FEASIBILITY STUDY ON IMPROVING OF 5-SEATER HELICOPTER FORWARD FLIGHT SPEED

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Dedicated to my beloved parents and family,
and to my wife...
Thank you for the endless support and encouragement.
You all always have a special place in my heart.

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In retrospect, this project did start humble but have grown to be a great success as now. There were many happy times and many disappointing moments, but now I am very happy because all the hardship I had to go through mostly alone finally paid off.

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ABSTRACT

In this study, two 5-seater helicopters that are in the same FAR 27 category were chosen for the forward flight speed comparison. In order to improve the helicopter cruising speed, the main rotor blade of a helicopter that posses a lesser flight speed was modified through the usage of different number of main rotor blade (from 3 to 4 blades), different value of blade solidity and the usage of new engine with better performance. For design and analysis purposes, the appropriate theory i.e. the closed-form equation from blade element theory (BET) which deals with both the blade dynamics and aerodynamics was used. By considering the retreating blade stall, figure of merit and the growth of reverse flow area, the new combination of rotor and engine that is suitable for a better helicopter cruising speed performance were obtained. For data comparison, the results obtained from BET analysis then were compared with the results obtained from the computational fluid dynamic (CFD) based analysis. Using CFD approach, the FLUENT software was used and the multiple reference frames (MRF) method was used to simulate the helicopter main rotor at steady and level flight condition. Finally, the performance results of the current and the new rotor design obtained from the BET and CFD analysis then were compared with the other helicopter forward flight speed performance and found that they were in good agreement.

ABSTRAK

Di dalam kajian ini, dua buah helikopter lima tempat duduk bagi penumpang eksekutif daripada kategori FAR 27 yang sama telah dipilih untuk dibandingkan kelajuan kehadapannya. Dengan matlamat untuk mencapai kelajuan penerbangan menjajap yang lebih baik, bilah rotor utama bagi helikopter yang berkelajuan lebih rendah telah diubahsuai dengan mengambilkira kesan penggunaan bilangan bilah rotor yang berbeza (daripada 3 kepada 4 bilah), nilai kepadatan bilah yang berbeza, dan juga engin baru yang lebih berkuasa tinggi. Untuk tujuan rekabentuk dan analisis, persamaan yang sesuai iaitu persamaan bentuk tertutup daripada teori elemen bilah (TEB) yang mana mengambil kira dinamik dan aerodinamik bilah telah digunakan. Dengan mengambilkira pegun bilah mengundur (retreat), 'Figure of Merit', dan peningkatan kawasan aliran terbalik; kombinasi baru di antara rotor dan enjin yang sesuai bagi keupayaan penerbangan menjajap yang lebih baik telah dikenalpasti. Untuk tujuan perbandingan data, keputusan-keputusan analisis yang diperolehi daripada analisis TEB kemudiannya telah dibandingkan dengan keputusan yang diperolehi daripada analisis dinamik bendalir berkomputer (DBB). Melalui pendekatan DBB, program berkomputer FLUENT telah digunakan dan kaedah bingkai pelbagai rujukan (BPR) telah digunakan bagi mensimulasikan rotor utama pada keadaan penerbangan searas dan mantap. Akhir sekali, keputusan-keputusan keupayaan bagi rekabentuk rotor asal dan baru yang diperolehi daripada analisis TEB dan DBB kemudiannya telah dibandingkan dengan sebuah lagi helikopter dan mendapati ia berada keadaan yang dipersetujui.

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NOMENCLATURE

Symbol	Definition
A	Area
A_1	Lateral cyclic pitch
B	Effective radius factor
B_1	Longitudinal cyclic pitch
$\overline{C_d}$	Drag coefficient corresponding to the 70% radial station
C_T	Coefficient of thrust
C_P	Coefficient of pressure
C_H	Coefficient of drag
F	Force
$D,\ H$	Drag
I_b	Blade moment of inertia
L	Lift
M	Moment
P_i	Induced power
P_o	Profile power
P_p	Parasite power
P_T	Total power
Q	Torque
R	Rotor Radius
T	Thrust
U_T	Tangential velocity
U_P	Perpendicular velocity
U_R	Radial velocity
f	Equivalent flat plate area
V	Speed

a	Speed of sound
a_o	Coning angle
a_{1s}	Longitudinal flapping
b	Number of blade
b_{1s}	Lateral flapping
c	Chord length
c_l	Coefficient of lift
c_d	Airfoil drag coefficient
h	height
m	Mass per running length
q	Dynamic pressure

Acronym

AR	Aspect ratio
DL	Disk loading
$G.W.$	Gross weight
FM	Figure of merit
RN, Re	Reynolds number

Greek Symbol

α	Angle of attack
υ	Induced velocity
θ_o	Collective pitch angle
θ_1, θ_{tw}	Twist angle
β_o	Coning angle
σ	Solidity $\frac{bcR}{\pi R^2}$
Ω	Rotor shaft rotational speed
Ψ	Azimuth angle
λ'	Inflow ratio
ϕ	Induced angle, roll angle
γ	Lock number

μ	Advanced ratio
ρ	Density

Subscript

c.g	Center of gravity
F	Fuselage
t	Tip
eff	Effective
Ref	Reference
hov	Hovering
CF	Centrifugal force
HP	Horizontal plane
HT	Horizontal tail
TPP	Tip path plane
MR	Main rotor
TR	Tail rotor
VT	Vertical tail

CHAPTER 1

INTRODUCTION

1.0 BACKGROUND

In its earlier history of development, the helicopter or direct-lift aircraft was used to replace the balloon and airship in observation purposes [1]. The special capability of the helicopter to hover out of ground, perform the axial translation (i.e., vertical ascent and descent, flying forward, backward and sideward) has permitted it to be used in some critical flight operations; for examples the search and rescue (SAR) operation, fire fighting, air observation, military purposes and air ambulance service where the utilization of hovering capability aircraft is more useful. Hovering capability is a criterion that makes the rotary and the fixed-wing aircraft become different between each other.

Nowadays, there were such types of rotary-wing flying machines the so-called helicopter which can be configured by its rotor(s) arrangement (i.e., conventional helicopter, side-by-side, synchropter, twin tandem, and coaxial rotor). According to the forecast by National Aeronautic and Space Administration (NASA), the forward flight speed of helicopter and other type of rotorcraft has shown an increment until year 2000. This increment can be modelled by linear curve as shown in Figure 1.0 and because the high demand especially in military needs this increment is expected to be continued year by year. The development of a high speed helicopter is normally originated with the reasons to reduce or cut-off the travelling time. According to Hooper [2] there are 3 major areas that can greatly be modified to realize the goal of the faster speed helicopter, i.e.; (1) *aerodynamics,* such as good aerodynamic shape, (2) *engine,* such as powerful engine performance, and (3) *structure,* such as light and stiff structure. However, the first two major areas (i.e.: *aerodynamics and engine*) will be considered in this study.

