Sir George Cayley, the Father of Aeronautics. Part 2. Cayley's Aeroplanes
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SIR GEORGE CAYLEY, THE FATHER OF AERONAUTICS PART 2. CAYLEY'S AEROPLANES

by

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SUMMARY

The first part of this paper (published in the May 2002 issue of *Notes and Records*) dealt with Cayley's invention of the aeroplane. This second part continues with a description of the subsequent development of his thinking and his construction of practical aeroplanes.

THE TRIPLE PAPER ON AERIAL NAVIGATION, 1809–10

Owing to a misunderstanding, for which the world must be forever grateful, in 1809–10 Cayley was moved to publish his findings in a three-part paper that ushered in the science of aeronautics. In 1809 reports had reached Britain that, earlier that year, Jacob Degen (1761–1848) had flown successfully in Vienna. Later it emerged that such reports had neglected to mention the hydrogen balloon that had substantially assisted the ascent of Degen's man-powered flap-valve machine. Nevertheless, this misunderstanding created the happy consequence of Cayley's publicly addressing, step by step, those four crucial areas—propulsion, structure, aerodynamics, and stability and control—necessary for the successful achievement of powered flight.

Propulsion

In the triple paper's first part Cayley summarizes the current situation with regard to engines.[1] For the steam engines then projected (expansion-operated, with lightweight tubular boilers), he can foresee no lower figure than *ca.* 163 lb per horsepower (0.97 N W^{-1}). Stokes has provided data (figure 1) corroborating this assessment and showing further that engine weight per unit power had to be decreased more than tenfold before practical powered flight became possible.[2] However, Cayley adds that

> lightness is of so much value in this instance, that it is proper to notice the probability that exists of using the expansion of air by the sudden combustion of inflammable powders or fluids with great advantage.[1]

Thus, Cayley, already the inventor and leading authority on the heated-air engine, here predicts the advantage of the internal combustion engine. He then gives a brief

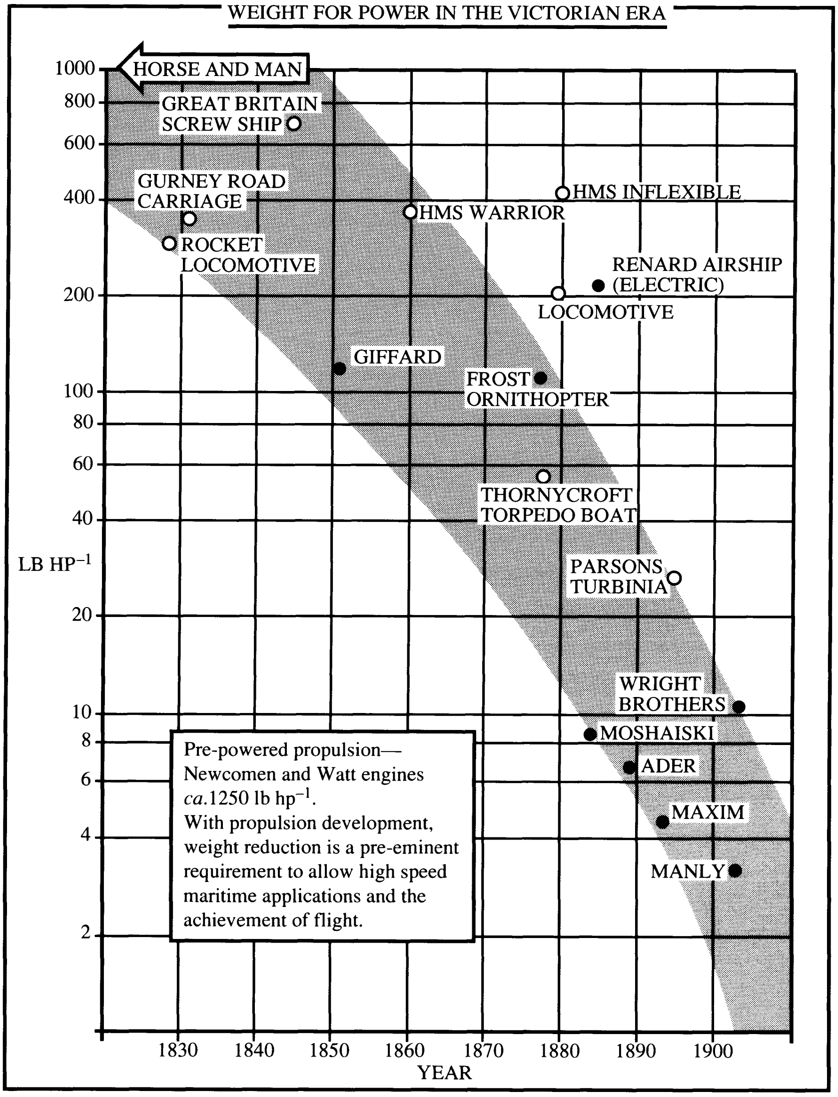

Figure 1. Improvement in engine power with time. (Courtesy of P. Stokes.[2])

indication of what had been done, what might be achieved, by the use of spirit of tar or gas as the combustible fluids. As to the manner by which power is to be translated into forward thrust, the second and third parts of the paper devote much space, fruitlessly as it turned out for future developments, to a description of the various flapper systems that he favoured.

