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SIR GEORGE CAYLEY, THE FATHER OF AERONAUTICS
PART 1. THE INVENTION OF THE AEROPLANE

by

J.A.D. Ackroyd

Aerospace Division, Manchester School of Engineering, University of Manchester, Manchester M13 9PL, UK

Summary

This paper, in two parts, seeks to describe and assess Cayley's technical development of his invention, the fixed-wing aeroplane. Particular attention is paid to such scientific results as were known to Cayley at that time. Part 1 deals with the invention of the aeroplane itself, this being prefaced by a biographical sketch outlining his wide-ranging interests, both scientific and humanitarian; part 2 will show how Cayley was not only able to develop his invention but through this was also able to demonstrate many of the basic principles of fixed-wing flight. The paper is based on the author's Cayley Lecture to the Royal Aeronautical Society in April 2000.

Introduction

The occasion of the millennium has provided an opportunity to celebrate great aeronautical progress. The timing has been apt indeed because by chance this almost coincides with the centenary of the Wrights' practical involvement with the aeroplane. Indeed, the acme of their tremendous contributions, the achievement of powered controllable flight itself, will no doubt rightly enjoy centennial celebration in 2003. Yet what might become overshadowed in this happy coincidence of timing is the fact that 1999 was also the bicentenary of the invention of the aeroplane itself. Moreover, following closely on the Wright centenary, the year 2004 should be remembered as the bicentenary of two further major events, namely the first measurement of wing lift and, more significantly, the flight of the world's first aeroplane. All this, including the invention itself, was the achievement of the Yorkshire baronet Sir George Cayley, at Brompton near Scarborough. Still in his twenties when his seminal idea created the aeroplane concept in 1799, he measured wing lift and flew his first glider in 1804, the year before the Battle of Trafalgar.

This therefore seems an appropriate moment to review Cayley's progress with his invention. Of the man himself and his activities, what is known is perhaps rather less than one might wish for. The more important material to survive provided the basis for the Royal Aeronautical Society's First Cayley Lecture[1] and the far more extensive and intriguing biography by Pritchard[2], which attempts to cover the full range of Cayley's multifarious activities. In contrast, Fairlie & Cayley[3] concentrate more on his domestic circumstances, the second author having access to family papers as the wife of the last baronet of the Cayley line. To this the booklet by Rivett & Matthew[4] adds information that has more recently come to light.

As to the technical detail of Cayley's aeronautical work, luckily we can delve deeper than his published material. Additional information is contained within his aeronautical notebooks, the first batch of these having been discovered at the family seat, Brompton Hall, as late as 1926. These are reviewed by Hodgson[5,6]. A further collection emerged from the same source in 1961 and its contents are included in the extensive survey by Gibbs-Smith[7] of all the known material. In a later paper, Gibbs-Smith[8] briefly revisits much of this, but his concern there is mainly to emphasize Cayley's stature and influence on subsequent developments in practical aeronautics. In addition, Sproule[9] describes his own experience of building replicas of Cayley's gliders. Regrettably, however, he makes virtually no comparison with such performance figures as Cayley has left to us.

As to Cayley's technical data, and indeed his arguments in general, in certain respects there has been a tendency to avoid detailed study of their meaning, while ascribing a significance to them that therefore might be beyond their value. There can be, of course, no doubt of Cayley's immense importance and stature, yet it does no service to this man to claim for him more than his due. Thus the present paper attempts to avoid ritual genuflection in favour of an assessment of the progress of Cayley's thinking on the aeroplane and the extent to which he saw his invention in the round.

Biographical sketch

George Cayley (figure 1) was born in the Yorkshire coastal town of Scarborough on 27 December 1773. His precise place of birth seems still to be a subject of debate. Pritchard[2] has him born in Paradise House, close to the Parish Church of St Mary's. Fairlie & Cayley[3], however, place the event somewhere within the surrounding Paradise district. Local historians, in contrast, point to Cayley's own statement of 1832 (see Pritchard[2] and Fairlie & Cayley[3]) that he was born 'within a hundred yards of' the steps of the then Scarborough Town Hall, currently the site of Lloyds Bank on St Nicholas Street. If literally true, this places his birth near to a half-mile from the Paradise district. His home during his early years seems to be equally unclear. Pritchard[2] believes this to have been at Helmsley, whereas Fairlie & Cayley[3] have him growing up at the village of Brompton.

