

Hermann Glauert FRS, FRAeS (1892 – 1934)

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Abstract

The paper deals with the life and work of Hermann Glauert who, at his untimely death, was Head of the Aerodynamics Department of the Royal Aircraft Establishment, Farnborough. After a biographical sketch, the paper describes his work in aeroplane performance including stability and control, aerodynamics, propellers, autogyros and helicopters, and finally his review papers and other contributions to the Royal Aeronautical Society.

All of Glauert's work in aeronautics sprang from his career at Farnborough. The vast majority of his published papers appeared as Reports & Memoranda (R&M) of the Advisory Committee for Aeronautics (ACA) which in 1920 became the ARC. He was well placed to appreciate the aerodynamic theory developed by Ludwig Prandtl and his associates at Göttingen, and he kept abreast of German developments; at times these provided seminal ideas for his own original researches. His classic textbook, *The Elements of Aerofoil and Airscrew Theory*, was first published in 1926. For helicopters in forward flight, he recognised that a rolling moment would be created by the advancing blade having a greater lift than the retreating blade. To remove this moment, he suggested arranging a periodic variation of blade angle during each revolution, a proposal later universally adopted.

1. 0. INTRODUCTION

Hermann Glauert's early death in 1934 dealt a serious blow to aerodynamics research not only in Britain but also worldwide. This was a time when the faster and more efficient monoplane had at last become reality and here Glauert had made major contributions to the understanding of wing aerodynamics. The prospect of even higher speeds lay temptingly ahead. Although the aerodynamic barriers to such future progress were rightly perceived to be enormous, certainly in Britain Glauert would have been exceptionally well-placed to overcome them. A further cause of regret is that in those days published records of the careers of outstanding scientists and engineers were often relatively short, four pages only being devoted to Glauert and his work in the Obituary Notices of Fellows of the Royal Society. It is felt that Glauert's considerable achievements merit a far more detailed record, and this is the purpose of this paper. Section 2 provides an

outline of his life and further Sections give more specific details of his achievements not only in aerodynamics but also in aeroplane performance, stability and control, propellers and in the newly emerging technologies of the autogyro and the helicopter.

2. 0. THE LIFE OF HERMANN GLAUERT

2. 1. Early Days and Cambridge

Hermann Glauert (Fig. 1) was born on October 4th 1892 in Sheffield where his father had established a cutlery manufacturing business at the Wallace Works in Furnival Street. His father, Louis Glauert, was a naturalised British citizen of German birth married to an Englishwoman, Amanda, née Watkinson, also born in Germany. The Glauert family had arrived in England during the latter half of the 19th Century and Hermann was the youngest of five children. He was educated at the King Edward VIIth School in Sheffield, and was elected to a scholarship at Trinity College, Cambridge in 1910, arriving there more or less on his 18th birthday. He enjoyed undergraduate life in Cambridge walking and talking with his peers, was an active member of a play-reading society, played tennis well and chess very well. His unusual mental powers were perhaps revealed during weekly Sunday evening games of bridge. In 1913 he was placed in the First Class of Part II of the Mathematical Tripos, gaining distinction in the higher subjects for which he was awarded the Tyson Medal for Astronomy. Undergraduate notebooks that survive demonstrate a precision and clarity of presentation that characterise his later work.

Following graduation he undertook research in astronomy, initially under the guidance of Arthur Eddington (1882-1944); his progress was rewarded in 1914 by the award of an Isaac Newton Studentship in Astronomy and Physical Optics and the Rayleigh Prize for Mathematics in 1915. In his first published paper ⁽¹⁾, and a follow-up ⁽²⁾, Glauert addressed some consequences of small changes in the rate of rotation of the Earth. It was known that deviations in longitude of the Moon from its theoretical orbit were due to these small changes. What he demonstrated was that errors in longitude of Mercury, Venus and the Sun may similarly be explained by minute changes in the rate of rotation of the Earth. A second, and more substantial, investigation ⁽³⁾ concerned the form of a rotating fluid mass when this is deformed by a satellite in a circular orbit in the equatorial plane of the fluid mass. Earlier work had assumed that the densities of the two bodies were identical and that the fluid mass was itself in solid-body rotation. This latter assumption was based on the idea that even for fluids of very small viscosity any relative movement of the fluid will be damped out. Glauert removed these two restrictions and, in particular, for an inviscid fluid took account of the motion of the fluid within the primary body. This paper provides an insight to both his familiarity with Euler's equations of motion for inviscid flow and his willingness to adopt approximate, or as we might prefer, asymptotic methods in the solution process. Further work in astronomy was no doubt under way but not obviously brought to a conclusion.

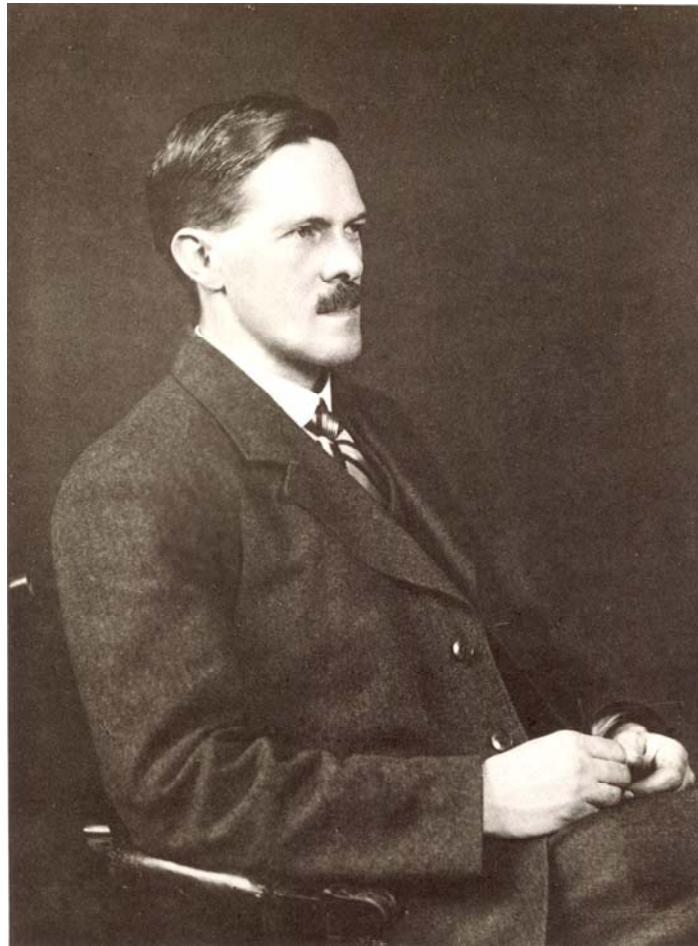


Figure 1. Hermann Glauert (1892-1934)

Source: Royal Aeronautical Society (National Aerospace Library)

2. 2. The Farnborough Years

Notwithstanding the Registered Aliens Act of 1905 which was specifically targeted at Polish and Russian Jews fleeing Tsarist Russia, in Britain before the First World War immigration controls were minimal; in the late 19th Century there was an influx of artisans from Continental Europe including many from Germany. On the outbreak of war old men who had not bothered to take out naturalisation papers during several decades in Britain found themselves interned in the Isle of Man, and their sons in the army. In the general hysteria people and shops with German-sounding names were liable to be attacked. This provoked some to change their names and so avoid anti-German sentiment, a notable example in the field of aerodynamics being Norman Tonnstein who in 1917 changed his name to his wife's maiden name of Piercy⁽⁴⁾. Unlike the situation during World War II, scientists and engineers were not drafted into the war effort on graduation. As we have seen, Hermann Glauert, whose German descent might have been an embarrassment to him, remained in Cambridge where such matters were of less concern, and where he could work in peaceful surroundings. But perhaps not with a peace of mind, and when a chance meeting with a friend from his undergraduate days, William Scott Farren (1892-1970),

led to an offer of a position at the Royal Aircraft Factory, Farnborough in 1916 he accepted. He joined the Aerodynamics Department of which Farren was Head.

In 1905 His Majesty's Balloon Factory was moved to Farnborough and by 1911 it had become the Royal Aircraft Factory (RAF). In 1909 Mervyn O'Gorman (1871-1958) took over as Superintendent (the position was not designated Director until 1941) with a determination to push into aeronautics. Aeroplanes were designed and built there throughout the ensuing war, notably the B.E.2 biplane series developed to a highly stable state and one of the war's outstanding single-seat fighters, the S.E.5a. However, in 1916 O'Gorman resigned as a result of political pressure from those who said it was unfair for Farnborough, as a government establishment, to design and build aeroplanes in competition with industry. In 1918 the establishment was renamed the Royal Aircraft Establishment (RAE) in part to reflect its change to a non-manufacturing role but also, of course, to avoid confusion with the newly-formed Royal Air Force.

As war approached O'Gorman had begun to build up the Factory's human resources by recruiting mainly Cambridge men, the last of whom was Glauert. From 1916 to 1922 he lived quite happily at 'Chudleigh', a large house effectively run as a private mess by some members of the Farnborough staff with F. M. Green, the Factory's chief engineer, as the unofficial Mess President. The permanent members were, in addition to Glauert and Green, Farren, H. Grinstead and R. M. Wood. Others, at various times, included F. W. Aston, B. M. Jones, F. A. Lindemann, D. H. Pinsent, G. I. Taylor, G. P. Thomson and H. A. Webb (Fig. 2). Life at 'Chudleigh' appears to have been congenial with a stimulating atmosphere. Many years later S. B. Gates recalls⁽⁵⁾ of the 'Chudleigh lot' that "...they were said to play erudite games like three-dimensional chess when they were not analysing what the day's inspiration and observation brought them. They were as wildly individualistic as any élite are – and about twice as hardworking..." By 1920 Farren, Aston, Jones, Taylor and Thomson were all back in Cambridge, Lindemann in Oxford, but perhaps surprisingly Glauert chose to stay on as an employee of the RAE. In 1920 Glauert himself was elected to a Prize Fellowship at Trinity. Shortly after the end of the war he went to Göttingen with Ronald McKinnon Wood (1892-1967), who had succeeded Farren as Head of the Aerodynamics Department. No doubt Wood's choice of travelling companion was, in part anyway, due to the fact that Glauert was a fluent German speaker. As Wood recalls⁽⁶⁾, the main purpose of their visit was to assess Prandtl's new return circuit wind tunnel with its novel 5:1 contraction ratio upstream of the working section. However what Glauert did find at Göttingen was the seminal work on wing theory that had been carried out by Prandtl, Betz and Munk. As we shall see, this had a profound effect upon his own research in the years ahead. Another encounter at about this time was to have an equally profound effect on his life.

Miss Muriel Barker (Fig. 3) from Nottingham went up to Newnham College, Cambridge in 1912, completing the Mathematics Tripos course in 1915. Under the then prevailing conditions for women, completion of the Cambridge course led to a degree awarded by London University. For three years she was a teacher in Liverpool, and then spent a year, 1918-1919, as a research assistant at RAE Farnborough. This was followed by a year as a graduate student at Bryn Mawr College, Philadelphia before returning to Newnham College as Bathurst Student in Aeronautics 1920-1922. Her first publication⁽⁷⁾ arose from her work at Farnborough. In that paper she uses a graphical method to determine the streamlines around a Joukowski (see Appendix) aerofoil. The streamline patterns are obtained from the streamlines around a circular cylinder, and the paper



Figure 2. Aerodynamics Department, RAE, 1918. Believed to be, from left to right up the steps; Glauert, Thomson, Lindemann, Grinstead, Farren, R. Hill, Pinsent. Centre foreground: Bairstow and R. M. Wood. [Courtesy of FAST.]

also determines analytically the angle of downwash at various stations downstream. A second paper⁽⁸⁾ is based upon experiments carried out in Cambridge at the suggestion of G. I. Taylor. In these the behaviour of a small Pitot tube at very low flow speeds is investigated. The apparatus used is very similar to Reynolds's tank⁽⁹⁾, its water being drained through a horizontal pipe in the centre of which sits the Pitot tube. At the conditions investigated, effectively those for which the Reynolds number is less than 30, Miss Barker finds that the flow at the Pitot tube's nose is akin to Stokes flow at the nose of a sphere for which the viscous normal stress is important. Consequently the difference between the Pitot tube's reading and the static pressure is proportional to the flow speed rather than to its square. It appears that she was the first to

observe this effect. At the end of this period in Cambridge she was offered a position at Cheltenham Ladies College, but had hardly taken that up before accepting a proposal of marriage from Hermann Glauert, and returning to Farnborough in 1922. What must have been ongoing research from the earlier Farnborough period was published in this Society's Journal ⁽¹⁰⁾. That paper deals exclusively with the method of conformal transformation to determine the flow past a body of aerofoil shape. Examples include the Joukowski aerofoil, the generalisation that yields a finite trailing-edge angle and von Mises' extension to obtain aerofoils with a fixed centre of pressure. Returning to research much later, she investigated ⁽¹¹⁾ the capture of raindrops by a cylinder and an aerofoil moving at uniform speed, a problem of ongoing concern due to ice formation in flight.



Figure 3 Muriel Barker (1892-1949). [Courtesy of Audrey Glauert]

There were three Glauert children, Michael (1924-2004) and the twins Audrey and Richard born in 1925. All three became distinguished scientists/academics in their own right, Michael following in his father's footsteps with a mathematics career which began with specialisation in aerodynamics ⁽¹²⁾. As his young family expanded, Hermann Glauert's research prospered, and he

was constantly at the service of the Aeronautical Research Committee (ARC) for advice on all aerodynamic problems. By the early 1930's he was one of the world's leading aerodynamicists, his stature recognised by election to Fellowship of this Society in 1926 and, in 1931, Fellowship of the Royal Society, the first serving member of the RAE to be so honoured. Shortly afterwards he succeeded Wood as Head of the Aerodynamics Department, taking concomitant administrative duties in his stride. On August 4th 1934, driving with his family and his elder brother, Otto, they were stopped near Norris Bridge by a team of Royal Engineers blasting tree stumps to extend the flying area at Laffan's Plain⁽¹³⁾. Tragically, standing at an allegedly safe distance he was struck by a large piece of debris and died shortly after: a particularly cruel blow for someone who had contributed so much to safety in the air. Dietrich Küchemann, who was Head of the Aerodynamics Department at the RAE 1966-1971, recalled⁽¹⁴⁾ that when news of Glauert's death reached the group he worked with at Göttingen (Prandtl's group) they all stopped work for the day in tribute. And for those who knew him⁽¹⁵⁾ Glauert "...never lost the essential modesty and gentleness which was so striking a feature of his character."

3. 0. AN OVERVIEW OF GLAUERT'S AERONAUTICAL WORK

All of Glauert's work in aeronautics sprang from his career at Farnborough. The vast majority of his published papers appeared as Reports & Memoranda (R & M) of the Advisory Committee for Aeronautics (ACA) which in 1920 became the ARC. All but one of his papers can conveniently be divided among four research areas, as follows: aeroplane performance including stability and control; aerodynamics; propeller performance; autogyros and helicopters. Indeed it is appropriate that his papers be reviewed in that order since to a large extent this will trace the development of his thinking. The single exception to this is his mathematical paper⁽¹⁶⁾. In it he determines the best linear relationship between variables determined by observation, and so liable to error, and other variables whose values are known accurately.

