the Calvert is 1.51/rev at cruise (346 RPM) and 1.3/rev at hover (400 RPM). In stiff in-plane rotor systems there is no possibility of ground and air resonance, so no additional damping is required.

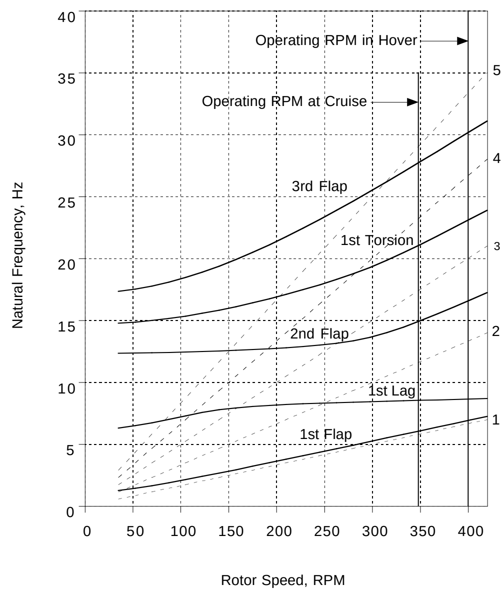


Figure 4.8: Fan diagram of the Calvert rotor blade.

Parameter	Cruise	Hover
First flap frequency	1.05/rev	1.05/rev
First lag frequency	1.51/rev (stiff-in-plane)	1.30/rev (stiff-in-plane)
First torsional frequency	3.57/rev	3.48/rev

Table 4.1: Main rotor natural frequencies of the Calvert.

4.3 Rotor blade kinematics and clearances

The unique combination of the intermeshing rotor with the lift compounding wing and the thrust compounding propeller gives rise to important clearance and safety issues. The maximum flap amplitudes of the main rotor blades of combat helicopters is of the order of $\pm 13°$ [TNC99]. Since the Calvert is a civil commuter aircraft a maximum blade flapping motion of $\pm 10°$ is considered for studying blade clearances.

For the Calvert, the possibility of the blades striking each other is eliminated by providing a lateral shaft tilt of 13° (total included angle between the shafts is 26°). This is of the same order as in the K-MAX which has an included angle of 25° between the rotor shafts.

The clearance between the rotor blade and the wing is improved by giving the wing a 5° anhedral resulting in a allowable flapping motion of 24° which exceeds the 10° requirement for civil transport applications.

The possibility of the rotor blade of one system striking the hub of the other system is examined in Figure 4.9 which is a front view of the helicopter rotor systems. In the baseline position (rotors turning) the blade subtends an angle of 14° with respect to the horizontal (13° shaft tilt and 1° hub precone). This results in a vertical separation between the rotor blade and the top of the hub of approximately 0.8 inches with a 10° flap motion.

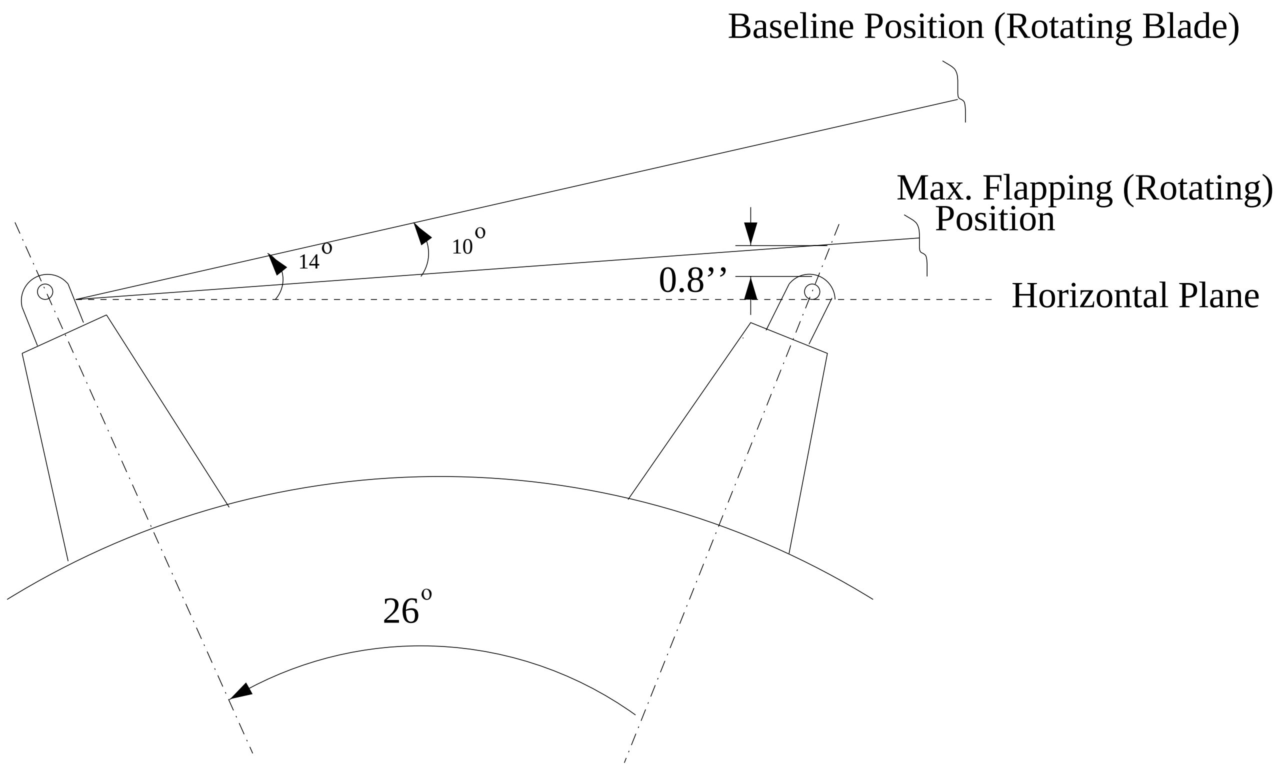


Figure 4.9: Blade and hub clearances (not to scale).

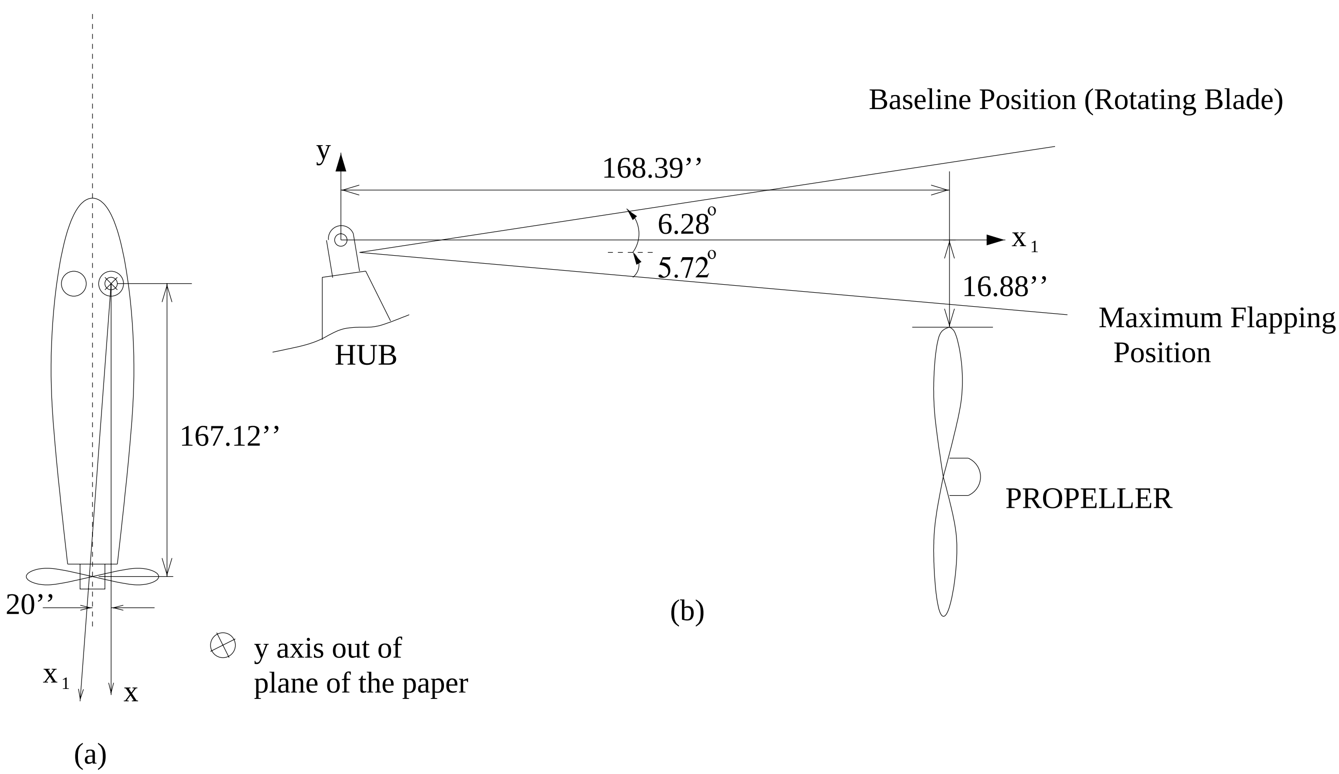


Figure 4.10: Blade and propeller clearances (not to scale).

The possibility that the rotor blade can strike the propeller is examined in Figure 4.10 which shows a schematic top view of the Calvert. Two reference planes are shown. The x-y plane is aligned in the longitudinal direction with the origin at the rotor hub. The x_1-y plane connects the rotor hub and the propeller centerline with the origin at the rotor hub. (see Figure 4.10). In the x-y plane the blade subtends an angle of 6.3° to the x axis (includes shaft tilt of 5.3° and hub precone of 1°). However in the x_1-y plane the blade subtends an angle of 6.28° with the x_1 axis. In the $x_1 - y$ plane, the vertical clearance between the x_1 axis and the propeller blade tip is 16.88 inches (this includes a 11.9 inch offset between the propeller tip and the rotor hub, and an additional 4.98 inches due to the lateral shaft tilt of 13°). Therefore the angle subtended by the propeller tip with respect to the x_1 axis is 5.72°. Consequently, the clearance is 12° (6.28°+5.72°) which is in excess of the maximum blade flap angle of 10°.

4.4 Vibration and noise issues

Helicopters are susceptible to high levels of vibration and noise due to the unsteady aerodynamic environment in which the blades operate as well as the coupled structural mechanical system comprised of the rotor, fuselage, transmission and engine. High vibratory loads result in accelerated fatigue of structural components and reduced ride quality. This structural fatigue impacts reliability and maintenance costs, while the poor ride quality adversely affects marketability as a commercial commuter aircraft. The high external noise further degrades marketability and reduces community acceptance. Because of these reasons, vibration and noise are very important issues and must be addressed at the very beginning of the design process.

4.4.1 Vibration reduction: passive design features

The Calvert is a thrust and lift compounded synchropter. In cruise, the main rotor is offloaded. The propeller provides 80% of the thrust while the wings generate 40% of the lift. Consequently, the main rotor induced vibratory loads are significantly reduced. In addition the blade frequencies are well placed to minimize the vibration levels (Figure 4.8). The stiff in-plane 2-bladed teetering rotor is provided with an undersling (1.4 inches) which helps in reducing the Coriolis component of the hub loads. The absence of a tail rotor and a relatively short. tail boom also help in reducing the fuselage vibration levels.

Additionally, UMARC (modified in-house for Calvert) simulations indicate that the synchropter configuration provides a significant reduction in the intrusion index, compared to a single main rotor, 2-bladed helicopter (AH-1G) and a single main rotor, 2-bladed helicopter with thrust and lift compounding (Figure 4.11). The reason for the reduced vibration is that the synchropter configuration provides a significant reduction in the 2/rev vertical vibration at the pilot's seat due to cancellation of the harmonics from the two individual rotor systems. At the cruise speed of 180 knots, the vibration intrusion index marginally exceeds the ADS-27 limits. This necessitates the use of passive vibration isolators/absorbers or an active vibration control system described in the following section.

4.4.2 Active vibration control

The Calvert is also provided with an Individual Blade Control (IBC) system to provide the passenger with a jet smooth ride. This IBC system will buy its way into the aircraft via the overall reduced maintenance costs and improved reliability. In this conceptual stage the financial impact in terms of acquisition costs vs reduced structural fatigue are not quantifiable and needs to be carefully considered in subsequent design iterations. In addition it is essential to ensure that a failure of the active vibration control system does not compromise the flight safety of the aircraft.

There are a variety of on-blade activation concepts for IBC. These include active integral twist, servo-flaps and active rotor blade tips. Of these, presently the trailing-edge flaps are the most promising option for near term

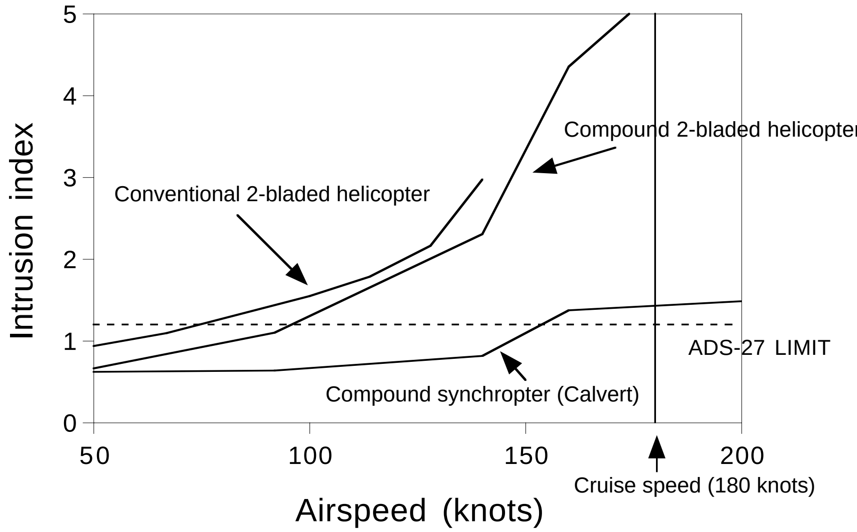


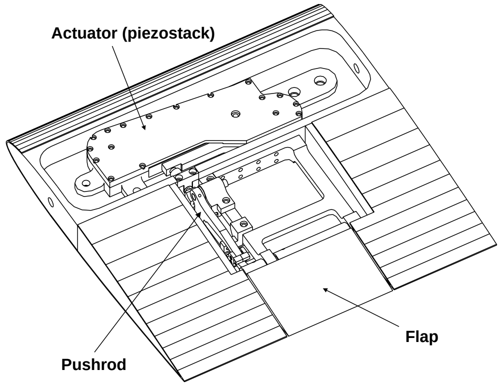
Figure 4.11: Intrusion index for the Calvert.

implementation. The University of Maryland has developed considerable analytic and experimental experience in the field of smart rotor systems. Based on this, it was decided to use a plain trailing-edge flap driven by a piezo-stack actuator using a double lever amplification mechanism [LC99]. Figure 4.12(a) shows a schematic of the flap and actuator system. The flap sizing and location are based on the parametric flap performance study carried out by Milgram and Chopra [Mil97]. The flap parameters are optimized to maximize flap effectiveness and minimize actuation power. For the Calvert a 15% span, 25% chord flap that is located at 70% of blade radius is selected.

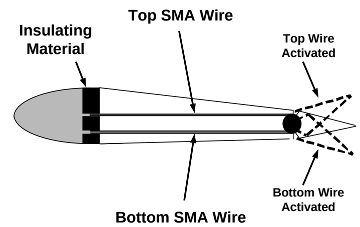
Higher Harmonic Control (HHC) control laws have been widely investigated for vibration reduction using trailing-edge flaps. A significant amount of prior information is required for the HHC formulation, in particular, the relation between the harmonic content of the control input and the resulting harmonics of the hub loads oscillation. For the Calvert (synchropter configuration) such detailed information is not readily available. Therefore a neural network based approach [SC99] is used to adaptively specify a trailing-edge flap sequence directly in the time domain. In this application, no off-line training is performed, instead the network learns in real-time the appropriate flap deflections that minimize the vibrations. This new algorithm has been implemented in the University of Maryland Advanced Rotor Code [SC99]. Figure 4.13 demonstrates the vibration suppression capacity of the neuro-controller for a typical 4-bladed helicopter with an articulated rotor system, for an advance ratio of 0.35. It is expected that the neuro-controller will be equally effective in suppressing the vibratory hub loads on the Calvert.

4.4.3 SMA-actuated inflight tracking tab

The rotor blade tracking system on the Calvert uses an SMA-actuated trim tab (5% span), located at 55% of rotor radius. In this scheme, a trim tab together with a controller [EC99] monitors the tracking of the rotor blades in flight. A Shape Memory Alloy (SMA) actuator is used to deflect the tab to the desired position. This compact and lightweight system ensures the elimination of aircraft downtime for tracking, a reduction in vibration due to rotor blades being out of track, and reduction of fatigue loads in the rotor blades and the hub, leading to substantial maintenance cost benefits.



(a) Piezo-stack actuated trailing-edge flap (active vibration control).



(b) SMA-activated trailing-edge tab (in-flight blade tracking).

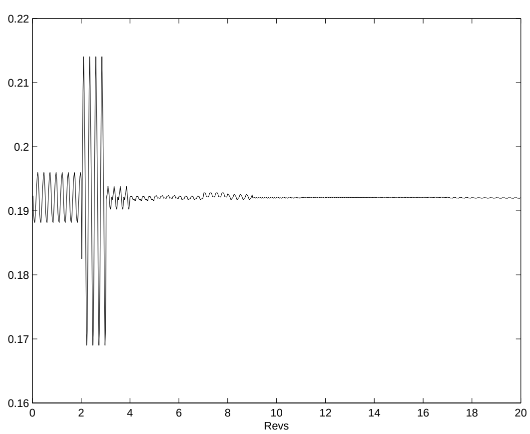
Figure 4.12: Active flaps.

4.4.4 Noise issues

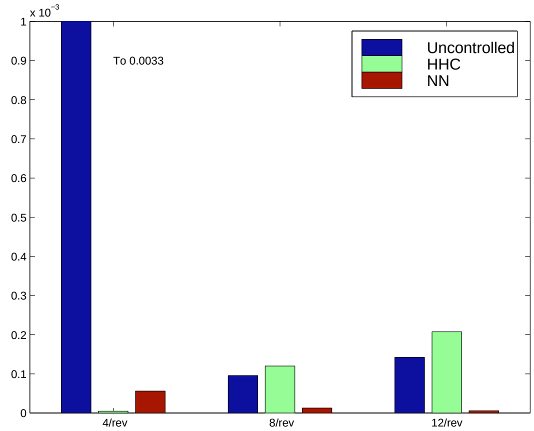
During take-off the helicopter is, in effect, climbing away from its own wake. Thus rotor noise generation is limited to blade self noise, coupled with noise from turbulence ingestion. Under these circumstances noise from the tail rotor and the engine are likely to be the more important sources. Due to the absence of a tail rotor the Calvert is expected to be quieter than a conventional helicopter with the same main rotor tip speed. (Propeller of the Calvert is non-thrusting in hover and low speed forward flight.) The MD520N (no tail rotor) has an effective perceived noise level of 85.5 EPNdB and hence during take-off the Calvert will meet the Stage 2 Limit of 93 EPNdB. There is also a good possibility that the Stage 3 limit (in effect in Austria and Switzerland) of 90 EPNdB can also be met.

Now let us consider cruise flight condition. According to Lowson [Low92], the flyover EPNL is directly proportional to the tip speed (raised to 7.8), all up weight (raised to 2), blade area (raised to -1), cruise speed (raised to 3.3) and blade number (raised to -1). The above formula suggests that the dominant design feature for a quieter helicopter will be a low tip speed. Note that the Calvert has a variable RPM engine. The tip speed in hover is 722 ft/sec which is reduced in cruise to 623 ft/sec. The MD520N which is in the same weight class as the Calvert has a tip speed of 680 ft/sec which is 9% higher than the Calvert in cruise. Therefore the Calvert main rotor should be significantly quieter than the MD520N. However the Calvert has a propeller which contributes to the EPNL during flyover. In addition the Calvert has a total of 4 blades as compared to 5 for the MD520N, further increasing the noise levels. The MD520N has an extremely low flyover EPNL of 80 dB (the Stage 3 limit is 90 dB). By virtue of its low cruise tip speed, the Calvert will meet the Stage 2 and Stage 3 limits.

Reduction of noise during approach remains a major issue. The radiation of noise during approach is not at present accurately predictable. This is due to the inadequacy of the theoretical prediction methods for blade vortex interaction. Under the circumstances it is impossible to predict with any certainty the EPNL during approach for a synchropter compound. However the Calvert has advanced geometry blades (similar to the BERP design) with tip sweep, taper and anhedral which all serve to reduce BVI noise. We were very concerned that coupling of the wakes of the two rotors could significantly increase BVI noise. We brought up this issue



(a) Time trace for normalized vertical hub shear.



(b) Harmonic amplitude of normalized vertical hub shear.

Figure 4.13: Active control of vertical shear.

with flight test pilots of the K-MAX during our trip to Kaman Helicopters. According to the pilots and ground test engineers, the K-MAX does not suffer from this problem during approach; however we feel that flight tests are necessary to determine whether the Calvert can meet the Stage 2 and Stage 3 certification requirements.

4.5 Propeller design

One of the primary design drivers for the Calvert was to minimize the engine power while working within stall and compressibility constraints. In an effort to keep the fuselage level, minimize shaft tilt, and prevent power losses due to the dwindling propulsive efficiency of the main rotor at high forward speeds (see Figure 6.1(a)), the Calvert uses a propeller that overcomes 80% of the total aircraft drag at cruise velocity. This design required the selection of several key parameters that define the propeller.

4.5.1 Configuration

Several configurations were studied using standard propeller design charts. These included 4 and 6 bladed single- and 4 and 6 bladed dual-rotating configurations [BH40, Nel44]. A typical tip speed of 230 m/s was chosen for the propeller. A propulsive efficiency of greater than 0.8 (at a thrust of 80% of the total aircraft drag in cruise) was chosen as a design constraint in order to minimize the Calvert's engine power. This choice was made after an exhaustive trade study involving several different configurations, propeller thrusts, propeller weights and cruise power. The propeller diameters required for achieving an efficiency of 0.82 at the same thrust (80% of total drag) for each of these configurations are shown in Figure 4.14.

From this trade study, it was found that an increase in number of blades significantly decreased the propeller diameter for the same efficiency, or the propeller power for the same diameter. However, contrary to our initial expectations, there was only a small decrease in diameter from the single to the counter-rotating configurations [BH40]. This decrease was not thought to justify the added complexity in the gearbox arrangement for the contra-rotating propeller. An optimum design of a 6 bladed propeller (thrust coefficient=0.13, linear twist=40°, tip speed=230 m/s, diameter=1.9 m and propulsive efficiency=0.82 at 180 knots) was chosen for the thrust augmenting of the Calvert. A Clark YM-15 airfoil (see Figure 4.15(a)) was selected because of its improved

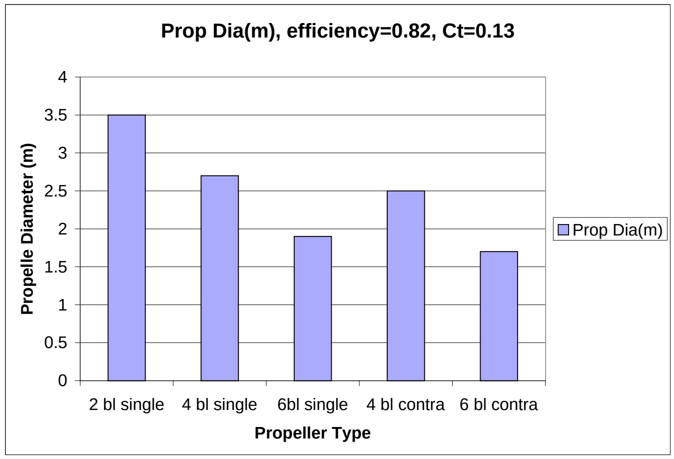


Figure 4.14: Variation of propeller diameter for various configurations.

thrust efficiencies at higher speeds over the baseline Clark-Y airfoil. The final propeller design is schematically shown in Figure 4.15(b).