Cayley's mother, born Isabella Seton (*ca.* 1745–1828), was a Scotswoman of education and intelligence whose determined views ensured her son's lively instruction in areas not merely those marked out as necessary for a young gentleman destined for a high place in society. Given her son's evident enthusiasm for all things mechanical, Isabella Cayley ensured that the then unusual subjects of mathematics

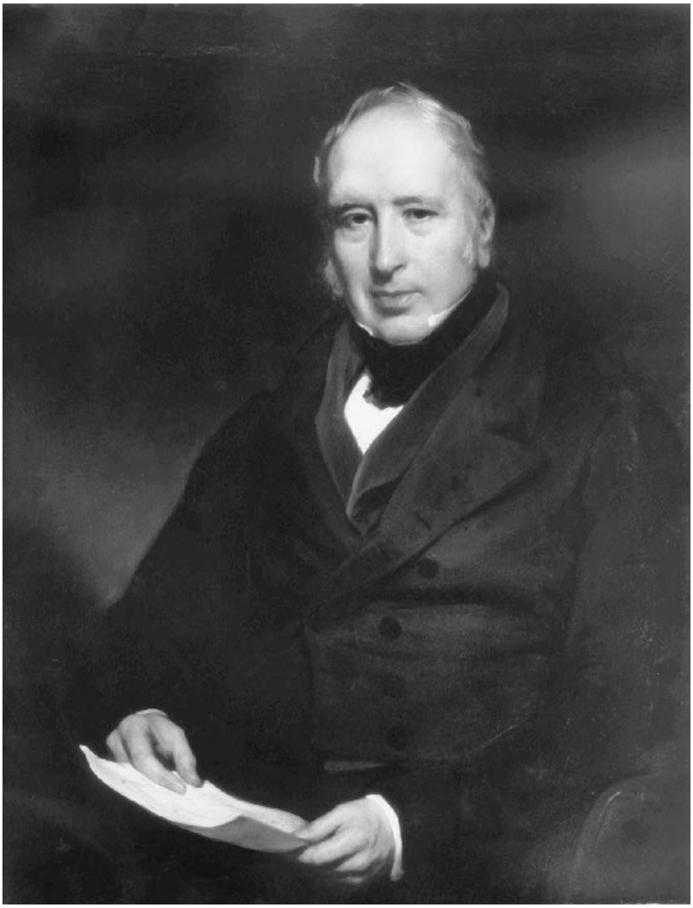

Figure 1. Sir George Cayley. Portrait by Henry Perronet Briggs, RA, 1841.
(By courtesy of the National Portrait Gallery, London.)

and the physical sciences became central to his curriculum. Thus, in 1791 he was placed in Nottingham with George Walker, F.R.S. (1734–1807), a distinguished mathematician and nonconformist minister; a man, moreover, who was noted for his reforming zeal. Walker had one child, a daughter, Sarah, who joined his Nottingham lodgers in the role of tutee. Two years Cayley's senior, mathematically accomplished and notably attractive, Sarah Walker (*ca.* 1771–1854) soon provided significant distraction for the young man. It seems[3] that for this reason Isabella Cayley, disapproving of Sarah, moved her son to Southgate, there to be tutored by George Cadogan Morgan (1754–98), also a nonconformist and a distinguished lecturer on such subjects as mechanics and electricity at Hackney College, London. Both Walker and Morgan had considerable influence on the young Cayley, and not only in the areas of mathematics and the physical sciences. Moreover, his residence in Southgate provided opportunity for him to move in London's circle of reformers. However, in 1792, after his move to Southgate earlier that year, he succeeded his father to become the sixth baronet in the Cayley line and thereby to inherit the family estates centred at Brompton Hall. Within a year of attaining his majority, in 1795 he married Sarah Walker. The union was to produce nine children, six daughters and three sons, two of the sons succumbing to a measles epidemic in 1813, whereas one daughter died around 1819 in Paris of heart disease, aged 16. By all accounts, the marriage proved to be a turbulent one.[2,3] The new Lady Cayley was possessed of a temper sufficiently ungovernable to leave her children in a state of shock and Sir George writing to friends and neighbours in apology for his wife's behaviour. Yet her death in 1854 left him desolate.

