A review of helicopter rotor blade tip shapes

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George N Barakos
University of Glasgow

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A review of helicopter rotor blade tip shapes

A. Brocklehurst, G.N. Barakos *

CFD Laboratory, Department of Engineering, University of Liverpool, Liverpool L63 3GH, United Kingdom

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ABSTRACT

A review of helicopter rotor blade tip design technology has been carried out with a view to undertaking subsequent computations to evaluate the performance of new tip designs. The review starts by briefly looking at (fixed) wing tip design concepts and the underlying fluid mechanics on which they are based in order to see if there is any carry-over of ideas on which improved tip design concepts might be based. Then, rotor blade tip shapes that have been used, or suggested for use, on past and present rotorcraft are examined to obtain a better understanding of the helicopter tip design problem. In parallel, the review traces the development of analysis tools to evaluate the performance of the rotor and blade tip design. It is clear that in the past, the designer relied heavily on classical aerodynamic knowledge, supplemented by experience and intuition, supported by wind tunnel and model rotor testing, and relatively low-order aerodynamic calculations. New rotor designs were, and still are the subject of intensive flight test verification. However, recent development of Computational Fluid Dynamics (CFD) now offers an opportunity to accurately predict the viscous, compressible flow-field in the tip region, and thus predict the performance of new rotor and tip designs, provided that the solver has adequate resolution, is able to handle all aspects of the helicopter problem, and sufficient computational resources are available to complete the design in a practical time-scale.

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1. Introduction

The unique combination of hover and forward flight capability makes the helicopter one of the most versatile types of aircraft. Yet these unique capabilities give rise to the need to reach a compromise in many aspects of the design, and the aerodynamic design of the rotor is no exception. The helicopter rotor must be both efficient in hover and capable of carrying a useful payload in cruising flight. The design of the rotor blade, and the tip in particular, has a powerful influence on the overall performance, vibration and acoustics of the helicopter.

For a conventional single main rotor with tail rotor configuration, in forward flight the tips of the blades experience a strong cyclic variation in the Mach number and the Reynolds number together with large changes in angle of attack and side-slip. The lift must be balanced between the advancing and retreating blades, and a significant proportion of the load is carried in the forward and rearward sectors of the rotor disc. On the advancing blade the flight speed adds to the rotational speed of the blade and the Mach number can approach the sonic boundary, while on the retreating blade high lift-coefficients are demanded due to the low dynamic-head, and the retreating blade stall boundary imposes a limitation on the flight envelope of the helicopter. Even in hover, where the

* Corresponding author. Tel.: +44 (0)1963 210700.
E-mail addresses: A.Brocklehurst@liverpool.ac.uk, alan.brocklehurst1@btinternet.com (A. Brocklehurst), G.Barakos@liverpool.ac.uk (G.N. Barakos).

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flow may be considered as steady (and in the idealised case of an isolated rotor may have axial symmetry of the wake), the blade tips must be designed for mid-subsonic Mach numbers (0.58–0.66), and also take into account relatively low Reynolds numbers, in the range of 1–4 million. While efforts to enhance the performance of the main rotor have a direct impact on the overall performance of the helicopter, there is also a need to provide an efficient tail rotor to avoid excessive power consumption and provide good manoeuvrability. Tail rotors tend to operate at high blade loadings, and so the need here is for a tip design that minimises, or at least delays, the drag rise associated with separation at high angles of attack at mid subsonic Mach numbers and associated low Reynolds. Other rotorcraft configurations are not exempt from the basic conflict between hover and cruising flight requirements. For example, in the case of the tilt-rotor the aim is to maintain the rotors in axial flow, although even here there are many compromises to be made and similar design conditions of high blade loading at moderate-sub-sonic Mach numbers and relatively low Reynolds numbers remain.

In addition to striving to enhance the aerodynamic performance, the helicopter designer must also consider the acoustic signature of the rotorcraft, perhaps by placing constraints on the tip Mach number, or blade loading. Most helicopters suffer blade–vortex interaction noise in descending flight manoeuvres on the approach. Nowadays, the demand is for both a quiet and efficient vehicle, with greater payload range capability than ever before.

Over the past 60 years or so, many blade designs have been put forward, and design trade-off studies undertaken. Blade taper and twist help to improve the Figure of Merit in hover, but give rise to premature stall and increase the risk of high vibration in cruising flight, although most modern helicopters now incorporate some twist and also employ advanced low-pitching moment aerofoil sections. When sweep is required, the problem is to avoid significant offset of the aerodynamic centre, and the tip shape should enhance, rather than degrade the performance of the rotor. While much can be learnt from fixed-wing wind tunnel tests, it is difficult to transfer the results directly to a rotor, and model-scale rotor testing brings its own low Reynolds number questions, not to mention difficulties in measuring all relevant parameters in the necessary detail. In the past, many model rotor tests have been undertaken to support the development of strip-theory-based rotor models with prescribed or free-wakes. More advanced theories to take into account compressibility were later applied, but even so it was difficult to capture all the flow states experienced by the rotor and the final blade tip design was the subject of much reasoning and sometimes arbitrary judgements.

However, as methods of analysis improve, some of the early guess-work can be replaced by a deeper understanding of the fundamental physics of the flow-field in the tip region. Recent developments in Computational Fluid Dynamics (CFD) now offer an opportunity to make further improvements and better optimise the tip shape for helicopter rotors. These modern numerical methods, such as the Helicopter Multi-Block (HMB) code which is used in the UK, start from the surface geometry and a set of boundary conditions and are well placed not only to capture the physics of the flow in the tip region, but also the flow around the complete helicopter.

The work presented in this paper reviews the development of helicopter tip shapes with a view to subsequent simulation and the evaluation of new helicopter blade tip designs. Against this background new designs may be put forward and properly evaluated. Once the blade airloads in the tip region are known with greater precision, the overall performance of the whole helicopter will be able to be better appraised.

2. Literature review

While the focus of this work is on helicopter tip shapes, much can be learnt by also looking at wing tip developments in the fixed-wing field since the underlying fluid dynamics are essentially common. This literature survey is therefore divided into two sections. Firstly ideas are considered from fixed wing aircraft which may be usefully applied to the rotorcraft problem. In the second part of the survey tip shapes used on past and current helicopter blades are identified, and the reasons for their development are probed. The available methods for analysis of blade tip aerodynamics are also reviewed.

2.1. Wing tip design

Since there may be considerable carry-over in tip design thinking between fixed-wing and helicopter tip shape, fixed-wing aerodynamic developments are considered in this first section of the literature review. However, it is recognised that there are major differences in the flow environment in which the tip shapes must function, not least of which for the helicopter are centrifugal effects and vortex wake interactions, and indeed dynamic and manufacturing constraints may also differ. Nevertheless, there is commonality of purpose towards enhanced performance, and in certain cases, design ideas may be adapted from one application to another. In addition, modern CFD methods are being eagerly applied in both fields, and it may therefore be possible to learn new techniques, or gain additional insight from the fixed wing field, which could be applied to the helicopter problem.

As with helicopters, early aircraft were generally of wooden construction and commonly had rounded wing tips on an otherwise rectangular planform. The wing planform later became influenced by the lifting-line theory of Prandtl [1], which established that an elliptic planform produces a uniform downwash to give minimum induced drag. However, since this type of planform was not easy to manufacture when metal construction was adopted, much more basic planforms rapidly became the norm. Pope [2] and Glauert [3], amongst others, present factors to account for the effect of wing taper and/or twist on the induced drag and lift-curve slope. In the US, the inverse of the induced drag factor is known as the Oswald efficiency factor, as given in McCormick [4]. The concept of breaking down the drag of an aircraft (or helicopter) into induced (vortex) drag due to lift, and profile (viscous and wave) drag, is fundamental to aircraft performance analysis.

While lifting-line theory is fundamental to wing design, and is often used to estimate the spanwise loading, it represents an idealisation of the flow over a real wing. Most notably lifting-line theory is not able to represent the chordwise loading which is known to vary markedly near the root and tip. More advanced (swept) planforms therefore demand the use of more sophisticated methods, such as lifting surface theory or panel methods, or Transonic Small Perturbation (TSP) methods if the flow speed is near sonic.

As numerical methods and computational resources evolved, 3D panel methods were developed to account for planform and tip shape effects, and this approach is now often used to model a complete aircraft. Despite their inviscid nature, most panel methods now also take into account viscous effects through the use of coupled integral methods for the boundary layer. Strong coupling is relatively common in 2D aerofoil codes, such as Xfoil and MSES, Drela and Giles [5]. Most 3D panel codes, such as VSAERO, employ only weak coupling, often in the form of a 2D approach, where the boundary layer development is computed along streamlines, Nathman [6], and responds to the predicted inviscid flowfield (although further developments are underway to improve the coupling). These methods work well provided the flow is attached, or separation points can be estimated with confidence. However, when modelling the flow around complex bodies and wing tips, it may be necessary to judiciously position the shedding location of the trailed vortices to represent edge separations. Panel methods usually solve the Laplace equation for incompressible flow, given boundary conditions on the surface of the body, but may also take compressibility into account by using Prandtl–Glauert or Karman–Tsien compressibility corrections, provided the flow remains well below sonic so that shocks are not present.

Where high sub-sonic Mach number flows are of interest (for high-speed sub-sonic aircraft and helicopter rotors) TSP Methods, Full-Potential, or Euler methods may be used, or when viscous effects are also important, Navier–Stokes CFD methods are required to simulate details of the flow. While CFD methods are good at capturing the local flow field, and conserve mass, momentum and energy, it is also important to ensure that the wake is well represented if the induced drag is to be computed correctly.

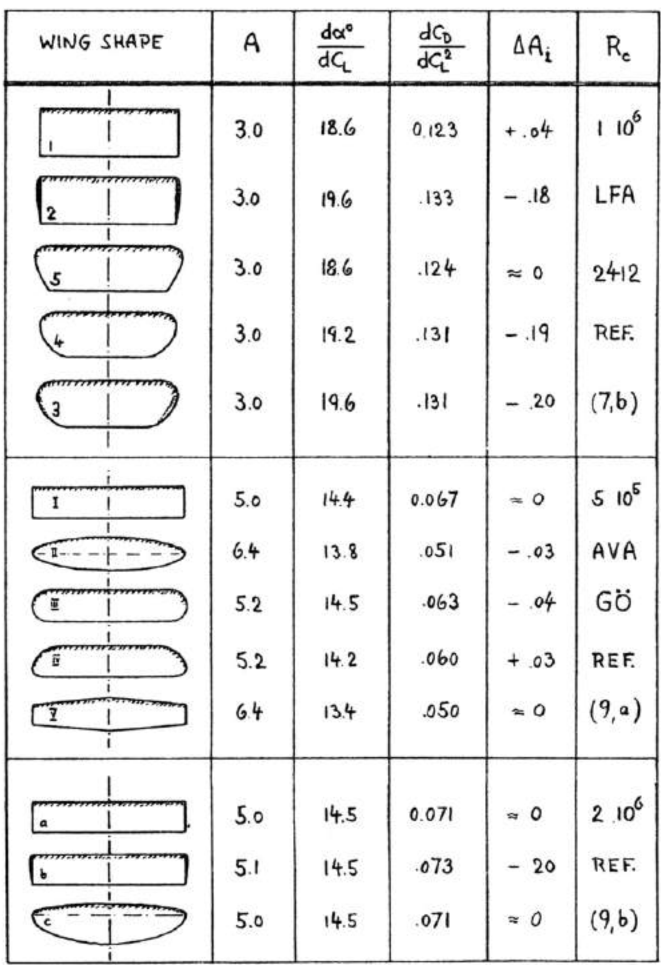

Fig. 1. Aerodynamic Performance of three families of wings as a function of planform and wing tip shape, Hoerner [7].

In practice, the viscous nature of the flow often makes it difficult, if not impossible, to distinguish between induced (drag-due-to-lift) effects and profile drag due to viscous separations. For wing tip design an accurate model of the flow which contains all the physics is required.

In his book, Fluid Dynamics of Drag, Hoerner [7] presents a series of wing tip shapes which had been previously tested in Germany and documented in the USA by Hoerner [8], Fig. 1. The tests were carried out in a low speed wind tunnel on model-scale wings of relatively low aspect ratio fitted with different tip caps. Hoerner summarises their induced drag performance by determining an effective aspect ratio for each tip, and in his report also compares their total drag polars and lift characteristics. Hoerner also considered the effect of cross-section shape on various styles of tip, Fig. 2. Hoerner's preference was to blend the lower surface up to meet the upper surface to achieve an overall beneficial effect, as on Tip No. 5, and the suggested roll-up mechanism is sketched in Fig. 3. Modern computational methods now have the potential to offer a deeper insight into the tip design problem, and it should be possible to reproduce the Hoerner results for a wing by a numerical approach, provided that adequate details of the flow can be captured.

The so-called Hoerner tips are featured on many light aircraft, and there seems to have been some disagreement as to what comprised a Hoerner tip. Some early Cessna's have tips that curl slightly downwards, while Beech tend to employ a slightly curved up, or slanted up tip shapes, and Mooney uses a simple square-cut tip. However, replacement tip caps are now available for range of

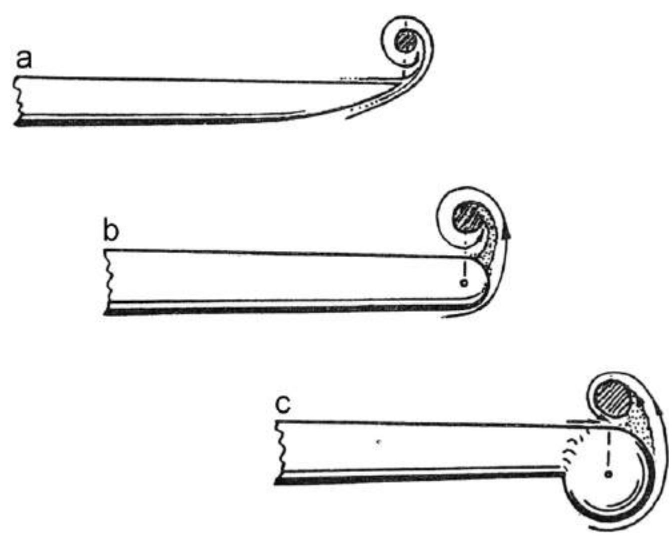

Fig. 3. Location of the vortex core in relation to the wing tip, (a) with sharp lateral edge (as preferred by Hoerner), (b) on wing with round edge, (c) flow around tip tank, Hoerner [7].

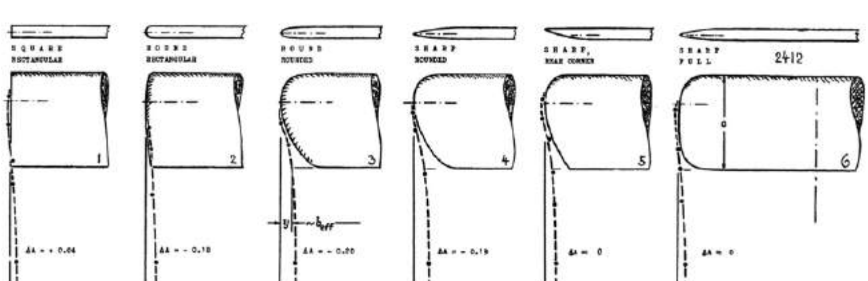

Fig. 2. Wing tip shape and wing tip vortex location of a family of wings tested at AR=3 and Re=1×10^6, Hoerner [7]. Hoerner expressed a preference for Tip No. 5 because of the good overall lift-drag characteristics, but note that the rectangular tip has the highest effective aspect ratio.

light aircraft that appears to closely resemble the tip shape preferred by Hoerner [9], Sakrison [10].

Hall [11] also clarifies the use of the Hoerner tip on sailplanes and compares several other shapes. The tip shape illustrated at lower-left of Fig. 4 appears to be a logical development to encourage the tip vortex to roll-up as far outboard as possible, and the tip edge now curves back to form a right-angle trailing edge corner, while retaining the cross-section of Tip No. 5, as shown in Fig. 4.

The choice of tip shape may also be influenced by aesthetic, or even marketing considerations. Nevertheless, the manufacturers are keen to enhance the performance of their aircraft, and the main aim is to influence the roll-up, and position the tip vortex as far outboard as possible. Avoidance of tip stall and enhanced CLmax may also be objectives. The tip shapes used in practice may vary from those sketched by Hoerner, to much more extreme examples.

Some composite tip caps, known as 'Booster Tips', were fitted to the otherwise rectangular wing of a Cherokee light aircraft, and were demonstrated to enhance performance during flight tests. These tips were strongly curled down, Ferguson [12]. Gains in the take-off distance, rate of climb (+200 ft/min) and maximum speed (+10 mph) were reported, together with a stalling speed reduction of 5 mph. A similar tip shape is used on the Fox light aircraft, Fig. 5, and have also been seen on a Husky crop-sprayer aircraft where the aim may also have been to increase maximum lift, or avoid tip stall. The opposite, though less extreme, configuration is seen on the curled-up tips of the Eurostar, Fig. 6, and has also been used in a milder form on sailplanes.

Wind tunnel tests on different tip shapes are reported by van Aken [13], who found relatively small changes in the overall wing loads for different tip planform configurations, Fig. 7. Van Aken reports that the lowest drag was found with the tapered tip, and that the tapered-drooped (anhedral) tip caused high drag without increasing the tip-lift, perhaps as a consequence of the high taper and sweep. This is opposite to the effect anticipated from applying anhedral to the tip of a helicopter rotor blade. As can be seen from the Figure, van Aken's tip shapes have no sophisticated tip cap shaping like that of the Hoerner tips discussed above.

For an aircraft, not only must the tip have good low drag qualities, and avoid a sudden stall, but it must complement the basic design of the wing. An economic means of approximating an ideal elliptic loading is to employ double, or triple, tapered wing (although care must be taken not to reduce the Reynolds number too much in the outer tip region of small wing tips). This style of wing planform and tip, which features a straight trailing edge and slightly swept leading edge, with increased sweep and taper at the tip, is employed on several aircraft, such as the Dornier 228, Zimmer [14], Fig. 8. Zimmer discusses the influence of the wing tip design and aerodynamic optimisation, and explores many configurations, including planar and non-planar tips. Burkett [15] also investigated the induced drag of several non-planar wing configurations and points out that the vertical displacement of the tip relative to the root which occurs on an aft-swept-tip may have a beneficial effect, Fig. 9. In particular, Burkett analysed the crescent shaped wing, and like van Dam (see later) found

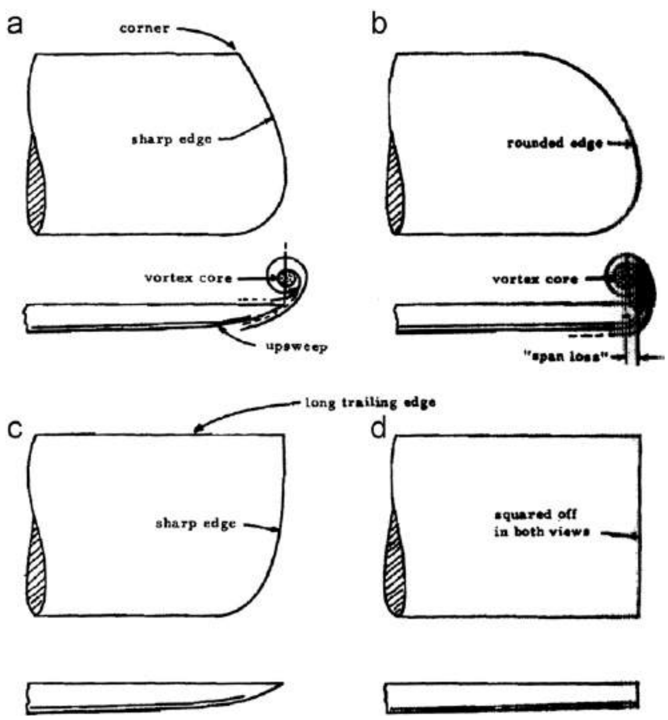

Fig. 4. Various applications of Hoerner tip to sailplanes, Hall [11]. The upper-left tip is the one preferred by Hoerner, and at lower-left is a further development for a modern sailplane. (a) The Hoerner Tip (the tip "preferred" by Hoerner) used on Zugvogel III et al. (b) A "poor" tip by Hoerner's definition. (c) SB-6 and Parker version of Hoerner Tip. (d) Tip that Hoerner's data indicates may be best of all (used on basic HP-10).

Fig. 6. The upwards curved tip of the Eurostar light aircraft, photographed at Kemble, 2003.

Fig. 5. The tip shape used on the 'Fox' light aircraft, photographed at Kemble, 2003.

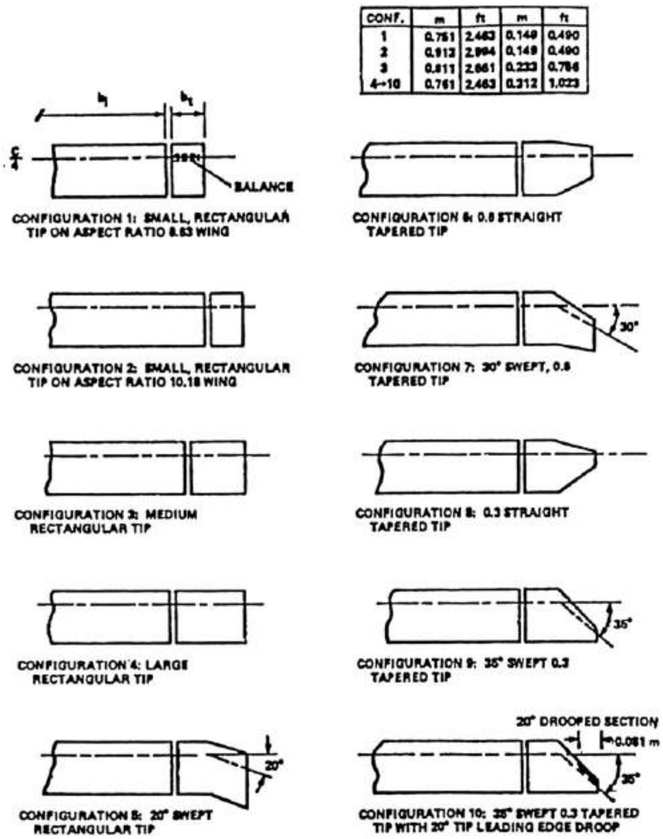

Fig. 7. Wing tip configurations of van Aken [13].

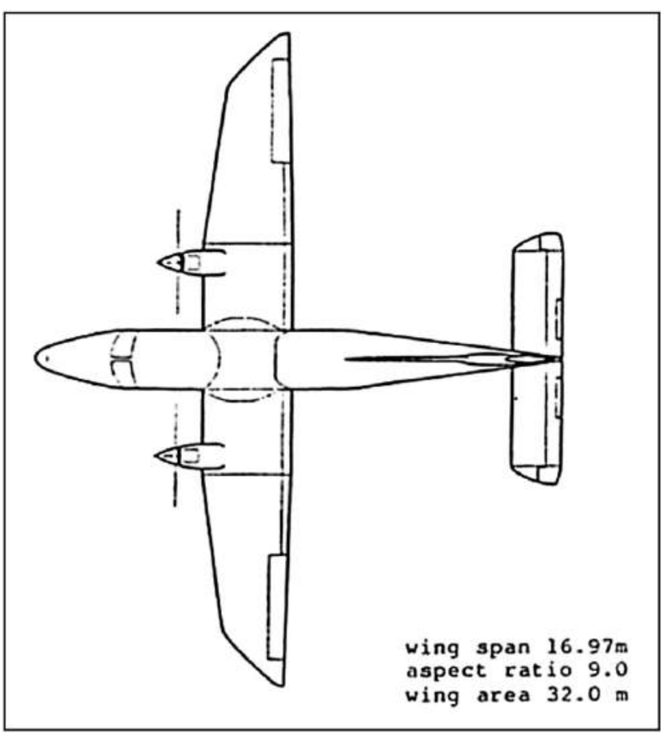

Fig. 8. Dornier 228 Commuter Aircraft with aft-swept triangular tips, from Zimmer [14].

a reduction of up to 4% in the theoretical induced drag. The use of sweep in the region of the tip leading edge will reduce the propensity for the isobars to cluster near the leading edge, and so avoid premature separation just inboard of the tip. However, the slanted outer tip edge and rapid taper could give rise to a large edge separation due to viscous effects, and possibly increase the lift-dependent drag.

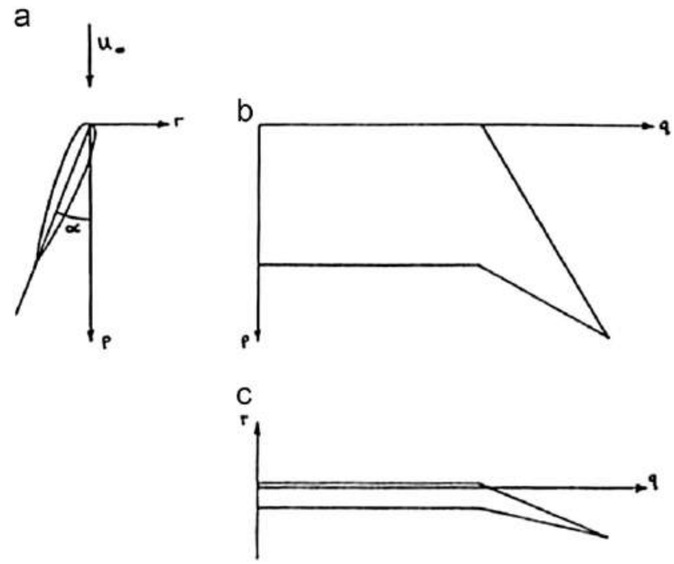

Fig. 9. Wing with aft-swept tip at angle of attack showing vertical displacement of the tip relative to the root, Burkett [15].

For the fixed wing case, the use of a tapered, or double tapered planform, brings the loading towards elliptic, and therefore closer to the ideal of a constant downwash. For a rotor blade the situation is rather different, as most of the lift is generated outboard, although it may be advantageous to taper the blade towards the tip if the goal is to achieve a high figure of merit in hover. However, in either case, excessive taper may lead to increased loading in the tip region, and a tendency for the tip to stall early. This is a particular concern at high sub-sonic Mach number conditions where isobars may bunch-up in the forward leading edge corner and lead to premature shock-induced separation.

The design of swept wings is covered by Küchemann [16], who prescribed a parabolic tip cap which has become known as the Küchemann tip and is currently used on many jet-transport aircraft, Fig. 10. In contrast to the so-called Parabolic Tip used on some European helicopters which are cut-off at the tip, the Küchemann tip has a smooth sweeping leading curve which extends to the (usually swept back) trailing edge. This type of tip shape has properties that would also be advantageous on the advancing blade of a helicopter rotor, in that it maintains the sweep and this helps to keep the drag low. These features may also have acceptable high-incidence characteristics for the retreating blade, and should have low drag in hover. However, it is understood that transport aircraft makes use of flaps when landing and hence generates significant aerodynamic washout at the tips, which avoids the low speed stalling problem. In cruise, it is essential that the tip vortex forms cleanly to minimise energy loss and hence low drag, and the Küchemann tip would seem to offer an ideal shape in this respect.

The Küchemann tip has been applied on many civil aircraft and greatly enhanced the performance of high-speed, highly loaded military aircraft, such as the BAe Hawk and Harrier.

The need to relieve the isobars bunching up in the forward leading edge corner was recognised during the design of the tail rotor for the EH101 helicopter, and a tip cap with a 45° blended chamfer at the leading edge corner was employed (see later).

The writer has also recently adopted Küchemann-like tip closures for both new main rotor and tail rotor blades, Robinson and Brocklehurst [17].

