# THE EFFECT OF VORTEX TRAP ON HELICOPTER BLADE LIFT

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## ABSTRACT

The 5-seater Aerospatiale AS350B helicopter has been chosen in this analysis in order to investigate the capabilities of the vortex trap in increasing the helicopter blade lift. Blade Element Theory (BET) was applied to scrutinize the lift force and angle of attack distribution along the helicopter blade. From BET, the retreating blade must operate at a higher coefficient of lift for the purpose to balance the lift force on both sides of the rotor. In the process of designing and analyzing the groove, commercial CFD, Fluent 6.3 and pre-processor Gambit were utilised in order to investigate the effect of groove which was applied on the upper surface of the helicopter airfoil. The Shear-Stress Transport (SST) $k-\omega$ turbulence model was utilized in this analysis because of its capability in producing the flow inside the groove and the ability on predicting the separation of the airfoil. The mesh sensitivity analysis had also been accounted in the numerical study. The optimization of the groove was done by analyzing the numbers and locations of the grooves, the design depth and length of the groove and modification of the groove shape to smoothen the velocities flow. Finally, the data from BET was used with data from numerical analysis to obtain the lift force achieved by the vortex trap method to increase the lift of helicopter blade. Thus, the small increment of lift was achieved when applying groove on the upper surface of the retreating blade due to the small area contribution at high angle of attack.

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# CHAPTER 1

# INTRODUCTION

## 1.0 Research background

Helicopter flight was probably the first type of flight envisioned by man. The idea dated back to ancient China, where children played with homemade tops of slightly twisted feathers attached to the ends of sticks. The flying Chinese top was a stick with a propeller on top, which was spun by hands and released [1].

Helicopter is a flying machine that uses the rotating wing to produce both the thrust and propulsive forces. The types of rotary-wing flying machines so-called helicopter that can be distinguished by its rotor arrangement, for example: conventional helicopter, side-by-side helicopter, synchropter helicopter, twin tandem helicopter, and coaxial helicopter. The capability to hover out of ground shows that the helicopter is a very practical flight vehicle for completing several flight missions such as air patrol, logistic, military application, air ambulance, skyscraper building construction, timber transporting, search and rescue (SAR) operation, and so on. Unlike the fixed-wing aircraft, the helicopter requires only a small area for take off and landing.

## 1.1 Research motivation

Nowadays, the flight speed of the helicopter is still considered slower than the fixed-wing aircraft. This is due to the complexity in the control mechanism and factors low speed of flight depicted in Figure 1.1.

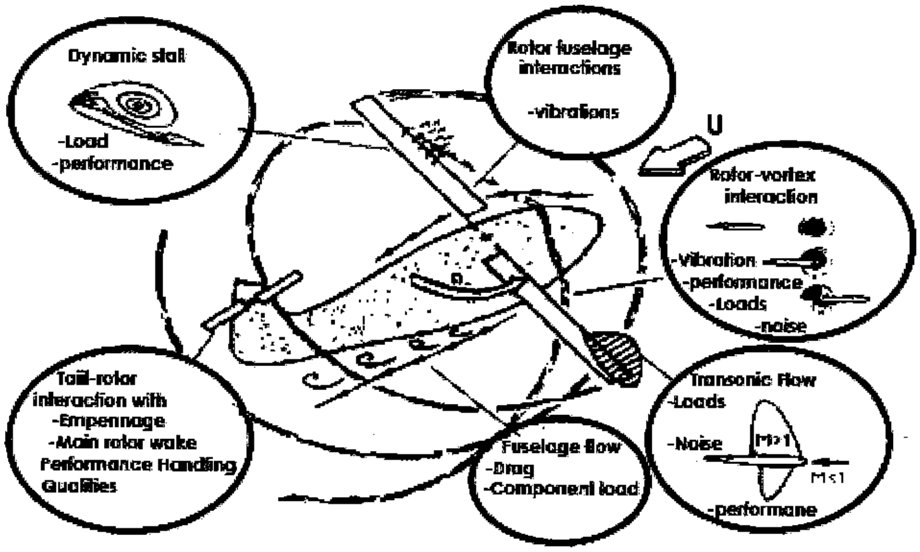


Figure 1.1: Multiple limitation factors occur during fast cruising flight [2,3].

One of the limitation factors in the helicopter speed is dynamic stall which occurs at retreating blade. Retreating blade is a critical condition due to the small area lift which must be equal to the large area lift of advancing blade in order to maintain level and coordinated forward flight which is depicted in Figure 1.2. The high angle of attack at retreating blade is required to generate a lift force that is equal to the lift force produced by the blade of advancing side [4]. In this regard, the retreating blade operates at much lower Mach number than the advancing side but encounters high angle of attack close to stall [5,6].

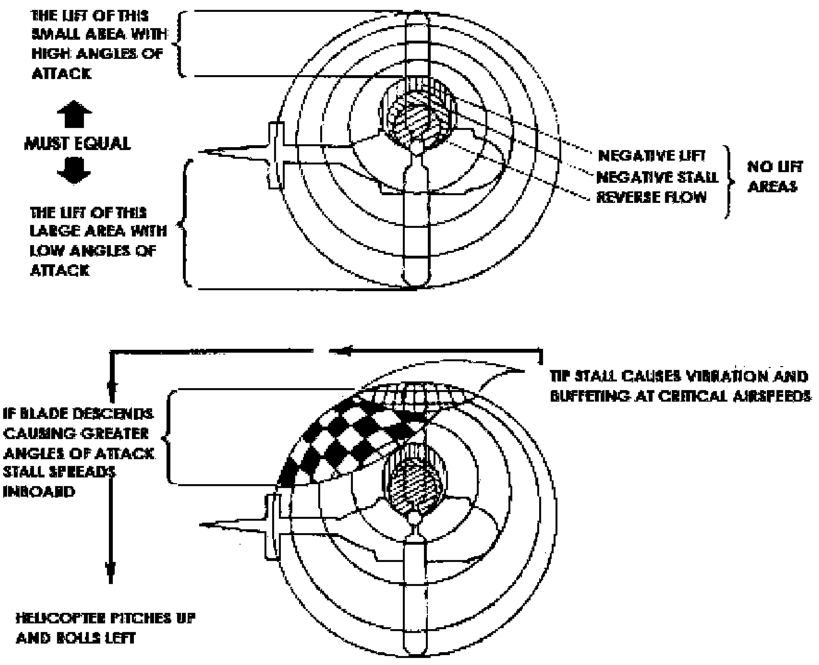


Figure 1.2: Retreating blade stall area [7].