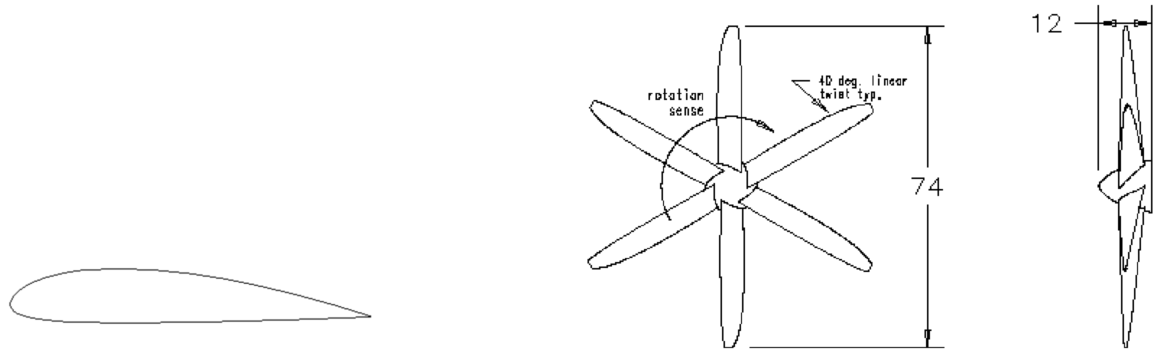
4.5.2 Shaft

Power is transmitted from the engines to the propeller via the transmission. The transmission is designed to provide the optimum propeller RPM in cruise (see section 4.9). The propeller-transmission separation is 148.1 in (3.76 m) horizontally and 9.3 in (0.24 m) vertically. Since the axes of the propeller and transmission are vertically offset, the shaft must be installed at an angle. Also, in order to avoid potentially damaging resonances while the engine RPM slowly changes during the transition from hover to cruise, the shaft is designed for subcritical operation throughout the entire RPM range.

The propeller shaft consists of four sections, each 2 in (50.8 mm) in diameter. The first section, which passes between the engines, is 45 in (1.14 m) long and is attached to the transmission using a flexible coupling. The axis of this shaft section remains aligned with the transmission output axis. This section is titanium to allow for high temperature operation while maintaining light weight. The remaining three sections are 34.4 in (0.87 m) long and are fabricated from composites. By choosing a uniform shaft length, commonality between each segment is achieved. The shafts are joined at each end by a Kaman KAflex flexible coupling and supported by bearing blocks. In order to accommodate the vertical offset between the transmission and propeller, the shafts must accommodate an angle of 5.15°. This angle is distributed over the three shafts so that the angle between the axis of any two shafts is only 2.57°. The KAflex couplings can operate continuously at this shaft angle while still providing enough flexibility to allow for shaft misalignment and fuselage bending as well as minimizing the transmission of loads (with the exception of torque) between the transmission and propeller. The shaft configuration is given in the inboard profile (Figure 4.1).

4.6 Wing

The Calvert's wing is designed to provide a lifting force in cruise (180 knots) equivalent to 40% of the aircraft take-off weight (2026 lbs (9034 N)). In order to minimize added complexity and weight penalty, the wing is not provided with any control surfaces such as flaps or ailerons. The rotor provides 60% of the aircraft lift



(a) Clark YM-15 (propeller airfoil).

(b) Propeller configuration.

Figure 4.15: Calvert propeller design.

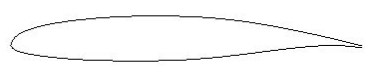


Figure 4.16: GA(W)-2 (wing airfoil: general aviation (Whitcomb)-2).

required in cruise, providing sufficient control authority for the aircraft. For this moderate freestream velocity, a General Aviation Airfoil, GA(W)-2 (Figure 4.16, adapted from [Mcg75]) is used. This airfoil was chosen due to its high Cl/Cd ratios and good low speed stall characteristics. The wing was designed using standard design codes [Ray92]. The associated wing dimensions are 14.93 ft span, 3.32 ft root chord, 1.66 ft tip chord. The aspect ratio and taper ratio is 6 and 0.5 respectively. An anhedral of 5° is provided to provide clearance between the rotor blades and the wing and to improve the Calvert's lateral/directional stability.

The wing is placed aft of the passenger cabin to allow passenger ingress and egress, and for CG balance considerations in cruise. As a compromise between keeping the center of the lift of the wing as close to the rotor as possible, and the aerodynamic efficiency of the wing, a mild forward sweep of 10° is chosen for the wing.

4.7 Empennage sizing

The horizontal tail was sized to trim the aircraft in cruise. For the Calvert, the main rotor lift (L_R) and pitching moment (M_R), wing lift (L_W) and pitching moment (M_W), and propeller thrust (T_p) generate a nose-down pitching moment about the vehicle center of gravity (Figure 4.17). Similarly the rotor and hub drag (D_{hub} and D_{rotor}) and the fuselage drag (D_{fus}) cause a nose-up pitching moment about the vehicle CG. The horizontal stabilizer generates negative lift due to it's inverted airfoil section. This results in an aircraft nose up pitching moment, which is used to trim the Calvert in cruise. The horizontal tail is sized by solving the Calvert's pitching moment equilibrium equation about the vehicle CG. For the horizontal tail sizing, the most forward CG position was considered (extreme condition). The quarter chord of the horizontal tail is situated 10 feet behind the vehicle CG. A clearance of 6 inches is maintained between the trailing-edge of the horizontal tail and the propeller. The horizontal tail has an inverted GA(W)-2 airfoil section and the aspect ratio is set at 6. The horizontal tail is sized such that the operating angle of attack (for most extreme CG position) is 5.4° (lift coefficient of 0.6). The span of the horizontal tail is 86.4 inches and the chord is 14.4 inches. The horizontal tail is unswept and untapered and is free to pitch about the quarter chord. The horizontal tail pitch attitude required to trim the aircraft depends on the CG location, forward speed and flight condition (climb, descent, cruise, autorotation etc). In hover the horizontal tail loses its effectiveness and the fuselage will tilt slightly forward.

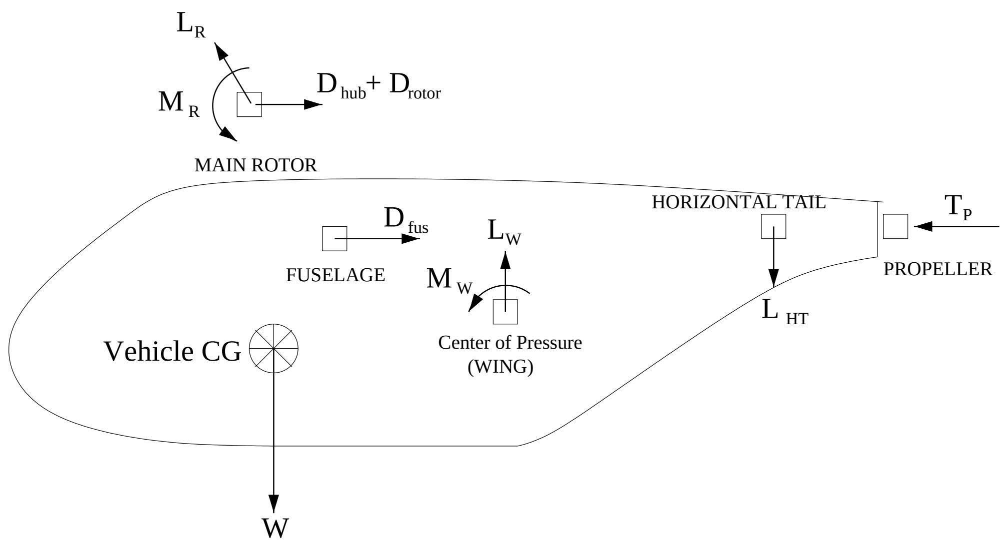


Figure 4.17: Vehicle trim in cruise (not to scale).

The vertical tail assumes great importance from the point of view of aircraft stability. This is particularly true for a synchropter configuration which can be susceptible to spiral instabilities while conducting turns in high speed forward flight. We visited Kaman Helicopters in late May and discussed these issues with several design engineers at Kaman. The K-MAX has three vertical fins which are specifically designed to prevent such dynamic instabilities. For the present design, the Calvert has three vertical tails which have been designed to mimic the K-MAX vertical stabilizers. The vertical tails at the end of the horizontal stabilizer have a root chord of 3 feet and a tip chord of 2 feet. The height of each vertical fin is 4 feet. The central fin which also provides the rear support point has a height of 4 feet, root chord of 3 feet and tip chord of 2 feet.

4.8 Engine

During the development of the Calvert, a parallel engine development will be undertaken as stated in the RFP. The Calvert requires a power plant which provides a maximum continuous power of 1050 HP (783 kW) maximum continuous. Hence, a two engine configuration was chosen for safety with each engine rated at 525 HP (391 kW) maximum continuous.

4.8.1 Characteristics

The engine characteristics have been determined using the equations in the RFP. In order to achieve the desired installed power (525 HP), a take-off/contingency power of 656 HP (489 kW) is required. This power requirement leads to an engine 27.3 in (.693 m) in length and 17.5 in (.445 m) in diameter, with a weight of 173 lb (78 kg). The output shaft speed is specified as 21000 RPM. However, an additional requirement of the Calvert engine is the ability to provide constant power over a range of rotational velocities. In hover, the Calvert requires a rotor speed of 400 RPM (the engine is operating at 21000 RPM). During transition to cruise, the rotor is slowed to 346 RPM (see Figure 6.4) which requires that the engine be slowed to 18136 RPM, a decrease of 14%. This technology has been proven by Mitsubishi Heavy Industries (MHI) who developed the MG5-100 turboshaft engine for their MH2000 helicopter. The MG5-100 has the ability to operate at two distinct RPM levels. In addition, the NASA Glenn Research Center has explored the concept of a broad-spectrum engine capable of operating with high power and good specific fuel consumption with as much as a 50% reduction in RPM [Tal91]. Thus, the variable RPM engine for the Calvert is considered feasible.

4.8.2 Performance

The engine of the Calvert was sized in order to meet the stringent high-speed requirement. A parallel engine development will be undertaken to develop two scalable Integrated High Performance Turbine Engine Technology (IHPTET) engines. The target for the IHPTET program is to incrementally achieve a significant increase (120%) in the power/weight ratio and a significant decrease (40%) in SFC.

Phase I (complete):	+40% Power/Weight,	-20% SFC
Phase II (complete):	+80% Power/Weight,	-30% SFC
Phase III (by 2003):	+120% Power/Weight,	-40% SFC

An additional advantage of the IHPTET engine is that it offers a very high short period emergency setting of 125% for 30 sec. The stipulated engine power includes several losses for installation (1%), gearbox (2%), compressor bleed (2%) and engine accessories (2%), as well as a power margin of about 5% to account for future growth. The engine given in the RFP is found to satisfy the required functions with a small increase in SFC at the design cruise speed of 180 knots (Figure 6.11(b)). The engine must be capable of delivering a relatively constant efficiency at a range of output shaft speeds not exceeding 15% of the initial rated output shaft speed (21000 RPM). Table 4.2 lists the various power ratings of the engine.

Settings	**Time Limit**	**Power Ratio***	**Power shp (kW)**	**SFC lb/shp/hr (kg/kW/hr)**
Emergency	30 sec	1.25	820 (611)	0.40 (0.24)
Take-Off/Contingency	2 min	1.00	656 (489)	0.36 (0.22)
Intermediate	30 min	.924	606 (452)	0.36 (0.22)
Max. Continuous	-	.800	525 (391)	0.38 (0.23)
Partial	-	.500	328 (245)	0.53 (0.32)
Idle	-	.200	131 (98)	0.81 (0.49)

* The power ratio is defined with respect to the nominal, uninstalled engine power.

Table 4.2: Calvert engine data (static, ISA, mean sea level).

4.8.3 Structural integration

The engine installation is given in Figure 4.18. The engines are located on the transmission deck behind the main gear box and have a center separation of 20 in (0.508 m). This location allows for good accessibility for maintenance and inspection. The engine/transmission cover may be opened and doubles as a work platform while the systems are being serviced. Each engine is mounted to the transmission deck using two bipods and two linkages. Torque is transferred to the transmission using a flexible coupling. In addition, since the propeller shaft must pass between the engines, the firewall separating the engines has been appropriately designed to accommodate it.

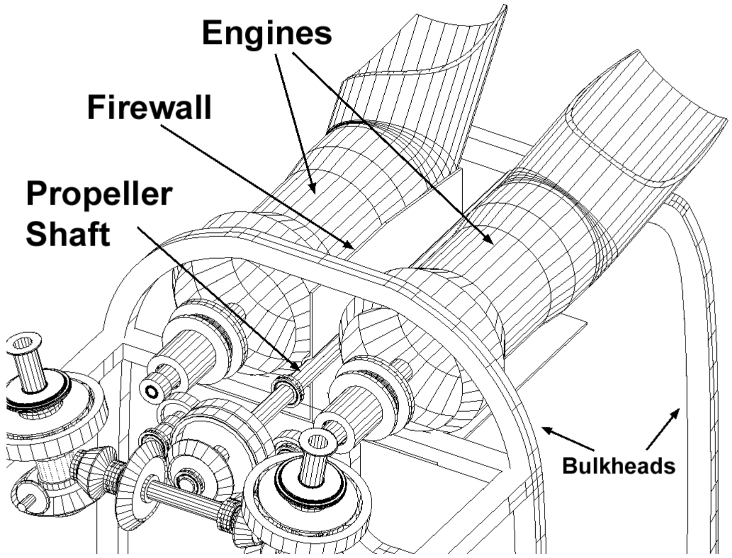


Figure 4.18: Engine installation.

4.8.4 Oil system

In order to improve reliability and safety, an independent oil system is provided for each engine. The oil system is assumed to be an integral part of the engine. Each system consists of a pump, tank, filter, cooler and two particle detectors. The particle detectors are monitored by the FADEC system. Each engine is estimated to use 1.59 gal (6.02 L) of oil given that the Calvert engine has an advanced design and the engine oil consumption decreases with each generation of engine. This oil capacity complies with F.A.R. §27.1011 (see section 4.9.4).

4.8.5 Particle separator

In order to minimize the risk of engine damage from dirt/debris ingestion, a particle separator is installed at each engine inlet. The particle separator is designed for efficient operation by increasing flow capacity and incorporating three filtration areas. Each separator is easy to access and remove for cleaning and maintenance. In addition, separator blockage is monitored by the FADEC system.

4.8.6 FADEC

The engine is integrated into the flight control system using the FADEC (full authority digital engine control) system. The FADEC system controls the overall engine settings to ensure optimal performance during nominal as well as OEI flight conditions [Bel97]. The engine, engine oil system and particle separator sensors are also monitored and any problems are reported to the Calvert PHM system (see section 4.14.2) for compensation. A significant additional function of the FADEC system for the Calvert is to ensure a linear variation in the engine rotational velocity, and thus the rotor tip speed, during transition between flight regimes as shown in Figure 6.4. The engine speed variation is displayed to the pilot in order to simplify flight operation.

4.8.7 Safety

Modern engines are very safe and reliable. The engines to be used in the Calvert have been designed so that a catastrophic turbine failure, considered the worst case failure, will be confined within the engine. In the event of an unconfined turbine failure, the transmission deck provides an additional layer of protection for the passengers and crew. In addition, any problems detected by the FADEC system is relayed to the PHM system. The PHM system then alerts the pilot of the problem (see section 4.14.2).

4.9 Transmission design

The Calvert transmission configuration is driven primarily by two design requirements. The first requirement is the ability to operate under two disparate flight conditions: take-off/hover and cruise. The Calvert powerplant consists of two engines rated at 656 shp (489 kW) take-off/contingency with a nominal speed which varies from 21000 RPM at takeoff to 18136 RPM at cruise. During takeoff, the main rotors rotate at 400 RPM and draw 317 hp (236 kW) each while the propeller (set to zero pitch) draws 147 hp (110 kW). Since the propeller is set at zero collective pitch (non-thrusting condition), its rotational velocity is unimportant. At cruise, the main rotors are slowed to 346 RPM and unloaded such that each rotor draws 103 hp (77 kW). In this flight regime, the propeller has a rotational velocity of 2308 RPM and draws 844 hp (629 kW). Given the mission profile in Figure 2.2, the Calvert spends the majority of its flight time in cruise. Thus, to increase the life of the gears which drive the main rotors, the transmission should distribute power separately to the main rotors and propeller. Specifically, the gears which drive the main rotors alone should be offloaded when the main rotors are off-loaded.

The second requirement for the Calvert transmission is the desired geometry. The transmission must accept input from two engines with a separation of 20 in (.508 m). In addition, the propeller output should be located between the two engines such that the propeller shaft can pass between the engines with enough clearance for a firewall. The propeller shaft should also be as low as possible to minimize the propeller shaft angle. The main rotor shafts are tilted outboard 13° from vertical (26° included angle) and forward 5.3°. The center separation of the rotor shafts at the transmission base is 28 in (.711 m).

4.9.1 Configuration

The resulting transmission configuration is given in Figure 4.20. Gear design was performed using the methods presented in the Handbook of Practical Gear Design by Darle W. Dudley [Dud84] as well as Tishchenko's method [TNC99]. The design transmission power ratings are given in Table 4.3. Note that the transmission was designed using 85% RPM since this is the higher tooth load case and thus an added margin of safety is provided.

To transmit torque from the engines to the transmission inputs, a flexible coupling is required. Lucas Aerospace flexible couplings were chosen due to their single piece design that is light weight, highly reliable, and easy to maintain. At the transmission inputs, the torque is accepted by a spring-type overrunning clutch (see Figure 4.19(a)).

The input is the location of the lowest driveline torque and thus, placing the clutch at this point allows its weight to be minimized [Whi98]. However, the input is also the location of the highest rotational velocity. Since spring clutches can operate at these velocities [Kis78], they were deemed ideal for this application. In order to keep the clutch assembly compact, the clutch is mounted inside the input pinion.

The first reduction stage consists of a 10-pitch, 30-tooth input pinion which drives a 54-tooth spur gear, both of which have a face width of 1.5 in (38.1 mm). Integral with the spur gear shaft is a 10-pitch, 25-tooth double-helical pinion. Each face of the double helix is 1.5 in (38.1 mm) wide yielding a total face width of 3 in (76.2 mm). The spur gear/double-helical pinion is allowed to float axially to control the load-sharing between the halves of the double helix. A single 109-tooth double-helical bull gear is driven by both pinions. This gear collects the torque from the engines and distributes it back to the propeller and forward to the main rotors. The rotor brake is mounted to the propeller shaft output. In this case, a Kaman KAflex flexible coupling is used to attach the propeller shaft. The KAflex couplings were chosen as a result of their ability to operate continuously at the desired propeller shaft angle, eliminating the need for a universal joint (see section 4.5.2).

The total reduction of the first two stages is 7.848:1, chosen to provide a nominal propeller rotational velocity

Settings	Time Limit	Power shp (kW)
One Engine Inoperative (OEI) (transmission input limit)		
Emergency	30 sec	845 (630)
Contingency	2 min	815 (608)
Intermediate	30 min	678 (506)
Continuous	-	656 (489)
All Engines Operating (AEO) (double-helix stage limit*)		
Take-Off/Contingency	2 min	1320 (984)
Intermediate	30 min	1215 (906)
Max. Continuous	-	1070 (798)

* The double-helical gear is the transmission maximum load point.

Table 4.3: Transmission ratings at 85% engine RPM (maximum tooth load).

of 2308 RPM in cruise. Since the engines are slowed for cruise, the reduction will yield the optimum propeller speed with the slower engine speed. Subsequently, during takeoff/hover, the propeller rotates at a higher than optimal speed. However, in this flight regime, the propeller blades are set to zero pitch.

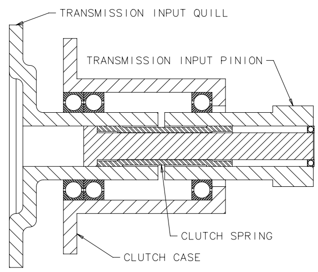
To distribute torque to the main rotors, a 4.8-pitch, 40-tooth spiral bevel pinion with a face width of 1.75 in (44.5 mm) is spline mounted to the collector gear. This pinion drives a 47-tooth spiral bevel gear, spline mounted to the cross shaft, resulting in a 90° change in the axis of rotation. A 4.8-pitch, 28-tooth spiral bevel pinion with a 2 in (50.8 mm) face width is spline mounted to each end of the cross shaft. Each pinion drives a 52-tooth spiral bevel gear. The shaft angle is 77° (to provide the 13° outboard shaft tilt) and the shafts are rotated 5.3° forward about the cross shaft axis. The final reduction stage is a planetary gear set. A 7.5 pitch, 41-tooth sun gear with a 2 in (50.8 mm) facewidth is mounted on the same shaft as each of the 52-tooth spiral bevel gears. The each sun gear drives six 22-tooth planet gears. The fixed 85-tooth internal ring gear is splined to the housing. The planet carrier is mounted to the rotor output shaft.

An important consideration in the design of this last stage is that the power is not necessarily distributed evenly between the two rotors, especially during maneuvers. Thus, each final stage was designed to handle 75% of the total rotor load in hover. The configuration of the final three reduction stages is similar to that used by the Kaman K-MAX [OG97], and ensures that the required counter rotation and phasing occurs. The reduction of these three stages is 6.706:1; yielding a total reduction of 52.63:1, which is designed to provide a nominal main rotor rotational velocity of 400 RPM in hover.

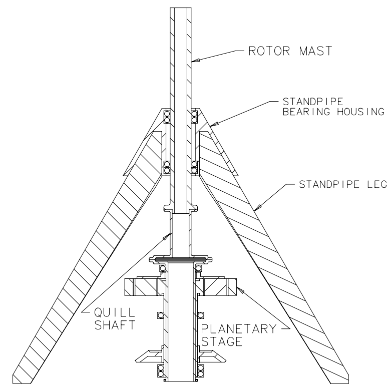
In addition to the main rotor and propeller outputs, two take-offs are provided for the electrical system. The Calvert has a redundant electrical system that uses two independent alternators. Each alternator output is driven by an 20-tooth spiral bevel pinion (with a face width of 0.5 in (12.7 mm)) which meshes with the 4.8 pitch, 52-tooth spiral bevel gear yielding a rotational velocity of 3188 RPM in hover and 2753 RPM in cruise. The alternators were chosen to provide sufficient performance over this RPM range.

4.9.2 Structural integration

Typically, rotor mast loads are transfered to the helicopter fuselage via the transmission housing. However, the synchropter configuration subjects the rotor mast support system to load environments that can be more severe



(a) Spring clutch.



(b) Standpipe mast support system.

Figure 4.19: Clutch and standpipe (not to relative scale).

than those experienced by a conventional helicopter. In order to minimize the rotor loads experienced by the transmission housing, an independent truss support, referred to as a standpipe, has been incorporated for each main rotor (see Figure 4.19(b)) [Kis93]. As in conventional rotorcraft, the rotor shaft carries the mast moment, thrust, side loads and torque. However, the standpipe transfers all loads but the torque directly to the fuselage. This configuration reduces the weight and increases the fatigue life of the transmission.

Each standpipe consists of a bearing housing and three legs, all manufactured from titanium. The bearing housing contains two tapered roller bearings and the rotor shaft. The three legs are attached to the bearing housing and then mounted to the transmission deck using nodal vibration isolators. An additional provision has been made to include active vibration cancellation in the legs. Torque is carried between the transmission and the rotor shaft by a steel quill shaft that has a flange designed to react minimal head moment, thrust and side loads while easily carrying the maximum torque loads. The quill shaft is mounted between the transmission output quill and the main rotor shaft.

