AIAA JOURNAL
Vol. 35, No. 4, April 1997

Historical Review Paper

Otto Lilienthal: "The Greatest of the Precursors"

Peter L. Jakab*
National Air and Space Museum, Smithsonian Institution, Washington, D.C. 20560

This brief treatment of Otto Lilienthal's overall aeronautical contribution details his aerodynamic research, the data as well as his data-gathering technique. Lilienthal's subsequent glider experiments also are covered from the perspective of both their technical and inspirational contributions. The heart of the paper is a discussion of the place of Lilienthal's aerodynamics in the work of others, primarily the Wright brothers. Included is a reassessment of the accuracy of Lilienthal's famous table of lift coefficients and the assumptions that the Wrights made in using Lilienthal's data. Historically, Lilienthal's data and their use by the Wrights has been one of the more complex and debated aspects of the Wright story. The article presents a brief review of how Lilienthal's contribution has been characterized and revised over time, with a discussion of the current thinking regarding the famous Lilienthal table of lift coefficients.

Introduction

IN the summer of 1896, the world's premier aeronautical experimenter was Otto Lilienthal. By the time of his death in a glider accident in August of that year, the German glider pioneer had developed and published the most advanced conceptual understanding of flight to date, and he had compiled the most viable set of lift data for an actual, flight-tested wing shape. He had more time in the air as a pilot than anyone else, and he was publicly the most widely recognized figure in the pioneering aviation community. By the time the Wright brothers entered the field in the late 1890s, Lilienthal had moved aeronautics significantly closer to realizing human flight. The age of the flying machine was finally near at hand.

Although the desire to fly was truly a millennia-old aspiration, it was not until the close of the 18th century that any genuine technical progress had been made toward a practical heavier-than-air flying machine. Lighter-than-air flight had just become a reality with a successful human ascension in a Montgolfier balloon in 1783. But a craft that could emulate the agility and independence of bird-flight was still little more than a fanciful vision. The burgeoning modern society of the era of the Industrial Revolution was hardly closer to gaining wings than the aeronautical dreamers of the Ancient World.

The path to the invention of the powered airplane witnessed its initial great watershed during the first half of the 19th century in the person of an English baronet named Sir George Cayley. Cayley conceived the modern airplane in its basic form as a machine with fixed wings, a fuselage, and a tail, with separate systems to provide lift, propulsion, and control. He understood in rudimentary form the aerodynamic forces of lift and drag and how they related to a flying machine. During the opening decades of the 19th century, he mounted the first systematic program of aeronautical research that included instrumental data gathering and flight testing of model and full-size aircraft. All of this research and experimentation was disseminated in published form. As the first to grasp and articulate these breakthrough ideas, Cayley stands as a seminal figure in the birth of heavier-than-air flight (for a summary of Cayley's work, see Ref. 1).

Just as Cayley's work laid the first meaningful foundations for modern aeronautics, Lilienthal closed the first century of true progress toward the airplane with the next quantum leap. Together, their achievements established a base of theoretical ideas, experimental data, and practical experience that undergirded the final success of the next generation of pioneers. The inventive accomplishments of the Wright brothers were highly original in many ways, and much of what they did is at the core of all modern airplanes. But the critical directions charted by Otto Lilienthal, that the Wrights initially pursued, cannot be denied as part of their success.

Otto Lilienthal (Fig. 1) was born in the small Pomeranian village of Anklam in 1848. From boyhood, the multitude of storks that populated the surrounding meadows spawned Lilienthal's and his younger brother Gustav's interest in flight. Fascinated by the grace and freedom of birdflight, they spent countless hours observing and analyzing the creatures' wing movements in an effort to unlock the secrets of natural flight. Many years later, Gustav noted that a fairy tale from their youth had influenced them. In the story, a willow wren is given a ride on the back of a stork and is tutored by the stork on the art of soaring without having to flap wings. "This clear description of sailing flight impressed us with the possibility of attaining such by simple means," Gustav recalled (Ref. 2, p. xi).

As young teenagers the Lilienthal brothers built their first small fixed-wing glider in 1862. Their mother, who always fostered her sons' mechanical interests, approved of the plan, despite some reservations concerning the cost of the project. They tested the glider at night at a nearby military parade ground to avoid ridicule from schoolmates. This first 2-m-span design was unsuccessful, but, enthusiasm undampened, Otto and Gustav built several more craft as funds and breaks in schoolwork permitted (Ref. 2, pp. xi–xiv).

Lilienthal's first serious investigations of the science of flight began in 1867 and 1868 when he and Gustav built several test rigs to explore the mechanics and aerodynamics of the beating movements of bird wings (Fig. 2). One was a full-size piloted ornithopter suspended via rope and pulleys from a beam extending from the side of a building, counterbalanced by a 40-kg weight. The operator would pump the flapping wings with his legs and the degree to which the pull on the counterweight was lessened was measured. This device was followed by a smaller design mounted on a stand

Fig. 1 Otto Lilienthal, 1848–1896.

Received Sept. 7, 1996; accepted for publication Nov. 17, 1996.

*Curator, Aeronautics Department, Room 3322/MRC 312.