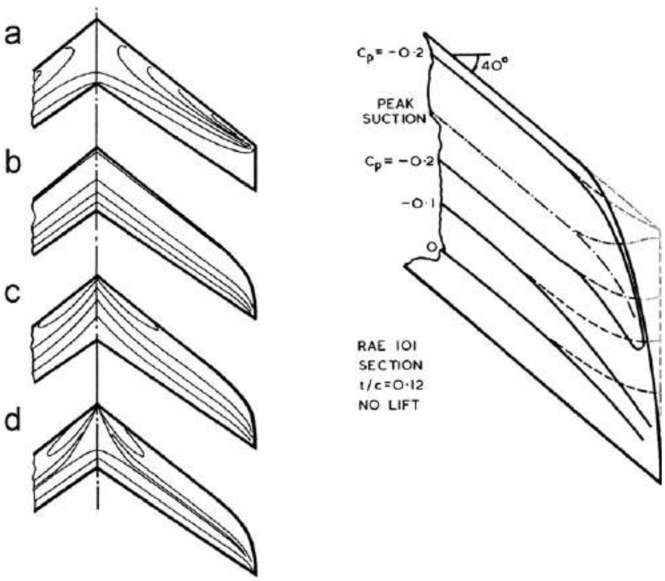

Fig. 10. Left: isobar patterns on sweptback wings. Right: isobars near the tip of sweptback wings: dashed lines constant sections and streamwise tip; full lines curved tip, from Küchemann [16].

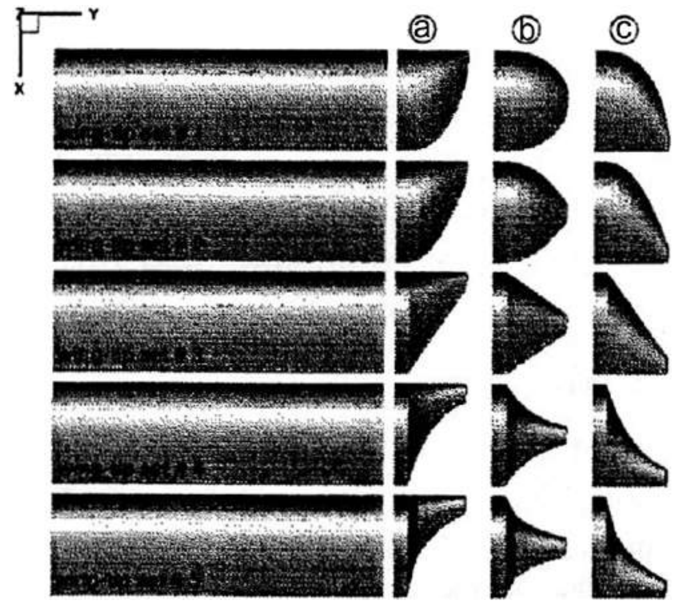

Fig. 11. Geometry of the wing-tips added to a rectangular planform by Bourdin [18].

As with helicopters, composite construction now offers the designer greater scope, depending on the type of aircraft. The need to produce accurate laminar flow aerofoils for sailplanes led to early adoption of composites, despite the potential aeroelastic problems. This trend has been followed for light aircraft, and is gradually being adopted on larger aircraft, while aluminium alloys are still employed because of their stiffness which is necessary for the use of sweep. Many aircraft employ composite components, such as root fairings and tip caps, not only to simplify manufacture, but also to clean up the design to achieve nearer to the optimum aerodynamic performance. The question of what is the best planform has intrigued aerodynamicists for many years.

One of the problems with the crescent shaped wing is that the tip vortex appears to form around an extended distance of the leading edge where the chord rapidly reduces. Hence, the flow may separate from the outer tip leading edge. At higher incidence, the tip vortex roll-up covers a significant portion of the span, and a stall cell develops inboard of this as shown by the flow visualisation. However, at moderate incidences, any premature drag rise near the tips takes place over a relatively small area such that its overall effect is small. The author has observed similar separation near the tip of parabolic and swept-parabolic tips that were tested in the Westland wind tunnel in early the 2000s.

However, the high sweep of this style of tip may well make it suitable for high-speed applications, and a modest increase of chord and tip modifications may relieve the tip-separation problem.

The effect of planform on induced drag is also discussed in a recent paper by Bourdin [18], who reports a parametric study of a family of 15 different wing tip shapes, Fig. 11, using a parametric geometry definition and grids generated in ICEM. However, Bourdin employed only an Euler solver, so while some induced drag benefits were discovered (for configurations that featured a straight trailing edge extending to the tip, column ‘C’ in Fig. 11), it is not clear whether there would be an overall drag reduction. Some of the tip shapes illustrated are also similar to those considered by Hoerner. The most successful of the tip shapes of Bourdin, although planar, leans towards the shape of a Winglet.

Winglets for fixed-wing transport aircraft were originally developed by Whitcomb [19] and reported by Flechner et al. [20], see Fig. 12. Following tunnel testing, winglets were initially flight tested on a KC-135A where a 7% increase in range was demonstrated. In this application, the objective is to reduce the total drag in cruise. Whitcomb discovered that, not only did the Winglet push the roll-up of the tip vortex outwards, effectively increasing the span and therefore reducing the induced drag, but also brought about a reduction in wave drag by preventing the isobars bunching up near the leading edge of the tip. This transonic effect may also justify the purpose of the small lower tip fence. The opportunity to reduce wave drag therefore helps to offset any increase in profile drag due to the added area of the Winglet. The addition of a winglet may increase root bending moments and the designer seeks a compromise between wing weight and maximising the effective span to improve the overall efficiency in cruise.

Winglets are now being incorporated into most commercial and business jets, including the Gulfstream III, IV and V, the Boeing 747-400, and the McDonnell Douglas MD-11 airliner and C-17 military transport. More recently, raked wing tips have been tried on the Boeing 767-400 and blended winglets have been applied to the Boeing 737-800 and Boeing 787 (Dreamliner), Fig. 13.

Once the concept of winglets had been proven for commercial jets, they were tested in other applications, for example, on light aircraft, ultra-lights and sailplanes. In these applications, there is no wave drag to trade off, so the designer must be careful to minimise profile drag in cruise.

After several years of development, winglets have been used to advantage on high-performance sailplanes, Eppler [21]. Eppler reports that although the winglets gave improvements in low speed performance, this had to be traded off against the additional profile drag incurred at high speed. Ironically, it was also reported that the pilots found that the winglets made the aircraft easier to circle in thermals, probably due to an improvement in lateral stability (dihedral effect), and an end-plating effect on the ailerons.

In contrast, the Europa motor-glider, Fig. 14, features a winglet to extend the span with only a small amount of dihedral, perhaps to avoid problems landing in cross-winds.

Maughmer [22] also considers the design of winglets for sailplanes, as shown in Fig. 15. The many geometric parameters make this a challenging design task, which lends itself to optimisation provided the geometry can be readily parameterised. The Winglet is required to reduce the induced drag at low speed (high CL), and

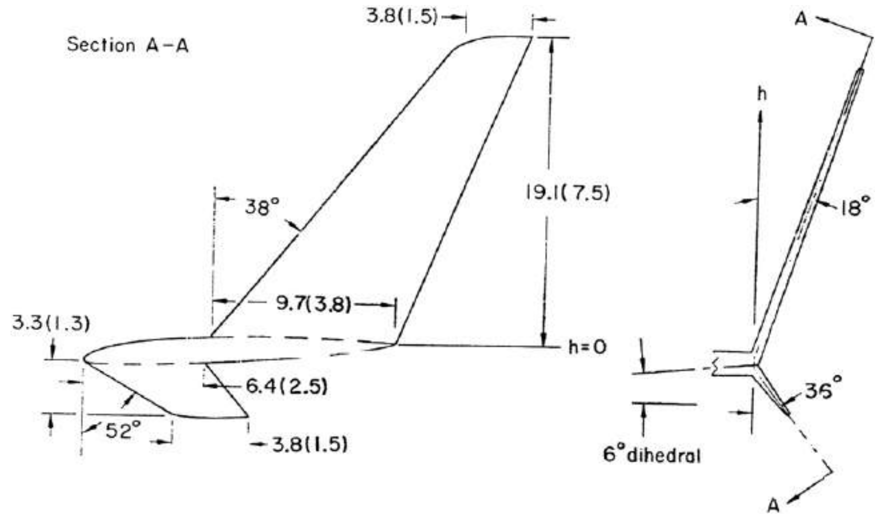

Fig. 12. Winglet details, from Flechner et al. [20].

Fig. 13. Comparison of winglet designs: Boeing 737-800 compared to Airbus A319 (left), Raked Winglet on B767-400 (centre) and Boeing 787 Dreamliner (right).

Fig. 14. Tapered 'flat' winglet on Europa (photographed at RAF Kemble, 2003).

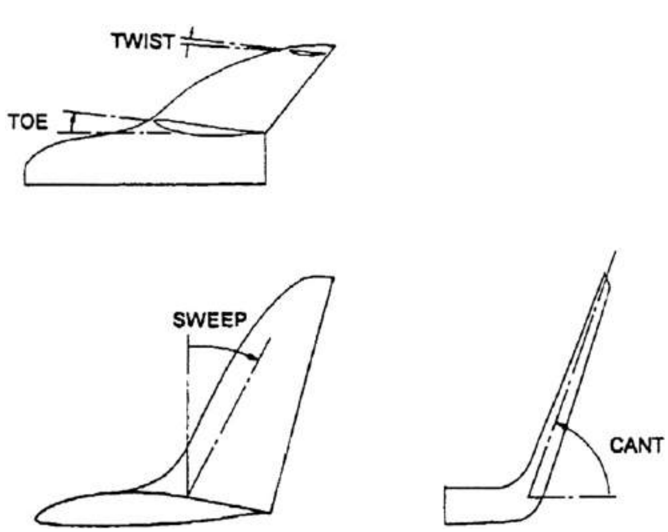

Fig. 15. Geometric quantities used to define sailplane winglets, from Maughmer [22]. Note the blending at the junction of the wing and winglet.

should not give rise to any significant increase in profile drag at high speed (low CL). Parameters such as toe-in and twist must be chosen to give the best compromise between these conflicting design requirements. Maughmer reports that, at the world championships in 1991, only about 20% of the competitors used winglets, but by 1998 virtually every sailplane had some form of winglet.

A subsequent paper by Maughmer et al. [23] considers the design of an aerofoil for a winglet on a high-performance sailplane. This is a difficult design problem because the airfoil must operate over a wide range of angle of attack at relatively low Reynolds numbers, and the design of the aerofoil is intrinsically linked to the design of the winglet.

Hepperle [24] also considers the role of winglets for sailplanes and illustrates the 1976 Whitcomb (NASA) Winglets which have the form of an upper and lower winglet, and also quotes a VFW design from 1977 which has a larger aspect ratio lower vane. Hepperle remarks that by 1986, Rutan's Voyager had blended winglets.

Some of the questions regarding winglet design are considered in a paper by deMattos et al. [25], where a figure of between 3.5 and 6.5% drag reduction is quoted. The need for extensive wind tunnel testing and CFD analysis is emphasised, and the trend towards optimising the wingtip design is highlighted. Blended winglets are used on the Embraer 170 airliner and Mattos makes the point that the navigation light was placed on the lower surface to minimise interference drag. As mentioned above, Boeing employed a raked wingtip for the 767-400 airliner instead of Whitcomb-like winglets. Compared to the Boeing 737-800 the raked wingtip provided a greater drag reduction. Fairchild–Dornier selected the so-called Super-Shark winglet for the Envoy-7 business jet which more gradually curve upwards. In some cases an extended trailing edge fillet has been added, to fair the angular junction region.

Brady [26] describes the blended winglets used on the Boeing-737, Fig. 13. The new 777 and 7E7 airliner employs a refined tip design where the winglet has been integrated into the wing planform so that the tip is swept upwards, and has a considerable amount of sweep-back. The European Airbus series also employ a range of winglet designs, and the A340 uses a large lower upper winglet. Park [27] discusses rudders on winglets, but warns that the addition of a rudder may negate the benefit of the winglet.

The concept of displacing the tip vortex outwards or favourably modifying the flow over the tip is interesting, and at first sight appears compatible with the desire to enhance the performance of the helicopter rotor. However, experience has shown that it is advantageous to displace the tip vortex downwards in the wake to lower the induced power, and for a helicopter in forward flight, the large dihedral angle of a winglet, is not admissible due to the loads which would be generated in edgewise flight. On the other hand, a limited amount of anhedral is viable, since it may also counter pitching moments which arise from the use of sweep and offset. Anhedral has been used on the BERP main rotor blades of the Lynx and EH101, and also on the S-92. Downward pointing Winglets for helicopters were also tested by Muller, initially in hover, and later in forward flight (see following section).

At first sight, tip-sails would appear to be unacceptable for the helicopter. However, the idea of dividing and therefore diffusing the tip vortex to reduce blade-slap noise was investigated by Tangler [28] with his sub-wing. Later, the concept of splitting the tip vortex into two smaller, separate vortices led to the Westland Vane Tip which greatly reduced the blade–vortex interaction (BVI) noise, Brocklehurst and Pike [29] (see following Section).

A further reason for attempting to modify the tip vortex for fixed-wing aircraft is to overcome the landing separation problem at airports, and this topic has been much researched, but is not directly relevant to the topic of this research. Various techniques are available to diffuse the tip vortex, including the use of deployable tip spoilers and blowing.

Whilst perhaps not as efficient as splitting the tip vortex, diffusion of the tip vortex by blowing may be useful as a means of reducing BVI noise. An alternative use of blowing, or suction (or other flow control devices), would be to clean-up the flow at the tip and, if possible, displace the tip vortex outwards and therefore reduce the induced drag by increasing the effective radius.

An experimental study on the use of wing-tip blowing aimed at diffusing the tip vortex is reported by Tavella et al. [30]. Experiments on the adaptive control of the tip vortex have been carried out by Matthewson [31], and Margaris and Gursul [32], and a flow deflector slot has been tested by Lin et al. [33]. Vakili et al. [34] also presents hot film measurements and smoke flow visualisation of the impact of tip blowing on the characteristics of the tip vortex.

Understanding the formation and roll-up of the tip vortex, is an essential for accurate evaluation of tip aerodynamics, and measurements behind a wing tip may be used to supplement the full-scale hot wire rotor tip vortex measurements. Francis and Kennedy [35], reported their experimental investigation of the formation of a trailing vortex, using hot-wire anemometry and helium bubble flow visualisation. The paper contains velocity contours in the cross-flow plane of the wing tip deduced from hot-wire measurements. Also around this time vortices on delta wings were being studied, for example at Boeing by Kulfan [36], where again details of the vortex structure were being observed. The delta wing is of interest here because of similarities with the flow on the outer swept tip of blades such as the BERP, and those proposed by Spivey at Bell (see following Section).

The roll-up and structure of the tip vortex have a direct impact on both acoustics and performance, and is strongly influenced by the tip design. Devenport et al. [37] present a study of vortex development where the flow has been measured by hot wire anemometers. It is also possible to measure the circulation around a tip vortex. This was attempted by the writer during the Vane tip experiments using a five-hole yaw probe, but this approach has limitations when the vortex core is approached, Freestone [38]. A vane-type vorticity meter was used by Flowers and Collar [39] and Wigeland et al. [40], but a better method is to use a hot-wire traverse, Sampson [41]. A rapid scanning (rotating arm) hot-wire anemometer surveys were carried out by Corsiglia et al. [42]. Johari and Moreira [43] and Desabrais and Johari [44] present circulation measurements for a delta-wing using an acoustic ultra-sound technique.

With regard to low drag tip shapes, near-field measurements at the start of the roll-up where the vortical flow first detaches from the tip surfaces, are of vital importance. The details of the flow around three type of tip caps; square, rounded, and square with bevelled edges, were recorded by Thompson [45], Fig. 16. As with many visualisation studies, no pressure or force measurements were made, and in this case the Reynolds number was in the region of 20,000.

In order to separate out the drag component, and hence better understand the breakdown of the drag of modern transport aircraft, many researchers have resorted to a far-field drag-analysis technique to evaluate wing design for instance Li [46], and Hunt [47]. The topic of drag prediction, and the breakdown of the drag from CFD simulations, was discussed in a paper by van Dam [48]. In this paper he computed the flow around one of his characteristic, elliptic planform wings with a straight trailing edge using the TLNS3D solver for an inviscid subsonic flow with artificial viscosity. Van Dam also considered the effect of the tip cap shape characteristics (rounded, bevelled and curved-bevel) on a wing, concluding that the bevelled tip gave the highest Oswald wing efficiency factor. In another article, van Dam et al. [49] also computes the flow at higher subsonic Mach number over his

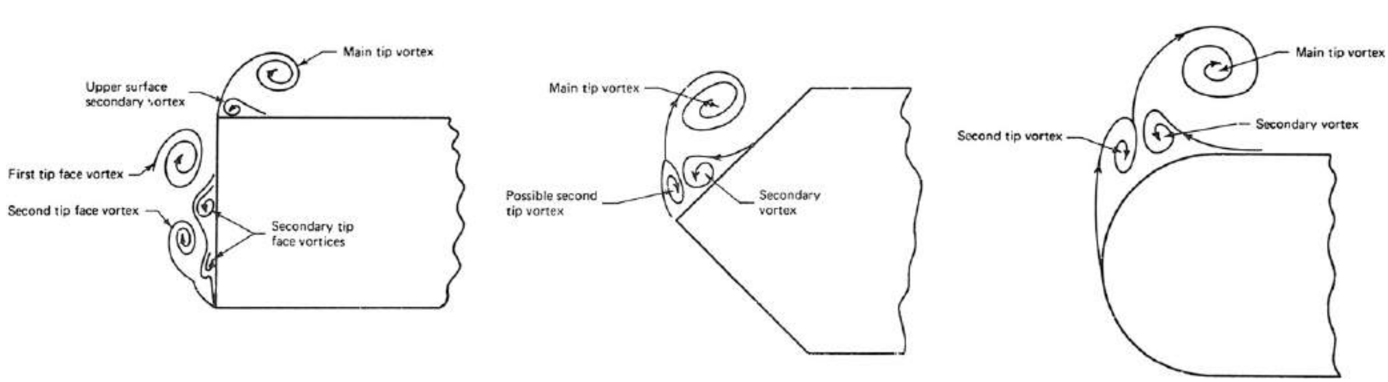

Fig. 16. Crossflow section through tip vortex system using dye technique (a) square tip, $\alpha = 12^\circ$, $x/c = 0.5$, (b) bevelled tip, $\alpha = 16^\circ$, $x/c = 0.4$, (c) rounded tip, $\alpha = 16^\circ$, $x/c = 0.6$, from Thompson [45].

crescent wing and the ONERA M6 wing, and compares the total drag from surface integration to that extracted from a wake analysis as induced and wave drag. Later, the topic of drag extraction is reviewed by van Dam [50]. Other researchers have also employed a downstream, or Trefftz plane analysis, e.g. Yates and Donaldson [51] extracted the induced drag and wave drag from CFD solutions of the flow-field. It is interesting to consider if a similar technique, such as taking a radial slice in hover, or a downstream plane in forward flight, could be similarly used to separate induced, profile and wave drag for rotorcraft CFD analysis.

Chao and van Dam [52] discuss airfoil drag composition to compare the surface integral and wake integration techniques in predicting the drag from computed solutions of the 2D RANS equations. Bushnell [53] also discusses drag break down in his review of Aircraft Drag Reduction.

Peace [54] describes the role of CFD in the design office (at ARA), and highlights drag prediction as one of the weak points of a CFD analysis. This view is confirmed by the writer's own experience, particularly with commercial codes such as Fluent, but as CFD methods become more developed, it is expected that the accuracy will improve. Studies at WHL have shown that HMB tends to over-predict the drag compared to the Drela 2D aerofoil code, MSES, but the predictions are much closer to test than Fluent, Brocklehurst [55]. For a 2D aerofoil, the problem is to accurately predict both the pressure drag and skin-friction drag components, and here a method is required which is able to distinguish between laminar and turbulent boundary layers, as this will affect both these components. In 3D, viscous drag is again important, and in the past it has been notoriously difficult to predict, but the induced drag arising from the vortex system of the lifting wing depends upon accuracy in modelling the overall flow field, and especially the trailed wake. For compressible flow cases, wave drag is also important and requires adequate resolution and accurate modelling of shock-boundary-layer interactions. For the helicopter, accurate prediction of overall thrust and torque is of paramount importance in assessing the performance of new rotor blade designs. It is therefore essential that both the profile drag (which may include wave drag) and induced power are well predicted. The latter involves preserving the circulation strength and the trajectory of vortices in the rotor wake.

Uygun and Tuncer [56] consider the problems of accurate drag prediction for a complete CN-235 cargo aircraft, using a FASTRAN Navier–Stokes solver.

Spall [57] examined the issue of excessive diffusion of wing tip vortex calculations using a second order accurate pressure-based finite volume method to solve the Euler equations, and concluded that with well-designed grid clustering the use of second-order methods were viable. However, higher order methods may be needed when viscous terms are present. Snyder and Spall [58] investigated the multiple vortex structures formed over a flat end-cap wing.

Since the drag prediction from CFD is crucial to the accuracy of any performance evaluation, it is important to be able to predict the transition location, and adjust the turbulence model of the solver accordingly to give the correct skin friction. Crouch et al. [59] has developed a transition prediction routine which can be invoked from within a 3D CFD code.

The EROS-UK (helicopter rotor simulation) project has led to a transition model being incorporated into the HMB code, such that in future static and dynamic simulations, the transition point can be estimated. The solver may then be adjusted accordingly to give a more realistic representation of the flow and a better calculation of the resulting skin-friction, Hill [60]. This implementation was initially for 2D aerofoils, but has since been developed for more general application by Zografakis, Barakos and Johnson [61].

Further studies of drag breakdown into viscous and wave drag components from a knowledge of the far-field have been carried out by Paparone and Tognaccini [62]. To determine the drag from the entropy variations in the flow, their approach was to allow for numerical and discretization error of the flow solver, such that accurate estimates of the drag components are available on moderately sized grids.

Methods of extracting the drag from numerical simulations have also been presented by Esquieu [63], again using Treffz-Plane methods.

The writer takes the view that the tip planform shape and the detail design of the tip cap will affect both the induced and profile drag components. The shape of the tip and the tip outer edge will also affect the structure of the tip vortex. Any edge separations that arise as incidence increases will present a source of disturbance which will be entrained into the vortex core. This idea is confirmed by the hot wire measurements of circulation and axial velocity within the vortex core which were carried out by Anderson and Lawton [64] on a NACA 0015 wing with a semi-span aspect ratio of 0.8. For small values of circulation, the axial velocity shows a velocity deficit, but as circulation increases, a progressive increase in axial velocity is observed. A linear relationship was found when the axial velocity exceeded 90% of the freestream value, and at high lift, the axial velocity near the centre of the vortex may exceed the freestream by as much as 70%. Anderson and Lawton also found that the axial velocity was sensitive to the shape of the end cap. Flat and rounded configurations were tested, and the axial velocities were found to be greater for the rounded cross-section tip cap, while the vortex core also had a smaller diameter. Unfortunately, no measurements were made of the drag of the wing, so it is not possible to link the reported vortex properties to the performance benefits of having a particular tip cap shape. Since the rounded tip cap produced a ‘cleaner’ vortex, it may be supposed that this would impose a lower drag.

Before going on to consider tip shapes specific to helicopters, it is perhaps useful to briefly summarise what has been learnt so far.

In this section of the literature review, the aerodynamic rationale behind several fixed-wing tip design concepts has been revealed. The work of Hoerner indicates that for good performance the tip should be designed so that the tip vortex forms as far outboard as possible, and the shape of the tip should encourage the tip vortex to roll-up cleanly with minimum energy loss. The cross-section preferred by Hoerner to achieve this was one where the lower surface blends up to meet the upper surface at the outer tip edge (based on the use of a cambered aerofoil section). Rounding of the leading edge corner is desirable for the best performance over a range of lift conditions, while excessive rounding of the tip near the trailing edge is to be avoided. Küchemann shows how to avoid isobars bunching up in the leading edge corner of the tip in compressible flow conditions, and this general principal should be effective even if the basic wing (or blade tip) is not highly swept, provided the effective Mach number is not too high so that a shock does not form inboard of the tip. This style of tip shape provides continuity of sweep and the sweep angle itself increases all the way to the tip. The tip also offers a nice clean outer edge for vortex formation. Küchemann employs a sharp trailing edge corner which places the roll-up as far outboard as possible, while maintaining sufficient sweep to suit transonic conditions. The basic Küchemann tip therefore addresses several of the problems encountered on helicopter blades, and in particular could be advantageously applied to the tip of highly loaded tail rotor blades, which are a particular focus of this research. In recent times, the addition of a winglet has been found to provide some fine tuning to further reduce shock-induced drag, and this non-planar spanwise extension has been shown to further reduce the induced drag for a minimal increase in wing bending loads. While highly non-planar features may be inappropriate for helicopter rotors, the thought occurs that there may be some potential to exploit mild non-planar design features, such as anhedral, to enhance the performance of highly loaded rotor blades in conditions near hover. It is also clear from the review that to achieve a optimum tip design for a given application, it is necessary to employ a method of analysis which includes all the physics of the flow so that the total drag can be properly evaluated. This requirement should be able to be fulfilled by the application of a good CFD method with adequate resolution to capture the flow features.

2.2. Review of helicopter rotor blade tip shapes

Helicopter blade design has always been a compromise between aerodynamic efficiency, structural and mass properties, and ease of construction. Since wood was a natural choice of material for early helicopter blades, the designer initially had some freedom in the choice of shape although it is clear that the ease of manufacture of long, slender blades soon became the overriding consideration. For example, Cierva's C8L autogyro had blades with an elliptic planform, while the later C30A, had parallel chord blades with elliptical tips. As the helicopter developed, twisted, tapered blades best suited to hovering gave way to simpler parallel chord low twist blades, which were almost universally adopted, as they were easier to manufacture and gave a better compromise between hover and forward flight.

While wood has good stiffness and fatigue properties, there are some drawbacks. One of the main problems was water ingress and the tendency for the ply to de-laminate or warp, not to mention the difficulty of maintaining aerofoil tolerances. Manufacture was also highly labour intensive, but the product was versatile, and had the potential been seen, the designer could have created more or less any tip shape he had desired.

However, through the 1950 and 1960s the use of wood in blade construction gave way to extruded aluminium spars and trailing edge skins. When the writer joined Westland Helicopters in 1973, the Sea King and Wessex were in production with this type of construction, with the trailing edge comprising 'pockets' of alloy skin and Nomex honey-comb. The early Lynx blades had a titanium spar with glass-fibre skins. The tips of these blades (and there are many other examples from around the world) had tip caps of the classical hemispherical shape. That is to say, the end of the blade was closed with a surface, usually formed from aluminium, which was based on the aerofoil volume of revolution, Fig. 17. In some cases, this shape was stretched in the spanwise direction giving an almost elliptic tip shape with some degree of thickness taper to the aerofoil. The symmetrical shape of the universally used NACA 0012 aerofoil lends itself to the creation of this type of tip. The tail rotor blades of the Wessex (S-58), Sea King (S-61) and early Lynx all followed similar styles of constant chord blades with aerofoil-of-revolution tip caps.

Later, during the 1970s and early 1980s composite materials gradually replaced the metal construction and offered an immediate performance improvement and much improved fatigue life.

At Westland Helicopters in the UK, the composite technology was embraced in several stages. First, a tail rotor blade was built for the Sea King, Cook [65]. For convenience of manufacture, the tip was simply cut square, and fitted with a flat metal tip cover. This blade was later produced with a cambered aerofoil, as reported by Byham [66], and has been used on both Sea King and Lynx, cropped to the appropriate length, and the tip is here illustrated in Fig. 18. The next step, as part of the British Experimental Rotor Programme (BERP), was to build a replacement main rotor blade for the Sea King. These blades had similar dynamic properties to the blades they replaced, but had superior aerodynamics, not because of shape (since the NACA0012 aerofoil section and parallel chord was retained), but simply because the aerofoil contour was smooth and could now be manufactured within a finer tolerance. Somewhat disappointingly, the tip of the composite Sea King blade was also cut off square, and has a metal tip cover incorporating anti-static devices which contribute to profile power and disturb the tip vortex.

