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Historical Review Paper

Langley's Aeronautical Research: A Modern Critique and Reassessment

John D. Anderson Jr.*
University of Maryland, College Park, Maryland 20742

Samuel Langley, third Secretary of the Smithsonian, was also the first U.S. government in-house researcher in aerodynamics. By 1890, he had carried out a carefully conceived, accurately engineered series of aerodynamic experiments that provided a database for the design of his steam-powered aerodromes, successfully flown in 1896. Langley's work is examined from a modern perspective. The aerodrome flights of 1896 are discussed. Particular emphasis is placed on a reassessment of Langley's aerodynamic experiments and data. The Langley law for the variation of power required as a function of velocity, which was immediately controversial in his time and remained so until the present, is finally explained for the first time, and the controversy removed. Also, Langley produced the first definitive data showing the aerodynamic superiority of high-aspect-ratio wings. Those data, if they had been properly appreciated by the Wright brothers, might have greatly improved their early glider designs. This presentation also compares and contrasts Langley's aerodynamic data with the contemporary data of Lilienthal. In general, Langley's aerodynamics, vis-a-vis the aerodynamics of Lilienthal and the Wright brothers, is brought into clearer focus.

The most important general influence from these experiments, as a whole, is that, so far as the mere power to sustain heavy bodies in the air by mechanical flight goes, *such mechanical flight is possible with engines we now possess.*

Samuel Langley,
Experiments in Aerodynamics, 1891

Introduction

THE time is 3:05 p.m. on May 6, 1896. Poised on a small, makeshift houseboat in the Potomac River near Quantico is a flying machine about to make history. Slung underneath a catapult mounted on top of the houseboat, the tandem-wing aircraft strains under the thrust provided by a one horsepower steam engine driving two small propellers. The flying machine is too small to sustain the weight of a person—the wingspan is barely 13 ft. However, carrying a person is not the intent of this machine. Rather, it is an experimental flying machine designed and developed by the third Secretary of the Smithsonian Institution, Samuel Pierpont Langley, purely for the purpose of demonstrating the technical feasibility of heavier-than-air powered flight. The catapult is fired, and the flying machine, called an aerodrome by Langley, sails majestically into the calm air. Shortly after the instant of launch, a photograph of the aerodrome in flight is taken (Fig. 1) by Alexander Graham Bell, inventor of the telephone and a close personal friend and supporter of Langley. The aerodrome stays in the air for a minute and a half, and covers a distance of 3300 ft before it literally runs out of steam and settles gently into the cold water of the Potomac.

Langley and Bell are elated, and justifiably so. What happened that afternoon was the most important advance and the most dramatic event in powered flight to that time. Fifteen years later, using his prerogative as editor of Part I of Langley's memoirs,[1] Charles Manly inserted the following comment, which tells it all:

Just what these flights meant to Mr. Langley can be readily understood. They meant success! For the first time in the history of the world a device produced by man had actually flown through the air without the aid of a guiding human intelligence. Not only had this device flown, but it had been given a second trial and had again flown and had demonstrated that the result obtained in the first test was no mere accident.

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*Professor, Department of Aerospace Engineering; also Special Assistant for Aerodynamics, Room 3312/MRC 312, National Air and Space Museum, Smithsonian Institution, Washington, DC 20560. Fellow AIAA.

Indeed, Samuel Langley had achieved the first successful flight of an engine-powered, heavier-than-air flying machine in history. And it was no accident. The Langley aerodrome was the product of an intensive, 10-year program of aerodynamic research by Langley—research that is the primary focus of this paper. However, it is useful first to examine some of the relevant aspects of the life of Samuel Langley.

Samuel Langley—The Man

Langley was born at Roxbury, Massachusetts, on Aug. 22, 1834. His family had some wealth and influence; his father was in the produce business. After attending the prestigious Boston Latin School and graduating from Boston High School, Langley moved to the Midwest, where he worked as a civil engineer and architect for a dozen years. Langley had only a high school education; he intentionally chose not to go to college. However, for the rest of his life, Langley learned from self-study—he was essentially a self-educated person. During the height of the American Civil War, Langley returned to Boston and directed his attention to astronomy. As part of his self-learning process, he toured Europe, visiting a number of European astronomical observatories. (Much later, as Secretary of the Smithsonian Institution, Langley developed the habit of making regular, summer visits to Europe.) Back in Boston in 1865, Langley accepted an invitation from the director of the Harvard Observatory to be an assistant. One year later, through the help of the same director, Langley was given an assistant professorship in mathematics at the U.S. Naval Academy in Annapolis. (In his recent book, Biddle[2] comments that the Academy must have been hard-pressed for faculty immediately after the Civil War to offer a mathematics professorship to someone who had only a high school education and no experience in mathematics or teaching.) However, within a year, Langley had applied for, and was given, a position of professor of physics and director of the Allegheny Observatory at the Western University of Pennsylvania (now the University of Pittsburgh).