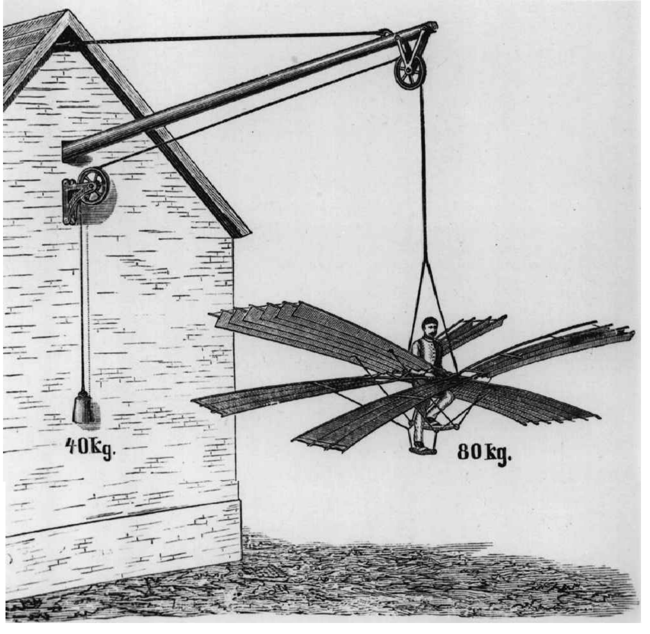

Fig. 2 Piloted bird-wing-beating-movement test rig, 1867.

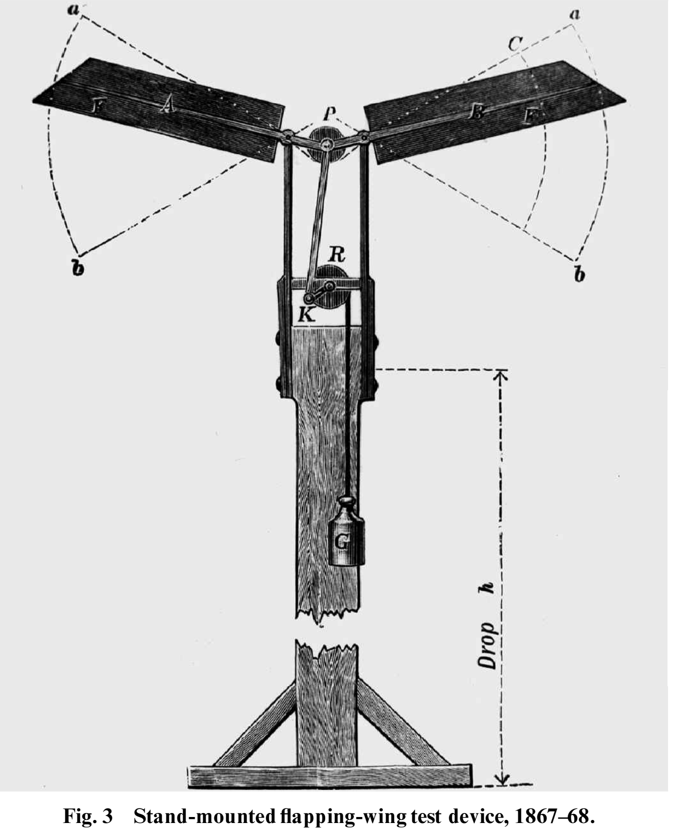

Fig. 3 Stand-mounted flapping-wing test device, 1867–68.

(Fig. 3) that flapped a pair of 0.1 m^2 surfaces by means of a crank and drop-weight arrangement (Ref. 2, pp. 28–36).

Although these experiments yielded some interesting results, they contributed little to the ultimate goal of a successful airplane. Although the flapping-wing motion of birds was an obvious conceptual model for mechanical human flight, it is technically a completely unfeasible means to copy on a human scale. The exponential increase in the power-to-weight requirements alone make ornithopters of any appreciable size impractical if not impossible. And, of course, if the power source on such a craft were to be the pilot, the strength and endurance demands would be well beyond human capabilities. Lilienthal continued intensive study of birds as a model for human flight for the rest of his life, but the later phases of his research focused more on the shape and curvature of bird wings and their aerodynamics during soaring flight. Lilienthal, however, never rejected entirely the notion of incorporating some form of flapping mechanism into his craft. In fact, his very last fixed-wing design before his death in 1896 featured flapping wing tips for propulsion.

In 1867, in the midst of the wing-beating research, Lilienthal entered the Royal Trade Academy to formally study mechanical engineering. Having held a number of apprenticeships before entering the Academy, Lilienthal was a product of the highly regarded German technical education system of his day. These credentials not only prepared him well for future professional success as a practicing engineer, but also afforded Lilienthal a good degree of credibility when his work in the less-than-publicly accepted field of aeronautics began to become widely known (Ref. 3, pp. 62–72).

Lilienthal graduated from the Royal Trade Academy in July 1870. Earlier that same month, the Franco–Prussian War began and Lilienthal volunteered for a one-year stint in the Prussian Rifle Guard. During the siege of Paris, he watched the gas balloons the French used to scout the German positions with great interest. "The Parisians are watching us from a . . . balloon," he wrote to his family, "and they light us up at night with large electric lights and concave mirrors" (Ref. 3, p. 73). The long periods of inactivity during the siege gave Lilienthal ample opportunity to busy his mind with flight. "When you have to stand eight hours of guard duty, what are you supposed to think about . . .," he wrote Gustav. "It is not worthwhile to speak of it further here, but later I will tell you what peculiar conclusions I have reached. I have already filled up half of my notebook with drawings" (Ref. 3, p. 75).

In the summer of 1871, Lilienthal left the service and returned to his aeronautical research in earnest. The years 1871–1875 yielded his most important work on aerodynamics. During this period he focused on gathering and analyzing air pressure data on wing shapes in an airstream. It was directly from these measurements that Lilienthal compiled his famous table of aerodynamic coefficients that corresponded to the wing shape of his highly successful hang gliders flown in the 1890s.