Elsewhere the industry was also looking for means of improving blade design to give enhanced performance and reducing noise and vibration, and parameters such as sweep, taper, and aerofoil section were being researched to take advantage of the freedom offered by composite construction.

The growing interest in dealing with the high tip Mach numbers encountered in cruising flight was discussed in a paper by Spivey [67] on 'Blade Tip Aerodynamics—Profile and Planform Effects'. This was followed 2 years later by another paper reporting work at Bell Helicopters, by Spivey and Morehouse [68], entitled 'New Insights into the Design of Swept Tip Rotor Blades'. The first of these papers describes the need for offsetting the swept tip panel forwards to maintain the aerodynamic centre near the blade feathering axis, Fig. 19, and also suggests a highly swept outer edge, while the second paper discusses tests on a single-swept tip and a triple swept tip, Fig. 20. The latter employs sweep forward and cranked aft-swept leading edge, with a small amount of trailing edge sweep. Although these tip shapes were not put into production at Bell, this work sowed the seeds for future development of swept tip blades.

The design emphasis in the US has mainly been on hover rather than forward flight performance, and this may have been one reason why the Bell tip shape was not adopted. Another reason may have been poor acoustics due to outboard location of the delta shape, and the high tipspeed of the UH-1.

The early 1970s saw development on (mainly) prescribed-wake lifting-line rotor models, and experimental work to measure performance and determine the wake structure. In the UK, a full-scale test facility was used by Cook [69], to carryout hot-wire measurements of tip vortices. This paper became acknowledged as a major source of information on tip vortex structure and circulation strength, despite the difficulties involved in making

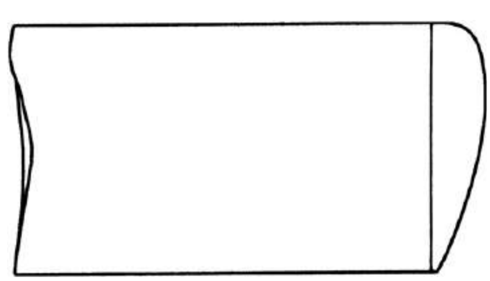

Fig. 17. Illustration of Sikorsky/Westland classical hemispherical tip cap used on main and tail rotor of S-58 Wessex, S-61 Sea King, and Early WG-13 Lynx metal-spar blades.

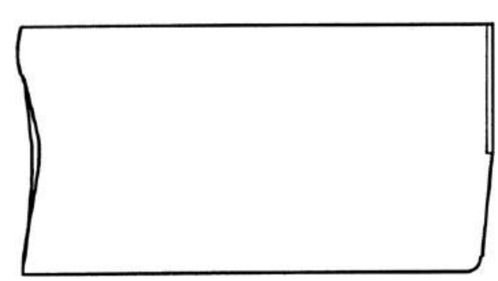

Fig. 18. Sketch of tip shape adopted for the Westland composite tail rotor blades for Sea King, W-30 and Lynx.

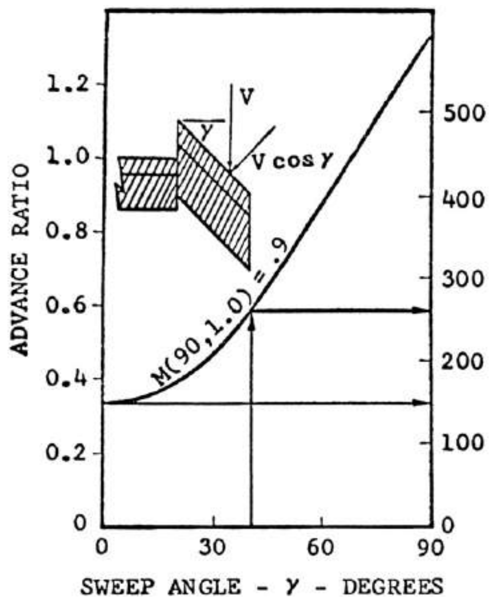

Fig. 19. Method of incorporating sweep to delay compressibility using leading edge sweep, from Spivey [67].

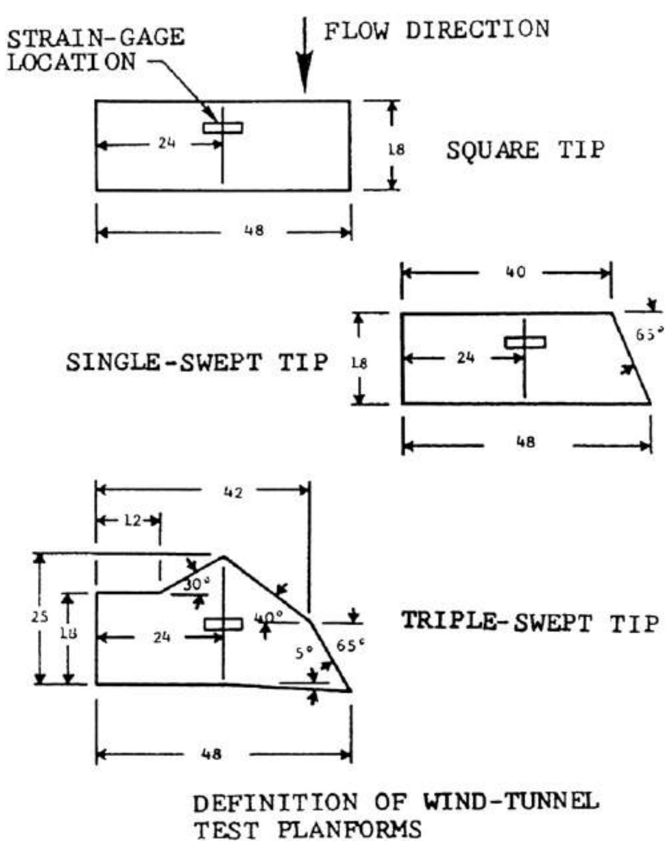

Fig. 20. Design of swept tip rotor blades, Spivey [68].

measurements in a coastal environment. The test rig, which was located at Weston-super-Mare, was later used in the early development of the BERP blade.

The design freedoms offered by composite construction led to the unique shape of the BERP tip employed on the Lynx which later gained the World Speed Record in 1986, see Perry [70]. Later, this same type of blade tip planform, Fig. 21, was employed on the EH101 because of its forward flight lift capability which allowed it to meet the constraints of operating a large helicopter from small ships. The main features that the BERP tip introduced were a large amount of sweep, and consequent use of notch offset, together with cambered aerofoils and the concept of an 'unstallable' tip. The BERP tip provides an excellent example of the way manufacturers were embracing the potential for new technology to expand the flight envelope of the helicopter.

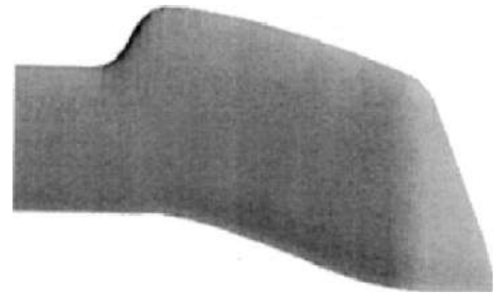

Fig. 21. The Westland BERP-III tip which resulted from the British experimental rotor programme.

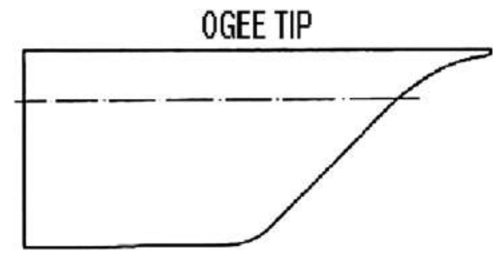

Fig. 22. The Ogee tip designed to reduce noise, Landgrebe [75].

At Westland the BERP tip shape was assessed as a fixed-wing model in the wind tunnel by Newman and Byham in 1975, and although these tests were preliminary, they did confirm the high incidence performance potential of the BERP tip and the tendency for separations to start inboard of the tip. Some oil flow was attempted, and some tests were also carried out with a leading edge slat fitted inboard of the BERP notch to suppress the inboard stall in an attempt to quantify the benefit of the tip.

During the 1970s, research in the USA was divided between improving hover efficiency, and the desire for low noise. Rotor models based on lifting-line or lifting-surface were developed, e.g. Kocurek and Tangler [71], and effort was put into wake measurements in order improve predictions of the tip loading in hover (due to the proximity of the tip vortex from the preceding blade). The lifting-line codes avoided the need to use Prandtl's tip loss factors which had been necessary in the earlier blade-element-momentum approach, e.g. Gessow and Myers [72], but they relied heavily on empirical tip corrections to account for compressibility and 3D shape effects in cruising flight. Landgrebe [73] reported measurements of the vortex wake in hover, and presented relationships which could be used in prescribed wake (hover) models. Kocurek and Tangler [71] made Schlieren measurements of the wake, and reviewed and generalised the vortex wake trajectory formulation. In this paper the authors put forward a lifting surface approach, capable of representing the effects of tip planform (although compressibility corrections would be required). Landgrebe and Egolf [74] also presented a forward flight wake analysis intended for incorporation into (lifting line) rotor performance codes.

The aim of reducing rotor noise led to several new tip shapes. The Ogee tip as described by Landgrebe and Bellinger [75], is shown here in Fig. 22. This tip was aimed at reducing the peak velocities of the tip vortex. While the reduction in area at the extreme tip may also have given some improvement in Figure of

Merit at low thrust, it may also have given rise to an early stall and an associated growth in profile power. Nevertheless, this type of tip was seriously considered as a low noise design, although it was never used on a production blade.

An alternative approach to reducing BVI noise was put forward by Tangler [28], who presented experiments on blades fitted with a sub-wing to generate a secondary vortex and "so diffuse the vortex prior to interaction with the following blade". Other configurations also put forward were a differential flap near the tip, and a split-tip where the trailing panel was bent down and the forward part of the tip was bent up, Fig. 23. However, in contrast to the Vane Tip developed by the writer (described later), the sub-wing comprised a small spanwise extension, which simply protrudes from the tip near the leading edge.

In this same time-frame, winglets were being developed for fixed wing aircraft by Whitcomb [19], and later Spillman and Allen [76] were active in promoting tip sails. These topics have already been covered in the first part of this literature review.

During the late 1970s there was a continuing need for detailed experiments alongside developing strip-theory analysis for rotor performance. Shivananda et al. [77] made detailed pressure measurements near the (rectangular) tip of a hovering rotor, and from flow visualisation noted the presence of a secondary tip vortex. Later pressure measurements were compared for a baseline rectangular tip and a (rounded) volume-of-revolution tip, Gray et al. [78].

Huber [79] discusses the development of swept tip rotor blades on the Bo105 Advanced Geometry Blade (AGB-III). Several aft and forward swept tips were studied, including some like those proposed earlier by Spivey. However, the AGB-IV tip is illustrated as a tapered tip with a curved, swept leading edge, and a slanted, highly swept extreme tip edge, Fig. 24. The paper by Huber is mainly concerned with blade stability and how the balance between dynamic and aerodynamic loading in the tip region would influence handling qualities. The AGB-IV tip has significant taper and this would probably help to minimise control loads and torsional deflections.

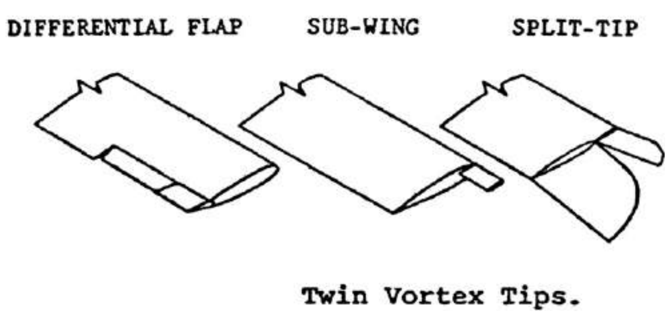

Fig. 23. Sub-wing and split tips, Tangler [28].

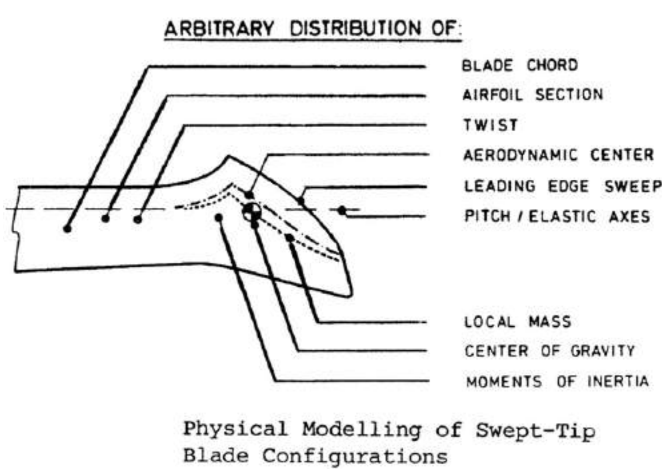

Fig. 24. The advanced geometry AGB-IV tip combined several features such as forward offset to facilitate sweep together with a tapered curved tip shape, Huber [79].

In the US, Maskew [80] applied an unsteady panel method to the tip design problem. In his paper entitled 'Influence of Rotor Tip Shape on Tip Vortex Shedding', he examined four tip shapes: rectangular, swept (sheared), straight tapered, and (once again) the Ogee tip. At Langley, Hoad [81] presented results from a wind tunnel test on rotor BVI noise on a similar set of tip shapes, which also included the sub-wing and end-plate tips, together with a 60° swept-taper tip, as shown in Fig. 25. Summa [82] also applied a panel method to the case of a hovering rotor, thus improving the accuracy with which the 3D tip loading could be predicted. This approach is only valid for mildly compressible flow when compressibility corrections may be applied, and shocks are unlikely to be present. However, most dedicated rotor codes continued to use simpler and faster lifting-line methods, often relying on 2D windtunnel data for aerofoil characteristics.

However, as early as 1980, Tauber and Hicks [83] applied a computerised full-potential method to the problem of improving advancing blade aerodynamics. They applied this method to aerofoil refinements on a blade with a straight trailing edge and 30° of leading edge sweep. The analysis was also tested for a tapered Alouette tail rotor blade, where the 'low aspect ratio' was shown to reduce shock strength through tip relief. Tip relief is an important factor in tail rotor tip design and will be referred to again.

An empirical allowance for the relief of compressibility effects has been included in many traditional (lifting-line) rotor performance codes, e.g. in the WHL R314 code, by Beddoes (1976) at Westland. Tip relief was also analysed by Grant for blades at advancing blade conditions of transonic speeds and zero-lift using TSP methods, Grant [84], and this work was later developed by the same author to include arbitrary tip shapes in 1979 [85].

In the USA model rotor tests were being undertaken to support the development of rotor models, and Caradonna and Tung [86,87], carried out their well known model rotor experiments on rectangular blades in hover and edgewise flight.

In search of improved hover performance, Bingham [88] considered blades with varying amounts of taper, twist, and RC-series aerofoils which are compared to the rectangular, NACA0012 blade of the UH-1 helicopter. As expected, the hover Figure of Merit improves with increasing taper, and with inboard location of the initiation of the taper. However, it appears that twist (which is usually taken to be a powerful factor in enhancing hover performance) is less effective when the maximum chord of the blades is located well inboard such that the blades are tapered over most of their length. Bingham recognises that it would be necessary to maintain a constant thrust-weighted solidity[1] to maintain the retreating blade boundary in forward flight.

A quarter scale model of the UH-1, with a standard rotor and an advanced, tapered rotor was tested by Berry [90], Fig. 26. The Mach scaled model demonstrated a full-scale equivalent 320 kg (700lb) increase in hover thrust for a given power, despite a slight increase in the fuselage download (due to the increased inboard loading and downwash). The advanced blade also delivered a power reduction in forward flight. However, the advancing and retreating blade limitations of the tapered rotor blade were not fully explored. It is logical that a tapered blade would have a lower profile power in attached flow, since profile losses vary as

[1] The concept of thrust-weighted solidity is often used in the US to compare the lifting capability of different blade planforms. However, while this concept may be useful in project studies it is considered too simplistic to be applied to complex tip planforms, such as the BERP blade, Perry [89].

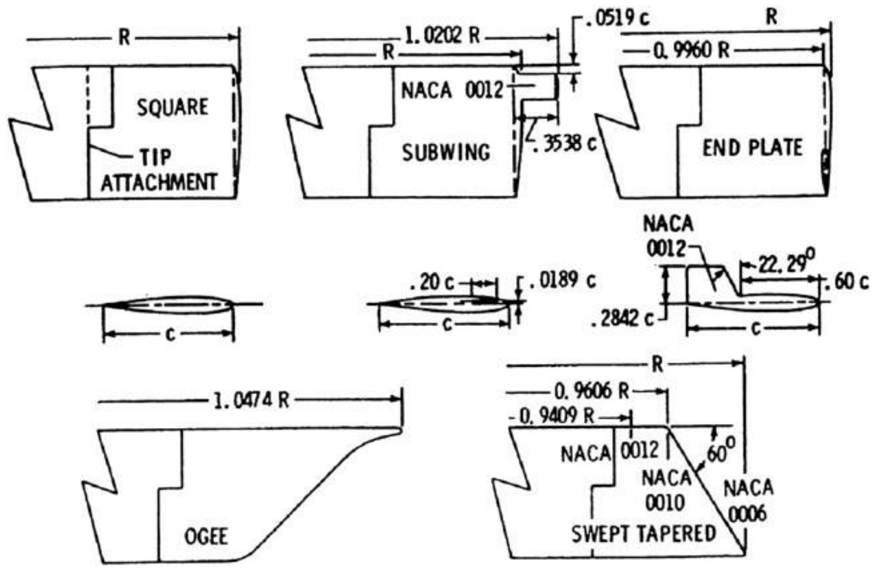

Fig. 25. Tips used in BVI noise tests, Hoad [81].

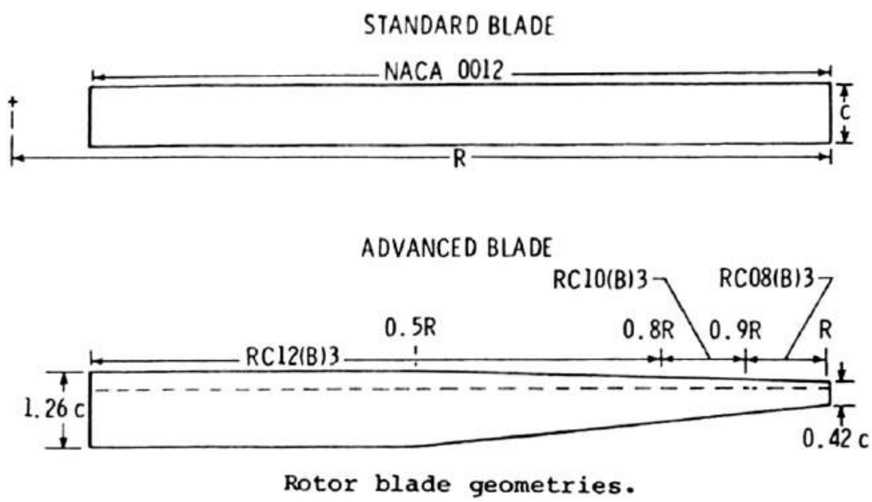

Fig. 26. Advanced tapered tip blade, Berry [90].

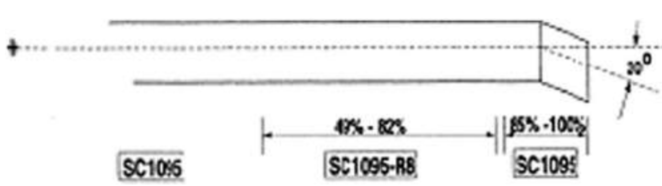

Fig. 27. Swept tip blade, Alansky [91].

radius cubed, provided the loading and tip Mach number is not too high (in hover a main rotor does not usually operate near maximum thrust). However, it is noted that the tapered blade has a narrow tip chord and no sweep. It would therefore be expected to be prone to advancing and retreating blade limitations.

Also in the USA, the UH-60 Black Hawk, and Sea Hawk blades, as described by Alansky et al. [91] featured a 20° sheared-swept tip outboard of about 92% R, Fig. 27. While this tip introduced much needed sweep to suppress shock development on the advancing blade, aeroelastic couplings were also introduced. The tip was not tapered, possibly to avoid any premature flow separation on the retreating blade (as observed in wind tunnel tests on a swept-tapered tip tested in the Westland wind tunnel). The Black-Hawk blade employs the SC1095 aerofoil section. During the late 1980s, a scale model rotor was tested by Lorber [92] and this data has since been used by many researchers (e.g. Strawn 1999, see later) to compare with CFD hover simulations.

While there may be some benefits in designing for a favourable aeroelastic response, simple application of an aft-swept tip to a rotor blade could lead to large one-per-rev pitching moments, and possibly a reduction in control gradients in forward flight. The approach taken in the UK during the development of the BERP blade was to align the aerodynamic centre of the tip on the quarter-chord feathering axis of the blade, and this leads to a leading edge 'notch' which helps to suppress shock development on the advancing blade, and also contributes significantly to the high angle of attack performance. The BERP-III blade design also integrates the properties of the tip with the use of a high-lift aerofoil just inboard of the tip. The aerofoils were designed by Wilby [93,94], and the cambered RAE9645 aerofoil is used as the main high-lift aerofoil, together with the thinner RAE934 in the tip region, a positive pitching moment aerofoil in the form of RAE9651 is used inboard to achieve moment balance, Perry [70].

In Europe, in the early 1980s, Aerospatiale developed the SA365N Dauphin-2 Helicopter, Roesch [95], Fig. 28, and compares the hover Figure of Merit for the old NACA0012 rotor with the new SA365N prototype rotor that replaced it. The latter used an increase in twist from 8° to 10°, new OA2-series aerofoils (OA212 at the root, OA209 outboard, and OA207 near the tip). The new blade featured a tip cap, which had the leading edge corner cut off at 45°, and the trailing edge clipped at an angle of about 15°. The tip cap also increased the diameter from 11.68 m to 11.93 m. The trailing edge tab was also used to extend the chord, outboard of the trim tabs to enhance the lifting capability of this blade.

A similar, 45° leading edge corner tip cap, is found on the tail rotor of the EH101. This type of tip tends to relieve the clustering of isobars in the forward leading edge corner, and would therefore be expected to reduce the tendency for a profile power growth due to shock induced separation at high lift and moderate tip Mach number (except that a weak shock may form at the outer corner, as later identified in CFD simulations by the writer). As mentioned earlier, the low aspect ratio of the tail rotor blades gives rise to a significant amount of tip relief. This avoids the need for sweep, particularly if the aerofoil in the tip region is not too thick and low tipspeed is used. On the EH101, the tail rotor tipspeed is lower than that of the main rotor for noise reasons.

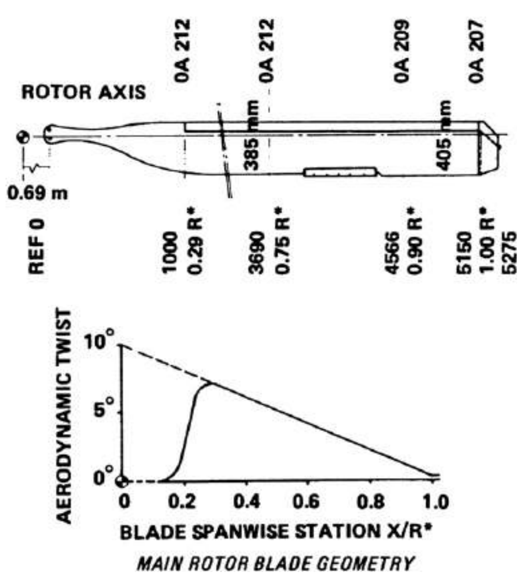

Fig. 28. Blade with 10° twist and swept-tapered tip, Roesch [95].

Hence there is a greater need for sweep on the higher aspect ratio main rotor blades.

A similar tip shape to the swept constant chord tip of the UH60 was employed on the AH-64 Apache, as reported by Amer and Prouty [96]. The aerofoil on this blade is a 9.5% HH02 airfoil, and uses a long reflexed tab to counter the slight nose droop, which would otherwise give a nose-down pitching moment. During the early stages of development the Apache suffered from interactional aerodynamic problems and a lack of tail rotor authority which led to many fin and tail re-designs [97]. The tail rotor is a double teetering scissors-type rotor with unequal azimuth spacing (of 60° and 120°). The tail rotor blades are typically of constant chord with a classical hemispherical, or volume of revolution, tip cap.

Mantay and Yeager [98] considered parametric tip effects for conformable rotor applications. In this work, the focus was on the aft location of the aerodynamic centre which results from a simple swept (sheared) back tip (Black Hawk and Apache). Tip shapes tested include rectangular, tapered, swept, swept-tapered, and for the first time tips with anhedral were tested in the form of rectangular anhedral, swept anhedral, and swept-tapered anhedral, Fig. 29.

In the UK, there were initial concerns that the potential hover benefit of anhedral might not be able to be realised due to the pitching moments in forward flight. However, it was soon realised that blade tip anhedral produces a pitching moment variation around the azimuth that compensates for the effects of sweep and forward (notch) offset, and so could be used to reduce once-per-rev control loads on advanced tip shapes. The author carried out tests in the Westland wind tunnel in 1985 on a model rotor with various tip shapes, including the BERP tip with 10° and 20° of anhedral angles. These tests were then followed by hover tests in 1986, which confirmed the expected beneficial effect of anhedral. It is now generally accepted that a tip with about 20° of anhedral will yield an increase of about 0.02 in the Figure of Merit, with no performance penalty in forward flight. However, it was later discovered through computational work that this benefit might not be maintained on main rotor blades with high aspect ratio.

In parallel with preliminary design studies for the BERP-III blade, which commenced in 1981, a swept tip was tested by RAE on the Puma, Fig. 30, as reported by Riley and Miller [99], following on from the collaborative work of Wilby and Phillipe [100]. The flight experiments were carried out with dissimilar tips, and showed that the new tip consumed less power due to the suppression of supercritical flow on the advancing blade. The flight measurements were compared with the earlier transonic small perturbation, TSP, analysis of Grant [85].

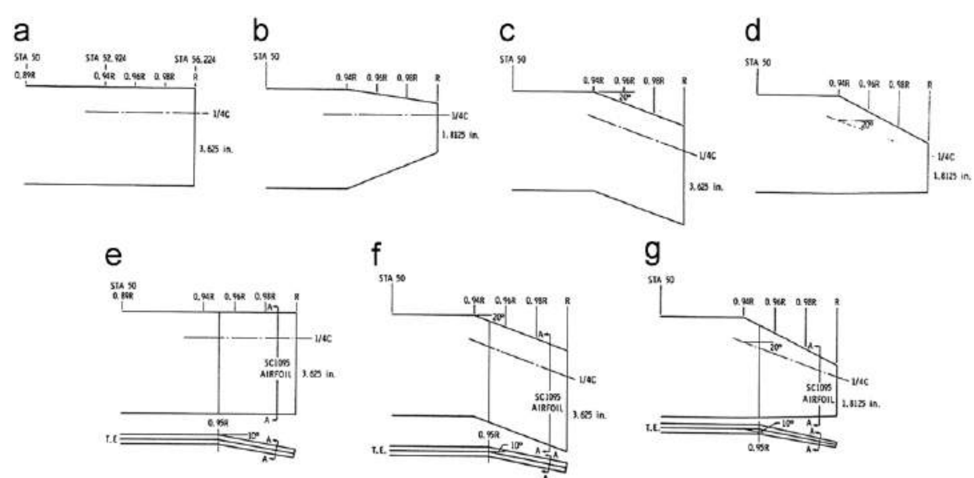

Fig. 29. Tests on a range of swept-tapered tips, Mantay and Yeager [98]. (a) Rectangular. (b) Tapered. (c) Swept. (d) Swept tapered. (e) Rectangular anhedral. (f) Swept anhedral. (g) Swept tapered anhedral.