This, then, was the background of the man who invented the aeroplane and whose passion for aerial navigation extended to designs for a number of dirigible airships. Moreover, he was actively involved in the steam engine work of his day, invented the heated-air engine and succeeded in building a small gunpowder motor. His other inventions included the tension wheel and a forerunner of the caterpillar tractor. Being a major landowner, he was much concerned by the periodic flooding of tracts of land adjoining the Derwent and Hertford rivers nearby, thereby becoming a leading authority on land drainage. He was also the first landowner to initiate a system of agricultural allotments, giving one acre of tillage land to labourers at Brompton. His humanitarian concerns expanded into such areas as the then considerable problems of railway safety—his most notable contribution here was a design for a block signalling system—and the design and construction of mechanically articulated artificial hands to assist amputees. His more scientific activities included papers on optics, acoustics, and the prediction of the absolute zero of temperature as –480 °F. Having helped to found the Yorkshire Philosophical Society, he became instrumental in the establishment of the British Association for the Advancement of Science. Active in the cause of parliamentary reform, for three years he sat as Member of Parliament for Scarborough. In 1839 he founded the Polytechnic Institution in Regent Street, London, later to become the Regent Street Polytechnic, which is now a part of the University of Westminster.

In much of his constructional work Cayley was assisted by a local mechanic, Mr Vick, of whom we can only wish that we knew more. It seems that they worked together largely in the hexagonal stone building set into the wall surrounding Brompton Hall. The testing of the aeroplanes was conducted often in Brompton Dale, its mouth lying directly opposite the entrance to the Hall.

Throughout his adult life Cayley retained an unshakeable belief that the fruits of his labours should be freely available to all mankind, particularly so to those far less fortunate than himself. Indeed, his energetic promotion of humane social improvement provides striking examples of relevance to today's debates on society's direction. Not least of these was his concern for railway safety. Commenting on the then unrestrained profit motive of the private railway companies, he asserted that

> If Government be not permitted to interfere with private property, for the purpose of protecting life, it is full time that this noble invention should be taken entirely into the hands of the Government, and thus ripened into safety.[2]

His remarks even now carry a certain resonance because once again, it seems, we must debate the virtues, or otherwise, of private or public responsibility for a national amenity provision far more extensive than our railway system.

Cayley's advocacy of education is clear from his involvement in the British Association and in the foundation of the Polytechnic Institution. Writing to his long-time friend, Charles Babbage (1792–1871), on the establishment of this institution, his advice strikes further resonance in today's academic debates:

> We much want a good scientific board confined by no aristocracy of orthodox men who sit like an incubus on all rising talent which is not *of their own shop*. … Freedom is the essence of improvement in science.[2]

Sir George died at Brompton on 15 December 1857, 12 days before his 84th birthday. The Parish Church of All Saints, Brompton, contains his remains.[10]

The evolution of Cayley's early ideas on the aeroplane

Cayley's work on the aeroplane attempted to cover those four main subjects that were—and must remain still—central to any reputable aeronautical curriculum: propulsion, structure, aerodynamics, and stability and control. Although it is tempting to deal with these separately, it is arguably more illuminating, in terms of the evolution of his thinking, to describe his work chronologically. Because he was balked by the lack of an engine sufficiently light and powerful for his purposes, he made little headway on the subject of propulsion. Thus his significant aeroplanes remained gliders. As to structure, here little sophistication had been achieved by his time so that his techniques, although sometimes remarkably advanced, otherwise erred on the side of the conservative. Thus it is in the two areas of aerodynamics and stability and control that his main achievements lie. When Cayley came to aeronautics, it must be emphasized, it was precisely within these two areas that the main problems in the understanding of flight were to be found.

Early thoughts on flight and air resistance

Cayley tells us (see Gibbs-Smith[7]) that his first thoughts on mechanical flight occurred at Southgate in 1792. However, it was perhaps in the year 1796 that he began active experiments, devising an adaptation of the helicopter toy demonstrated in 1784 by Launoy and Bienvenu in Paris. The interesting point about this toy is that, although it served as Cayley's practical introduction to flight, he largely avoided the use of the propeller throughout his career with the aeroplane. In 1799 Cayley took the seminal step that launched the aeroplane concept on its lengthy journey. He engraved his idea on one face (figure 2*a*) of a small silver disc now at the Science Museum, London. The idea itself, like many others that have changed the world, is extremely simple: the propulsion and lifting systems are completely separated. Hitherto, flight had been attempted, unsuccessfully, by the use of flapping wings in a supposed emulation of bird flight. In Cayley's concept the lifting wing is a fixed low-aspect-ratio sail, its flexible surface cambered taut by the surrounding air pressure field. The separate propulsion system is a pilot-operated flapper arrangement owing