Structure

Cayley's thinking on structural design is contained entirely within the third part of the triple paper, this being otherwise devoted to flapper propulsion systems. And it is in his concern with the latter that it is possible to detect some of the reasons for

Cayley's restricting himself to wings of low aspect ratio. Because he wishes such wings to serve also as flappers, he is concerned for the loading applied when they are so used and therefore favours wings of a generally short span. Nevertheless, expanding on his brief structural note of 1808 (see pp. 178–179 of part 1 of this paper[3]), Cayley[4] offers the general principle that the stiffness of hollow tapered tubes can be enhanced further by diagonal wire bracing. Cayley's suggestions here proved apt advice, as later constructors were to demonstrate. Yet Cayley, like those before him and indeed many after, is rather optimistic in his belief that such bracing 'produces but a trifling resistance'. However, he is concerned for the resistance produced by the thicker structural members. In commenting on an exposed shaft used in one of his wing structures, Cayley notes that this

> is the only part that opposes much direct resistance to the current, and this is obviated in a great degree by a flat oval shape, having its longest axis parallel to the current.[4]

Aerodynamics

In the first part of the triple paper Cayley[1] uses the example of bird-flight to explain the action of the lifting wing. This is a distillation of his earlier notebook entries described earlier.[3] Again, the wing's total resistance is taken to act perpendicularly to the wing's surface, the triangle of forces then being employed so as to determine the wing's lift and drag components. The lift, of course, is always known, being equal to the weight of the bird or aeroplane. And, according to Cayley's assumption on resistance direction, the wing's drag force is also known, being related to lift by the tangent of the wing's incidence angle. However, there is a further 'direct resistance' due to the bulk of the bird or to the aeroplane's remaining structure. This, he says, is to be discussed later. At this point Cayley encapsulates the problem of flight in the now-classic statement, often quoted, that

> The whole problem is confined within these limits, viz. To make a surface support a given weight by the application of power to the resistance of air.[1]

Apart from the fact that this is the first moment in aeronautical history at which such a simple, even obvious, statement is made, it has to be said that the simple, the obvious, can sometimes only become so having once been stated.

Cayley then turns to the question of resistance itself, contrasting the results of Robins (see Wilson[5]), Rouse and Smeaton[6] with his own conclusion that, in modern terms, amounts to the result that, for the flat plate held normal to a stream, C_D is *ca*. 1.5. Incidence effects are then addressed and here he relies once more on the results 'of the French Academy', again a reference presumably to d'Alembert *et al.*[7] The latter, as he had earlier noted,[3] show

> that in acute angles, the resistance varies much more nearly in the direct ratio of the sines, than as the squares of the sines of the angles of incidence.[1]

He then turns to his belief in the superior lifting ability of the bird's cambered wing, and here provides a perceptive conjecture as to its cause. He suggests that, at the leading edge, the air's upward motion over the upper surface's convexity 'creates a slight vacuity' there. Meanwhile,

> the current is constantly received under the anterior edge of the surface, and directed upward into the cavity.... The fluid accumulated thus within the cavity has to make its escape at the posterior edge of the surface, where it is directed considerably downward; and therefore has to overcome and displace a portion of the direct current passing with its full velocity immediately below it; hence whatever elasticity this effort requires operates upon the whole concavity of the surface, excepting a small portion of the anterior edge.[1]

The lift force is thus the consequent reaction on the wing due to its imposition of a vertically downward change of momentum to the air's motion. However, here we meet for the first time some of the rudiments of our understanding that lift is created by the ability of a wing not only to impart trailing-edge downflow but also to remove leading-edge upflow. Such ideas first emerged in their modern form through the work of Kutta[8] and Lanchester[9], whereas earlier, in 1889, Lilienthal[10] envisaged that only a downflow was created by a lifting wing. Moreover, Cayley's suggestion that an upper-surface partial vacuum is achieved, and near the leading edge, is a further important advance.

Using a combination of the results of 'the French Academy' and estimates based on his observations of bird flight, in modern terms Cayley arrives at a C_L of *ca.* 0.7 for a wing at 6° incidence. This is remarkably realistic for a modern wing of moderate camber with an aspect ratio of *ca.* 6 or 7 (typical of that of a bird). However, this C_L at that incidence is rather more than three times that given by his own whirling-arm results for uncambered plates of unit aspect ratio. This difference might explain why his plate incidence results are not mentioned. Nevertheless, Cayley immediately applies his conclusion to a practical example, that of a machine weighing 200 lb (890 N) and of wing area 200 ft^2 (*ca.* 18.6 m^2) (his favoured wing loading, that of the crow, is often 1 lb ft^{-2}, or *ca.* 48 N m^{-2}). This, he believes, will fly at 6° incidence and at a speed of 35 ft s^{-1} (10.7 m s^{-1}). The thrust required to overcome wing drag he estimates, from the tangent of the incidence angle, as being *ca.* 21 lb (93 N). This implies a wing C_D of *ca.* 0.07, about double that for a modern wing of this aspect ratio but more in line with the value for a plate of unit aspect ratio.