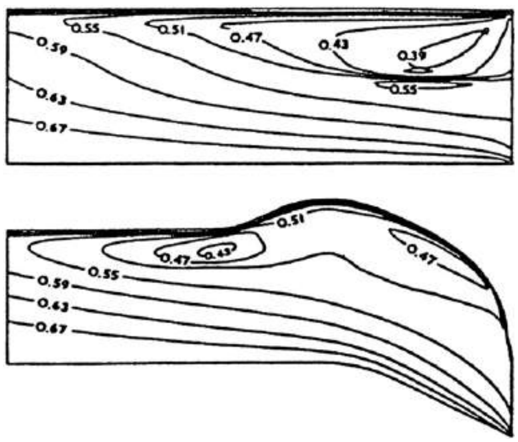

Fig. 30. Pressure contours on rectangular and swept tip showing reduced tendency for a shock to develop, Riley and Miller [99].

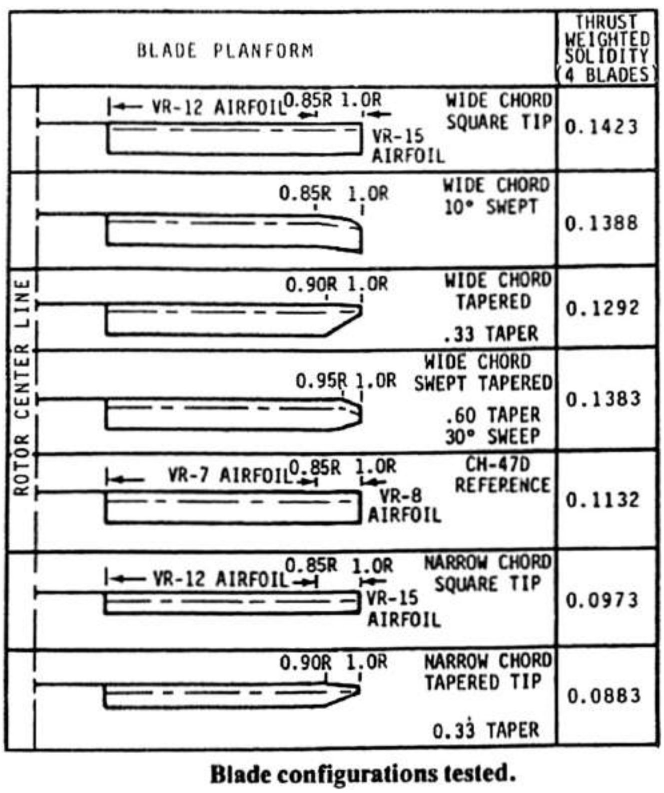

Fig. 31. Variety of tip shapes tested at Boeing vertol, McVeigh and McHugh [102].

Further wind tunnel tests together with rotor aerodynamic studies, and dynamics and composites design work, were carried out in the early 1980s. The BERP tip was first demonstrated on Lynx in 1985.

While forward flight performance was being sought in the UK, acoustic measurements on a full-scale rotor with four tip shapes (rectangular, tapered, swept, swept-tapered), tested in the NASA Ames 40 ft × 80 ft tunnel were reported by Marianne Mosher [101].

McVeigh of Boeing-Vertol [102] reports the effect of different tip shapes on hover Figure of Merit (FoM), and also includes a discussion of aerofoil performance, in addition to acoustics. McVeigh compares the performance of square, swept, swept-tapered and tapered blades, Fig. 31. It is interesting to note that although the tapered tip has the best hover FoM, this rapidly falls off at high disc loading, presumably due to early power divergence which arises as a consequence of the vortex-induced loading peak near the tip, combined with a narrow tip chord. If the tip chord is too small, power divergence occurs despite the fact that most helicopter main rotors are not particularly highly loaded in hover.

Further 3D transonic computer analysis is reported by Tauber [103] of NASA Ames, who compares experimental and computed results for a tapered blade with a swept (sheared) tip, and shows shock de-localisation for a rectangular and 30° swept-back tip. Here the sweep angle quoted is that of the leading edge. It is apparent from these computations of compressibility effects on the advancing blade at zero lift, that this amount of sweep, whilst it relieves the shock strength, is not really sufficient, and at least a 40° swept tip was required to reduce de-localisation. Due to pitching moment considerations, recourse was made to the 30° sweep with modified aerofoil sections, but the problem of de-localisation still persists, Fig. 32. One feature of the swept-tapered tip is that there is an effective loss of leading edge sweep near the tip leading edge (sharp) corner. Also, when the shock is well aft, as in the computed conditions, the effective sweep of the trailing edge is relatively low and with the tip edge simply cut square the effective sweep is reduced where it is most needed. The reluctance to employ higher sweep is probably a consequence of the desire to suppress any adverse aeroelastic effects arising from a rearward aerodynamic centre.

Apparently, several tip shapes were considered for the Sikorsky UH-60 Black Hawk and S-76, as described by Balch [104], Fig. 33. In this paper, the performance of the main rotor in proximity to the tail rotor is also considered. Again the emphasis is on achieving a good figure of Merit.

In Europe, Wagner [105] made comparative measurements of unsteady pressures on four oscillating wing tip models, of NACA 0012 aerofoil, having rectangular, swept, trapezoidal and Ogee tips, Fig. 34. The tests were at low speeds, so any compressibility effects were not included. The paper shows how the isobars bunch up in the forward corner of the tip, especially on the Ogee tip, which experiences extreme CL's. Measurements of the vortex roll-up were made using an ultrasonic measuring device. Wagner reports observing up to 2 vortex cores behind the Ogee tip.

In the mid 1980s techniques such as the wide-field shadowgraph were developed to study the rotor wake in hover, and Parthasarathy et al. [106] confirmed the earlier work of Landgrebe, and Kocurek and Tangler, already cited. These experiments supported the effort to obtain a better understanding of the

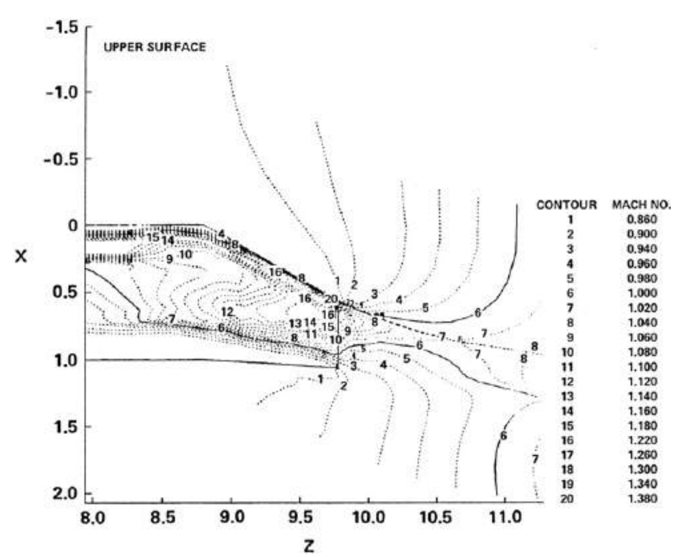

Fig. 32. Prediction of the Mach Number contours on swept-tapered tip showing de-localisation of shock outwards from the tip, Tauber [103].

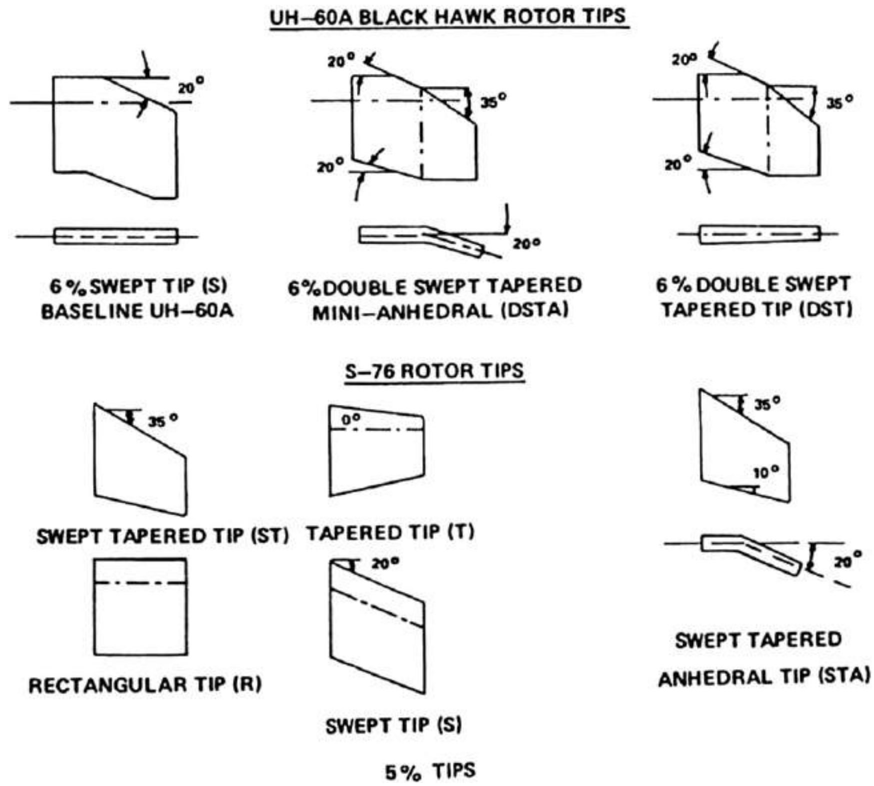

Fig. 33. Tip shapes tested by Balch [104].

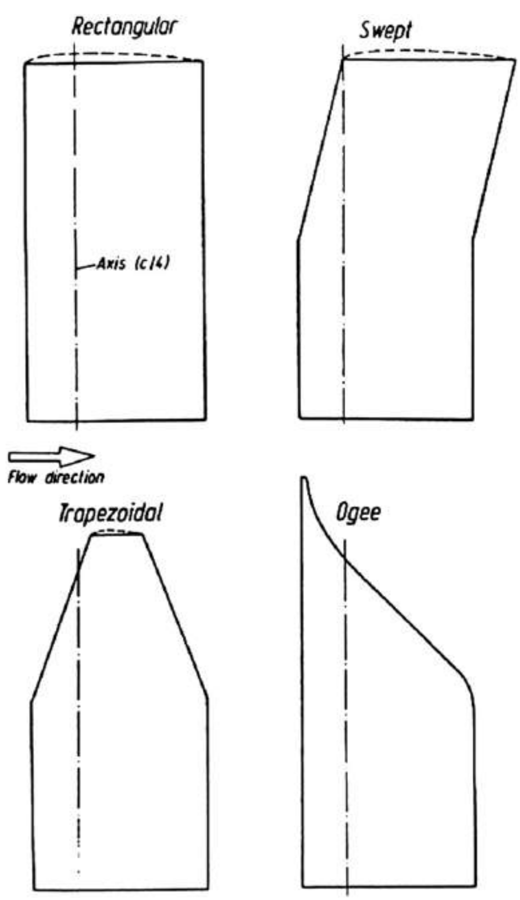

Fig. 34. The four tips used by Wagner on oscillating wing tip model [105].

wake and verify the prescribed wake and free wake methodologies, which were being developed at this time. Favier et al. [107] describe a lifting line vortex wake model for hover and axial climb, and later Quackenbush [108] describes the development of a free wake rotor model.

It is perhaps worth remarking that, most of the vortex wake visualisation and wake trajectory measurements, which were available to validate vortex wake models, were initially carried out on blades with rectangular tips. Only recently has there been interest in identifying the differences in vortex structure due to different tip shapes, as will be described later in this review.

Also in the mid 1980s a research effort was underway to design blades for the V22 tilt rotor, Felker et al. [109], and several tip shapes were considered for this application. These included a clipped-ellipse baseline tip, a swept-tapered tip, and a square tip, Fig. 35. Again the aim was to maximise the hover FoM, while noise was probably also a consideration due to the high tipspeed of tilt rotor aircraft.

Development flying of the BERP blade was carried out in the early 1980s on the Lynx. An extensive flight programme was undertaken to establish the loads on the new composite blade design and provide data for comparison with theoretical models. Vibration and loads were analysed by Hansford [110] to gain insight into the structural load characteristics of the new composite BERP blade compared to the standard metal blade. The BERP blade gave the Lynx good manoeuvre capability and the expanded flight envelope has enabled weight growth from 8500 lb to somewhere in the region of 15,000 lb for the latest variants.

The BERP blade enabled the Lynx to gain the World Speed Record, which still stands for this class of helicopter, and the blade design is described by Perry [70], Fig. 36. The speed attained was 400.87 km/h (216.3 kts or 249.1 mph), corresponding to a tip Mach number of 0.977, and the rotor reached an advance ratio of 0.5.

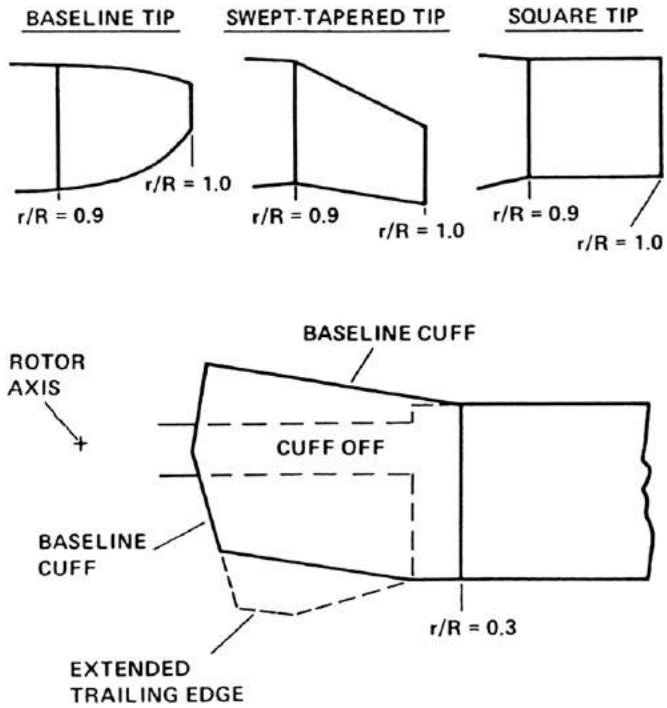

Fig. 35. Tip shapes considered for the advanced technology blade (ATB) of the V-22 Tilt-Rotor Aircraft, Felker et al. [109].

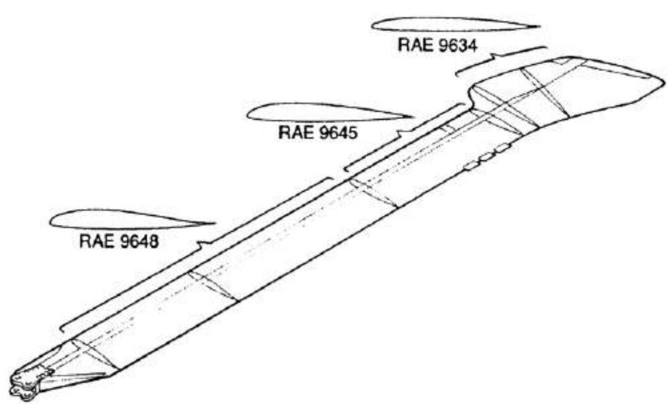

Fig. 36. Distributed aerofoil section on the british experimental rotor programme (B.E.R.P.) blade, Perry [70].

The various fight trials of the BERP blade also included pressure measurements on the Lynx composite main rotor blade (CMRB), which were reported by Isaacs and Harrison [111].

In contrast to the BERP activity to expand the forward flight envelope, Kelly and Wilson [112] describe a model blade of an 'Advanced Rotor' for the AH-64 Apache aimed at improved hover performance. The model blade had constant chord out to 80% radius, and then had a 5:1 taper, see Fig. 37. The test results showed that the tapered blade produced a 6.4% improvement in FoM, and had lower power in the forward flight tunnel tests. However, it is doubtful whether the retreating blade envelope would have been maintained.

A team from Boeing Vertol, of Cowan et al. [113] also tested a model-scale advanced rotor, both in the Boeing Vertol Wind Tunnel and in the DNW tunnel where acoustic measurements were obtained. In these tests the blades had VR12 and VR15 aerofoils, and were highly tapered (3:1) outboard of about 85%R, with a non-linear twist of 12.75°. The highly tapered tip was probably intended to give a good Figure of Merit in hover and

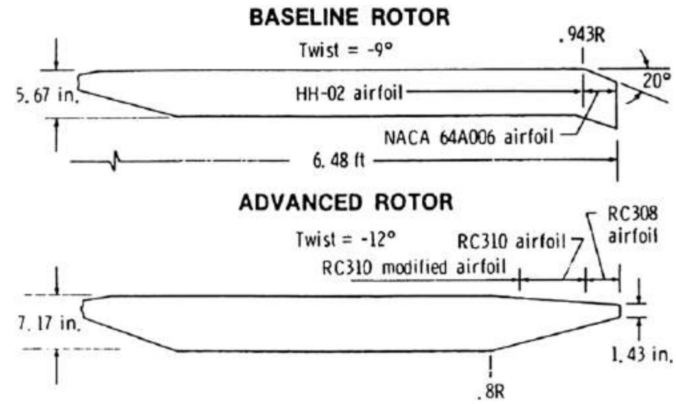

Fig. 37. The advanced rotor for the AH-64 Apache designed to improve figure of merit in hover, Hover et al. [112].

have a low acoustic signature. The tip planform has only a very small amount of sweep-back, and so might be expected to suffer compressibility problems at high tip Mach numbers, and perhaps premature tip-stall at high loading. However, within the flight envelope, the torsional loads would be expected to be low on a blade with this type of tip planform. Data from the above tests was compared to a Boeing Vertol rotor analysis (B65), NASA Transonic Flow Analysis for Rotors (TFAR), and an Army Finite Difference Rotor (FDR) code. The TFAR and FDR codes were also coupled with the B65 rotor model in an attempt to match the chordwise pressures at 80%R for azimuths in the first and second quadrants.

While more sweep-back is often desirable to relieve compressibility effects, it also has some disadvantages. On an aft-swept tip it is almost inevitable that the c.g. will move aft, and in some cases the tip aerofoil may be wholly behind the blade quarter-chord line. Aft movement of the c.g. can be minimised by adopting very thin, light-weight materials for the trailing edge skins in the tip region, although this may make the blade vulnerable to damage and could incur a cost penalty. The use of lightweight trailing edge skins also helps to reduce the torsional inertia of the tip. In contrast to a simple aft-swept tip, the forward notch offset of the BERP tip helps to the bring the c.g. forward, and also avoids the aerodynamic centre becoming too far aft.

An alternative is to consider forward swept tips. Such tips were tested in the Westland wind tunnel in 1987, but the general conclusion was that this type of tip shape had a tendency for premature flow separation due to the bunching of isobars in the junction region. A rearward protruding area distribution was used in an attempt to alleviate this problem, but tends to reduce the effectiveness of the forward sweep and leads to a tip with a large surface area which may adversely affect the hover performance. Some effectiveness of the forward sweep may also be lost at the outer end of the tip. Also, since the aerodynamic centre is ahead of the torsional axis (shear centre), the blade would be aerodynamically unstable, and aeroelastic stability would certainly be an issue, although the c.g. can be placed well forward on a swept forward tip. More recently, the writer reviewed the concept of a forward-swept tip in a further design study. The aim was to alleviate advancing blade compressibility effects, while ensuring the c.g. would be well forward, but the design was not taken further due to concerns over retreating blade performance.

Later in this review, the subject of swept forward tips is raised once again, when the potential for avoiding shock de-localisation is discussed by Baeder and supported by CFD analysis.

The topic of noise reduction is an important consideration in rotor design. The main driver is the tipspeed, and to a lesser extent blade loading. For this reason the EH101 was designed with a low main rotor tipspeed, and an even lower tail rotor tipspeed. Also the highly swept BERP tip has a thin aerofoil and a low tip volume. However, helicopters such as Lynx and Chinook have higher tipspeed and BVI noise is often a concern.

In the late 1980s, a new model rotor rig was developed at WHL with the intention of carrying out acoustic tests on a range of tip shapes. In a theoretical study, Beddoes (1986) found that splitting the tip vortex was more effective in reducing BVI noise than attempting to enlarge the core size. This led the first-author to design the Vane Tip, Fig. 38 which was then tested as a fixed-wing model in the WHL wind tunnel in 1987. These tests confirmed that the Vane Tip configuration generated twin vortices which remained distinct over a wide range of incidence, as shown by smoke visualisation in the working and diffuser sections of the wind tunnel. Following commissioning tests in hover, and shake-down tests in the WHL tunnel, the Vane Tip was tested on a model rotor in the acoustically lined 24 ft wind tunnel at Farnborough. A 5.6 dB reduction in BVI noise was demonstrated, as reported by Brocklehurst and Pike [29]. The Vane Tip has been included here as an example of the developments in rotor research which were taking place in this era. In contrast to Tangler's sub-wing, previously cited, which aimed to diffuse the trailing vortex, the Vane Tip produced two equal vortices that remained discrete for many chord lengths as verified by the windtunnel tests. The Vane Tip was subsequently modelled using the VSAERO panel method in the early 1990s, Fig. 39.

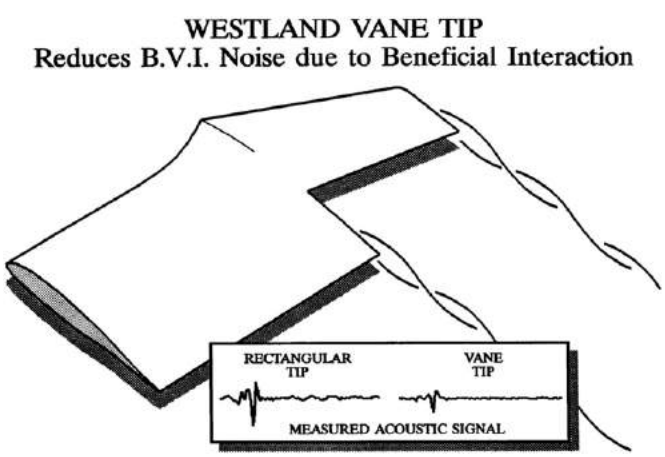

Fig. 38. The Westland Vane Tip as tested on a Mach-scale model rotor blade by Brocklehurst and Pike [29].

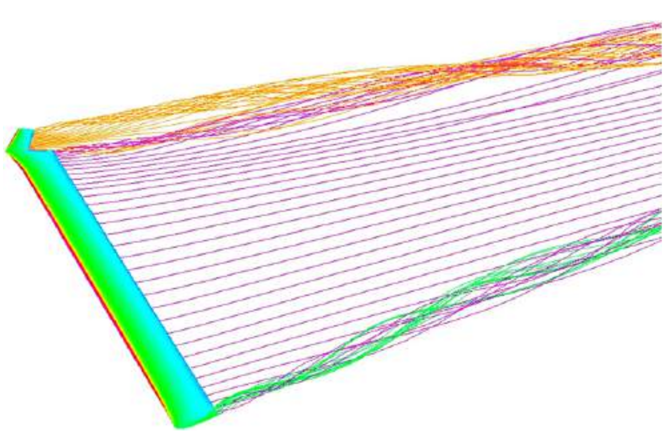

Fig. 39. Analysis of the Westland Vane Tip using VSAERO, Brocklehurst and Pike [29].

In the late 1980s, interest in the effect of sweep on BVI was highlighted in a paper by Hardin and Lamkin [114] where a cranked blade is considered to 'reduce interaction length' and thus minimise the time during which the parallel blade/vortex interaction is taking place. The cranked rotor is not without dynamic problems, but was further tested in the mid 1990s, and the concept of a forward swept tip has since been examined by Baeder (see later). The interaction length of the BVI event may work against an aft swept tip, since at some advancing blade azimuths the vortex may be aligned with the leading edge of the swept tip.

Towards the end of the 1980s, anhedral was introduced on the BERP blade to alleviate once-per-rev control loads, and back-to-back flight tests were carried out on EH101. As found in model rotor tests carried out by the first-author, the effect of sweep and notch offset were balanced by anhedral in forward flight, and the benefit to hover performance was also confirmed.

Although anhedral was used to advantage on the BERP blade, the mechanism by which this reduces the hover power was not completely understood at the time, although it was clear that the position of the tip vortex was initially displaced downwards in the wake. Measurements by the writer at Westland in the 1983 on a model of the BERP blade showed that the tip vortex tends to snake back towards its usual position near the first blade passage. This snaking of the tip vortex trajectory has also been noted in the computational results presented later in this thesis for a tail rotor blade with a 20° anhedral tip, where it was found that the anhedral induced an inboard shift of the blade loading in the tip region.

The non-planar properties of the BERP swept-back anhedral blade tip may also come into play, as postulated by van Dam for swept-tip wings, and may become progressively more effective as incidence increases (as discussed in the first part of this literature review). Subsequent computational work at Westland has suggested that while the BERP blade benefits significantly from anhedral in hover, the same may not be true for high aspect ratio (R/c) main rotor blades with a more conventional tip shape.

Other researchers have also been intrigued by the idea of gaining performance through the use of an anhedral or a small winglet. Muller [115–117] has investigated downward pointing winglets for rotorcraft, initially in hover, but also in forward flight, Fig. 40. Muller mounted the downward pointing winglet on an otherwise rectangular tip, and found the winglet height limited by yawed flow considerations. As with anhedral, the hover efficiency was improved by a small amount.

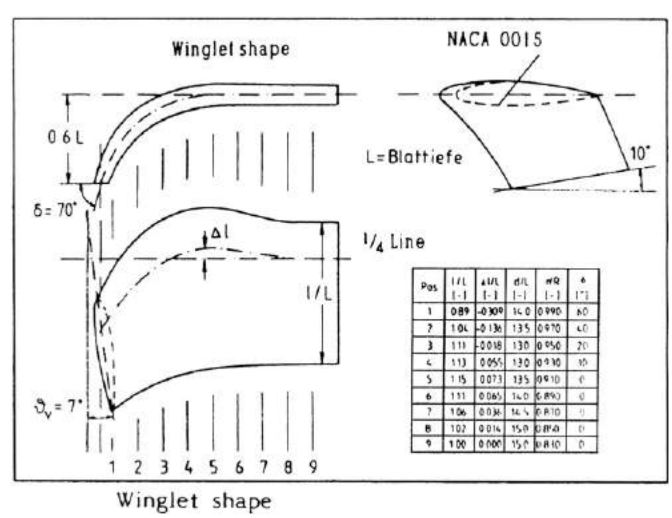

Fig. 40. Downward pointing winglets by Muller [116].

Anhedral has also been used to improve the static thrust on propellers, although little information has been found in the scientific literature. A practical example is shown in Fig. 41, as manufactured by the small American company, Prince Aircraft Inc. However, the impact of anhedral on a propeller in cruise is likely to be minimal (unless other small benefits accrue from the tip design) since the vortices quickly pass downstream. Anhedral has also been suggested for use on Tilt-Rotor Blades by Patt and Karem (2011) as revealed in their US Patent [118], again as a means of improving the hover Figure of Merit. Loading distributions are shown where the peak loading is reduced due to the trailing vortices being further away from the following blade.

Fig. 41. Propeller blade with anhedral to improve efficiency and enhance the static thrust, as Manufactured by Prince Aircraft Inc.