The occurrence of dynamic stall on a rotor blade has adverse effects on the performance of the helicopter which includes:

a) High control system loads.
b) Vibration affecting the helicopter dynamic performance in terms of speed, lift, manoeuvres capability and handling qualities.
c) Aerodynamic performance limitations such as a loss of lift thrust and control.
d) Stall flutter, causing blade structural damage and excessive cabin vibration.

The understanding and modification of the dynamic stall vortex that is formed under such conditions remains a major research topic in the rotorcraft industry. Suppressing or eliminating the formation of the dynamic stall vortex will enhance the performance of the helicopter rotor and, hence, expand the helicopter flight envelope and vehicle utility [8, 9]. Several researches have been carried out to control the flow separation on aircraft wing and helicopter rotor blade. Nevertheless, some of the designs are very complicated to be adapted to the helicopter rotor blades that require high structural intensity.

## 1.2 Problem statement

The problem of dynamic stall is caused by the rapid change in angle of attack that occurs at the retreating blade of the rotor when helicopter is in forward flight. As the blade revolves to the retreating side, it must operate at a higher coefficient of lift to balance the lift force on both sides of the rotor. This is done by increasing the angle of attack of the blade. However, the helicopter has a limitation angle of attack in producing a lift at retreating blade. So, this phenomenon will limit the speed of the helicopter and its manoeuvrability. Therefore, with using the vortex trap method, it may be will increase the lift at retreating helicopter blade and also delay the dynamic stall.

## 1.3 Research objective

The objective of this research is to increase the lift of existing helicopter airfoil when blade in the retreating condition.

## 1.4 Research scope

The research study covered the following scopes:

i. Theoretical determination of the aerodynamic characteristics of an existing helicopter airfoil.
ii. Analyze the lift coefficient and the angle of attack of helicopter blade when helicopter in steady and level flight at sea level using Blade Element Theory (BET).

iii. Numerical simulation in two dimensional of unmodified helicopter airfoil and airfoil with vortex trap at below Mach Number, $M < 1$ and Reynolds Numbers in range between $6.5 \times 10^5 < Re < 6.3 \times 10^6$ are applied for simulating the effect of the vortex trap on the upper surface of the helicopter airfoil at retreating blade and advancing blade.

iv. Analyze and simulate the effect of vortex traps on helicopter blade.

## 1.5 Research design

The research design comprises of

i. Literature review on the previous works which related to main rotor blade of helicopter.

ii. Theoretical analysis on the aerodynamic characteristic of the helicopter airfoil using Blade Element Theory (BET).

iii. Computational fluid dynamic (CFD) analysis using Fluent and Gambit software in simulating the effect of the vortex trap on helicopter blade.

iv. The optimization of vortex trap for an application on the helicopter airfoil.

## 1.6 Project significance

Vortex trap is used to delay separation thus increasing the stalling pitch angle of the retreating helicopter blade. This will give the safer helicopter operation margin.

## 1.7 The type of helicopter used

The 5-seater Aerospatiale AS350B helicopter has been chosen for the present study. This helicopter is first version manufactured by Eurocopter company for AS model. Dimension of fuselage, main rotor and tail rotor are nearly same for all AS models but different in aerodynamic and engine which used for new version. The basic parameter descriptions of this helicopter are given in Table 1.1 and three view drawings are illustrated in Figure 1.3.

Table 1.1: Parameter of descriptions of Aerospatiale AS350B helicopter [10].

| **DESCRIPTION** | |
|---|---|
| **Weight (kg)** | |
| Empty | 1051 |
| Maximum Takeoff with Internal load | 1950 |
| Maximum Takeoff with External load | 2100 |
| **Engine Rating** | |
| Type of Engine | 1xTurbomeca Ariel IB |
| Maximum Takeoff power | 478kW |
| **Main Rotor Parameters** | |
| Airfoil | NACA 0012 |
| Radius (m) | 5.345 |
| Chord (m) | 0.3 |
| Solidity | 0.0536 |
| Number of Blades | 3 |
| Blade Twist Angle (Deg) | -12.275 |
| Maximum Cruise Speed (km/hr) | 232 |
| Maximum Speed (km/hr) | 272 |