4.9.3 Housing

The primary function of the transmission housing is to support and enclose the main transmission components, in addition to reacting the residual loads transferred by the quill shaft. The housing consists of four sections bolted together, each section cast from a magnesium-zirconium alloy. The bottom half of the gearbox is a single continuous casting and the top half is divided into three separate sections. Care must be taken during the detail design stage to eliminate any possibility of oil leakage between the housing sections. Cored passages are incorporated into the housing to transfer lubricant to the gear meshes and bearings and an oil sight gauge is included to check the oil level. The transmission housing is mounted to the transmission deck via the same vibration isolators used by the standpipe legs.

4.9.4 Oil system

The basic components of the Calvert transmission oil system are the oil filter, magnetic particulate trap (MPT), cooler, pump, and fan. Two separate oil filters are installed, one at the sump and the other at the MPT output. The MPT will detect metallic particles and burn up small particles with a high voltage spark. Both filters will contain element detect switches (to ensure the filters are installed and operating properly) and bypass valves allowing for continued transmission operation if the filters are clogged. The MPT and filters each have integral alarms and any abnormal operation will be reported to the Calvert prognostic and health management (PHM) system. An visual oil level gauge is provided for each oil tank. Each indicator is easy to view from outside the aircraft without opening or removing any panels.

F.A.R. §27.1011 states that the helicopter is required to carry 1 gal (3.8 L) of oil for every 40 gal (151.4 L) of fuel. Given the 182.5 gal (690.8 L) fuel capacity, the F.A.R. would require an oil capacity of 4.56 gal (17.26 L). Analysis of the transmission indicated a worse case 98% efficiency. At an operating condition of 1320 hp (978.3 kW), this results in 26.4 hp (19.69 kW) being dissipated as heat. A preliminary heat transfer analysis was used to size the transmission oil requirements. The heat flux is calculated from the transmission efficiency given the maximum oil temperature, the design oil cooler outflow temperature and the constant pressure specific heat of the oil. Modern oil cooler designs allow an oil inlet temperature of 230°F (110°C) and a transmission outlet temperature of 450°F (232.2°C) [HB93]. The mass flow rate is given as

$$\dot{m} = \frac{q}{c_p * (T_{h_{in}} - T_{h_{out}})} \tag{4.1}$$

where q is the power dissipated, c_p is the constant pressure specific heat, and $T_{h_{in}}$ and $T_{h_{out}}$ are the oil inlet and outlet temperatures, respectively. From Equation 4.1, the resulting oil flow rate is 1.3 gal/min (4.92 L/min). Total oil capacity, based on a 16 second recycle time is 0.347 gal (1.31 L). This quantity is quadrupled to 1.39 gal (5.26 L) to provide a large safety margin. In addition, each engine will require 1.59 gal (6.02 L) (see section 4.8.4) of oil yielding a maximum oil capacity of 4.57 gal (17.3 L). This value is in compliance with the F.A.R.

If the oil leaks at the maximum flow rate, the pilot will have one minute before the transmission runs dry to effect a landing. However, if a landing cannot be made within this time, the main gear box will have the capacity to operate for 30 minutes dry but will require a tear down inspection after landing. A thermostat controlled electric fan provides positive airflow when the airspeed provides insufficient ventilation.

4.9.5 Summary of transmission advanced technologies

A number of advanced technologies have been incorporated into the Calvert transmission to reduce weight and improve reliability. These technologies are summarized below.

- Advanced alloys and treatments used for gears to increase the allowable bending and surface stress and maximum operating temperature.
- High-contact ratio gear tooth geometry for noise and vibration reduction and an increased operational life.
- Spring clutch for higher speed operation resulting in reduced weight.
- Ceramic spherical roller bearings for increased operational life.
- Standpipe/quill shaft rotor mast support system to reduce the loads experienced by the transmission housing yielding a transmission weight reduction and fatigue life increase.
- High temperature oil system.
- Advanced PHM system (see section 4.14.2).

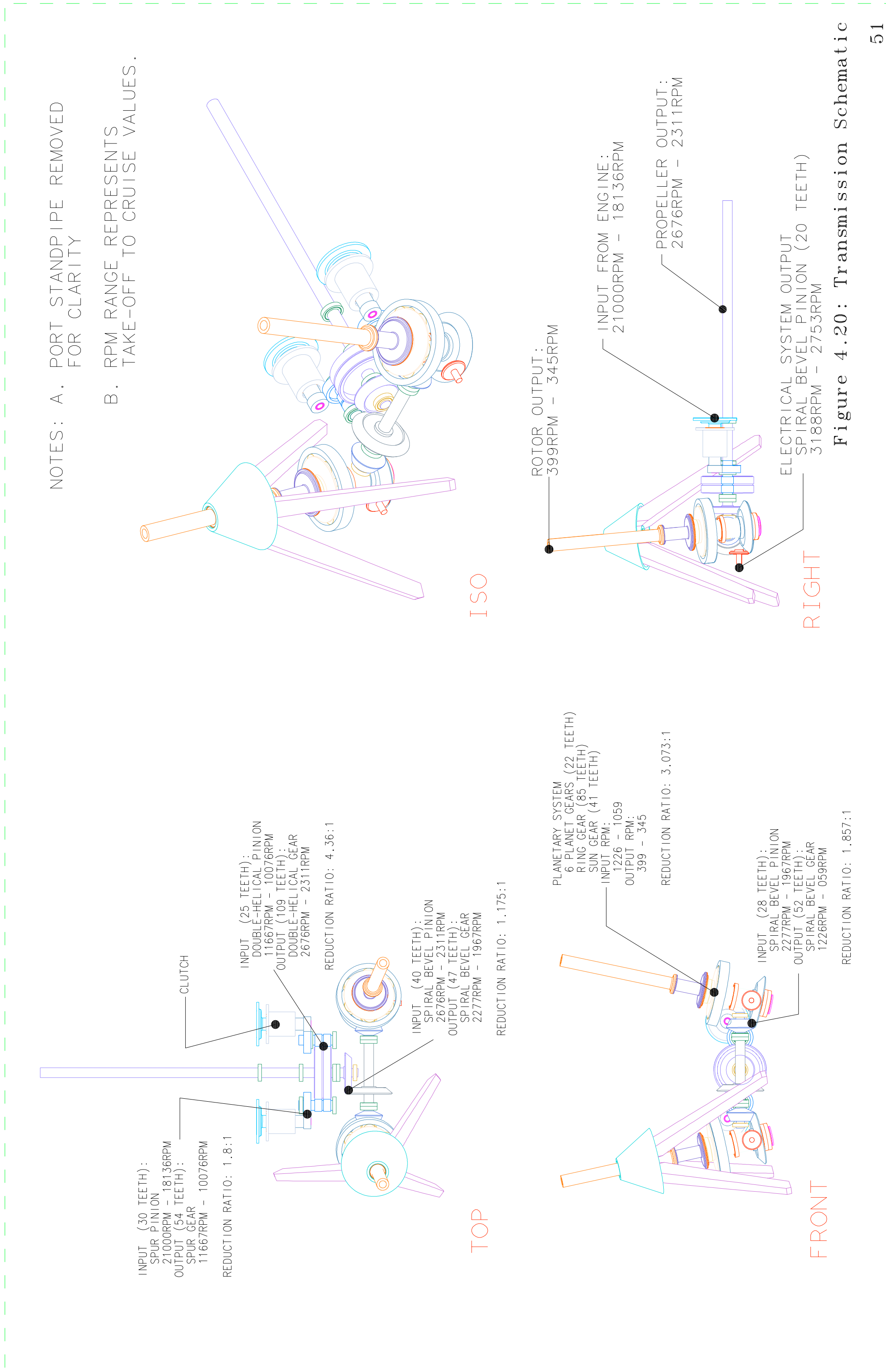
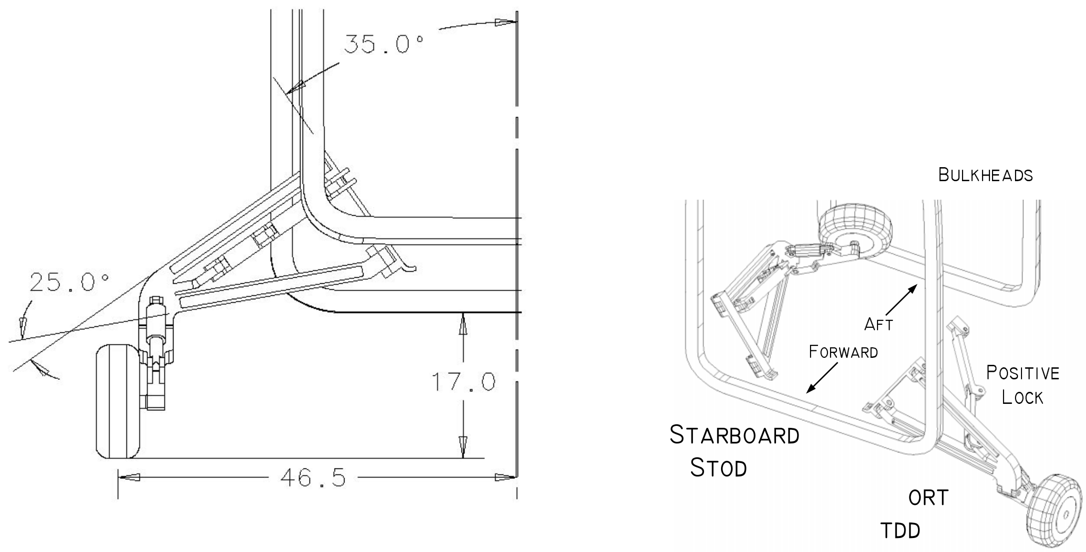


Figure 4.20: Transmission schematic.

4.10 Landing gear design

The Calvert has a retractable tricycle landing gear with two main wheels and a nose wheel (see section 2.4.4). The landing gear location has been driven by three major requirements. First, the relative position of the rear wheels versus the vehicle CG is such that the main wheels support 73% of the aircraft weight and the remaining 27% is supported by the nose wheel at aircraft gross weight. This provides good ground handling performance. Second, the track and wheel base dimensions give an overturn angle of 62.3° worst case. This is within a recommended limit of 63° [Ray92] to avoid aircraft turn-overs during a landing or ground maneuver. Finally, the landing gear location takes into account crashworthiness considerations. If a vertical crash occurs with wheels fully lowered, the main gear will not penetrate the passenger cabin and the nose gear will go through the floor beneath the instrumentation console in front of the crew.



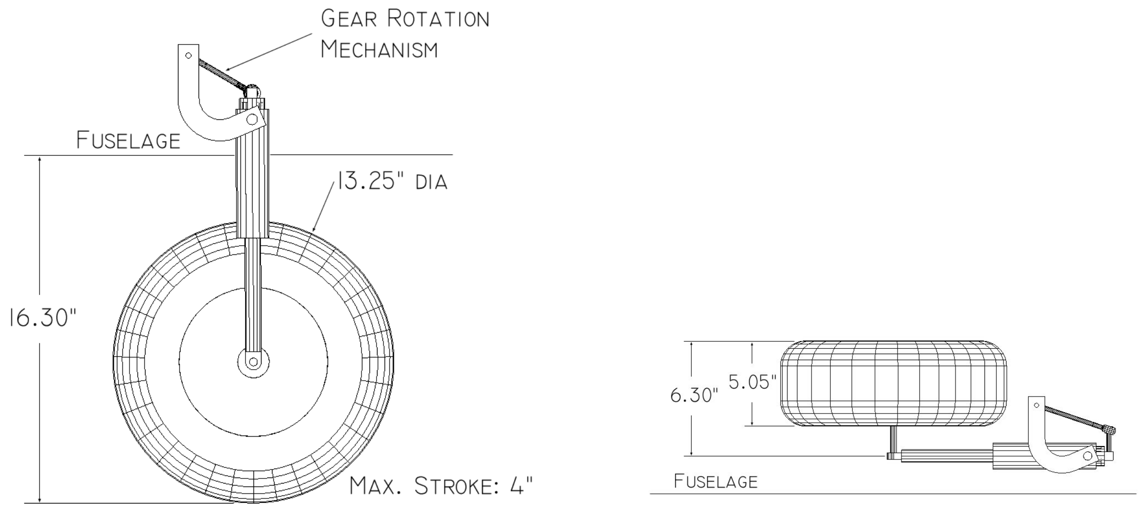
(a) Front view. (b) Isometric view.

Figure 4.21: Main landing gear.

4.10.1 Configuration

In order to keep the turn-over angle within the suggested limit, the main wheels are set 46.8 in (1.19 m) from the centerline and 154.5 in (3.9 m) from the nose of the aircraft. Thus, the extension/retraction configuration must pull the wheels toward the center of the fuselage as well as up. This is achieved via an A-frame mounted 35° from vertical (see Figure 4.21). This configuration is similar to that used by the Kaman SH-2G Super Seasprite, and was chosen due to its simplicity and small stowed frontal profile. Given the fuselage space limitations, the main gear is designed to retract back into the base of the Calvert's tail. Disk brakes are installed in the rear wheels to hold the aircraft stationary when parked and to provide braking during ground rolls. A positive down lock and mechanical up lock are incorporated to prevent unexpected gear motion.

The nose wheel is set 33.6 in (0.85 m) from the nose of the aircraft to ensure stability during ground maneuver.



(a) Side view extended. (b) Side view retracted.

Figure 4.22: Nose landing gear.

The steering control uses a turning nose wheel actuated by a push-pull device that also incorporates a shimmy damper. The pilot controls the aircraft using rudder pedals linked to the nose wheel. The maximum turning angle of the wheel is 60°, which allows all ground maneuvers to take place within a reasonable space. Given the limited vertical space at the nose gear location, the retraction mechanism has been designed to rotate the wheel 90° so that it is horizontal when stowed (see Figure 4.22). Once again, a positive down lock and mechanical up lock are incorporated to prevent unexpected gear motion.

4.10.2 Tire sizing

Low pressure tires have been selected to allow the aircraft to land on semi-prepared runways. At gross weight, each main gear tire must carry (static) 1850 lb (839 kg). Hence, Type III 5.00-4 tires with a maximum load of 2200 lb (998 kg), 12 plies and an inflation pressure of 95 psi (0.66 MPa) were chosen. The nose gear tire is sized for dynamic breaking loads. From Raymer [Ray92], this load is 762 lb. Thus, a Type III 5.00-4 tire with a maximum load of 1100 lb (499 kg), 6 plies and an inflation pressure of 55 psi was chosen.

4.10.3 Oleo sizing

Single oleo-pneumatic shock absorbers are used for both main and nose gear. The stroke is sized to meet FAR §27.725: each gear must be able to withstand a 13 inches drop test (vertical touchdown velocity of 8.35 ft/s). Assuming a tire stroke (1/3 radius) and shock absorber efficiencies of 0.47 (tires) and 0.85 (oleo), the estimated stroke equals 3 in (76.2mm). The value is increased to 4 in (101.6mm) to account for any errors and provide a margin of safety[Cur88]. Oleo sizing design requirements are [Cur88]: internal pressure of 1800 psi, external diameter of 1.3 times the internal diameter, length of 2.5 times the stroke, external diameter related to static load (for main wheels) and to dynamic load (for nose wheel). The main gear incorporates a mechanical advantage system to reduce the required oleo stroke for a given wheel stroke. This system is included in the oleo sizing computations. The resulting oleo specifications are: nose gear outside diameter 1.54 in (38.4mm) and length 12.52 in (254mm) and main gear outside diameter 2.5 in (63.5mm) and length 7.3 in (185.4mm).

4.11 Airframe

The Calvert airframe consists of a substructure which supports the fuselage skin panels, external structures and internal components. The airframe has been designed to meet the FAR 27 crashworthiness requirements.

4.11.1 Substructure

The Calvert uses seven primary metal bulkheads and several smaller bulkheads for load transfer and to maintain structural shape (see Figure 4.1). The first primary bulkhead is at the front of the cockpit and supports the nose gear, the avionics bay, and the nose section of the aircraft. The crew seats and rear-facing passenger seats are suspended from the second primary bulkhead, which separates the cockpit from the main passenger cabin. By suspending the seats from the bulkhead, the belly tanks can safely carry fuel without fear of puncture by energy absorbing seats that might otherwise stroke into the floor. Additionally, this second primary bulkhead forms the front support for the transmission deck. The third primary bulkhead forms an intermediate support for the transmission deck and the front of the rotor mast support standpipes. The fourth primary bulkhead forms the rear of the passenger cabin and the rear support point for the transmission deck. It is also the mounting point for the forward-facing passenger seats, and the front mounting point for the engines. The aft mounts of the engines are on the fifth primary bulkhead, which also supports the rear of the fuel system. The final pair of primary bulkheads sit at the end of the tailboom. The forward one supports the empennage, while the aft one supports the propeller shaft and propeller bearing. The fuselage skin panels are attached to the primary and secondary bulkheads

To support the cabin floor two keel beams are mounted to the primary bulkheads. The keel beams run between the first and fourth primary bulkheads. Keel beam sections with sine wave webs have been chosen as they have been proven to exhibit good crash energy absorption characteristics. This ensures fuselage crashworthiness.

4.11.2 Tail boom

The synchropter configuration lends itself to a short tail boom resulting in weight savings. The tail boom is a semi-monocoque structure (see Figure 4.1). There are only two structural bulkheads within the tail, and all of the loads from these bulkheads are transmitted by the stringers, minor bulkheads, and skin to the primary substructure. The propeller shaft bearings are supported by the minor bulkheads.

4.11.3 Pylons

The pylons are designed to support the rotor system. To reduce drag, each pylon incorporates an aerodynamic fairing that encloses the stand-pipe, rotor shaft, non-rotating controls and the swashplate. This fairing terminates 6 inches below the rotor hub and reduces the number of exposed linkages to two (pitch links). The top of the fairing terminates in a specially designed flange to minimize interference drag (wind tunnel tests are necessary to determine the flange profile).

4.12 Subsystems

4.12.1 Inlet and exhaust system

The Calvert has three inlets; the two primary inlets provide air for the engines and the secondary inlet provides air for the cooling system and cabin ventilation. The primary inlets are located aft and outboard of the pylons as shown in the inboard profile (see Figure 4.1). The particle separator is mounted at the inlet flush with the fuselage. The secondary inlet (a NACA flush inlet) is located between the pylons.

The exhaust system is designed to take into account heat, corrosion, thermal expansion and to optimize for pressure recovery. The exhaust ducts extend just past the fuselage and are surrounded by another set of composite ducts. This outer shell serves three purposes: it ensures that air is circulated around the exhaust ducts for cooling, provides for smooth air flow minimizing drag, and adds rigidity to the aft fuselage.

4.12.2 Fuel system

The Calvert has a required fuel capacity of 182 gal (689 L) (see section 5.2). For crash worthiness, the fuel tanks should only be filled to 70% of their total capacity. The resulting fuel tank volume is 274 gal (1036 L), allowing an additional 3% for the tank wall thickness. To accommodate this requirement, six main fuel tanks are incorporated; four below and two behind the passenger cabin. Each of the four tanks below the cabin has a volume of 35.9 gal (135.8 L) and each of the two tanks aft of the cabin has a volume of 65.2 gal (246.4 L). Placing the fuel below the cabin floor eliminates the need for sponsons and ensures an aerodynamically clean configuration. It should be noted that the crashworthy seats are mounted to the bulkheads rather than the floor to avoid puncturing the fuel tanks in the event of a crash (see section 4.11.1). The Calvert's fuel system has been designed to maintain independent fuel supply to each engine. Electric booster pumps are provided inside each main fuel tank. The fuel tanks will be cross connected to ensure even fuel levels. In addition to the main fuel tanks, there are two collector tanks (one for each engine). Each collector tank is equipped with an independent fuel pump.

4.12.3 Fire protection systems

Post-crash fire is an ever present danger and the source of many fatalities. Great care was taken in this design to ensure that the passengers and crew are shielded from potential fire hazards. Shutoff valves and self-sealing breakaway couplings are used to prevent post-crash fires. Proper grounding of the fuel system will minimize potential lightening strike damage. Large doors on both sides of the cabin and cockpit provide adequate vehicle egress. The fuel is stored in crashworthy tanks below the cabin floor and the fuel lines run behind the fourth primary bulkhead from the fuel tanks to the transmission deck. This ensures there will be no fuel or vapors in the cabin. Manually operated and thermostatically regulated HALON bottles are provided to suppress any engine fire. Temperature, and smoke alarms are provided, to alert the pilot to any potential problem.

4.12.4 Heating, ventilation, air conditioning, and anti-ice (HVACAI) system

The windshield and window defrosting, cockpit and cabin heating, and cockpit anti-ice systems use hot engine bleed air. No combustion heaters are used for safety reasons. Separate anti-ice plumbing is provided for the empennage and engine inlets. The anti-ice system has been designed for outside air temperatures of 15° to 30° (−9.4° to −1.1°C), as per FAR requirements. Since the Calvert is high speed cruise power limited, bleed air is available for anti-ice in all flight regimes. The anti-ice ability will allow the vehicle to safely pass through icing altitudes. The rotor hub will need no anti-ice since all movable controls are internal to the pylon fairings. A heating strip is incorporated into the rotor blade leading edge cap for de-icing.

The source of the cabin and cockpit airflow is engine bleed air. The HVACAI system has been designed to preclude excess fuel vapor and engine exhaust from entering the cabin and carbon monoxide detectors provide additional safety. Outside air for ventilation is provided by the secondary inlet located between the pylons.

Separate cooling systems are provided for the transmission, engine and cabin. Air for each of the cooling systems is provided by the secondary inlet. The cabin cooling system heat exchanger is located in front of the transmission. Hot bleed air will be sent through the heat exchanger to cool the air as required for air conditioning. The cockpit, cabin and avionics are cooled by this air conditioned air.

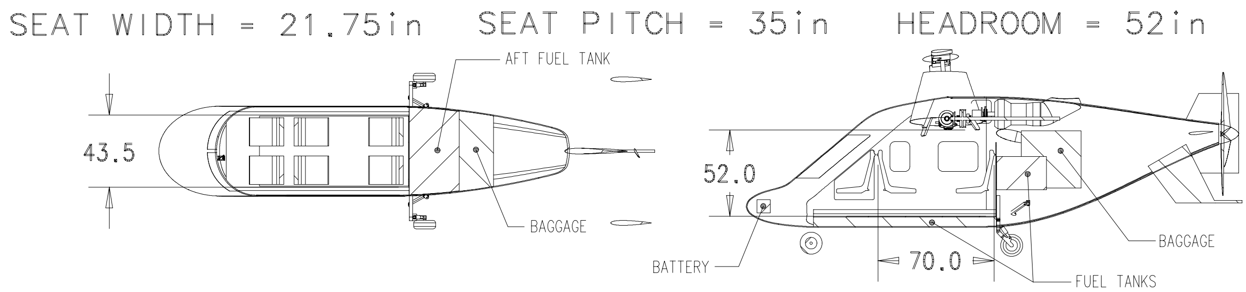


Figure 4.23: Cabin layout.

4.13 Interior layout

Given the mission flight time of three hours, comfort is an important consideration for the Calvert. Thus, the interior layout has been optimized to provide comfort for passengers and crew alike while minimizing the drag penalty associated with high speed flight.

4.13.1 Cabin

Few helicopters routinely travel at speeds for which the Calvert has been designed. These high speeds require the fuselage frontal area to be minimized in order to keep parasite drag to a minimum. In order to minimize the frontal area, the seating is provided in three rows of two seats each (see Figure 4.23). By seating passengers only 2-across and providing doors on both sides of the fuselage, the Calvert avoids the need for additional height for passengers to enter and exit the fuselage. Hence, the headroom can be sized for a person in the seated position. The resulting passenger compartment height and width are 52 in and 43.5 in, respectively. The seat pitch of 35 inches provides adequate leg room. The volume of the passenger compartment and cockpit is 127.9 ft^3, which gives a volume per person of 21.3 ft^3 This is greater than the Augusta 119 (15.25 ft^3) and the Bell 407 (18.0 ft^3). The seats are mounted to primary bulkheads for crashworthiness (see section 4.11.1).