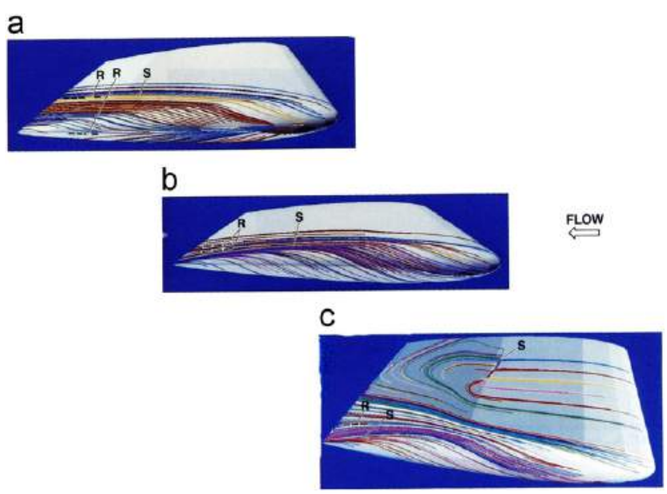

Fig. 42. Surface particle flow traces in the tip region of rotating and fixed blades, $M_{tip} = 0.877$, Re$=3.93 \times 10^6$, Srinivasan and McCroskey [122]. (a) Rotating blade. (b) Fixed blade—$M_\infty(y)$. (c) Fixed blade—$\theta(y)$.

In the 1987 Nikolsky Lecture, Drees [119] compares schematics of the roll-up from a square tip, a curved swept tip and a BERP tip, and ponders the question of placing the vortex roll-up further outboard to maximise the apparent rotor radius.

During the late 1980s, computer resources had reached the point where numerical solutions to the Euler and Navier–Stokes equations were now possible for 3D configurations, at least within research organisations, if not in industry. Srinivasan et al. [120] present a numerical simulation of tip vortices from wings in subsonic and supersonic flow. In this paper Srinivasan modelled a rectangular wing with a square-cut tip (H-H grid), a so-called hemispherical or rounded tip (O-O grid), and a bevelled tip (H-H grid), together with a swept-tapered wing, the ONERA wing, and a modified ONERA Wing of AR 5. This paper is concerned with validation and demonstration of the potential of the CFD method, rather than making any pronouncements on the performance of the tips themselves, and shows that CFD provides a powerful tool for analysing and understanding the aerodynamic characteristics of wings and rotor blades. In a second paper, Srinivasan and McCroskey [121] extended the method to include a Navier–Stokes calculation for a hovering rotor. Results for a rotating blade are compared to the data of Caradonna and Tung [87]. The surface particle traces and pressure contours from Srinivasan and McCroskey [122] are re-produced in Fig. 42, together with some examples of the clustering of the pressure contours in the tip region of the blade, Fig. 43. This work was the first application of CFD to a hovering helicopter rotor.

This ground breaking computational effort lead to the need to compare with high quality test data, and also a desire to explore and compare different rotor tip planforms to test and demonstrate the newly available CFD methods.

Through a collaborative US–UK agreement, a full-scale model of the Lynx-BERP tip was tested as a fixed-wing in the Westland wind tunnel by the first-author in 1989 and the computational effort was reported by Duque [123,124], Fig. 44. Further comparisons, including some sideslip cases were reported by Brocklehurst and Duque [125], Fig. 45 and some extreme Mach number/incidence cases, Fig. 46. At that time CFD methods were only available at large

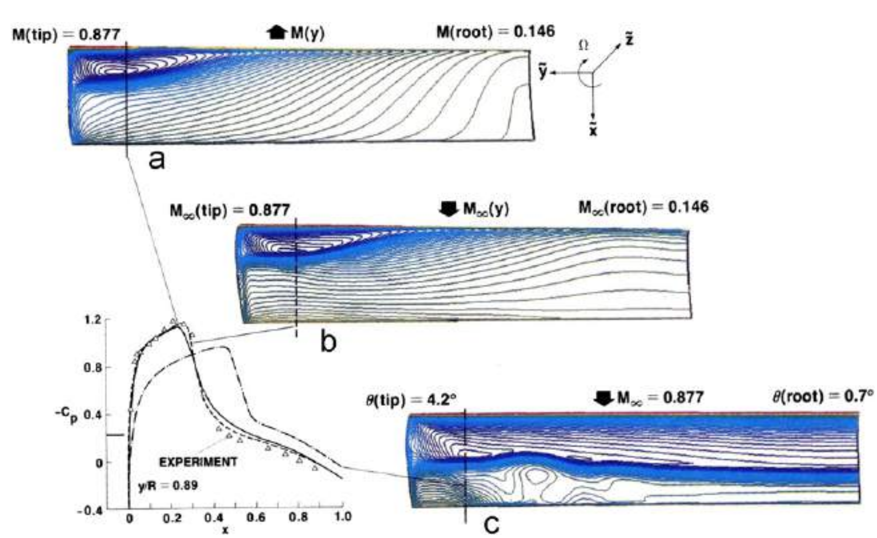

Fig. 43. Surface particle flow traces in the tip region of rotating and fixed blades, $M_{tip} = 0.877$, Re$=3.93 \times 10^6$, Srinivasan and McCroskey [122]. (a) Rotating blade. (b) Fixed blade—variable Mach number. (c) Fixed blade—variable pitch (twisted).

research establishments, and the LANS3D code was run by Duque on the Cray YMP at NASA Ames. Different tip shapes, including the Puma tip, were also compared by Duque [126], Fig. 47.

In addition to simulating the separation on the BERP blade at very high incidences, Beddoes [127], Fig. 48, also modelled the stall pattern on a swept-tapered tip, Fig. 49, which had been tested in the WHL wind tunnel.

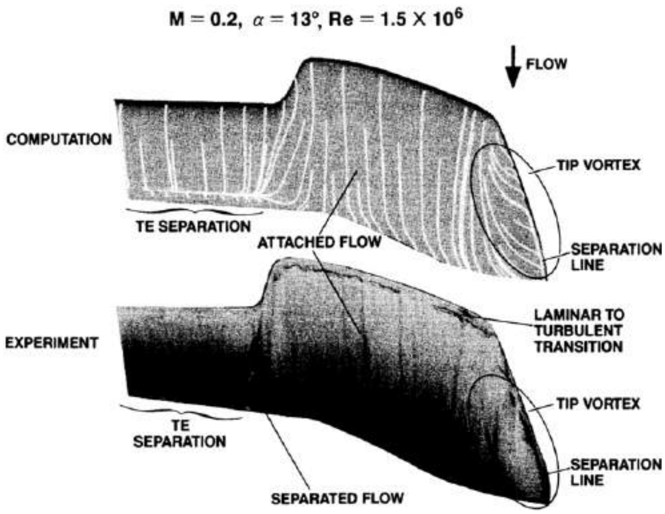

Fig. 44. Surface flow validation, Duque [124].

The Lynx-BERP database has since been used to provide support for the development of rotor codes, such as ACROT, Beddoes [128], and CFD simulations, such as those presented later in this thesis. At the time the computational effort was similar to that required for the test, whereas simulations are nowadays much cheaper than parametric tests. However, the wind tunnel is still a valuable facility, and is has an important role in providing data for confirmation of a new design and for validation of CFD methods.

Recently, the HMB code has been used to simulate the BERP blade, and considered as a means of extending reduced-order rotor models, Beedy (see later). Comparisons were made with the wind tunnel pressure measurement tests described above, and some of the simulations also included unsteady conditions, Brocklehurst et al. [129].

The agreement between the CFD of Duque and the pressure measurements on the BERP wing was particularly good at incidences below stall, but failed to provide a correct simulation when the inboard part of the wing was stalled. Nevertheless, the potential of the RANS method for predicting the performance of future rotor tip designs was clearly demonstrated.

Following the collaborative BERP tip investigations, NASA commissioned unsteady tests on a rectangular tip wing (with aerofoil of revolution end closure), Piziali [130]. This data has

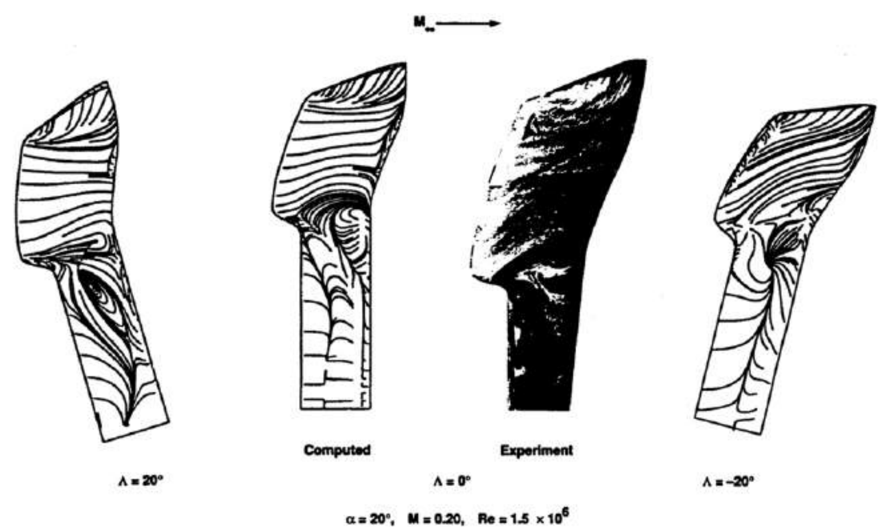

Fig. 45. Computed and experimental surface streamline patterns at high incidence and sweep, Brocklehurst and Duque [125].

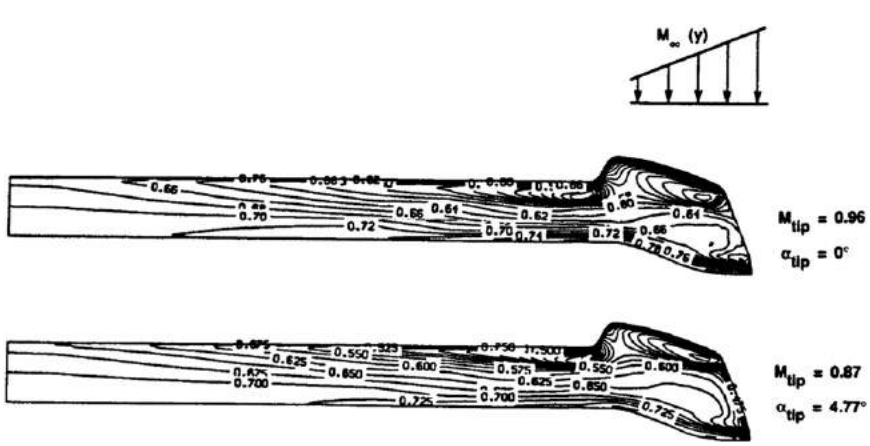

Fig. 46. Computed surface pressure contours with sheared free-stream Mach number, Brocklehurst and Duque [125].

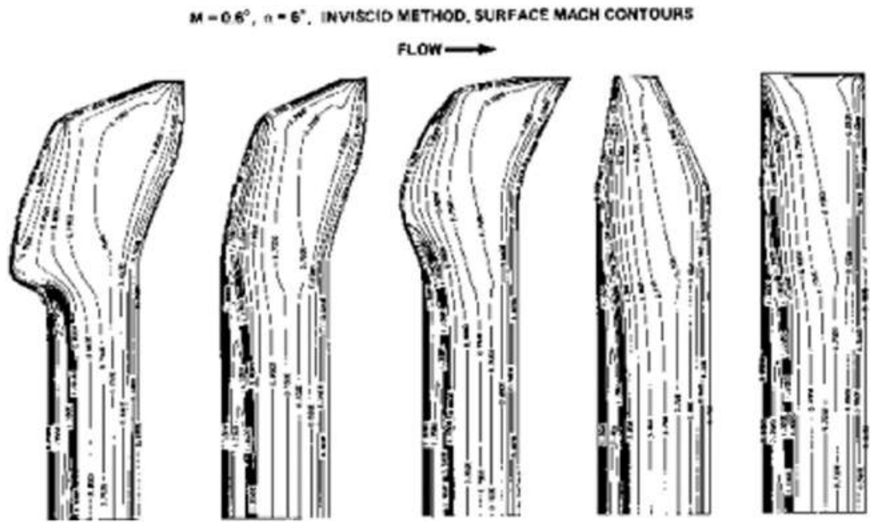

Fig. 47. Planform effects at transonic speed from inviscid CFD computations at $M = 0.6$ and 6°, by Duque [126].

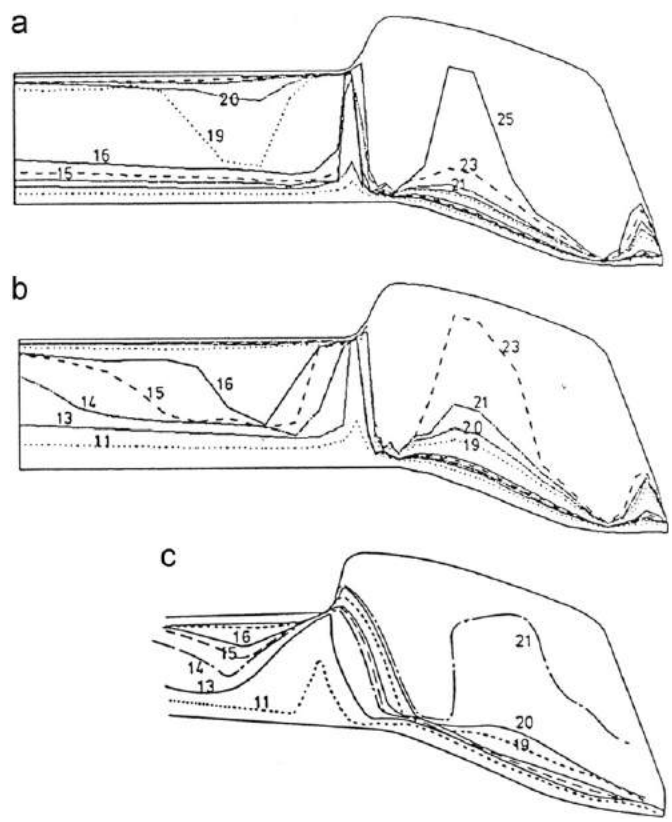

Fig. 48. Progression of separated flow with root angle of attack and comparison of prediction and test, Beddoes [127]. (a) Simulated, Trans.Free, RN$=3.0\times10^6$. (b) Simulated, Trans.Fixed, RN$=1.5\times10^6$. (c) Experiment, Trans.Fixed, RN$=1.5\times10^6$ (RN$=1.0\times10^6$. For $\alpha > 15$ deg).

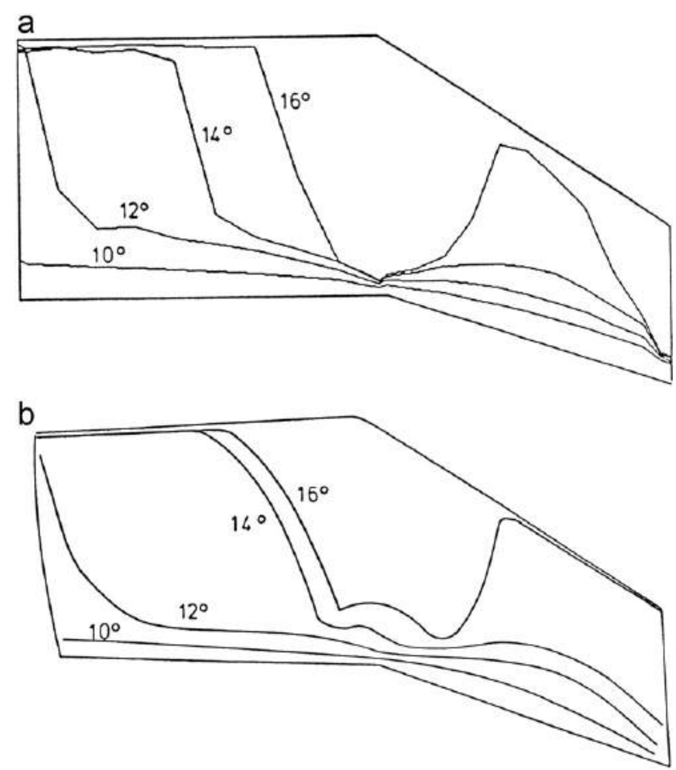

Fig. 49. Progression of predicted separation on a swept-tapered tip compared to wind tunnel data, Beddoes [127]. (a) Simulated steady state. (b) From flow visualisation.

been used by Beddoes at WHL to develop the ACROT model, and continues to form a useful database for further substantiation of 3D unsteady CFD simulations.

While the NASA Ames effort employed a full CFD analysis with structured grids to discretise the true geometry, Rajagopalan and Lim [131] at Iowa State University developed a laminar Navier–Stokes solver to model a rotor in hover. They used point momentum sources distributed along the radius to represent the rotor blade. At Maryland, Kim and Chopra [132] investigated the aeroelastic response of various blade shapes, including straight (rectangular), swept (sheared, UH-60 type), anhedral and tapered tips, Fig. 50.

A further example of these developments in the USA is provided by Srinivasan et al. [133] where shock-induced separation on the tip of a hovering rotor is studied. This was followed by Duque and Srinivasan [134] where they illustrate the use of embedded, or overset grids (see later).

In a subsequent paper Srinivasan et al. [135] analysed a modern helicopter rotor in hover, and compared the UH60 and BERP blades. Duque [136] then simulated a complete helicopter model of the AH-66 Comanche in forward flight using an actuator disc for the

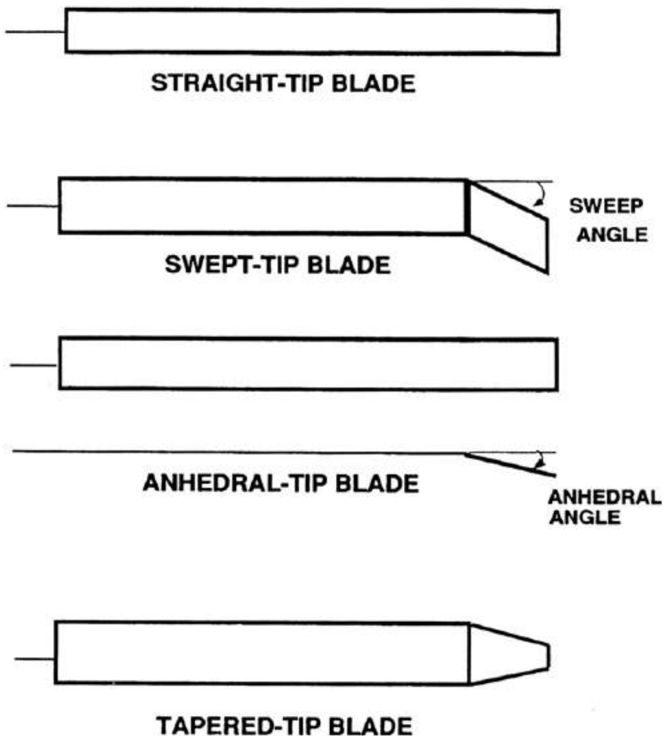

Fig. 50. Tip shapes defined by Kim and Chopra [132].

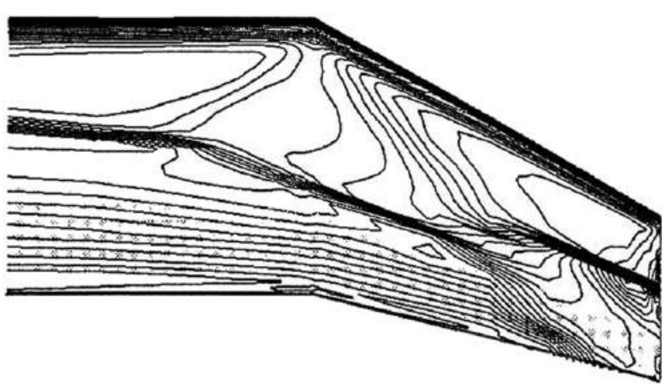

Fig. 51. Surface pressure contours on the AH-66 Comanche Tip et al. [136].

rotor, and also presented results for the swept-tapered tip in hover. As an example of this work, the surface pressure contours on the tip are reproduced in Fig. 51. A double shock occurs on the swept panel, and the tendency is for the shock to strengthen towards the tip. This suggests that more sweep is required in the extreme tip region if this tip is not to generate a shock pattern which will adversely affect rotor (loading) noise, due to de-localisation of the shock beyond the tip of the blade. Similar compressibility problems have been noted by the writer in recent computational work at Westland during explorations of the advancing blade characteristics of a variety of tip shapes. The severity of the shock de-localisation problem depends on the planform, but a strong driver is the tip Mach number which stems from the forward speed and cold temperature design requirements of the helicopter.

Srinivasan and Baeder [137] summarised the capabilities of the Transonic Unsteady Rotor Navier–Stokes code, TURNS, to calculate simultaneously the aerodynamics and acoustic loading noise, using grids of 100,000 to 960,000 grid points.

Despite the rapid progress in CFD, traditional rotor tools continue to be used because of their fast turn around time. Aeroelastic optimisation was explored by Callahan and Straub [138] using CAMRAD/JA and CONMIN to vary several blade design parameters. Limitations in the simple aerodynamic model were recognised, especially when dealing with sweep. Blade twist was found to be a powerful design parameter affecting vibration, and somewhat surprisingly they found an optimum close to that required for best performance.

At Bell Helicopters, Yen [139] considered the effects of blade tip shape on dynamics, cost, weight and performance, and compared a swept-tapered tip design with swept, tapered and rectangular blades. In high-speed flight the swept-tapered tip reduced pitch link loads and vibration, and depending on the thickness of the tip aerofoil, reduced the power requirement. Yen states that this tip gave a small increase in blade weight and manufacturing costs, and concluded that 'the performance of the swept-tapered tip depends on many design parameters, such as solidity, aerofoil thickness, tip speed, rotor dynamics and blade torsional stiffness. Therefore it is imperative that it is integrated into the overall design process'.

Meanwhile, manoeuvre trials proved the thrust capability of the BERP rotor, and noise tests were then carried out. The tests were arranged to avoid ground reflections, by flying the Lynx towards a microphone suspended below a hot-air balloon. In these tests a tip Mach number of 1.02 was reached with the BERP blade, as described by Pike and Harrison [140].

Also in 1995, a team from Japan, Aoyama et al. [141] computed the formation of shocks on the advancing blade using an Euler method for blades which had a NACA0012 aerofoil. In their paper, they present the location of the shock on a rectangular blade for advancing blade azimuths of 60°, 90° and 120°, where the shock reaches the tip and would de-localise, see Fig. 52. They compare the pressure rise across the shock for several (sheared) swept tips and tapered tips, and even show the tip relief due to a change in aspect ratio. They then introduced a delta shaped extension to the leading edge, although the shock still persisted at the square cut tip, Fig. 53 and finally they added a 75° swept outer edge (similar to the BERP tip, but more abrupt) which helped to relieve this problem, Fig. 54.

Wake and Baeder [142] evaluated the TURNS Navier–Stokes CFD method against the data of Lorber et al. [92] for the Black Hawk (UH-60A) model rotor and a 3:1 tapered tip for a range of thrust conditions in hover, Fig. 55. The code used a

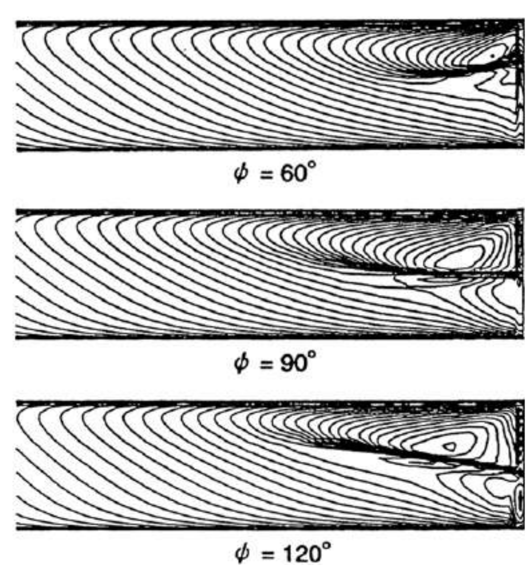

Fig. 52. Mach contours on blade surface, $M_{tip} = 0.7$, $\mu = 0.3$, non-lifting, Aoyama et al. [141].

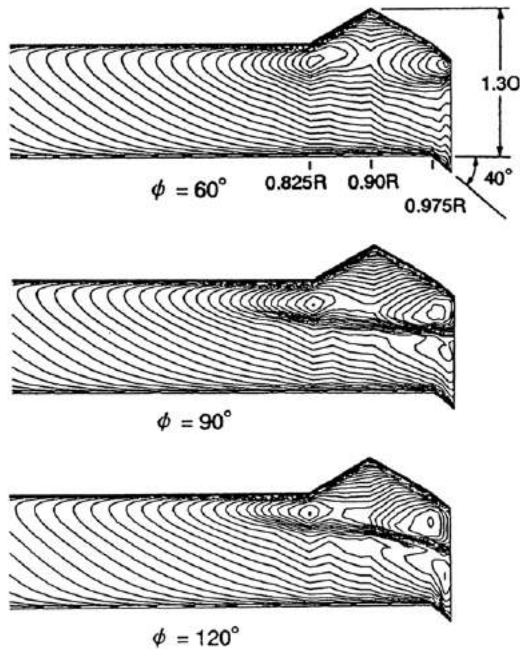

Fig. 53. Mach contours on blade surface, $M_{tip} = 0.7$, $\mu = 0.3$, NACA0012, Aoyama et al. [141].

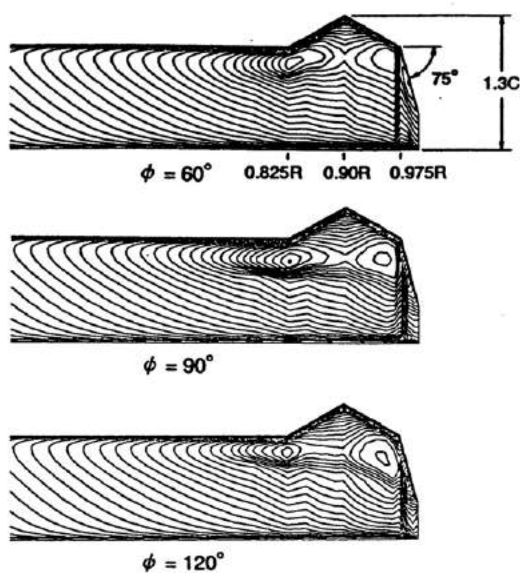

Fig. 54. Mach contours on blade with large sweep-back and delta-shape extension of leading edge, $M_{tip} = 0.7$, $\mu = 0.3$, NACA0012, Aoyama et al. [141].

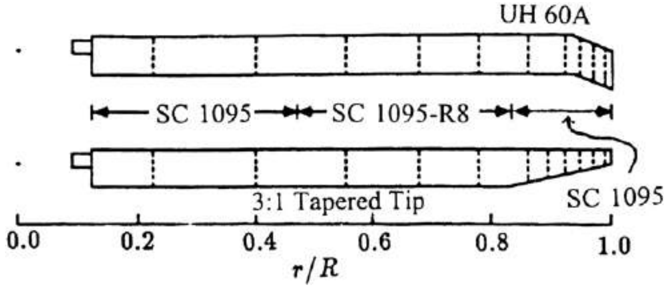

Fig. 55. Model rotor planforms for UH60A and 3:1 Taper Tip, Wake and Baeder [142].

low-dissipative 3rd order upwind solver. Periodic grids of 380,000 to 950,000 cells were used, and measured blade deflections were taken into account. Discrepancies with experimental results were found mainly in the tip region, although these were improved with the finer grid. While fair comparison with the measured FoM was obtained, there were compensating errors related to the lack of definition in the tip vortex which diffused by the time the following blade was reached, and the profile power was not accurately predicted.

In 1996, Ahmad and Duque [143] were testing computations in unsteady rotor cases in forward flight using overset grids. This method allows a well-formed structured grid to surround the blade, with the remainder of the domain meshed with a Cartesian or cylindrical grid, as appropriate. The method involves interpolating (in 3D) between the results obtained on the two grids at each time-step, and this must be done without loss of accuracy.

In Europe, the overset grid concept was also tested in the EROS project, Renzoni [144]. Subsequent development of a helicopter Navier–Stokes code by the EROS–UK consortium has concentrated on sliding grid-planes using a deforming mesh to accommodate blade motion. During the Rotorcraft DARP, and for the EU-GoAhead project (see later), this approach was developed and refined by Steijl and Barakos [145].