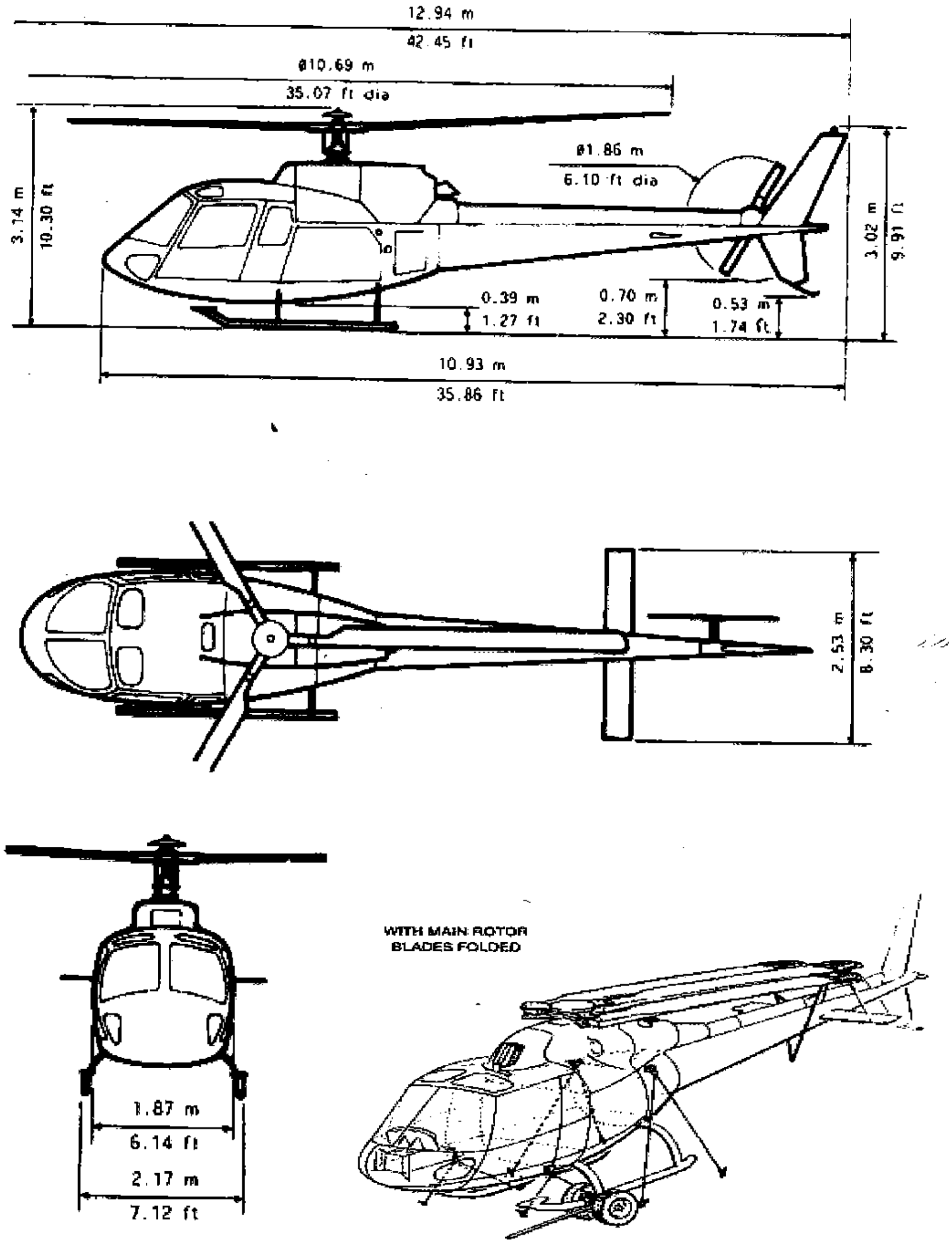


Figure 1.3: Three view of Aerospatiale AS350B Helicopter [10].

## 1.8 Thesis outline

This thesis is organized in six chapters. The chapters are briefly described as follows. **Chapter 2** reviews the previous works related to the helicopter blade and also discovers the previous stall control method used at helicopter blade and the vortex trap method.

**Chapter 3** discusses the theory of blade element theory (BET) which was used to investigate the blade lift and blade angle of attack of the Aerospatiale AS350B helicopter. The equations of rotor blade motions with trim control angles for helicopter in forward flight were discussed in this chapter. This chapter also discusses the theory of computational fluid dynamic that uses throughout this analysis.

**Chapter 4** describes how simulation is carried out using Fluent 6.3. This chapter explains the airfoil geometry with the groove, the type and size of mesh, the boundary condition, the flow solver and turbulence model used in this analysis.

**Chapter 5** evaluates the capability of the groove (vortex trap) on increasing the lift of retreating helicopter blade. The data from blade element theory (BET) was used with the data from numerical analysis to obtain the lift force achieved by the vortex trap method to increase the lift of helicopter blade.

Lastly, **Chapter 6** summarizes the works that have been done and followed by the recommendations for future studies.

# CHAPTER 2

# LITERATURE REVIEW

## 2.0 Introduction

The aim of this research is focused on the increasing lift of helicopter retreating blade by delaying the stall effect using the vortex trap method. Thus, it is necessary to investigate the characteristic which are related to the helicopter blade. This chapter will spread out the effect of the changing number of blade, the blade planform modification, researching on British Experimental Rotor Program (BERP) blade which attained the world speed record and the dynamic stall of helicopter blade. This chapter also discover the previous stall control method used at helicopter blade and the vortex trap method.

## 2.1 Number of blade

The feasibility on improving a Eurocopter AS 355F2 helicopter forward flight speed via applying the different combination between rotor and engine was presented by Nik Mohd N.A.R. and Wahab A.A [11]. Their study was emphasizing the changing of the number of blade from 3 to 4 blades and also blade sizing in order to find the better forward flight speed from the existing rotor design. The modification of the blade dimension by reducing the blade radius is about 10.19% and chord about 11.4% of Eurocopter AS 355F2 helicopter which can improve the maximum cruising speed by about 6.687%. The increment of the main rotor number of blade from 3 to 4 blades did not excessively affect the cruising speed capability of this particular aircraft. However it had shown a slightly improvement on helicopter Figure of Merit (FM)[12]. Nik Mohd [11] also found that the large ratio between reverse flows to the rotor area will cause the unstability of the helicopter.

The effect of changing the number of blades also depends on the solidity (the ratio of total blade area to disc area) of the blade to discover the better efficiency of hover performance. It was clearly show from the experimental done by Micheal A. M and Francis J.M [13] in Figure 2.1. The lower solidity is the best in hover performance rather than the highest solidity because of the increments of the Figure of Merit (the ratio of induced power to actual power). Prouty [10] explained that in determining the number of blade, the vibration, noise, weight and the blade storage should be concerned. Some of the concern can be organized in terms of the advantages shown in Table 2.1.

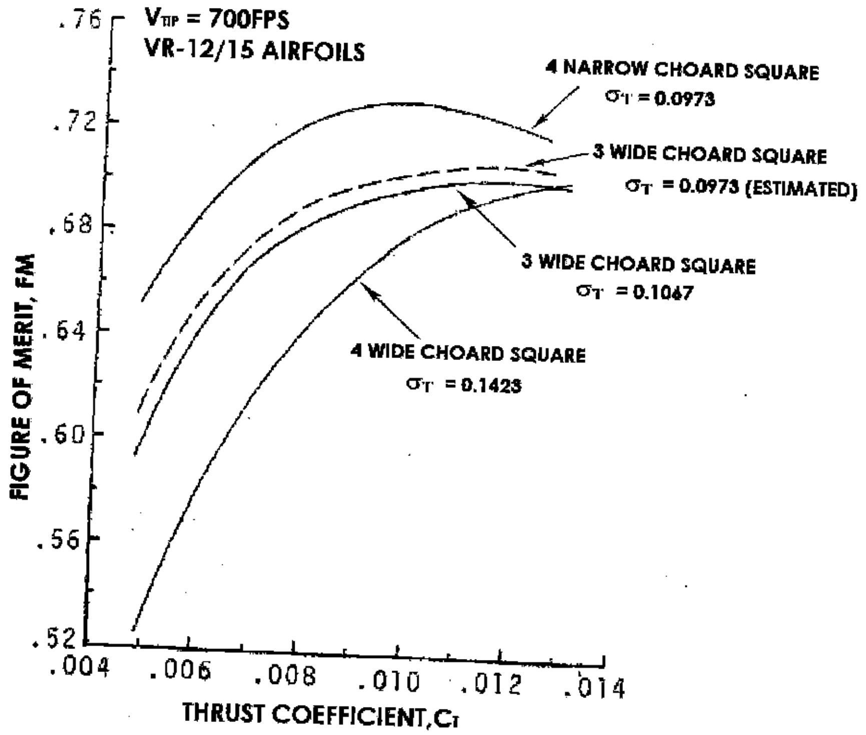


Figure 2.1: Effect of blade number and chord on hover performance

Table 2.1 Advantages of low and high number of blades

| Advantages of Low Number of Blades | Advantages of High Number of Blades |
|---|---|
| Low rotor weight | Low rotor-induced vibration |
| Low rotor cost | Reduce induced tip loss effect |
| Easy of folding or storing | Less distinctive noise signature |

## 2.2 Blade planform modification

An alternative approach to improve the aerodynamic design of helicopter rotor blade is by using the blade planform modification. In this method, the modification of the blade tip is the most popular one. The blade tips play an important role in the aerodynamic rotor performance. The blade tips encounter the highest dynamic pressure, highest Mach numbers and strong trailed tip vortices. The poorly blade tip design will contribute to the serious implications on the rotor performance.