4.13.2 Doors

Four doors have been provided for ingress and egress. The crew enters and exits the cockpit using standard hinged doors that swing forward. Passengers access the cabin via “clam-shell” doors located on either side of the fuselage. The lower half of each door doubles as a step to ease ingress and egress.

4.13.3 Cockpit controls

A glass cockpit improves pilot visibility, and a careful design of displays and advanced avionics keeps pilot workload to a minimum. Dominating the pilots instrument panel are two large flat panel displays, 5.5 in (139.7 mm) by 7.5 in (190.5 mm), stacked one above the other. These multi-functional displays (MFD) work as the primary flight instruments and provide visual cues for system monitoring. An MFD configuration was chosen since flat panel displays are cost effective, reliable and more versatile than the plethora of gauges, bars and dials they replace. The upper MFD is the primary flight instrument display. The required instruments consisting of an airspeed indicator, an altimeter, and a magnetic direction indicator will be augmented with a slip-skid indicator, an artificial horizon and a clock to ease piloting. The lower MFD contains performance gauges for engine parameters, (oil temperature/pressure, turbine temperature and RPM, gas generator speed, and torque), main rotor and propeller RPM, propeller pitch, and a fuel gauge for each tank. In addition, the prognostics and health management system (PHM) (see section 4.14.2) status and documentation will be displayed on the lower MFD. To ensure fail-safe operation, the MFD system provides redundancy: if one flat panel display fails, the other can display all of the most vital information. Basic analog gauges are also included.

The overhead panel is reserved for the helicopter startup, shutdown and rotor controls. The center console holds the throttle and landing gear controls as well as the radio equipment. The basic instrumentation package will be VFR only. Since helicopters operate under much less restrictive rules than fixed-wing aircraft, this is not a major limitation. However, the provision for expansion to full IFR instrumentation is provided.

4.14 Reliability and maintainability

A safe, affordable and dependable helicopter must have good reliability and maintainability (R&M). The direct operating cost (DOC) of a helicopter is directly related to its R&M. For the Calvert, the $217/flight hour maintenance costs (including scheduled inspection, overhaul retirement, unscheduled maintenance and on condition maintenance - see section 8.2) constitute approximately 40% of the DOC per air-seat-mile. Adequate R&M can be achieved when it is included in the design process. This is a constraint placed upon the designer in addition to manufacturing, corrosion, weight, and cost constraints. Additionally, R&M considerations tend to increase development costs. However, upfront attention to R&M pays for itself many times over during the life of the helicopter, as has been adequately demonstrated by many US military programs, especially the numerous unmanned aerial vehicle programs where costs skyrocketed due to a lack of R&M planning. Thus, R&M has been included as a major factor in the development plan of the Calvert.

4.14.1 Accessibility

A helicopter designer has the goal of ensuring that each part may be inspected, serviced, and replaced with single level access; i.e. the inspection of any primary part should not require the removal of another. For example, the engine should not need removal to service the transmission. Adequate access panels are the single most important item for ease of maintenance. The fuselage is made from composite panels bolted to a frame. Hence, access panels have been incorporated during the design stage itself to avoid costly rework of the moulds. In addition, there should be a high commonality of fasteners and subsequently, a limited number of tools are required to remove any line replaceable units (LRU's).

Easy access to the drive system, including the transmission, engines, and shafting, is of utmost importance since these systems constitute the vast majority of inspection and maintenance hours. The upper fuselage is designed as a left and right cowling, each of which can be easily opened providing access to the transmission and engines. In addition, the interior of each cowling serves as a work platform. The rotor pylon fairings are also easily removable to give access to all rotating assemblies. If additional access is needed, the entire upper fuselage skin may be removed for full access. The propeller and the propeller shaft and bearings can be accessed by removing skin panels in the aft fuselage.

4.14.2 Prognostics and health management

A proven method to reduce maintenance costs is to only perform maintenance when needed; i.e. base helicopter maintenance on condition. In order to successfully perform condition based maintenance, each primary system of interest should be continuously monitored for signs of abnormal performance or incipient damage. Once a potential problem is detected, the nature of the problem is determined and a prognosis of the remaining life of the system is computed. The prognosis is given to the pilot along with suggestions for limitations on the flight envelope to maximize the remaining life. The Calvert will include a fully integrated, comprehensive and robust prognostics and health management (PHM) system. The primary systems monitored are the transmission, engine, rotor system and propeller system as well as certain miscellaneous subsystems. In addition, the PHM system includes a system for self-diagnosis, so that, for instance, sensor failures do not lead to erroneous indications. The PHM system status and documentation is shown on the multi-functional display. In the case of a malfunction, the PHM system flags the fault, displays the checklist and provides emergency procedures.

Under normal operating conditions, the PHM system records only small data sets at large time intervals. However, upon the detection of a potential fault, the PHM system begins recording larger data sets more frequently. Upon landing, this data will be downloded by maintenance personnel and will aid in the analysis of the problem. The central PHM unit is a self contained box which receives data from each sensor. In order to minimize the required wire runs, data transfer from more distant sensors is performed wirelessly using a spread spectrum technology with multi-path and data relay capabilities [SPT98, BLN99]. Specifically, each sensor node can act as a data relay path for sensors, either too distant to the central PHM or whose data path is blocked by intervening objects. Periodically, the central PHM will need to verify the data relay paths. Part of the development will be to determine this interval. Presently, it is expected that this will be at the 50 hour inspection interval. Included with each wireless sensor is a small receiver/transmitter assembly. In certain cases, the sensor also performs some degree of on-board processing and data compression in order to minimize the bandwidth required for transmission [SPT98]. Since the transmission distances are small, only low power transmission is required, minimizing the risk of inducing electromagnetic interference with other systems. Electromagnetic interference caused by external sources is minimized by the use of spread spectrum technology and incorporation of a Reed-Soloman error detection/correction and rebroadcast system.

Transmission. Transmission diagnosis and prognosis is performed using two types of information: oil particulate content from the magnetic particulate trap (MPT) and vibration data from accelerometers. Since the transmission is not located near the PHM box, MPT and accelerometer data is transmitted to the PHM system wirelessly. The MPT relays information regarding oil particle content, particle detection rate and particle size to the PHM system. These data have a very low bandwidth; hence, it can be transmitted in raw form. In addition, the MPT is equipped with a high voltage zapper to burn up smaller chips.

Approximately 10 accelerometers will be installed on the transmission housing and standpipe assembly to monitor gears and bearings. The location of the accelerometers will be determined using an experimentation/model-based methodology [JDL96]. Transmission vibration data analysis tends to require a very large bandwidth. Hence, for wireless transmission to be feasible, some local processing is necessary. This leads to a transmission sensor which incorporates an accelerometer, micro-electric circuitry for data recording and processing, and a transmitter. Each sensor is a cylinder, approximately 1.5 in (.038 m) in diameter and 1 in (.025 m) in height. The micro electric circuitry first records a vibration data set (approximately .1 sec). These data are then processed using a wavelet-based algorithm which produces output in the form of a normalized energy (NE) metric [SPL98]. The NE metric is a vector which can be used for transmission diagnostics and prognostics and requires a relatively low bandwidth signal to transmit.

The PHM system receives the data from the transmission sensors and uses neuro-fuzzy sensor fusion/classification techniques to provide a diagnosis of the transmission condition [SP99, EDZSG98]. If incipient damage is detected, damage trend models based upon experimentation are used to provide a prognosis of remaining life.

Engine. The engine has embedded sensors to monitor shaft, bearing and disk vibration, oil pressure, level and particle content, engine RPM and torque, as well as particle separator blockage. The FADEC system monitors the sensor output and performs local analysis of the vibration data. Neural network data fusion techniques [LFYOP96] are then used to combine the output of all the sensors and determine the engine condition. Any problems are reported wirelessly to the PHM system. Since all processing is performed locally, only a low bandwidth signal is required.

Rotor system. The rotor system incorporates sensors for monitoring the condition of each of the hubs, pitch links and blades as well as rotor track and balance. Given the weight and space limitations on the rotor system, small MEMS accelerometers are used. The data from each of the sensors are sent to a transmitter at each hub that then wirelessly transmits the data to the PHM system. Vibration data from the hubs and pitch links are analyzed using wave propagation methods [LP97, PLP98]. To monitor the blade condition, an array of sensors is distributed along the span of each blade. Once the data has been received by the PHM system, the health of each blade is determined using its modal dynamics [KP98]. Initially, the rotor blade natural frequencies are monitored to detect any significant changes. Upon detecting a change, a more comprehensive modal approach is used to locate and characterize the damage.

The rotor track and balance is performed using the accelerometers located on each standpipe as well as two accelerometers under the crew seats. Vibrations detected by these sensors are processed by the PHM system, which subsequently performs trim tab adjustments using the active trim tab system (see section 4.4.3) for improving the track and balance.

Propeller. The propeller typically needs little maintenance. However, the pitch control system will be monitored to ensure proper operation. In addition, wireless sensors will be included to monitor the high torque propeller shaft and its support bearings. These sensors will include micro-electric circuitry for local processing in order to reduce the bandwidth of the signal.

Miscellaneous systems. Various other subsystems can be included in the PHM system. Avionics, electronics, and environmental control systems are all possible candidates. As designs become more electrically integrated, it is easier to gather data for comprehensive tracking of vehicle maintenance.

4.14.3 Flight data system

Numerous accidents are caused by component damage from unreported excursions outside the flight envelope and these can be potentially avoided in the Calvert. In order to avoid this problem, a flight data system is included in the Calvert as a supplement to the vehicle management system to ensure proper use of the helicopter. This system will monitor the aircraft's operation and ensure that any excessive flight maneuvers are recorded. This system will then inform the maintenance personnel of the needed maintenance.

4.14.4 Vibratory database

The vibratory database (dBV) will be created during the development, testing and FAA certification of each of the salient systems. The initial limited database will help to initialize the PHM system. Additionally, suitable inspection and overhaul intervals can be recommended. As experience and supporting data are gathered, the PHM system will be fine tuned and the intervals will be increased. This database will be supplemented by tear down inspections. As different failures are detected, either during testing or hard field use, they will also be included and, potentially, many failure modes could be predicted and prevented by this robust database.

4.14.5 Information age

The Calvert's PHM system data can be downloaded at selected time intervals, for example every 50 flight hours, and the data can be electronically transmitted to the OEM database. The data can then be analyzed and the necessary maintenance action provided to the operator. This potentially new line of work by the OEM - tracking faults and recommending maintenance - could significantly reduce maintenance costs and also prove to be a very lucrative business in the information age.

4.15 Aircraft operation

The Calvert has been designed to transport 4 people at a cruise velocity of 180 knots over a distance of 540 nm. Alternatively it can transport 6 people over a distance of 552 nm at a cruise speed of 160 knots. It can also transport 6 people a distance of 580 nm at a cruise speed of 142 knots. The Calvert's speed and range will not only provide a significant improvement over existing helicopters but will also help it compete favorably with some fixed wing aircraft thereby potentially increasing its market share.

Because the Calvert has large installed power to achieve high speed cruise, One Engine Inoperative (OEI) operations at lower speeds are considerably less severe compared to existing helicopters. The Calvert has sufficient power to hover with OEI, with 4 passengers and 30% of maximum fuel capacity (see Table 4.5). For ISA+20 conditions, the reduced density has only a marginal adverse effect on the helicopter's performance with the unsafe OEI flight speed increasing from 30 knots to 35 knots and the hover power increasing from 780 to 850 hp. There is less operating margin on hot days and extra care must be taken to avoid potentially dangerous operating regions.

4.15.1 ISA and ISA+20 flight profile

The mission profile is based on the RFP that requires a helicopter to fly 540 nm at 180 knots. Performance was calculated at both ISA and ISA+20 conditions. The basic flight profiles remain the same in both conditions, but increasing temperature decreases the excess power. Since the Calvert's engines were sized for cruise at 180 knots, it has a very high rate of climb (ROC) at lower speeds (Figure 6.7). FAR limits the ROC to 1250 ft/min for unpressurized aircraft. By utilizing the 30-minute engine power rating, the Calvert can climb at 1250 ft/min at a cruise speed of 180 knots up to 8,000 ft altitude. This high ROC capability is advantageous with a view to minimizing the transit time, and for bad weather conditions. The ROC at cruise (1250 ft/min) is the same for ISA and ISA+20 conditions.

4.15.2 Flight procedures and instructions

This section describes the procedures that must be followed to complete the mission profile safely and efficiently.

Preflight. A flight begins with a proper preflight. After loading the passengers, the rotor is engaged and the engines are warmed up during taxi to the takeoff location.

Takeoff. The pilot should takeoff and quickly accelerate past the unsafe OEI speed region of 0-30 knots. He should then continue to accelerate the helicopter and climb to a safe operating altitude. This altitude will depend on the location of takeoff. (For instance, this value will be different for an oil rig from the corresponding value for a metropolitan area.) After clearing the terminal area, the helicopter should be accelerated to 180 knots. Upon reaching that speed it establishes a 1250 ft/min climb rate which is now maintained until the helicopter reaches cruise altitude. The analysis indicates that the Calvert would require about 30 seconds and just over 1 nm to accelerate to 180 knots.

Cruising flight. The Calvert is designed to fly at a cruise speed of 180 knots at 4,000 ft, ISA. For ISA+20 conditions, the cruise speed is 170 knots. To fly at 180 knots, under ISA+20 conditions the cruise altitude is reduced to 3000 ft. The corresponding numbers for ISA and ISA+20 conditions at the bad weather altitude of 8000 ft are 170 knots and 166 knots respectively.

Descent. To minimize flight time, the Calvert should be operated at cruise speed as long as possible. The Calvert cruises at 3 nm/min. For a descent rate of 1000 ft/min, it would descend 1000 ft for every 3 nm of cruise. The Calvert would therefore require 24 nm to descend to ground level from a cruise altitude of 8000 ft. The pilot should enter the landing pattern, land normally and then taxi to the unloading location. The rotors should be shut down prior to disembarking passengers. In summary, the recommended operations are:

- Preflight, load, and taxi.
- Takeoff and accelerate past OEI speed.
- Clear the terminal area and climb to a safe operating altitude.
- Accelerate to the 180 knot cruise speed.
- Climb to desired cruise altitude.
- Upon reaching the landing location, decrease power to descend.
- Decelerate to safe terminal operating speed.
- Land, taxi, and unload.

4.15.3 OEI procedures

For the Calvert, the two regions for unsafe OEI operations are at forward speeds of less than 30 knots and greater than 140 knots for the Maximum Continuous Power rating. The corresponding speeds are 20 knots and 150 knots for the TOP rating (1-5 minutes). The Calvert may be safely operated OEI at speeds from 30 -140 knots. In the event of engine failure, the goal is to return the helicopter safely and quickly to the ground. If an engine failure is detected, the FADEC will increase the power of the remaining operating engine to either equal the output power of both engines or to TOP (takeoff power), which is typically a 1-5 minute rating. The pilot will be immediately notified on his instruments that an engine failure has occurred and he should quickly select a landing site. Table 4.4 indicates the OEI flight restrictions at the design gross weight (2298 kg). Table 4.5 indicates the OEI critical speeds for different values of remaining fuel as a percent of total fuel capacity. For 30% remaining fuel (fuel weight: 167.8 kg, aircraft weight: 1906 kg) the Calvert can safely hover OGE in a one engine inoperative condition.

Speed knots	**Effect on Helicopter**	**Corrective Action**
< 30	Descend	Lower nose and accelerate or prepare for immediate landing
30 - 80	None	Maintain 75 knots and land
80 - 140	None	Maintain 75 knots and land
> 140	Decelerate to 140	Maintain 75 knots and land

Table 4.4: OEI flight restrictions at gross weight, ISA conditions.

Takeoff and landing. OEI operations are critical at speeds below 30 knots. Above this speed, the helicopter can accelerate and climb safely. At speeds below 30 knots, the helicopter will start to descend after an engine failure. This is a potentially dangerous situation. The pilot must either lower the nose and accelerate past 30 knots or prepare for an immediate landing. After selection of a suitable landing site, the pilot must conduct a normal airport approach and execute a rolling landing. This rolling landing ensures that the speed remains above 30 knots.

Hover and low speed flight. Due to the high installed power, OEI on the Calvert is less severe as compared to the same condition on existing helicopters. Single engine safe operation is obtained above 30 knots - in less than 2 seconds after takeoff. The aircraft can fly up to the best range cruise speed of 140 knots with one engine. However, it cannot hover and must perform slow 20 knots rolling takeoff and landing with OEI (TOP rating).

Cruise flight. Since the installed power in the Calvert is cruise speed limited, there is not enough power in one engine to overcome the drag at 180 knots. In the event of an engine failure in the normal cruise operation at speeds greater than 140 knots, the aircraft will naturally slow down and descend. To prevent losing altitude, it is recommended that the pilot should increase collective in the OEI operation. Below 140 knots the Calvert will enter into the safe OEI region. The pilot can then decrease the aircraft speed to the speed for maximum endurance (75 knots) in order to look for a place to land. The actions that need to be performed by the pilot in OEI conditions at cruise speeds of 140-180 knots are within the normal operating regime for the pilot, and are thus not viewed as a major concern. In all events, the speed of the aircraft must be carefully monitored to perform the appropriate corrective actions listed in Table 4.4.

Weight of Fuel	**OEI Critical Speed (knots)**	**OEI Hover (OGE)**
0% - 30 %	0	Yes
50%	7.5	No
75%	18	No
100%	30	No

Table 4.5: OEI weight sensitivity, ISA conditions.

OEI for ISA+20 conditions The basic procedures remain the same as for the ISA+20 condition but extra speed margins are required to compensate for the lower excess power. The Calvert cannot hover with OEI. Therefore, the pilot must perform rolling takeoff and landing. The OEI speed at gross weight is increased from 30 knots to 35 knots. Hover power increases from 780 HP to 850 HP. The pilot must consider the increased power, speeds, and distance to safely operate the helicopter.

4.15.4 Autorotation characteristics

Autorotation performance depends on several factors such as rotor disk loading (which affects the descent rate) and the stored kinetic energy in the rotor system (which influences the entry and completion of autorotation). It is important to numerically compare the autorotative capabilities of the Calvert with other helicopters in the same weight class. One such comparative measure is an index used by Sikorsky [Whit82], that is defined as the kinetic energy of the main rotor divided by the product of the gross weight of the helicopter and its disk loading. The Autorotative Index (AI) is given by

$$AI = \frac{1}{2}\frac{I_\Omega \times \Omega^2}{W \times DL} \tag{4.2}$$

where I_Ω is the polar moment of inertia, Ω is the rotor speed, W is the weight, and DL is the disk loading. Table 4.6 lists the AI of the Calvert and other existing helicopters in the same gross weight category. The AI has been listed at both the cruise and hover RPMs for the Calvert. The Calvert has very good autorotation characteristics compared to other helicopters in its weight class. In cruise, the AI is lower than in hover due to

Helicopter	Max TOW (lb)	Polar moment of inertia $(slug - ft^2)$	Rotor speed (rad/sec)	Disk loading (lb/ft^2)	AI (ft^3/lb)
Calvert: each rotor					
(hover)	2533.85	343.37	41.9	2.68	44.28
(cruise)	2533.85	343.37	36.2	2.68	34.3
BO 105 LS	5730.4	676.73	44.39	6.93	16.79
Aerospatiale AS 350B	4297.8	733.5	39.88	4.39	30.85
MD 500E	3000	263	51.51	5.48	21.22

Table 4.6: Comparison of Autorotation Indices (AI).

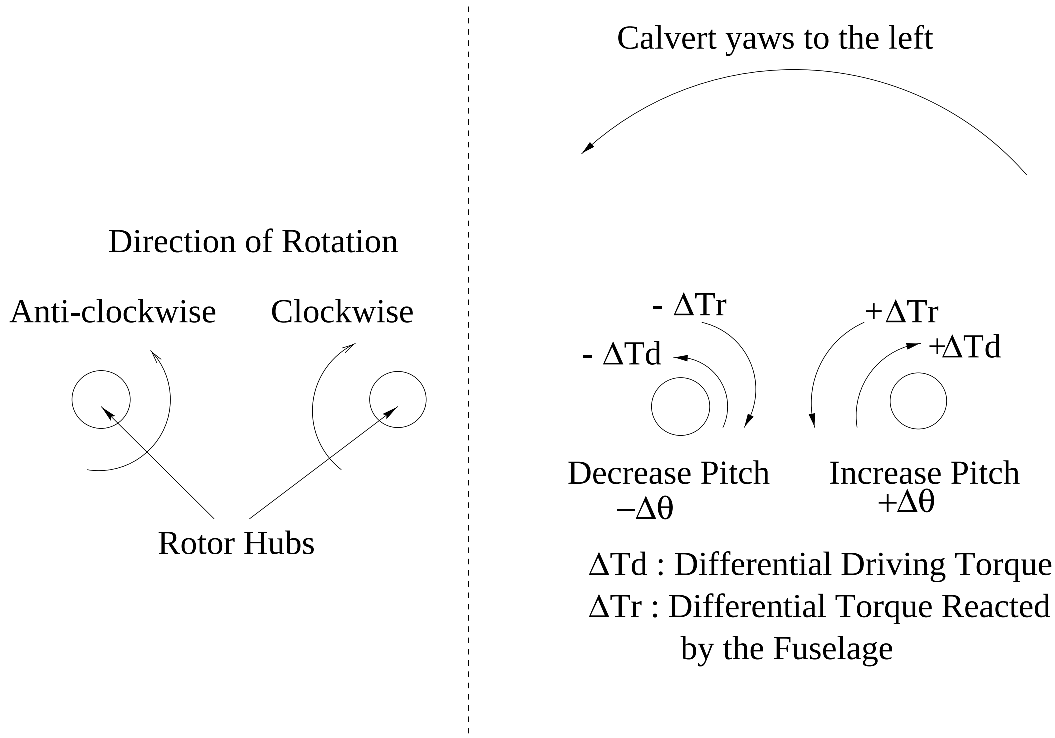


Figure 4.24: Aircraft response to differential pitch input (with engines driving rotor).

the lower engine RPM. However, in cruise the rotor carries only 60% of the required lift and hence entry into autorotation is less hazardous than in the case of conventional helicopters.