His early work on aeroplane performance, stability and control served as his introduction to aeronautics, and from this he was well placed to appreciate the solid basis of aerodynamic theory developed by Ludwig Prandtl (1875-1953) and his associates at Göttingen which Glauert acquired from his visit there shortly after the close of the First World War. Thereafter he kept abreast of German developments and at times these provided seminal ideas for his own original researches. More to the point, he had the deep physical insight and outstanding mathematical ability to put such ideas convincingly before an often doubting British aeronautical community. His educative role in this respect is particularly noteworthy in his review papers and lectures presented to this Society, a feature which will be described in the final Section of this paper.

4. 0. AEROPLANE PERFORMANCE, STABILITY AND CONTROL

Glauert's earliest work in aeronautics was in this area, his first paper⁽¹⁷⁾ being written in conjunction with that other recent arrival at Farnborough, Sidney Barrington Gates (1893-1973). Their interest was in aeroplane performance and their analysis begins with an application of the energy equation to climbing flight in which various empirical relations are required to account for engine power and airscrew efficiency variations. Lift and drag coefficient data are drawn from full-scale experiments on a B.E.2c (Fig. 4). An appendix derives the atmosphere's density

variation stemming from the observation that temperature decreases linearly with altitude; in this respect the analysis is that used to obtain the modern International Standard Atmosphere (ISA) although the values of the constants needed are not those of the ISA. With these various relations, Glauert and Gates are able to estimate maximum altitude and the time to climb to intermediary heights, results for the latter being obtained by expanding the integrand involved in ascending powers of its small non-dimensional density term. A perturbation analysis is then used to judge the effects on maximum altitude and time-to-climb produced by small changes in the B.E.2c's design. Level flight conditions are analysed using a suitably restricted form of the energy equation and again small changes in design relating to the B.E.2c are explored; unsurprisingly, the more noticeable effects are those for changes in engine power, airscrew efficiency and drag. Longitudinal stability is then examined, the analysis being based on the dual conditions of trim (zero moment about the centre of gravity) and the equality of total lift and weight. However, the analysis concentrates on the long period phugoid motion first described⁽¹⁸⁾ by Frederick William Lanchester (1886-1946) and later examined in more detail⁽¹⁹⁾ by George Hartley Bryan (1864-1928). In order to employ the latter's results, Glauert and Gates draw on recent full-scale stability tests⁽²⁰⁾ on a B.E.2c so as to estimate the aerodynamic stability derivatives involved. Their perturbation analysis reveals that centre of gravity location and changes in tailplane area have the most noticeable effects on the phugoid's period.



Figure 4. B.E.2c.

Source: Royal Aeronautical Society (National Aerospace Library)

Glauert's next paper⁽²¹⁾ provided an assessment of full-scale elevator experiments on an R.E.8 (Fig. 5), a tractor biplane replacement for the ubiquitous B.E.2c which by then had been recognised as possessing limited performance. Various elevator sizes were tried, ranging from 30% to 60% of the tailplane area, and for which stick forces were measured. He concludes that a reduction in elevator size reduces the stick force and suitable adjustment of the stick gearing reduces stick movement. As a continuation of these experiments with the R.E.8, Glauert⁽²²⁾ then assesses tests with tailplanes shaped to have either raked-back or raked-forward tips, the elevators in both cases occupying 40% of the chord. He concludes that, from the point of view of control

effectiveness, the raked-back tip is superior. Glauert's experience of control surface design then became applied to the ailerons ('flaps' in Farnborough parlance at the time) of the R.E.8⁽²³⁾. In these experiments the standard flaps of 24in chord were replaced by those of 16in chord, standard flaps with washout toward the tips (9° decreased incidence angle at the tips) and standard flaps with chords tapering to 8in at the tips. Measurements were made of the time to bank to 45° with different forces on the control column, of the flap angle under these conditions, and of the minimum time to recover from the bank at different speeds. The variation of flap angle with movement of the control column was also obtained on the standard flap arrangement. In an attempt to minimise pilot preferences, most of the experiments were repeated with a second pilot. Glauert's conclusions are that washout improves flap efficiency, a less marked improvement being obtained with the smaller chord flaps.



Figure 5. R.E.8.

Source: Royal Aeronautical Society (National Aerospace Library)

Around this time, 1918, Glauert became involved in experiments⁽²⁴⁾ conducted in the RAE 4ft wind tunnel to measure the downwash behind a model biplane wing assembly. Two lifting brass aerofoils (3in by 18in) of RAF 6a section provided the downwash which was detected by a tailplane (2.5in by 9in) set on a spindle adjusted so as to sit at the zero lift condition and thereby reveal the local downwash angle. The tailplane was moved progressively from directly behind the wings to a distance of three wing chords downstream. Wing incidences ranged from - 4° to 20° and, in one tailplane position only, 40°. The report⁽²⁴⁾, written with Sandison and Jones, concludes that downwash decreases 'exponentially' from its maximum value directly behind the wing. It is pertinent to point out that, in this same year, Piercy⁽²⁵⁾ at the East London College (later, Queen Mary College) had also carried out downwash measurements, in his case behind a monoplane wing. He found a similar decay which, significantly, he likened to that produced by a body subject to circulation, an observation which was one of the first in Britain to lend credence to Lanchester's ideas on aerodynamics⁽²⁶⁾ set out in 1907. As already mentioned, in 1921 Miss Muriel Barker⁽⁷⁾, the future Mrs Glauert, published downwash patterns calculated for circulation around a Joukowski aerofoil.

Since the beginning of manned flight, wing stall and the almost inevitable subsequent spin were often fatal and the least understood of aeroplane motions. In 1918, while a detailed understanding of stall still eluded Britain's aeronautical community, Glauert became involved in the understanding of spin. The RAE's Frederick Alexander Lindemann (later Viscount Cherwell) (1886-1957) is credited with being the first to perform detailed observations whilst piloting a spinning aeroplane. The first officially to undertake this then exceedingly dangerous manoeuvre, and recover from it to report some of its characteristics, appears to have been Farnborough's Chief Test Pilot, Major Frank Widenham Goodden (1889-1917), flying an F.E.8 biplane in August 1916. However, it seems that, among others, Sopwith's pilot, Harry George Hawker (1889-1921), had earlier discovered how to recover from a spin by centralising the rudder while pushing the stick forward. Yet the spin aside, flying was still an exceedingly dangerous business in those days: both men were to lose their lives in flying accidents, Hawker while practising for a post-war Aerial Derby at Hendon, his name already adopted in 1920 for Sopwith's resurrected aircraft company. And by the time of Lindemann's spinning tests Goodden was already dead as a result of wing structural failure on the second prototype of the S.E.5 he was testing. So it must have taken considerable courage for Lindemann coolly to assess in detail his experiences of spinning a B.E.2e biplane, tests which led to the first correct description of the kinematics and dynamics of this motion. His report, written in 1918 in conjunction with Glauert and Harris, is given in Ref. 27. The spins were performed above a camera obscura so as to record the aircraft's helical track and the small motions of its controls. On the aircraft, airspeed and height loss readings were taken, longitudinal and lateral spirit levels provided the direction of the resultant force and its value was determined from a spring accelerometer in the pilot's seat. With these data it was then possible to conclude that structural loads during spin are not excessive, rarely exceeding 2.5g. The main structural dangers were likely to be experienced in getting into the spin at too high a speed, and getting out of it if recovery from the final diving motion is attempted too forcefully.

The report ⁽²⁷⁾ also provides detailed analyses of the spinning aircraft's centre of gravity motion and motions about its centre of gravity, the latter providing results for rolling, pitching and yawing moments which are in keeping with observations. That these analyses are largely Glauert's work is confirmed by him in a further and very thorough report ⁽²⁸⁾ on spin issued in the following year, 1919. Here the analyses are significantly extended by taking account of such matters as the variation of effective wing incidence along the span. Many of the issues such as structural loads, the effects of control surfaces and their sizes, wing aspect ratios and Lindemann's original observations are re-visited and discussed in considerably greater detail. Results from spinning tests on a Sopwith Camel, Bristol Fighter and an S.E.5a are included. The report also discusses wind tunnel tests ⁽²⁹⁾ conducted at the National Physical Laboratory (NPL) by Relf and Lavender on the auto-rotation of a stalled model wing and includes as an appendix a description of Bryant's experiments ⁽³⁰⁾ at the NPL on a twisted wing. A further appendix reproduces Goodden's original report on spinning an F.E.8 on 23rd August 1916. The Relf and Lavender tests ⁽²⁹⁾ are returned to in a paper ⁽³¹⁾ of 1919 in which Glauert develops a theoretical model based on the experimentally determined characteristics of the RAF 6 section, the analysis covering incidences from 0° to 90°. He demonstrates that auto-rotation is possible only within a limited range of incidences.

At this time Glauert became involved in the use of an aeroplane accelerometer developed by Searle and Cullimore⁽³²⁾ which also provided a measurement of airspeed. Glauert⁽³³⁾ concentrates on the possible errors in establishing an accurate time scale for the recordings made, this scale being dependent on correct markings by the pilot. Drawing on data recorded during the phugoid oscillations of an S.E.5a (Fig. 6) and an unidentified Avro aircraft, he concludes that, while the errors are not great, a clockwork time marker would be beneficial.



Figure 6. Royal Aircraft Factory S.E.5a, 1918?
Source: Royal Air Force Museum, photograph PC72/40/1

Meanwhile, Glauert had been working on the problems of aeroplane control and in 1918 produced a short paper⁽³⁴⁾ on the stick forces required to achieve trim. As a hypothetical example he considers an aircraft having a monoplane wing of RAF 14 section for which various centre of gravity locations, tailplane positions and settings are explored. With these he is able to demonstrate that large stick forces would be required to move the aeroplane from trim when the centre of gravity is too far forward, whereas with the centre of gravity too far aft the stick forces are again considerable and the aeroplane becomes dangerous to handle. However, the question of stability is addressed only in so far as the phugoid oscillation is assessed for the various settings chosen. Glauert's experience in this area was applied in the following year to an actual aeroplane referred to, perhaps diplomatically, as Type 'X' which was exhibiting very unsatisfactory behaviour at the top of loops and when diving at high speed. All that can be deduced from Glauert's report⁽³⁵⁾ is that the aircraft was a two-seater biplane which, in its original form, possessed a high-lift wing section. Various modifications had been tried, including the fitting of a normal wing section and two different amounts of back-stagger to the upper wing. The authors of the present paper are grateful to Gordon Bruce for his suggestion

that this aeroplane is most likely to have been the D.H.6; certain of its unsatisfactory characteristics are mentioned in Ref. 36 and, indeed, in his earlier paper ⁽³⁴⁾ Glauert had already mentioned this aeroplane by name for its possession of such characteristics. However, in Ref. 35 Glauert here again concentrates on reducing the need for excessive stick forces required to bring the aeroplane into trim, showing that a decrease in the tail-setting and the addition of an 'elastic' (unspecified) to the stick reduce the large pull required when diving what he judges to be an unstable aeroplane.

An abiding interest in the phugoid is central to Glauert's very lengthy report ⁽³⁷⁾ on longitudinal stability which also appeared in 1919. He begins with the work initiated by Bairstow, Jones and Thompson ⁽³⁸⁾ at the NPL on the basis provided by Bryan ⁽¹⁹⁾. For what is to follow, it is necessary for Glauert to trace out carefully the mathematical path by which the stability biquadratic (quartic in later parlance) is reduced to two separate quadratics, one of which he notes yields the short period oscillation which is normally damped, the other, if stable, being the longer period phugoid. He points out that a necessary condition for phugoid damping is that the pitching moment about the centre of gravity must decrease as the incidence is increased. This, it should be remembered, is nowadays settled by static stability arguments which draw on the modern aerodynamics not yet in British possession at the time. Glauert merely comments that this is usually settled by experimental work. Thus far, Glauert has been working with the stick-fixed case of constant elevator angle but he then turns his attention to the stick-free case in which the elevator hangs freely to rotate about its hinge. This leads to a sextic and Glauert carefully picks through the conditions necessary for this to be reducible to a quartic which is then separable into quadratics. Essentially, what comes out of this is that longitudinal stability can be assessed by the combined uses of the stick-fixed and stick-free cases, particularly with regard to the control forces employed in the former case. This, he notes, is an approach then currently being explored by Gates ⁽³⁹⁾. Glauert then goes through a lengthy and detailed analysis to determine the stability derivatives, aerodynamic and otherwise, involved in the stability relations. Thus the wing and tailplane contributions (stick-fixed and stick-free) are evaluated and such other contributions as the effect of airscrew slipstream. The report concludes with a numerical example for a typical aeroplane; two cases in which the airscrew thrust's line of action passes above the centre of gravity are chosen to illustrate the importance of this factor. This supports his earlier point that increased damping can occasionally occur in an unpowered glide.

Glauert's remarks on static stability, mentioned above, are interesting since they reveal a common problem in Britain at this time. Considerable progress was being made concerning dynamic stability whereas static stability remained something of a mystery since the influence of the wing's centre of pressure movement with incidence change had yet to be fully understood. Admittedly, it was known from various experiments ⁽⁴⁰⁻⁴²⁾ on aerofoils which happened to have more or less circular arc camber lines that the centre of pressure moves forward with increasing incidence. To the modern eye such movements asymptote toward the quarter chord point aft of the leading edge, yet the significance of this point (the aerodynamic centre of the section), particularly the constant pitching moment coefficient there, was not realised since the teachings of modern aerofoil theory had not then reached Britain. What seems to have been generally accepted ⁽⁴³⁾ was that it is best to have the aircraft's centre of gravity well forward of the furthest forward location of the measured centre of pressure prior to wing stall occurring, an effective recipe for safety but which ignores the tailplane's contribution to static stability. This recipe in part had emerged from the full scale experiments by Edward Teshmaker Busk (1886-1914)

which had contributed to the B.E.2 series of biplanes being developed to a highly statically stable state ⁽⁴⁴⁾. Yet, in modern terms, how much the static margin might, with safety, be reduced remained an open question since the most rearward centre of gravity location, that which produces neutral static stability, could not yet be estimated with certainty.

In 1920 Glauert issued an extensive survey paper ⁽⁴⁵⁾ on both longitudinal and lateral stability which lists the large number of relevant NPL and RAE reports and provides concise summaries of their findings. These reports covered not only the development of theoretical stability analyses but also model experiments and experience gained with specific aircraft such as the B.E.2e, R.E.8 and S.E.5a. Glauert's survey includes appendices listing papers dealing with dynamic stability derivatives, control surfaces and the effects of wing downwash and airscrew slipstream. However, he indicates that further progress is needed as follows (our emphasis in italics):

“(1) to obtain the values of the stability derivatives due to wings from model tests and *to develop satisfactory formulae for predicting these values from their geometrical properties*;

(2) to obtain the stability derivatives due to the airscrew, and also the effect of the airscrew on the derivatives due to the slipstream;

(3) to compare the observed and predicted behaviour of aeroplanes.”

As to our emphasis in (1) above, it should be pointed out that, at the time of the report's issue, Glauert must have already been getting to grips with the new aerodynamic theory which, in his hands, would largely answer this need. Indeed, this was to be a major contribution on his part; such derivatives hitherto evaluated only from, at the time, rather intricate experiments could now be calculated with reasonable accuracy.