Lilienthal began these air pressure experiments with a whirling-arm device, similar to the ones pioneered in the previous century for use in ballistic studies. The concept was simple. By mounting a test shape on the end of a rotating arm, a flow of air over the object would be generated and the forces acting on it could be observed and measured. Cayley was the first to adapt such a device to aeronautical research. He mounted flat planes to one end of a whirling arm and measured how much weight they lifted at various angles and speeds (Ref. 1, pp. 16–17).

Unlike Cayley, the Lilienthal arm (Fig. 4) had two identical surfaces mounted at both ends and the rotation of the arm was driven with a pulley and drop-weight arrangement located centrally on the supporting structure of the device. To measure the lift force, a balancing lever linked to the central spindle of the arm would deflect in conjunction with the lift generated by the test surfaces. Weights were added to a tray attached to one end of the balancing lever. The amount of weight required to maintain the lever in an equilibrium position was equal to the lift for a given rotation speed and angle of attack of the test surface (Ref. 2, pp. 41–46).

Lilienthal measured the drag force on the test surfaces directly from the magnitude of the drop-weights that drove the device. The torque on the vertical supporting rod of the whirling arm induced by the drop-weights exactly balanced the torque on the vertical support due to the aerodynamic drag. Thus, knowledge of the magnitude of the drop-weights led to a direct calculation of the drag force (Ref. 4, p. 402. Anderson derives this method of measuring the drag force by analyzing the device; Lilienthal never actually stated in print how he did it.)

From the measured lift and drag forces, Lilienthal was able to calculate the resultant aerodynamic force. (The resultant aerodynamic force is the combination of the vertical lift-force component and the horizontal drag-force component that act on surface in a flow.) Lilienthal then graphically plotted this resultant force data over a range of angles of attack from 0 to 90 deg. Beyond the data collection itself, what was especially significant about this phase of Lilienthal's work was *how* he plotted the data he generated with the whirling arm and how he interpreted and used those graphs. This was Lilienthal's great, central contribution to the advancement of aerodynamics.

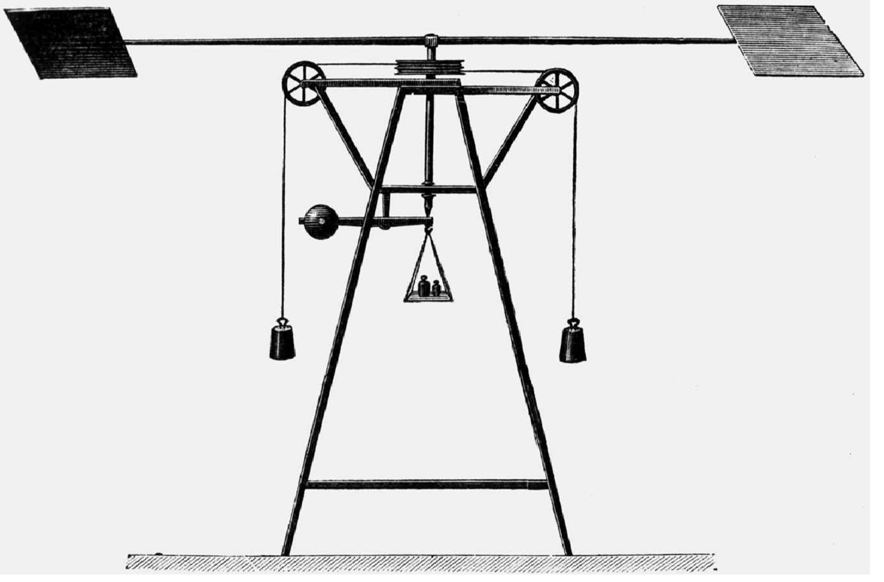

Fig. 4 Lilienthal whirling arm, 1871.

Key to these breakthroughs was Lilienthal's recognition that not only does the magnitude of the resultant force change as a wing moves through different angles of attack, but the direction of the force also varies with differing angles of attack. Others before him had argued that the resultant force is always perpendicular to the surface, regardless of angle of attack. Lilienthal strongly disagreed. "[i]t is not alone the *magnitude* of this air pressure which is a measure of the effect: to a greater extent the *direction* of the air pressure influences the result," he wrote (Ref. 2, p. 82).

Lilienthal plotted the changing magnitude and the changing direction of the resultant aerodynamic force as a function of angle of attack in two ways. In one he oriented the vertical lift component of the resultant force normal, or perpendicular, to the surface being tested. In the other, the lift component was normal to the flow. With the first, Lilienthal generated what today we call normal and axial coefficients. (Lilienthal used the terms normal and tangential.) Although rarely used in modern engineering practice, these were the type of coefficients that Lilienthal published in his famous table of air pressure data that was widely disseminated after his death and used by many experimenters, including the Wright brothers (Ref. 2, pp. 43–44).

With the second method of graphing the data (Fig. 5), Lilienthal created what is known in modern terminology as a drag polar, although he never called it that. In basic form, a drag polar is a plot of coefficient of lift vs coefficient of drag. The coefficient of lift or drag for any angle of attack can be taken from the curve by simply reading off the vertical and horizontal coordinates of the point on the curve corresponding to the angle of attack of interest (Ref. 4, pp. 404–405).

Lilienthal's use of these clever means of graphing the resultant forces calculated from the lift and drag measurements enabled him to easily obtain aerodynamic coefficients from the plotted curves. He recognized that if a surface is oriented 90 deg to an oncoming flow, i.e., an angle of attack of 90 deg, the resultant aerodynamic force is due entirely to drag and therefore has a force vector oriented perpendicular to the surface. In other words, there is no lift component to the resultant force. (This is somewhat oversimplified. There are other forces involved beyond drag. But for the purposes of this discussion, we can think of the resultant force in this situation as being due entirely to drag.) Lilienthal drew his plots of the resultant forces such that the vector for an angle of attack of 90 deg was set equal to a unit length of 1. Then he plotted the remaining resultant force vectors for further angles of attack along the varying angular directions he calculated. Finally, he drew solid curves connecting the tips of the force vectors. He could now obtain coefficients from these graphs by simply measuring the vertical and horizontal coordinates for any angle of attack along a particular curve, and then take the ratio of these measurements and the length of the vector for angle of attack 90 deg, which was given a unit length of 1.