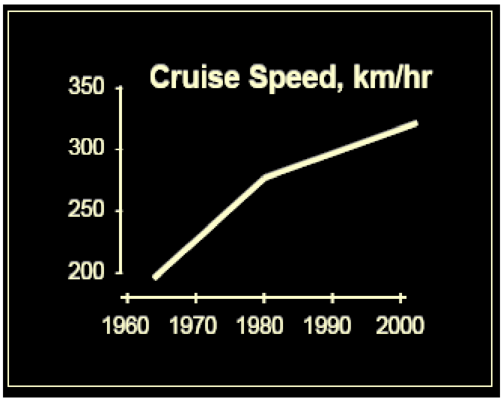


Figure 1.0: Representative the Future Forecast of Rotary-Wing Aircraft Flight Speed.

In forward flight, the helicopter rotor provides propulsive forces to overcome the aircraft drag by tilting the plane of the rotor forward. In this flight condition, the rotor blades encounter an asymmetric velocity fields, which maximum on the blade which advances into the relatives wind and minimum on the blade which retreats away from the relative wind (Figure 1.1) [3, 4]. The local dynamic pressure and the blade airloads therefore are considerably more complex than that of a fixed-wing aircraft, mainly because of the individual wake trailed from each blade. For a helicopter in forward flight, the blade tip vortices can remain closed to each rotor and to the following blades for several rotor revolutions. As a result of a low disc loading (thrust carried per unit area of a rotor disc) being created and generally causes low average flow velocities through the rotor disc. These vortices remain close enough to produce a strongly three-dimensional induced velocity field [5, 6].

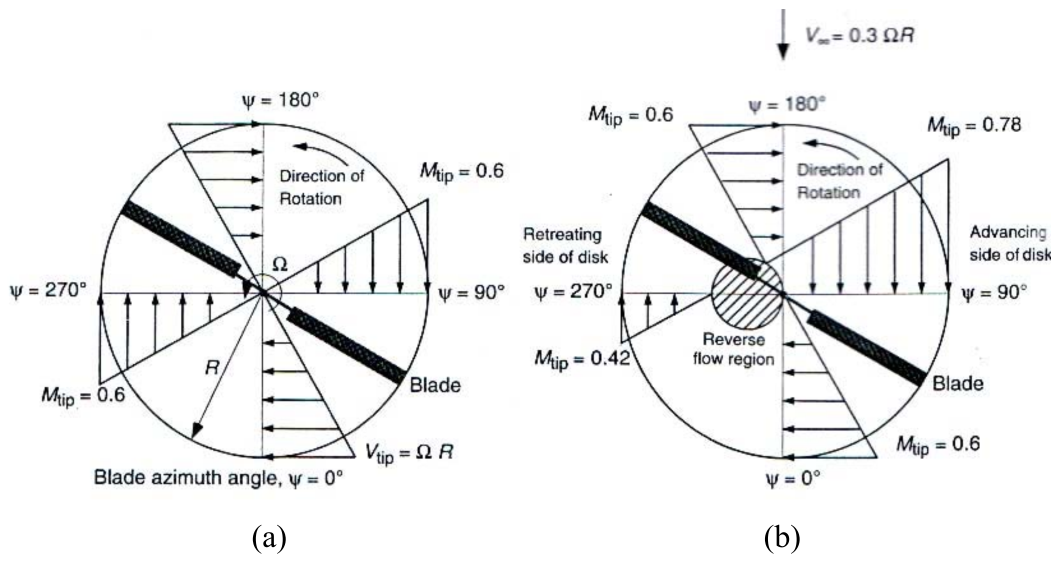


Figure 1.1: Velocity field of helicopter rotor in (a) hovering and (b) forward flight [3].

It has been observed that in high forward speed of flight, the conditions that could restrict the forward flight speed are listed as follows:

1. Compressibility Effect
2. Reverse flow region
3. Retreating blade stall

At high speed of flight, the rotor blade on the advancing side operates at relatively high Mach number closed to transonic regime [7] and this speed regime will be exceeded as the rotor rotational and flight speed is increased. Compressibility of the air influences the rotor performance and motion (i.e.: flapping, pitching and lagging) by its effects on the blade forces. The most importance are the increase in lift curve slope with Mach number and the sharp increase in drag and pitching moment above a certain critical Mach number.

The second factor limiting the speed capability of a helicopter at high forward flight speed is the retreating blade stall [8]. Just as the stall of an airplane wing limits the low speed possibilities of the airplane, the stall of a rotor blade limits the high speed potential of a helicopter. The airspeed of the retreating blade (the blade moving away from the direction of flight) slows down as forward speed increases. The retreating blade must, however, produce an amount of lift equal to that of the advancing blade. Therefore, as the airspeed of the retreating blade decreases with forward flight speed, the blade angle of attack must be increased to equalize lift throughout the rotor disk area. As this angle increase is continued, the blade will stall at some high forward speed. According to McCroskey et al [9], the two primary flight conditions requiring high blade angle of attack are *high thrust* and *high speed*. Blade stall phenomenon also limits the flight performance of a helicopter in high "g" manoeuvres [10, 11].

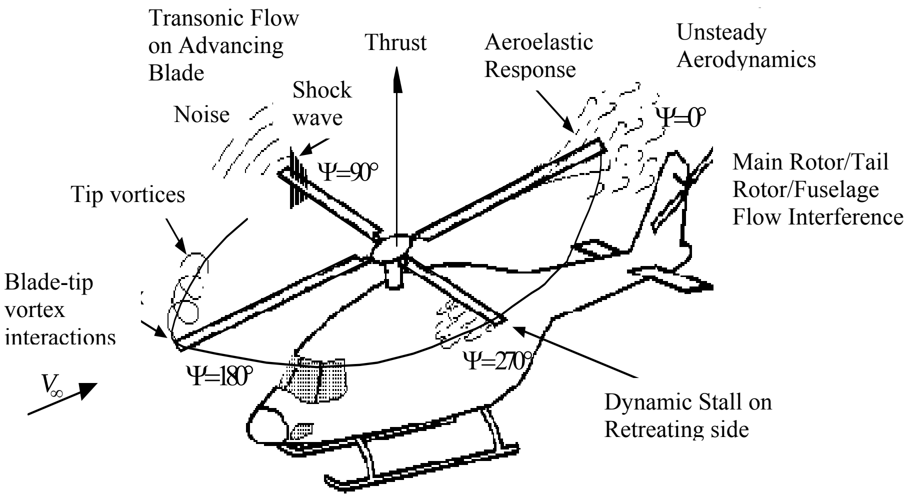


Figure 1.2: Multiple Limitation Factor Occur During Fast Cruising Flight [9].

Forward flight stall is also encountered because of the reverse flow region [5]. Near the reverse flow boundary or the third factor, the small reverse velocity produce a large inflow angle, and hence a large angle of attack. Sufficient near the reverse flow boundary the angle of attack will always be above the stall value, but the dynamic pressure is so low that the effects of this stall near the boundary are not great. The blade angle of attack or lift coefficient (the actual value or some representative value) is the primary criterion for stall of rotary-wings.