There had only been one other applicant for the position; the observatory itself was only a few years old, but when Langley arrived, it was in a state of disrepair. The observatory had been started by a group of private citizens in Pittsburgh who had bought an expensive German telescope but none of the supporting equipment to properly point it. In setting up the observatory, the members of this private association were soon over their heads, so they deeded it to the local university, along with a meager endowment for a professorship. It was this position that Langley walked into. It was the best decision of his life. Taking advantage of the "big fish in a small pond" situation, Langley quickly befriended a wealthy railroad executive, William Thaw, who provided funding to properly equip the observatory. Thaw also made a $100,000 grant to the university with the

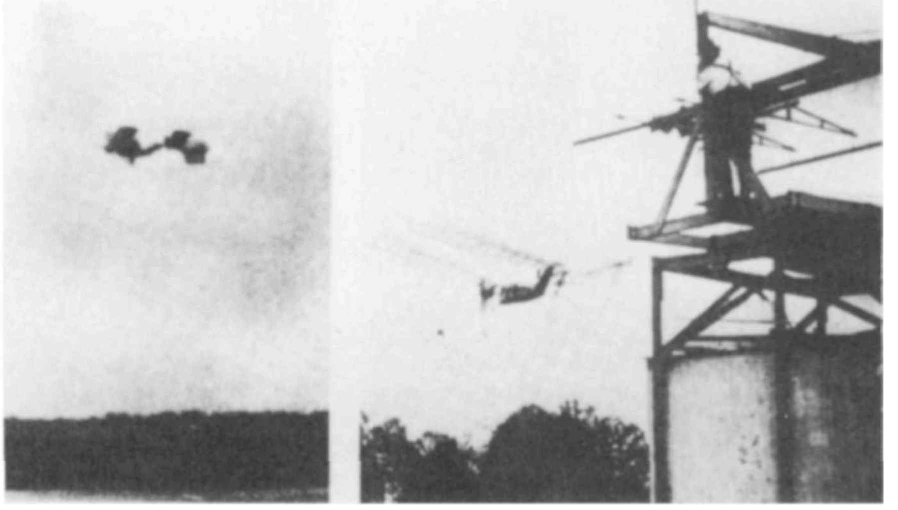

Fig. 1 Flight of Langley's steam-powered aerodrome, May 6, 1896.

stipulation that Langley be freed of any teaching duties and that he be given full time to pursue his observatory research. Thaw continued to be a lifelong benefactor to Langley's work and career.

During the next 20 years, Langley carved out a distinguished reputation as director of the observatory and as an observational astronomer. Langley's lack of mathematical background pointed him in the direction of experimental rather than theoretical astronomy. This same experimental emphasis would later dominate his aeronautical work. On the practical side, Langley set up a source of income for the observatory by providing the exact time of day to the railroads; this he accomplished by making star observations and then telegraphing the results to his customers twice a day. On the scientific side, Langley specialized in a study of the sun, especially the study of sunspots and the energy produced by the sun. In the late 1870s, he developed the bolometer, an instrument to measure the spectral variation of the sun's energy incident on the Earth, and he widely published the results obtained with the help of this instrument. In particular, in 1884, Langley organized an expedition (funded by Thaw) to Mount Whitney in the Sierra Nevada of eastern California to measure the heat-absorbing characteristics of the atmosphere; two years later he published a widely used 239-page report on the results. Langley's data also allowed him to determine a value for the solar constant (a measure of the amount of energy reaching the Earth's atmosphere). This work brought Langley lavish praise from his scientific colleagues, and solidified for him an international reputation. (Much later, in 1914, the scientific community eschewed Langley's value of the solar constant, finding it to be too large by 50%.) The pinnacle of Langley's scientific reputation was reached in 1886 when he was awarded the Rumford medals by both the Royal Society in London and the American Academy of Arts and Sciences, and the Henry Draper medal from the National Academy of Sciences.