Lilienthal was the first person to plot experimentally gathered air pressure data in this manner, and in so doing he was the first to introduce the concept of aerodynamic coefficients. Lilienthal was the first to calculate and articulate values, namely aerodynamic coefficients, that mathematically describe changes in lift and drag on a given surface over a range of angles of attack. Further, in the course of these history-making achievements, he also definitively demonstrated that cambered, or curved, wing surfaces were superior flat plates in terms of generating lift. This had long been suspected, but Lilienthal determined it unequivocally by plotting drag polars of data from curved surfaces along with that measured on flat plates. The graphs clearly showed the higher degree of aerodynamic efficiency of curved wing shapes (Ref. 2, pp. 54–59 and plates 1 and 6; Ref. 4, pp. 419–424).

Lilienthal's work in the early 1870s was a great leap forward. He not only was broadening the conceptual understanding of aerodynamics, but he was developing a more detailed mathematical description of what was happening on wing surfaces in a flow. Much was left to be learned concerning the complex phenomenon of lift and drag, but Lilienthal was beginning to bring the science of flight into a realm of aeronautical engineering that was recognizably modern.

As Lilienthal was conducting his air pressure tests, potential experimental errors inherent in the whirling-arm device were a concern. Obviously, as the arm rotated, it created a local circulation of the air, which caused an undesired disturbance of the flow over the test surfaces. In 1874, Lilienthal designed a different type of test rig to make comparative measurements. Rather than moving the test surface through still air with a whirling arm, the new device held the surface stationary and exposed it to the natural wind (Fig. 6). The simple mechanism mounted the test surface on a horizontal pivot arm with a counterweight, which was in turn linked to a vertically oriented spring scale. When the natural wind imparted a lift force on the test surface, the magnitude could be read from the scale. To measure drag, the pivot arm was merely reoriented vertically and the spring scale horizontally. Although this approach eliminated the problems of circulatory flow of the whirling arm, it introduced its own avenues for error. Because of the continually shifting speed and direction of the natural wind, Lilienthal had to make instantaneous and simultaneous measurements of the aerodynamic forces and the wind velocity. No matter how careful the readings are taken, any data gathered under such uncontrolled conditions certainly would be suspect (Ref. 2, pp. 74–77).

Lilienthal plotted the new data collected in the natural wind just as he had the whirling-arm data. He found that the lift-to-drag ratios were significantly higher for the natural wind data over the whole