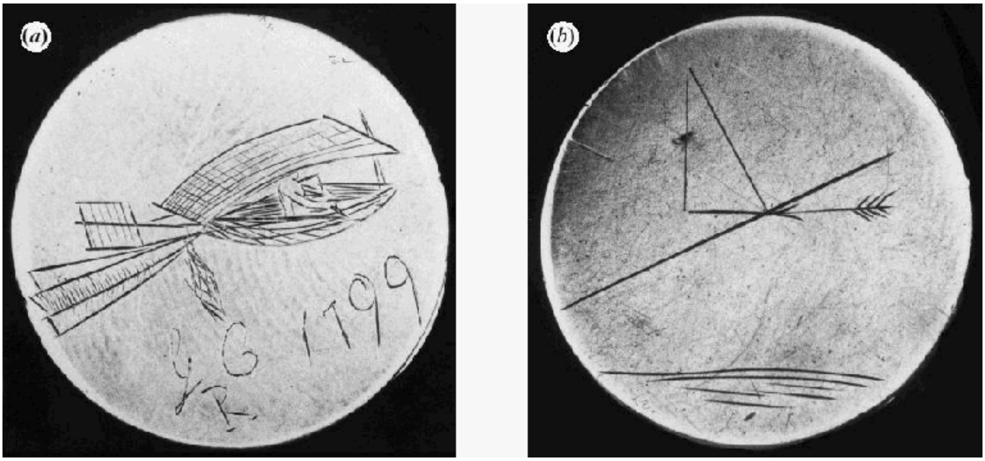

Figure 2. Cayley: silver disc, 1799. (Science and Society Picture Library/Science Museum.)

much to the past. A cruciform rudder is provided, presumably with the intention that the machine be steered like a boat. The pilot is seated within a boat-like fuselage; because Cayley grew up near the sea there are several nautical allusions in his aeronautical work.

The reverse of the disc (figure 2*b*) shows Cayley thinking scientifically about the problem of flight. The force of air resistance is shown acting perpendicularly to a flat surface, an oversimplifying assumption as to force direction that was to remain with him throughout his career. This assumption might have arisen from Cayley's belief either that the force would be due entirely to air pressure or that it would follow the dictates of the 'rare medium' concept to be found in Newton's *Principia*[11] of 1687. In the latter, a fluid flow is seen as a stream of disconnected particles all moving in parallel straight lines so as to collide with a body, creating resistance by a change in particle momentum perpendicular to the body's surface. However, the crucial step evident on the disc is Cayley's employment of the simple device of the triangle of forces, by which he resolves the air resistance into its lift and drag components.

In an early notebook entry, which Gibbs-Smith[7] places in about 1801 (the full text can be found in Hodgson[5,6]), Cayley again employs the triangle of forces in an attempt to describe the flight of birds. He deals not only with gliding flight but also with the bird's wing movement required to obtain propulsive thrust. In the end, of course, solid results depend on the variation of lift with wing incidence. Here Cayley notes that

> Theory would estimate the increase of resistance … as the square of the sine of the angle of incidence, but experiment determines it to be in a mean between the direct ratio of the sines and that of their squares.[6]

The theory to which Cayley refers springs from the Newtonian 'rare medium' concept, the definitive derivation of the sine-squared relation for the flat plate being due to Euler[12] in 1745. However, it is rather unclear precisely which experiment

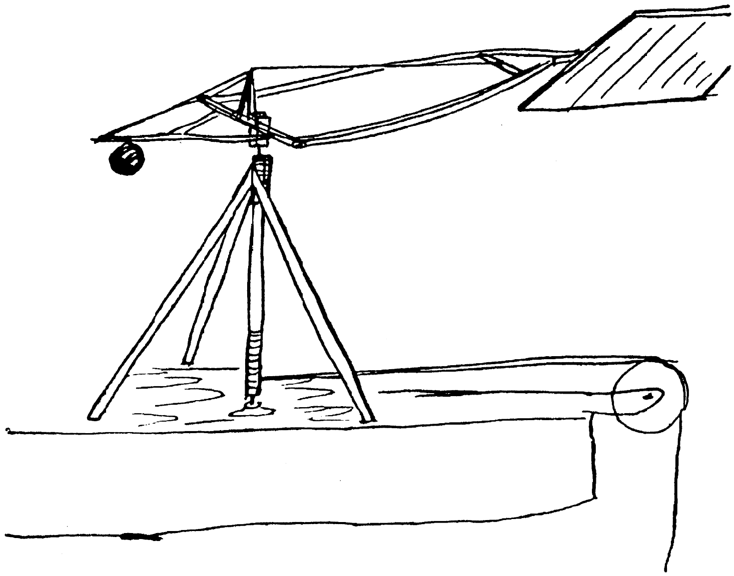

Figure 3. Cayley: whirling arm, 1804.