Figure 2.2 shows several of blade tip designs which are very successful design to optimize the hovering flight. The result of a flight test of a swept back parabolic tip on a Dauphin 365N helicopter was reported by Guillet, F and Phillipe, J.J. [14]. Additional weights were added at 45% radius for the dynamic tuning of the second lead-lag mode. The tip planform improved about 1 to 6% of forward flight performance by minimizing the profile power and also improve overall rotor cruise efficiency.

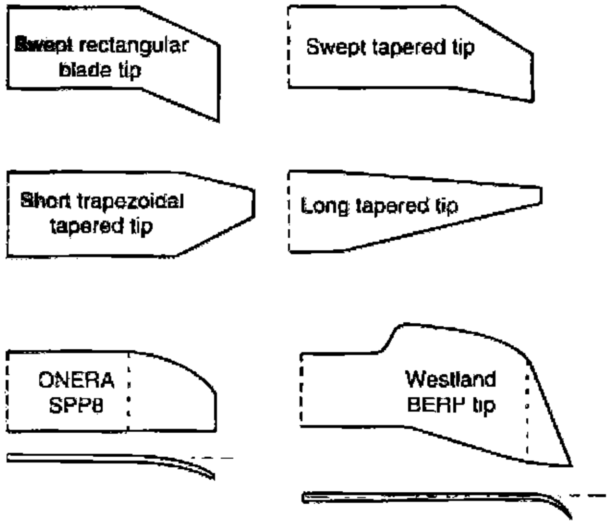


Figure 2.2: Variety of blade tip designs

The tip shapes of blade affected the efficiency of hover performance. It was done by Michael A.M and Francis J.M [15] using wind tunnel testing with the rotor of same twist, airfoils and main chord is shown in Figure 2.3. The basic square tip blade reaches a peak figure of merit (FM) of 0.707 at $C_T$= 0.016. Tapering the tip to 60% and sweeping the quarter chord 30 degrees starting form 0.95R resulted in a very small improvement in efficiency but did not change the maximum value, although the thrust coefficient at which the maximum figure of merit achieved was reduced. The effect of $10^\circ$ of sweepback from 0.85R to the tip has increase a peak performance at 1% and provides a small increment in the operating range over the square tip blade. Reduction of the blade area in the tips improves the loading by moving the peak circulation inboard which can decrease the velocity induced by tip vortex on the following blade.

Michael A.M and Francis J.M [15] also study the effects of tip shape on overall rotor performances and cruise lift to drag ratio (L/D). All four rotors were flown at the same lift and propulsive force and were trimmed into zero one-per-rev flapping. The tapered tip was found to give about 10% higher equivalent L/D ratio compared to the rectangular blade. From the Figure 2.4, the rectangular blades provide a better maximum cruise L/D ratio than either of the swept or swept tapered blade.

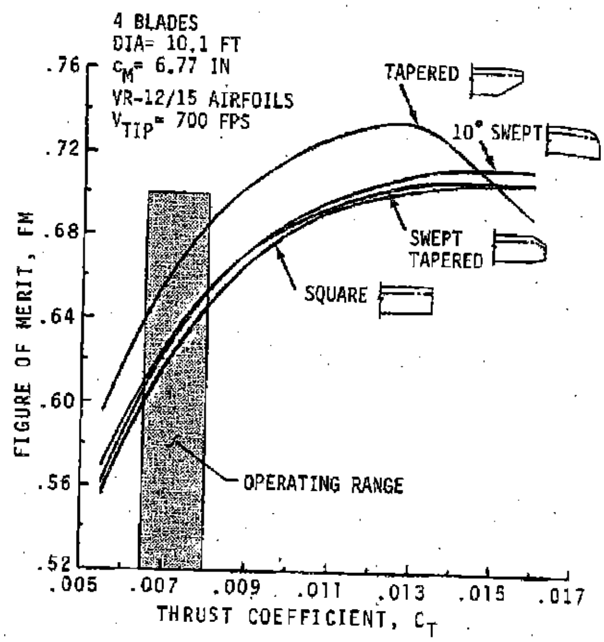


Figure 2.3: Effect of tip shape on hover performance for rotor.

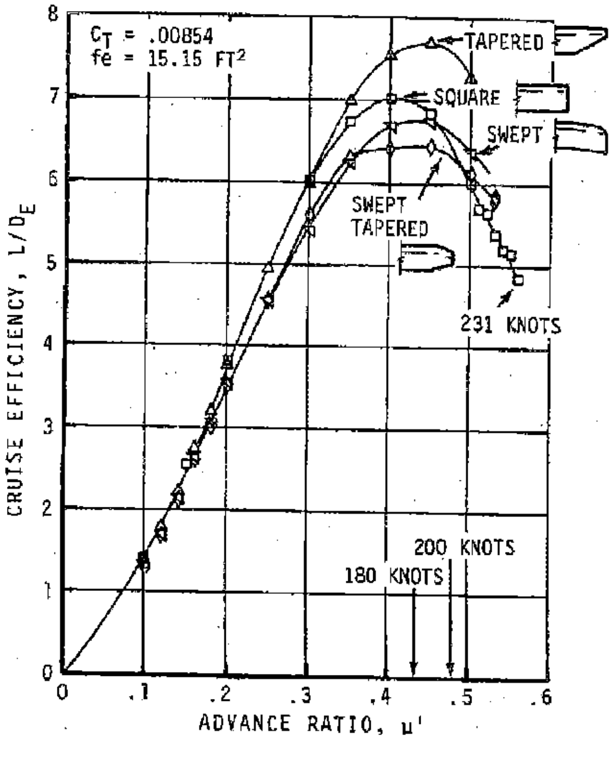


Figure 2.4: Effect of tip shape on cruise efficiency

Hong Hu [16] was used Computational Fluid Dynamic (CFD) code to apply at four types of tip shapes which are elaborated in Figure 2.5. This analysis was investigated to obtain tip vortex strength and aerodynamic load when helicopter was in hovering motion. There was several conclusions that had been made on his investigation:

1. The tip vortices of Ogee-type and sub wing tips were weaker than the tilt and 45° swept-tapered tips under hovering motions.
2. The double vortices were found on Ogee-type and sub-wing tips that reduce strength of tip vortices and reduce blade interaction vortex (BVI) noise.