This is followed by a truly remarkable, yet frustratingly incomplete, description of a machine he has tested during that summer. He refers to this again, and in a little more detail, in the second part of his paper issued in the following year:

> Last year I made a machine, having a surface of 300 square feet ... its steerage and steadiness were perfectly proved, and it would sail obliquely downward in any direction, according to the set of the rudder. Even in this state, when any person ran forward in it, with his full speed, taking advantage of a gentle breeze in front, it would bear upward so strongly as scarcely to allow him to touch the ground; and would frequently lift him up, and convey him several yards together.[11]

The first part of the triple paper gives the following additional information:

> It was very beautiful to see this noble white bird sail majestically from the top of a hill to any given point of the plain below it, according to the set of its rudder, merely by its own weight, descending in an angle of about 18 degrees with the horizon.[1]

Whether or not this can be claimed to have provided the first successful man-carrying glider take-off in history, the aircraft nevertheless seems to have been the first successful full-scale unmanned glider. In a later paper of 1843, when apparently writing of this same aeroplane, Cayley[12] claims a gliding angle of *ca.* 1 in 8. If correct, this gives a lift-to-drag (*L*/*D*) ratio of 8, whereas the earlier-quoted gliding angle of 18° (which could be one further misprint to add to those bedevilling the triple paper) gives the far more modest value of 3, in line with that achieved by the 1804 glider. Gibbs-Smith[13] opts for the 1 in 8 incline. The corresponding *L*/*D* ratio of *ca.* 8 is just about achievable, and at *ca.* 6° incidence, with a wing of aspect ratio of about unity, the value often used by Cayley.

The subject of 'direct resistance' is returned to in the closing pages of the third part of the paper. The explanation that Cayley provides,[4] based on a modification of the 'rare medium' concept of Newton's,[14] pays scant regard to the continuity principle and is largely mistaken. However, in a return to his usual acute common sense linked to clear observation, Cayley then comments that

> It has been found by experiment, that the shape of the hinder part of the spindle is of as much importance as that of the front, in diminishing resistance. This arises from the partial vacuity created behind the obstructing body. If there be no solid to fill up this space, a deficiency of hydrostatic pressure exists within it, and is transferred to the spindle. This is seen distinctly near the rudder of a ship in full sail, where the water is much below the level of the surrounding sea. The cause here, being more evident, and uniform in its nature, may probably be obviated with better success; in as much as this portion of the spindle may not differ essentially from the simple cone. I fear however, that the whole of this subject is of so dark a nature, as to be more usefully investigated by experiment, than by reasoning....[4]

At that point he turns to a description of his trout-based solid of least resistance (see pp. 171–173 and figure 8 of part 1 of this paper[3]) and the shape of the woodcock. The experiment to which he refers at the beginning of the above passage might have been that of Du Buat,[15] the only person by that time to have displayed a rudimentary understanding of the advantages of streamlined shapes. Previously, the general belief, supported by the Newtonian 'rare medium' concept, had been that it is entirely the forward shape of a body that determines resistance. And, like Du Buat,[15] Cayley here grasps the vital point that it is the 'deficiency of hydrostatic pressure' acting at the rear of poorly streamlined bodies that is the main source of their resistance. However, as remarked in part 1 of this paper, the cause of this deficiency of pressure was to retain its 'dark nature' until Prandtl[16] provided illumination of it in 1904. Meanwhile, Cayley's prescription of copying nature remained sound advice.

Stability and control

The paper's second part is largely an extended essay on how the principle 'must be applied, so as to be steady and manageable'.[11] Here, then, Cayley addresses the problems of stability and control. He begins by describing the first successful parachute descent by André Jaques Garnerin (1769–1823) in 1797. Having no vent at its apex and therefore no doubt suffering from alternate spillage around its canopy edge, Garnerin's parachute produced a markedly oscillatory descent. Cayley seizes on this instability in his search for a method of providing lateral stability for aeroplanes. He believes this instability to be due merely to direct resistance

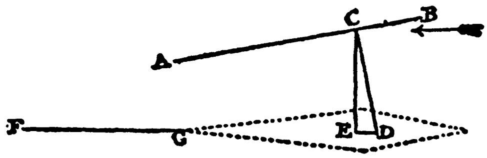

Figure 2. Cayley: glider at trimmed condition, 1810.

differences across the canopy when tilted. From this he argues that an inverted parachute canopy should be stable, a conclusion that he immediately applies to the aeroplane so as to suggest wing dihedral. His argument, of course, is over-simplistic and, in the aeroplane case, ignores the crucial element of sideslip. Nevertheless, using an argument carrying some credence at the time, Cayley has arrived at dihedral provision so as to enhance lateral stability.