A numerical investigation of the tip vortex, and the effect of a tip spoiler for vortex diffusion is given by Russell et al. [146] using a 5th order accurate multizone Navier–Stokes code, and comparisons are made with the tests of McAlister et al. [147]. Further work on a hovering rotor is presented by Liu et al. [148] where the tip vortex structure is altered by blowing without incurring the drag penalty of a spoiler.

In France, Beaumier et al. [149] considered CFD predictions of power for a rotor in hover or forward flight, using a 3D Euler solver (WAVES) and a 3D unsteady full potential (FP3D) method, respectively. In each case, the inviscid flow solution was coupled to a laminar-turbulent boundary layer code (MI3DI) in order to compute the viscous drag. A straight tip with a slight trailing edge taper and a swept tip were studied. The benefit of sweep in reducing the shock strength compared to the straight blade is readily apparent, and the state of the boundary layer shows a significant amount of laminar flow, Fig. 56. Navier–Stokes analyses are sometimes weak in the area of drag prediction, and the traditional assumption of using a turbulence model to compute the skin friction, while ignoring transition, must be questioned. Beaumier et al. [150,151], switch between laminar and turbulent

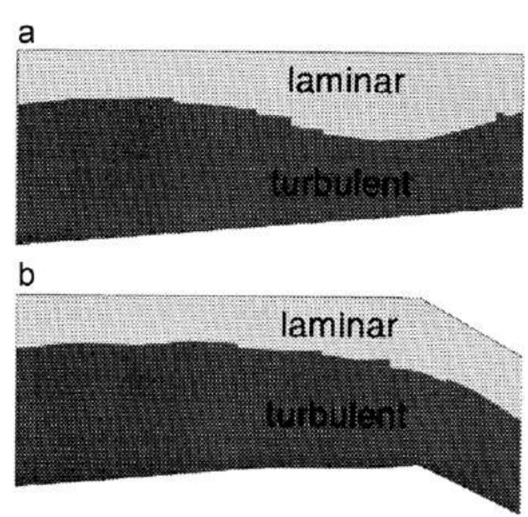

Fig. 56. State of the boundary layer on blades with straight and swept tips, Beaumier et al. [149].

solver options. In unsteady conditions, such as dynamic stall, modelling of transition will be important if accurate results are to be obtained.

Over the last few years, computational methods have been increasing in popularity to determine the performance of new tip designs. A paper by Manke et al. [152] supports the idea that ‘semi-empirical tip corrections currently used in comprehensive rotor codes to model rotor tip-relief effects are not sufficient for designing (or representing) advanced blade tips’. The team from Boeing coupled their FPR code to the Tech-01 multi-disciplinary rotor code. The current coupling is limited to blade lift, but represents a ‘significant advance’ in modelling rotor aerodynamics and was successful in modelling tip-relief effects.

In Europe, a full-potential code was developed under a Brite-Euram programme, with the acronym, HELIFP, as described by Costes et al. [153]. This collaborative development effort was aimed specifically at predicting compressible inviscid flow on helicopter rotor blades in hover and forward flight. A later version, HELIFP-X, included provision for an integral boundary layer model. In the UK, work has also been carried out at DERA, Farnborough to couple this full-potential code to a forward flight rotor code. In this approach, a first estimate of trim angles and induced flow are generated from a rotor code, and the full-potential code is used to compute the detailed pressure distribution and hence a better estimate of the aerodynamic loads on the blades, especially near the tips.

Despite the rapid development of CFD methods, lifting line methods are still in use in industry, since they have a fast turn-around time and lend themselves to parametric studies and design explorations. Provided the lifting-line approach is closely linked with a vortex wake model, it provides an acceptable method of studying parameters such as twist and taper, but is not able to accurately resolve the effects of tip shape. Despite this limitation Joncheray [154] uses a non-rectilinear modification of a lifting-line method to model the tapered ‘dihedron’ tip, SPP8, and compares to model rotor hover test data from the Modane wind tunnel. The SPP8 design is essentially a parabolic tip blade with a relatively small amount of anhedral, which gradually reaches a tip angle of 17°. This style of blade, Fig. 57, was subsequently demonstrated on the Super Puma.

Bridging the gap between lifting-line, or lifting-surface models, and full potential or Navier–Stokes CFD is the incompressible

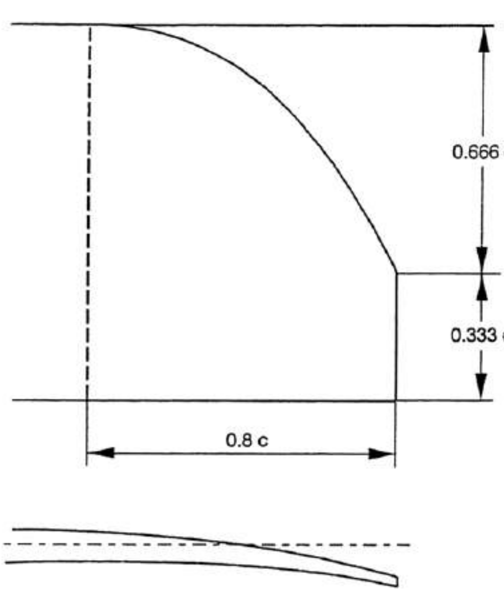

Fig. 57. Parabolic tip shape (SPP8), Joncheray [154].

unsteady panel method described by Ahmed and Vidjaja [155]. In this method a source sink distribution represents the blade thickness, while a doublet distribution is solved on the camber line, and the force-free wake is allowed to evolve at each time step. Ahmed remarks that, in contrast to the CFD methods, there is no diffusion of the vortex after it is formed, and the consequence could be an ‘over-simulation’ of vortical motion in comparison to the real viscous flow. The method was aimed at providing airloads for the determination of BVI noise, and does not appear to include a coupled boundary layer to determine profile power, and hence overall performance. This method is restricted to conditions where compressibility is unimportant, but the panel method approach is otherwise capable of resolving the flow around arbitrary tip shapes (only the rectangular blade of the Bo105 was considered in the paper).

Interest also continues in developing free-wake models, such as the CHARM model of Quackenbush (see later), where the trailed circulation from the rotor is fed into the wake, and the vortices are displaced according to the induced flowfield. Laser Doppler Velocimetry (LDV) techniques have been used to make measurements in support of these and other numerical models. Bhagwat and Leishman [156] provide data on a hovering rotor. The aim of the tests was to determine the bound circulation along the blades, together with the swirl velocities and core sizes of the tip vortices.

A set of interesting tip shapes are studied by Baeder [157] using an Euler/Navier–Stokes solver. Baeder argues that forward sweep is more effective in reducing noise than rearward sweep by effectively delaying de-localisation, although in the writer’s opinion this is highly dependent on the outer tip shape, which was simply cut-off in the tip shapes presented in this reference. Fig. 58 illustrates the effect of different tip shapes, and Baeder goes on to refine the detail design by introducing more area at the dog-leg and taper further outboard. At high speed, phasing effects become important, and forward sweep becomes more effective at reducing high-speed impulsive noise. A dog-leg planform is considered in order to maintain the aerodynamic centre on the quarter chord, and according to Baeder, the Forward Aeroacoustically Swept Thin and Tapered (FASTT) tip was seen to delay de-localisation well beyond a tip Mach number of 0.95. In comparison, computations by the writer for the BERP-III tip at Westland during 2001 were presented at The Burn 2003 [55], and later work on BERP-IV in 2008 [17], show no signs of de-localisation at this tip Mach number. As mentioned earlier, the BERP tip has been flown to a tip Mach number of 0.977 during the world speed record and up to 1.02 in subsequent acoustic tests.

An economical method of exploring the aerodynamic characteristics of a rotor blade tip shape using CFD is to consider the blade as a wing. This approach has its drawbacks, and ignores differences in radial loading, Mach number variation and induced velocity, however, the wing problem is much easier to compute, and allows comparison between test data and CFD, before attempting the rotor problem. The differences between the loading on a wing, and that on a rotating blade in hover, are discussed by Hu [158]. In his paper, Hu describes the development of TLNS3DR code for rotary wing calculations, and shows examples of pressure contours for wings and rotor blades in hover. The comparisons are at zero-lift, although a lifting rotor case is shown for a high tip Mach number on a grid of about 545,025 points. The same author has also carried out computations on BERP-type blades, Hu [159,160].

One of the major problems in accurately computing the performance of a rotor in hover, is to conserve the vortices in the wake. For accurate performance predictions it is vital that the induced velocity at the blade is correctly represented, and this can only be done if the vortices in the wake have the correct location

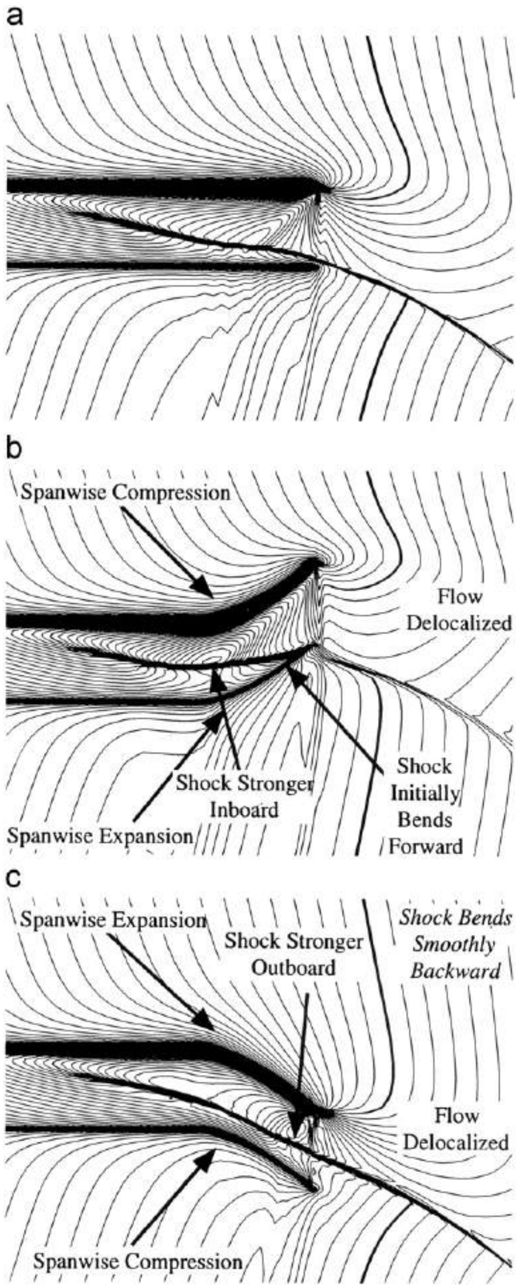

Fig. 58. Mach number contours in the plane of the rotor at $M_{tip} = 0.95$ for blades with different sweep, Baeder [157]. (a) Baseline blade. (b) FS-C blade. (c) BS-C blade.

and strength. Dindar et al. [161] applies an adaptive refinement technique to an unstructured grid in order to study the effect of tip vortex resolution on the UH-60 blade in hover. The method works by computing error indicators to aid the efficient resolution of small-scale features in the flow field.

In addition to ensuring an adequate description of the wake, it is also necessary to know the dynamic deflections of the blade. Torsional deflections are the most important, although flap and lag deflections may also have a significant impact on certain flight cases. The topic of aerodynamic loading and aero-elasticity is discussed by Bousman [162] and the problem of correctly phasing of airloads is taken up by Datta in a more recent AHS Forum paper in 2003 [163]. In the latter reference, CFD was used to obtain a better prediction of the azimuthal variation in loading, based on measured torsional deflections from the comprehensive flight data obtained for the UH-60A Black Hawk. Recently, Kufeld and Bousman [164] have pointed out that the data requires a 14° reduction in the azimuth previously quoted, due to a 7° error. This reduced the differences between prediction and measurements, but the phase-lag due to changing incidence and Mach number on the advancing blade is still significant. This phenomenon has also been investigated recently by Steijl and Barakos [165].

In contrast to the UH-60 type of swept-sheared planform, hover performance and acoustic considerations have led to the development of the parabolic tip, which has become adopted for many European helicopters. Philippe [166] shows the benefits of the parabolic tip relative to a rectangular blade, Fig. 59. However, this style of tip design may pose some limitations at high forward flight speeds, especially on highly loaded rotors, or rotors with a relatively high tipspeed. In a paper concerning the design of the EC135, Kampa et al. [167] show Mach contours on a parabolic tip which suggest that a strong shock forms outboard, and is only slightly alleviated by the tip, suggesting that the tip has a lack of sweep, Fig. 60. Similar results were obtained by the first-author in 2002 for this type of tip in a representative sheared Mach number flow at zero-lift.

Bebesel et al. [168], discussed the development of the Advanced Technology Rotor (ATR) at Eurocopter Deutschland, Fig. 61. A reference blade design with a parabolic tip (tip chord 1/3 of the main chord) was compared with EC3 and EC4 blades. The EC3 blade had reverse taper, together with a tapered parabolic tip (and trailing edge swept forward), while EC4 had a tip which was swept back at approximately 25° from about 85%R. The main aim of these designs appears to have been towards noise reduction, hence the desire for a low tip volume. The ATR rotor was built with the means to test a variety of tip shapes, including a tapered parabolic tip, and an elliptic tip (to minimise the chord in the tip region). To accommodate a swept leading edge, while retaining the aerodynamic centre of the tip close to the quarter chord, a Bulge tip was put forward, and finally a Vane

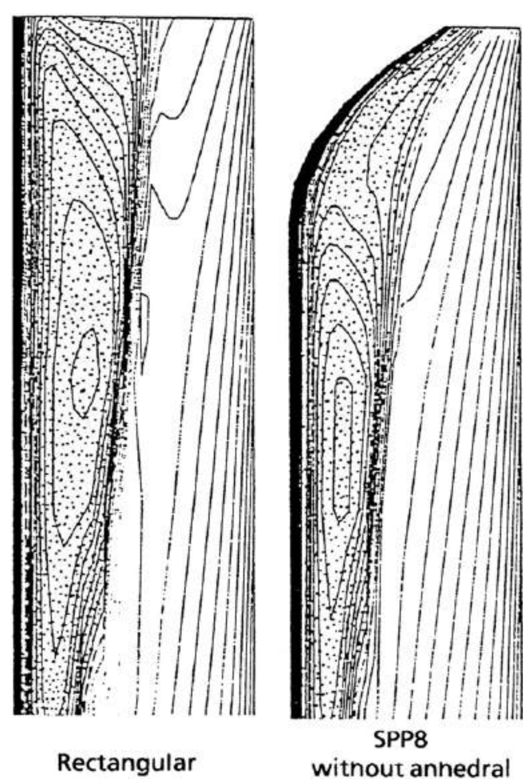

Fig. 59. Iso-Mach lines on rectangular and parabolic tips, Philippe [166].

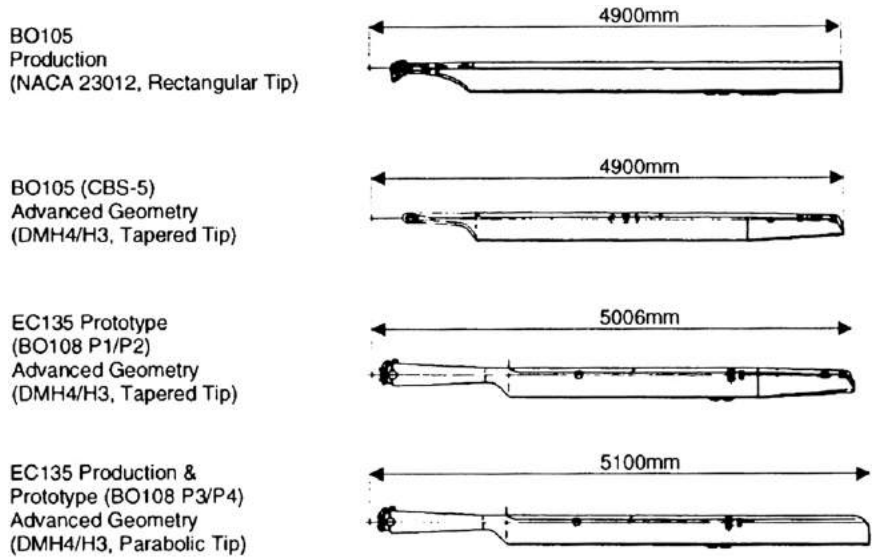

Fig. 60. Advanced blade planforms developed for the Bo105 and EC135, Kampa [167].

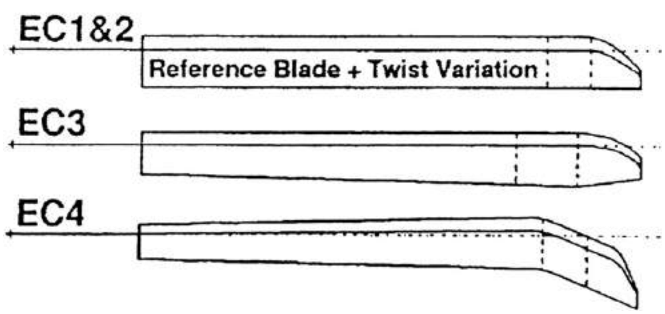

Fig. 61. Optimised rotor blades, Bebesel [168].

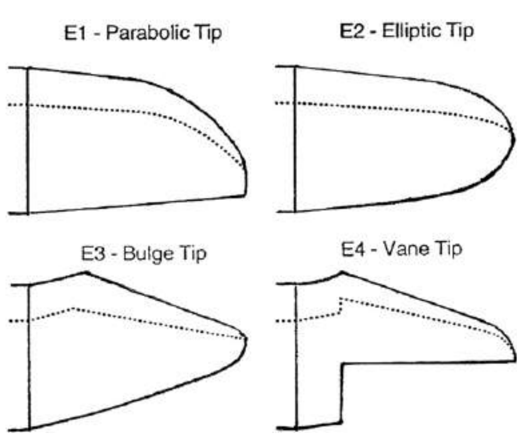

Fig. 62. Advanced technology rotor (ATR) blade tip shapes, Bebesel [168].

Tip was also tested (similar to that designed by the first-author), Fig. 62. The Figure of Merit plots indicate the superiority of the parabolic tip over the elliptic tip and the standard (rectangular) rotor blades of the BK117. Bebesel reports that the cruise speed was increased by 17 km/hr (9.2 kts), and the thrust in hover was increased by about 5% at the same power consumption. In all flight conditions tested, the parabolic tip showed a small noise improvement over the elliptic tip, presumably due to the benefit of sweep and a thin aerofoil in suppressing transonic loading. Variable rotor speed was also adopted for the ATR, which allowed a noise reduction in descending flight.

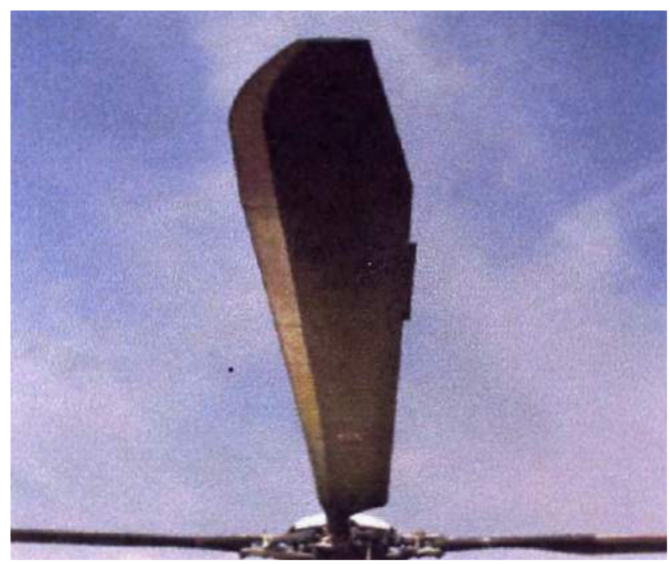

Fig. 63. The Quiet blade for the EC155, Allongue [169].

Allongue et al. [169] discuss a Quiet Helicopter demonstrator for the EC155 derivative of the Dauphin, Fig. 63. Five blades and a larger diameter are used, and a variable tipspeed was demonstrated. The tip shape again has a parabolic leading edge and a tapered trailing edge such that the tip is highly tapered, and therefore has low volume, but little sweep. The aerofoils employed are (inboard) OA415, OA312 and (towards the tip) OA409. While there is little doubt of the benefits with regard to the hovering efficiency and low noise performance of this type of tip design, the use on heavier, faster helicopters may be limited by advancing compressibility and retreating blade stall. Judging by the planform, and the low pitching moment aerofoils, this blade design would exhibit low control loads during normal operations.

As noise regulations become more stringent, and with the ongoing development of the V22 tilt-rotor aircraft, there is a continuing interest in reducing rotor noise and, in particular, BVI noise on the approach, both for conventional helicopters and tilt-rotor configurations. The sub-wing topic has again been the subject of further experimental investigations, as reported by Bhagwat et al. [170], where hover smoke flow visualisation and wake measurements are given. Bhagwat reports that the sub-wing modification did not significantly affect the hover wake geometry, once the vortices had merged. Lower peak swirl velocities were observed, together with a larger core radius of the merged vortex, compared to the baseline tip. The sub-wing was found to be effective in enhancing diffusion of the tip vortex. However, the lack of twist and blending on the sub-wing may introduce turbulence into the vortex roll-up, and therefore cause an increase in the power required.

The effort to reduce BVI noise is the topic of a paper by McAlister et al. [171] where the effect of a small 'turbulence generating device', or spoiler, attached to the tip of a hovering rotor on the structure of the trailing vortex is discussed. As shown in Fig. 64, several tip planforms were considered, including a new non-planar curved anhedral tip, an Ogee tip, stepped chord, several spoiler arrangements, lateral tip blowing, and a (deployable) 'spline' tip. The tip spoiler device was effective at reducing the peak velocities in the tip vortex, but caused an 18% increase in rotor torque, and should therefore be retracted when not required.

Yang et al. [172] describe an experimental and numerical investigation of the effect of tip blowing for fixed and rotary wings, as a step towards the reduction of BVI noise. The authors find that not only does blowing diffuse the tip vortex, but also may displace the tip vortex outwards, causing an effective increase in wing-span, or radius. In the UK, recent tests at the University of Bath were also reported by Margaris and Gursul [32]. While the main aim of research on tip blowing has been to achieve a reduction in blade–vortex interaction noise, potential may exist to enhance performance and moderate control loads by active blowing techniques.

More recently, Han and Leishman [173] have put forward a tip which employs natural blowing to diffuse the tip vortex. A series of openings on the leading edge of the blade lead to outlets on the edge of the tip such that air is injected close to where the vortex forms and is therefore entrained into the tip vortex as illustrated in Fig. 65. In their paper Han and Leishman present excellent flow visualisation and LDV measurements of the tip vortices, with and without blowing, on a model-scale rotor and conclude that the peak swirl velocity is reduced by nearly two-thirds and the core size is increased by two to three times for increase in power of less than about 3%.

In looking forward to applying high-resolution CFD methods to rotorcraft design evaluation problems, it is essential to be able to economically predict the vortex roll-up process and the trajectory of the wake vortices. In practice, the circulation strength of the trailed vortices will gradually decay through natural (viscous) diffusion, and one of the main challenges for CFD is to avoid accelerated diffusion due to numerical effects.

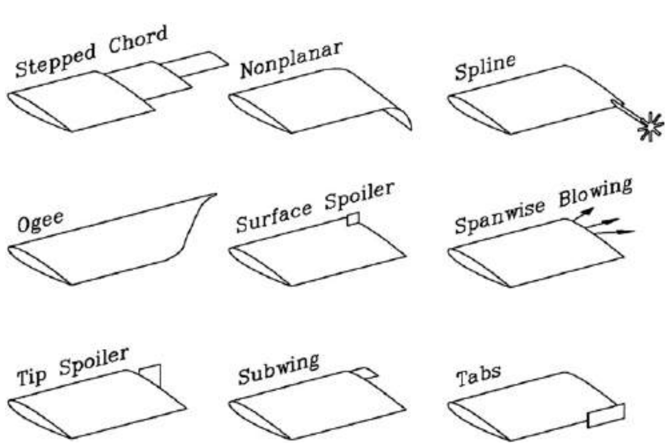

Fig. 64. Examples of attempts to modify the tip vortex, McAlister et al. [171].

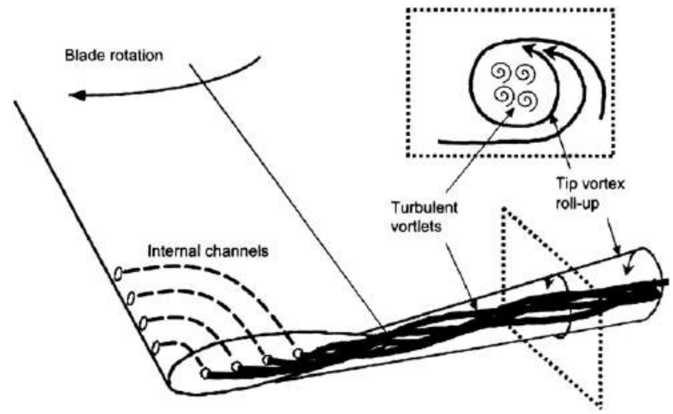

Fig. 65. Illustration of the method of dissolving the laminar inner region of the tip vortex by the action of turbulent vortlets generated at the slot exits, from Han and Leishman [173].

The use of a seventh order spatially accurate ENO method was implemented by Hariharan and Sankar [174] and benefits in efficient vortex capturing were assessed. A moving, tracking, overset grid technique was employed. A fifth order scheme was used to compute the tip vortex behind a wing, and the importance of capturing the axial momentum was highlighted. It is claimed that the high order scheme can capture the tip vortex for 180° with less than 10% dissipation, and for a wing tip vortex a distance of 50 chord lengths was computed with negligible dissipation of the vorticity. Further work on 5th and 7th order schemes is also reported in a later paper by Hariharan [175].

While a higher order scheme is able to capture a trailing vortex with a minimum of grid points, these methods work best on a Cartesian grid. This implies the need to use an overset grid to track the vortices in the rotor wake, and this process may present some difficulties. An alternative would be to use a very fine grid, which would then demand longer runtimes.

Tang and Baeder [176] present an improved Euler method for a hovering rotor and validate the results against the data of Baghwat and Leishman [156], using a third order accurate method. Improvements in both grid generation and flow solver reveal a numerical diffusion of the same level as viscous diffusion prior to the first blade passage.

Hall and Long [177] employ a fourth order Euler scheme and compare to the NASA CFL3D code. The lower diffusion of their simulation is shown to produce a stronger tip vortex that follows a trajectory closer to the experimental data for the development of the wing tip vortex of Devenport [37].

Several papers have been presented by Strawn on computational modelling of helicopter rotors. Ahmad and Strawn [178] present a Navier–stokes CFD analysis of a hovering rotor using an overset grid, and compare the results to the rectangular tipped blade of Caradonna and Tung, and to the UH-60 model rotor tests in the DNW tunnel by Lorber [92]. The loading was underpredicted inboard and overpredicted at the tip. In their 2001 paper Strawn and Djomehri [179] again discuss the hovering rotor and wake aerodynamics, and employ grids of 10.6 million points and 64 million points to check grid sensitivity, and although the wake is better resolved with more points, the performance results were not particularly sensitive to the number of grid points. Again, the computations consistently over-predicted the thrust near the rotor tip and it was suggested that this was due to a mechanism of vorticity migration, although other factors, such as differences in boundary conditions for computation and test, and the overprediction of the vortex core size, may also be at fault. The vortex core size may be affected by the local grid density in the region of the tip vortex, or could be influenced by the choice of turbulence model.

Strawn and Djomehri [180] used structured overset grids with high resolution on the blades, and systematically vary the grid resolution in the rotor wake and the outer boundary locations. The solver used is now of fourth order, but even so, the thrust in the tip region is still overpredicted.