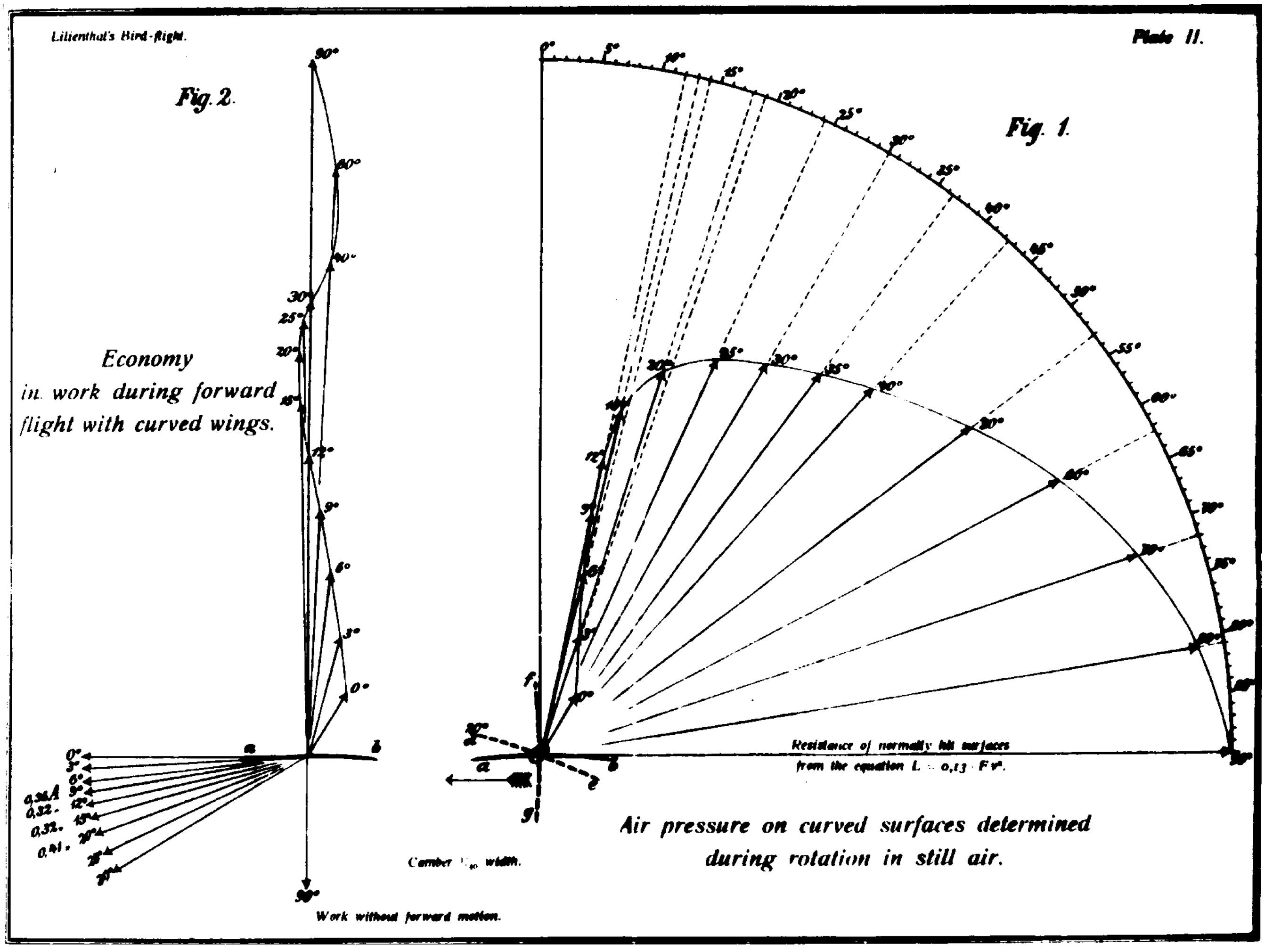

Fig. 5 Lilienthal aerodynamic data plotted as a function of angle of attack. On the left, the lift component of the resultant aerodynamic force is normal to the surface. On the right, the lift is plotted normal to the flow. The solid curve is data gathered in the natural wind; the broken line is data gathered with the whirling arm. The curve on the right is the first example of a drag polar.

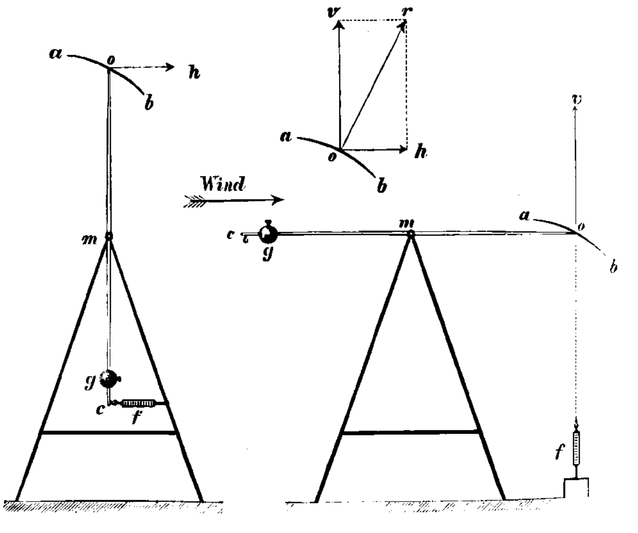

Fig. 6 Lilienthal's devices for testing in the natural wind: The instrument on the left measured drag; the device on the right measured lift.

range of angle of attack. Concerned over the large discrepancy, Lilienthal conducted experiments to investigate extraneous effects of the natural wind on his aerodynamic data. After trials under a variety of conditions, he concluded that, "The discrepancies are due to the errors introduced by the whirling machine..." (Ref. 2, p. 82). Nevertheless, although he felt more comfortable with the data from the natural wind, he was clearly aware of the inadequacy of his data-gathering techniques.

After 1875, the pace of Lilienthal's aeronautical work slowed dramatically. In fact, from 1881 to 1888 he performed no experiments at all. During this period Lilienthal focused on family and business matters. He married in 1878 and the first of four children arrived the following year. Also, beginning in 1880, Lilienthal's research partner, his brother Gustav, left Germany for eight years. After six years in Australia, Gustav operated a business in Paris for two more years before returning home in 1888. These years saw Lilienthal rise to prominence as an engineer and local businessman. He had established his own manufacturing plant near Berlin that produced steam engines, boilers, mining equipment, and marine foghorns among other things. Lilienthal also secured numerous patents in these fields. In 1886, he moved into a well-appointed home he had built in the Berlin suburb of Gross-Lichterfelde. (For biographical material on Lilienthal, see generally Ref. 3; see also Ref. 5.)

With the return of Gustav and business and family matters in good order, Lilienthal resumed his aeronautical work in 1888. With still no data from other experimenters to compare, he began with verification of his 1870s data with improved instruments, among them a 7-m whirling arm. The experiments of 1888 showed no appreciable differences from the data collected a decade earlier. With this work Lilienthal brought to a close the core of his contribution to the advancement of aerodynamics.

In 1889, he published his magnum opus, *Der Vogelflug als Grundlage der Fliegekunst* (Ref. 2, p. xi). In this remarkable volume, Lilienthal presented all of his data collection techniques, experimental findings, theoretical analyses, and graphical representations of his critical air pressure data. Interestingly, the famous Lilienthal table did not appear in the book. However, the graphs of the normal and axial coefficients from which the table was drawn were included. The table was first published in 1895, in a German handbook on

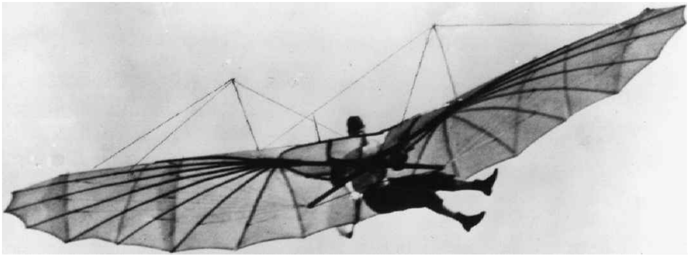

Fig. 7 Lilienthal gliding in his standard monoplane glider, 1894.

Fig. 8 Lilienthal making a public gliding demonstration at Gross–Lichterfelde in 1895.