At the onset of peace the RAE turned its attention to civil aviation, and now Glauert was able to demonstrate his mathematical mettle in dealing with two complex problems in this area: economic long range flight and methods for landing civil aircraft.

Glauert's treatment of long range flight ⁽⁴⁶⁾, published in 1919, appears to have been prompted by a slightly earlier paper by Berry ⁽⁴⁷⁾ based, Glauert felt, on certain assumptions which did not approximate too closely to actual conditions. Glauert's analysis concentrates on level flight conditions and ignores the initial climb to height and final descent. With certain close approximations such as that which fits the power curve of current engines, Glauert obtains differential relations for fuel consumption and distance travelled with the aeroplane flying at constant attitude. From these he is able to deduce that in order to obtain maximum range or minimum fuel consumption the aeroplane should be flown at a definite attitude which is almost independent of the load carried and of the height. It should be added that a grasp of Lanchester's teaching ⁽²⁶⁾ on minimum drag and minimum power attitudes would have been helpful here. However, Glauert concludes that, owing to the gradual decrease in weight due to fuel consumption, the height will tend to increase and it would appear better to allow the aeroplane to climb slowly rather than maintain the initial height by throttling the engine; these conclusions, he points out, are in agreement with those of Berry ⁽⁴⁷⁾.

Glauert's initial analyses of landing are covered in two papers ^(48,49) published in 1920. In the first of these ⁽⁴⁸⁾ he contrasts the usual approach to landing with one which he demonstrates will reduce the landing distance. The usual approach involves a fairly rapid descent, a rapid

flattening out in centripetal motion along a curved path which brings the aircraft skimming above the ground until stalling speed is reached, and then a final ground run retarded by drag and ground friction. Glauert's new approach involves a more gradual descent followed by a centripetal phase in which flattening out and loss of flying speed take place simultaneously; here it is supposed that the aeroplane reaches the ground flying horizontally at stalling speed and incidence. Glauert⁽⁴⁸⁾ develops analyses covering all of the various phases of these two approaches to landing and uses numerical examples to demonstrate that the second approach leads to a reduction in total distance travelled. He notes that further measures such as reversible pitch airscrews and what he terms 'variable camber' wings might well produce even greater improvements. These matters are explored in his second paper⁽⁴⁹⁾ for which his earlier analyses are suitably adapted. Numerical examples suggest the following reductions in landing distance:

- Reversible pitch airscrew 38%
- Wheel brakes 16%
- Flaps at 20° 16%

He notes, however, that the use of hinged flaps will require greater longitudinal control to deal with wing centre of pressure changes.

Glauert returned to the landing problem in 1926 and, despite this being out of historical sequence, it is appropriate to describe the work at this point since it is based on the approaches used in his earlier work^(48,49). In this case he sets out to determine the size of airfield required in the event of engine failure soon after take-off. His report⁽⁵⁰⁾ reviews his earlier work⁽⁴⁸⁾ on the landing run and the analysis by Wood and Miss Bradfield⁽⁵¹⁾ to calculate take-off distances. Glauert then produces analyses of a gliding turn, a straight climb interrupted by engine failure resulting in a straight glide and finally a climbing turn again interrupted by engine failure but now followed by a gliding turn of the opposite sense so as to land in the initial take-off direction. His results are expressed in terms of the power loading and stalling speed of the aeroplane, using performance curves relating to weight and power loadings given by Bairstow⁽⁵²⁾. He concludes, rather predictably, that using a climbing turn reduces considerably the size of the airfield required and that the necessary size of airfield decreases as the climb angle increases and as the stalling speed decreases. However, his results are presented in the form of useful graphs (Fig. 7) showing the necessary size of an airfield in terms of the stalling speed and power loading of the aeroplane.

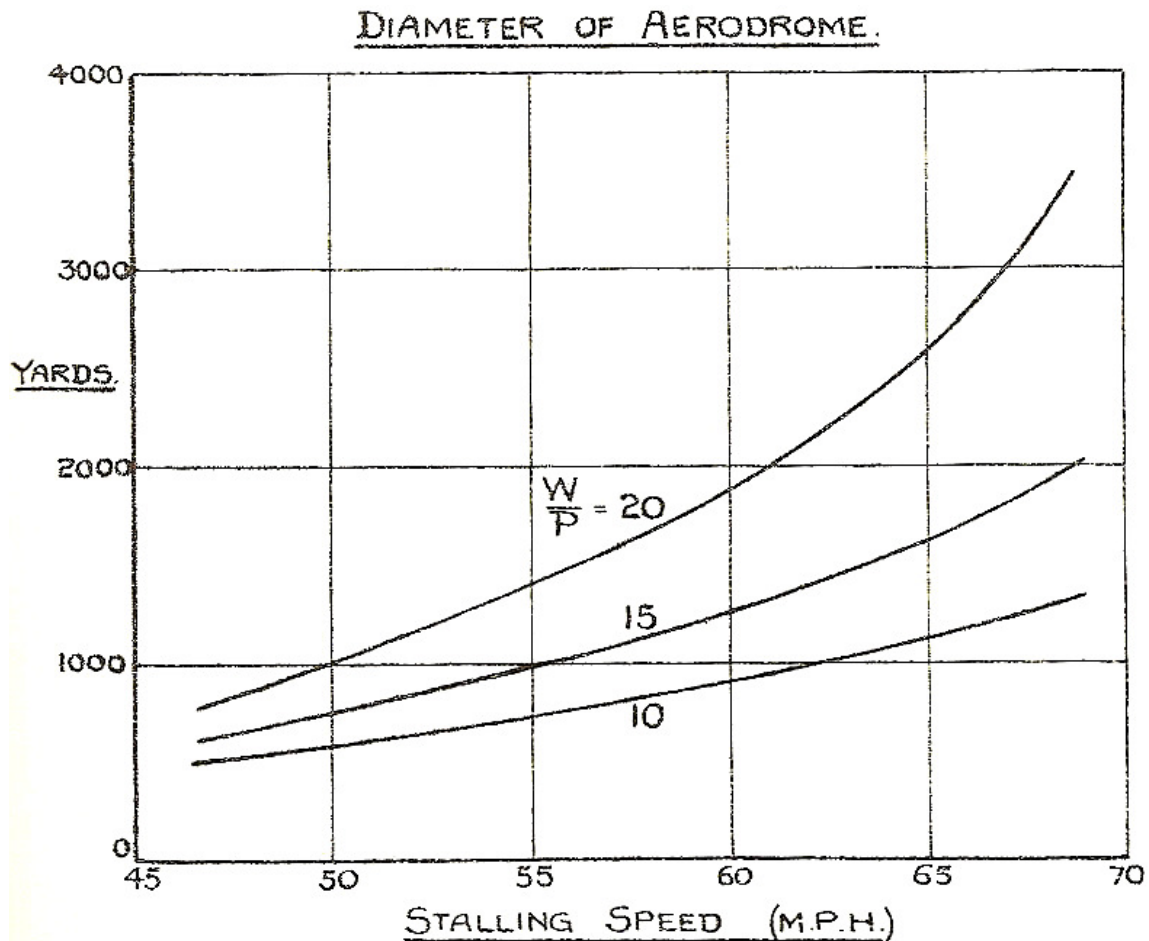


Figure 7. Airfield size for various weight-to-power ratios (W/P) and stalling speeds. (Glauert⁽⁵⁰⁾)

Over the years Glauert occasionally returned to stability and control matters, the first being in 1921. This suggested a resolution of an evident discrepancy between theory and wind tunnel experiments to measure the tailplane's contribution to pitching moment due to pitch rate (M_q). The paper⁽⁵³⁾, written with Cowley of the NPL, suggests that the discrepancy might be resolved by taking account of the time lag between the wings' disturbances and their effects reaching the tailplane. A detailed stability analysis on this basis suggests the necessary corrections although experimental corroboration is recommended. A second contribution appeared in the same year, this as an appendix to a paper on the NPL wind tunnel work by Relf, Lavender and Ower⁽⁵⁴⁾ to measure M_q and the rotary derivatives involved in lateral stability. The 1/8th scale models investigated were of the B.E.2c and S.E.5a, these being held in the tunnel airstream by an ingenious wire suspension system whilst being subjected to forced oscillations. Glauert, by now in command of the new aerodynamic theory developed at Göttingen, is able to provide analytically obtained values for the derivatives based on the elliptic loading case which give satisfactory results.

A rather more routine involvement with the S.E.5a and two of its modified versions also appeared in 1921. Glauert's report⁽⁵⁵⁾ with Peatfield compares model lift and drag measurements in the RAE 7ft tunnel with full-scale tests both in gliding flight with the airscrew stopped and

with the engine at full power. Although a measure of agreement is obtained, the discrepancies are put down mainly to an inability to achieve sufficiently high Reynolds numbers in the model tests. A second report ⁽⁵⁶⁾ with Peatfield, also in that year, again concerns the S.E.5a, in this case its tailplane characteristics. It had long been realised that aeroplane tailplanes were less efficient than indicated by model tests on tailplanes alone. The report's comparison of full-scale and model tests for an S.E.5a indicates that the loss of tailplane efficiency can be ascribed mainly to fuselage and wing interference but also to the gap at the elevator hinge.

A paper ⁽⁵⁷⁾ in which Glauert again applied the new wing theory to stability problems appeared in 1925. Here he is concerned with the rolling moment induced by the use of ailerons and the associated yawing moment which must be overcome by the use of the rudder. He notes that this problem had recently been studied by Munk ⁽⁵⁸⁾ and independently by Scheubel ⁽⁵⁹⁾. Munk had used a Fourier series for the wing's circulation distribution but had confined himself to the elliptic loading case, whereas Scheubel had used uniform lift distributions along each wing half, these being adjusted by a method unspecified in his paper. Glauert's analysis ⁽⁵⁷⁾ also uses a Fourier series to represent the circulation distribution, from which he obtains general expressions for wing lift, induced drag, the wing's rolling moment and the induced yawing moment. A variety of monoplane wing planforms are then investigated, correction factors for biplane arrangements being provided. He concludes that the only possibility of reducing the induced yawing moment is by use of wings with rapid taper toward the tips.

In 1927 Glauert ⁽⁶⁰⁾ suggested a non-dimensional scheme for dealing with the stability equations so that they might more easily facilitate comparisons between aircraft of considerably different sizes and weights. In particular, he recommends that time be non-dimensionalised by a quantity equal to aircraft mass divided by the product of air density, wing planform area and airspeed. The non-dimensionalisation of moments, he suggests, should include their division by the corresponding moments of inertia and, as choice for a suitable length scale, he recommends the distance between the centre of gravity and the tailplane. Moreover, it should be noted that Glauert retains the current forms of drag and lift coefficients, k_D and k_L , which have half the values of the modern coefficients, C_D and C_L , adopted in the late 1930s. Despite his often sound suggestions, however, Glauert's system did not find widespread favour and it was not until 1967 that a consistent system became adopted when this Society recommended a system based on Hopkin's work ⁽⁶¹⁾ of the previous year.

In the same year, 1927, Glauert turned aside from his usual activities to resolve a confusing problem concerning the variation of piston engine performance with altitude ⁽⁶²⁾. A number of tests (bench tests, rate-of-climb tests on various aircraft under differing atmospheric conditions) had led to a variety of suggestions for semi-empirical rules. As Glauert ⁽⁶²⁾ notes, an engine's indicated horse power is proportional to the charge density, suggesting a direct relationship with air density at altitude. However, since the engine temperature will fall with that of the air at altitude, and since the air entering the cylinder will not be fully warmed up to the engine temperature, the rule may in practice be more complicated. After examining the various results and the suggested rules following from them, he favours that recently devised by Capon ⁽⁶³⁾ giving power as a function of $(\text{pressure})^{2/3} \times (\text{density})^{1/3}$.

Glauert returned to the subject of aeroplane performance in a paper⁽⁶⁴⁾ of 1929 which provided analyses of the various stages of its diving motion. He begins with the case of terminal velocity in a dive under the limitation that the engine and propeller revolutions remain constant, accepting that this requires a continual variation of the throttle setting during the accelerated motion. For these conditions he provides results for the non-dimensional velocities achieved for a range of values of dive angle and of the lift to drag ratio at the initially horizontal flight condition (Fig. 8). The next section provides an analysis for the height lost in such dives. Glauert then turns to the centripetal transition path into the dive. His analysis assumes that here the aircraft is initially flying horizontally at top speed, from which it departs to follow a centripetal path at its zero lift condition. He then considers the case in which the aeroplane recovers from its dive along a centripetal path limited throughout by a constant load factor, n . He gives results for various values of dive angle and height loss for the case $n = 3$, noting that this case probably represents current practice. Finally he provides an analysis of the decelerated horizontal motion after recovery from the dive.

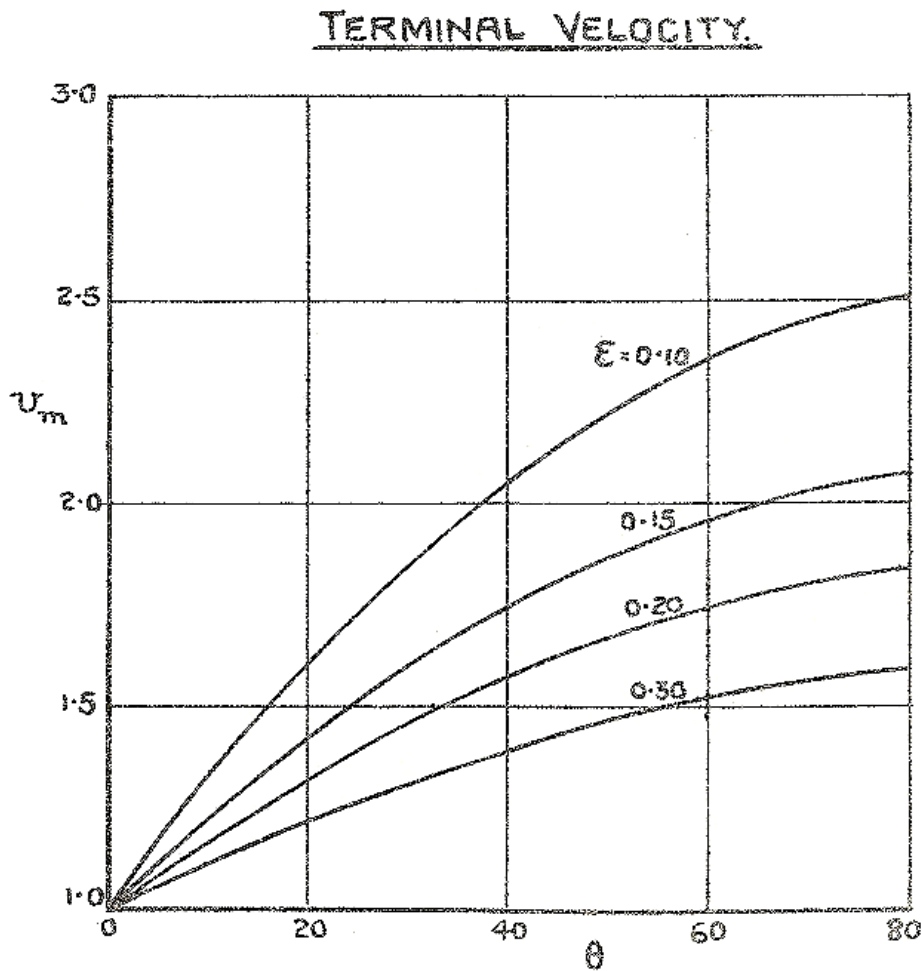


Figure 8. Ratio of terminal velocity in a dive to the initial velocity in horizontal flight, v_m , against dive angle to the horizontal, θ , for various values of the drag-to-lift ratio in initial horizontal flight, ϵ . (Glauert⁽⁶⁴⁾)

The practice of towing instrumented bodies so as to keep them well clear of the towing aircraft's influence raised interesting questions of stability which Glauert addressed in a paper ⁽⁶⁵⁾ of 1930. He begins with an analysis of a light towing wire subjected to its own aerodynamic drag and the towed body's drag and weight. The case of a heavy wire, specifically its curved shape, he notes, had earlier been studied by McLeod ⁽⁶⁶⁾. Here, however, the wire is assumed to be so light that its weight can be ignored. With this assumption he obtains the wire's curve and its three modes of oscillation when the aerodynamic restoring and damping forces are ignored. He gives as an example the case of a 65ft wire for which the oscillation periods are as follows: lateral and pendulum oscillations of the order 6 to 10 seconds; bowing oscillation of order 1 to 4 seconds. He then turns to the longitudinal stability of the body itself when towed by a light wire attached at the body's centre of gravity. This leads to a sextic relation for disturbed motions from which he is nonetheless able to deduce criteria for stability. Lateral stability considerations lead to a quartic and again stability criteria are obtained. His broad conclusions are that, provided the wire is not unduly short, for a body possessing a reasonable amount of static stability the instability arises only in the normal oscillation in the plane of symmetry which is associated with bowing of the wire. The factors which tend to produce instability of the bowing oscillation are short body length and a low body drag compared with the drag per unit length of the wire.