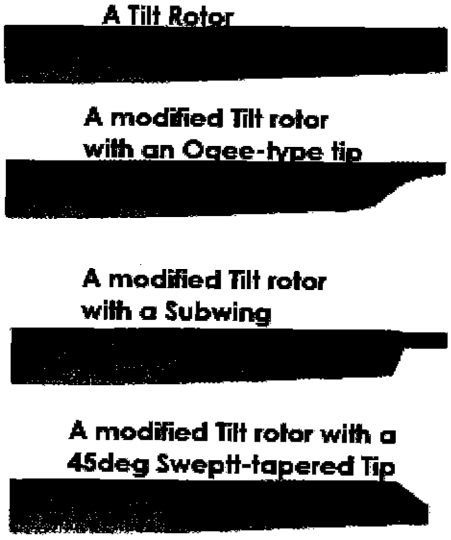


Figure 2.5: Planform of four tip shapes

Fu-Shang Wei and Cliff Gunsallus from Kaman Aerospace Corporation [17] presented the new design concept to select an optimal in a systematic manner. Five different blade planforms in Figure 2.6 were chosen in the analysis. These were:

i. Baseline blade with the rectangular planform
ii. 6 :1 taper ratio blade starting from 85% radius to the tip
iii. 4 :1 taper ratio blade starting from 75% radius to the tip
iv. 3 :1 taper ratio blade starting from 50% radius to the tip
v. Modified 4 :1 taper ratio blade starting from 75% radius to the tip

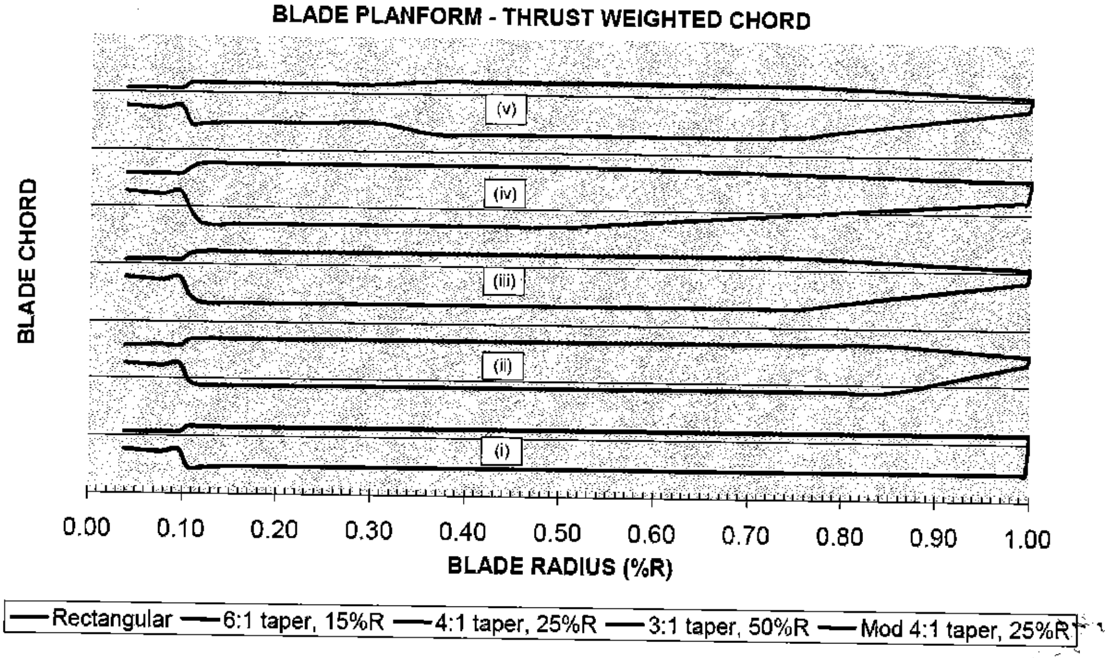


Figure 2.6: Sketch for five blade planform

The entire blade was divided into three major sections: (i) tip region, (ii) mid-span region, and (iii) inboard region. Each region can be adjusted separately to have non-constant blade local chords to enhance the performance:

i. In the outboard blade section, reduce the tip chord to improve blade out of ground effect (OGE) hover performance. The blade to tip chord ratio can be designed as high as 3:1, 4:1 or 6:1. The blade chord reduction station starts at approximately 50%R, 75%R or 85%R depending on the design requirements. The minimum blade chord is located at the tip. It can be designed as small as 33%, 25% or 15% of the original blade chord.

ii. In the blade mid-section, increase the blade local chords starting from station 40%R to 75%R. The increment of the blade chord will increase the blade lift capability. The aerodynamic loading area increases will benefit blade forward flight performance. But in real blade design, there is a certain limitation in choosing the blade airfoil thickness. Because of the limitation of the airfoil thickness used on a helicopter and the shop manufacturing technique restriction, the maximum blade local chord can not be 50% larger than the original blade.

iii. In the inboard blade section, reduce the blade local chords to reduce aerodynamic drag. The starting blade radial station is from 10%R to 30%R. The maximum reduction in blade local chord is also limited to 50% of the original blade chord.

There are several design options to design helicopter blade [17]:

i. Maximum blade local in the mid-section up to 150% of the original blade chord
ii. The maximum chord is designed around the 75% blade radial section area
iii. Design a very small blade chord with very ratio around 15%,25% or 33% of the original blade chord at the tip
iv. The airfoil also can be started at 14% thickness at the inboard section of the blade, then transitioning to 12% and 10% thickness around the mid-span region and finally transitioning to 8% thickness at the tip.

Desopper et al [18] 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 2.7). And as reported by Desopper, for almost all the advancing blade side:

a) The intensity of the transonic flows was 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 was possible to decrease the intensity of the transonic flow for a large azimuth 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 showed that the PF2 tip has made a possible significant reduction (5-8%) in the power required by the rotor.