Fig. 9 Lilienthal flying one of his biplane designs, 1895.

aeronautics compiled by Hermann Moedebeck, and subsequently was reprinted in numerous places including Octave Chanute's widely circulated article, "Sailing Flight."[6,7] After a decade and a half of imaginative and rigorous experimental research, Lilienthal now turned to the second phase of his influential aeronautical career: the construction and testing of a series of elegant piloted gliders.

Between 1891 and 1896 Lilienthal made close to 2000 brief flights in 16 different glider designs based on his aerodynamic investigations (Figs. 7–9). Most were monoplanes with stabilizing tail surfaces mounted at the rear. He also tried a few biplane and folding-wing designs, but the original monoplane glider, or *Normal-Segelapparat* (standard sailing machine) as he called it, produced the best results. Upon seeing an assembled Lilienthal glider, Robert Wood, a Boston-based news correspondent, commented enthusiastically, "Here was a flying machine, not constructed by a crank, . . ., but by an engineer of ability. . . . a machine not made to look at, but to fly with."[8]

The gliders had split willow frames covered with cotton-twill fabric sealed with collodion to make the surface as airtight as possible. Collodion is a viscous solution of nitrated cellulose in a mixture of alcohol and ether that dries to form a tough elastic film. The wings ranged in area from 10 to 20 m^2 and could be folded to the rear for easier transport and storage. Control was derived by shifting body-weight. The pilot cradled himself vertically in a harness suspended below an elliptical opening between the wings. Swinging his legs from side to side and fore and aft, the pilot could adjust the center of gravity and thereby maintain equilibrium. Lilienthal did most of his gliding from a man-made hill he had constructed near his home at Gross–Lichterfelde and from the hills surrounding the small village of Rhinow, about 50 miles from Berlin. His best efforts with these gliders covered over 1000 ft and were 12–15 s in duration.

In the summer of 1896, Lilienthal's aeronautical experiments came to an abrupt end. On August 9, while soaring in one of his standard monoplane gliders, a strong gust of wind caused the craft to nose up sharply, stall, and crash from an altitude of 50 ft. Lilienthal suffered a broken spine and died the following day in a Berlin hospital.[9]

As dramatic as they were, Lilienthal's glider experiments actually contributed relatively little to the technical advancement of aeronautics. The principal problem was his means of controlling the craft. Lilienthal's technique of shifting body weight as a means of maintaining equilibrium did place him ahead of other experimenters in so far as he recognized the need for a control system and gave attention to developing one. But, as revealed in his fatal crash, the control response of his method was very limited. Even more significant, shifting body weight as a means of control placed a severe restriction on the aircraft's size. Because control was achieved by altering the aircraft's center of gravity as a result of repositioning the pilot's body weight, the weight of the aircraft had to be kept comparatively low. This presented a great problem in the design of a powered airplane. Any aircraft capable of lifting an engine and pilot, let alone any sort of a payload, would be of a size so large that shifting body weight would be totally ineffectual.

Further, the airfoil of Lilienthal's gliders, although extensively tested and documented during his earlier aerodynamic research, was very inefficient in actual practice. Lilienthal always preferred a perfect arc for the shape of his glider wings with a very deep camber of 1 in 12. His investigations demonstrated that a curved surface was the most efficient shape, but he never abandoned the perfect arc in his gliders to experiment with parabolic airfoils, which later proved to be superior. The deeply cambered perfect arcs of Lilienthal's glider wings resulted in aerodynamic efficiency and stability problems.

Despite the technical limitations of Lilienthal's gliders, his flights did, however, make a significant contribution to the advancement of aeronautics from a psychological point of view. He demonstrated unquestionably that gliding flight was possible. Granted, he was flying for only seconds at a time, but he was truly flying. Lilienthal's tentative trips through the air made headlines everywhere. He was hailed the "Flying Man," the "Winged Prussian," and the "German Darius Green."[10] Inspirational photographs showing Lilienthal soaring gracefully over hillsides appeared in newspapers and magazines the world over, and made him quite a sensation in an age when, for most, human flight still seemed a distant possibility at best. This notoriety and visible proof that a human being could actually fly contributed as much to spurring other experimenters forward as did Lilienthal's groundbreaking aerodynamic research.

The impact of Lilienthal's aeronautical work upon the next generation of experimenters, the generation that would finally achieve heavier-than-air powered flight, was powerful. By the time of his death in 1896, his book, *Der Vogelflug*, had been out for seven years. Subsequent articles written by Lilienthal had appeared, several of them translated into English. His table of aerodynamic coefficients for the wing shape of his gliders had been published. Indeed, Lilienthal's achievements had been well chronicled in the aeronautical community's literature. Moreover, the popular press had embraced Lilienthal. His article, "The Flying Man," appeared in the widely circulated *McClure's Magazine* in 1894, for example.[11] In short, with his pioneering aerodynamic research and his success in the air, Lilienthal had established a new starting point for anyone entering the field.

The most important members of the generation of pioneers to follow Lilienthal were, of course, Wilbur and Orville Wright. After the Wright brothers' success at Kitty Hawk, they frequently cited the death of Lilienthal as the moment they were inspired to pursue aeronautics. While this was probably less clear at the time than Wilbur and Orville made it appear later, there is no question that Lilienthal's research was at the center of their thinking through much of their own early work. To begin with, they followed Lilienthal's lead in using gliders as an interim step to the powered flying machine. The Wrights initially concerned themselves with the problem of control. They correctly reasoned that they would require extended periods of time in the air to master their craft. "[i]f you wish to learn," Wilbur wrote, "you must mount a machine and become acquainted with its tricks by actual trial."[12] Gliders of the type tested by Lilienthal were the ideal means to gain this experience.