Early in 1934 Glauert returned to the towing problem ⁽⁶⁷⁾, in this case to re-visit McLeod's analysis ⁽⁶⁶⁾ of the heavy towing cable from which its curved shape had been obtained. Having repeated and developed further McLeod's original analysis, Glauert ⁽⁶⁷⁾ derives a family of curves, depending on the cable's weight to drag ratio, which should suffice to cover all practical problems involving the towing of heavy bodies. He illustrates the use of these curves through typical numerical examples.

To backtrack slightly, Glauert had earlier become involved with the porpoising of seaplanes and in 1932 he and Perring issued a lengthy and highly mathematical report ⁽⁶⁸⁾ on the matter. Their analysis centres on the use of the stability equations, here complicated by the fact that little is known about the additional hydrodynamic derivatives involved. However, an attempt to deal with the latter difficulty is made through an analysis in which the planing surface is taken to be a flat board of constant width. From this they draw useful conclusions, one of which is that tests on bare models lacking wings and tailplanes are valueless and misleading, and that a complete model should have the correct ratio of mass to moment of inertia. Nonetheless, wherever comparisons have been possible the results of the theoretical investigation agree with the recorded porpoising cases observed in the tank testing of models and also with full-scale results for the Supermarine Seagull (Fig. 9). It should be added that, according to Ref. 69, the Seagull had a nasty habit of porpoising at take-off and three Seagulls had been subjected to tests on this at the Marine Aircraft Experimental Establishment, Felixstowe, followed by comparative tank tests on models at the NPL.



Figure 9. Supermarine Seagull. (1922)
Source: Royal Aeronautical Society (National Aerospace Library)

5.0 AERODYNAMICS

At the close of the First World War, such understanding of aerodynamics as had been acquired by Britain's aeronautical establishments had largely been achieved by experiment. Commonly used aerofoil section shapes such as those developed at the Royal Aircraft Factory (the RAF sections) had been obtained mainly by cut-and-try methods (see, for example, Stevens⁽⁷⁰⁾). Similarly, results for the effects of planform shape, particularly the influence of aspect ratio, had been gained from wind tunnel experiments and full-scale work. In 1918 Relf⁽⁷¹⁾ at the NPL attempted to draw general conclusions from the data accumulated. As to aspect ratio, he notes that most of the available data had been obtained with the RAF 6 section and many of the experiments had concentrated on an aspect ratio of six as standard. However, he is able to provide graphical estimates of performance for aspect ratios ranging from 4 to 13, commenting that "there is a general tendency for the lift coefficient to rise and the drag coefficient to fall with increasing aspect ratio."

Both of these tendencies had already been predicted by Lanchester's wing theory⁽²⁶⁾. Moreover, he had also proposed a rather crude model for the boundary layer from which he had deduced something of its behaviour. Yet despite Lanchester having been a member of the ACA since its foundation in 1909, his explanation of such matters had largely been ignored in Britain. Britain also remained ignorant of the circulation theory for lifting aerofoil sections proposed by Kutta⁽⁷²⁾ and Joukowski⁽⁷³⁾, its extension to finite wings developed by Prandtl⁽⁷⁴⁾ at Göttingen, as well as Prandtl's concept of the thin viscous boundary layer⁽⁷⁵⁾ which formed the keystone for these new ideas in aerodynamics. English translations of Refs. 72, 73 and 75 can be found in Ref. 76.

During the war years Glauert had little involvement in entirely aerodynamic investigations; as we have seen, his work was mainly in the application of their results to problems on aircraft performance and stability and control issues. However, in January 1919 he published one paper⁽⁷⁷⁾ concerned with an entirely aerodynamic problem. This was an exercise to check that some of the wing pressure distribution data were consistent with measured lift coefficients and centre of pressure locations. The latter were found to lie at the same fraction of the chord along the span and, as Glauert was shortly to learn, his graph of spanwise load distribution sits close to that predicted by the modern wing theory as yet unknown in Britain. This situation was about to change dramatically, however, as a result of Glauert's visit to Göttingen, from which he returned with the main features of the new aerodynamics.

Glauert's ARC review paper⁽⁷⁸⁾ of Göttingen's advances in aerodynamics appeared in 1921 and was based on reports by Prandtl^(74, 79, 80) and Betz⁽⁸¹⁾ together with the two doctoral theses of Betz⁽⁸²⁾ and Munk⁽⁸³⁾. Glauert⁽⁷⁸⁾ begins with descriptions of the inviscid flow field proposed by Kutta⁽⁷²⁾ and Joukowski⁽⁷³⁾ for a lifting aerofoil section subject to circulation, the Kutta-Joukowski condition of smooth flow at the trailing edge together with a statement of the Kutta-Joukowski theorem linking lift to circulation. Brief descriptions follow of Prandtl's views that the lifting wing is supported by increased pressure on the ground beneath and that profile drag's origin lies in the boundary layer. Glauert then turns to the monoplane wing of finite span, describing how the circulation reduces toward the tips, how vorticity is cast off to roll up into two distinct vortices so that "the flow pattern agrees in considerable detail with the suggestions put forward by Lanchester" in Ref. 26. Here at last, then, is British official acknowledgement of Lanchester's ideas; Prandtl, in contrast, had grasped their value at least a dozen years earlier. Glauert⁽⁷⁸⁾ then proceeds with a description of induced drag and its calculation, from which it is shown that its minimum value occurs under the elliptic loading condition, this being most easily achieved by an elliptic variation of wing chord along the span. The Göttingen effective incidence method is explained for dealing with wings of different aspect ratios before turning to Betz's work⁽⁸²⁾ on wings of rectangular planform. A comparison (Fig. 10) between RAE data, particularly the mean loading curve noted earlier by Glauert⁽⁷⁷⁾, and the theory for rectangular wings provides pleasing agreement, as does a comparison of predicted and measured drag. However, lift prediction is less satisfactory. Prandtl's horseshoe vortex system⁽⁷⁴⁾ is then described, mention being made of the starting vortex left behind at take-off which closes the vortex circuit. Munk's theorems⁽⁸³⁾ for multiplane assemblies are reviewed and these lead to the analysis for unstaggered biplanes which agrees well with experimental data. Prandtl's corrections for open and closed wind tunnel working sections⁽⁷⁴⁾ are then described, particular attention being paid to square and circular closed working sections for which experimental comparisons are recommended.

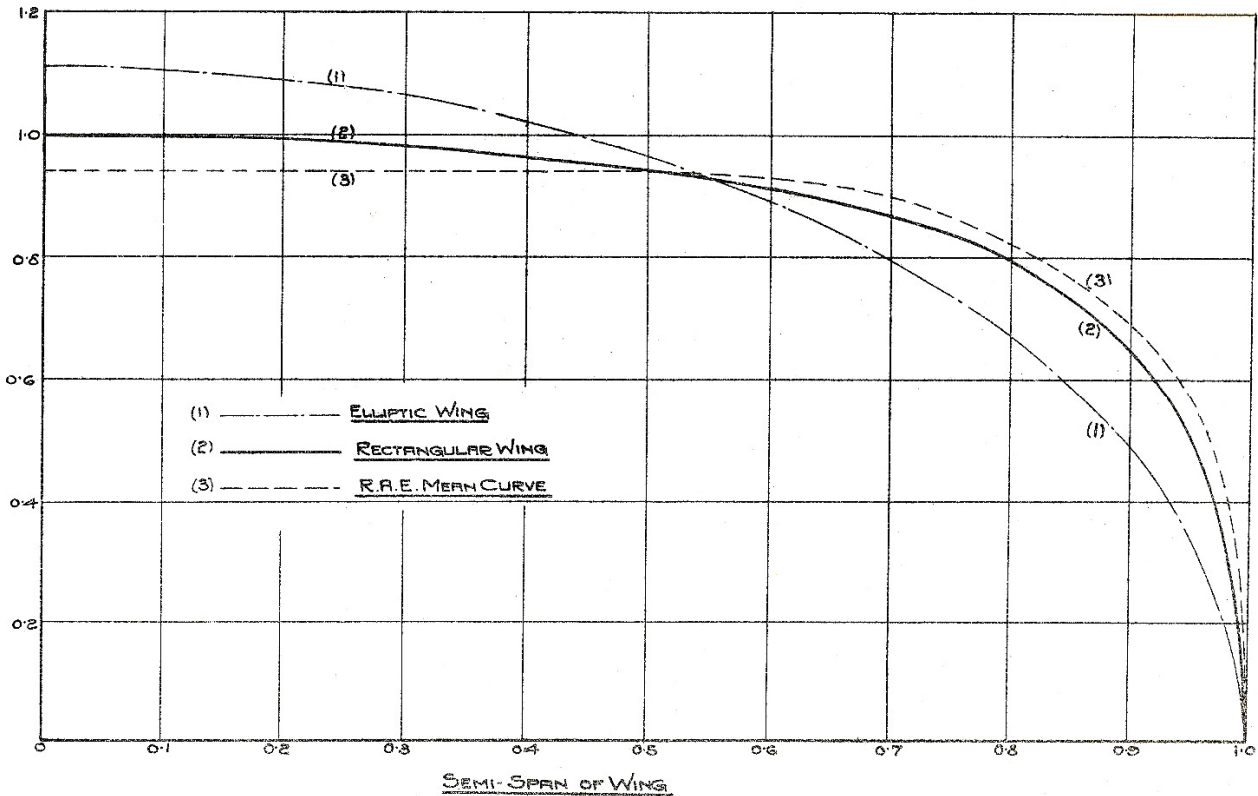


Fig. 10. Load distributions on wings of elliptic and rectangular planforms compared with RAE mean load distribution. (Glauert⁽⁷⁸⁾)

The message from the above was crystal clear: these are extremely important ideas which must be carried further. Glauert's own response⁽⁸⁴⁾ was immediate and resulted in a comparison of the airflow around wings and the vortex theory's predictions. The latter are found to be not very accurate for downwash near a tailplane, probably because the vorticity sheets have not yet rolled up into the two distinct trailing vortices assumed in the theoretical model. In the same year, 1921, Glauert⁽⁸⁵⁾ applied the wing theory to tapered wings, and this involved a rather cumbersome series expansion in terms of the non-dimensional spanwise ordinate requiring ten terms to achieve reasonable accuracy. Far more successful was Glauert's paper⁽⁸⁶⁾ of the following year on the same subject. Here he uses a Fourier series for the circulation distribution, a method introduced by Trefftz⁽⁸⁷⁾ in the previous year. Four terms only are needed in the series which is applied to rectangular, tapered and twisted rectangular wings, for which good agreement with observations is found in every case.

A further paper⁽⁸⁸⁾ from 1922, for unknown reasons delayed in publication until 1924, investigated the unusual layout of a tandem wing aircraft. Here it is necessary to calculate the upwash ahead of, and the downwash behind a monoplane wing and this Glauert⁽⁸⁸⁾ does in the second part of his paper. The paper's first part analyses a tandem wing system in which each wing is of the same size and carries elliptic loading. However, as he points out, for static stability the rear wing must be set at reduced incidence so that it carries little of the total lift. Owing to this, as he puts it⁽⁸⁸⁾, "it would appear to be very uneconomical to use a wing of equal size to the front wing from the point of view of performance."

A diversion from Glauert's endeavours on wing theory occurred in 1922 with an examination⁽⁸⁹⁾ of the experimental data on leading edge slots and trailing edge flaps provided by the Handley Page Company. In the previous year Frederick Handley Page (1885-1962) had presented a lecture⁽⁹⁰⁾ to this Society in which he gave details of his Company's work on these subjects. Glauert's examination⁽⁸⁹⁾ of the Company's original data emphasises the 35% improvement in C_{Lmax} to be expected of thick aerofoil sections when aided by a leading edge slot, increases as high as 60% being achievable with the addition of a slotted trailing edge flap. Glauert also draws attention to similar work on slots⁽⁹¹⁾ published in 1921 by Gustav Victor Lachmann (1896-1966), who later pooled his ideas with the Handley Page Company. It should be mentioned that Glauert's review was closely followed by a report⁽⁹²⁾ on the independent and extensive experiments on slots and flaps conducted by Miss Bradfield at the RAE which substantiated the Company's findings.

Glauert returned to applications of wing theory in a paper⁽⁹³⁾ of 1923 concerned with the calculation of the rotary derivatives L_r and N_r , respectively the rolling and yawing moments due to rate of yaw. Clearly by now Glauert was keeping abreast of Göttingen developments since his investigation was prompted by Wieselsberger's paper⁽⁹⁴⁾ on the same subject and in which the wing was assumed to have an elliptic planform. Having repeated Wieselsberger's analysis, Glauert⁽⁹³⁾ then extends the method through use of a Fourier series to represent the circulation distribution. He applies his results to the case of a rectangular planform wing, noting in conclusion that earlier calculations from the pre-circulation theory days are inadequate. In the same year, 1923, Glauert⁽⁹⁵⁾ extended the analyses on biplanes reported in Ref. 78, pointing out that, while stagger does not change the results for induced drag, account should be taken of the slight changes of effective camber due to the proximity of one wing to another and which changes slightly the zero lift incidence. A small correction term is obtained which agrees with observations for the zero and positive stagger cases but is less successful for negative stagger, a feature as yet unexplained.