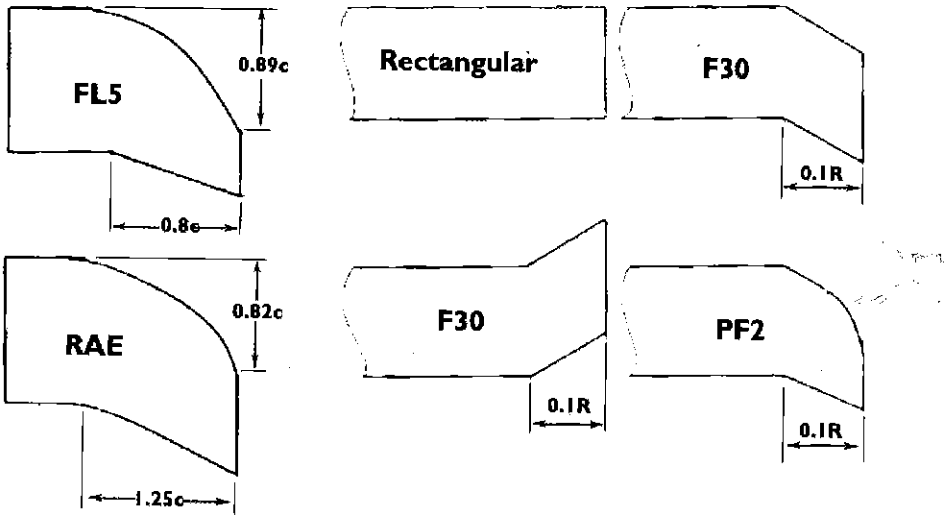


Figure 2.7: Example of rotor blade tip tested in S2 Chalais-Meudon wind tunnel [20].

Matthew T.Scott et el [19] reported comparisons of computational predictions with data from a BERP tip configuration with rectangular tip, swept tip, ONERA PF2 and FL2 tips in fixed wing mode. Swept tip reduce the shock strength but not continuously as much sweeping the leading and trailing edge. The PF2 and FL5 tips both lessen the shock strength appreciably over the outer two chords of the blade. The double-swept BERP planform, however, decreases the strength of the shock farther inboard than any single-swept tip. The maximum Mach number on the surface of the BERP tip was lower than that found on any of the other tips, and that the shock was diffused over the outer three chords of the blade. The BERP tip generates downwash (Figure 2.8) which induced over the paddle part of the planform between the vortices.

This downwash energizes the boundary layer and reduces the local angle of attack seen by the outboard portion of the blade. Thus, the flow over the blade between the two vortices is braced and remains attached at higher angle of attack. The corollary to this rule also holds the flow inboard of the forward sweep break was more likely to separate because of the presence of the nearby vortex.

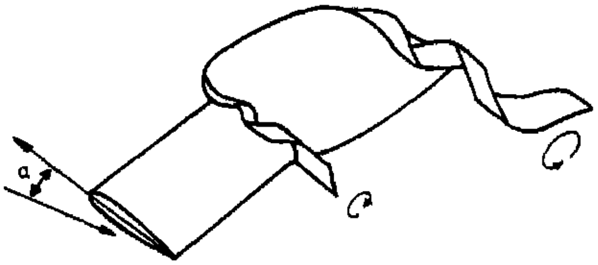


Figure 2.8: Vortical flows for the BERP planform at high angle of attack

## 2.3 British Experimental Rotor Program (BERP) blade

The collaboration between Westland Helicopter Limited and the Royal Aerospace Establishment (RAE) developed the unique design of helicopter blade called British Experimental Rotor program (BERP) blade. The BERP rotor was designed specially to meet conflicting requirement of the advancing and retreating blade condition, either of which can limit the $C_L/C_D$ of the blades and the performance of the rotor in high-speed forward flight. The BERP blade was started design since 1975 which called BERP I where this blade was changed from the metal to composite blade. However, the enhancement in the blade profile consistency resulted at 5% reduction in fuel burn [20]. After BERP I, the BERP II was introduced with new advanced composite apply in the blade. Then in year 1986, with using the new shape BERP III fitted at GKN-Westland Super Lynx which aerodynamic of the blade design refine attained the world absolute speed record of 400.87km/h for conventional helicopter [21].The BERP III blade shows in Figure 2.9 uses a number of high performance airfoils based on the RAE family.

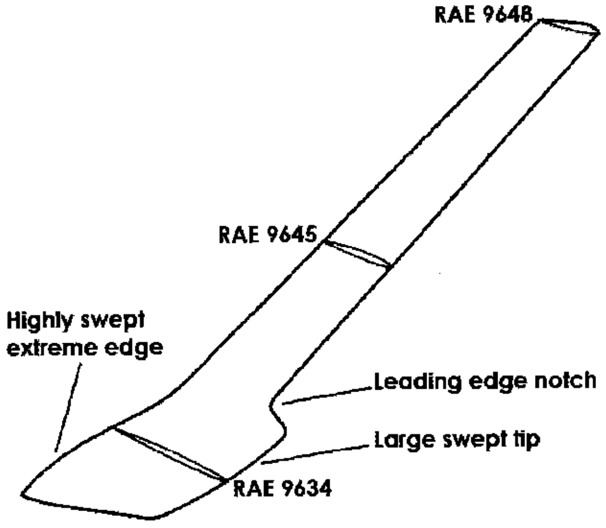


Figure 2.9: BERP blade geometry

The BERP blades have a large swept tip, which also incorporated forward notch offset and highly swept outer tip edge. The RAE airfoils were distributed by the sections along the blade shows in Figure 2.10 which get the greater 30% of the thrust and extends the forward speed potential of the edgewise rotor to well in excess of 200 knots [22].

The BERP blade uses a high performance airfoil based on the RAE family. The RAE 9645 is an aftloaded which is located on the blade from 65 to 85% radius, high-lift airfoil with a nose-down pitching moment. To counteract the 9645's pitching moment, the reflexed (nose-up pitching moment) RAE 9648 was used on inboard blade sections [23]. The thinner RAE 9634 airfoil used outboard for more reduction of transonic effect and produced the best advancing blade performance [23,24]. The shape of the tip of the BERP blades are design in order to perform as a swept tip at high Mach numbers and low angle of attack. Yet, it is also designed to operate at very high angles of attack without stalling [25]. It was also for the purpose to reduce transonic effect of advancing side [24], the outboard 15% of the span was swept back to reduce Mach Number normal to leading edge [23,24], produced the best retreating blade performance in as much as it is best able to maintain attached flow conditions to the highest angle of attack and most tip sweep produced the best advancing blade performance [20], reduce noise [26] and vibration [24]. Tip with anhedral has contributed greatly to the success of the BERP blade, in that is helps to balance sweep effects in forward flight and also enhances the performance in hover [27]. To delay retreating-blade stall, Westland incorporated a delta-wing-like platform at the extreme spanwise location (delta wings maintain high-lift at high angles of attack by forming a stable vortex structure over the wing surface) [23].