It was also in this year that Langley's scientific career took a new direction that was to dominate him for the rest of his life. In August 1886, the American Association for the Advancement of Science (AAAS) met in Buffalo, New York. Through the encouragement of Octave Chanute, then a vice president of the AAAS, the subject of aeronautics was placed on the meeting program. In particular, an amateur experimentalist, Isreal Lancaster, was invited to present his work on "soaring effigies" of birds—models that he launched in the air. Although Lancaster's presentation was not as spectacular as expected, Langley was inspired by what he heard and began to think seriously about the idea of manned flight. After his return from Buffalo, Langley was successful in obtaining the Observatory Board of Trustees' permission to construct a whirling arm device for aerodynamic experiments. Although the Observatory's mission was astrophysical observation, and Langley's reputation was built on his contributions in astronomy, especially his studies of the sun and sunspots, Langley was allowed to construct and operate a major facility for the sole use of obtaining aerodynamic data. Funding for the whirling arm and the initial experiments came from his wealthy friend, William Thaw.

Fig. 2 Samuel Pierpont Langley (1834–1906).

In 1887, Langley was offered the position of Secretary of the Smithsonian Institution in Washington, DC—he snapped it up. At that time, the position of Secretary of the Smithsonian was considered by many as the most prestigious scientific position in the United States. Hence, in 1887, we have Samuel Pierpont Langley becoming, by definition, the most prestigious scientist in the United States. In regard to his aerodynamic experimentation, it only increased with time. In 1887, Samuel Langley became the first U.S. government in-house researcher in aerodynamics.

A photograph of Langley is shown in Fig. 2. If we examine Fig. 2 closely, we might detect in Langley an air of self-confidence, self-centeredness, arrogance, and even pompousness. Indeed, all this and more was Samuel Pierpont Langley. He was a prim man, regularly inspecting Smithsonian facilities wearing a morning coat and striped pants. He was a strong taskmaster and exerted continuous and sometimes unreasonable pressure on those who worked with him. Crouch[3] sums up the "darker" side of Langley's nature as follows: "What a friend would characterize as 'an eagerness to push on in specific pursuits which amounted at times to impatience,' the secretary's subordinates viewed less kindly. At best, Langley was a difficult man to work for. He was an impatient, demanding perfectionist who insisted on absolute obedience."

Langley had an imperious attitude and ruled the Smithsonian accordingly. Worse, he was sometimes accused of taking credit for work done by others. He demanded that his subordinates always walk behind him. However, there were some who revered Langley. His closest assistant and collaborator after 1898, Charles Manly, writing in Part II of the memoir[4] published after Langley's death, said of Langley: "He had given his time and his best labors to the world without hope of renumeration." Earlier, in the preface to the memoir, Manly wrote devotingly of Langley as follows:

> He began his investigations at a time when not only the general public but even the most progressive men of science thought of mechanical flight only as a subject for ridicule, and both by his epoch-making investigations in aerodynamics and by his own devotion to the subject of flight itself he helped to transform into a field of scientific inquiry what had before been almost entirely in the possession of visionaries.

Manly wrote this in 1911, five years after Langley's death, a reasonable maturing time for the process of idolatry. Langley walked in the best intellectual and scientific circles in Washington. One of his closest friends and supporters was Alexander Graham Bell, who himself would contribute to aeronautics by forming the effective Aerial Experiment Association in 1907. Another close friend was Albert Zahm, head of the Department of Physics and Mechanics at Catholic University, located just a few miles north of the Smithsonian. Zahm was responsible for building the first aerodynamic laboratory in an American university. Langley's status in life is no better illustrated than by noting that he was a member of and lived at the Cosmos Club, still today one of the most prestigious addresses in Washington. Langley remained a bachelor all of his life.

All of these traits, for better or worse, led Langley to a glorious success in 1896. The engineering development of his steam-powered aerodromes is given in great detail in the memoir,[1,4] and the general process is nicely summarized by Crouch.[3]