In a paper⁽⁹⁶⁾ also issued in 1923 Glauert explored further the subject of wind tunnel corrections first set out in his review⁽⁷⁸⁾ of Prandtl's work. The latter, restricted to the case of a square working section, had been shown to bring into better agreement the results obtained in the RAE's 4ft and 7ft wind tunnels. His new analysis also based on the method of images extends the analysis to rectangular working sections of any dimension. This shows that, for a given cross sectional area, the interference will be a minimum when the breadth of the section is $\sqrt{2}$ times the height. In the following year this advance in the understanding of wind tunnel corrections was built on in a co-operative effort⁽⁹⁷⁾ with Hartshorn to determine the effects of tunnel constraint on downwash angle and the tailsetting for trim. The experimental results had been obtained with a 1/10th scale model of a Bristol Fighter suspended in both the 4ft and the 7ft RAE tunnels. Extensions of Glauert's earlier analysis⁽⁹⁶⁾ are found to produce very good agreement with the observations, thus confirming the theoretical corrections.

The year of 1924 became highly productive since Glauert now attacked the problem of designing aerofoil section shapes and determining their aerodynamic characteristics. His attack was two-pronged: on the one hand, he developed methods for dealing with thin aerofoils and, on the other, aerofoils of thick section. Both methods, however, depended on the use of conformal transformation, this mathematical device having been developed by Joukowski from his earlier graphical conformal mapping procedure introduced⁽⁷³⁾ for the design of thick sections.

Glauert's thin aerofoil theory ⁽⁹⁸⁾ is essentially that introduced by Munk ⁽⁹⁹⁾, now working in the USA. However, Munk's analysis, as Glauert puts it, "is not quite free from errors" so therefore Glauert presents a more careful analysis set out in a more logical order. The thin aerofoil is represented by its camber line which deviates only slightly from that of a circular arc; essentially the deviation is represented by a Fourier series. For this Glauert obtains general expressions for lift, zero lift incidence and pitching moment about the leading edge. One specific shape possessing reflex camber toward the trailing edge is amenable to analytical solution and this indicates a fixed centre of pressure position. Other more common examples are then considered but here graphical integration is required for the various functions involved. Comparisons between such predictions for the RAF 14, 15 and 18 sections show good agreement with those experimental data obtained at the higher values of Reynolds number used. The theory is then applied to a tailplane and elevator although here comparisons with experiment are less satisfactory, probably, as Glauert points out, because of the sharp change in angle at the tailplane-elevator junction.

Earlier in 1924 Glauert ⁽¹⁰⁰⁾ had carried out a survey of the thick sections then available, including some of his own design described in his later paper mentioned below. His survey includes those sections tested as models by Fokker and by the Göttingen, Eiffel, St. Cyr and NACA laboratories. However, comparisons are difficult due to 'scale effects' (Reynolds number effects), a problem during this period which was at last being recognised (see Ref. 101).

Glauert's analysis of thick sections ⁽¹⁰²⁾, also published early in 1924, is based on the work of von Kármán and Trefftz ⁽¹⁰³⁾ from 1918. Their analysis removed the Joukowski section's impractical feature of a cusped trailing edge by the use of an extended form of the original Joukowski transformation which yields a finite acute angle at the trailing edge. As mentioned in Section 2.2, Muriel Glauert's paper ⁽¹⁰⁾ on this topic had been published by this Society in the previous year. Glauert summarises the work on thick sections and calculates the ordinates of three specimens. Using general expressions obtained by von Mises ⁽¹⁰⁴⁾ for an aerofoil's lift and pitching moment, he calculates the lift curve slope, zero lift angle and leading edge pitching moment coefficient for his three specimen sections. For a fourth section shaped to have reflex camber, the centre of pressure is fixed in location and for this he obtains its zero lift incidence.

Toward the end of 1924 Glauert contributed to an assessment ⁽¹⁰⁵⁾ of a Junkers single-engined monoplane possessing a thick section wing. The photograph included in the report (Fig. 11) indicates this to have been a Junkers F13, the prototype of which flew in 1919. Clark at the RAE had provided full-scale test results, whereas tests in the RAE's 7ft tunnel had been conducted by Hartshorn and Coombes on a 1/12th scale model. For the latter, care had been taken to include most of the features of the full-scale aeroplane, including its corrugated skin. It was left to Glauert to compare the full-scale and model test results. He remarks that adjustments to the model results are necessary due to the effect of the airscrew, the windmill on the pressure head (both absent on the model) and 'scale effects' on the undercarriage struts. Even so, comparison is bedevilled generally by scale effects and, he suspects, the effect of the corrugated skinning of the complete aircraft.



Figure 11 Junkers monoplane. (Clark, Coombes, Glauert and Hartshorn ⁽¹⁰⁵⁾)

Also toward the end of that year, Glauert ⁽¹⁰⁶⁾ published results obtained from a further series of aerofoil sections designed according to the method described in Ref. 102. One aerofoil (RAF 30) was essentially a symmetric section whereas most of the others had the same thickness distribution as RAF 30 but various camber values, the camber lines being shaped as circular arcs. However, one further section used reflex camber so as to possess a fixed centre of pressure location. As was usual at that time, and since the sections were designed around the basic Joukowski method, all of the sections had their maximum thicknesses at 30% chord. The predicted characteristics such as the effect of camber on pitching moment are largely in agreement with results obtained from wind tunnel tests so that it is felt that aerofoil design could now proceed on a rather more logical basis.

By the mid-1930s these early methods for the design of smoothly contoured aerofoil sections were largely superseded by the more general and versatile transformation method ⁽¹⁰⁷⁾ devised by Theodore Theodorsen (1897-1978) at the NACA. However, this method, like its predecessors, required rather laborious computation. A new approach set out by Piercy, Piper and Preston ⁽¹⁰⁸⁾ in 1937 avoided such difficulties and provided the added benefit that the trailing edge angle could be specified *ab initio*. Moreover, use of this design method allowed maximum thicknesses to lie further aft than the usual 30% chord point, a feature which on test revealed an aerofoil section of significantly lower drag through its possession of a greater extent of laminar boundary-layer flow ⁽⁴⁾. However, subsequent British efforts on low drag laminar flow sections largely centred on sophisticated adaptations of thin aerofoil theory produced by Sydney Goldstein (1903-1989) and his team at the NPL during the Second World War ⁽¹⁰⁹⁾.

To revert to Glauert's work in the mid-1920s, for a few years he turned aside from aerodynamics research to work, as we shall see below, on propeller theory. However, according to Wood ⁽⁶⁾, as Head of the RAE's Aerodynamics Department he encouraged Glauert to lecture on his aerodynamic and propeller work to recent graduate recruits who had little background in

aeronautics. From this came Glauert's textbook⁽¹¹⁰⁾ on these subjects, *The Elements of Aerofoil and Airscrew Theory*. First published in 1926, the book had a second edition in 1947 revised by Michael Glauert which included notes on later work by H. B. Squire. A more recent edition in Cambridge University Press's Classic Series has extended further the work's well deserved longevity.

Glauert⁽¹¹⁰⁾ begins with a brief description of the main characteristics of aerofoils. He then provides the essential elements of inviscid flow theory: Bernoulli's equation, the stream function, circulation and vorticity, velocity potential and the potential function. This background established, he embarks on conformal transformation so as to obtain the circular arc and Joukowski aerofoil sections together with their lift and moment characteristics. Invariably, however, the moment coefficient is obtained about the leading edge although it is easy to deduce that, for these sections built around circular arc camber lines, the coefficient about the quarter chord point is constant, a valuable result for static stability issues. However, he mentions that, for symmetric sections, the centre of pressure lies fixed at the quarter chord point. This matter will be taken further in the next paragraph. In his treatment of thin aerofoils, Glauert departs from his earlier method⁽⁹⁸⁾ based on Munk's work⁽⁹⁹⁾ and instead uses an alternative approach proposed by Birnbaum⁽¹¹¹⁾ in which the thin section is represented by a vorticity sheet; it is now the general distribution of this rather than shape which is expressed as a Fourier series. The essential results, however, are unchanged. Glauert then makes clear that the origin of drag lies in viscosity, describing a number of its features: von Kármán's vortex street, form drag, laminar viscous shear in flows between plates and in pipes, dimensional analysis leading to the importance of Reynolds number, flat plate boundary-layer flows which are either laminar or turbulent. He is thus able to describe the physical basis for the Kutta-Joukowski condition at a sharp trailing edge before providing a lengthy review of his and other work on wing theory described earlier in this section. For the monoplane wing it is interesting to note that, having used the Göttingen effective incidence approach in dealing with changes of aspect ratio, for the elliptic loading case he obtains the useful results that, for a wing of aspect ratio A , the induced drag coefficient C_{Di} and the C_L variation with incidence α are given in modern notation by

$$C_{Di} = C_L^2 / (\pi A), \quad \partial C_L / \partial \alpha = 2 \pi A / (2 + A). \quad (1)$$

Results for rectangular, tapered, twisted and biplane wings are then provided, followed by methods, including the method of images, for dealing with wind tunnel interference. The book closes with chapters on the momentum theorem for propellers and windmills, propeller blade element theory and wind tunnel interference effects on propeller tests. For the practising aeronautical engineer the book can still be read with profit; for today's student it remains a goldmine.

To return to Glauert's result⁽¹¹⁰⁾ for aerofoil pitching moment, in the following year, 1927, Gates issued a paper⁽¹¹²⁾ in which he took the matter further. The paper⁽¹¹²⁾ to some extent is a companion piece to Glauert's work⁽⁶⁰⁾ suggesting the non-dimensionalisation scheme for stability analyses mentioned in the previous Section, but here Gates⁽¹¹²⁾ not only shows that the pitching moment coefficient about the quarter chord point is constant but also refers to this point as the "aerodynamic centre". It seems that this is the first occasion in the English literature that this concept appeared. As we shall see, in the following year Glauert and Gates used the concept in their joint work on the aerodynamics of sweptback wings.

Glauert returned to aerodynamics research in 1927 with the densely mathematical analysis of a wing carrying a hinged flap⁽¹¹³⁾. The thin aerofoil theory used is not that of Ref. 96 but the approach developed in his book⁽¹¹⁰⁾, here extended to deal with a wing of rectangular planform and to calculate the flap's hinge moment. Data from elevator tests on R.E.8 and S.E.5 biplanes are used to provide comparisons with his theoretical predictions. The agreement is found to be very satisfactory so that he feels his results can be used with confidence to predict the effects of flap size or wing aspect ratio variations.

In the same year Glauert published his only paper on high-speed effects⁽¹¹⁴⁾. From his comments it is clear that it is the RAE's experimental high-speed propeller programme (see Ref. 115) which has prompted his analysis of subsonic compressible flows about thin section aerofoils. Using the adiabatic flow relations coupled to the continuity equation and the irrotationality condition he shows that, in keeping with the usual results of two-dimensional theory for irrotational flows, for a body subject to circulation the drag remains zero whereas the lift is given by the usual Kutta-Joukowski theorem but in which the density is here that of the free stream. Turning to the aerofoil modelled as a vorticity sheet, he shows that, to a first approximation, the strength of each elementary vortex is increased by the factor $(1 - M^2)^{-1/2}$, M being the free stream subsonic Mach number. Consequently the value of the lift coefficient, C_L , is related to its corresponding value at zero Mach number, C_{L0} , by

$$C_L = C_{L0} / (1 - M^2)^{1/2} . \quad (2)$$

However, the zero lift angle remains unchanged. He then confirms these results through a linearization of the flow equations. For supersonic conditions he briefly mentions the work of Ackeret⁽¹¹⁶⁾.

A result similar to Equation (2) had been given in Prandtl's Göttingen lectures as early as 1922, as Glauert⁽¹¹⁴⁾ acknowledges in a footnote, so that the equation is now known as the Prandtl-Glauert rule. However, it was not until 1930 that Prandtl published⁽¹¹⁷⁾ his findings, these appearing in the printed version of the second of his three lectures presented in the previous year at Tokyo Imperial University. As to experimental verification of the rule, Glauert demonstrates good agreement with the recent C_L results of Douglas and Perring⁽¹¹⁸⁾ for their bi-convex No 2 aerofoil in the subsonic Mach number range before the rapid drop in lift and drag rise occur (Fig. 12). Subsequently Glauert's paper⁽¹¹⁴⁾ frequently provided excellent guidance to the British aeronautical community in its approach to flight near sonic conditions.

Slope of lift curve.

V/a	0	0.4	0.6	0.7	1.0
Observed ..		0.060	0.075	0.060	0.058
Calculated ..	0.055	0.060	0.069	0.077	

Fig. 12. Table of calculated and observed lift curve slopes for various values of V/a (Mach number). (Glauert⁽¹¹⁴⁾)

In the same year, with a remarkable change of scene Glauert⁽¹¹⁹⁾ turned to the low speed flow phenomenon of the von Kármán vortex street. Having repeated von Kármán's analysis⁽¹²⁰⁾, he then turns to the constraints imposed by the presence of channel walls parallel to but spaced not too closely to the vortex rows. For this he uses the method of images. However, he, like von Kármán, is left with two unknown parameters but, rather than appeal to experiment, he introduces two assumptions concerning the pressures and mean velocities in the channel flow which lead to realistic results. However, it should be added that an abiding interest in the phenomenon of the von Kármán vortex street has since produced a considerable literature (see, for the earlier examples, Refs. 121, 122).

A number of Glauert's remaining contributions to aerodynamics were concerned with wind tunnel interference effects. Thus in 1928 he produced two papers^(123, 124) concerned with the occurrence of pressure gradients along the length of a closed working section. In the first paper⁽¹²³⁾ he remarks that in the correction of wind tunnel drag measurements the usual practice has been to deduct an additional drag due to the pressure gradient effect, the deduction being equal to the product of the pressure gradient and the volume of the test body. This he demonstrates is unsatisfactory. Using calculations based, for example, on doublets and normal flat plates in convergent streams, he obtains corrections which can be extended to three-dimensional conditions. He concludes that a more realistic drag deduction is equal to the product of the pressure gradient and a volume which is always greater than the test body's volume and that the former volume can be calculated by the method he describes. His second paper⁽¹²⁴⁾ provides an analysis of the working section pressure gradient due to boundary-layer growth. For this he uses the 1/7th power law turbulent boundary-layer velocity profile given by von Kármán⁽¹²⁵⁾, showing that the pressure gradient decreases along the tunnel axis and that this effect decreases as the Reynolds number increases. However, this does not entirely explain the differing behaviours of some of the RAE and NPL tunnels, a factor which leads him to suspect that the cause might lie in tunnel leakage. An analysis of leakage leads to realistic results which indicate the importance of reducing this effect.