Autorotation presents a problem that is unique to synchropters. In synchropters, yaw is effected using differential collective. Figure 4.24 shows the direction of rotation of the Calvert's main rotors (similar to the K-MAX). In the normal operating condition (engine driving the rotor), an increase in blade pitch for the clockwise spinning rotor and/or a decrease in collective for the anti-clockwise spinning rotor results in a leftward yawing motion of the Calvert (see Figure 4.24). During autorotation the same control action results in the Calvert yawing to the right (Figure 4.25). This can be explained with the help of blade element theory. The rotor disk can be divided into three regions: the stall region, region A (in-plane lift component exceeds the in-plane drag component) and region B (in-plane lift component is lower than the in-plane drag component). Region A generates a positive or accelerating torque while region B generates a negative or retarding torque. During autorotation these two regions are in equilibrium (the rotor consumes no net power). While autorotating, an increase in blade pitch on the clockwise spinning rotor causes region B and the stall region to expand while region A contracts, resulting in a retarding (slowing) torque on the rotor. This retarding torque is reacted by

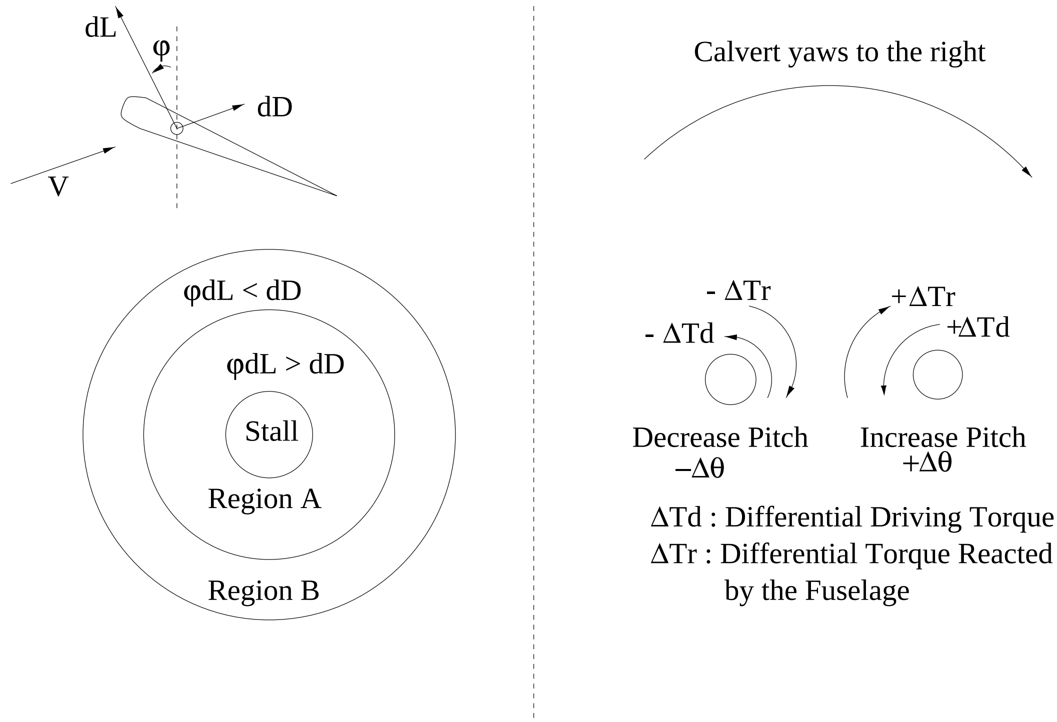


Figure 4.25: Aircraft response to differential pitch input (autorotation).

the airframe (see Figure 4.25) and causes the Calvert to yaw right. Similarly a decrease in collective for the anti-clockwise spinning rotor results in an accelerating torque (Region A expands, region B and the stall region contracts) which also results in the Calvert yawing to the right.

This presents a serious problem for the pilot, since the yaw control action during autorotation is opposite to that during normal operating conditions. This problem has been solved on the K-MAX by the use of a control mixing box, which reverses the action of the pilot's pedal during autorotation. The Calvert will use a similar device located in the lower control system. A torque sensor will be used to measure the engine output torque. In the event of both the engines failing resulting in a complete loss of torque, the control mixing box would flip the pilot controls, thus ensuring that the application of collective to a particular rotor is in the opposite sense to the collective applied during normal operation. This ensures ease of use which is one of our primary design goals.

4.15.5 Special safety provisions

The synchropter configuration chosen for the Calvert requires certain safety issues to be considered in addition to those normally associated with conventional helicopters. The clearance between the rotor blades and the ground is 6.5 feet, which occurs to the left and right of the fuselage. Hence, when the rotor is engaged, the aircraft must be approached from the front since the propeller eliminates approach from the rear. However, to minimize the risk to the passengers, crew and other operations personnel, the main rotor should, if possible, remain stationary until all persons are clear of the aircraft. This constitutes special ingress and egress procedures for passengers and crew. As per FAR §27.783(b), a clearly written notice in bold lettering will be placed on the interior of the cabin door near the handle stating the special procedures. This notice will inform passengers that they are not to exit the aircraft until the main rotor has stopped rotating. The notice will also state that in the event of an emergency the passengers should, upon exiting, move immediately towards the front of the aircraft. An additional notice will be placed on the Calvert's exterior stating that the aircraft should only be approached from the front.

5 Weight and Balance

5.1 Weight estimation

Research and Technology Labs (RTL) has developed a weight estimation procedure based on the regression method [SS83]. RTL formulae have been used to estimate the weight of the main parts of the Calvert (airframe, rotor group, landing gear, propulsive system,...). These formulae are of the form:

$$W_{comp} = const \times A^l \times B^m \times C^n \times ... \tag{5.1}$$

Since these formulae are based on historical trends and do not include several low weight advanced systems (composite airframe, composite blades, etc), appropriate weight reduction factors have been applied to the RTL formulae. Accessory parts (furnishing, air conditioning, load and handling group, etc...) of the aircraft are estimated using Raymer's method [Ray92]. The weight estimation gives special consideration to the synchropter rotor, wing and propeller as well as crash safety issues (crashworthy-cabin design, long-stroke passenger seats). The Calvert gross weight and empty weight are used to calculate the aircraft weight efficiency :

$$Weight\ \ Efficiency = 1 - \frac{Empty\ \ Weight}{Gross\ \ Weight} \tag{5.2}$$

Note that empty weight is defined as the dry empty weight plus the unusable fuel (1.3% of the total fuel weight) and trapped transmission and engine oil (20% of the total oil weight).

5.2 Weight breakdown

The aircraft weight is divided into groups according to MIL-STD-1374. The detailed component weight breakdown is presented in Table 5.1. The detailed MIL-STD-1374 Weight Breakdown is presented at the end of this report (pp. 96-99).

Table 5.1: Weight breakdown and CG locations.

Parameter	Mass, lb	Mass, kg	% GTOW	Long. CG, in	Vert. CG, in
Aircraft					
Gross	5067.7	2298.7	100	121.8	35.3
Payload and fuel	2141.1	971.2	42.2	119.69	40.47
Empty	2926.6	1327.5	57.8	120.15	46.82
Component					
Fuselage	506.6.0	229.8	10.0	123.75	49.32
Horizontal stabilizer	15.4	7.0	0.3	123.75	49.32
Vertical stabilizer	7.5	3.4	0.15	123.75	49.32
Rotor Group	324.8	147.3	6.4	116.4	103.62
Propeller	131.4	59.6	2.6	287.5	55.6
Engine & propulsive sub-systems	444.1	201.5	9.1	162.62	67.5
Engine oil	26.5	12.0	0.52	162.62	67.5
Gear box	347.5	166.76	7.24	123.96	66.3
Gear box oil	43.2	10.5	0.46	123.96	66.3

continued...

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Parameter	Mass, lb	Mass, kg	% GTOW	Long. CG, in	Vert. CG, in
Cockpit flight control	53.9	24.5	1.1	43.8	11
Rot and Non rot. flight control	56.0	25.4	1.1	120.2	96
Fuel (usable)	1233.8	559.6	24.3	128.5	19.2
Fuel system	75.3	34.1	1.5	128.5	19.2
Wing	49.2	22.3	1.0	154.36	52.82
Nose landing gear	39.3	17.3	0.7	38.5	-9.8
Main landing gear	157.0	70.7	3.1	157.3	-6.23
Hydraulic and Pneumatic sys.	5.1	2.3	0.1	108	60
Electrical	176.5	80.1	3.5	5	12
Avionics	121.3	55	2.4	10	12
Glass cockpit	10.1	4.6	0.2	38.6	20
Flight computer	10.1	4.6	0.2	30.2	10
Air-conditioning	59.0	26.7	1.2	98	63
Furnishing and Equipment	215.2	97.6	4.2	95.8	20.8
Load and Handling group	30.4	13.8	0.6	55	-7.5
Passenger/crew(4)	661.3	300	13.0	100	13
Baggage	176.4	80	3.5	185.6	35.73

Fuselage. The Army/Bell advanced Composite Airframe Program (ACAP)[RT86] showed an airframe weight reduction of 22% by using composites (without sacrificing crashworthiness). Considering the improvements in the use of composite materials since the 1986 ACAP Program, the RTL weight estimation is decreased by 25%. The resultant fuselage weight is 506.6 lb. Horizontal and vertical tail are respectively estimated at 15.4 lb and 7.5 lb.

Rotor group. The rotor and hub weight are estimated using RTL formulae. These formulae take into account rotor characteristics and material used (composite for blade and titanium for yoke). Unsworth and Sutton [US84] show that a Integrated Technology Rotor (ITR) is lighter than a current rotor by at least 2% of the aircraft gross weight. This weight saving has been applied to the RTL estimation. Based on the above assumptions, each blade weighs 51.9 lb and the hub weighs 58.6 lb. The rotor system weight (hub + 2 blades) is 162.4 lb. Since we have a dual main rotor configuration, the total system weight is 324.8 lb.

Propeller. The weight of the propeller is estimated using Corning's method [Cor79]. This method takes into account the power required by the propeller and yields a weight of 131.4 lb for a 6 bladed propeller with pitch control.

Propulsive group. Engine weight is given by the RFP, based on power required. The formula yields a weight of 173.6 lb (78.7 kg) for each engine. The transmission weight is estimated using the method given by Arling Schmidt [Sch76]. This weight is modified to account for advancements in transmission technology including high strength materials and optimization of gear mesh architecture [Dye91]. The resulting gearbox weight is 367.55 lb (166.72 kg). The remaining propulsive system weights are determined using the RTL formulae. The drive shaft (from gear box to propeller) weighs 17.3 lb (7.9 kg) and the propulsive subsystem weight is 97.0 lb (44.0 kg). Hence, the total drive system weight (transmission, shaft, and propulsive subsystems) is 481.85 lb (218.56 kg). In comparison, the Eurocopter B0-105 has a drive system weight of 435.9 lb (197.7 kg) [TNC99]. Given the added complexity of the Calvert's drive system, the estimated weight is accepted as reasonable.

Fuel system. The fuel capacity of the Calvert is driven primarily by its performance requirements (540 nm at 4000 ft), its weight and its flat plate area. A fuel (Jet A) weight of 1233.8 lb (559.6 kg) was determined through iteration. This fuel weight has a volume of 182 gal (689 l). Included in the fuel computation is an increase of 5% to provide enough fuel for taxing and hovering. The fuel system (tank, pump and lines) is designed to have two independent circuits (one for each engine), as specified by FAR §27.953 (see section 4.12.2). The RTL formulae give a fuel system weight of 75.16 lb. The estimated engine oil is 1.59 gal (6.02 l) (see section 4.8.4) and weighs 26.5 lb (12 kg). The transmission oil capacity (see section 4.9.4) is 1.39 gal (5.26 l) and weighs 23.15 lb (10.5 kg).

Flight control group. The RTL estimation of flight control system weight is 109.9 lbs consisting of 53.9 lb for the cockpit controls and 56.0 lbs for the rotating and non-rotating controls.

Wing. Wing weight estimation formulae are based on historical data from fixed wing aircraft [Ray92] . Because no fuel tank is housed in the wing and because of the use of advanced composites, the wing weight is 49.2 lb.

Landing gear. Landing gear weight is estimated to be 196.3 lb. Since the main gears carry 73% of the total aircraft weight, their weight is assumed to be 143.3 lb.

Hydraulic and pneumatic group. Special attention to the routing and to the choice of material (titanium) of the lines allows for substantial weight savings. Raymer's method estimates the weight of this system at 5.1 lb.

Electrical. Electrical system includes 2 batteries to start the engines. In order to save weight, fiber optics, instead of electric wires, are used whenever possible. Based on Raymer's method [Ray92], the weight of the overall electric systems is estimated to be 176.5 lb.

Avionics. As specified by the RFP, avionic weight is taken at 121.3 lb.

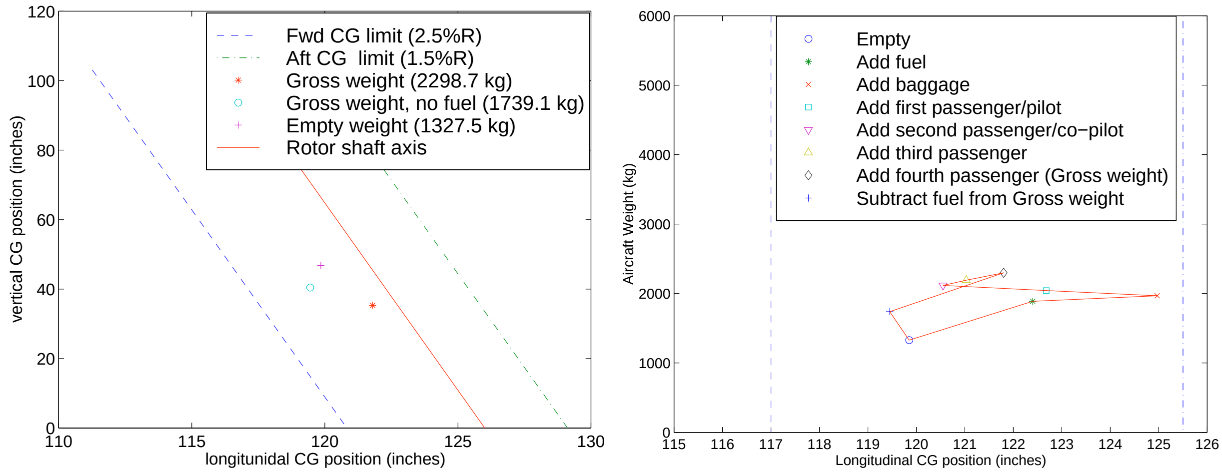
Instrumentation. Instrument group includes the flight computer, cockpit controls (compass, altimeter, airspeed, rate of climb, turn and bank indicators) as well as a two glass cockpit panels for tracking all other aircraft parameters (engine parameters, navigation, weather radar). Since a glass cockpit is very light, Raymer's formulae is used with a 50% reduction factor. It yields to a total of 20.3 lb (10.15 lb for the flight computer and 10.15 lb for the glass cockpit and analog instruments).

Air conditioning. Based on Raymer's method [Ray92], the weight of the air conditioning system is estimated to be 59.0 lb.

Furnishing and equipment. Furnishing group included 6 seats (2 pilot seats and 4 passengers seats from Simula INC) of 14 lb (6.3 Kg) each. The furnishings group also includes carpeting, cabin lights and other miscellaneous items. Noise abatement components are also included in the group and are estimated at 1% of the gross vehicle weight. The entire furnishing group contributes 215.2 lb to the total weight.

Load and handling group. Aircraft towing points and jack hard points are some items included in this group. Its weight is estimated to be 30.4 lb.

Manufacturing variation. Manufacturing variation are estimated at 0.4% (20.3 lb) of the gross weight.



(a) Longitudinal and vertical CG locations

(b) Longitudinal CG locations for different payload conditions

Figure 5.1: Calvert CG travel.

Weight growth. Some allowance for weight growth is made in the conceptual design weight estimation. According to historical data [Ray92], a growth weight of 1.5% (76 lb) of the total gross weight is added to the empty weight. This margin in weight gives the designer some allowance during the fabrication and assembly process.

Crew, passengers and baggage. The aircraft is designed to meet the RFP requirements with 4 passengers. Since the Calvert is a personal transport aircraft the passengers will include the pilot. The RFP specifies that each passenger is estimated to weigh 165.3 lb and is allowed to carry an additional 44 lb for baggage. Therefore the total weight of crew, passengers and baggage is estimated as 837.52 lb.

5.3 Weight efficiency

Table 5.1 shows that the Calvert gross weight and empty weight are 5067.7 lbs and 2926.6 lbs respectively. This results in a vehicle weight efficiency (Equation 5.2) of 42.2%. This value is lower than existing 4-6 seater helicopters (46%). The primary reason for this is the weight penalty associated with the lift off loading (wings) and thrust off loading (propeller).

5.4 CG travel

The center of gravity (CG) location of main components are given in Table 5.1 and Figure 5.2. The longitudinal CG locations listed in Table 5.1 are referenced with respect to the nose of the aircraft while the vertical CG locations are referenced to the base of the fuselage. For stability and control reasons, the CG must be limited to travel, during the flight, to 2.5% of rotor radius forward of the shaft and 1.5% aft of the shaft [TNC99]. The Calvert's longitudinal and vertical CG travel is shown in Figure 5.1(a). The Calvert has a maximum longitudinal CG travel of 2.4 inches and a maximum vertical CG travel of 11.5 inches. The CG locations for empty weight, gross weight and full payload/no fuel conditions are all within the specified limits. Figure 5.1(b) shows the longitudinal CG travel during a typical mission. At the beginning of the mission the fuel and baggage are

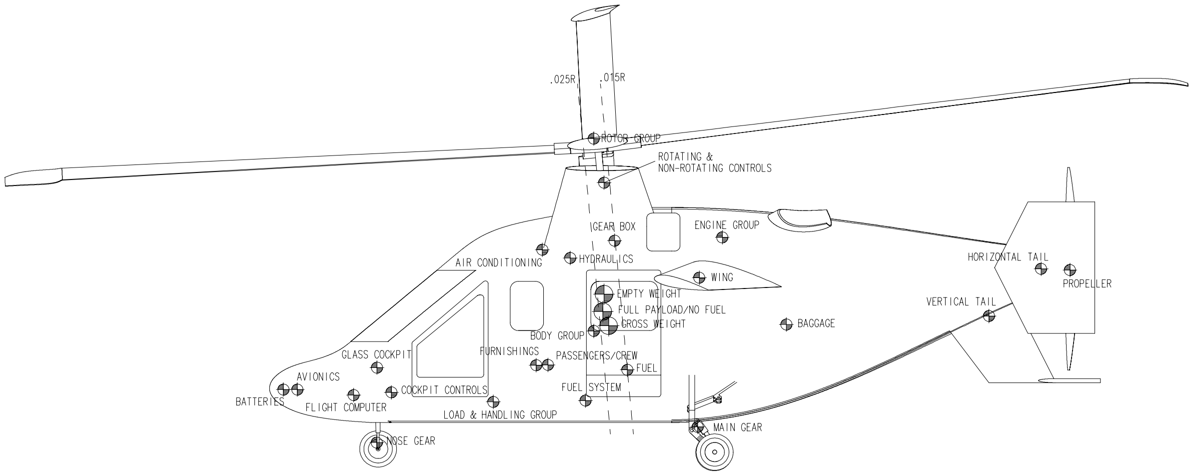


Figure 5.2: CG location diagram.

loaded. Next the pilot (first passenger) and co-pilot (second passenger) are seated in the front two seats. Next, the final two passengers are seated in the two rear seats (facing forward). The two intermediate seats (facing backwards) are only utilized for the 6-passenger flight mode. The Calvert takes off with a gross weight of 2298 kg and on completion of the mission the aircraft weight at the time of landing is approximately 1739 kg. Figure 5.1(b) indicates that the Calvert's CG travel lies within the specified limits for the mission profile.

6 Performance

The analysis of the performance of a compound helicopter entails some special problems and requires modifications to conventional performance analysis methods. The performance analysis for the compound helicopter developed in-house was seminal in directing the overall design process. At each stage, the performance analysis and preliminary design analysis were tied in with the weights analysis described in chapter 5 to ensure convergence of all-up weight.

The effects of a lifting wing, pushing propeller and an offloaded rotor are determined in two stages. The first stage focuses on obtaining a first estimate of power and fuel required in hover and cruising flight, and in making the configuration trade-off studies to arrive at the optimum configuration for the aircraft. This unique method is adapted from [TNC99] and uses nodal 'catch-all' parameters such as lift to drag ratios, propulsive efficiencies and energy efficiencies to estimate the performance characteristics of the aircraft, while keeping track of important parameters like blade loading (Ct/σ) and advancing tip Mach number. This analysis was used to determine critical parameters such as wing and propeller sizing, rotor RPM profile and approximate power and fuel requirement calculations.

In the second stage, the detailed estimates of the control settings, inflow, interference effects and thrust and lift compounding are calculated using an in-house code developed for compound helicopters. The aircraft trim is calculated after making modifications to the existing trim code in UMARC (University of Maryland Advanced

Rotor Code) to allow for the effects of thrust and lift compounding. This code also included the RTL weights estimation methodology (chapter 5) to calculate all-up weights, and the preliminary design methodology from [TNC99] that gives important parameters such as rotor radii, chord, wing areas, propeller sizing etc. The results obtained from this approach compared well with that obtained from the first method. The optimal design thus emerged alongside the performance and weight estimations of the aircraft.

6.1 Drag breakdown

The main ingredient for the success of the Calvert as a high speed vehicle is reducing the drag. High drag items such as the rotor shaft, pylons, and hubs were carefully designed to minimize drag, even at the expense of increasing material costs and manufacturing complexity. While significant attention was given to optimizing the aerodynamics of the fuselage, care was taken to ensure that the fuselage crashworthiness and pilot visibility requirements were not compromised. This section will describe the drag estimation techniques used and the component-by-component drag breakdown.

Component	Drag Area(ft^2)	Percentage
Rotor Hub and Shaft	2.655	35.3%
Fuselage: Body	1.5418	20.5%
Fuselage: Afterbody	0.524	7.0%
Rotor-Fuselage interference	0.854	11.3%
Exhaust	0.200	2.7%
Nacelles	0.180	2.4%
Transmission Deck interference	0.141	1.9%
Horizontal tail	0.126	1.7 %
Induced Drag	0.309	4.1 %
Vertical Tail	0.496	6.6%
Miscellaneous	0.5	6.6%
Total Drag	**7.527 ft^2**	**100%**
	0.699 m^2	
Drag loading	**747.943lbs/ft^2**	

Table 6.1: Drag buildup for the Calvert.

Rotor hubs. The Calvert has two hubs. Typically, the hub is the single largest contributor to drag and with two hubs it was vital to minimize their drag. A compact teetering hub (door-hinge type) similar to the AH-1G was chosen. A simple two piece door-hinge type hub is very thin and slender resulting in low drag. Additionally, the hub is enclosed within a hub cap, based on a wind tunnel tested design [YGS87]. The compact streamlined hub provides a significant reduction in drag.

Rotor Pylons. The rotor pylon encloses virtually all of the rotor hub drive mechanism. The shaft, swash plate, and pitch links are all enclosed in an aerodynamic fairing. This results in a major reduction in drag and allows the two-rotor design to possess acceptable drag characteristics. To prevent pressure buildup in-between the two pylons, the fairing are cambered toward the outboard side. The secondary inlet was placed between the pylons to take advantage of high velocity air from the front of the helicopter. This reduces the air flowing between the pylons and will minimize the pressure drag between the pylons. Attention to small details ensures a believable low drag design.

Fuselage drag. Fuselage design is a compromise between interior space and drag. The fuselage internal volume is 127.9 ft^3 (including passenger cabin and cockpit) and the height and width of the passenger cabin are 4.37 ft and 3.62 ft respectively. Special Attention was devoted to the aerodynamic design of the fuselage and the fairing between fuselage and windshield, boat tail drag, and empennage drag. The boat tail is a significant source of drag, and can be mitigated, but not eliminated by careful shaping. The pusher propeller will reduce the drag, at the cost of some loss in efficiency, by creating a low pressure region upstream of the propeller disk which reduces separation from the aft upswept fuselage. The empennage drag has been reduced by minimizing its size, using thinner airfoil sections, and fairing junctions carefully.

Interference drag. Interference drag at the junction between the pylon fairing and transmission deck, and between the fuselage and the transmission deck, wing, nacelles, and tails is minimized by smooth fairings and fillets of generous radius.

Inlet and exhaust drag. The inlet drag is included in the fuselage drag. It is calculated as nacelle drag, but its physical cause is spillage and interference between the nacelle and the fuselage. We have reduced this drag by placing the primary inlets aft of the pylons and flush with the fuselage. Additionally, the secondary inlet is placed between the pylons thereby reducing the pylon's mutual interference drag. The exhaust drag is very difficult to predict without engine details. Based on the assumed engine mass flow of 7.5 lbs/sec and exhaust airspeed of 200 ft/sec, the equivalent flat plate area due to exhaust drag was 0.2 ft^2.

Miscellaneous drag. This drag from gaps in doors, antennas, door handles, lights, steps, skin gaps, cooling leakage, ventilation, ram removal, air data systems, etc was assumed to have an equivalent flat plate area of 0.5 ft^2.