Cayley refers to here. In a following notebook passage, he appeals to 'the French experiment on angular resistance'. The most likely candidate is then the paper by d'Alembert *et al.*[13] of 1777. Commenting in 1778 on the results presented there, Euler[14] believes them to be applicable to plates in the small incidence range, for which case he then argues that a plate's resistance is more nearly proportional to the sine of its incidence angle. This assertion, correct but fortuitous because wedge shapes rather than plates had been tested, was to be mirrored in Cayley's later statements about wings. Clearly, however, Cayley was now finding himself in the position of having to address this crucial question of lift dependence on incidence angle.

Incidence dependence apart, theoretical results obtained until then[11] had indicated a direct proportionality between resistance and fluid density, an area characteristic of the body and the square of the flow speed. Experiments[11,13,15–18] had largely supported these conclusions and, indeed, Cayley took them almost as axiomatic in his own experiments of 1804 to determine the effect of incidence. Details of these tests and their results are given in his notebook entry[7] for December 1804. The apparatus itself (figure 3) was an adaptation of the whirling arm first demonstrated by Benjamin Robins (see Wilson[15]) in 1747. To this Cayley added a horizontal hinge at the arm's junction with the vertical drive shaft so that the arm acted as a lever. At rest the arm and test plate were counterpoised by the weight shown (figure 3) on the arm's leftward extension. The test body was a paper plate 1 ft square (0.093 m^2), this and its supporting arm being driven in rotation by the cord-and-pulley system shown. The driving weight descended the stairwell of Brompton Hall, a height sufficient for the plate to travel a circular distance of *ca.* 600 ft (183 m). Because of this circular motion, Cayley realized that the plate's centre of

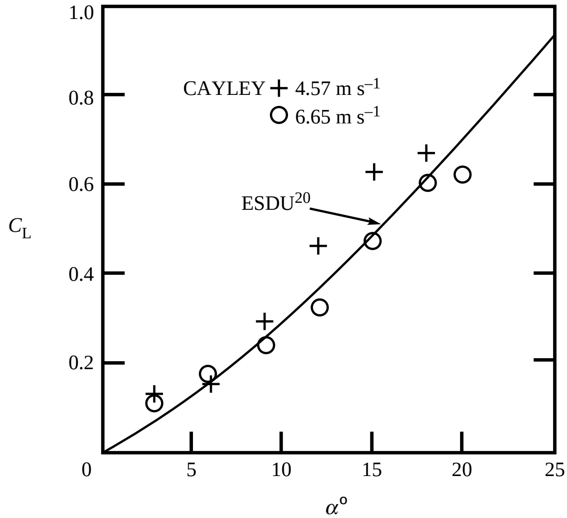

Figure 4. Cayley: whirling-arm results, $C_L \sim \alpha$.[19,20]

pressure location must lie outboard of the plate's mid-span position. Assuming the validity of the velocity-squared resistance rule, he estimated this location by dividing his plate into chordwise strips so as to apply numerical integration to the moment contribution of each strip. Because he went to this trouble and writes of 'the weights lifted upon the path of the plane', the more obvious assumption is that he measured the lift force by placing weights at the plane's computed centre of pressure so as to keep the arm rotating in a horizontal plane. Alternatively, he could have changed the value of the counterpoise weight so as to achieve horizontal rotation. Again, the computed location of the centre of pressure would have been required, to be used in conjunction with the method of moments so as to calculate the lift force. Two arm rotation speeds were used and the plate incidence was varied in 3° steps from an initial incidence of 3° up to 18°. The results have been reduced to the modern notation of lift coefficient, C_L, by Yates.[19] They are here shown (figure 4) not only to exhibit a reasonable collapse according to the velocity-squared rule but also to compare favourably with modern data[20]. Although indicating a variation near to a sine relationship at small incidences, the data at higher angles hint at the drift to a sine-squared variation characteristic of plates and wings of very low aspect ratio.

Although Cayley could also have measured the plate's variation in drag force with incidence, in the Robins manner (see Wilson[15]), he seems not to have done so and his notebook data are insufficient for such results to be obtained. However, because of his assumption that resistance acts in a direction normal to the surface, he later adopted the practice of estimating drag from lift results by the use of simple geometry. Although this procedure was adequate for most cases, it failed, of course, at zero incidence. In his 1804 whirling-arm experiments he also tested the plate at 90° incidence and at two rotation speeds. Reduction of his results suggests a drag coefficient, C_D, of *ca*. 1.5, a marked improvement on the value *ca*. 1.9 that follows from the results quoted by Smeaton[21] in 1759 and provided by his friend, a certain

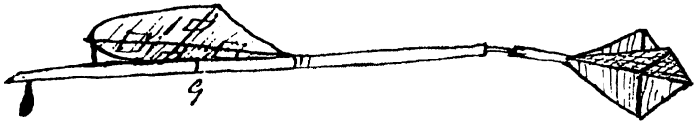

Figure 5. Cayley: glider, 1804.