During 1928 and 1929 Glauert issued three papers⁽¹²⁶⁻¹²⁸⁾ which, among other things, provided a useful starting point for later flutter investigations. In the first of these papers, issued early in 1929, Glauert⁽¹²⁶⁾ converts the standard relations for the irrotational flow about a two-dimensional body in accelerated motion into a form which involves only the vorticity around the body's surface. The only limitation is that the circulation around the body remains constant in order to secure irrotationality of the flow. As he explains, the chief merit of this approach is that it facilitates the calculation of the resultant force and moment acting on the body. His analysis then examines a body possessing both rectilinear and angular motions, both of which vary with time, and from this he obtains general expressions for the forces and moment in terms of integrals involving the surface vorticity. As examples, he considers firstly the accelerated motion of an elliptic cylinder and then a flat plate aerofoil describing a circular path with constant speed and incidence angle. In a companion paper⁽¹²⁷⁾, issued late in 1928, Glauert specifically draws attention to flutter problems, mentioning that his intention is to deal with oscillating aerofoils later. Here, however, he restrains himself to extending his previously mentioned analysis⁽¹²⁶⁾ to a cambered aerofoil and then to a rectangular planform wing, both in constant circular motion. He concludes that lift and pitching moment due to pitching (M_q) are independent of the incidence angle but vary rapidly with the position of the centre of rotation. For the final stage in this sequence of papers, Glauert⁽¹²⁸⁾ turns to the case of a flat plate aerofoil in constant rectilinear

motion while performing a steady, small oscillation. Here the requirement of Refs. 126, 127 that circulation remains constant has to be relaxed due to the effect of cast off vorticity; the condition now applied is in the spirit of the Kutta-Joukowski condition in that the velocity at the trailing edge must always remain finite. Having developed his analysis along these lines, Glauert⁽¹²⁸⁾ finds that his general expressions for force and moment are in agreement with those obtained by Wagner⁽¹²⁹⁾ for a similar problem. Turning to the oscillating aerofoil, he finds his results in fair agreement with the only experimental evidence then available, that provided in a report by Frazer and Duncan⁽¹³⁰⁾ of the NPL. Glauert's general conclusions are that the lift and pitching moment due to oscillation are independent of incidence but vary rapidly with the centre of rotation's position and sometimes with the frequency of oscillation. Moreover, the damping moment at small frequencies can be unstable if the centre of rotation lies in the first quarter of the chord. As to future developments, it should be mentioned that by 1932 Duncan and Collar⁽¹³¹⁾ at the NPL had extended Glauert's work to obtain the complete set of the required derivatives for a thin aerofoil in two-dimensional motion, covering oscillations of constant amplitude, exponential oscillations and non-oscillatory divergence.

As mentioned earlier, in 1928 Glauert joined Gates in an analysis⁽¹³²⁾ of the aerodynamic characteristics of a sweptback wing, this incorporating straight taper and uniform twist. Here the concept of aerodynamic centre is used and for the aerofoil sections envisaged this lies at the quarter chord point of each section. The sweepback is then taken to be the angle between the lateral axis and the straight locus of the sections' aerodynamic centres. The circulation distribution along the span is expressed as the usual Fourier series from which lift, induced drag and pitching moment are calculated. Static stability is then discussed, this being complicated by two factors: due to taper and sweepback, the aerodynamic centre of the complete wing lies aft of that at the centre section, the second factor being that the aircraft here envisaged is tailless. Glauert and Gates⁽¹³²⁾ point out that for the conventional tailed aeroplane the centre of gravity usually lies behind the wing's aerodynamic centre so that the wing is statically destabilising, compensation being provided by the stabilising effect of the tailplane. For the tailless aeroplane, in contrast, the centre of gravity must always lie ahead of the wing's aerodynamic centre in order to achieve static stability. There is then the question of achieving trim and this, they point out, must be provided by the wing's twist; twist therefore performs the same function as the tailplane-elevator combination of the conventional aeroplane. Calculation of the stability derivatives M_q and M_w (the pitching moment due to heave velocity) then reveals that the damping of oscillations on an otherwise statically stable tailless aeroplane is relatively poor compared with that of the conventional aeroplane. Unpublished experiments by Miss Bradfield at the RAE and certain Göttingen results largely confirm these predictions.

In the closing passage of their report, Glauert and Gates⁽¹³²⁾ make it clear that the tailless layout investigated is that for the Westland Pterodactyl series of aeroplanes (Fig. 13). In flight tests the early versions were found to exhibit poor damping in pitch (see Ref. 133). Moreover, these versions of the Pterodactyl design used rotating outboard sections of the wing for control; when rotated in-phase these 'controllers' acted as elevators whereas in anti-phase rotation they acted as ailerons. For a later version, Mark IV, the 'controllers' were replaced by trailing edge flaps and these, together with other aerodynamic changes, resulted in much improved stability⁽¹³⁴⁾. Earlier in 1928 Gates⁽¹³⁵⁾ had used wing theory to analyse a rectangular planform wing having such outboard rotating 'controllers', finding that "the analysis shows strikingly the loss of efficiency of

the tips due to their separate movement.” What is also strikingly apparent is the considerable versatility now offered by Glauert’s development of wing theory.

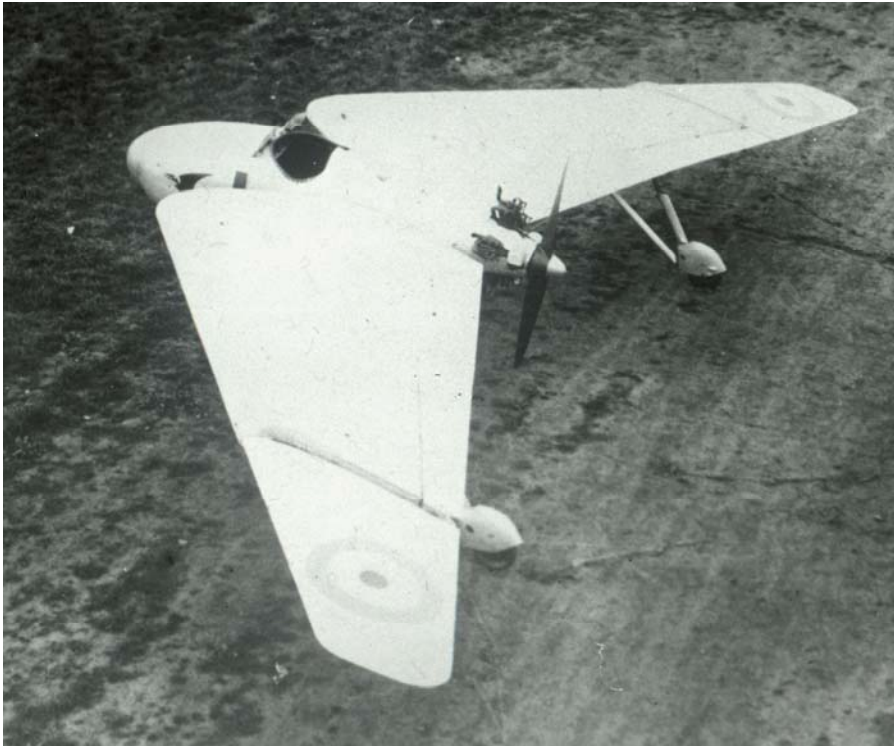


Figure 13 Westland-Hill Pterodactyl 1A, J9251.
Source: Royal Aeronautical Society (National Aerospace Library)

In 1931 Glauert returned to the subject of wind tunnel interference, issuing a report on the constraints imposed on a lifting wing when enclosed within a circular working section⁽¹³⁶⁾. He is critical of earlier work (Prandtl⁽⁷⁴⁾, Rosenhead⁽¹³⁷⁾) in which the wing’s lift distribution is assumed to be elliptic, pointing out that a wing possessing an elliptic load distribution in free air might not be so loaded when enclosed in a tunnel. As the starting point for his own analysis he, so to speak, takes one step back by considering not specific loadings but two specific planform shapes, elliptic and rectangular. His analysis is necessarily highly involved since it requires the use of multiple image systems to calculate the induced velocities created by the trailing vortices. He concludes that even when due account is taken of the modification to lift distribution due to tunnel constraint, the tunnel corrections for elliptic and rectangular wings which were based on elliptic loading are sufficiently accurate. However, this is not the case for tunnel constraint estimates which assume for simplicity a uniform load distribution; such methods produce over-estimates. In the following year, 1932, these arguments were applied to the more complicated case of a tunnel of rectangular cross-section⁽¹³⁸⁾, a case also considered by Rosenhead⁽¹³⁷⁾ and by Terazawa⁽¹³⁹⁾. The latter had produced an analysis based on the uniform loading case, this also having been analysed by Rosenhead⁽¹³⁷⁾ who had added the elliptic loading case. However, neither method lent itself to ease of computation and therefore Glauert⁽¹³⁸⁾ carries further Rosenhead’s analysis to the point at which it can be expressed in terms of Bessel functions. The corrections to the approximate formulae developed earlier by Glauert⁽⁹⁶⁾ are found to be

relatively unimportant for a square tunnel but are important for the 7ft Duplex tunnel for which the breadth is twice the height.

Later in 1932 Glauert produced a paper setting out two general theorems on tunnel constraint⁽¹⁴⁰⁾. The first theorem states that the interference on a very small aerofoil in an open tunnel of any shape is of the same magnitude, but opposite in sign, as that on the same aerofoil, rotated through a right angle, in a closed tunnel of the same shape. Glauert's analysis replaces the very small wing by a doublet, representing the enclosed boundary by a vorticity sheet, whereas for the open boundary the imposed boundary condition is that of constant velocity potential. The derivation of the second theorem builds on the results of the first theorem, from which he shows that the tunnel interference velocity is uniform across the span of a wing in any elliptic tunnel having the wing's tips as foci.

In 1933 Glauert⁽¹⁴¹⁾ turned to tunnel corrections caused by body wakes, a subject which he judges to be in an unsatisfactory state since such corrections as exist depend heavily on whether the symmetric bodies investigated were blunt or streamlined. Reviewing the various data available (Refs. 142-146) together with his own investigation⁽¹¹⁹⁾ of the von Kármán vortex street, he uses semi-empirical methods to produce more general results for wake effects.

In the same year his lengthy and comprehensive survey of wind tunnel interference effects was published as a separate monograph⁽¹⁴⁷⁾. Indeed, the work is written as a textbook in the spirit of his earlier book⁽¹¹⁰⁾, the reader being introduced to the essential features of the subject and then guided logically through specific examples, most of which have been covered in his earlier work mentioned in the present survey. In dealing with closed working section pressure gradient effects, however, he makes the practical suggestion, often subsequently adopted, that sections should be slightly expanding to compensate for this effect. The sequence of his discussions is, however, a little surprising: three-dimensional wings are dealt with before those in two dimensions, these being followed by symmetrical bodies. The monograph concludes with a section on tunnel constraints on airscrew tests largely built around material to be mentioned in the next Section of the current survey. Again in the spirit of Ref. 110, the reader is directed throughout to the original research papers for the lengthy, detailed mathematical analyses. Occasionally there are corrections to earlier work; Prandtl⁽⁷⁴⁾, for example, is caught out in a slip with one of his expansion coefficients for the closed circular tunnel case, this having been corrected by Rosenhead⁽¹³⁷⁾. Of the forty five references cited, nearly a quarter are to Glauert's own work, the others covering not only the work of his colleagues at the RAE and the NPL but also investigations undertaken at Göttingen and by the NACA.

Early in 1934 Glauert produced two papers concerned with the influence of jets on aerofoil sections and wings. In his first paper⁽¹⁴⁸⁾ the practical problem Glauert has in mind is that in which a lifting wing is close to or within a jet of higher speed such as a propeller slipstream or a lower speed jet such as the wake of an upstream body. Considering two-dimensional motion, he replaces the aerofoil section by a line vortex and uses an image method devised by von Kármán⁽¹⁴⁹⁾ to analyse the situation in which the aerofoil sits below a surface of velocity discontinuity. This method he extends to the case of an aerofoil sitting below a jet of finite breadth, the method then being further extended to the case of an aerofoil sitting within a jet of finite breadth. His results agree with recent tests by Miss Bradfield⁽¹⁵⁰⁾ in that lift increases with slipstream breadth and has

its maximum value when the aerofoil sits slightly below the jet's centre. A final extension considers the case in which the aerofoil sits within an infinite series of jets.

Glauert's second jet paper⁽¹⁵¹⁾ considers the case in which an aeroplane is tested with parts of its wings projecting beyond the boundaries of an open jet working section. He notes that preliminary experiments of this nature by Perring and Callen⁽¹⁵²⁾ indicate that this method gives reliable results. Glauert's analysis⁽¹⁵¹⁾ of this problem is based on his earlier work⁽¹³⁶⁾ for a closed tunnel of circular section but here modified in two ways. The first is a change of boundary condition to allow for the fact that now the tunnel section is open. The second modification is to use a method introduced by Lotz⁽¹⁵³⁾ in which incidence and the inverse of the chord are expressed as Fourier series. He concludes that the effective wing aspect ratio spanning a free jet is only slightly greater than one half the aspect ratio of the part of the wing in the jet. His analysis provides a calculation method for lift and induced drag although he admits that this may need modification in view of the fact that the jet boundary is modelled as a discontinuity in the flow rather than the free shear layer of finite width observed in practice.

One final paper⁽¹⁵⁴⁾ under this heading should be mentioned, and this concerned an investigation associated with an unspecified cooling problem. The paper⁽¹⁵⁴⁾, issued in 1932, was written in conjunction with Hirst and Hartshorn and describes measurements of the drag coefficients for a number of wire gauzes set in the middle of various pipes aligned with the airstream of the RAE 7ft tunnel. Using a combination of approximate theoretical models, a realistic description of the pipes' flow fields is established, from which the required drag coefficients are estimated.

6. 0. PROPELLERS

Like wing theory, propeller theory was also in a state of flux when Glauert came to it at the close of the First World War. His last publication, a review⁽¹⁵⁵⁾ notable for its scholarly accuracy, describes the theory's historical development and this will serve to outline its main features at this point in our review. It is for this reason that his review is introduced out of sequence here.

Glauert's review⁽¹⁵⁵⁾ makes clear that propeller theory began with the application of momentum flux arguments to propulsion by Rankine⁽¹⁵⁶⁾, this being followed by the work of W. Froude⁽¹⁵⁷⁾ and his son, R. E. Froude⁽¹⁵⁸⁾. While the latter created the idea of the propeller as an actuator disc across which a discontinuous jump in pressure occurs, his father had earlier initiated the blade element approach to propeller analysis. As Glauert⁽¹⁵⁵⁾ points out, the actuator disc model represents an idealised situation which takes no account of swirling flow, propeller blading and such. And whilst the model has the advantage of predicting an upper limit for propulsive efficiency, it can provide no information on the most effective means by which high efficiency can be achieved. However, the actuator disc model predicts that the axial flow velocity increase at the disc is one half that achieved by the propeller's eventual slipstream. This factor of one half became known as the inflow factor and subsequently various stratagems employing experimental investigation or blade element theory were used in attempts to obtain empirical adjustments to its value so as to take account of swirl, blade interference and so forth. None, however, were entirely successful. As to the development of the blade element method itself, although this was initiated in a crude way by W. Froude, it was Drzewiecki who brought the concept to a usable model. In this, each propeller blade element is regarded as an aerofoil element subject to its local

airflow vector, the propeller's overall thrust and torque being obtained by integration from root to tip of the blade. This Drzewiecki set out in articles beginning in 1892 in the *Bulletin de L'Association Technique Maritime*, these being followed by his books^(159, 160) on the subject published in 1909 and 1920. However, as Glauert⁽¹⁵⁵⁾ acknowledges, in 1907 Lanchester⁽²⁶⁾ had developed a similar approach based on his wing theory although it should be added that, yet again, this seems to have been largely ignored in British official circles, Drzewiecki's approach being preferred at Farnborough and the NPL.