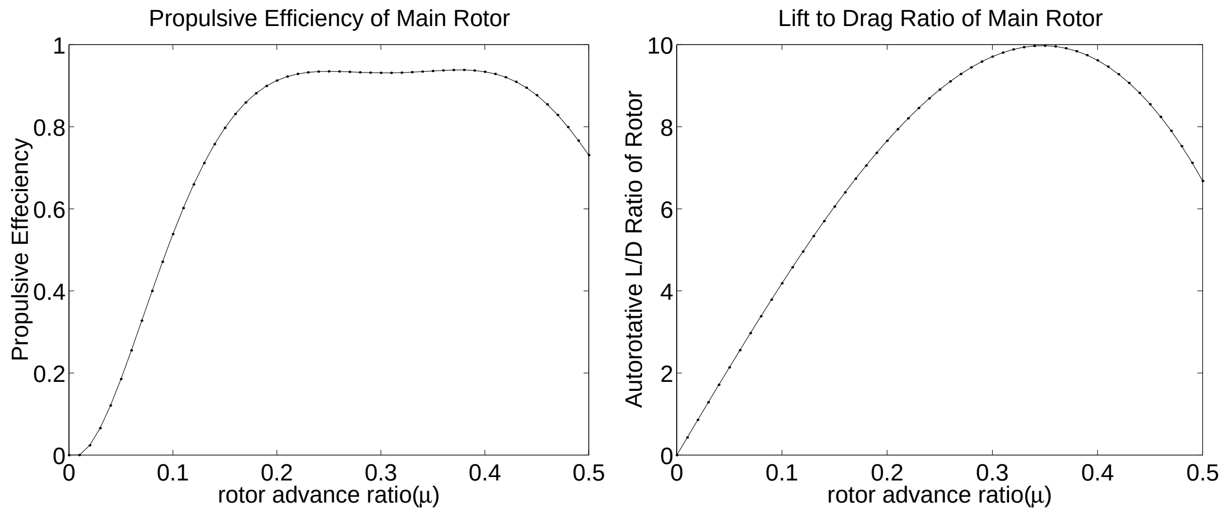
Drag estimation methodology. Three methods were used in performing a drag buildup. Since there are few public domain techniques for helicopter drag estimation, standard textbook techniques were used. Prouty [R.90], Keys [KS84], and a proprietary NAVAIR method were used in the drag buildup and the result were compared to build confidence in the methods. These three techniques use slightly different methods. Prouty based drag on L/D ratios and analytical similarities, Keys used empirical techniques, and the NAVAIR method used mainly skin friction techniques with other corrections. All techniques gave similar results in the drag buildup calculation.

The results have sufficient accuracy for performance assessment and sizing with good confidence in the answer since realistic, not highly optimum, assumptions were used in the drag build up.

6.2 Performance analysis: methodology

Tishchenko method for rough sizing. After selecting the configuration of the aircraft, several parametric studies had to be performed to determine the weights, power requirements, and component sizing for the aircraft. These crucial design decisions were made with the help of a simple but effective method of calculating rotor performance with the help of a very few key parametric inputs [TNC99]. The calculation of power and fuel for the aircraft from initial configuration sizing was obtained using a simple set of parameters which indicate the efficiency of the various aerodynamic surfaces .

In this method, the airfoil C_l and C_d characteristics obtained from wind tunnel data (for a baseline airfoil, NACA 23012) were used to first calculate lift-to-drag ratio L/D (Figure 6.1(b)) and propulsive efficiency (η,



(a) Propulsive efficiency of main rotor.

(b) L/D ratio of main rotor.

Figure 6.1: Effect of advance ratio on propulsive efficiency and lift/drag ratio of main rotor.

Figure 6.1(a)) of the isolated rotor airfoil as a function of Mach number, blade loading (Ct/σ) , and advance ratio (μ). Note that the rotor L/D ratio includes the rotor induced and profile power losses. Figures 6.1(b) and 6.1(a) show that the L/D ratio and propulsive efficiency of the main rotor decrease dramatically at high advance ratios. This necessitates thrust and lift compounding device to decrease engine power requirements in cruise. The total drag of the non-lifting parts was then calculated using the flat plate drag area obtained from the drag buildup. A wing offloading factor (wing thrust at cruise velocity/Take-off weight) and a propeller offloading factor (propeller thrust/total drag at cruise) were then assumed as inputs for the parametric study. The propeller efficiency and diameter were obtained from propeller charts described in section 4.5. The wing lift and drag were obtained from the wing L/D ratio (assuming variation with forward velocity), and the assumed wing lift at cruise speed (from wing offloading factor). The total aircraft drag was calculated by summing the drag of the non-lifting parts, rotor (from rotor L/D ratio) and wing (from wing L/D ratio). Based on the wing and propeller offloading factors, the required rotor, propeller and total powers were calculated using the wing and propeller thrusts and the propulsive efficiencies of these thrusting devices.

At each forward speed, the maximum normal tip speed on the advancing blade, and the blade loading of the rotor disk (which is a measure of retreating blade stall) were calculated. This value of blade loading (Ct/σ) was compared with the maximum allowable blade loading on a baseline rotor (from [R.90]). The main rotor tip speed was changed in such a way as to keep the advancing tip Mach number to less than the airfoil normal drag divergence Mach numbers, and to keep the blade loading well within the maximum blade loading at that advance ratio. This was done keeping the constraints of the FADEC system in view (linear, not more than 15% variation in tip speed from hover value for good fuel efficiency characteristics). As each of these parameters was varied, the engine power and the converged aircraft weight were recalculated, thus pivoting the trade-offs around these key aspects.

This initial configuration study found that a lift augmentation of above 25% of aircraft gross weight was required in order to alleviate retreating blade stall while retaining certain compressibility constraints on the advancing tip Mach number (max. normal Mach number limited to 0.8). An optimization involving take-off weight, hover downwash penalty and rotor blade loading yielded results shown in Figure 6.2. It can be seen that the take-off weight reaches an optimum value because of decrease in the engine power and fuel weight at a ratio of wing lift to take-off weight of about 0.4. Figure 6.2 also shows that the vehicle L/D ratio improves from 2.9 (10% offloading) to 3.7 (40% offloading). Although the wing has a low aspect ratio and therefore does not significantly increase the vehicle cruise efficiency, it provides the critical stall margin that makes the Calvert capable of a cruise speed of 180 knots. As a compromise between the rapid increase in take-off weight and hover power and the decrease in cruise power and stall alleviation, the wing was sized based on a lifting force of 40% off the gross weight in cruise.

It is seen that the lift to drag ratio (Figure 6.1(b)) and propulsive efficiency (Figure 6.1(a)) of the rotor (from wind tunnel tests) fall off dramatically in high-speed forward flight. Coupled with this, the parasitic drag area increases rapidly with a tilt in the fuselage attitude when the rotor acts as the primary thrusting device. The large forward tilt that is entailed by the rotor as the propulsive device also imposes limitations on the speed of flight. In an effort to improve the propulsive efficiency of the rotor and unload its inclination to reduce drag, a thrust offloading is provided by the propeller. A trade off between the weight of the propeller and the decrease in cruise power and fuel capacity resulted in the choice of a thrust compounding of 80% by the propeller for a reasonably high propeller efficiency of 0.82. This ensures that the fuselage remains level at all speeds, and hence the effective flat plate area does not vary significantly with forward speed.

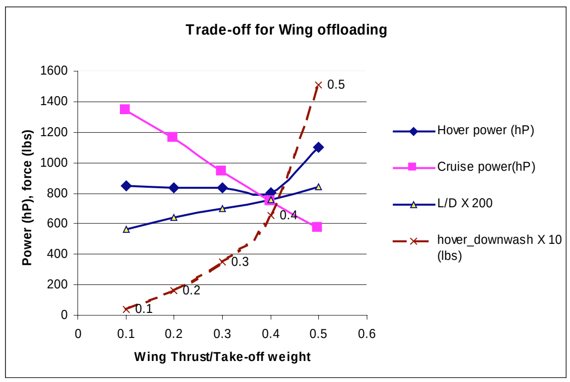


Figure 6.2: Wing size trade-off results.

Detailed trim calculation. Having fixed the configuration of the aircraft and obtained the approximate values for the total power and fuel, a detailed analysis involving the sizing of the various components was undertaken. This involves a performance calculation shown in Figure 6.3.

This methodology ties in the performance and preliminary analysis with the weight analysis, thus allowing optimization of the design. A gross weight from initial calculations was first assumed. The wing and propeller were then sized for the design thrust and lift at cruise speed. These inputs were taken to the weight analysis and used to find a converged all-up weight for the aircraft. The weight analysis also assumes parameters such as engine power, rotor radii, fuel weight etc. These inputs were provided by the preliminary design analysis developed by Prof. Tishchenko [TNC99]. The new weights and aircraft parameters were iterated with the wing and propeller sizing to achieve convergence.

Once the convergence was established, the performance of the aircraft was evaluated. A coupled rotor-fuselage trim analysis was carried out after making modifications to account for the extra lift and thrust from the wing and propeller respectively. The results of this code for the control settings are shown in Figure 6.9 and were used to calculate the profile and induced power from the rotor. The wing/rotor interference effects were

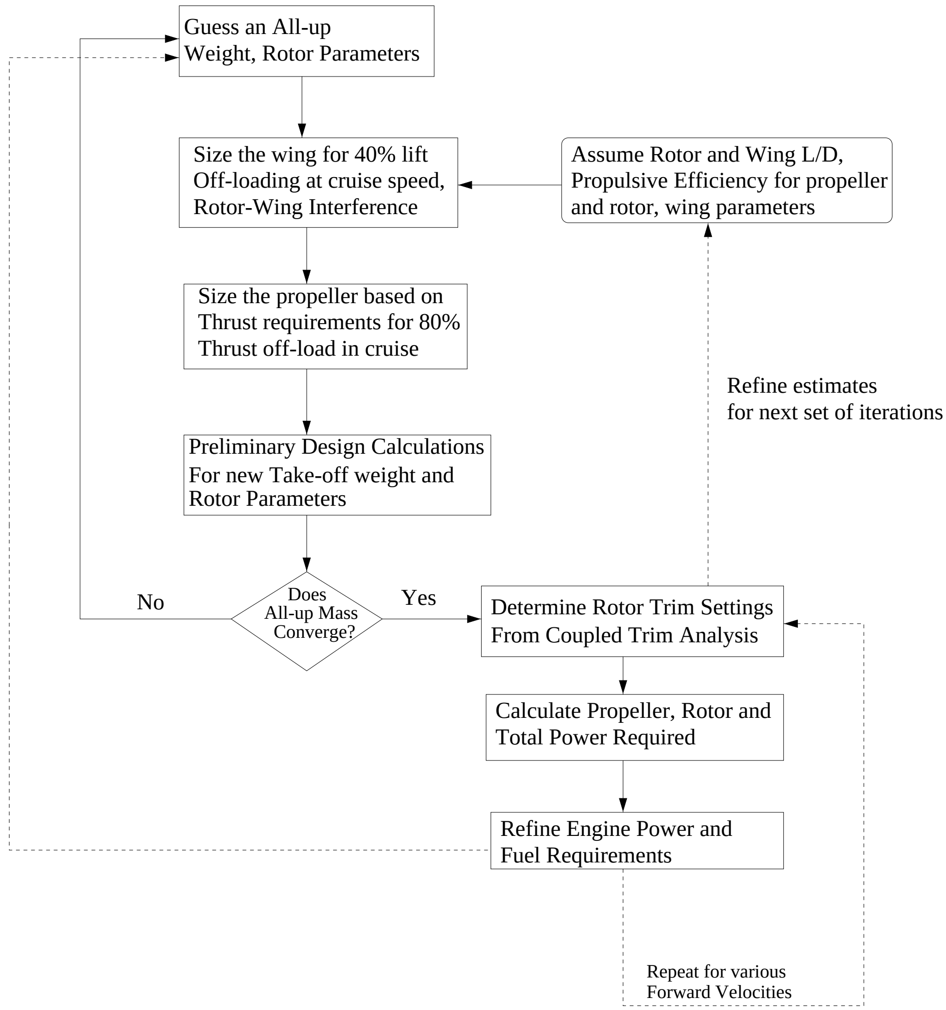


Figure 6.3: Performance and preliminary design methodology.

computed using the method described in [KS84]. The variations in the angles of attack of the wing and the fuselage interference due to variations in rotor downwash velocities, and the effects of a low aspect ratio wing and fuselage-wing interference were also taken into account. The blade loading and maximum normal tip Mach number were also computed. Based on the results of the performance analysis, inputs were given to the aircraft configuration for the next set of iterations.

This design code represented a fusion of the preliminary sizing, weight estimation and performance analysis, and thus directed the overall design process.

6.3 Performance analysis: results

The engine assumed in the power calculations is a scalable engine as described in the RFP. It is labeled as the RFP IHPTET engine. Since a parallel engine development will take place with the Calvert, no available engine is chosen as a benchmark. The engines are sized to meet the following salient requirements: 1) Maximum cruise at ISA, two engines at MCP: 180 knots at 4000 ft with 540 nm range capability. 2) Capability of having maximum power conversion efficiency over a range of RPM to accommodate the decrease in rotor RPM. This range is required to be no greater than 15% of the initial hover RPM. 3) Equipped with a FADEC (Full Authority Digital Electronic Control) system to change the engine output RPM with forward speed. The full details of the capabilities of the engine are listed in Section 4.8.2.

Flight at 180 knots offers a significant challenge in terms of working within stall limits on the retreating side and compressibility effects on the advancing side. In order to minimize cruise power while working within these limits, the Calvert uses a reduced RPM in the cruise mode. As the rotor gets offloaded by the wing and propeller at high speed forward flight, the engine RPM is lowered to keep the advancing blade within the drag divergence Mach number of the tip airfoil. The offloading due to the wing helps alleviate the stall on the retreating side of the rotor disk.

The rotor tip speed profile is shown in 6.4. The maximum blade loading (Ct/σ) for this configuration was found to be 0.064 and the maximum tip Mach number of 0.83, which are both within the stall and compressibility limits of the airfoils used in the main rotor (see Figure 4.3).

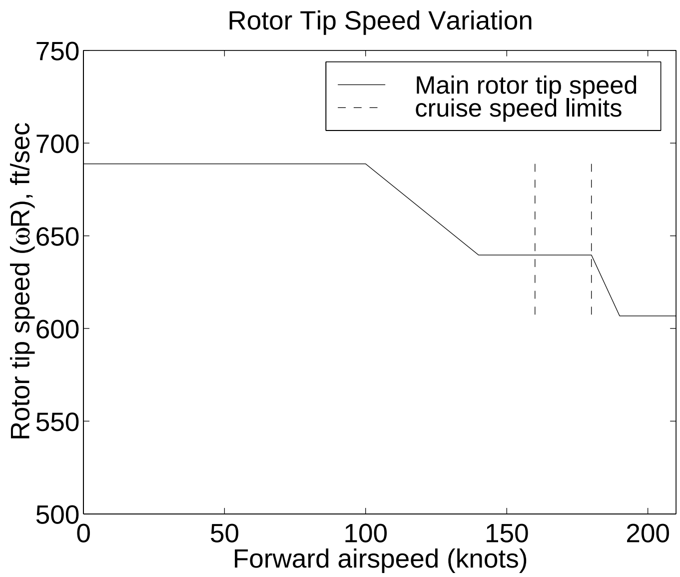


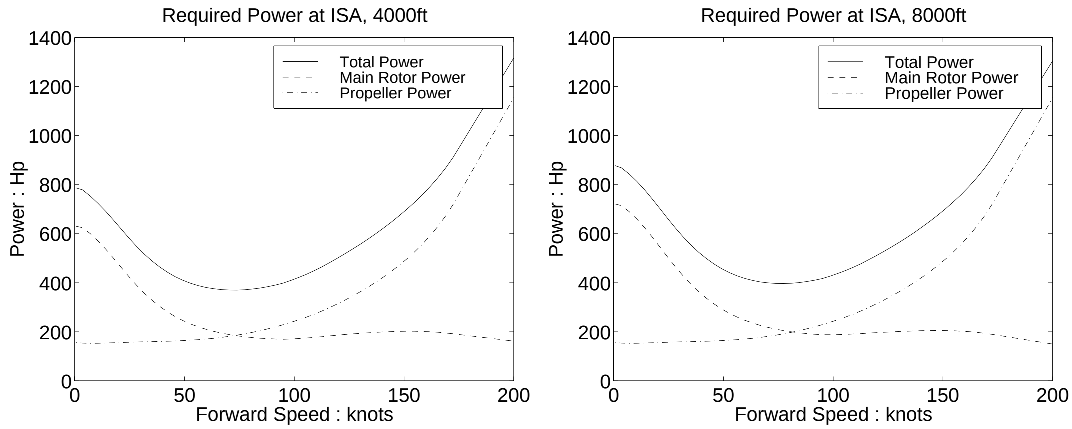
Figure 6.4: Main rotor tip speed profile.

The large installed power to meet high cruise speed requirements allow sufficient margin for maneuverability. The engine power drawn can be increased to the 30 second rating in order to perform a rate 1 turn at a bank angle of 30 degrees. The installed power also allows extremely high rates of climb (Figure 6.7), thus permitting the optimum cruise altitude of 4000 ft to be reached fairly quickly. The calculated engine power also includes several losses in the installation (5% loss), bleed (1%), and transmission (1%).

Figures 6.5(a) and 6.5(b) show the power consumed by the main rotor, propeller and the total power in forward flight, ISA. Figures 6.6(a) and 6.6(b) are the corresponding power curves for 'hot day' (ISA+20) conditions.

It may be noted that although the aircraft is designed to fly at 180 knots with a range of 540 nm, the speed for best endurance (75 knots) and speed for best range (140 knots) occur at lower speed. From the outset, the Calvert has been envisioned as a multirole aircraft capable of high range and cruise speeds, but also more suited to replace existing helicopters in conventional missions with a superior technological alternative. Keeping this factor in mind, the economical cruise speed is rated as 160 knots, and the maximum cruise speed as 180 knots. However, it may be noted that the power required to fly at 180 knots is considerable less compared to the power required for an existing helicopter to fly at high speeds. The aircraft is also capable of flight speeds upto 210 knots without encountering stall or compressibility boundaries. The unique features offered by a compound helicopter of this nature make it capable of high speed flight while not sacrificing the advantages of a conventional helicopter in a lower speed mission.

The power required at 4000 and 8000 feet for the aircraft are found to be nearly the same. This is because the loss of efficiency of the engine at higher altitudes is compensated by the decrease in the parasite drag of the aircraft at lower ambient air densities. The hover power, however, shows a significant increase at an altitude of



(a) 4000ft.

(b) 8000ft.

Figure 6.5: ISA power curves, TOW=5068 lbs.

8000 feet from 780 hp to 867 hp.

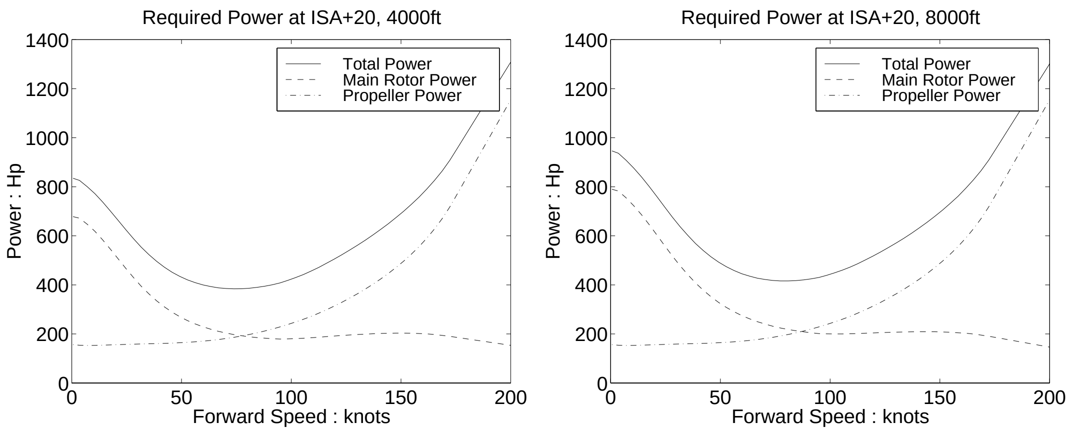
The minimum speed for safe One Engine Inoperative (OEI) aircraft operation is found to be 30 knots. This results in a relatively small 'avoid' region in the prescribed height-velocity diagram for the pilot in case of a one engine failure scenario. This helps in the pilot exchanging the speed for height in an autorotative landing. The maximum rate of climb for the Calvert as a function of forward speed is shown in Figure 6.7. Since the power in the engines of the Calvert are cruise-limited, the aircraft is capable of achieving extremely high rates of climb at lower speeds. It can be seen that at almost every forward speed within operating capabilities, the climb rate capability is larger than the unpressurized cabin rate of climb limit of 1250 ft/min (stipulated in the FAR 27).

Figure 6.8 shows the hover ceiling for the aircraft out of ground effect (HOGE) for different take-off weights. For the design payload, the nominal flight altitude of 4000 ft is well below the hover ceiling specified by the aircraft.

Figure 6.9 shows the results of the modified trim code. It can be noticed that the required cyclic settings for high speed flight are considerable lower than those in a conventional helicopter. This permits high speed flight without large rotor disk tilts (maximum rotor disk tilt is about 6°, of which 5.3° is built into the rotor shaft tilt).

Figure 6.10 shows the altitude vs. maximum continuous speed for ISA and ISA+20 conditions. The aircraft maximum cruise speed at an altitude of 4000 ft is specified as 180 knots and 170 knots at ISA and ISA+20 conditions respectively. The corresponding numbers for the bad whether altitude of 8000 ft are 170 knots and 166 knots respectively.

Figure 6.11(a) shows the fuel consumption in lbs/hour as a function of forward airspeed. It may be noted that the minimum consumption of the current engine is achieved with a speed of 75 knots, which is the speed for best endurance. The fuel sizing is based on an un-refueled 540 nm range stipulated by the RFP, plus a reserve for 30 minutes of flight and 25 nm. Figure 6.11(b) shows the fuel required vs. range for the take-off weight of 5068 lbs. The endurance and range of the aircraft are obtained by integrating the specific fuel consumption over the mission profile of the aircraft. The payload range capability for the Calvert is shown in 6.12, and the corresponding payload-endurance capability is shown in 6.13. The increase in range and endurance for a more fuel-efficient flight speed of 140 knots against payload is also shown. For the maximum cruise speed of 180 knots, the range is 540 nm, as stipulated in the RFP. However, this range can be further increased to 580 nautical miles for the same payload by flying at 140 knots.



(a) 4000ft.

(b) 8000ft.

Figure 6.6: ISA+20 power curves, TOW=5068 lbs.

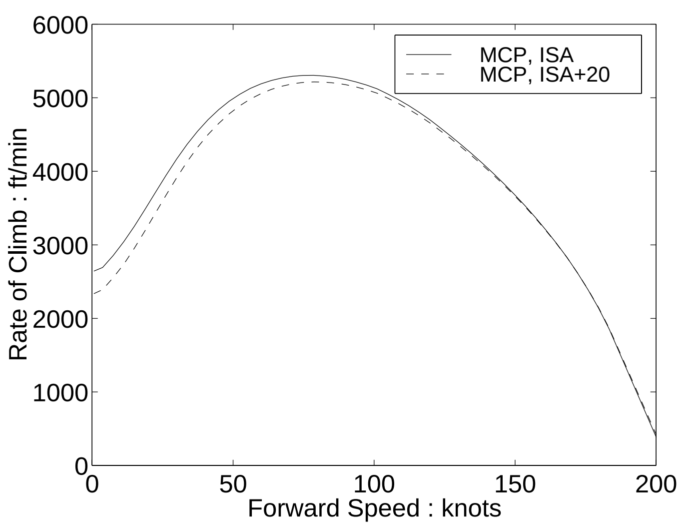


Figure 6.7: Rate of climb *vs.* forward speed sea level, TOW=5068 lbs.