1.1 PREVIOUS WORK

To achieve greater forward or cruising flight speed, numerous design concept of the rotary-wing aircraft have been proposed and tested; for the example the Compound helicopter [12] (Figure 1.3), Central lift fan concept [13], Tilt-wing aircraft [14], Advanced Blade Concept (ABC), Tilt-rotor aircraft, Folding tilt-rotor concept, Trailing rotor concept, Single stowed rotor concept, X-wing concept and Variable diameter rotor concept [15, 16]. However most of these design concepts encountered with a lot of complexity and costly. Currently, the technologies for advanced helicopter have their own trends of developments. Hooper [2] has stated 4 requirements for advanced helicopter design and one of these requirements is it should be “fast”. The most significant progress in helicopter performance has resulted from the introduction of airfoils specially tailored to the high lift requirement of the retreating blade and Mach number penetration necessary to operate in the transonic environment of the advancing blade.

Follows are few concepts of high speed helicopter (HSH) that have been proposed by some of helicopter manufacturer such as Sikorsky, Boeing, Bell Helicopter, Piasecki, Augusta and etc. However, only tilt-rotor helicopter i.e.; Bell/Boeing Osprey V-22 and Bell/Agusta BA609 has successfully passed the airworthiness regulation that will allow them to enter in service.

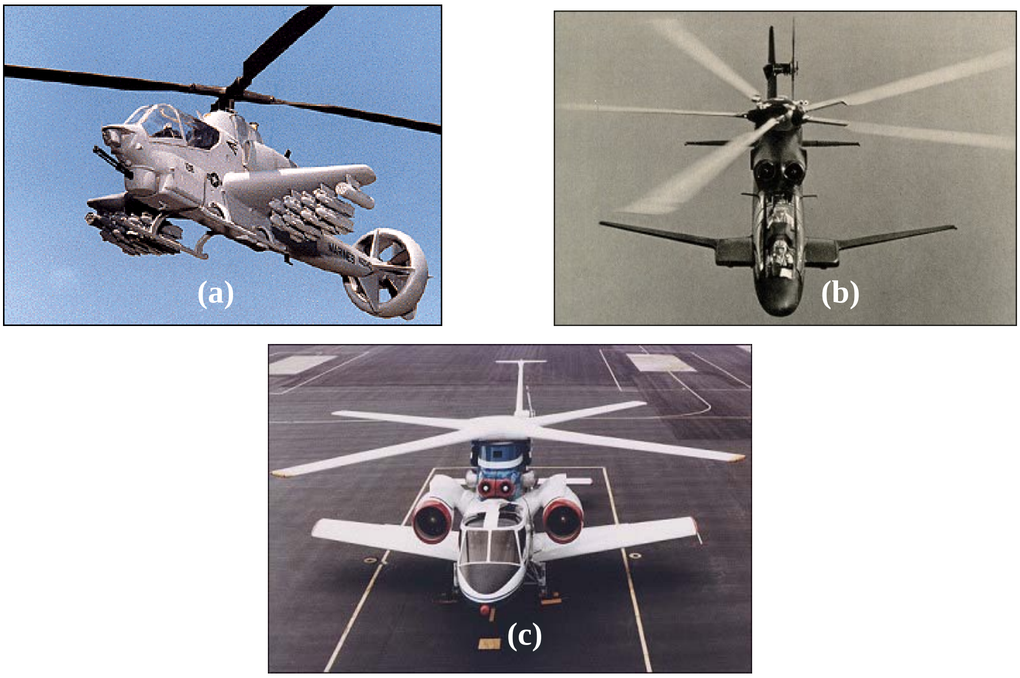


Figure 1.3: Example of Compound Helicopter (a) With Pusher (b) With Fixed-Wing [12] and (c) X-Wing Helicopter [16].

1.1.1 **Compound Helicopter** – The compound helicopter is derived by the adding of wings and some auxiliary propulsion to a helicopter [12]. The NH-3A (S-61F) aircraft which can fly at speed up to 425.96 km/hr was based on Sikorsky S-61 but incorporated with wing, two turbojets for auxiliary propulsion, and airplane type control surface. The fastest experimental compound helicopter was a derivative of the Bell UH-1 which was installed with a high jet thrust to weight ratio. This aircraft has a capability to fly at speeds up to 509.3 km/hr. One such helicopter that had been planned for production in the past was the Fairey Rotodyne. This aircraft used a pressure jet rotor with tip burning. The compound helicopter is a very feasible aircraft configuration with low technical risk, but there are not in economical viability. The compound helicopter has one large advantage over the other type, since for nearly any existing helicopter can be compound.

1.1.2 **ABC** – In the 1960s, two rigid co-axial, counter-rotating rotor systems called Advanced Blade Concept **(ABC)** was used by Sikorsky S-69 aircraft [12]. This concept was design to alleviate the problem of retreating blade stall by allowing more symmetrical distribution of lateral airloads over the rotor. Furthermore, the lift potential of the advancing blade may be realized because of the strength and stiffness of the blades and counterbalancing of the two rotors. Lift capability of the ABC increases with speed, unlike that of the conventional helicopter rotor. This machine would reach maximum speed of 487 km/hr.

1.1.3 **Tilt-Rotor** – This V/STOL aircraft has two lifting rotor mounted on pods at the tips of wing, and capable to tilt the rotor shafts 90 degrees. The Bell/Boeing V-22 Osprey that now goes on trial and becomes the first rotorcraft to do so. The principle operation of this aircraft is by tilting the rotors to 90 degree for forward flight and tilted to 0 degree for hovering, and axial translation condition. According to Fradenburgh, the probable speed regime for reasonably economic operation of this aircraft is about 463 to 648.2 km/hr [15]. A typical envelope of lift and propulsive force through the entire tilt range at a moderate flight speed (~125 knots) and despite the two rotors supply all of the propulsive force at high speed, the wing provides 100% of the lift to the aircraft.

1.1.4 **X-Wing** – One possible approach for helicopter to having a speed range of 740.8 to 926 km/hr is the X-Wing concept. This aircraft is designed to fly like a helicopter at low speeds, and once to enough speed for the wings and external turbines to sustain the craft, the rotor will stop in the X position and function more as supplemental wings [16].

1.1.5 **Variable Diameter** – Other concepts are by incorporating a variable geometry of the rotor. Many variable-diameter concepts have been envisioned. In late 1960's and early 1970's, Sikorsky Aircraft has developed aircraft called Telescoping Rotor AirCraft (TRAC). This concept was farther along the road to successful flight demonstration than any other variable-diameter scheme. The main lifting surface of the blade is outboard, sliding over the streamline handle (torque tube) when it telescopes in [15, 16].