Cayley[11] then turns to longitudinal stability. He begins by discussing the flight of his aeroplane shown in figure 2. In this case he assumes that the tailplane FG is set so as to carry no load. The wing AB has its centre of pressure at C. He points out that the line of action of the wing's resistance must therefore pass through the aeroplane's centre of gravity at D. The lines EC and DE then represent the lift and drag forces, respectively. The aeroplane is therefore in equilibrium under the forces and moments acting on it. In modern terms, the aeroplane is at a trimmed condition. He then turns to the situation in which the aeroplane becomes disturbed in pitch. Here his argument depends on two items of information. First, as implied in figure 2, he recognizes that at small incidences the wing's centre of pressure can lie forward of the wing's mid-area. His earlier work on the 1808 glider (see the first part of this paper) had suggested such a location. Secondly, he believes that, at 90° incidence, the resistance acts at the wing's mid-area. Cayley[11] therefore assumes a monotonic rearwards movement of the centre of pressure with incidence increase so as to conclude that the tailless aeroplane is inherently stable longitudinally. Had Cayley been describing the movement of the centre of pressure on conventional wings well beyond stall, the continually stalled flow of flat rectangular plates, or indeed the more complicated stalled flow of his reversed slender delta wing of the 1804 glider,[3] he would have been correct, as later experiments were to confirm. However, for the unstalled cambered wings of higher aspect ratio employed later, the centre of pressure moves in the opposite direction, causing a destabilizing moment that requires the compensation provided by a fixed stabilizing tailplane. In the context of the wings used by Cayley at that time—often of low aspect ratio, of unusual planform and poorly shaped for good boundary-layer behaviour—it is probable that his belief was correct. However, as to what was to come later in the shape of cambered wings of higher aspect ratio, his assumption was clearly misleading.

The subject of this destabilizing movement of the centre of pressure was a further topic to retain its 'dark nature' for a considerable period. Although the Wrights were the first to observe this effect in the testing of their No. 2 glider in 1901, they kept this, like many of their findings, to themselves. The aeronautical world only learnt of their discovery at the release of their collected papers in 1953.[17] By that time, of course, the matter was well understood as a result of the aerofoil theory of, for example, Kutta[18] in 1910. However, that is not to suggest that the point was grasped immediately. It was not until after World War I that the British, for example, grafted the idea, in the form of a correct wing-pitching moment coefficient, onto the small-disturbance stability theory begun by Bryan & Williams[19] in 1904 and extended by Bryan[20] in 1911.

Despite Cayley's failure to grasp the stabilizing function of the tailplane at this stage, he nevertheless accepts the necessity of having a horizontal tail surface that is adjustable in incidence. This is required, he realizes, for the purposes of re-trimming for different flight speeds, and therefore different incidences, so as correct for his recognized movement of the centre of pressure. A further function of the adjustable tail, as Cayley sees it, is for steering [my explanatory addition in brackets]:

> The powers [moments] of the machine being previously balanced, if the least pressure be exerted by the current, either upon the upper or under surface of the rudder, according to the will of the aeronaut, it will cause the machine to rise or fall in its path, so long as the projectile force is continued with sufficient energy.[11]

The point here, which Cayley seems not quite to grasp, is that a supposed 'steering' in the vertical plane, with the use of a movable elevator, does not necessarily steer the aeroplane in the intended direction but merely changes the pitch angle. For example, up-elevator raises the nose, the C_L, but also the C_D and therefore the drag, so that the aeroplane slows down and begins to sink. Greater thrust is also needed (yet this could be used alone to make the aeroplane climb). Recognition of this last requirement might be implied at the close of Cayley's statement.

As to the further requirements of the tail unit,

> this appendage must be furnished with a vertical sail, and be capable of turning from side to side, in addition to its other movements, which effects the complete steerage of the vessel.[11]

Again the emphasis is on steering. There is no hint of recognition here either that a fixed vertical fin is required to provide weathercock lateral stability or that a movable rudder's primary function is to change the yaw angle. Thus, at this stage, contrary to what has been supposed by Gibbs-Smith[13], Cayley has failed to grasp the stabilizing function of the tail's fixed surfaces and is rather limited in his understanding of the functions of the tail's movable surfaces. Moreover, as Gibbs-Smith[13] allows, the vital additional control in roll needed for a correctly banked turn completely eludes him. Indeed, this further control had to await the Wrights' introduction of wing warping in their kite experiment of 1899.[17]

The kite-based glider of 1818

After the publication of the triple paper, Cayley turned to a variety of other activities. He retained his interest in aeronautics but concentrated mainly on airships and ornithopter designs. Indeed, he remained largely silent on the aeroplane until

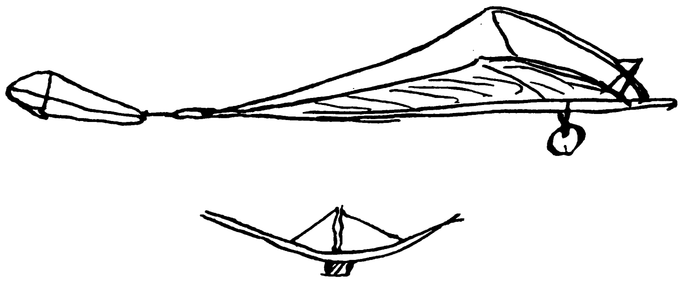

Figure 3. Cayley: glider, 1818.

prompted to return to it by the publication of Henson's design for his 'aerial steam carriage' in 1843. However, before that year one small item relevant to the aeroplane problem appears in the Cayley papers.