In the UK the alternative technique of employing a sliding grid (in the plane of the rotor) has been developed for forward flight simulations, and blade pitch variation is achieved via a distorting mesh. This technique has been adopted in the Helicopter Multi-Block code (HMB) because of its ease of programming and potentially greater accuracy.

The writer has also used the sliding mesh approach in the commercial FLUENT code for an unsteady 2D aerofoil, and to obtain quasi-steady solutions for a rotor blade at various azimuths in forward flight, Brocklehurst [181,55]. Azimuth position was controlled using a large cylinder aligned with the axis of rotation of the rotor, but the requisite pitch angle of the blade was set by simply rotating the blade about the (coned) feathering axis within a local cylindrical grid. The idea of enclosing the blade in a fixed mesh, and convecting the flow and wake across a sliding mesh boundary, appears a sound idea provided that this can be done without loss of accuracy. This technique would also minimise the amount of distortion that has to be accommodated by the deforming grid, since the cyclic pitch rotation is handled by the sliding grid, and only the blade deflections need to be addressed by grid deformation. These test cases used an Euler solution (for economy) and an unstructured grid (for convenience), and could have been readily extended to a time-accurate solution for rotating blades, had sufficient computational resource been available at the time. However, a much finer, structured grid would be preferred.

The current deforming grid scheme within HMB is able to handle large pitching displacements by allowing movement of the block boundaries to minimised overall distortion, and so maintain the quality of the grid.

However, not only is it important to know the dynamic deflections of the rotor so that the loads can be accurately determined, but it is also necessary to understand how the aerodynamic design of the tip impact the dynamics. Maier and Abrego [182] discuss the aeroelastic stability of a model rotor with a swept-sheared tip, and establish good correlation of CAMRAD-II with regard to the dynamics.

Clearly, the trim of the rotor and blade deflections are of paramount importance in forward flight, but blade deflections, particularly torsion, may also be important in hover simulations. As mentioned previously, Beaumier et al. [151] computed the performance of a hovering rotor, and accounted for the aeroelastic torsional deflection in order to improve the loading in the tip region.

Yang and Zhuang [183] also discuss the numerical simulation of a rotor in hover, and compare with Caradonna and Tung. Yang introduces an angle correction from a vortex model to overcome the problem of vortex diffusion for the 8° lifting case.

As computational methods continue to be developed, there is a need to compare with high quality tests data. Phase-resolved stereoscopic PIV has been used to measure the wake of a model helicopter by Martin et al. [184] and Bhagwat and Leishman [185,186] have measured the bound and trailed circulation. High-resolution measurements of the wake of a hovering rotor were also reported by Martin et al. [187] using LDV. This information is important in establishing the wake structure, and provides a good database to support the development of both high-order computational techniques and free-wake methods for noise and performance predictions. Stability of the wake in hover is also considered by Bhagwat and Leishman [188].

Wind tunnel studies have also been undertaken in Europe, and a low noise rotor blade was designed and tested in the DNW tunnel by ONERA and DLR in a bilateral project, Muller et al. [189]. On the

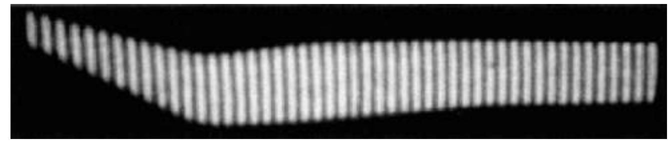

Fig. 66. Fringe patterns indicate the shape of the ERATO blade, Muller et al. [189].

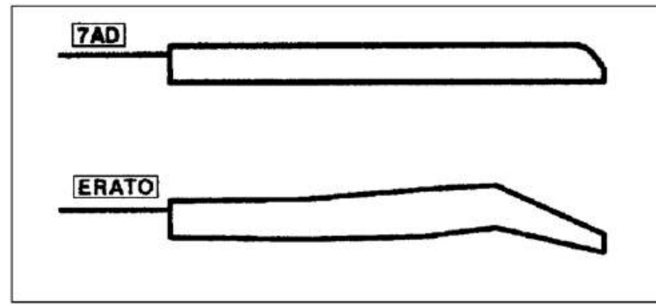

Fig. 67. Comparison of ONERA 7AD and ERATO blades, Beaumier and Delrieux [190].

ERATO rotor the blade curves forwards and the main sweep-back starts well inboard, at about 75% radius. The highly tapered blade planform sweeps back at about 25°, as shown in Figs. 66 and 67. At the tip, the blade is simply cut off normal to the inboard-quarter-chord reference axis, perhaps risking some de-localisation due to the shock re-forming since the sweep is limited, depending on the advancing blade tip Mach number. With this type of planform, torsional deflections are important, and the paper describes the analysis of strain gauge data, and the non-intrusive optical fringe correlation method (FCM), also known as the projected grid method (PGM). The aim of this blade design is to reduce blade–vortex interaction (BVI) noise as described by Beaumier and Delrieux in their 2003 ERF paper [190].

Pahlke and Chelli [191] through the French/German CHANCE program have developed the CFD methods for multi-bladed rotors in forward flight, and compare results for the 7A (rectangular tip) and 7AD (parabolic tip) rotors with data from tests in the S1-Modane tunnel. The blades are here assumed rigid and the Chimera technique is used to allow for the relative blade motion, by surrounding the blade with a grid, which moves with the blade, and overlaps the background grid. It is concluded that the results could be improved with rotor trim changes and by taking the aero-elastic deflections into account.

As expertise with CFD methods is steadily developing, the more ambitious goal of simulating a complete helicopter has been taken up. In Europe, collaboration between ONERA and DLR is reported by Sides et al. [192] where the aim is to develop the CFD methods and enhance high-speed impulsive aero-acoustic predictions using Euler/Kirchoff methods. Sides also describes the application of Navier–Stokes codes to the prediction of the flow around helicopter fuselages, including the effects of boundary layer transition. This collaborative work formed the basis for the CHANCE project (Complete Helicopter AdvaNced Computational Environment). The DLR FLOWer code makes use of overlapping grids, while the elsA software at ONERA employs moving grids.

The development and application of CFD methods in the French/German CHANCE programme are also described by D'Alascio [193]. The elsA software combines the former ONERA models of CANARI, FU3M and WAVES, while FLOWer was further developed by DLR. The paper focuses on the Advanced Technology Rotor (ATR), and the ATR-A rotor is the subject of analysis, see Fig. 68. This rotor has a small amount of inverse taper, such that the chord at about 85%R is wider than the chord at the root, and the tip is a tapered parabolic planform with a swept leading edge.

The trailing edge has a slight forward sweep, and the end of the blade is cut off square to the reference axis. Such a blade tip would have low torsional loads. The aerofoils used are the ONERA OA-4 series and the 3-series OA312 at mid span. The aerofoil section is 15% thick at the root, and in the tip region the thickness tapers from 9% to 7% at the tip. Such thin aerofoils are required to cope with advancing blade compressibility when the sweep is not large, and could give an early stall on the retreating blade. However, this tendency may well be alleviated by the use of sufficient blade area in the region of 75–85%R. One would also expect such a blade with a tapered parabolic tip to have a high peak Figure of Merit in hover.

Pahlke and van der Wall [194] introduce weak fluid–structure coupling, and present test cases for the 7A and 7AD isolated rotors using the FLOWer code with Chimera grids. This improved the solution and the performance difference between the two sets of blades was fairly well predicted. In a later paper, Pahlke and van der Wall [195] report progress on the use of weak fluid–structure coupling for multi-bladed rotors in high-speed flight, and show much improved phase agreement with experiment when coupling is used.

Fig. 68. Illustration of the ATR blade analysed by D'Alascio [193].

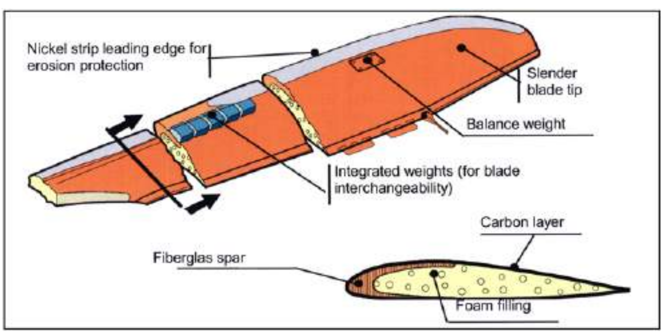

Fig. 69. Detail design features of the advanced technology main rotor blade, Humpert and Schley [197].

Pomin and Wagner [196] from the University of Stuttgart have also applied a Navier–Stokes method to the hovering rotor case and compared to the 7A test data. Use of a Chimera grid is being developed to encompass the forward flight, complete helicopter problem.

The combined efforts of ONERA and DLR are used to support ECF and ECD in the development of improved rotor blades. Application of the ATR blade on the EC145 is described by Humpert and Schley [197]. Details of the ATR blade configuration are shown in Figs. 69 and 70. A similar tip shape (on a parallel chord blade) is also used on the civil EC225 and military EC725, which supersedes the Super Puma, Faury [198].

In parallel with the European effort, the ATIC team from Japan has carried out a programme of research into rotor design, performance, loads and noise in a series of tests in the DNW wind tunnel, Kondo et al. [199], Fig. 71. A baseline rectangular blade was compared to the AT1 rotor, which had a BERP-type tip with a forward offset of the trailing edge as well as the leading edge, while the AT2 rotor has a swept tip with no forward offset and 20° of anhedral, Sato [200], Fig. 72. The AT-2 tip has leading edge sweep and a straight-swept trailing edge, such that there is a small increase in chord at the tip. This contrasts with the NH-90 style rotor blade where the tip planform is highly tapered towards the tip.

In the second series of tests, summarised by Murashige et al. [201], the main objectives were noise and Higher Harmonic Control (HHC). Flow-field PVI data was gathered and blade deflections were

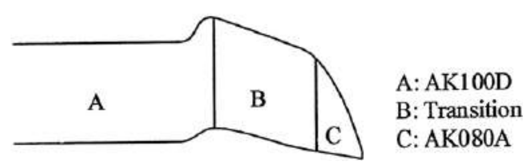

Fig. 71. The AT1 blade was selected from several similar tip shapes, Kondo [199].

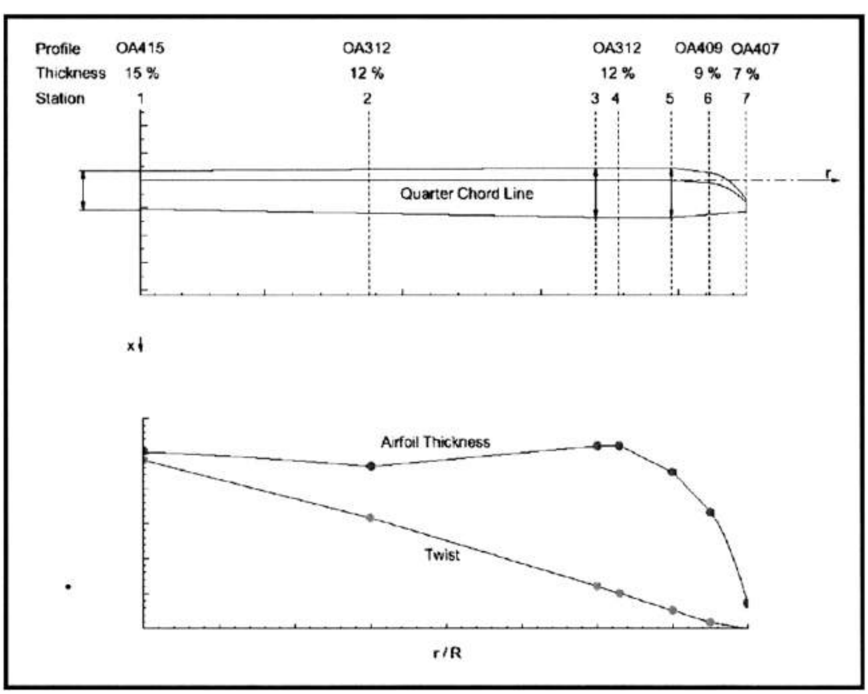

Fig. 70. Aerodynamic layout of the advanced technology main rotor blade, Humpert and Schley [197].

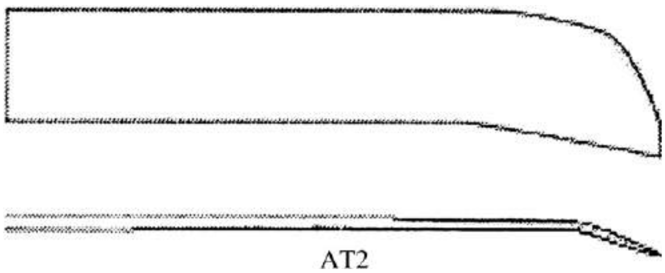

Fig. 72. The AT2 blade described by Sato [200].

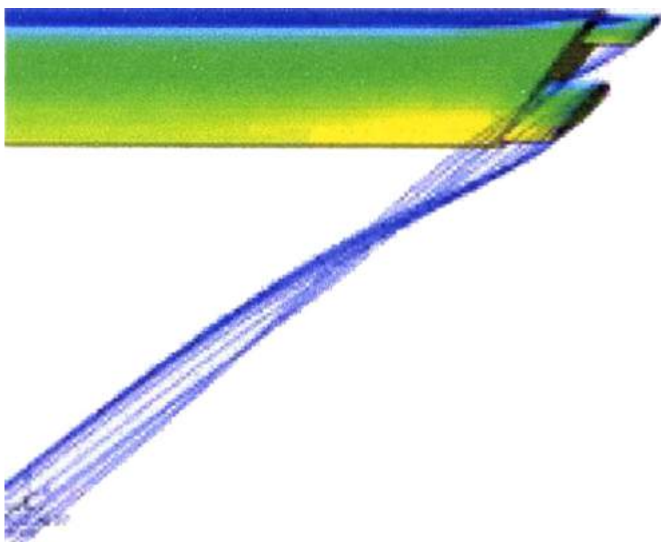

Fig. 73. The canard tip has twin rectangular tip vanes, Ota [204].

also measured to aid the subsequent analysis and enhance understanding. The results were compared to CAMRAD-II and a multi-bladed CFD forward flight analysis, and a reduction of torque was established for the AT-2 rotor. Level flight noise was reduced, although there was an increase in BVI noise for this swept, anhedral tipped rotor. It was suggested that the BVI noise was due to twin vortices arising from the anhedral, and that this could be cured by removing the anhedral. This conclusion is interesting and highlights the complexity of the tip design and BVI problem.

Further validation of Japanese rotor aerodynamic and acoustic prediction methods based on the second ATIC model rotor test is also reported by Kondo et al. [202]. The performance, acoustic and flow visualisation tests are reported in detail by Murashige [203].

Also in Japan, a novel Canard Tip configuration was put forward by Ota et al. [204]. The Canard Tip was tested on a model rotor, and featured rectangular lifting surfaces towards the leading edge and trailing edge of the main blade, Fig. 73. A noise reduction of 2.5 dbA is reported (compared with 5.6 dbA for the Westland Vane Tip). One of the main problems with attempting to develop a tip of this nature is the difficult design compromise between advancing and retreating blade performance, and the Canard Tip of Ota therefore employs a leading vane which may be controlled in pitch. However, even with active control, the simple rectangular shape of the Canard tip would probably impose some penalty on performance.

In the past, the lack of a detailed computational method has prohibited a thorough evaluation of blades with the added complexity of a tip vane(s), and such configurations have therefore been the subject of experimental investigation, usually focused on acoustics as discussed above. However, there are some difficult design issues to be resolved if the advancing and retreating blade performance are not to be sacrificed.

The Vane Tip concept was taken a step further in the mid 1990s by adding a vane to the BERP tip, and several configurations were tested by the writer in the Westland wind tunnel. This work led to a patent entitled 'Splitting the Tip Vortex on a Swept Tip' (1999) [205]. A related configuration is the KBERP tip as described by Hwang et al. [206], where a vertical leading edge vane is employed to shed an additional tip vortex, Fig. 74, but as far as is known neither tip was put into production.

A swept tapered tip was preferred for the 'new affordable' Apache blade, as described by Loftus [207], and shown in Fig. 75.

While some new designs of helicopter blade tip test out new ideas, others, out of necessity, are more conservative. Curtiss et al. [208] report development of the 'Carson' replacement main rotor blades for the S-61. Curtiss describes several small refinements to the design in order to stay within centrifugal and control load constraints. The new rotor blade employs 12° twist (increased from 8°), the NASA Langley RC-series aerofoils and a swept-tapered tip, see Fig. 76. The design emphasis was on hover performance

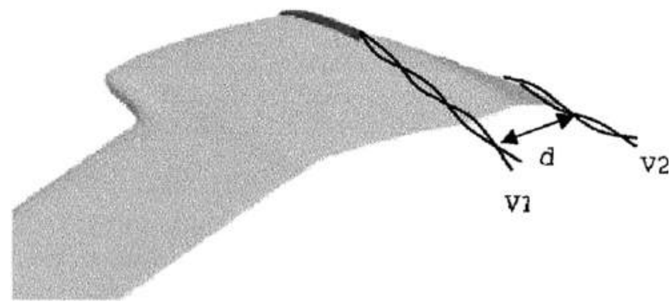

Fig. 74. The advanced KBERP tip, Hwang et al. [206].

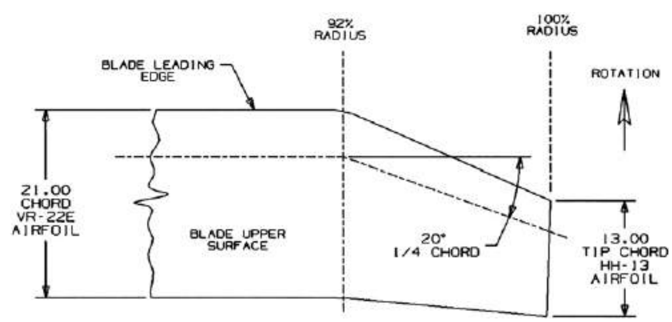

Fig. 75. Plan view of swept tip geometry for the 'new affordable' Apache blade, from Loftus [207].

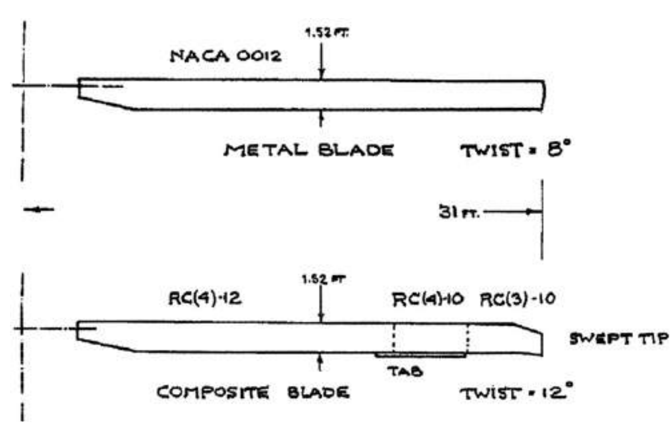

Fig. 76. The Carson replacement blade for the S-61, Curtiss [208].

enhancement and the analysis was done using the EPIC free-wake code of Quackenbush [209]. This rotor model employs a free-wake methodology which is linked to a lifting surface solution for the loading distribution. Recent developments in this high-fidelity free-wake model used in the CHARM comprehensive rotor analysis code were described by Wachspress et al. [210]. The free-wake method has been developed over the last 20 years to be numerically efficient and has been designed to provide a 'first-principles' free-vortex method without the need to adjust model parameters from configuration to configuration. The method also includes dynamic coupling, and has shown good agreement with rotor loads and BVI predictions. However, while the efficient computation of the induced velocities is an obvious strength, one area of weakness in common with all such models is the difficulty of adequately representing the compressible, viscous flow in the tip region.

In order to fully understand the detailed aerodynamics of the tip region recourse has often been made to wind tunnel tests, either on model rotors, or for convenience on fixed-wing models. In the latter case, low-speed static fixed-wing tests economically provide industry with useful insight into the characteristics of one tip shape compared to another, and provide data for validating the analysis methods in the process of applying the results to the rotational case. As mentioned earlier, the writer has carried out several wind tunnel campaigns covering a wide variety of tip shapes, and these were recently extended as part of the development of the BERP-IV tip, Fig. 77. These fixed-wing wind tunnel tests established the stalling characteristics, while the advancing blade aerodynamic characteristics were subsequently assessed using computational tools, Fig. 78. Hover performance of BERP-III and BERP-IV was later compared using the Navier–Stokes solver of the Helicopter Multi-Block Code (HMB), as illustrated in Fig. 79.

The idea of testing a wing rather than a rotor for validation of CFD codes is particularly useful for the unsteady case of a wing oscillating or ramping in pitch, since the test conditions can be more readily controlled and therefore boundary conditions are accurately known.

The work of Piziali in the early 1990s has already been referenced, but other workers have carried out similar tests to provide a deeper insight into dynamic stall and to furnish data for CFD validation. Since Piziali's landmark effort on a rectangular tip, tests have been carried out in France at LABM by Berton (see later), in the US by Ramaparian (see later), and at the University of Glasgow on a range of tip shapes, including tips with a highly swept outer edge.

The unsteady stalling characteristics of three types of wing tips undergoing ramp motion have been studied experimentally by

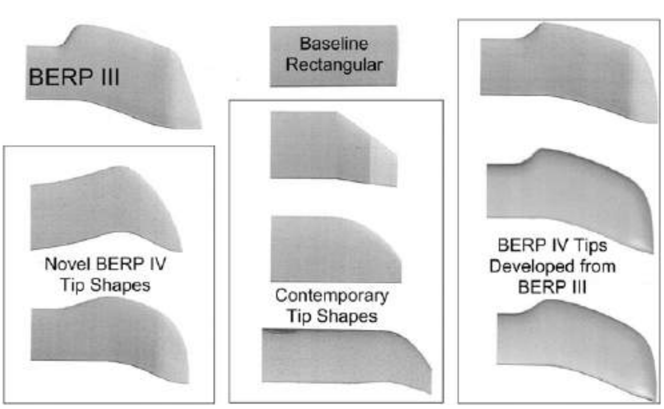

Fig. 77. A range of rotor tip shapes tested (by the author) as fixed wings in the wind tunnel during the BERP-IV programme to establish their stalling characteristics, from Robinson and Brocklehurst [17].

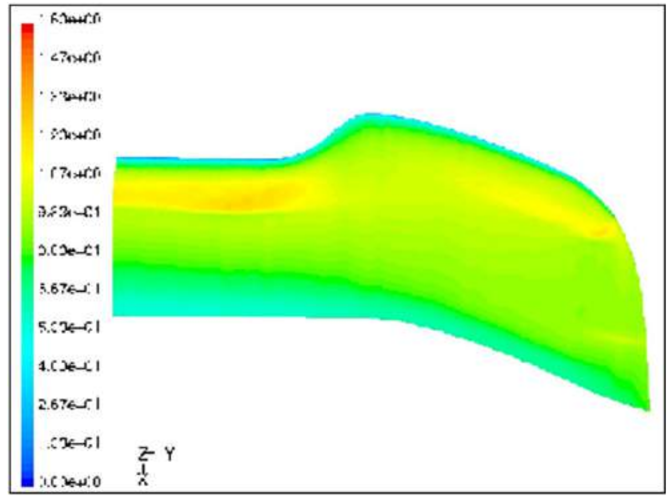

Fig. 78. Advancing blade characteristics were assessed by computations carried out (by the author) during the early design phase of BERP-IV, from Robinson and Brocklehurst [17].

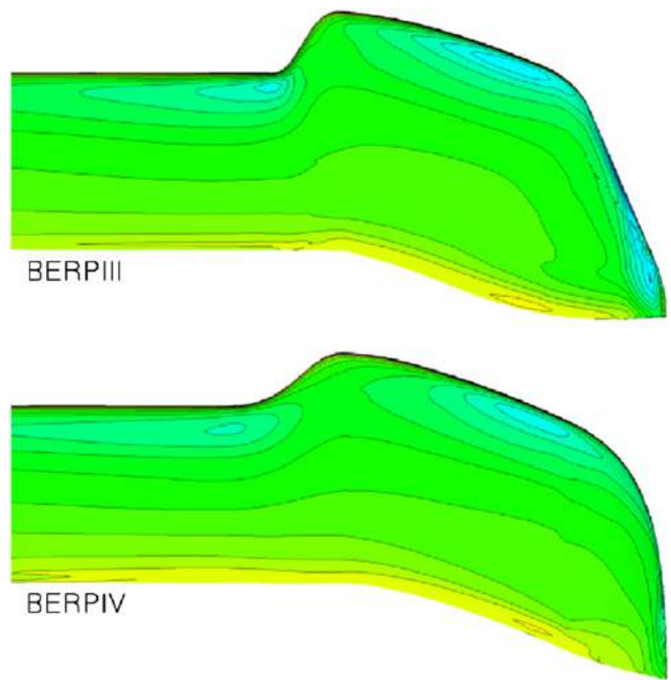

Fig. 79. Comparison of BERP-III and BERP-IV tips in Hover using HMB, from Robinson and Brocklehurst [17].

Coton et al. [211]. These included a rectangular tip, a swept-tip and a delta wing. The experiments were undertaken to meet the need to obtain a better understanding of the dynamic stall characteristics of helicopter blades. By way of comparison, the dynamic stall on the delta wing was characterised by a progressive lag in the forward movement of vortex breakdown, while on the rectangular and swept-tip wings generated a strong dynamic stall vortex that interacts with the tip vortex system. The study concluded that development of the vortex system during dynamic stall is highly dependent on the tip planform.

Coton and Galbraith [212] also describe an experimental study of the dynamic stall and 'Omega' vortex shedding mechanism on a rectangular wing.

In Korea, Chang and Park [213] have carried out an experimental study of a tip vortex roll-up of an oscillating wing. In this work, the interest is focused on the structure of the tip vortex, rather than on the loading of the wing. The authors present results for the variation in tangential velocity, axial vorticity, tip vortex circulation against angle of attack, and movement of the vortex centre during the oscillation cycle. During pitch-up, the axial velocity deficit increased, while the area of the axial velocity defect was much larger and the deficit was considerably smaller on the down-stroke. The turbulent intensity around the wing tip vortex being much greater on the up-stroke than on the down-stroke.

Berton et al. [214] describe a collaborative programme of research with TSAGI, Moscow, and model rotor tests undertaken at LABM, Marseille, France. Two free-wake methods were used to analyse the hovering rotors with different twists and tip shapes, Fig. 80. The work concludes that the methods are very efficient and there is good agreement with test, except in the case of the swept tip blades where further development of the analysis is required to overcome discrepancies in circulation distribution, vortex trajectories and instantaneous velocities in the far wake.

Schreck [215] has also carried out tests on a 2D NACA0015 aerofoil to study the boundary layer separation mechanism from measurements of shear stress obtained from hot film gauges. Ramaprian [216] has carried out tests to determine in the near field of the tip vortex behind an Oscillating Rectangular Wing.

Using the HMB code, Spentzos et al. [217] have performed unsteady computations and compared to the pitching wing tests of Ramaprian and Shreck. Beedy [218] has also carried out similar calculations for the BERP tip.

Against this background, the Helicopter Multi-block (HMB) code has been extensively validated against most of the available aerofoil, wing and rotor data in the public domain leading to the development of a full-helicopter capability, as summarised and presented by the writer in an ERF paper, Barakos et al. [219].