The helicopter's forward speed is limited by aerodynamic constrain inherent in its design. Beside the above technique, there are other techniques (i.e.: blade planform modification, nose-droop concept, and direct synthetic jet concept) that have been studied to improve the forward flight speed of helicopter. The Soviet Union's Hind A-10 held the helicopter world speed record of 368.37 km/h for eight year until Westland Helicopter Ltd. flew its modified G-Lynx to 400.87 km/hr in 1986. After Westland attained the world speed record, the helicopter industry realized that the aerodynamic of helicopter rotor blade is could still be improved. One of the significant different between Hind and G-Lynx was the unique helicopter rotor blade known as British Experimental Rotor Program (BERP) blade [27].

Unlike fixed-wing aircraft, helicopter rotors have traditionally relied upon relatively simple airfoils because of the conflicting aerodynamic requirements, aeroelastic constraints, vibration, and the need for structural simplicity and operational reliability. As a consequence the significant performance benefits of high-lift airfoils that are taken for granted by fixed-wing aircraft designers have not been exploited for rotorcraft. In view of the potential benefits, there is increasing interest in developing variable geometry airfoils and aerodynamic flow control technologies for rotorcraft [51]. Nowadays, most of the research study to build a High Speed Helicopter has been carried-out by studying the rotor blade aerodynamic phenomenon such as blade stall, compressibility effect, and rotor wake difficulties. It is also possible to extend the helicopter forward flight speed margin by reducing vibration effect and dynamic motion of the rotor blade.

Flow control technology by "Nose-droop" concept has progressively been developed in Germany. Under the scope of the German AROSYS (Adaptive Rotor Systems) between DLR, ECD and DaimlerChrysler AG; Geissler, W. et al [17-19] had carried out the studies on the "Nose-drooping" blade concept on the modified airfoil A1581 section. The investigation was focused at influencing separation (dynamic stall) on the retreating side and trying to reduce the strength and local excursion of the shock wave on the advancing of the loop. About 10% of the airfoil leading edge will be oscillating about the axis of rotation with the maximum deflection angle of the flap, $\Theta = 10^0$ (Figure. 1.4).

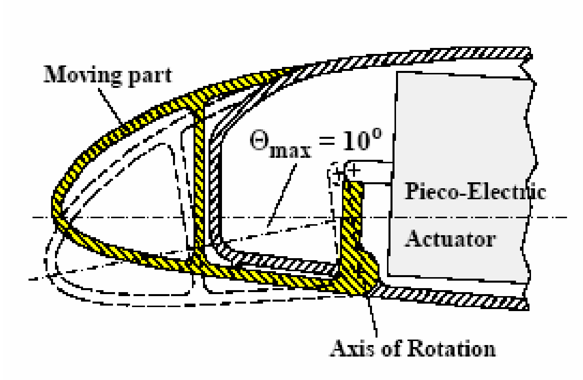


Figure 1.4: Structural Realization of Nose-Drooping design [17].

The nose-drooping airfoil is possible to largely reduce the leading edge pressure peak, reduce the secondary pressure peak due to the dynamic stall vortex and have similar effects due to the moving shock front. The extra pressure peaks are caused by the dynamic stall vortex travelling over the upper surface of the airfoil and shock front is starting close to the airfoil leading edge and is moving downstream and again upstream similar to a sin-wave. Dynamic nose-droop yields attached flow conditions even at high blade angle of attack and thus lead to an increased helicopter lift and forward flight speed capability.

The attempts to reduce the boundary layer or flow separation of the retreating rotor blade at high angle of attack by using the Direct Synthetic Jet (DSJ) concept was presented [20, 21]. In 1998, the initial application of the Directed Synthetic Jet (DSJ) to control airfoil separation was performed in a low speed steady flow facility. The pulsed air was expelled from a series of slots near 6% of chord. This experiment demonstrated how the DSJ could operate as an unsteady excitation device at lower momentum coefficient, $C\mu$ and as a separation suppression device at higher $C\mu$. An alternative to the synthetic jet for generating unsteady $C\mu$ is modulating net blowing produced by an air source. In a similar approach performed by Seifert et al [22], mass-less jet generated by flexible cavity walls are used to alter the boundary layer behaviour and prevent stall.

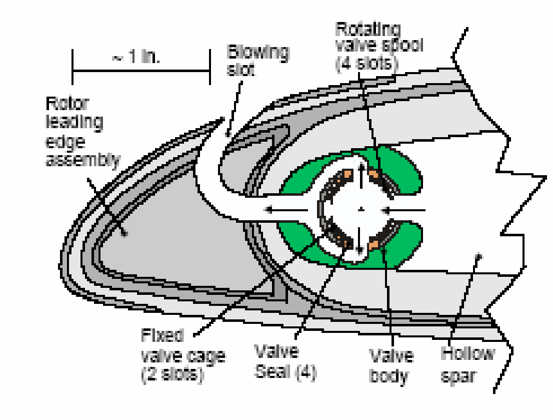


Figure 1.5: Implementation of a cylinder rotating valve for periodic bleed air modulation [20].

A conceptual rotary valve design (Figure. 1.5) was developed based on two concentric cylinders with slots; the inner cylinder rotating to align these slots for flow out of the valve. A number of slots in the rotating cylinder controls the RPM required to obtain a given frequency and the size of the slots controls the airflow and pressure drop. Enhanced rotor performance from a blade flow separation control system is incrementally shown for two moderate levels of improvement

i. The first level increment represents a 5 degree increases in the stall angle of attack, and
ii. The second level increment adds an additional 10% increases in $C_{L_{\max}}$.

The work by Magill et al [23] described in this paragraph extends previous results in pulsed-jet separation control to the problem of dynamic stall. In this study the actuators, Pulsed Vortex Generator Jets (PVGJs) consist of discrete circular air jets on the upper surface of the airfoil was applied to control the flow separation. The PVGJs produce vortices that promote mixing, energizing the boundary layer and preventing separation. PVGJs generate vortices that promote mixing of high energy free stream air into the boundary layer to displace low-energy fluid (Figure 1.6). This keeps the boundary layer from separating and allows operation at higher angles of attack, resulting ultimately in higher lift and lift-to-drag ratio. The presence of slat at leading edge of the blade also shows the quite similar application as the nose-droop concept where their function is to prevent the production of reverse flow region or air bubble that could produce the turbulent flow air separation.