In a letter to Lord John Campbell, dated January 1818, Cayley briefly describes one of his recent kite-winged gliders and includes sketches of it (figure 3). The dihedral shown in the sketch is referred to in the letter but, as to the centre of gravity location and tail setting, he merely recommends [my emphasis in italics]

> a weight to fasten to the middle stick till it will sail from the top of a hill slanting to the bottom, with perfect steadiness, obeying the rudder *which should be turned a little up*....[13]

The tailplane's negative incidence is indicated in the sketch. It seems probable that this setting, enhanced by wing downwash, resulted in a tailplane download and nose-up moment at the glider's flight condition. Apart from the dihedral and this tail setting, the glider is very similar to that of 1804. The interesting point is Cayley's probable choice of a downloaded tail here. This happens to be the tail load direction that usually emerges from trim and stability considerations for modern aeroplanes. Such considerations, of course, could not have been known to Cayley. In comparison with his 1804 glider, he might simply have selected a rather more forward centre of gravity position for the 1818 glider, here guided by his 1808 realization that centres of pressure can lie further forwards than he supposed in 1804.

Such a possibility, of course, is no more than speculation. All that can be said of the 1818 glider is that, at its flight condition, its wing's centre of pressure probably lay behind the centre of gravity, the latter probably being fairly forward. However, this negative setting of the tailplane was to be retained for the remainder of his involvement with the aeroplane. It was to be adopted by such subsequent constructors as Alphonse Pénaud (1850–80), the term 'longitudinal dihedral' being coined both to describe it and to give apparent credence to its use. As to the stability of the 1818 glider, the only other evidence to hand is the comment by Sproule[21] about his replica of it. It was, he says, 'a wonderful performer', from which we can assume stability.

Cayley's return to the aeroplane

The release of the details of Henson's design for his 'aerial steam carriage' of 1843 renewed Cayley's interest and involvement in the aeroplane. By now he was 70 years old, yet even at that advanced age he had much still to contribute.

The two papers of 1843

Cayley's immediate response to the release of the Henson design was to publish the first of his two papers of 1843 in which he deals retrospectively with many of his earlier achievements.[22] It is here, moreover, that he states the gliding angle of 1 in 8 (and, by implication, an *L*/*D* ratio of 8) for the full-scale glider of 1809, which is described all too briefly by Cayley.[1,11] He also mentions for the first time an idea for a convertiplane, which, as it turned out, was to be described in more detail in his next paper.

Cayley's second paper of that year begins with a detailed criticism of Henson's design.[12] He draws attention to the design's lack of wing dihedral but reserves his main criticism for what he considers to be an excessively large wing span. However, his doubts on the structural integrity of the wing's design prompt the following suggestion (his emphasis in italics):

> If, therefore, so large a surface be contemplated … would it not be more likely to answer the purpose to compact it into the form of a *three decker*, each deck being 8 or 10 feet from the other, to give free room for the passage of the air between them?[12]

And with that, of course, Cayley has produced the seminal idea behind the biplanes and triplanes of the future. Cayley then turns to airships but follows this discussion with a detailed description of the convertiplane mentioned in his earlier paper of that year.[22] Apart from this being the single aeroplane for which he contemplates propeller propulsion, this design includes a horizontal tail surface, its primary purpose being for steering. But now, significantly, this surface 'forms also the chief means of stability in the path of the flight'.[12] No further explanation is given at this stage for this recognition of a tailplane's stabilizing function. The vertical tail surface's function, in contrast, is referred to entirely in terms of its steering action.

The boy-carrier, 1849

Having suggested triplane construction in 1843, Cayley took up the idea himself in 1849, his notebook for that year recording the testing of such a machine. This is shown (figure 4) in his later sketch of 1853. The wings have the low aspect ratio generally favoured by Cayley and also incorporate a slight dihedral. Flappers were to be used for forward thrust, perhaps driven by a heated-air motor. However, the machine was first tested unpowered as a form of kite-glider. As the notebook entry states:

> The balance and steerage was ascertained, and a boy of about ten years of age was floated off the ground for several yards on descending a hill, and also for about the same space by some persons pulling the apparatus against a very slight breeze by a rope.[13]

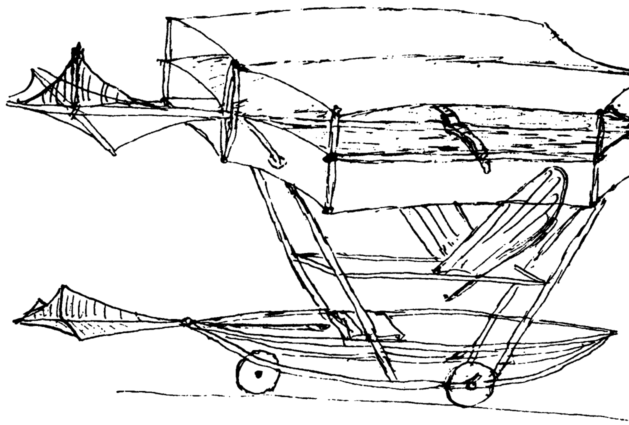

Figure 4. Cayley: the boy-carrier, 1849.