Even more important, Lilienthal's aerodynamics were a critical jumping-off point for the Wrights. Like all good engineers, Wilbur and Orville began with a thorough literature search. They quickly became familiar with the German experimenter's ideas, most importantly his already well-known table of air pressure coefficients. The Lilienthal table would occupy the Wrights' thinking, and frequently confound them, for the first few years of their aeronautical experimentation.

The brothers built their first full-size glider in 1900. It was based on Lilienthal's coefficients and the mathematical relationship between lift, air speed, and surface area that had become standard by that time. Much to the Wrights' disappointment, in actual practice at Kitty Hawk, the lift generated by the glider was only one-third of what their calculations predicted. Puzzled, the Wrights built a larger glider in 1901, again using the Lilienthal pressure coefficients (Fig. 10). The second craft fared little better.

At this point, the brothers began to question the accuracy of Lilienthal's aerodynamic data. They had checked and rechecked every aspect of their design and calculations and could find no errors. Reluctant to doubt the work of the venerated Lilienthal, Wilbur and Orville nevertheless concluded that the pressure coefficients obtained from the Lilienthal table likely were at the root of the problem. In the fall of 1901, Wilbur informed his now colleague and confident, Octave Chanute, that he was "arranging to make a positive test of the correctness of Lilienthal's coefficients."[13] Only ten days later Wilbur followed up to Chanute, "I am absolutely certain that Lilienthal's table is very seriously in error."[14]

The Wrights made this test with a crude wind tunnel and instruments of their own design. So well did the device work that the brothers immediately built a larger, more sophisticated tunnel (Fig. 11) and instruments to begin a broad series of aerodynamic tests on many different wing shapes. These wind-tunnel experiments performed in late 1901 were at the heart of the Wrights' successful path to the powered airplane. All of their subsequent design decisions stemmed directly from their wind-tunnel data. The Wright wind tunnel of 1901 is as much a part of the invention of the airplane as the craft that lifted off the beach at Kitty Hawk in 1903.

Despite Wilbur's confident assertion to Chanute that Lilienthal was "very seriously in error," the Wrights' wind-tunnel experiments continued as an impetus for reevaluating Lilienthal's coefficients for some time. Not two weeks after his rejection of Lilienthal, Wilbur admitted to Chanute, "It would appear that Lilienthal is very much nearer the truth than we have heretofore been disposed to think."[15] The Wrights then reminded themselves that the Lilienthal table was for only one surface, a perfect arc of a camber of 1 in 12, a surface

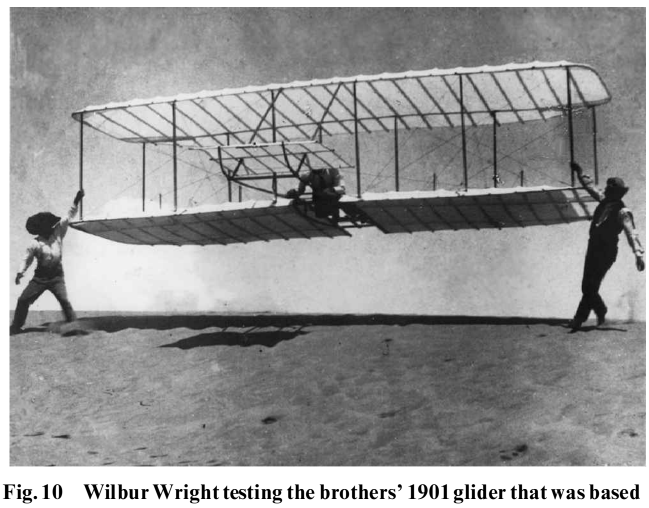

Fig. 10 Wilbur Wright testing the brothers' 1901 glider that was based on Lilienthal's aerodynamic data.

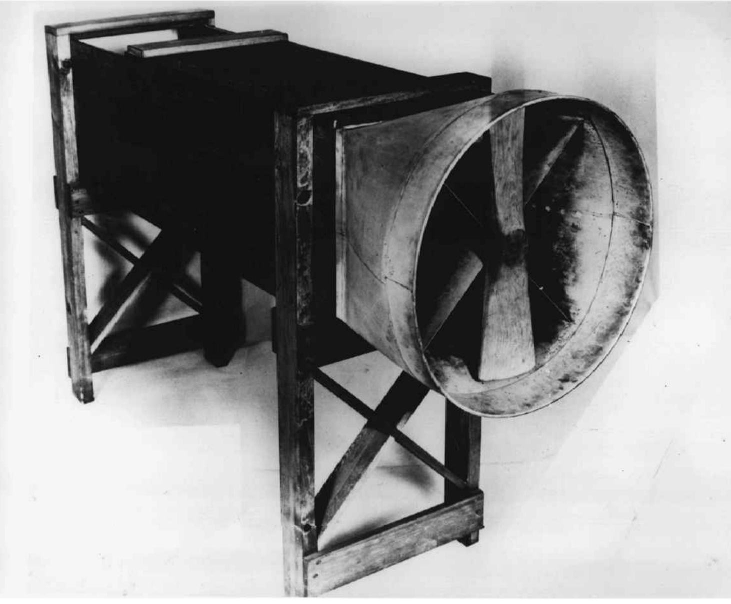

Fig. 11 Wright brothers' wind tunnel.

very different from their own parabolic airfoils of quite shallow curvature. "It is very evident," Wilbur proclaimed, "that a table [Lilienthal's] based on one aspect and profile is worthless for a surface of different aspect and curvature." He went on, "This no doubt explains why we have had so much trouble figuring all our machines from Lilienthal's table."[16] The following week, Wilbur yet again brings up the subject of the Lilienthal data with Chanute. "The Lilienthal table has risen very much in my estimation since we began our present series of experiments for determining lift."[17]

These vacillating statements on the part of the Wrights have been the source of much debate among historians over the true accuracy of the famous Lilienthal table. For the Wrights, however, after 1901 it clearly became a moot point. They were using wing shapes very different from Lilienthal's and had independently developed an instrument to generate accurate lift and drag coefficients. They no longer had any reason relevant to their aeronautical experiments to concern themselves with the accuracy of the table. That Lilienthal's work taught the Wrights of the need to concern themselves with aerodynamic coefficients generally is a far more significant point from an historical perspective than the brothers' analysis of the table itself.