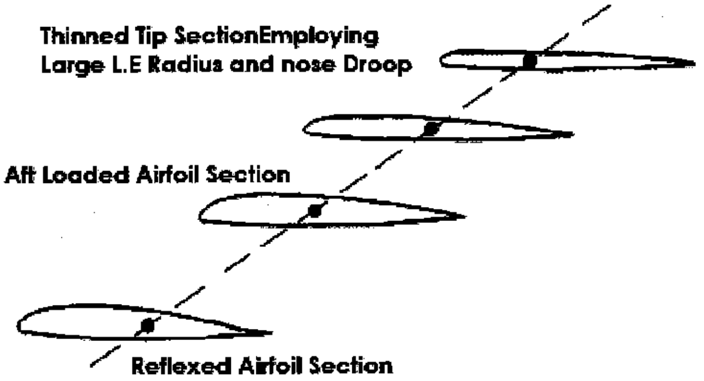


Figure 2.10: Cambered airfoil section distributions [22]

Brocklehurst et al [23] in their work have observed in experimental and simulation using CFD to obtain detailed information of the flow over the BERP tip for range of angle of attack. In their observation, both the computation and experiment exhibit attached flows on the regions beyond the north. A tip vortex formation at the delta wing planform part of the blade is also captured show in Figure 2.11. The location of the primary separation line inboard of the notch was not well predicted. However, the trend for the flow is to change from stalled flow inboard of the notch to attach flow outboard of the notch is captured.

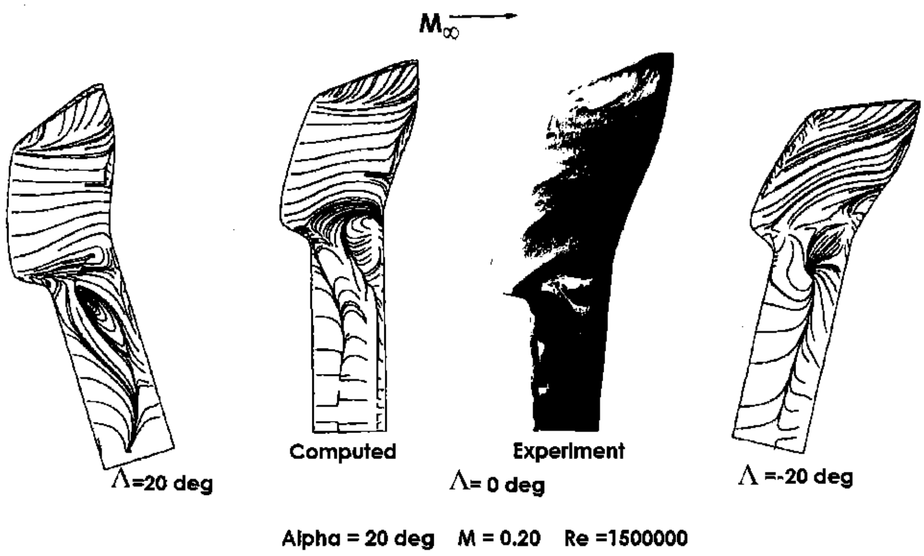


Figure 2.11: Computed and experimental surface streamline patterns at high incidence and sweep.

In year 2003, Brocklehurst [27] continued the previous work with producing a complete helicopter Navier-Stokes analysis in CFD and validate with experimental using wind tunnel. The flow separation patterns at swept tip in Figure 2.12 same in previous work in Figure 2.11, when angle of attacks increase, the stall areas are closely to the notch of the blade. This work also comes out with flow stall pattern along the blade without swept tip. Figure 2.13 shows the stall areas were nearly at trailing edge when angle incident were increased.

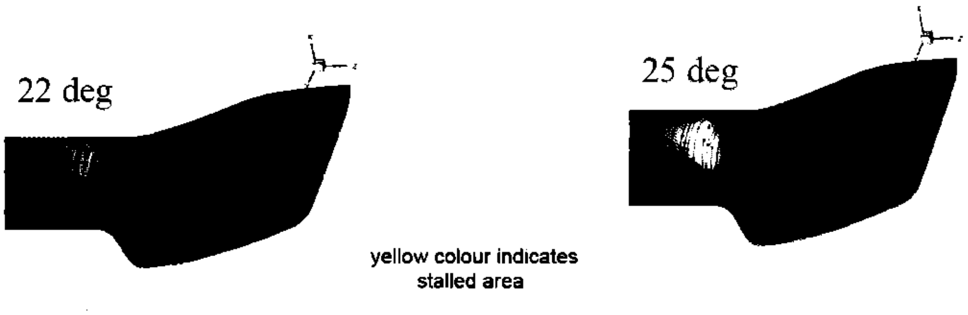


Figure 2.12: CFD Results for the flow separation near the notch region of a BERP blade.

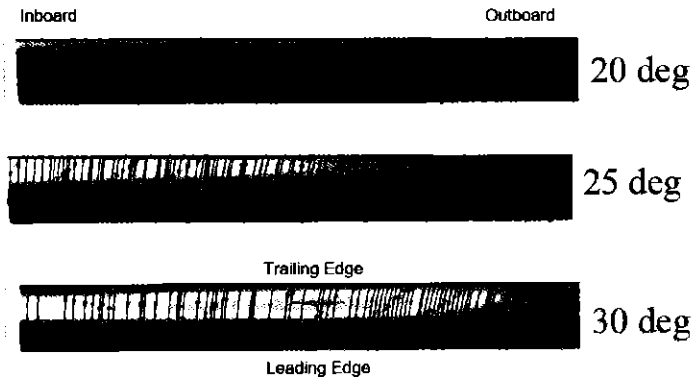
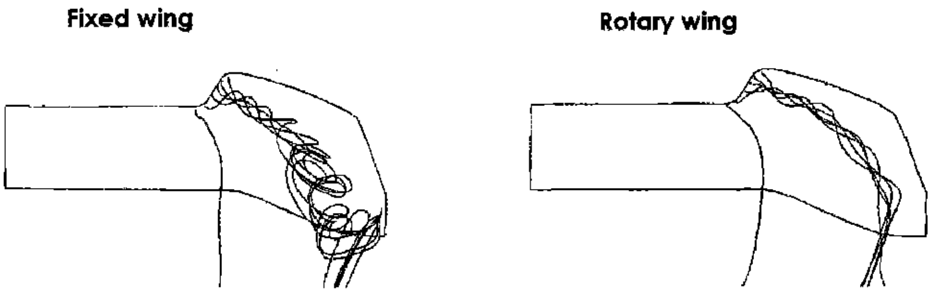


Figure 2.13: Stall area in yellow colour along the BERP airfoil when the angles of attack increase (Re=$0.64x10^6$, M=0.2) [27].