However, the interesting feature is the duplicated tail unit, the lower unit seeming only to provide steering. The implication is that the upper unit is fixed and for stability purposes. This feature was to be repeated in a later design of 1852, for which Cayley there reveals rather more of his thinking on stability.

The model gliders of 1849 and 1853

Cayley's notebook for 1849 records details of a new type of glider with which he

> tried some experiments with a view to ascertain with accuracy the real angle that any plane makes with its line of flight when supporting a given weight, and also the power shown to be necessary in that line of flight to sustain that weight.[13]

The glider is shown in his sketch (figure 5) as having a slightly cambered rectangular planform wing of moderately low aspect ratio, probably *ca.* 1.5. The wing is fixed parallel with the pole fuselage. The tailplane is again depressed, here by 'about an angle of 8°'. Total weight and wing area produce Cayley's favoured wing loading of 1 lb ft^{-2}. Flying it, he found that [my explanatory addition in brackets]

> a velocity of about 33 feet [per second] at an angle of 7° with the line of path (one 8^{th} of radius) sustains on 16 sq. ft. 16 lb. This agrees precisely with the weight of the crow, and his surface of wing.[13]

The wing loading and speed give a C_L of *ca.* 0.77. This value is far too high for a wing of this aspect ratio if we are to interpret Cayley's 7° as the true wing incidence, as he seems to imply it to be in both his statement of intent and his stated result. For this C_L value a more realistic incidence would be *ca.* 17°, suggesting the possibility of a misprint. Gibbs-Smith[13], in contrast, interprets the 7° as the gliding angle (an incline of *ca.* 1 in 8), implying an *L*/*D* ratio of *ca.* 8, again a value just about achievable with this wing aspect ratio. If correct, this suggests that, even now, Cayley might be misinterpreting wing incidence angle. An alternative possibility, as we shall see, is that some of Cayley's data are incorrect.

Some support for Gibbs-Smith's interpretation might be provided by Cayley's performance data for a very similar glider (or gliders) that appeared on the scene in

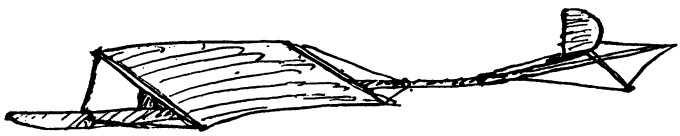

Figure 5. Cayley: glider, 1849.

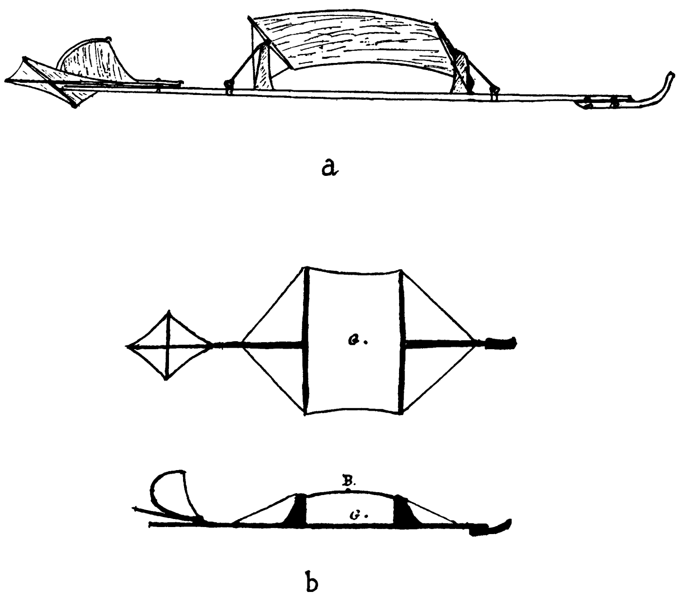

Figure 6. Cayley: glider, 1853. (*a*) The French paper; (*b*) the notebook.

about 1853. The sources of these data are Cayley's notebook for that year and the paper he sent at that time to the Société Aérostatique et Météorologique de France. Although the paper was never published because the Société's journal foundered, happily the original text survived and is reproduced in Pritchard,[23] some corrections being added by Gibbs-Smith[13]. Cayley's drawing for the French paper is shown in figure 6*a*, and his notebook sketches in figure 6*b*. Although the two datasets differ slightly, the glider's rectangular planform wing, here again set parallel with the pole fuselage, had a span of 6.167 ft, chord 4.25 ft, giving a wing area of 26.2 ft^2 and an aspect ratio of 1.45. The glider's weight is quoted as being 16 lb. As to its performance, Cayley says [my explanatory addition in brackets]:

> When used, it is projected by hand from the edge of a hill or lofty building; and it will fly from 4 to 8 times horizontally the height of its perpendicular fall, according to the correctness of its adjustment. The rudder [tailplane] gives the most stability to the course of flight, when slightly elevated, so as to receive a small degree of pressure downwards; but when truly balanced by the weight of the prow, it flies farthest, when the rudder is in the same plane as the sail.[13]