To divert briefly from Glauert's review, for the design of their propellers the Wright brothers used actuator disc theory and their own wind tunnel data for wings coupled to Drzewiecki's blade element method. Their propellers achieved efficiencies in the mid-60% range whereas those of their contemporaries barely touched 50%, one factor among many which explains why the Wrights were successful in achieving powered flight in 1903. However, the Wrights' propeller theory, arguably their finest scientific achievement, only came to light at the publication of their papers⁽¹⁶¹⁾ in 1953.

At the close of the First World War various theories of the actuator disc-Drzewiecki type were being explored, one being by De Bothezat⁽¹⁶²⁾, another by Fage⁽¹⁶³⁾, currently the NPL's propeller expert. Wood relates⁽⁶⁾ that his earliest work at Farnborough involved propeller testing and in 1919 he produced a lengthy survey⁽¹⁶⁴⁾ detailing the knowledge gained during the war years. This included his joint paper⁽¹⁶⁵⁾ with Glauert of the previous year in which they analysed results from an experiment involving a serried array of aerofoils tested in the RAE's 4ft wind tunnel. Their purpose here was to gain information on the mutual interference of blades so as to adjust the disc actuator theory's inflow factor; their results, however, were rather inconclusive.

Thus drawn into the currently rather confused state of propeller theory, in 1919 Glauert⁽¹⁶⁶⁾ added to a paper by Harris⁽¹⁶⁷⁾ from the previous year, the latter having analysed the forces and moments on a propeller due to a constant angle of pitch or yaw. As we have seen in Section 4.0 above, at this time Glauert had become involved in the calculation of stability derivatives and his purpose now was to determine all of the propeller's contributions to these. For this he uses blade element theory to show that for longitudinal stability the derivatives of main importance are those for forward force and pitching moment changes due to change of forward speed. For lateral stability he finds three derivatives important: side force and yawing moment due to rate of sideslip and yawing moment due to rate of yaw.

By 1922 Glauert was in command of Göttingen wing theory and in that year he applied it to propeller blade element theory⁽¹⁶⁸⁾. From this he concludes that the aerofoil characteristics to be used should be those for infinite aspect ratio. This, he states, removes the current discrepancies between empirical inflow factors and the theoretical value of one half, the latter here being established as the correct value to be used. The paper is a lengthy mathematical exposition requiring additional appendices on such matters as the energy relationships used. However, a final appendix discusses current propeller theories and here Glauert mentions a paper by Betz⁽¹⁶⁹⁾ who had sought to obtain the blade load distribution which yields maximum efficiency, the approach being similar to his own although the aim had been rather different. As to a comprehensive review of current inflow theories, he recommends the book by Bairstow⁽⁵²⁾. Later in 1922 Glauert issued a paper⁽¹⁷⁰⁾ in which he points out that his earlier vortex theory⁽¹⁶⁸⁾ took the forward speed of the propeller as the fundamental speed. This, however, is unsatisfactory for

low or, presumably, zero forward speeds and he has therefore re-cast his analysis using rate of rotation as the fundamental speed.

As to the analysis by Betz ⁽¹⁶⁹⁾ mentioned above, it is worth adding that this contained a mathematical difficulty at the propeller tip which Prandtl had attempted to resolve. However, it was Goldstein ⁽¹⁷¹⁾ in 1929 who provided a satisfactory outcome to the problem and his method was later extended by Lock ⁽¹⁷²⁾ at the NPL.

In the following year, 1923, Glauert produced a paper ⁽¹⁷³⁾ which demonstrates the versatility of his new vortex theory for propellers. In this he builds on his earlier papers ^(168, 170) so as to analyse a tandem pair of propellers set close together. In particular, he explores the possibility of contra-rotation, pointing out that energy losses should be reduced by the elimination of rotational kinetic energy in the slipstream and demonstrates that indeed this does create a small gain in efficiency. For a tandem pair rotating in the same direction with the same angular velocity, he shows that there is a best position for the rear blades relative to the forward blades which depends on the distance between the two propellers.

For the next few years Glauert remained silent on propeller theory, but in 1926 he produced five papers on the subject. One paper ⁽¹⁷⁴⁾ discusses propeller conditions observed by Lock, Bateman and Townend ⁽¹⁷⁵⁾ of the NPL in which a propeller acts as a windmill or is in slight backward motion so that vortex motions occur around its tips, both conditions not being covered by the conventional vortex theory. Glauert ⁽¹⁷⁴⁾ analyses the experimental data so as to produce empirical performance curves which join the conventional curves. However, he notes that his empirical curves remain somewhat uncertain until tunnel interference is accurately known. In a further paper ⁽¹⁷⁶⁾ Glauert notes that his earlier vortex theory neglects the contraction of the slipstream aft of the propeller, this usually being small. However, this may not be the case at slow speeds and in this paper ⁽¹⁷⁶⁾ he uses successive approximations to correct for this. His solution is consistent with the momentum equation but the ratio of the wake's induced velocity to that at the propeller disc is less than the usual factor of 2 for a propeller and greater than 2 for a windmill.

In a third paper ⁽¹⁷⁷⁾ from 1926 Glauert demonstrates how his theory can be adapted for use in propeller design. He notes that for practical purposes it is necessary to estimate efficiency for a propeller designed to absorb a given power and hitherto for this it has been necessary to rely on empirical curves or rather crude calculation methods. However, using a few simple approximations to his earlier theory ⁽¹⁶⁸⁾ his paper offers general formulae by which efficiency can be rapidly calculated, the results of which are in close agreement with experimental data. He adds that his analyses take no account of efficiency losses caused by tip speeds approaching the speed of sound. A thorough examination of the experimental data for propellers accumulated by both the RAE and NPL is undertaken in a lengthy review ⁽¹⁷⁸⁾ written in co-operation with Lock, now in charge of propeller development at the NPL. Agreement with the vortex theory ^(168, 170) is generally good and remaining discrepancies are found to be in such cases as motion at small velocity, propellers with a small number of blades and propellers having high pitch ratios. The report also draws attention to slight uncertainties created by tunnel interference. This latter difficulty is explored in a further paper ⁽¹⁷⁹⁾ with Lock in which tunnel interference in propeller tests is analysed and a case made for the use of an open jet tunnel of the Göttingen type for such tests.

By the late 1920s aircraft speeds were increasing dramatically, spurred on particularly by such events as the Schneider Trophy races⁽¹⁰¹⁾. In a paper⁽¹⁸⁰⁾ issued in 1930 Glauert explores the means by which propellers could be designed to facilitate this while still avoiding sonic conditions at their tips. Such propellers, he notes, will have a high pitch-diameter ratio yet this will inevitably yield a low static thrust. On the basis of his earlier work, he provides approximate formulae from which the characteristics of high pitch propellers can be calculated. His formulae cover such characteristics as the torque coefficient, propeller efficiency (Fig. 14), propeller solidity in regions of high efficiency and static thrust values. For current racing aeroplanes he concludes that the most suitable propeller is a two-blade unit of 10ft diameter, but for higher speeds a smaller diameter unit with a larger number of blades will be required. Here his calculations envisage aeroplanes travelling at 450mph with engine powers in the 3000hp class for which propeller efficiencies exceeding 80% might still be possible. As to the abiding problem of low static thrust, he states that “the only hope of improvement is to use a variable pitch airscrew.” In view of the technological developments spurred on by the impending cataclysm which exploded within a decade later, Glauert’s calculations and conclusions here are prescient indeed.

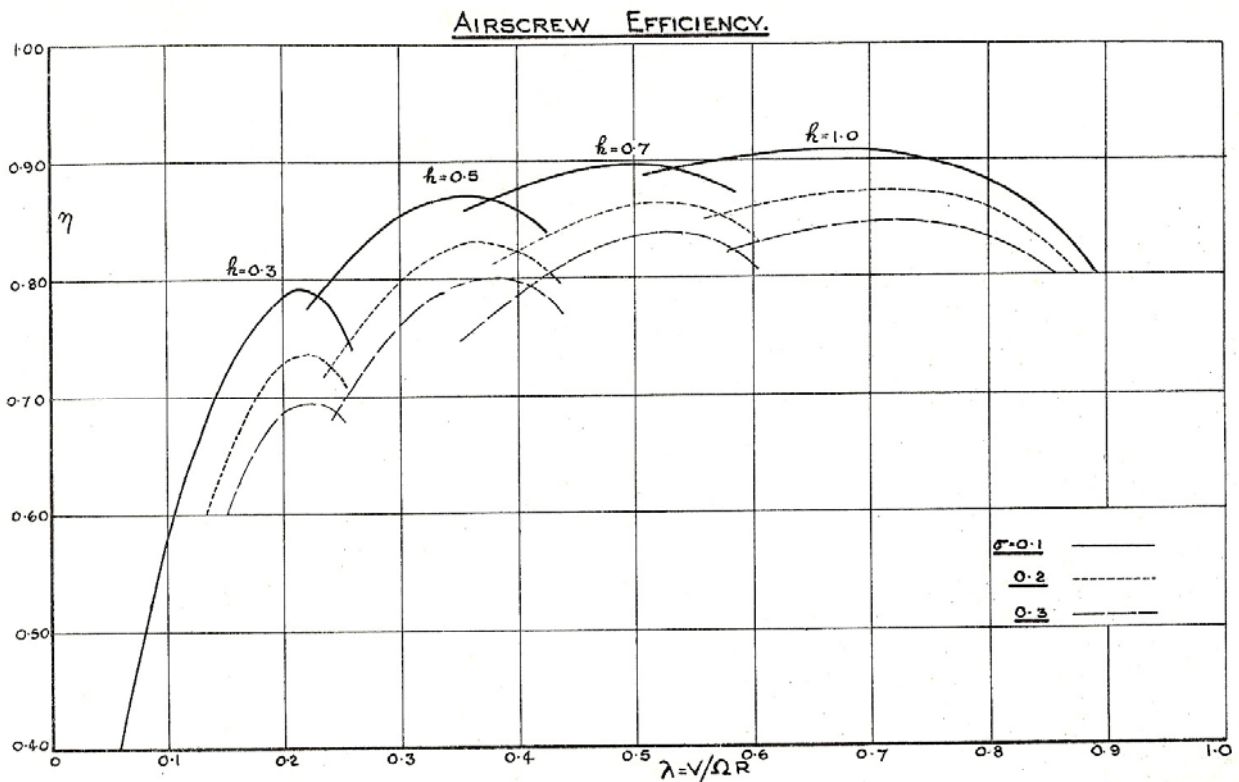


Fig. 14. Propeller efficiency, η , against forward speed to tip speed ratio, λ , for various values of pitch ratio, h , and ratios of total blade area to disc area, σ . (Glauert⁽¹⁸⁰⁾)

Glauert’s last contribution⁽¹⁵⁵⁾ to propeller theory has already been mentioned at the beginning of this Section. It was published posthumously and, as Durand, the editor of the series in which it appeared acknowledges, the proofreading was performed by Muriel Glauert and the man whom Glauert had succeeded as the RAE’s Head of Aerodynamics, R. M. Wood. Glauert’s review⁽¹⁵⁵⁾ of propeller performance is again in the spirit of his earlier textbook⁽¹¹⁰⁾, massively comprehensive in scope and some 190 pages in length. After an introduction to the basic ideas in

propeller theory and the theory's historical development, already mentioned, Glauert then covers the following topics: axial and general momentum theories, propeller efficiency, blade element and vortex theories, propellers of higher efficiencies, body and wing interference, the experimental study of propellers including scale and compressibility effects, helicopter airscrews, windmills and fans, and finally a miscellany of topics including tandem propellers and other items of his work outlined earlier in this Section. Yet the achievements of others are duly recorded; it is difficult to detect anyone and anything by then published which has been left out. It is also impossible here to do justice to this final article ⁽¹⁵⁵⁾ by Glauert but merely to suggest that, under the sad circumstances, it stands as a massive memorial to an exceptional career.

7.0. AUTOGYROS AND HELICOPTERS

The practical autogyro is the invention of Juan de la Cierva (1895-1936), whose lecture on his machine appeared in this Journal in 1926 ⁽¹⁸¹⁾. A demonstration of the Cierva C.6 (Fig. 15) had been given at the RAE in the previous year and this had been followed by further tests on a C.8 together with model tests of the autogyro's blades at the NPL. These activities resulted in a short series of papers by Glauert, some written in conjunction with Lock of the NPL, on the performance of autogyros and also of helicopters. As to the latter, it should be added that practical examples did not appear until after Glauert's death. The Focke-Achgelis Fw 61 twin-rotor machine (Fig 16) flew in 1936 and the first successful single-rotor helicopter, the VS-300 (Fig. 17) of Igor Sikorsky (1889-1972), did not appear until 1939.



Figure 15 Cierva C.6. (1924)

Source: Royal Aeronautical Society (National Aerospace Library)



Figure 16 Focke Achgelis Fa61.
Source: Royal Aeronautical Society (National Aerospace Library)



Figure 17 Igor Sikorsky at the controls of the Sikorsky VS-300. 17 April 1941
Source: Royal Aeronautical Society (National Aerospace Library)

In 1926 Glauert⁽¹⁸²⁾ published a lengthy and detailed mathematical analysis of the autogyro, the analysis being subject to a number of simplifying assumptions, some of which are as follows: blade element incidence angles are small, interference is similar to that for aerofoils rather than propellers and only the first harmonics of periodic terms are retained in the equations. Three appendices consider energy losses, the conditions for maximum speed and vertical descent. He concludes that an autogyro's maximum lift coefficient based on rotor disc area and forward speed lies between 0.5 and 0.6 and that the best lift-to-drag ratio is, at most, between 6 and 8. Owing to the necessity of maintaining a sufficient ratio of tip speed to forward speed, an autogyro's stalling speed must rise with maximum level flight speed. Thus the autogyro's principal merit of a low landing speed would disappear in the case of a high speed aircraft.

In the following year Lock⁽¹⁸³⁾ at the NPL took the analysis further in an equally lengthy paper in which he removed a number of Glauert's simplifying assumptions. His results, however, do not produce substantially different conclusions to those of Glauert. The NPL's model tests had been reported⁽¹⁸⁴⁾ in the previous year, indicating that in vertical descent the normal force coefficients based on rotor disc area lie between 0.58 and 0.71.

Close on the heels of Lock's paper⁽¹⁸³⁾, in 1927 Glauert issued a second paper⁽¹⁸⁵⁾ in which he extended his earlier analysis so as to predict an autogyro's lift and torque when standing on the ground while being exposed to a range of wind speeds. His calculations concentrate mainly on a wind speed of 20mph, for which case he concludes that lift is proportional to tip speed. At a given tip speed the lift increases and the torque decreases as the incidence angle increases from 8° to 12°. In 1928 Glauert and Lock combined to produce a summary⁽¹⁸⁶⁾ of current findings on autogyro characteristics. It is here that they describe the demonstration of the Cierva C.6 at the RAE and the subsequent responses of the RAE and NPL mentioned earlier. Having summarised the theoretical and experimental results obtained, they conclude that their results are in satisfactory agreement on all essential points. From this they judge the autogyro's performance to be inferior to that of corresponding aeroplanes. However, the autogyro possesses the valuable qualities of stability at large incidence angles and ease of landing.