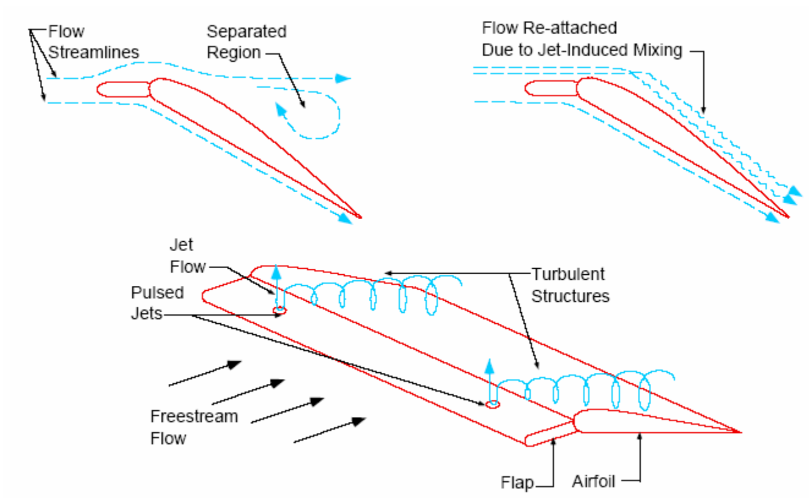
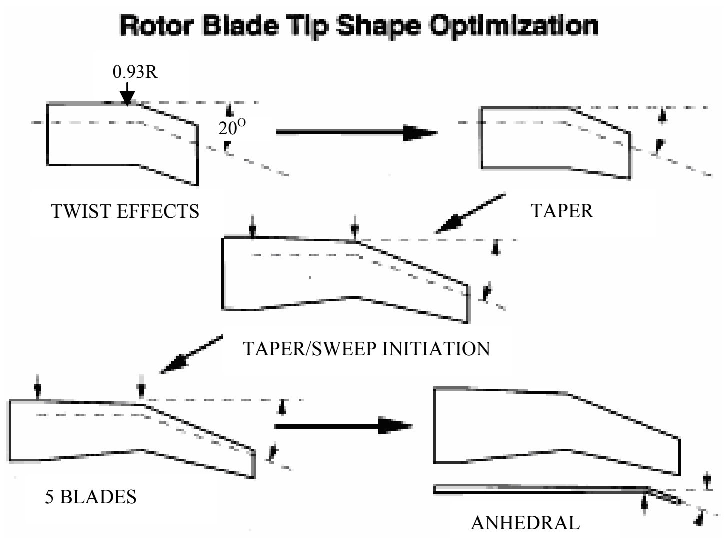


Figure 1.6: Pulsed vortex generator jets create mixing structures that prevent flow separation [23].

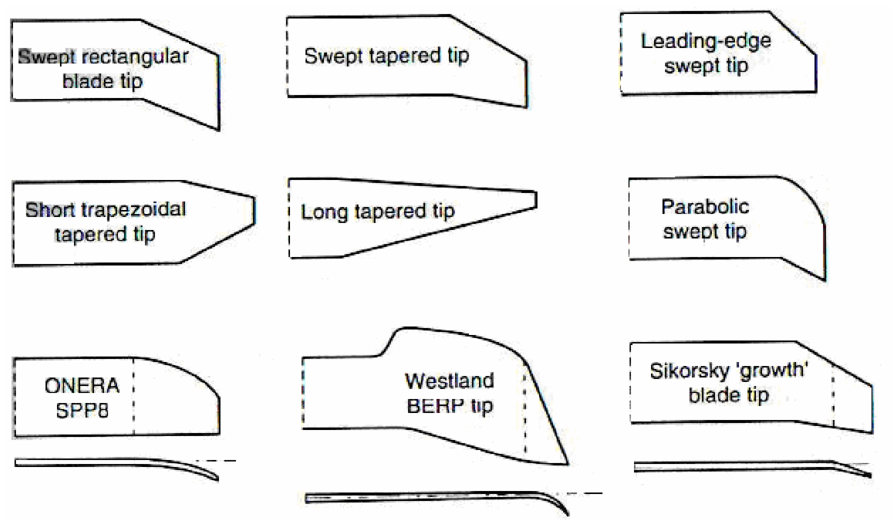
Many dynamic stall load-alleviation concepts have been proposed in literature i.e; a leading edge slat device, which operates much like a slat on a wing and suppresses the leading edge stall [24]. Tuncer and Sankar [25] have numerically studied this using a two-dimensional multi-element dynamic stall solver. A limited number of 3-D calculations have also been done to demonstrate that leading edge slats are effective in alleviating dynamic stall [26]. The major drawback of slats is the high drag penalty associated with their use at off-design conditions. A retraction mechanism similar to that found on aircraft will be heavy and costly. For these reasons, this device has not been pursued by the industries.

An alternative approach to improve the aerodynamic design of helicopter rotor blade is by Blade Planform Modification (BPM). In this method, the blade tip modification is the most popular one [27-31]. The blade tips play an important role in the aerodynamic performance of the rotor. The blade tips encounter the highest dynamic pressure and highest Mach numbers, and strong trailed tip vortices. The poorly designed blade tip can have serious implications on the rotor performance. Figure 1.7 shows several of tapered blade tip designs which are the very successful design to optimize the hovering flight. The result of a flight test of a swept back parabolic tip on a Dauphin 365N was reported by Guillet, F and Phillipe, J.J. [32]. Additional weights were added at 45% radius for the dynamic tuning of the second lead-lag mode. The tip planform improved forward flight (1 to 6%) performance by minimizing profile power and significantly improve overall rotor cruise efficiency.

Another version of the swept-tapered/anhedral blade tip design was flown on the AS 332 Super Puma MK II [33]. The onset of the sweep/tapered was at 96% radius. While improvement in hover (1%) and forward flight (9.3 km/hr at sea level ISA) performance was realized.



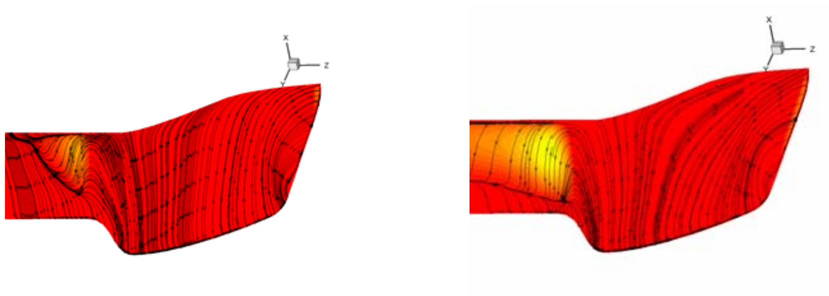
(a)



(b)

Figure 1.7: (a) Tapered tip and (b) Variety of blade tip designs [3].

The British Experimental Rotor Programme (BERP) blade was the result of ten-year (1976-1986) aerodynamic research collaboration between Westland helicopter and the Royal Aircraft Establishment. It was designed to meet the conflicting aerodynamic requirements of advancing and retreating blade conditions, either of which can limit the performance of the rotor in high forward flight. The technical details of the BERP research program were described by Perry [34]. BERP research paid off in 1986 when a GKN-Westland Super Lynx attained the world absolute speed record for a conventional helicopter. As shown in Figure 1.8, the BERP blade is distinctive because of its unique tip shape. The aerodynamic improvements shown with the BERP rotor are the result of several innovations in both airfoil design and tip shape design. The BERP blade uses a number of high performance airfoils based on the RAE family. One of the most recognizable features of the BERP blade is the use of high sweepback over the tip region, which is an effective means of reducing compressibility effects and delaying their effect on the rotor to a higher advanced ratio [35,36]. The BERP blade is specifically designed to perform as a swept tip at high Mach numbers and low angles of attack, but it also designed to operate at very high angle of attack without stalling.