Here, however, no flight speed is quoted. Despite the rather low aspect ratio, this wing is nearer in geometry to those used nowadays. In this context it is revealing to apply modern flight performance theory to this aeroplane. As Lanchester[9] was the first to establish in 1907, the minimum gliding angle is achieved at the maximum C_L/C_D. Given Cayley's value for the minimum gliding angle as 1 in 8, and making a suitable allowance for wing aspect ratio, the results suggest that, at this condition, the glider flew at a C_L of 0.26, the glider's C_{D0} (drag coefficient at zero lift) being 0.016. The corresponding result for flight speed is not 33 ft s^{-1} (the 1849 case cited above) but 44.6 ft s^{-1} (13.6 m s^{-1}). To attain this value for C_L (and the maximum C_L/C_D) for a wing of this aspect ratio, the incidence might have been *ca.* 7°. This suggests that, in his 1849 tests, Cayley had misjudged not the incidence but either the glider's weight or, more probably, the flight speed. The C_{D0} value suggests that most of the drag was due to the wing itself, a result not entirely surprising in view of the vestigial pole fuselage. Cayley's statement, quoted above, to the effect that the minimum gliding angle was achieved with the tailplane set parallel to the wing, suggests, in view of the wing's downwash, that the tail actually carried a slight download. Thus, the wing's centre of pressure would lie a little aft of the centre of gravity.

Cayley's additional notebook data for this (or a very similar) glider reveal a centre of gravity position a little forward of a modern estimate of the neutral point position based on wing and tailplane sizes. This suggests that an adequate static margin was achieved so as to ensure longitudinal static stability. The sole comment by Sproule on his replica of this Cayley glider is that it 'flies beautifully', implying that the original was indeed stable longitudinally.[21]

The governable parachute, 1852

The final published design for a man-carrying controllable glider—named 'governable parachute'—appears in Cayley's paper of 1852 (figure 7).[24] The monoplane wing, again of an aspect ratio a little over unity, has a planform unique in Cayley's designs, and surviving records tell us little of its provenance. However, notebook entries[13] give the merest hint that model tests with this planform might have been conducted. Cayley again recommends a dihedral angle for lateral stability, in this case an angle of between 8° and 10°.[24] The wing's central structural member is a beam

> obtained by nailing and glueing together four flat pieces of timber into a hollow square, and making these taper both in width and thickness from the centre towards each end … and this compound beam will be very nearly double as strong as the same weight of wood used as a solid square beam….[24]

Here again, Cayley displays his earlier perceptiveness concerning tapered hollow structural members.[24] The structure is otherwise stiffened by his usual method of wire bracing. The structural weight is given as 150 lb so that, with the weight of 'the aëronaut', the total weight becomes *ca.* 300 lb (1334 N). Although no absolute dimensions are given, the wing area is quoted as being 467 ft^2 (43.4 m^2) so that the wing loading is reduced from Cayley's earlier favoured value of 1 lb ft^{-2} to *ca.* 0.64 lb ft^{-2} (30.7 N m^{-2}). If the glider were to descend vertically, literally as a parachute, Cayley estimates its terminal velocity to be 16.25 ft s^{-1}. Somewhat

Mechanics' Magazine,

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SIR GEORGE CAYLEY'S GOVERNABLE PARACHUTES.

Fig. 2.

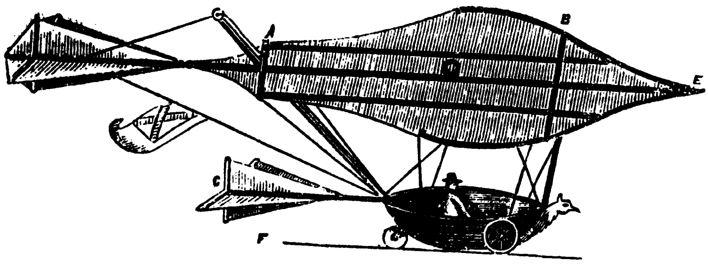

Fig. 1.

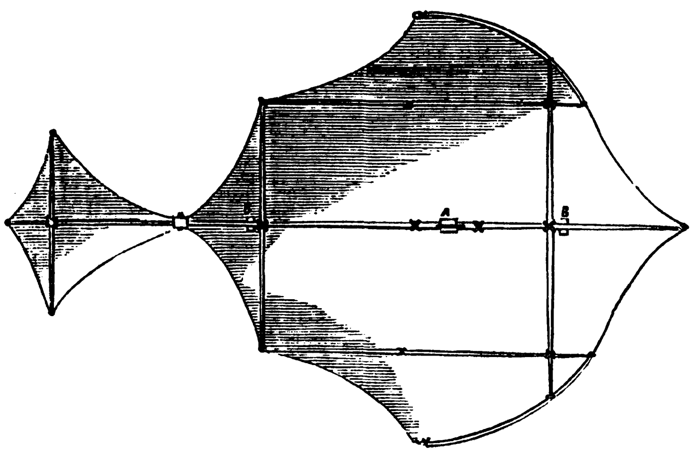

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Figure 7. Cayley: the governable parachute, 1852.[24]

confusingly, his next sentence reads, 'Its angular velocity may be taken at about 30 feet per second'.[24] The technical adviser to Gibbs-Smith,[13] J.L. Nayler, finds this comment incomprehensible and suspects an omission in the text. It might be, however, that Cayley's term 'angular velocity' refers simply to the speed in angular descent, that is in gliding flight, and the quoted value is intended to be read in contrast to the speed of vertical descent.