Mr Rouse of Harborough. In contrast, the currently accepted value for square plates[20] is the even lower value 1.14.

The first glider, 1804

Carrying the same date as the description of the whirling-arm tests, 1 December 1804, Cayley's notebook immediately follows that description with this rather surprising comment:

> I have my doubts however whether this mode of circular motion does create as much resistance as when the plane moves on in a right line keeping parallel to itself.[7]

Apparently motivated by this doubt, what follows is Cayley's description of his tests with a simple kite modified to perform as a glider, the first aeroplane to fly (figure 5). The wing had an area of 154 in^2 (0.1 m^2) and was fixed at 6° to the bamboo rod fuselage. There is notebook evidence from as early as 1801 that he took such an angle to be typical of a crow's wing in flight. The glider wing's aspect ratio, in contrast with that of the crow, was markedly low, probably around unity. Cayley's choice of location for the centre of gravity is revealing [my explanatory additions in brackets]:

> The centre of gravity was varied by sticking a weight with a sharp point into the stick. The whole weight was 3.82 oz., and when the centre of gravity, G, was under such part of the kite as left 75 [square] inches on the anterior part and 79 [square inches] behind it, and with the tail at an angle of 11.5°…, then if a velocity of 15 feet per second was given to it in an horizontal direction, it would skim for 20 to 30 yards supporting its own weight, and if pointed downward in an angle of 18°, it would proceed uniformly in a right line for ever with a velocity of 15 feet per second.[7]

The passage can be read as if Cayley had deliberately chosen to locate the centre of gravity so as to lie close to the wing's mid-area in the belief that the latter location would be the centre of pressure. If so, he may have been guided by a belief that the wing was subject either to a uniform pressure distribution or to the dictates of the Newtonian 'rare medium' concept. Experience had then taught him that the tail-plane should be set at its high positive incidence to achieve successful glides. In this notebook passage there is no mention of trim considerations (zero overall moment about the centre of gravity), from which he could have deduced that the wing's centre of pressure must have been forward of a mid-area location. Of course, owing to the wing's likely substantial downwash, the tail's probable nose-down moment would not have been as large as its high positive setting angle of 11.5° might suggest.

This near-triangular wing of low aspect ratio—a form of reversed slender delta—is something of an aerodynamicist's nightmare. One envisages the leading edge as inducing gross upper-surface separation like that on a flat plate. However, the

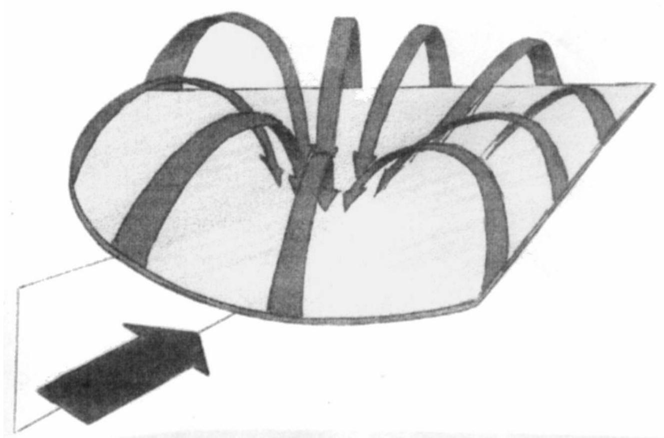

Figure 6. Flow field about a wind-tunnel model of the 1804 Cayley wing. (From Potter[22].)