25 degrees **30 degrees**

Figure 1.8: Example of CFD Results for the Flow Separation near the Notch Region of A BERP Blade [27].

However, the world speed record was achieved as a result of the following four accomplishments [45]:

1. Very good aerodynamic drag cleanup,
2. Water-methanol inject,

3. A reduction in engine tailpipe area in order to obtain a significant part of the available engine power in the form of jet thrust, and
4. A novel main rotor blade tip called BERP tip.

In his report, Amer [45] has concluded that the BERP tip has only improved rotor stall by about 5% and this tip was only a minor contribution to the speed record.

As previously discussed, one of the many problems confronting the helicopter rotor aerodynamic is the compressibility effect that occurs at the advancing blade side. The influences of compressibility are clear and potential to restrict the helicopter forward flight speed. At high-speed forward flight, advancing side blade(s) will involve with unsteady transonic, viscous, and highly non-linear phenomena [31]. The flight envelope of a helicopter rotor is set by the compressibility effects experienced by the advancing rotor blade and the retreating blade dynamic stall. As the helicopter forward flight speed is increased, the freestream velocity observed in the reference frame of the advancing blade is that of the sum of the helicopter forward flight speed and the speed of the advancing blade. At high cruise speeds, the freestream Mach number observed by the advancing blade reaches levels where local supersonic zones on the surface of the rotor blade are present. These regions usually terminate with a shock wave which causes a sudden increase in wave drag. During the retreating phase, the blade incidence approaches the stall angle, thus causing separation to occur on the upper surface of the blade which leads to a loss of lift [37].

In most attempts, the blade planform modification has been applied on reducing the compressibility effect [38-42]. Desopper *et al* [39] in their work have observed that modification of the blade-tip planform may improve the aerodynamic performance of the rotor by reducing the wave drag and the intensity of the transonic flow that appear on the rectangular blade for fast forward flight speed. Several blade-tip designs including rectangular, sweptback with constant sweep angle, swept forward with constant sweep angle, sweptback-parabolic tip, FL5, RAE, PF2 and rectangular with an anhedral tip shape have been tested in S2 Chalais-Meudon wind tunnel (Figure 1.9). And as reported by Desopper, for almost all the advancing blade side:

a) The intensity of the transonic flows is smaller on the PF2 tip when compared to the straight tip,
b) The swept tip rotor has a lower drag and requires less power than the same rotor with straight tip,
c) It is possible to decrease the intensity of the transonic flow for a large azimuthal sector of the advancing side by using a 30 deg swept back tip, and therefore it is possible to decrease the power needed to drive the rotor, and
d) The total performance measurements of the model rotor for rectangular and sweptback parabolic tips shows that the PF2 tip has made possible a significant reduction (5-8%) in the power required by the rotor.

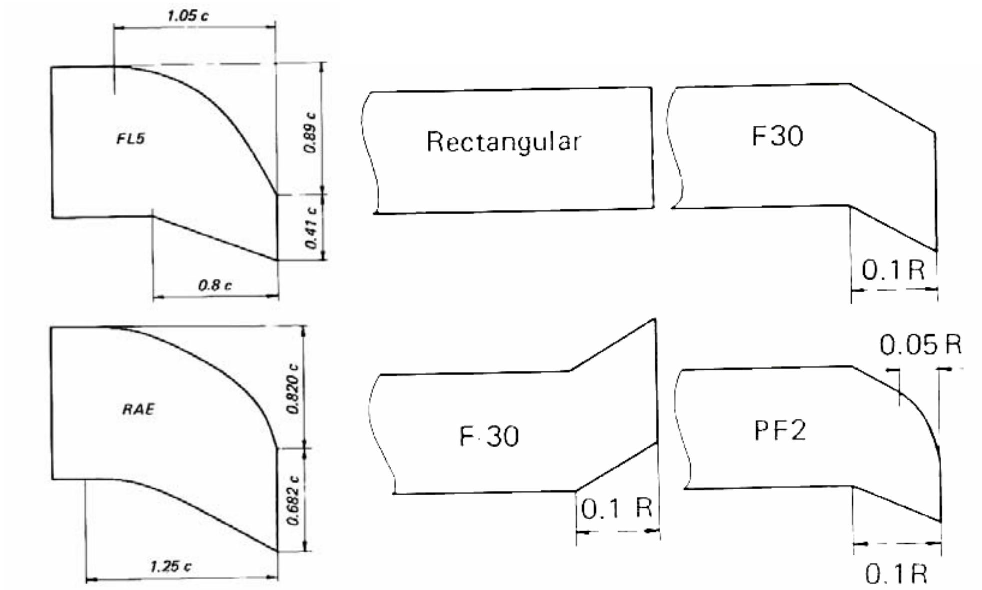


Figure 1.9: Example of Rotor Blade Tip Tested in S2 Chalais-Meudon wind tunnel [39].

Beside most of studies have focused on tapered, swept-tip, and parabolic blade tip-shape, a computational fluid dynamic (CFD) analysis on more advanced blade tip design which combined the several tip shapes and having a different value of blade solidity was carried-out [43, 44]. From this study the Mach number normal to the leading edge of the blade has reduced, thus allowing the rotor to attain a higher advanced ratio before compressibility effect manifest as an increase in power required. The use of different angle of sweep angle also affects tip vortex formation, its location after has been trailed from the blade, and overall vortex structure.

1.2 HELICOPTER GENERAL DESCRIPTION

There are a many helicopter models that currently being operated in Malaysia. In this study, two 5-seater helicopters under the same Federal Aviation Regulation category 27 (FAR 27) have been chosen for design and analysis purposes. The Eurocopter AS 355F2 (Eurocopter) and Agusta A 109A (Agusta) helicopter that are respectively being utilized by Royal Malaysian Police Air Wing and by some private operator (Fig. 1.10) were considered. The basic descriptions of these aircraft are given in Table 1.0, and the selections of these aircraft are based on the following criteria:

i. FAR 27 or JAR 27 category [50] for small rotorcraft,
ii. Comparable gross weight,
iii. Comparable installed powerplant performance, and
iv. Different in cruising speed performance.

Figure 1.10: (a) Agusta A 109A and (b) Eurocopter AS 355F2 helicopter.

Figure 1.11 depicts a 3-view drawing of 5-seater executive passenger Eurocopter AS 355F2 helicopter. This helicopter is powered by 2 Allison 250C 20F free turbine engines and installed in two independent fireproof bays. The main gear box is modular design, i.e. consisting of subassemblies that can be replaced without adjustment or special tooling, and without returning the gearbox to the factory. This result in lower maintenance costs. The main gear box drive train of this aircraft consists of planet pinions that are driven by the sun gear. They (planet pinions) in turn drive the planet pinion carrier and thus the rotor mast at 394 rpm. This gearing system has gearing speed ratio of about 3.59 between sun gear and bevel ring gear, and speed ratio of about 4.33 between gears in the planet pinion. With the engine shaft rotational output of 6016 rpm, this gearing system will transfer the rotation output of about 394 rpm to the main rotor shaft. This main rotor mast rotational speed afterwards will then determine the helicopter cruising speed performance.