Trailing vortex measurements in hover have also been carried out by Martin and Leishman [220], for various tip shapes

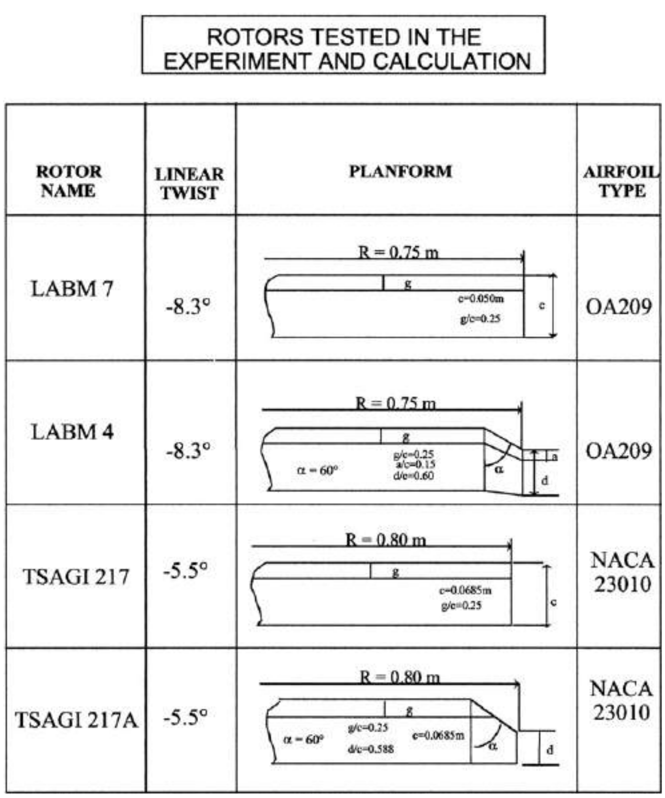

Fig. 80. Rotors tested in the experiment and calculations, Berton [214].

including rectangular, tapered, swept, and sub-wing tips. One of the primary differences noted was the change in wake geometry for a given tip shape. The tapered tip reduced the initial swirl velocity, increased the radial convection and decreased the axial convection, while the merging of the sub-wing and primary vortices created a less coherent vortical structure. The Black-Hawk style swept (sheared) tip of constant chord trailed a tip vortex outboard of 100% radius because of its geometry, and appeared to decrease both the radial and axial convection of the vortex core. Unfortunately no thrust and power measurements are presented, so the effect of tip shape on performance cannot be directly ascertained.

The formation of the tip vortex in hover has been captured numerically for two different tip edge designs; square-cut and aerofoil of revolution, Kang and Kwon [221]. They employ a solution-adaptive unstructured mesh refinement technique, with a grid of 830,000 cells, and compare viscous and inviscid computational results. They conclude that the inclusion of viscous effects significantly affects the surface pressures and the blade airloads for transonic tip Mach numbers, especially where strong shock-induced separations occur. The formation of the tip vortex was qualitatively investigated and revealed primary and secondary tip vortices merging in to a single tip vortex, coupled with a vortex sheet roll-up. They see the unstructured grid as a 'strong' alternative to previously used structured grids, however, some mesh dependency issues may still remain. The effect of wake adaption is also highlighted in a further paper by the same authors (2001) [222].

Several techniques are available to meet the objective of preserving the circulation of the vortices. Currently vorticity confinement methods are receiving attention, as represented in 2D by the work of Morvant [223], and for 3D hovering flows by Tsukahara et al. [224], who also compared with test data for a wing. Biava and Vigevano [225] also carried out an assessment of the vorticity confinement technique applied to rotorcraft and concluded that whilst a better representation of the flow field is achieved, further work was required to automatically determine a suitable confinement parameter. A numerical method for vorticity confinement in compressible flow was also presented by Hu et al. [226]. Here the application is to vortex formation on a flat delta wing, but the method has clear application to 3D rotor wakes.

Wenren et al. [227] apply vorticity confinement to the prediction of the flow over complex bodies, such as a helicopter fuselage, where bound vorticity is shed, and also for cases of convecting vortices for a complete helicopter configuration. The vorticity confinement techniques avoid the need for logic, or Lagrangian marker arrays, and according to Wenren, shed vortex filaments can be convected indefinitely with no numerical spreading.

At ONERA, Canonne et al. [228] described cylindrical mesh refinement to better capture the wake of an isolated rotor in hover. The computations also employed Chimera overset grids to contain the rotor blades within the cylindrical background domain. The latter is then periodically adapted to allow the tip vortex to be captured for approximately 380° on a grid of approximately 600,000 points. Pomin and Wagner [196] also develop techniques for preserving the tip vortices in the wake.

An alternative to the higher order CFD methods and vorticity confinement techniques described above is to re-cast the Navier–Stokes equations in a vorticity conservation form as presented by Brown [229]. This computational method was originally intended as an alternative to a free-wake model for the Glasgow RASCAL flight mechanics code. However, the method is computationally expensive, despite recent attempts to accelerate it, and excludes compressibility and viscosity in the primary formulation. Several papers have now been published where the Vorticity Transport Model (VTM) has been used to study the effect of blade twist on the vortex ring state, Brown et al. [230] and in cruising flight by Line and Brown [231]. Further studies of the vortex ring state in forward descending flight were described by Brown et al. [232]. The VTM provides a detailed description of the wake, but relies on a lifting-line or lifting surface model to provide the blade bound circulation, hence is not currently capable of capturing the effects of compressibility for specific tip design features. However, this limitation could be overcome by coupling this wake model to a RANS solver.

The multigrid TLNS3DR CFD code has been used by Hu [233] to model a tilt-rotor in hover with various tip shapes reminiscent of those tested in earlier acoustic studies in the US. These include an Ogee-type tip, a sub-wing, and a 45° tapered tip, and datum rectangular tip (see earlier Figures). The two 'low noise' tips, while producing a weaker, or more diffused (pair of) tip vortices were found to consume more power. The author claims that this CFD code provides an efficient tip analysis tool for initial design analysis, and quotes a runtime of about 1.5 h on a Cray-YMP single processor using grids of just over 500,000 points. However, this grid density seems rather low, and the studies appear to have been carried out with the rotor at low pitch.

CFD models for rotor performance still require further development, but have now advanced to the stage where it is possible to consider their use in an optimisation process. A paper on numerical optimisation of rotor performance in hover was presented by LePape and Beaumier [234]. Here, the authors validate their method against the tests on the 7AD rotor, and show an optimised clipped-elliptical tip with no sweep, and a constant chord swept tip with no chord taper, and then go on to consider an anhedral tip. Their OPT-2 configuration employs a form of anhedral which arches over the tip vortex from the preceding blade (in hover), before being angled downwards towards the tip (retaining a rectangular planform), Fig. 81. They then apply the optimisation method to the ERATO rotor to obtain a curved planform shape, with a small amount of anhedral. The final design shows a significant improvement in hover Figure of Merit, due to reduced loading in the tip region.

If CFD methods are to be routinely used in the design environment to seek an optimum solution, both high-resolution and fast run-times are a pre-requisite. An alternative approach to the wake problem that would appear to hold promise of faster run-times is the embedded vortex wake technique of Bhagwat, Moulton and Caradonna [235], Fig. 82. The authors describe the ideas behind embedding a force free vortex-lattice wake within a CFD simulation such that the convection velocity is determined by the solution of the full-potential equations, rather than by direct application of the Biot–Savart law. Whilst initial stability issues were explored with a constant circulation strength in the wake, the aim is to provide an 'outer flow' representation that will relieve CFD methods of the burden of resolving the (downstream) shed and trailed wake. The approach put forward by Bahgwat is clearly an alternative to the use of higher order schemes, or vorticity confinement methods, and would appear to offer a more economical solution. The paper presents some preliminary hover performance results for the UH-60A rotor using a 288,000 point grid. Whilst this new method is currently being developed in hover, it seems reasonable to expect that it will soon be extended to forward flight.

The application of hybrid CFD methods was anticipated by Aiken et al. [236] in a review of 'Future Directions for Rotorcraft Technology at Ames Research Center'. Aiken considers the optimisation of rotor performance through improvements in tip shape, Fig. 83, using such methods. Aiken also recognises the trend towards smart actuation of aerodynamic devices, such as flaps, to enhance aerodynamic performance of future rotorcraft. While most flaps currently envisaged are located inboard of the tip, the addition of a flap (or other device) to provide closer to

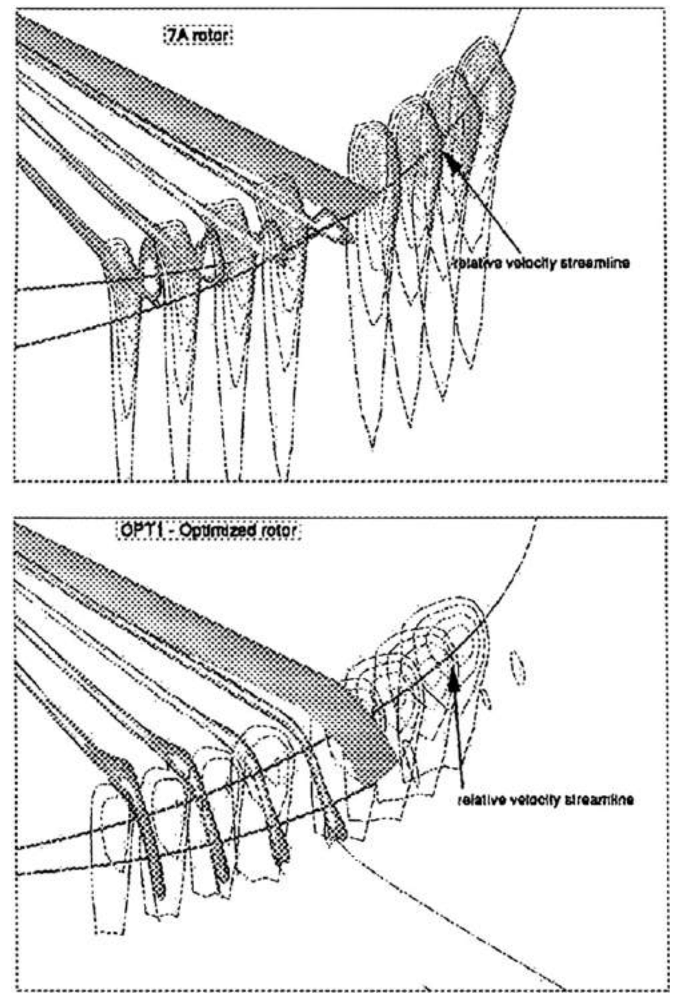

Fig. 81. Vorticity contours for 7A reference blade and anhedral tip optimised rotor blade, LePape and Beaumier [234].

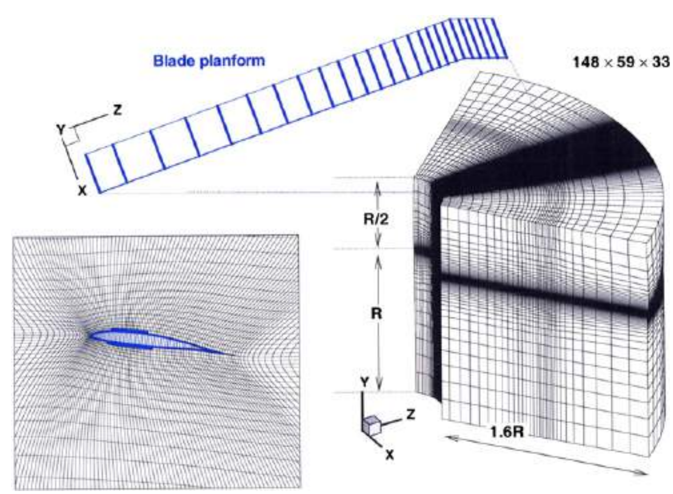

Fig. 82. Application of CFD to a UH-60-type blade with a swept tip, Bhagwat et al. [235].

ideal aerofoil characteristics, may later have some influence on the choice of planform and tip shape, Fig. 84.

An active flap mounted on the MD900 blade has been recently tested in the Ames 40×80 foot wind tunnel during a Boeing/ NASA project, Fig. 85. In this case the tip shape is parabolic, and

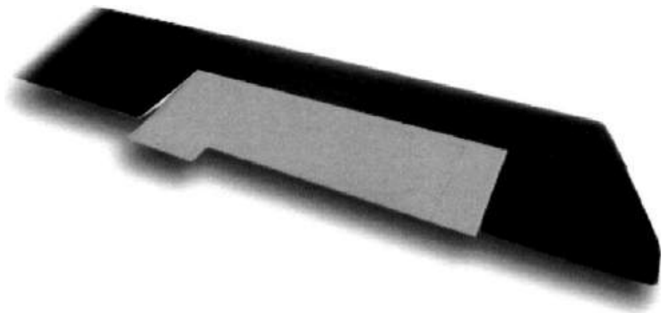

Fig. 83. HeliFlap electromagnetic actuator for on-blade control whirl tested on OH58, Aiken et al. [236].

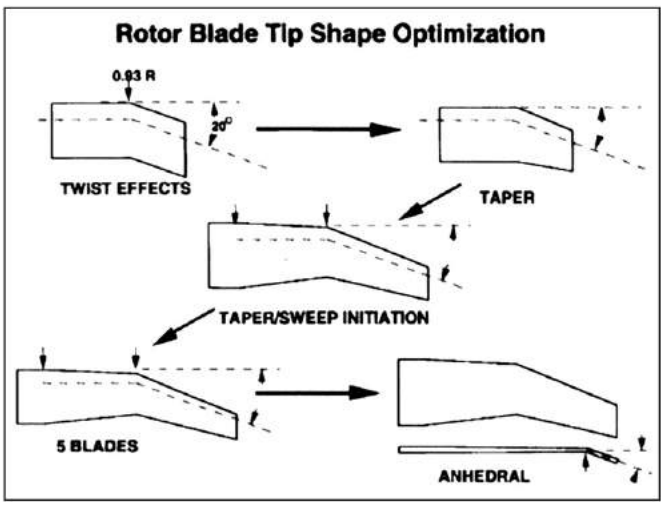

Fig. 84. Advanced design methodology to improve rotor hover performance, Aiken et al. [236].

vibration reduction aspects were discussed in a paper by Hall and Anand [237]. This tip shape and flap combination is also shown during earlier hover tower tests in Leishman's RAeS Cierva Lecture [238], and in his subsequent book (2007) [239].

Imiela [240,241] provides a recent example of the further application of optimisation to enhance hover performance, taking into account the aeroelastic deformation as well as employing computational aerodynamics for a high fidelity solution, and arrives at a swept-tapered anhedral tip with enhanced hover performance. For this blade the tip starts well outboard, in contrast to his rigid blade optimal solution where he shows a swept forward blade with the sweep commencing further inboard. The result of the initial rigid blade optimisation is shown in Fig. 86, while the final blade shape obtained taking aeroelastic deflections into account is shown in Fig. 87. Both blades also have twist which helps to increase the loading inboard and decrease it in the tip region.

A further example of optimisation is given by Chae et al. [242] where an improvement in the Aeroacoustic performance in Hover is sought. Their analysis leads to a blade, arising from a Self-Organisation Map (SOM) process, with a blended swept and tapered tip with forward notch offset, Fig. 88, similar to that used on the BERP blade, although somewhat surprisingly the outer edge of the tip is cut-off square.

Clearly, the blade shape that results from any attempt at optimisation will depend on the flexibility of the design parameters, the constraints imposed, and the objectives set. Thus it is not surprising that widely differing blade geometries result, even for applications that are currently focused on the simpler hover case.

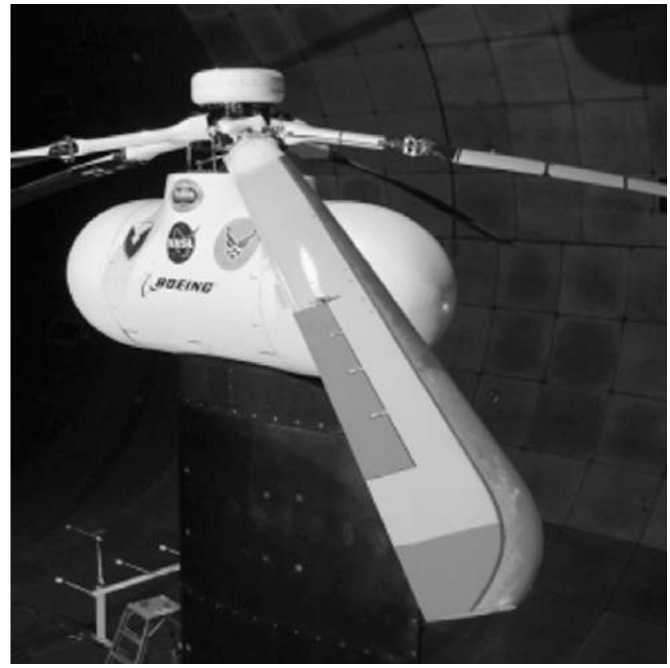

Fig. 85. Active flap and parabolic tip of the MD900 blade as tested by Boeing/NASA in the NASA Ames 40 × 80 foot wind tunnel, from Hall and Anand [237].

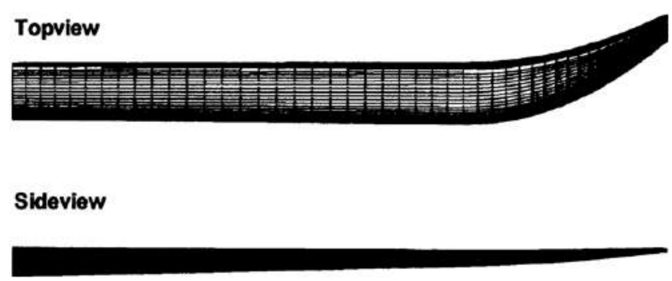

Fig. 86. Forward swept blade shape for optimum hover performance using an initially rigid blade as obtained by Imiela [241].

In addition to optimisation work being carried out in hover, Johnson and Barakos [243] have made a start in considering the optimisation of blade tip shapes in forward flight using the HMB CFD framework and parametric changes to the geometry. In this way the effect of sweep and anhedral, etc., on the performance and control loads can be assessed. It is anticipated that CFD will become more widely used as a design optimisation tool as faster CFD methods, e.g. Woodgate and Barakos [244], are implemented and computational resources further enhanced. This latter method builds up the flowfield from several harmonics for which steady solutions may be obtained, in lieu of the more traditional time-stepping approach, thus offering a substantial reduction in runtime for each flow solution, whilst still capturing the salient non-linear flow feature such as shocks which occur on the advancing blade.

The trend toward coupled CFD/CSD analysis and the continuing demand for a quiet blade with good hover performance has led to the development of the EuroCopter Blue-Edge blade, as recently announced by ONERA [245], and shown in Fig. 89.

This section of the literature review has discussed the evolution of helicopter blade designs and tip shapes, alongside the development of methods for their analysis and evaluation. Perhaps because of past difficulties in accurately predicting the flow field at the tip of a helicopter rotor blade, there appears to be no general consensus for helicopter tip shapes, and different types

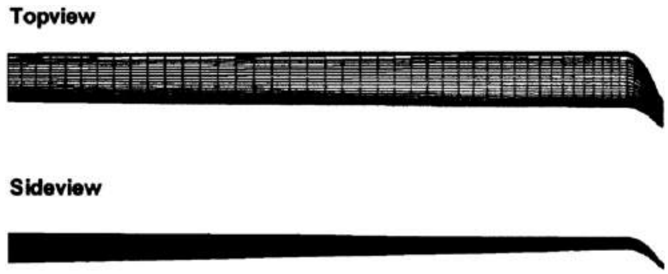

Fig. 87. Final aft swept anhedral tip shape for optimum hover performance using an aeroelastic blade, Imiela [241].

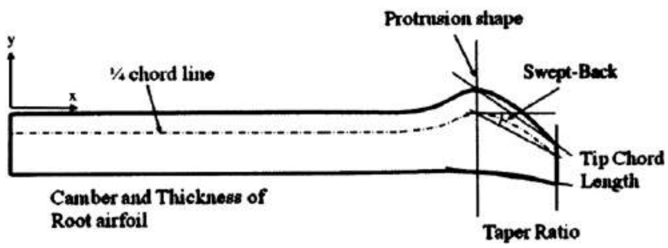

Fig. 88. The blade design shape features used by Chae et al. [242].

Fig. 89. The EuroCopter blue edge blade, as announced by ONERA [245].

of tip have been adopted in the USA, the UK, and the rest of Europe. The swept (tapered) tip, the parabolic tip and the BERP tip, have all been the subject of recent development aimed towards specific goals. However, now that modern analysis methods are becoming more available to industry, and the coupling between the aerodynamics and the dynamic blade deflections is starting to be taken into account, companies are starting to make further refinements to their designs. In addition there are several tip shapes intended to alleviate BVI noise by splitting, or diffusing the tip vortex. The review has also revealed sources of data suitable for CFD validation, either from model rotor tests, or from steady or unsteady fixed-wing wind tunnel data where these tests have been specifically aimed at the helicopter problem. Amongst all the research and development effort expended for the main rotor it would appear that the tail rotor has received relatively little attention.

2.3. Outcome from literature survey

Reported developments in rotor blade design and fixed-wing aerodynamics have been surveyed with particular focus on the aerodynamic design of the tip. It is evident that a wide variety of tip shapes have been explored over the past 20–30 years, although there is no clear consensus as to a best design for helicopters.

The helicopter is a unique vehicle which lends itself to fulfilling a variety of roles, and therefore spends varying amounts of time in hover and forward flight. In the past it has been difficult to accurately assess the overall impact of design changes by use of simple tools due to the complex physics involved. Manufacturers are now faced with the need to produce more efficient vehicles, and so it is more important than ever to quantify detailed improvements to the design. Modern computational methods are now available to do this.

The major emphasis for rotor blade design has been on aerodynamic performance, with efforts to reduce noise playing an important, but somewhat secondary role. For main rotor performance, two main themes have emerged. On the one hand, there has been great focus on improving the hover Figure of Merit by employing twist and taper. On the other hand, high-speed forward flight requirements have also give rise to important design considerations, and in some cases have dominated the blade tip design. While it is highly desirable to relieve compressibility effects through sweep, it is difficult to incorporate sufficient sweep into the overall blade design, leaving a need to employ relatively thin aerofoils at the tip. Thin aerofoils and some degree of planform taper will give advantages in hover as they offer to minimise the profile power, however, they may lead to premature separation and a reduction of lift on the retreating blade. Modern helicopters tend to operate at high disc loading, and this places even greater emphasis on good blade and tip design to provide the maximum possible retreating blade performance, at the same time requiring the optimum figure of merit to be achieved at ever increasing thrust coefficients. This in turn places greater demands on the tail rotor to provide more thrust to compensate torque and maintain or expand control margins, although little has been found in the literature on developments in tail rotor aerodynamics in general, or tip design in particular.

However, in seeking a means to predict the performance of new main and tail rotor blade designs, the author has recently applied the computational method of HMB to evaluate a range of tail rotor tip shapes, both in hover and forward flight, Brocklehurst [246,247]. Navier–Stokes predictions of the thrust and power allowed trends in induced power and profile power to be determined, and the computations were also extended to evaluate the performance of the tail rotor at high pitch angles. From this work a preference was found for a Küchemann-type tip with a small amount of anhedral.

The modern ethos is also to minimise fuel consumption and noise. The design of the tip plays an important role in all aspects of main and tail rotor performance. Blade structural design, dynamics, vibration, ease of manufacture and cost are also strong design drivers.

Three types of main rotor blade tip designs have been identified. In the USA, the simple sheared-swept tip or swept-tapered-anhedral tip represents the state of the art, while in Europe the parabolic tip has been widely adopted, except in the UK where the BERP tip remains a unique option. Each tip is probably well suited to its particular operating requirements, which perhaps vary according to locally perceived mission requirements, although no doubt fashion and company bias have played a role. These three types of tip still tend to dominate the choice for helicopter main rotors, whilst a variety of simpler tip shapes are generally found for tail rotors. For the tail rotor, the modern trend towards blades with low radius/chord ratio is also helpful in relieving compressibility effects, and perhaps explains why tail rotors tend not to feature large amounts of sweep at the tip.

Anhedral has been used to good effect on several main rotor designs and appears to be particularly effective on the BERP-type tip at high rotor loadings and offers an improved hover Figure of Merit. In forward flight anhedral can be useful to balance the effects of sweep and notch offset. Anhedral has also been used on propellers and tilt-rotor blades, and has potential to be used advantageously on tail rotor blades which are required to efficiently produce high thrust to compensate the main rotor torque and provide a good manoeuvre margin in hover.

A separate design challenge has been to reduce rotor noise, and BVI noise in particular. Several tip shapes have been put forward to achieve this goal, sometimes with little regard to performance. Several examples have been seen of tip shapes which have been designed to split, or diffuse the tip vortex, but these have not been subsequently adopted due to their limited performance potential, and perhaps an easier option has been to use low volume tips at lower tipspeeds and/or adopt alternative descending flight procedures. In general, a main rotor blade with a well designed thin swept-tip shape that has good advancing blade aerodynamics, may need only small refinements to also have acceptable thickness and loading-noise, especially if the tip speed is moderate.

This literature review has also identified some overlap with fixed-wing aircraft, particularly with regard to tip aerodynamics and the details of vortex formation. While there are some obvious fundamental differences, both fixed-wing and rotary-wing configurations require accurate resolution of the flow-field if the results are to be useful in tip design studies. The nature of the helicopter problem is, however, much more complex than fixed-wing and is much more demanding from a modelling point of view due to the need to preserve wake vortices, take into account variations in incidence and sideslip (in cruising flight), and also include unsteady effects. The design must also work within much tighter moment constraints. Nevertheless, much can be learnt from validating the methods against fixed-wing tests, and there is considerable carry-over in some of the detailed design thinking. In particular, the work of Hoerner and Küchemann has provided a basis for generating improved tip shapes.

The review has also covered the development of computational methods. Analysis techniques have developed from rotor models based on lifting-line and lifting-surface theory, with a prescribed or free wake, to the application of sophisticated CFD methods. Initially the numerical approach required some of the world's largest computers, but these modern methods are now becoming available in industry, and offer greater insight and higher resolution than traditional design methods.

Two main features of the computational approach would appear to require further development for helicopter applications. One is that it is important to fully capture the wake in order to determine the correct flow-field around the rotor blade, and the other is that the solver needs to include boundary layer transition in both steady and unsteady (3D) conditions, if accurate overall performance and the effects of retreating blade stall are to be predicted. Much effort has been expended on coupling wake models with near-field Navier–Stokes solutions in an effort to obtain the desired accuracy at acceptable computational cost. It is also clear that rotor trim and blade deflections are important aspects of helicopter simulation. Often, the rotating and pitching blades may operate in proximity to a stationary fuselage, or fin, and this presents challenges in grid generation, requiring the use of sliding grids, or Chimera overset grid techniques. From the literature there appears to be a preference toward structured grids to resolve the flow features, but some developers favour the Chimera approach. It is also clear that CFD methods are maturing quickly and through rapidly growing computer resources will soon be universally accepted and indispensable for rotor blade design evaluations.

Recent research effort on CFD has been directed towards tackling the challenging problems of whole helicopter simulations. Coupling of CFD with structural dynamics to take into account blade deflections has also been a focus of attention, and offers to greatly improve the fidelity of the simulation. Most recently, fast harmonic-balance methods have begun to emerge which promise further run-time reductions for forward flight simulations. However, while CFD has been applied to a range of rotors problems, including investigations of tilt-rotors, little new work has been found on the use of CFD for the design of new tip shapes, particularly for tail rotors.

3. Concluding remarks

The review of helicopter tip shapes presented in this paper has discussed the evolution of helicopter blade designs and tip shapes, and the development of methods for their analysis and evaluation. The review has identified three main types of helicopter tip designs: the parabolic tip, the swept (tapered) tip, and the BERP tip. In addition there are several tip shapes intended to alleviate BVI noise by splitting, or diffusing the tip vortex. Despite a considerable research effort over the last 30 years, no single best tip shape has emerged, perhaps because the tools required for accurate evaluation have not previously been available, or because design requirements and manufacturing constraints have also been evolving. Modern high-resolution CFD methods now offer an opportunity to gain deeper insight into the aerodynamics of blade and tip design, and with continued rapid development, will soon have sufficient maturity to make a major impact on the design process.

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