Earlier Glauert had been asked to develop a theory for helicopter performance and in 1927 he issued his first paper⁽¹⁸⁷⁾ on this, concentrating on vertical ascent. After a general introduction in which he notes that the efficiency of power transmission is unlikely to exceed 65%, he develops airscrew theories for constant chord and blade angle conditions as well as those for constant chord and pitch. He then turns to the helicopter in vertical ascent so as to calculate rate of climb which he finds to vary almost linearly with height. He concludes that helicopter blades should be of large area and large diameter so as to secure light loading of the disc. To obtain the best rate of climb he recommends that the blade angles be adjustable in flight. In his second paper⁽¹⁸⁸⁾ he deals with the helicopter in horizontal flight and it becomes clear that at this time the configuration of a successful machine was far from settled. For example, he considers the possibility of using a tractor propeller to overcome drag but later suggests the option subsequently adopted, that of inclining the helicopter shaft in the direction of motion. If the blades are rigid in forward flight, he recognises that a rolling moment would be created by the advancing blade having a greater lift than the retreating blade. To remove this moment, he suggests either hinging the blades at their roots so as to allow them to flap up and down freely or alternatively arranging for a periodic variation of blade angle during each revolution. The latter suggestion was later universally adopted. However, no mention is made of the need to

counteract the rotor's torque on the airframe in the case of a single rotor machine. Nonetheless he is able to conclude that in forward motion the power required for sustentation is reduced and since the drag force is unlikely to be high the helicopter should be able to achieve a satisfactory forward speed.

In his final and posthumous publication ⁽¹⁵⁵⁾ reviewed at the close of Section 6.0, Glauert returns to the helicopter but confines himself largely to blade aerodynamics. In this the analyses he summarises are mainly his own earlier work mentioned above. However, he mentions the analysis of Flachsbarth ⁽¹⁸⁹⁾ in 1928 to determine the best thrust distribution along a helicopter blade. In brief comments on the choice of rotor arrangements for the removal of rolling moments he suggests as alternatives to periodic blade incidence variation the choices of two airscrews rotating in opposite senses either on a common shaft or on two separate shafts. The latter option was adopted for the Fw 61 and this obviated the need to counteract rotor torque; a tractor propeller was required, however, for forward flight. In the case of the single-rotor Sikorsky VS-300, periodic blade incidence variation was used, the main rotor's torque being counteracted by a tail rotor.

8.0. REVIEW PAPERS & LECTURES TO THIS SOCIETY

Glauert's important role as an educator has been mentioned in Section 5.0 above: in the mid-nineteen-twenties he not only lectured on aerodynamics and propeller theory to Farnborough recruits but also produced a much needed textbook ⁽¹¹⁰⁾ on these subjects. However, his role here began even earlier and continued throughout his career in his endeavour to put recent advances before a wider aeronautical community. In most of this, in contrast to Ref. 110, he largely eschewed mathematics, favouring detailed and persuasive physical arguments, an important, perhaps essential, choice of approach in view of the fact that few in British aeronautics at that time had the background to grasp the theoretical work involved.

His earliest contributions, two in number, appeared in a short-lived journal published in 1920 and named *Aircraft Engineering* (not the journal of the same name which first appeared in 1929 and subsequently enjoyed far greater longevity). Glauert's first article ⁽¹⁹⁰⁾ concerns scale effects. Having made clear that the lift, drag and moment coefficients depend on what we nowadays call Reynolds number, he points out that wind tunnel model tests are invariably conducted at much smaller values of that number compared with those at full scale. He then reviews the available data for struts and wing sections and discusses how such scale effects are dealt with. Glauert's second article ⁽¹⁹¹⁾ provides his earliest description of the important work he has discovered during his visit to Göttingen. Referring to what are probably the results contained in the paper by Wiesselsberger ⁽¹⁹²⁾ of 1919, he emphasises how well theoretical predictions and experiment compare. Brief mention is made of Kutta's circulation theory for wings of infinite span ⁽⁷²⁾ before the paper turns to flows about wings of finite span. In this he makes clear that the general nature of the flow patterns involved had been described by Lanchester ⁽²⁶⁾ - in view of the latter's neglect, an advocacy much needed at the time. The remainder of the paper reviews the theoretical results obtained - the first of equations (1) is quoted, for example - and the paper closes with a detailed comparison of the performance predictions for monoplane and biplane wings.

At this point it is of interest to mention one other paper appearing in these issues of *Aircraft Engineering*, this being by Hermann Glauert's elder brother, Otto (1881-1962). He too had attended the King Edward VIIth School in Sheffield, matriculating in 1899 and thereafter progressing to Clare College, Cambridge, where he read Mathematics and Natural Sciences. His working life seems to have been spent largely as a schoolmaster: prior to the First World War, assistant master at Pocklington School, later at Norwich School, headmaster of Somerville Preparatory School, New Brighton and finally at Wrekin College during the Second World War⁽¹⁹³⁾. As recorded in Section 2.2 above, he was present at his brother's death and appeared as a key witness at the inquest⁽¹³⁾. Otherwise, little seems to be known of him. However, his paper⁽¹⁹⁴⁾, spread through a number of the journal's issues, suggests that immediately after the First World War he too was closely involved in aeronautics. The paper provides a detailed and remarkably comprehensive textbook on the subject of aeroplane stability as it then stood. Although Otto modestly claims no advance on the texts of Lanchester⁽¹⁸⁾, Bryan⁽¹⁹⁾ and Bairstow⁽⁵²⁾, his exposition benefits from his brother's ACA reviews^(37, 45) of the subject. Throughout the paper, mathematical exposition is extensive although Otto assumes "the reader's knowledge is limited to the standard of a pass degree in Arts or Science who has taken mathematics as a subject." Having derived the equations of motion, Otto deals with equilibrium in steady horizontal flight in which the role of the tailplane, elevators fixed and free, is explored. Steady rectilinear motion which is then subject to small oscillations is considered next, the conditions for stability being presented in determinant form involving the aerodynamic derivatives. The latter are then obtained theoretically for both longitudinal and lateral stability; the discussion includes the effects of climbing and gliding as well as level flight. However, as mentioned in Section 4.0, the modern concept of static stability has yet to emerge. The paper ends with extensive, detailed calculations for a particular aeroplane. This is a two-seater tractor biplane, unidentified in the paper, but for which the calculated stability characteristics are in reasonable agreement with the pilot's experience of flying the machine. Once again, the authors are grateful to Gordon Bruce for identifying this aeroplane as the P9 built by Boulton & Paul in Norwich⁽¹⁹⁵⁾. Otto had been assistant master at Norwich School until 1918 and retained an association with the School for some time thereafter, a period during which he might have been employed by Boulton & Paul. A further family connection is suggested by evidence that at this time the aircraft company may have consulted Hermann Glauert on the subject of airscrews.

Hermann Glauert's remaining educative reviews appeared as lectures and papers presented to this Society. The first of these was a paper⁽¹⁹⁶⁾ in 1923 in which he again describes the key ideas in wing theory obtained from Germany but now he is able to provide his own extensions of this work. As to the work of Prandtl and his colleagues, he lists Refs. 74, 87 and 104, his own papers cited being Refs. 78, 84 and 168. Both two-dimensional and three-dimensional flow fields are described and in the former case the method of conformal transformation is briefly outlined in dealing with Joukowski-type sections. Throughout he provides persuasive physical arguments for the view that cyclic or circulatory systems of flow are created by the behaviour of the thin viscous boundary layer. Although Glauert does not discuss the boundary layer itself in any detail, his remarks here prompted an immediate response from Piercy. In the same year, 1923, his two papers to this Society described experimental investigations corroborating Prandtl's model of a wing's flow field. One investigated the boundary layer around an aerofoil section⁽¹⁹⁷⁾, the other revealed the thin viscous core within the irrotational flow of the trailing vortex behind a wing tip⁽¹⁹⁸⁾. These were the first British experimental investigations of such flows (see also Ref. 4).

Glauert's next presentation to this Society was a lecture ⁽¹⁹⁹⁾ delivered in 1927, the subject being the theory of the autogyro. In this he draws heavily on his own work contained in Ref. 182 and the results quoted are taken from there, his conclusions on the autogyro being unchanged. Here again he avoids the densely analytical work of that reference, favouring instead the simpler path of using force and moment arguments to outline what is an exceedingly complex problem, not least the role of the rotor hinge. The discussion following the lecture elicited mixed feelings from the audience on Glauert's prediction of autogyro performance. The most critical of these came from Cierva himself in a written submission in which he disagreed on a number of points in Glauert's analysis and claimed better performance than Glauert's analysis predicted. The crux of the matter lay in the paucity of full-scale experimental data which left the performance question, if the pun can be excused, rather up in the air.

In 1930 Glauert again lectured to the Society, the printed version ⁽²⁰⁰⁾ appearing in the following year. Having mentioned recent advances in wind tunnel technology – compressed air tunnels for high Reynolds number simulation and high-speed tunnels being examples – he sets out to plead for the continued use of small tunnels in aeroplane design. In this he seeks to reassure his audience that much useful data can still be obtained from small tunnels despite their Reynolds number limitations and, because of their small size, the difficulty in reproducing small but significant detail in the models used. His case is based on recent successes in predicting tunnel constraints and, as to these, he cites the work contained in Refs. 74, 96, 97, 137 and 139. From such examples he shows that corrected results from simple 4ft tunnels compare well with those from larger tunnels. He argues, therefore, that small tunnels can still be valuable at the preliminary design stage, the higher Reynolds number facilities being employed to clear up areas of uncertainty. This was an era in which the pitfalls of tunnel testing were at last being recognised and the lecture elicited a lengthy discussion, a critical one in the case of some industrial members. Nonetheless, some in the audience conceded that the simple 4ft tunnel might still enjoy a further lease of life whilst others favoured improved tunnel design incorporating such features as return circuits and a general move toward lower power factors. In replying to the discussion, Glauert conceded that any attempt to measure such things as maximum lift coefficient on multi-slotted wings at high incidence in a 4ft tunnel was, as he put it, “a waste of time”.

Glauert's last lecture to the Society was presented to the Leeds and Hull Branch in 1930, the printed version ⁽²⁰¹⁾ appearing in the following year. His subject here is the importance of the boundary layer and his treatment is, to say the least, brisk whilst nonetheless touching on many of the major advances following Prandtl's original idea. Glauert lists no references but it is clear to which author's work he refers. Thus, of course, Prandtl's original paper ⁽⁷⁵⁾ appears, as does Blasius's flat plate solution for laminar flow ⁽²⁰²⁾, von Kármán's use of the $1/7^{\text{th}}$ power law for turbulent flow velocity profiles ⁽¹²⁵⁾ and his work on the vortex street ⁽¹²⁰⁾. Glauert also mentions the alternative solution to the Blasius flat plate problem given by Bairstow ⁽²⁰³⁾ in a lecture to this Society in 1924, this being the first British analytical investigation of the boundary layer. Other advances in understanding which he briefly describes are transition and the roles of boundary-layer turbulence in drag reduction for blunt bodies and the Handley Page leading-edge slot in the layer's regeneration. His lecture concludes with the use of either suction or injection for boundary-layer control, although here he stresses that these measures come at the price of the power required for them.

9.0. CONCLUDING REMARKS

It is hoped that the above provides a fitting tribute to a man of quite exceptional ability. His major achievements are all the more astonishing when it is realised that they occurred over the mere fourteen year period following his acquisition of Göttingen's aerodynamic theory. Had he lived, it is intriguing to speculate what else he might have achieved, and in that spirit we offer the following.

In the year after Glauert's tragic death, 1935, the Volta Congress on high-speed flight was held in Rome⁽¹¹⁵⁾. Had he lived, Glauert would have attended as the RAE representative and would have heard Busemann's lecture on the use of sweepback for supersonic flight. Doubtless he would have grasped Busemann's key idea that it is the Mach number normal to the leading edge which is important and that this is less than the free stream Mach number. With his background, particularly his work of Ref. 114, he would have been almost uniquely placed in Britain to see that such ideas on the efficacy of sweepback could be applied to high subsonic flight so as to delay the critical Mach number. In the event, it was Betz at Göttingen who saw the connection and by 1939 Ludwig had provided experimental verification⁽²⁰⁴⁾. By the war's end Britain had established a leading capability in jet engine technology, so was well-placed in that respect to participate strongly in the next major advance in aeronautics, namely high-subsonic/supersonic flight. Unfortunately however, progress was slowed by the fact that the importance of sweepback for implementing that advance had not yet been appreciated in Britain. So, tragic though Glauert's death had been in the personal sense for his family, friends and colleagues, when viewed in this light his premature departure from the aeronautical scene may also have had a far-reaching effect in slowing the post-war progress of the British aeronautical industry.

ACKNOWLEDGEMENTS

It is a pleasure to record the generous assistance of Brian Riddle, Librarian of the Royal Aeronautical Society, Christine Woodward and Chanshika Wijesinghe of the National Aerospace Library, Farnborough, Joanne Crane of the John Rylands Library, University of Manchester, and Geoffrey Butler FRAeS of the Farnborough Air Sciences Trust (FAST). Gratitude must also be expressed to the following for biographical and other information: Frank W. Armstrong FREng, FRAeS, Gordon Bruce FRAeS, A. H. Fraser-Mitchell FRAeS, Dr Audrey M. Glauert, Professor John Glauert, Dr John Green FREng, FRAeS, Professor Peter Hamel, Peter Laws, Dennis Lister, Dr Christopher Mitchell FRAeS and Elizabeth Stratton (Archivist, Clare College, Cambridge).

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APPENDIX

The Cyrillic Николай Егорович Жуковский is nowadays transliterated as Nikolai Egorovich Zhukovskii. In Glauert's era the surname appeared as Joukowsky or Joukowski and both are used here so as to avoid confusion in cited references.

J A D Ackroyd

Born in Bradford, Yorkshire, in 1938, John Ackroyd graduated in Aeronautical Engineering in 1960 at Queen Mary College, University of London. After doctoral and postdoctoral research in shock tubes there, he joined the staff of the Department of the Mechanics of Fluids (later the Aerospace Division, Manchester School of Engineering) of the Victoria University of Manchester. He taught in aerodynamics, flight dynamics, aircraft structures and propulsion whilst carrying out research in boundary-layer theory. He retired in 2000 as Senior Lecturer. His interest in the technical history of aviation resulted in him giving the Royal Aeronautical Society's Lanchester and Cayley Lectures, and the Inaugural Cody Lecture.

N. RILEY

Born in Hebden Bridge, Yorkshire in 1934, Norman Riley graduated in Mathematics in 1956 at Manchester University. Following his PhD there he was appointed as a member of faculty at Manchester before moving to Durham University in 1960 and subsequently to the then new University of East Anglia in 1964. His research has embraced a wide range of topics in applied mathematics, including aerodynamics with studies of leading-edge vortices stimulated by visits to the former Royal Aircraft Establishment. He retired in 1999 as Emeritus Professor of Applied Mathematics.