Table 1.0: General Description of Eurocopter [51] and Agusta [52] Helicopter.

DESCRIPTION		
Engines Rating		
	Eurocopter	**Agusta**
Take-off Power (kW)	2 x 313	2 x 313
Maximum Continuous Power, MCP (kW)	2x 276	2x 276
Main Rotor		
Airfoil Type (Inboard)	Onera 209	Naca 23012
(Outboard)	Onera 209	Naca 13006
Rotor Radius (m)	5.345	5.50
Chord	0.35	0.335
Shaft Rotational Speed (rad/s)	41.26	40.30
Twist Angle (deg)	-9	-6
Number of Blades (N)	3	4
Blade Disc Area(m^2)	89.75	95.0
Never Exceed Speed (km/hr)	278.0	296.0
Maximum Cruise Speed @ MCP (km/hr)	222.0	263.0
Weight		
Maximum Authorized Gross Weight (kg)	2540	2600
Empty Weight (kg)	1205	1418

As listed in Table 1.0, the most obvious physical different between Agusta and Eurocopter is in the number of blades. They have 4 and 3 blades respectively. The effect of using the different number of blade on forward flight performance has become the interest of this study. In term of blade airfoil profile, Agusta helicopter uses a combination of different airfoils at inboard and at outboard of blade. The rotor that uses single airfoil on the entire span of blade cannot meet all the various aerodynamic requirement. This is because the angle of attack and Mach number of blade element vary continuously along the blade span. Unlike Agusta, Eurocopter using a single ONERA 209 airfoil with tab at the trailing edge (Figure 1.12). A general discussion about ONERA 209 airfoil will be given in subsection 2.5.1.2.

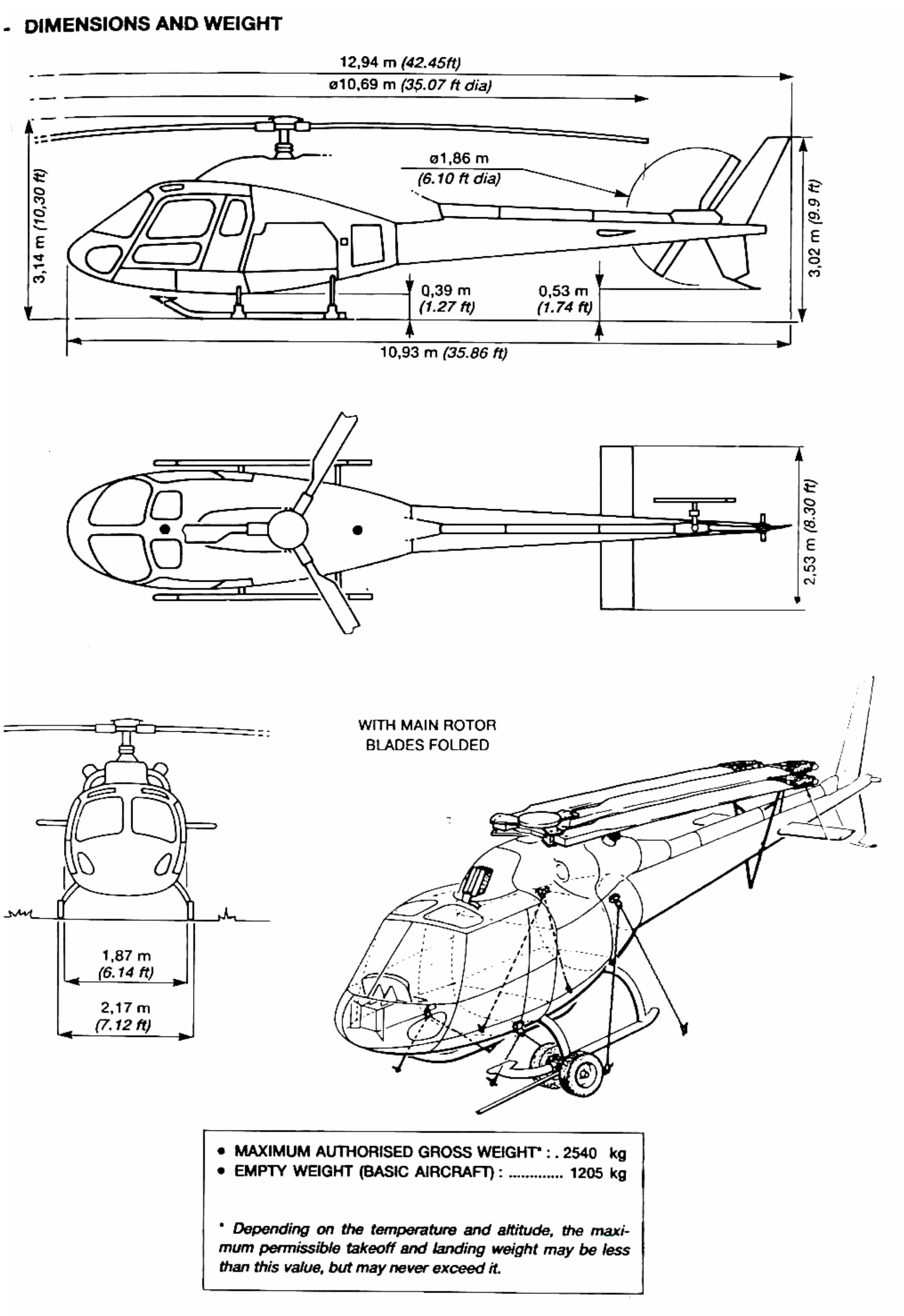


Figure 1.11: 3-view of Eurocopter AS 355F2 Helicopter

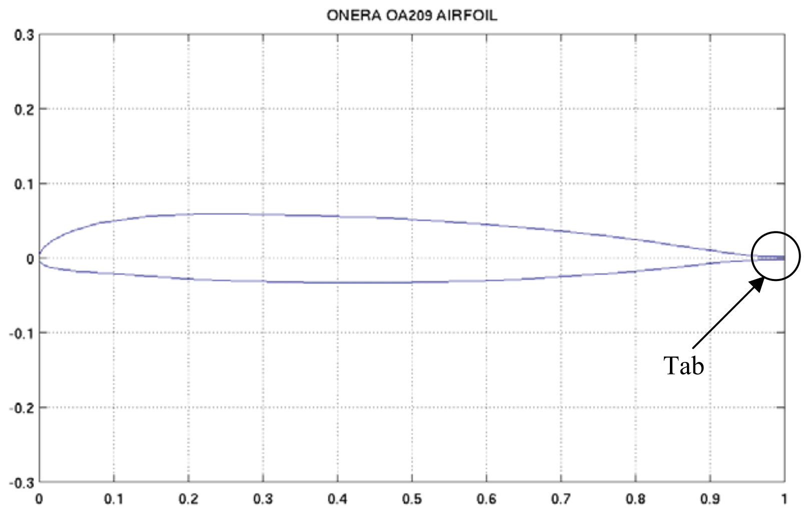


Figure 1.12: ONERA 209 Airfoil, t/c = 9% [51]

Both the helicopter's main-rotor blades consist of the negative (nose down) twist. The purpose of negative twist of the blade here is to redistribute the lift over the blade and help reduce the induced power. The proper use of blade twist can significantly improve hover figure-of-merit. In forward flight however, the rotor with a high nose-down blade twist may suffer some performance loss. This is because of the reduced angle of attack on the tip of the advancing blade resulting in a loss of rotor thrust and propulsive force. In this study, the blade twist value and blade profile of the new rotor design will be kept the same as the current blade design. However, the attentiveness of this study is given to the methods of increasing the number of blade and optimizing the blade and rotor size due to increasing in the number of blade.