The work of Brocklehurst [23,27] obtained a flow configuration along the BERP planform wich only for fixed wing configuration and also not include the effect of rotor centrifugal force. This centrifugal force are studied by Fu-Lin Tsung [28] done in CFD using 3-D Navier Stokes to simulate the flow separation for rotor and fixed wings. This study concentrated on the outer 35% of the planform, from just inboard of the forward sweep notch to the tip of the platform. The Figure 2.15, Figure 2.16 and Table 2.2 show the difference of flow separation between rotor and fixed wing at r/R = 0.65 and r/R=0.88 during 20 degree of angle of attack.


**Fixed wing**

**Rotary wing**

Figure 2.14: Particle trace of outboard flowfield for both rotor and wing at 20 degree

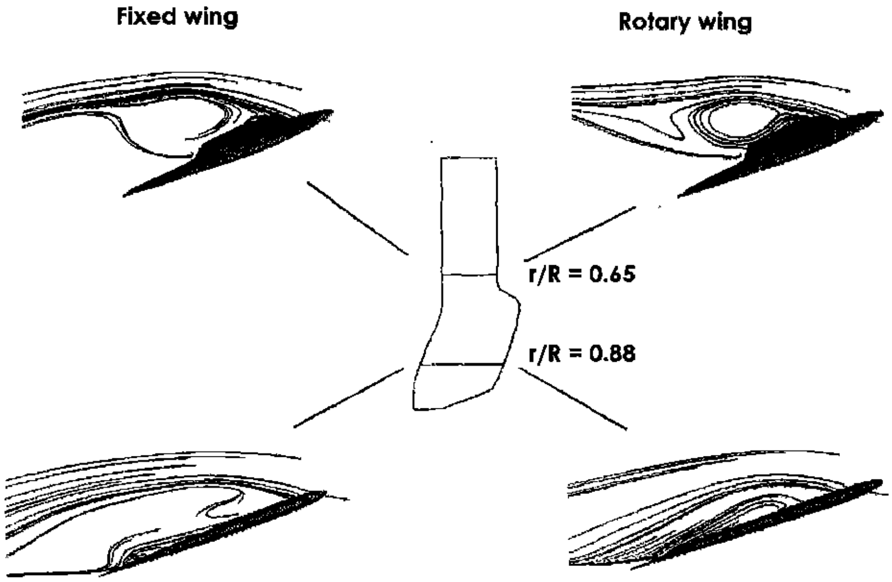


Figure 2.16: Cross-sectional view of flowfield at two spanwise stations for both rotor and wing at 20 degree

Table 2.2: Comparison the flow separation between fixed wing and rotary wing of BERP blade at angle of attack 20 degree [28].

| | Fixed wing | Rotary wing |
|---|---|---|
| Figure 2.15 | The leading edge separation and the tip vortex have merged into one. The vortex burst on the planform about half way to trailing edge. | The leading edge separated flow and the tip have merged into one dominant vertical flow over the outboard region, similar to the high angle of attack delta wing flow. Strong vortex is dominant, it is bounded and tightly wound vortex. |
| Figure 2.16 | The size of vortex burst caused a large separation at 65 % of the tip radius (0.65 r/R) and 88 % radius (0.88 r/R) | |

The new BERP introduced in 2008 is called BERP IV. Rob Harrison et el [20] were design the new tip concepts apply to BERP IV that considered are shown in Figure 2.16.

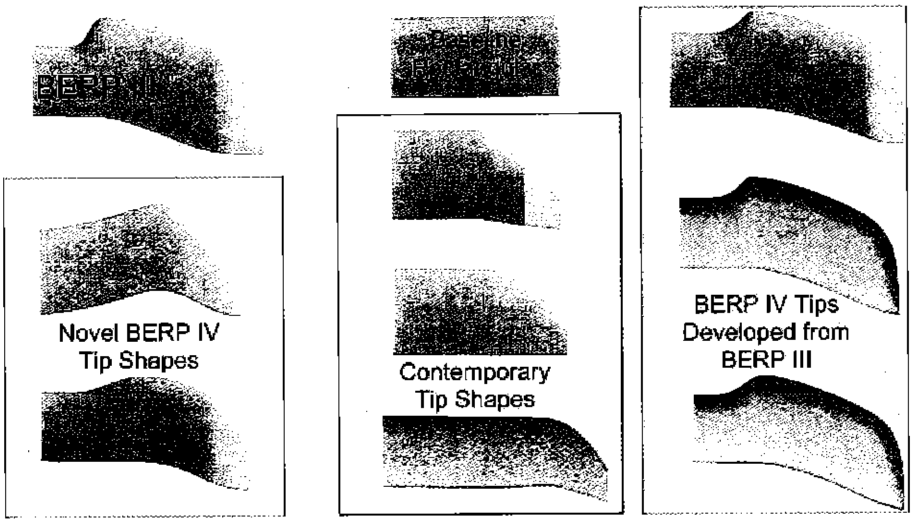


Figure 2.16: Various tip shapes assessed during BERP IV [7].

With this tip concept the BERP IV was improving the BERP III in influencing the advancing blade, retreating blade and hover performance. In particular, the outer tip edge of BERP IV is now more streamwise and the notch refinement reduces the tendency for any local separation at high angle of attack. The new tip also gave the better chordwise balance, giving improved stability and some relief on control load. The designs are summarized below and illustrated in Figure 2.17 [20].

1) The tip has a more smoothly blended notch geometry (the feature at the inboard end of the forward chord extension) that acts to reduce drag
2) The increased tip chord was fundamental to the tip's high incidence capability. This was retained in the BERP IV design and was optimised for reduced profile drag, whilst still maintaining the high incidence performance.

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