If we wish to concern ourselves with the accuracy of the table, a modern knowledge of aerodynamics can suggest reasons why the Wright gliders designed with Lilienthal's data performed as they did. Lilienthal's data might well have been quite accurate. The significant difference in the location of maximum camber of the airfoil between the Wright craft and Lilienthal's, along with the dissimilar aspect ratios of the wings, could have contributed to the reduced lift of the Wright glider. In other words, the Lilienthal data may not have been wrong, just different, and inappropriate to the Wright design. Or, on the other hand, the crude instruments Lilienthal used to gather his coefficients easily could have led to great errors in the measured lift values. Unfortunately, Lilienthal did not publish anything that spoke to the performance of his gliders in terms of his data. Nor did he record that he even designed the gliders based on his coefficients, although it is hard to imagine that he did not.

Interesting as these suppositions may be, in the final analysis, it is much less important to determine the accuracy of the table than it is to recognize the tremendous conceptual advancement to aeronautics embodied in Lilienthal's work. The recognition of the varying direction of the resultant force with angle of attack, the need for aerodynamic coefficients and the means of obtaining them, confirming experimentally the superiority of cambered airfoils, the drag polar, the importance of actual flying experience, and the important psychological impact of his glider flights all were critical building blocks leading toward the final achievement of human flight. It is for these accomplishments that Lilienthal should be remembered as a pivotal figure in the history of aviation. Even though at his death he was still a long way from a successful powered airplane, the progress he made was profound. Wilbur Wright summed up Lilienthal's place in aeronautics succinctly and eloquently: "[H]e was without question the greatest of the precursors . . . ."[18]

References

[1]Gibbs-Smith, C. H., *Sir George Cayley's Aeronautics 1796–1855*, Her Majesty Stationery Office, London, 1962.

[2]Lilienthal, O., *Birdflight as the Basis of Aviation*, translated by A. W. Isenthal, Longmans Green, London, 1911.

[3]Schwipps, W., *Lilienthal: Die Biographie des ersten Fliegers*, Aviatic Verlag, Munich, 1979.

[4]Anderson, J. D., *The History of Aerodynamics and Its Impact on Flying Machines*, Cambridge Univ. Press, New York, 1997.

[5]Trischler, H., and Heinzerling, W., *Otto Lilienthal: Flugpionier, Ingenieur, Unternehmer*, Deutsches Museum, Munich, 1991, pp. 160–188.

[6]Moedebeck, H. W. L., *Pocket-Book of Aeronautics*, translated by W. Mansergh Varley, Whittaker London, 1907, pp. 286–90.

[7]Chanute, O., "Sailing Flight," *The Aeronautical Annual*, 1897, pp. 115–116.

[8]Wood, R. W., "Lilienthal's Last Flights," *Boston Transcript*, Aug. 1896.

[9]Jakab, P. L., *Visions of a Flying Machine: The Wright Brothers and the Process of Invention*, Smithsonian Institution Press, Washington, DC, 1990, pp. 34–35.

[10]Crouch, T. D., "Engineers and the Airplane," *The Wright Brothers: Heirs of Prometheus*, edited by R. P. Hallion, Smithsonian Institution Press, Washington, DC, 1978, p. 14.

[11]Lilienthal, O., "The Flying Man," *McClure's Magazine*, Sept. 1894, pp. 1–10.

[12]Wright, W., "Some Aeronautical Experiments (Sept. 18, 1901)," *The Papers of Wilbur and Orville Wright*, edited by M. W. McFarland, 2 vols., McGraw–Hill, New York, 1953, p. 103.

[13]Wilbur Wright to Octave Chanute, Sept. 26, 1901 (letter), *The Papers of Wilbur and Orville Wright*, edited by M. W. McFarland, 2 vols., McGraw–Hill, New York, 1953, pp. 120–122.

[14]Wilbur Wright to Octave Chanute, Oct. 6, 1901 (letter), *The Papers of Wilbur and Orville Wright*, edited by M. W. McFarland, 2 vols., McGraw–Hill, New York, 1953, pp. 123–128.

[15]Wilbur Wright to Octave Chanute, Oct. 16, 1901 (letter), *The Papers of Wilbur and Orville Wright*, edited by M. W. McFarland, 2 vols., McGraw–Hill, New York, 1953, pp. 31–37.

[16]Wilbur Wright to Octave Chanute, Nov. 24, 1901 (letter), *The Papers of Wilbur and Orville Wright*, edited by M. W. McFarland, 2 vols., McGraw–Hill, New York, 1953, pp. 163, 164.

[17]Wilbur Wright to Octave Chanute, Dec. 1, 1901 (letter), *The Papers of Wilbur and Orville Wright*, edited by M. W. McFarland, 2 vols., McGraw–Hill, New York, 1953, pp. 68–71.

[18]Wright, W., "Otto Lilienthal," *Aero Club of America Bulletin*, Vol. 1, Sept. 1912, p. 21.

G. Sutton
Associate Editor