Another significant different between Agusta and Eurocopter that may contribute to the better forward flight speed is the use of different type of landing gear. The use of different type of landing gear may give either an advantage or a disadvantage to the helicopter forward speed performance. It may cause either increasing or decreasing in the aircraft parasite drag. Usually, the low fuselage drag is required in the design of helicopter for improved performance. The drag of a helicopter fuselage may be up to one order of magnitude higher than that of fixed-wing aircraft of the same gross weight. Figure 1.13 depicts the effect of parasite drag on helicopter performance. For a helicopter, there are 2 types of parasite drag: *the* *streamline drag* where the flow closes smoothly behind the body; and *the bluff body drag*, where the flow separates behind the body. Theoretically, the bluff-body drag represents for 20% of the total fuselage drag [28]. A large portion of the drag of a helicopter is due to the bluff body drag of the rotor hub and landing gear. The nonretracting landing gears or skid gears as used by Eurocopter also produce bluff body drag. Skid gears used by Eurocopter are the combinations of tubes and struts of tabular shapes. This approximately creates about 1.01 in aircraft drag coefficient (or $C_D = 1.01$) [48]. Agusta helicopter however uses the retracting landing gear which it nose and main landing gear are stored in the fuselage during flight. This reduced drag coefficient, C_D of about 1.01 on the Agusta parasite drag than the Eurocopter helicopter [3].

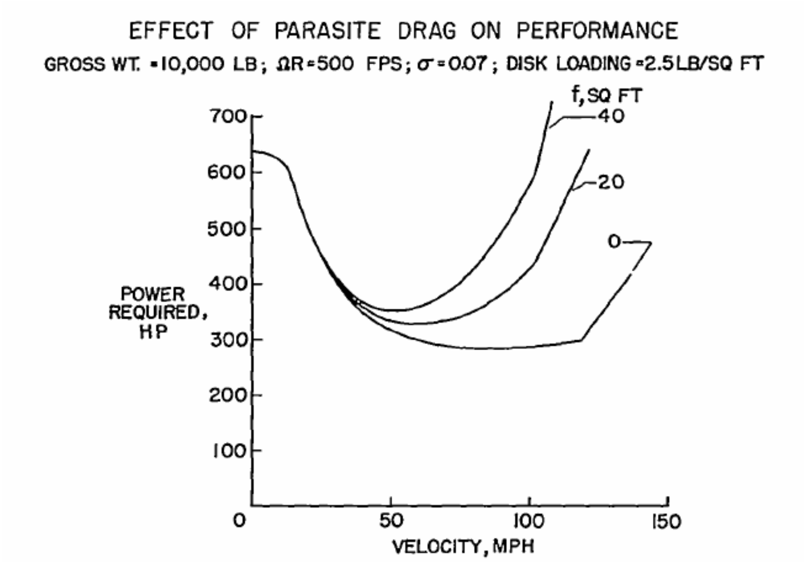


Figure 1.13: Effect of Parasite Drag on Helicopter Speed Performance. [54].

The semi-empirical drag method was used to evaluate the fuselage aerodynamics drag. Based on component testing in the wind tunnel, and with some additional engineering judgement, this approach gives reliable estimates of fuselage drag [48]. An estimate of the fuselage parasite equivalent wetted or flat-plate area, *f* can be determined from knowledge of the drag coefficient of the various components that make up the aircraft using an Equation 1.0 of the form

$$f = \sum_{n} C_{D_n} S_n \tag{1.0}$$

1.3 HELICOPTER SPEED LIMITATION

As for fixed-wing aircraft, the maximum speed of a helicopter in level flight is limited by the power available, but with a rotary wing there are a number of other speed limitations as well. This includes the stall, compressibility, and aeroelastic stability effect. The primary limitation with many current designs is retreating blade stall, which at high speed produces an increase in the rotor and control system loads and helicopter vibration, severe enough to limit the flight speed. The result of these limitations is that the design cruise speed of the pure helicopter is generally between 277.8 and 370.4 km/hr with current technology. To achieve a higher forward speed requires either an improvement in rotor and fuselage aerodynamic or a significant change in the helicopter configuration.

The absolute maximum level flight speed is the speed at which the power required equals the maximum power available. At high speed the principle power loss is the parasite power. To increase the power-limited speed requires an increase in the installed power of the helicopter or a reduction in the hub and body drag. Because of the parasite power is proportional to cube of flying speed, V^3, a substantial change in drag or installed power is required to noticeably influence the helicopter speed. The rotor profile power also shows a sharp increase at some high speed as a result of stall and compressibility effects.

A measure of stall effects on the rotor is the ratio of the thrust coefficient to solidity C_T/σ, which represents the mean lift coefficient of the blade. In hover, quite high values of C_T/σ can be achieves before the profile power increase due to stall is encountered. In forward flight, however, the angle of attack increases at the retreating side of the disc to maintain the same loading as on the advancing side, hence the stall is encountered at significantly lower values C_T/σ.

The maximum advanced ratio at which the helicopter may be operated depends on several factors. As advanced ratio μ, increases, the aeroelastic stability of the blade motion decreases, the blade and control loads increase because of the asymmetry of the flow, and the aerodynamic efficiency and propulsive force capability of the rotor decrease. Retreating blade stall often constitutes the primary restriction on μ. For a specified maximum advanced ratio, the rotor tip speed must be increased to obtain a high forward speed of the helicopter. However, compressibility limits the possible tip speed and thus limits the helicopter speed.

1.4 OBJECTIVE

To study the feasibility of improving the 5-seater helicopter forward flight speed through the increase in the number of blade, different blade size and engine sizing.

1.5 SCOPE OF RESEARCH

The scopes of this project were established as follows:

i. To determine the performance of the existing helicopter rotor.
ii. To study the possible factor (increase in the number of blade, different blade size and engine sizing) that could improve the existing flight speed.
iii. To determine the speed increment.

1.6 RESEARCH DESIGN

The research design comprises of:

i. Preliminary study to select the appropriate and available helicopter.
ii. Theoretical analysis by using closed-form equation from blade element theory [48].
iii. CFD analysis by using Fluent Inc. and Gambit software for flow simulation and grid generation.

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