sharply angled long trailing edges might be expected to produce along their lengths a system of rolled-up vortices that could, on a wing of such small span, cause rearward reattachment at the upper surface along the wing's centreline. Although the upper surface's fairly low suction would therefore be restricted to the forward part of the wing, its chordwise extent perhaps contracting with increasing incidence, the undersurface stagnation point can be expected to move rearward with increasing incidence, but probably not as far as that on a square plate. Consequently, it is difficult to predict the centre of pressure's movement with change of incidence. In an attempt to settle this and several other points related to this first wing to fly, Potter[22] has recently performed wind-tunnel experiments on a model of the wing. Using surface flow visualization methods he has been able to construct a picture of the flow field on the wing's upper surface (figure 6), which confirms the presence and suspected effect of the angled trailing edge vortices. Moreover, he has found the presence of a secondary vortex aligned a little aft of the leading edge, this caused by the forward motion of the separated layer from the leading edge after the layer's reattachment. Lift and drag-force measurements have also been made, the values for C_L being found to lie close to those for the square plate shown in figure 4 and reaching 1.1 at 30° incidence. Potter[22] also provides calculations of C_L and C_D based on lifting-line and cross-flow theories, the latter being found to agree closely with his measurements. Although gratifying, this is to be expected because cross-flow theory is valid for wings of low aspect ratio, such as this, whereas lifting-line theory applies strictly to wings of higher aspect ratio. However, the crucial part of Potter's investigation is his measurement of the position of the centre of pressure. This is found to lie near $0.15c$ (c being the wing's maximum chord) at low incidence and then to move steadily rearwards to *ca.* $0.3c$ at an incidence of 30°. Two important points follow from this. The first is that, within this incidence range, the centre of pressure is forward of the wing's mid-area at *ca.* $0.4c$, the location of the centre of gravity chosen by Cayley for his glider, so that a nose-down moment from the tail would indeed be required for trim. The second point is that, because of this rearward movement of the centre of pressure with increase in incidence, this type of wing is statically stable and no tailplane is needed for stability purposes. It therefore seems that Cayley's inclusion of a tailplane would merely enhance the static stability inherent in the wing itself. However, this might not be true of some of Cayley's subsequent designs, to be discussed later, in which he used higher-aspect ratio wings of more modern shape for which a tailplane would be necessary for stability.

To return to Cayley's flight test of 1804, the glider's downward path of 18° to the horizontal reveals a modest lift-to-drag (L/D) ratio of 3. As Yates[19] calculates, the glider probably set itself in trim at a wing incidence of 20° to that path—not the 6° wing setting angle assumed by Cayley in his notebook at this time—and with a C_L of 0.7, the corresponding C_D being therefore about 0.23. Cayley's assumption of a wing incidence of 6° reveals his misunderstanding of true incidence at the time. Nevertheless, this mistake caused him to suspect that the apparently large discrepancy between his glider's lift and his whirling-arm results might be due not to the rotation of his test plate (his original source of disquiet) but rather to the glider's flexible wing surface becoming cambered. The latter effect he already suspected as enhancing the lift of birds and indeed anticipated further beneficial effects from the use of wings with a higher aspect ratio. He returned to these features in a notebook entry for February 1808. In the following month, now no doubt emboldened by his own whirling-arm experiments, Cayley asserts that 'the resistance … varies nearly as the sine of the angle of incidence…'.[7] The aeronautical world had to await rigorous confirmation of this in the circulation theory of lift provided by Kutta[23] in 1910, although Lanchester[24] had accepted it as correct for his rudimentary wing analyses from about 1894 onwards (see Ackroyd[25]).

The glider of 1808

In April of 1808 Cayley applied his thinking on camber and high aspect ratio to the glider shown in figure 7. His notebook records that this was

> a large kite formed of an hexagon with wings extended from it, all so constructed as to present a hollow curve to the current….[7]

Later in this same note he again remarks on this use of camber:

> It should be observed that these wings were considerably hollow and much wood that made direct resistance, and that they were not in one plane but inclined upwards.[7]

Evidently, then, Cayley was now also experimenting with dihedral. The wing planform, of course, is of major interest. The leading edges of the hexagonal centre section would no doubt act as modern leading-edge extensions and, like the slender delta, generate mid-semi-span upper-surface vortices that would enhance lift at higher incidences. Although no span dimensions are given, only wing surface areas being recorded, the wings themselves seem to have been of reasonably high aspect ratio. Remarkably, this feature was to be repeated in only a few of Cayley's other designs. However, the interesting point is that here, for the first time, Cayley attempts to determine trim conditions for an aeroplane. He writes that

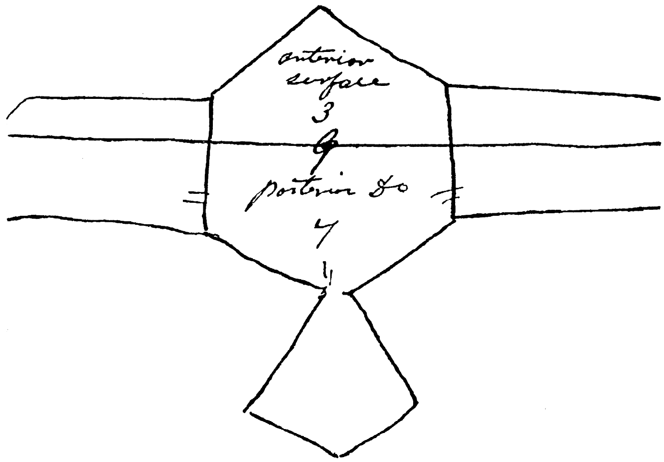

Figure 7. Cayley: glider, 1808.