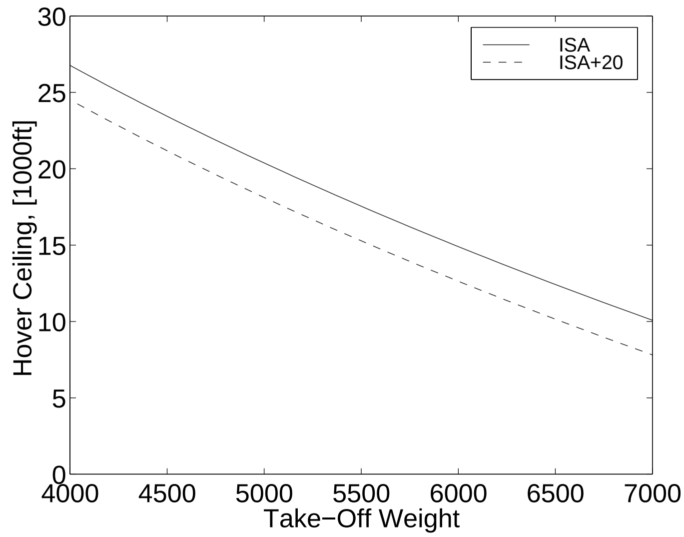


Figure 6.8: Out of ground effect hover ceiling.

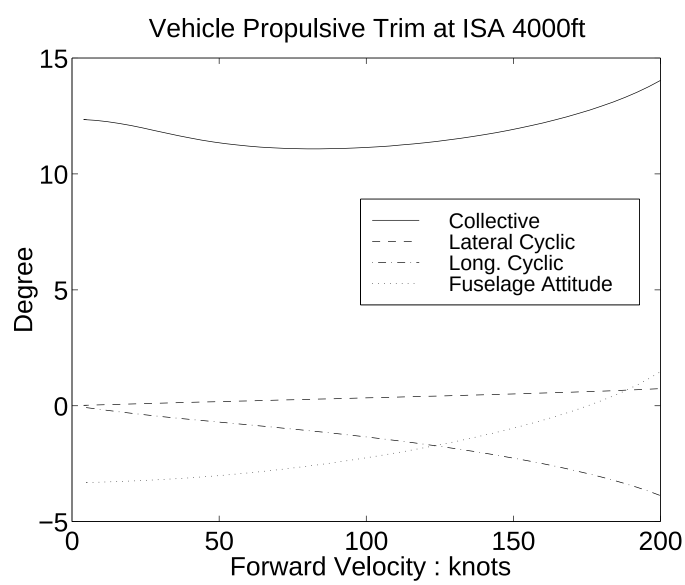


Figure 6.9: Control setting, ISA, 4000 ft, TOW=5068 lbs.

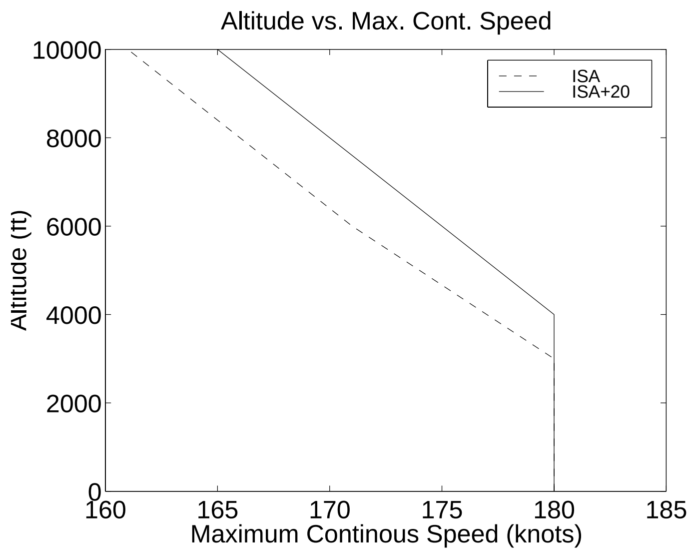
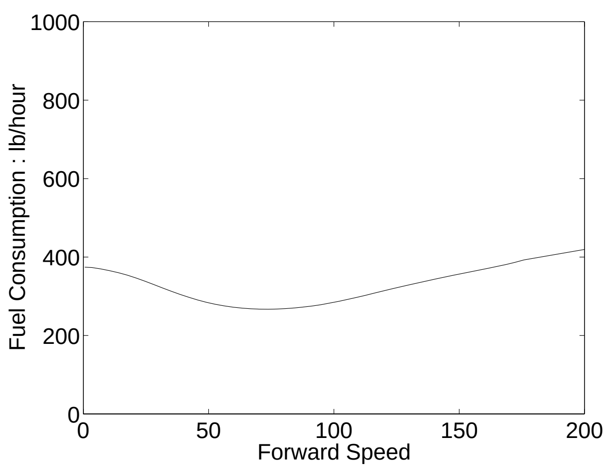
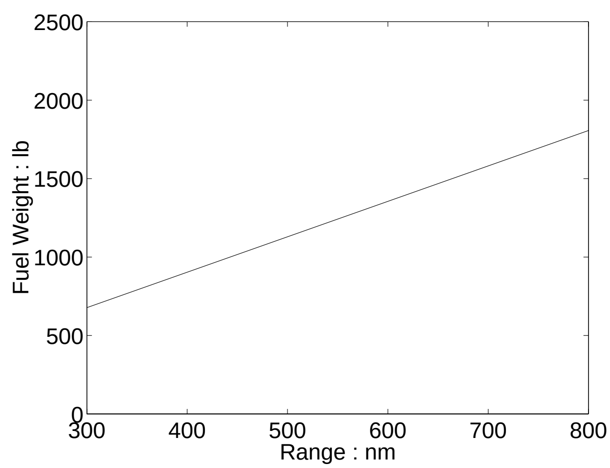


Figure 6.10: Altitude *vs.* max. continuous speed.



(a) Fuel consumption ISA, 8000ft, TOW=5068 lbs.



(b) Fuel required vs. range ISA, 8000ft, TOW=5068 lbs.

Figure 6.11: Fuel requirements.

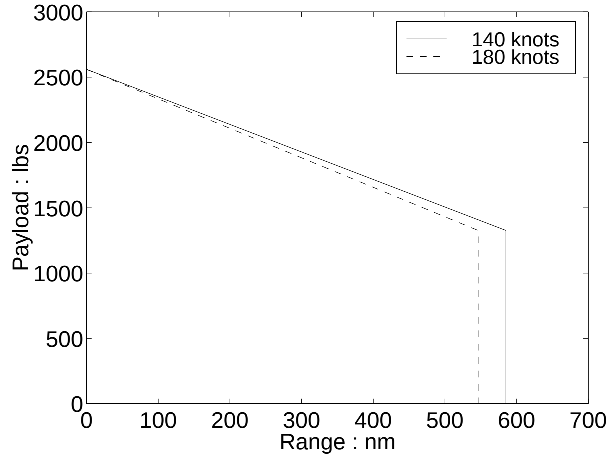


Figure 6.12: Payload-range capability, ISA, 4000ft, TOW=5068 lbs.

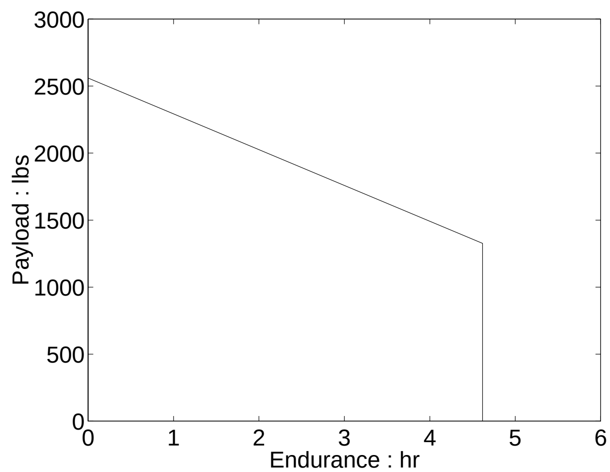


Figure 6.13: Payload-endurance capability, ISA, 4000ft, TOW=5068 lbs.

7 Manufacturing

The primary focus of the design of the Calvert is the maximization of overall value to the customer. Manufacturing is one of the most important steps in the process of delivering a high value product. Designing, from conceptual through detailed design, with the goal of reducing manufacturing and total life cycle costs will produce the most cost effective product. In addition, safety is a very important part of value. Hence, crashworthiness, lightning protection, and structural safety have not been compromised in the manufacturing of the Calvert.

7.1 Technology

The information age has made it possible to use technology for manufacturing. The design process has made and will continue to make full use of CAE, CADAM, electronic document tracking and optimizers. These tools have been proven to pay for themselves, primarily by reducing costs associated with reworking.

7.2 Lean manufacturing

Lean Manufacturing is a systematic approach to perform the minimum work necessary in production. Continual quality improvement, small production runs and the ability to reconfigure the production line for different products are the major benefits of this manufacturing philosophy. There are many elements of lean manufacturing: the basic ones being (i) elimination of waste (ii) continuous flow and (iii) quality control. For the small production run stipulated by the RFP, continuous flow is of primary importance. Continuous flow manifests itself as the ability to easily convert the production line from one product to another at the conclusion of a production run or between production runs so that manufacturing down-time is minimized. Additionally, facility overhead costs are spread over more products. Optimizing the manufacturing process for low rate production will keep production costs low.

7.3 Manufacturing details

7.3.1 Primary structure

Material options. Four construction techniques were examined for the primary structure:

- Metal.
- Composite with autoclave curing.
- Composite wet layup with room temperature/vacuum bag cure.
- Mixed metal and composite.

These techniques were evaluated for their ability to yield low initial production costs and low life cycle costs.

All-metal construction is a tried and true construction technique with many advantages including low cost, available facilities, excellent crashworthiness and lightning protection, and easy structural repairability. The corrosion issues associated with metals can be mitigated by modern coatings applied during manufacture and an aggressive corrosion tracking and inspection regime. However, the cost of airframe monitoring programs, continual corrosion inspections and the replacement of affected parts decreases the initial cost savings and increases life cycle costs.

Composite structures are light and strong and offer a reduction in part count. However, they suffer from lightning, crashworthiness, water absorption and impact damage issues. The typical aerospace industry approach is to use high technology elevated temperature cured resins with graphite fibers. this technique requires molds, bonding, and autoclaves and yields light but expensive components with all the attendant issues relevant to composite structures as outlined above. Another composite manufacturing option is wet layup with room temperature cure. This technique has its own set of advantages and disadvantages. While they are inexpensive and have good finish quality, weight savings are sacrificed thereby partially offsetting the price advantage. In addition, manufacturing consistency can be difficult to achieve.

An all-composite design could face difficulties during FAA certification since only one composite design, namely the Beach Starship has been FAA certified. The FAA has little experience with composite airframe certification and this lack of experience will manifest itself as requirements for additional testing, lower allowables for material properties and increased certification time and expense.

The final construction technique examined was a hybrid method: composite skin over a metal frame. In this technique, a metal frame is constructed, onto which composite panels are fastened. Both the skin and frame serve as load bearing structures. The design will maintain crashworthiness, lightning protection, and have a more predictable fatigue life while reducing part count.

Material selection. Of the many choices, the hybrid composite-metal frame emerged as the obvious choice. With proper design, it is possible to have the advantages of both construction techniques: the lightening protection, crashworthiness, repairability of metal construction and the reduced parts count, corrosion protection and simplified construction of composite construction. In addition, there is synergistic benefit in the combination of construction methods. Reduction in the number of jigs, simple panel removal for airframe access and molding in multiple parts will combine to reduce the total life cycle cost of the helicopter.

There are potential disadvantages also arising out of a hybrid construction. Two of the most significant are different coefficients of thermal expansion and the possibility of galvanic material corrosion. Care in the detail design stage will ensure that no undue stresses will occur with dissimilar material expansion due to temperature changes. The greatest potential for galvanic corrosion in this design is between aluminum and the carbon/graphite fibers. Every location where these two materials are joined will be doubly insulated. Carbon fiber will be insulated by a fiberglass cloth layer. Aluminum will be coated with primer followed by several layers of paint. Each coat will be a different color so that the depth and severity of any scratch can be easily determined. This technique has been used successfully on underwater submersibles.

Construction techniques. Our design will have one master jig onto which the frame, subassemblies and composite panels will be attached. All subassemblies will be connected directly onto the frame. Composite panel construction will allow us to mold in multiple parts thereby speeding assembly. Additionally, these composite parts can be designed to have less warpage. Capital savings can result from reducing the number of large jigs. The removable skins will greatly simplify airframe inspections for maintenance and inspection and simplify repairability.

7.3.2 Jigs

A minimal number of jigs will be needed to construct the Calvert. Three jigs are proposed: transmission and engine deck, rear airframe and the center (including nose piece) airframe. The center airframe construction jig will double as the assembly (master) jig. Three jigs will greatly reduce the initial capital outlay needed for a production line and allow shut down and restarting of the line to be less cumbersome due to the reduction of tooling.

The assembly jig is an external frame, which serves as the construction stand, alignment fixture and assembly line transporter. This assembly jig will securely hold the metal frame in proper alignment as the subassemblies and composite panels are attached. The metal frames are bolted to the jig and then to each other. As the helicopter moves down the assembly line, the subsystems, hydraulic and electric lines are located in their proper places.

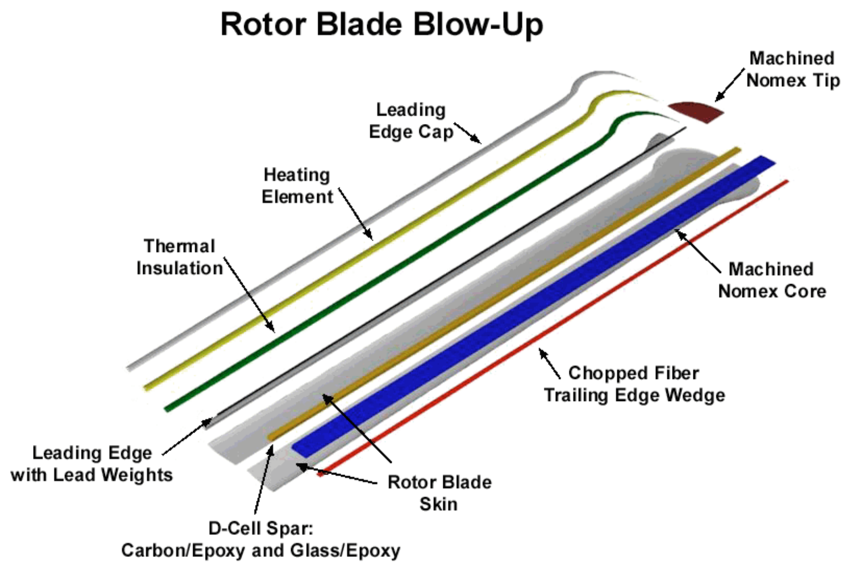


Figure 7.1: Rotor blade manufacturing details.

7.3.3 Frame

The bulkheads will be NC machined from aluminum stock. To minimize waste, the frames will be made in sections: four for the nose frame and six for each of the center fuselage frames. They will be placed onto the construction jig, aligned with alignment marks and fastened with standard fasteners. The longerons and stringers will be made from standard z-section aluminum extrusions thus minimizing cost.

7.3.4 Composite panels

The aircraft has numerous panels. The molds for the panels are machined from aluminum, finished to a mirror surface, and electrodeposited with nickel to provide a long lasting surface. A tape laying machine places the prepreg at the correct locations and orientations onto molds, which are subsequently vacuum bagged and cured.

7.3.5 Rotor blades

The rotor blades are of all composite construction, save the leading edge protection strip. Figure 7.1 shows the rotor blade manufacturing details.

A detailed cross-section of the blade is shown in Figure 7.2. The basic structural materials of the blade are fiberglass/epoxy, graphite/epoxy and a Nomex honeycomb core. The blade spar consists of 2 layers of $\pm 45°$ graphite/epoxy (ply thickness=0.005 inches), constituting the outer torsion wrap and unidirectional glass fibers on the inner layers. Nomex honeycomb has been selected for the core since it has a lower weight compared to a foam core and presents fewer problems in producing a satisfactory bond to the skin. Furthermore, it exhibits low moisture absorption.

Molds. Rotor blade fabrication consists of three major cure cycles. The spar assembly is laid-up and cured. The cured spar, the skin, and the Nomex core are then assembled and cured. Three separate molds will be used:

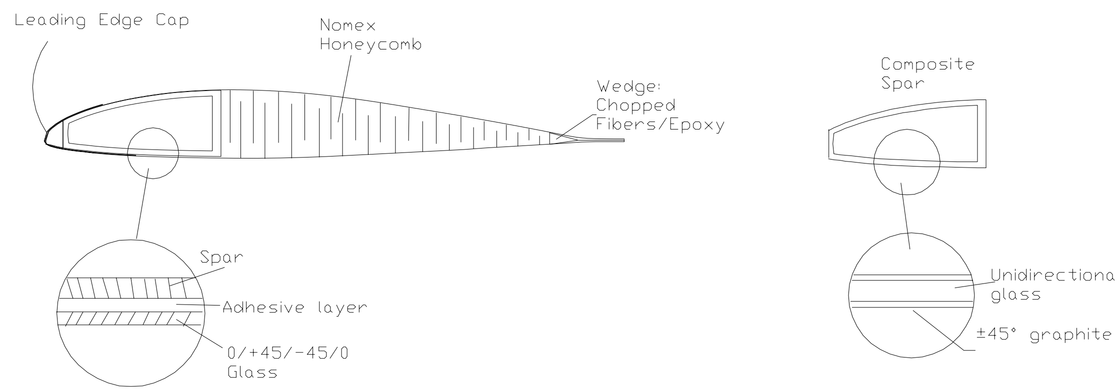


Figure 7.2: Blade cross-section.

the trailing edge block mold, the D-spar mold, and the complete rotor blade mold. The molds are machined from aluminum billets, finished to a mirror surface and covered by nickel.

Leading edge. The leading edge cap consists of three parts: erosion cap, electrical insulation and the heating element. Due to its complex geometry, the erosion cap at the tip should be fabricated using electrodeposition of nickel on a suitable mold. The rest of the leading edge cap can be made in suitable lengths using standard sheet metal techniques. The insulation and heating elements are then bonded to the inside of the leading edge erosion shield.

Trailing edge wedge. The trailing edge wedge is made from chopped fiber using a V-channel machined from stock aluminum. The mold is coated with a release agent, the channel is filled with chopped fiberglass/epoxy and cured at room temperature.

Assembly. The lower and upper skins ($0°/\pm45°/0°$ fiberglass) are placed in the molds by a tape-laying machine. The precured spar, Nomex core, lead weight and trailing edge wedge are laid onto the lower mold. The two molds are then bolted together (see Figure 7.3) and connected to pipes supplying hot oil. Hot oil is then circulated through the mold during the heating and cooling cycle providing a cost effective, thermally uniform and stable cure. After curing, the blade is removed from the mold and is ready for the final assembly.

Final rotor blade assembly consists of applying an adhesive to the leading edge of the blade and attaching the erosion cap, electrical insulation, and heating element onto the rest of the blade using a suitable bonding jig.

Balancing. After curing, each blade is statically balanced. It is then mated with another blade and they are dynamically balanced on a spin tower.

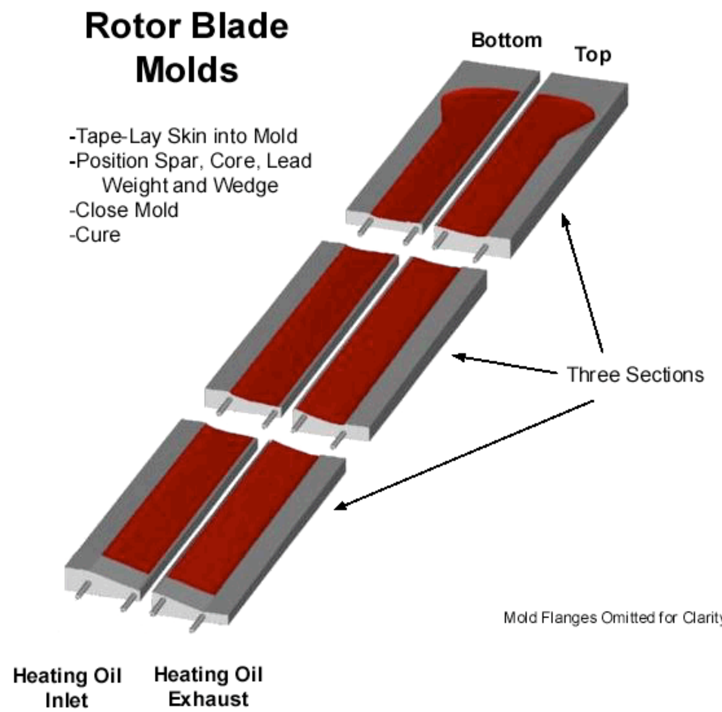


Figure 7.3: Mold for rotor blade manufacture.

7.3.6 Rotor hub

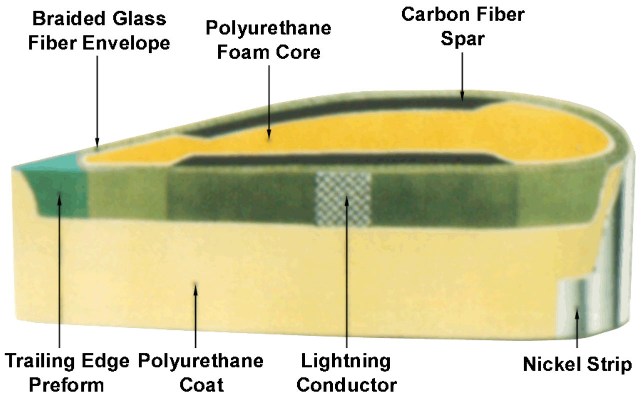
The hub will be a forged assembly made out of titanium. The drawings will be electronically transferred to the vendor complete with grain alignment. There is no need for machining the finished part: modern forgings maintain dimensional accuracy without rework. The Calvert will be built at a low production rate and the manufacturing of the hub is so specialized that it must be subcontracted.

7.3.7 Propeller

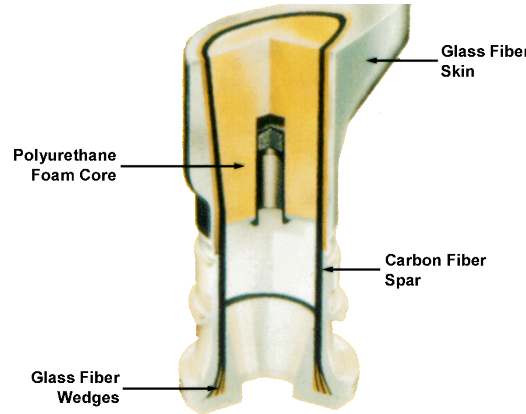
The propeller is made in a similar manner as the rotor. The hub and collar will be cast and NC machined to the proper tolerances. The blade consists of a polyurethane core, unidirectional carbon fibers, a trailing edge wedge and a lightning strip, all of which are wrapped in fiberglass and co-cured with the collar. A nickel leading edge is added for erosion protection and the entire assembly is coated with a polyurethane spray coat.

Molds. The propeller blade final assembly mold is machined from an aluminum billet, polished to a mirror finish, and covered with nickel. A suitable mold will be used to form the core from expanding closed cell polyurethane foam. The trailing edge wedge is made from chopped fiber in a mold in the same manner as the rotor.

Assembly. To assemble the propeller blades, the tape laying machine first lays the fiberglass, then the lightning strip is hand laid. The machine then lays the carbon fiber tape into both molds. Next the fiberglass and graphite are fed into the collar and the collar fastened to the mold for proper alignment. Finally, the core and trailing edge are laid in place and the mold is bolted together and cured. Six blades are needed for each helicopter. Figure 7.4(a) shows the propeller cross section and Figure 7.4(b) shows the propeller root section.



(a) Propeller blade cross section.



(b) Propeller root.

Figure 7.4: Propeller blade manufacturing details [Dow97].

7.3.8 Wing

The wing will be manufactured using composites. It's mold will be NC machined from aluminum, polished to a mirror finish and nickel covered for long mold life. A right and left mold will be needed as the wings have an asymmetric airfoil section. The wing consists of the spar (fiberglass/epoxy and graphite/epoxy), the front D-cell (closed cell foam) and the rear core (Nomex). No wedge is needed as there is no axial force.