In this short paper we find Cayley's final thoughts on stability. Concerning the duplicated tail unit, featured earlier on the 'boy-carrier', Cayley says

> there are two rudders formed of horizontal and vertical sails. The larger one is, when it has once been adjusted so as to give a straight and steady steerage, to be permanently secured in that position. It gives the most steady and secure course when slightly elevated, which also tends to secure the parachute from pitching, should it be exposed to an eddy of wind, and, together with the weight of the car, immediately restores the horizontal position.[24]

Here at last we find Cayley's clear recognition of the stability requirement for a fixed horizontal tail surface. Again, this is to be set at slight negative incidence, suggesting a forward centre of gravity. However, there is no mention of the fact that the consequently fixed upper vertical surface provides weathercock stability. Towards the end of the paper, Cayley adds rule-of-thumb advice on loading that might, in effect, ensure a centre of gravity ahead of the neutral point.[24] As to range, he predicts a horizontal progress of about five or six times the glider's initial release altitude. This implies L/D ratios lying between 5 and 6, values that again are realistic for a wing of this aspect ratio.

The full-scale replica of this glider that Sproule describes, built for an Anglia Television programme on Cayley in 1973, flew successfully at Brompton Dale.[21] Sproule gives few details of the tests, so that little on the glider's performance can be gleaned directly. However, he gives a wing area of 440 ft^2 with a span of 28 ft (Cayley's suggestion is 467 ft^2, but no span value is given), so that the aspect ratio is 1.8. Modern flight performance calculations based on Cayley's expected minimum gliding incline of 1 in 6 and estimated weight of 300 lb (exceeded in the replica) reveal a flight C_L of 0.42, the speed being 37 ft s^{-1} (11 m s^{-1}). The glider's C_{D0} is 0.035, much higher than that estimated above for the 1849/1853 glider. This can be attributed to the car, pilot and extra bracing present in the governable parachute. Sproule notes that the replica's centre of gravity was set well forward, a little aft of the wing's mainspar.[21] He adds that a one-sixth scale model of the glider, built before completion of the full-scale replica, 'performed very well' with the centre of gravity in this position. Once again, it seems that acceptable longitudinal stability could be achieved. As to lateral stability, Sproule says:

> The machine, while extremely sensitive to wind direction in yaw, exhibited great stability in roll and lack of control in this mode did not produce problems of any kind.[21]

This suggests that a greater upper fin area or tail arm would have been beneficial. The replica, for many years resident at the Manchester Air and Space Museum, has recently been transferred to a more appropriate home at the Yorkshire Air Museum, Elvington.

The coachman-carrier, ca. *1853*

The final record of Cayley's involvement with the aeroplane is the recollections of his granddaughter, Mrs Dora Thompson, when aged about 80.[13] She recalled witnessing, at about the age of nine, the testing of some form of flying machine at Brompton Dale in about 1853. The sole occupant of the machine was Cayley's 'coachman', who, upon landing, leaped out in some agitation, crying, 'Please Sir George, I wish to give notice, I was hired to drive and not to fly'.[13]

No detailed description of this machine survives, but Gibbs-Smith suggests that it was probably similar to the triplane 'boy-carrier' while now incorporating the wing planform of the governable parachute.[13] As to the identity of the 'coachman', no such person having that position is listed in the Brompton census of 1851. Both Gibbs-Smith[13] and Rivett & Matthew[25] opt for the groom, John Appleby, who would have been aged about 20 at the time of the flight.

Conclusions and recommendations

It is hoped that the foregoing provides a more detailed technical account of Cayley's achievements than is given elsewhere. Although his grasp of some of the major features of the aeroplane emerges as being not quite as comprehensive as some have claimed, he nevertheless retains his immense stature as the 'father of aerial navigation'. Throughout his aeronautical career he retained his uncanny knack of arriving at sensible engineering solutions through a combination of keen observation and plausible argument. Although some of his arguments have been shown to be simplistic, even on occasions faulty, he nevertheless arrived at many of the basic aerodynamic, structural and stability features of the successful aeroplane. These he tested and showed that they worked. At the time of his death, no other person in aeronautics had acquired a grasp remotely approaching his in this field. And, as Gibbs-Smith remarks, if those who followed him had paid more attention to his findings then the progress of glider development, to say the least, would have been more rapid.[13]

As to recommendations, these are twofold.

1. Although it might suit our national taste for understatement to restrict the only memorials to this great man's efforts to a blue plaque at his supposed birthplace and a small tablet at Brompton, others could well see this as a national disgrace. One remedy for such criticism might be to erect some more substantial memorial at either Brompton or Scarborough.

2. Considering Cayley's advocacy of education, a further, and living, memorial might be to establish Cayley Scholarships for young people of outstanding ability who wish to study aeronautics at advanced level. Funding for this should be considered by those national institutions that have benefited, and continue to do so, from his invention.

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