> I found that … it required the centre of gravity to be suspended so as to leave the anterior and posterior portions of the surface in the ratio of 3 to 7.[7]

This ratio is recorded in his sketch (figure 7). However, the tailplane is set at a positive incidence, as it had been on the 1804 glider. In the next sentence he attempts to judge the effect of its nose-down moment so as to re-estimate the location of the wing's centre of pressure as being in the ratio of 5 to 12. Again he is in no position to understand the effect of wing downwash on tailplane lift. Consequently, with this argument he places the wing's centre of pressure perhaps a little too far forward. However, in both estimations he has nevertheless arrived at the important point that a wing's lift can lie forward of the wing's mid-area and, indeed, here a little aft of the quarter chord point. This strikes him as remarkable [my explanatory addition in brackets]:

> It is really surprising to find so great a difference, and it obliges the centre of gravity of flying machines to be much forwarder of the centre of bulk [centroid of area] than could be supposed a priori.[7]

Significantly, there is no indication here that Cayley investigated the *movement* of the centre of pressure with incidence change, contrary to the claim made by Gibbs-Smith[8].

Structural ideas, 1808

A notebook entry for May 1808, records his thinking on the provision of light yet rigid structures for flight. He refers to

> the lightest and strongest form of a middle pole and seat for aerial navigation, the pole to be made in halves, tapering each way from the cross-pieces and hollowed to form a tube. Bamboo canes would be most excellent rods for aerial navigation purposes.[7]

Cayley's perhaps instinctive idea here seems to be one of the earliest to employ what the emerging structural theory was beginning to teach. Nowadays we all accept the

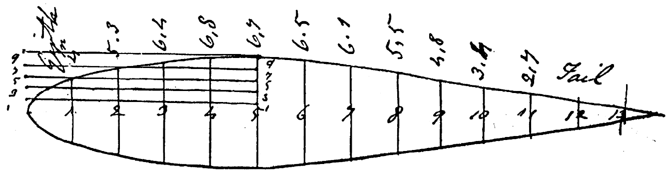

Figure 8. Cayley: solid of least resistance, 1808.

advantages, in terms of lightness and rigidity, of the use of section shapes having high second moments of area, so as to resist bending moments and torsion. The reasoning underpinning such principles had begun to emerge during the eighteenth century in the work of Jacob Bernoulli, Euler and others (see, for example, Timoshenko[26] and Truesdell[27]). However, it is doubtful that much of this had been recognized by the engineering practitioners of those days and that Cayley himself would have been aware of it. Nevertheless, Cayley's ideas, particularly that regarding the use of *tapered* hollow sections, emerge as being remarkably advanced for their time. Later, as we shall see in the second part of this paper, he was to add his thoughts on diagonal wire bracing so as to enhance further a structure's stiffness. Little advance was made in this area until Octave Chanute (1832–1910) introduced the Pratt truss cross-bracing system to aeronautics in the Chanute–Herring glider of 1896 (see Crouch[28]).

The solid of least resistance, 1809

Cayley, the countryman, delighted in recording his observations of nature. His deductions were frequently acute, not least in his dealings with the shape of a trout. His note, dated June 1809, records this as 'a well fed fish'. Measuring its girth distribution, he writes that [my explanatory addition in brackets]

> the girths are divided by three [as an adequate approximation to π] and reduced to a mean diameter so as to give a spindle the same girth at the respective places that the trout had … and should probably have the real solid of least resistance.[7]

Cayley's sketch of the cross-section of the resulting axially symmetric body is shown in figure 8. Von Kármán[29] has noted how very close this cross-section is to that of a modern NACA 63A016 aerofoil shape, even though the latter is a Cartesian two-dimensional section. Despite the long history of shipbuilding, constructors rarely seem to have questioned the use of the relatively streamlined shapes that they employed. The first investigator in more modern times to suggest such shapes, specifically for the reduction of resistance on barges and bridge piers, seems to have been Du Buat in 1786.[30] The correct reasoning behind streamlining, given in terms of the suppression of separation, did not emerge until 1904, when Prandtl revealed the concept of the thin viscous boundary layer.[31] By 1907 Lanchester had also independently grasped a rudimentary understanding of this concept.[24]

Part 2 of this paper resumes the story at the point at which Cayley not only became publicly known for his interest in fixed-wing flight but also began to explain how this was to be achieved.

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