A tape laying machine will lay fiberglass in the molds to form the upper and lower wing skins. Adhesive will be applied to the spar, D cell, and rear core. These three pieces will be placed onto the lower wing skin. Finally, the mold will be bolted together, hot oil fed into the pipes, and allowed to cure.

8 Cost Analysis

8.1 Purchase price

The price is estimated via the RFP model. Total production quantity and production rate as well as weight are primary cost driver. However several factors are used to account for differences in manufacturing complexities (for instance metal vs composite) and technologies (tiltrotor vs conventional helicopter). Table 8.1 gives the purchase price breakdown from this model.

8.2 Cost model

In this section, the cost analysis is described. All costs are in 1998 dollars. The cost analysis has been made assuming that the aircraft flies according to the RFP (ie, 540 nm at 180 knots with 1 pilot and 3 passengers). According to the NASA Rotorcraft Economic Workshop [Les96], airline aircraft operating costs can be divided into 2 categories: Direct Operating Costs (DOC) and Indirect Operating Costs (IOC). Table 8.2 shows the aircraft operating cost breakdown. Note that DOC is usually incurred per flight hour of the aircraft whereas IOC depends on the operator policy, airport location and must be calculated for specific operating areas. Therefore IOC calculations are not included in the present analysis.

In chapter 2 (section 2.3.2), the DOC of the compound helicopter and tilt rotor was compared by assuming

Aircraft subsystem	Cost (in $)
Propeller	17378
Wing group	17849
Rotor group	140656
Vertical stabilizer	1402
Horizontal stabilizer	3192
Body group	133260
Landing gear	43457
Nacelle group	22621
Air induction	7006
Engine	226260
Drive system	165360
Flight controls	17795
Instruments	7846
Hydraulics	1186
Electrical group	40605
Avionics	62789
Furnishing and equipment	39195
Air conditioning	15551
Load and handling	6244
Final assembly	248994
MANUFACTURING COST	1229269
Tooling amortization and profit	614635
TOTAL COST	1843904

Table 8.1: Purchase price breakdown.

suitable values for the insurance rate, financing rate, maintenance cost, fuel cost, flight crew cost, etc. Since information given by aircraft firms vary, this method is not very reliable. For the present analysis we will use global cost models based on historical data. Two such models are described. The first one is based on Tishchenko's formula [TNC99] which gives DOC/flight hour as:

$$DOC_H = 2.25 \times \frac{P_r}{10000} + P_{fuel} \times Q \tag{8.1}$$

where P_r is the initial purchase price (in \$), P_{fuel} is the fuel price (\$1.5/gal) and Q is the fuel consumption (in gal/flight-hour). Equation 8.1 yields a DOC of \$499/fh for the Calvert. The second model uses the DOC breakdown presented at the NASA Aircraft Economic Workshop [Les96]. Typically the fuel cost contributes 12% of the total DOC. The Calvert has a fuel cost/fh of \$60 (assuming the fuel price at \$1.5/gal). This results in a DOC of \$504/fh, which correlates pretty well with the Tishchenko method (\$499/fh). Table 8.3 shows the details of the DOC breakdown.

We introduce two more indices to characterize the cost performance of the aircraft. Direct Operational Cost per air seat mile (DOC/asm) and Rentability Index (RI) are given by the following formulae:

Direct Operating Cost (DOC)	Ownership costs	Depreciation, Hull insurance, Finance
	Cash DOC	Maintenance, Flight crew, Fuel and oil
Indirect Operating Cost (IOC)	Airplane related	Ground property, Control and communication, Landing fees, Ground handling, Ground power, Cabin crew,...
	Passenger related	Amenities, Liability insurance, Passenger handling, Baggage handling, Reservations and sales, Commissions, Advertising and publishing

Table 8.2: Operating cost breakdown.

DOC breakdown[Les96]	**Percentage[Les96]**	**DOC ($/flight hour)**
Fuel	12	60
Crew	22	111
Engine	23	116
Scheduled Inspection	6	30
Scheduled Overhaul	5	25
Unscheduled Maintenance	6	30
Scheduled Retirement	11	56
On condition	15	76
Total DOC	100	504

Table 8.3: DOC breakdown.

$$DOC/asm = \frac{DOC/fh \times TravelTime}{FlightDistance \times \#seats} \tag{8.2}$$

$$RI = \frac{V_b^{0.4}}{DOC/asm} \tag{8.3}$$

where V_b is the effective flight speed, based on the passengers total flight time from boarding to disembarking. The DOC/asm is an indication of the cost incurred by the operator to fly the aircraft. The RI is a composite index that includes the DOC/asm and the effective flight speed (V_b). The RI is a cost measure that is used to quantify the premium the passenger is willing to pay to fly faster. The cost performance of the Calvert is summarized in Table 8.4.

Next, the Calvert's cost estimates are compared with existing helicopters of similar performance and price. Using the current civil rotorcraft report by ARC Professional Services Group[Gro93], data from several helicopter are used to generate DOC/fh, DOC/asm and RI. Table 8.5 compares the Calvert with other light helicopters.

Purchase Cost (in Million $)	1.84
DOC/fh (in $)	504
DOC/asm (in $)	0.604
RI	16.65

Table 8.4: Cost analysis summary.

Parameter	**Calvert**	**Bell 206**	**MD500E**	**AS 350D AStar**	**BO-105CBS**
Gross Weight (kg)	2298.7	1454	1362	1954	2505
# seats	4	5-6	4	5-6	5-6
# of engine(s)	2	1	1	1	2
V_{cr} (knots)	180	115	135	125	110
Range (nm)	540	369	228	416	310
Price ($M)	1.84	0.66 (1993 $)	0.675 (1993 $)	0.75 (1993 $)	1.9 (1993 $)
DOC/fh ($)	504	187	203	228	510
DOC/asm ($)	0.604	0.32	0.37	0.36	0.92
RI	16.65	26.3	23.95	24.18	8.96

Table 8.5: Performance and cost comparison.

Note that the Bell 206, MD500E and AS 350D Astar are single engine helicopters and have been produced in large numbers. The only comparable helicopter is the BO-105CBS which is a twin engined helicopter. The Calvert's purchase price estimate ($1.84M) is for the RFP requirement of 300 aircraft at the rate of 60 per year. This price will come down if the production quantity and production rate are increased. Moreover, the price quoted for the Bell 206, MD500E, AS 350D Astar and the BO-105 are in 1993 US $ [Gro93] and hence must be corrected for inflation.

From Table 8.5, we conclude that the high performance of the aircraft has a downside. The Calvert DOC/fh, DOC/asm and Rentability Index are not favorable compared to the single engined Bell 206, MD 500E and the AS350D AStar. However all these aircraft have comparatively lower cruise speed and range compared to the Calvert. Also the Calvert has two engines which is important for flight safety. On the other hand, the only other twin engine aircraft of the table, the BO-105CBS, has roughly the same take off weight and initial purchase cost as the Calvert. The BO 105CBS offers 5-6 seats but is not able to fly at 180 knots over 540 nm. The Calvert trades two passengers for fuel and high speed devices. But because it has been designed with a cabin capacity to fit 6 passengers, it can meet the performance of the BO 105CBS, whereas the BO 105CBS cannot operate as a high speed helicopter.

Note that the above economic model has several limitations. In the present analysis, the effects of production rate and total production quantity are included on the purchase price of the aircraft but they also influence maintenance and operating cost. Similarly, effects of automated manufacturing and quality control techniques (specially for composites) are not captured by the model, since the model is based on historical data. Finally, software development cost have to be added to this model, specially for an aircraft incorporating a glass cockpit which requires multi-function displays. However, due to lack of more accurate historical data, this cost model is used as a first approximation.

9 Alternate Flight Modes

In chapters 1 through 8 we describe how the Calvert is designed to meet the RFP performance requirements (180 knots, 540 nm) with a total of 4 passengers (including pilot). However we provide the Calvert with 6 seats. The reason being that we want the Calvert to be a multi-purpose, multi-mission aircraft. Because production quantity is what ultimately drives cost a versatile aircraft with good mission adaptability is of paramount importance. Since the Calvert has a maximum seating capacity of 6 passengers it can operate in several alternate flight modes.

9.1 6-passenger maximum cruise speed

For the 6-passenger mode the Calvert's empty weight and fuel weight are the same as the baseline 4-passenger mode. However due to the extra two passengers the aircraft gross weight is increased by 190 kg. Therefore the rotor stall limits are reached at a lower forward speed. For the 6-passenger mode the stall limit is encountered at 190 knots as opposed to 210 knots for the baseline 4-seater mode. Therefore the never exceed speed for the 6-passenger mode is 190 knots. A safety margin of 30 knots is maintained to account for unexpected flight conditions like turbulence/bad weather or high speed maneuvers. Therefore the cruise speed for the 6-passenger mode is set at 160 knots (85% of never exceed speed).

9.2 6-passenger maximum range

In this mode the Calvert cruises at 142 knots with 6 passengers. The cruise speed of 142 knots is selected to maximize the mission range. For this particular flight condition the Calvert can travel a distance of 580 nm which exceeds the RFP range requirements of 540 nm.

9.3 Maximum payload mode

Without any modification the Calvert (with a single pilot) can fly up to 75 Knots at 4000 ft ISA with an external payload of 3050 lbs over a range of 200 nm. This mode of operation is suited for logging and external heavy lift operations similar to the K1200 (K-MAX). The Calvert's propeller consumes approximately 147 HP in hover and does not contribute to it's lifting capability. By declutching the propeller, the Calvert can lift 4027 lbs of external load at 75 knots over 200 nm at 4000 ft ISA. The performance of the Calvert with a declutching system is comparable to the K-MAX which can lift 6000 lbs of external load over 269 nm. The Calvert's synchropter configuration and its powerful engines (sized for high speed cruise), allow it, with only slight modification (declutching system), to perform heavy lifting operations.

9.4 Surveillance/search and rescue

The Calvert is well suited for Surveillance or SAR modes due to its efficient hovering capability coupled with its high speed cruise (180 knots) and high speed dash (210 knots) capability. The endurance limit of the Calvert with 4-passengers (380 kg payload) and 6-passengers (570 kg) is 4.6 hours and 4.4 hours respectively.

9.5 Performance comparison

The Calvert is primarily designed for high speed cruise at 180 knots with 4 passengers. However the 6-passenger (max. speed) mode offers some substantial advantages over the 4-passenger flight mode. Table 9.1 compares the performance and cost for the Calvert's 4-passenger and 6-passenger flight modes with existing light helicopters [Gro93]. The performance and cost calculation for the Calvert was carried out using the methodology described in chapter 6.

Property	**Units**	**Calvert (4-pass.)**	**Calvert (6-pass.)**	**Bell 206**	**MD500E**	**B0-105CBS**
Cruise speed	knots	180	160	115	135	110
# seats		4	6	5-6	4	5-6
# of engines		2	2	1	1	2
Gross weight	kg	2298.7	2488.7	1454	1362	2505
Range	nm	548	552	369	228	310
Purchase price	M$	1.84	1.84	0.66 (1993 $)	0.67 (1993 $)	1.9 (1993 $)
DOC/asm	$	0.6	0.39	0.32	0.37	0.92
RI		16.65	24.65	26.3	23.95	8.96

Table 9.1: Comparison of the Calvert's four and six passenger flight modes.

Table 9.1 indicates that the Rentability Index (RI) and Direct Operating Cost per air-seat-mile (DOC/asm) of the Calvert (6-passenger) mode is comparable to the Bell 206 and MD500E helicopters and superior to the Calvert (4-passenger) mode and the BO 105. However the cruise speed of the Calvert (4-passenger) mode is 13%, 33%, 56% and 63% higher than the Calvert (6-passenger) mode, Bell 206, MD 500E and BO 105 respectively.

From the point of view of the operator, the Calvert (4-passenger) mode provides the unique capability of 180 knots cruise at the cost of a 53% increase in DOC/asm and a 32% reduction in the RI with respect to the Calvert (6-passenger) mode. The final choice of operation (4-passenger/6-passenger civil transport, Search and Rescue, Surveillance, logging) rests with the user. Our design philosophy has been to provide the Calvert with the mission flexibility required to allow the mass production of one platform that can fulfill many missions.

10 Summary and Conclusions

The RFP provided the challenging requirement of designing a helicopter that has much higher speed and range capabilities than those of existing helicopters, but which should not cost more than these machines. As outlined in chapter 2, a wide variety of configurations were evaluated to determine the optimal design. The tradeoff study indicated that, from the point of view of cost and risk, a compound helicopter was an affordable design with minimum technological risks.

The Calvert is a thrust and lift compounded synchropter. The thrust and lift off-loading of the main rotor improves high speed cruise efficiency and delays the onset of retreating blade stall. This enables the Calvert to meet the RFP performance requirement of 180 knots cruise. The intermeshing rotors eliminate the need for an anti-torque system and provide a compact design. The twin two bladed composite rotors use active vibration control for a smooth ride. The teetering hub is very compact, simple, and has low drag. The propeller is also composite and is driven from the second stage of the transmission, which increases the transmission life. The transmission design is unique; it is compact and provides high efficiency at only a moderate weight penalty. The fuselage layout, rotor design, landing gear, and the use of thrust and lift compounding all contributed to make the Calvert a viable configuration for a 180 knot cruise requirement. Drag reduction was critical to the overall success of the design. Low drag is achieved by using retractable landing gear, a streamlined body, and extensive rotor treatment, fairings, hub cap, etc. The Calvert can carry 4 people for 548 nm at a cruise speed of 180 knots.

Alternatively, it can carry 6 people for 552 nm at 160 knots or 6 people for 580 nm at 142 knots. The design is powered by two variable speed 656 HP engines specially developed for this design. It can hover OGE at 17000 ft in ISA+20 conditions.

Since the goal was to have a purchase price equal to that of existing helicopters, cost needed to be attacked with innovative designs and manufacturing technology. This has been achieved by merging proven technology, repackaged in a unique manner, with innovative design, manufacturing, and supportability concepts. Three proven helicopter configurations, synchropter, lift compounding (via wing) and thrust compounding (via propeller), were combined to yield the lightest, least expensive configuration. The wing generates 40% of the required lift in cruise, thus providing sufficient separation between the 180 knots operating condition and the rotor stall boundary. Not only is the rotor generating 60% of the lift, but is also providing sufficient control authority that the wing could be of simplified design (no flaps, spoilers, or ailerons). The propeller provides 80% of the required thrust in cruise. This reduces the rotor shaft forward tilt and allows the fuselage to remain level in high speed forward flight, thereby greatly reducing the drag and improving cruise efficiency. The combination of lift and thrust compounding together with the synchropter configuration results in a low vibration intrusion index that is within the ADS-27 limits up to 160 knots. At the cruise speed of 180 knots, the Calvert marginally exceeds the ADS-27 limits. This can be rectified with the use of passive isolators or the active trailing-edge flaps on the rotor blades.

Significant innovation was included in the subsystems. New technologies were included without affecting the validity of the basic design. The prognostics and health maintenance (PHM) system, engine FADEC, active vibration control for the blades, in-flight blade tracking, active interior noise control, and advanced transmission and oil cooler are all proposed technological innovations that will enhance various aspects of the helicopter performance, such as reduced maintenance, improved safety, improved comfort, and reduced weight and cost. To minimize cost, computerization and optimization are proposed for cost effective manufacturability, reliability and maintainability. Computer Aided Design (CAD) can optimize parts for weight and strength and the output of these computerized drawings can be sent directly to the shop floor. Computer controlled NC machines, tape layers, filament winders, rolling presses, etc will produce parts with repeatable accuracy.

Future capabilities of the Calvert can include a helicopter only version by removing the lift and thrust compounding. This would reduce costs for the slow speed version of the Calvert. The Calvert is designed to perform fast long range transportation at the same cost as existing helicopters in its class. The use of innovative configurations, design and manufacturing processes, and advanced technology features ensures a safe, fast, smooth and quiet helicopter.

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GROUP WEIGHT STATEMENT

AIRCRAFT

(INCLUDING ROTORCRAFT)

ESTIMATED - CALCULATED - ACTUAL

(CROSS OUT THOSE NOT APPLICABLE)

CONTRACT NO.	N/A		
AIRCRAFT, GOVERNMENT NO.	N/A		
AIRCRAFT, CONTRACTOR NO.	N/A		
MANUFACTURED BY	N/A		
		MAIN	AUX
ENGINE QUANTITY	2		
ENGINE MANUFACTURED BY	N/A		
ENGINE MODEL	N/A		
ENGINE TYPE	N/A		
PROPELLER QUANTITY	1		
PROPELLER MANUFACTURED BY	N/A		
PROPELLER MODEL	N/A		

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MIL-STD-1374 PART I - TAB **GROUP WEIGHT STATEMENT (KG)** PAGE 2

NAME UMD **WEIGHT EMPTY** MODEL <u>CALVERT</u>

DATE JUNE 27 1999 REPORT

1	WING GROUP			WINGLETS	GLOVE / LEX	WING	
2	TOTAL						22.3
3	BASIC STRUCTURE						
4	CENTER SECTION						
5	INTERMEDIATE PANEL						
6	OUTER PANEL						
7	SECONDARY STRUCTURE						
8	AILERONS / ELEVONS						
9	SPOILERS						
10	FLAPS - TRAILING EDGE						
11	- LEADING EDGE						
12	SLATS						
13							
14							
15	ROTOR GROUP						147.4
16	BLADE ASSEMBLY					94.20	
17	HUB & HINGE					53.20	
18							
19	EMPENNAGE GROUP	CANARD	HORIZ. STAB.	VERTICAL FIN	VENTRAL FIN	TAIL ROTOR	
20	TOTAL		7	3.40			10.4
21	BASIC STRUCTURE						
22	SECONDARY STRUCTURE						
23	CONTROL SURFACES						
24	(INCL. BALANCE WEIGHTS)	( )	( )	( )			
25	BLADES						
26	HUB & HINGE						
27	ROTOR / FAN DUCT & ROTOR SUPTS						
28							
29							
30	FUSELAGE GROUP				FUS. / HULL	BOOMS	
31	TOTAL						176.8
32	BASIC STRUCTURE						
33	SECONDARY STRUCTURE						
34	ENCLOSURES, FLOORING, ETC.						
35	DOORS, RAMPS, PANELS & MISC.						
36							
37							
38	ALIGHTING GEAR GROUF TRICYCLE	MAIN	NOSE / TAIL		ARR. GEAR	CAT. GEAR	
39	TOTAL	71.70	17.30				89
40	RUNNING GEAR / FLOATS / SKIS						
41	STRUCTURE						
42	CONTROLS						
43							
44							
45	ENGINE SECTION OR NACELLE GROUP	AUXILIARY ENGINES		MAIN ENGINES			
46	LOCATION **						
47	TOTAL - EACH LOCATION						39
48							
49							
50							
51	AIR INDUCTION GROUP	AUXILIARY ENGINES		MAIN ENGINES			
52	LOCATION **						
53	TOTAL - EACH LOCATION						3.6
54	INLETS						
55	DUCTS, ETC.						
56							
57	TOTAL STRUCTURE						488.5

* LANDING GEAR "TYPE": INSERT "TRICYCLE", "TAIL WHEEL", "BICYCLE", "QUADRICYCLE", OR SIMILAR DESCRIPTIVE NOMENCLATURE.

** WING, FUSELAGE, ETC.

MIL-STD-1374 PART I - TAB **GROUP WEIGHT STATEMENT (KG)** PAGE 3

NAME UMD **WEIGHT EMPTY** MODEL CALVERT

DATE JUNE 27 1999 REPORT

58	PROPULSION GROUP		AUXILIARY		MAIN		469.8
59	ENGINE					157.50	
60	ENGINE INSTALLATION						
61	ACCESSORY GEAR BOXES & DRIVE					44.00	
62	EXHAUST SYSTEM						
63	ENGINE COOLING						
64	WATER INJECTION						
65	ENGINE CONTROLS						
66	STARTING SYSTEM						
67	PROPELLER / FAN INSTALLATION					59.60	
68	LUBRICATING SYSTEM						
69	FUEL SYSTEM					34.10	
70	TANKS - PROTECTED				24.80		
71	- UNPROTECTED						
72	PLUMBING, ETC.				9.30		
73							
74	DRIVE SYSTEM					174.60	
75	GEAR BOXES, LUB SYS & RTR BRK				166.70		
76	TRANSMISSION DRIVE						
77	ROTOR SHAFTS				7.90		
78	GAS DRIVE						
79							
80	FLIGHT CONTROLS GROUP					49.90	
81	COCKPIT CONTROLS				24.50		
82	AUTOMATIC FLIGHT CONTROL SYSTEM				25.40		
83	SYSTEM CONTROLS						
84	AUXILIARY POWER GROUP						
85	INSTRUMENTS GROUP						9.2
86	HYDRAULIC GROUP						2.3
87	PNEUMATIC GROUP						
88	ELECTRICAL GROUP					80.10	
89	AVIONICS GROUP					55.00	
90	EQUIPMENT						
91	INSTALLATION						
92	ARMAMENT GROUP						
93	FURNISHINGS & EQUIPMENT GROUP					97.60	
94	ACCOMMODATION FOR PERSONNEL						
95	MISCELLANEOUS EQUIPMENT						
96	FURNISHINGS						
97	EMERGENCY EQUIPMENT						
98	AIR CONDITIONING GROUP					26.70	
99	ANTI-ICING GROUP						
100	PHOTOGRAPHIC GROUP						
101	LOAD & HANDLING GROUP					13.80	
102	AIRCRAFT HANDLING						
103	LOAD HANDLING						
104							
105	TOTAL SYSTEMS AND EQUIP. (LINES 80 - 104)						323.1
106	BALLAST GROUP						
107	MANUFACTURING VARIATION						9.2
108	CONTINGENCY						34.5
109							
110	TOTAL CONTRACTOR CONTROLLED						
111	TOTAL GOVERNMENT FURNISHED EQUIP.						
112	TOTAL CONTRACTOR - RESPONSIBLE						
113	TOTAL GOVERNMENT - RESPONSIBLE						
114	TOTAL WEIGHT EMPTY PG. 2-3						1336.6

MIL-STD-1374 PART I - TAB — **GROUP WEIGHT STATEMENT (KG)** — PAGE 4

NAME UMD — **USEFUL LOAD AND GROSS WEIGHT** — MODEL CALVERT

DATE JUNE 27 1999 — REPORT

115	LOAD CONDITION						PRIMARY
116							
117	WEIGHT EMPTY						1336.6
118	CREW (QTY _ 0)						
119	UNUSABLE FUEL						
120	OIL						
121	TRAPPED						
122	ENGINE						12
123	TRANSMISSION						10.5
124	AUX. FUEL TANKS QTY						
125	INTERNAL						
126	EXTERNAL						
127							
128	WATER INJECTION FLUID						
129	BAGGAGE						80
130	GUN INSTALLATIONS						
131	GUNS LOC FIX. OR FLEX. QTY CAL.						
132							
133							
134	SUPPORTS *						
135	WEAPONS PROVISIONS **						
136							
137							
138							
139							
140	CHAFF (QTY ________)						
141	FLARES (QTY ________)						
142							
143							
144	SURVIVAL KITS						
145	LIFE RAFTS						
146	OXYGEN						
147							
148							
149							
150	OPERATING WEIGHT						
151	PASSENGERS						300
152							
153	CARGO						
154							
155	AMMUNITION QTY CAL.						
156							
157							
158	WEAPONS **						
159							
160							
161							
162							
163							
164	ZERO FUEL WEIGHT						
165	USABLE FUEL TYPE LOC GALS						559.6
166	INTERNAL						
167							
168	EXTERNAL						
169							
170	TOTAL USEFUL LOAD						962.1
171	GROSS WEIGHT						2298.7

* IF REMOVABLE AND SPECIFIED AS USEFUL LOAD.

** LIST STORES, MISSILES, SONOBUOYS, ETC. AND PYLONS, RACKS, LAUNCHERS, CHUTES, ETC. THAT ARE NOT PART OF WEIGHT EMPTY. LIST NOMENCLATURE, LOCATION, AND QUANTITY FOR ALL ITEMS SHOWN INCLUDING INSTALLATION.