Langley's Aerodynamics

After his return from the 1886 meeting of the American Association for the Advancement of Science, Langley designed his first aerodynamic test facility—a whirling arm. Whirling arms were not new; the English ballistician Benjamin Robins in 1742 was the first person to use a whirling arm. Another Englishman, George Cayley, the inventor of the concept for the modern configuration airplane, used a whirling arm for aerodynamic measurements in the first decade of the 19th century. And the German engineer Otto Lilienthal carried out some of his aerodynamic measurements with a whirling arm near the end of the 19th century (see Ref. 5 for a more thorough discussion of early work with whirling arms). However, at its completion in September 1887, Langley's whirling arm had the distinction of being the largest built to date; the arms swept out a circle of 60-ft diam, revolving 8 ft above the ground. A top view of this device is shown in Fig. 3. By comparison, Lilienthal's largest whirling arm had a diameter of 7 m (23 ft). Both men recognized the importance of having a large diameter, so as to minimize centrifugal-force effects on the airflow over the lifting surface mounted at the end of the arm and, more important, to minimize various flow nonuniformities created by the circular motion of the arm. In 1887, Langley began a series of carefully designed and executed aerodynamic experiments with his whirling arm—experiments that continued for more than four years, resulting in the publication of a book that elevated Langley to world-class status in the circle of late 19th century aerodynamic researchers. This book, entitled *Experiments in Aerodynamics*[6] and published in 1891, constituted the first substantive American contribution to aerodynamics. With it, and with Langley's subsequent work on actual flying machines after he became Secretary of the Smithsonian Institution in Washington in 1887, the virtual monopoly in aerodynamic experimentation held by western Europe was broken. For the remainder of this paper, we examine the nature of Langley's experiments in aerodynamics and make some value judgments as to how much they contributed to the advancement of the state of the art.

To begin, there is absolutely no doubt about the ultimate goal of Langley's experiments—he intended to explore and uncover the basic physical laws of aerodynamics that would scientifically prove the practicability of powered, heavier-than-air flight. Specifically, he wrote in the introduction to *Experiments in Aerodynamics*[6]:

> To prevent misapprehension, let me state at the outset that I do not undertake to explain any art of mechanical flight, but to demonstrate experimentally certain propositions in aerodynamics which prove that such flight under proper direction is practicable. This being understood, I may state that these researches have led to the result that mechanical sustentation of heavy bodies in the air, combined with very great speeds, is not only possible, but within the reach of mechanical means we actually possess, and that while these researches are, as I have said, not meant to demonstrate the art of guiding such heavy bodies in flight, they do show that we now have the power to sustain and propel them.

These comments reflect Langley the scientist. Later, Langley was driven to design a series of actual flying machines to confirm without a shadow of doubt his conclusion from his whirling-arm data, as stated above. We have already discussed these machines, Langley's aerodromes, which successfully flew in 1896. In this regard, we see Langley the engineer.

Langley's published aerodynamic data obtained with the whirling arm was all for flat plates, although he mentions in various places some unpublished work on cambered surfaces. His attention to the flat plate is due in part to his desire to examine the accuracy of the Newtonian sine-squared law, which had been used since the 18th century to calculate the normal force on a flat plate.

Langley's aerodynamic experiments can be divided into four general categories: 1) some preliminaries, 2) direct aerodynamic force measurements, 3) the "plane dropper" experiments, and 4) "soaring experiments." Specific contributions were made in each category; we look at each one in turn.

Some Preliminaries

Langley was concerned about experimental inaccuracies inherent in the whirling-arm setup. For example, he recognized that, as the lifting surface at the end of the arm whirled around in a circular path, the outer tip would see a greater freestream velocity than the inner tip. Clearly, for a lifting surface of given span, the larger the radius of the whirling arm, the smaller the relative difference in velocity between the inner and outer edges, and hence the smaller the flow nonuniformity across the span of the surface. This is one of the advantages to having a large-radius arm on a whirling-arm device. Indeed, Langley reported a calculation for a flat plate of a span of 30 in. mounted at the end of a whirling arm with a radius of 30 ft. He first calculated the pressure distribution over the span of the plate, assuming a local application of Newtonian theory, and then integrated this distribution to obtain the net aerodynamic force on the plate. He then compared this with a calculation of the force, assuming a constant pressure over the span of the plate equal to that pressure at the center of the plate. The difference in the two forces calculated by the two methods was less than 0.2%. From this, Langley states that "such disturbing effects of air-pressure arising from circular motion are for our purposes negligible." Another disturbing effect addressed by Langley was that, if the device is housed indoors, the "rotating arm itself sets all the air of the room into slow movement, besides creating eddies which do not promptly dissipate." He felt that "the erection of a large building specifically designed for them (the experiments) was too expensive to be practicable." Therefore, Langley conducted his whirling-arm experiments in the open air, and every effort was made to conduct tests only when the outside air was calm. However, Langley laments that "these calm days almost never came, and the presence of wind currents continued from the beginning to the end of the experiments, to be a source of delay beyond all anticipation, as well as of frequent failure." These problems so aptly itemized by Langley are basically inherent in the operation of a

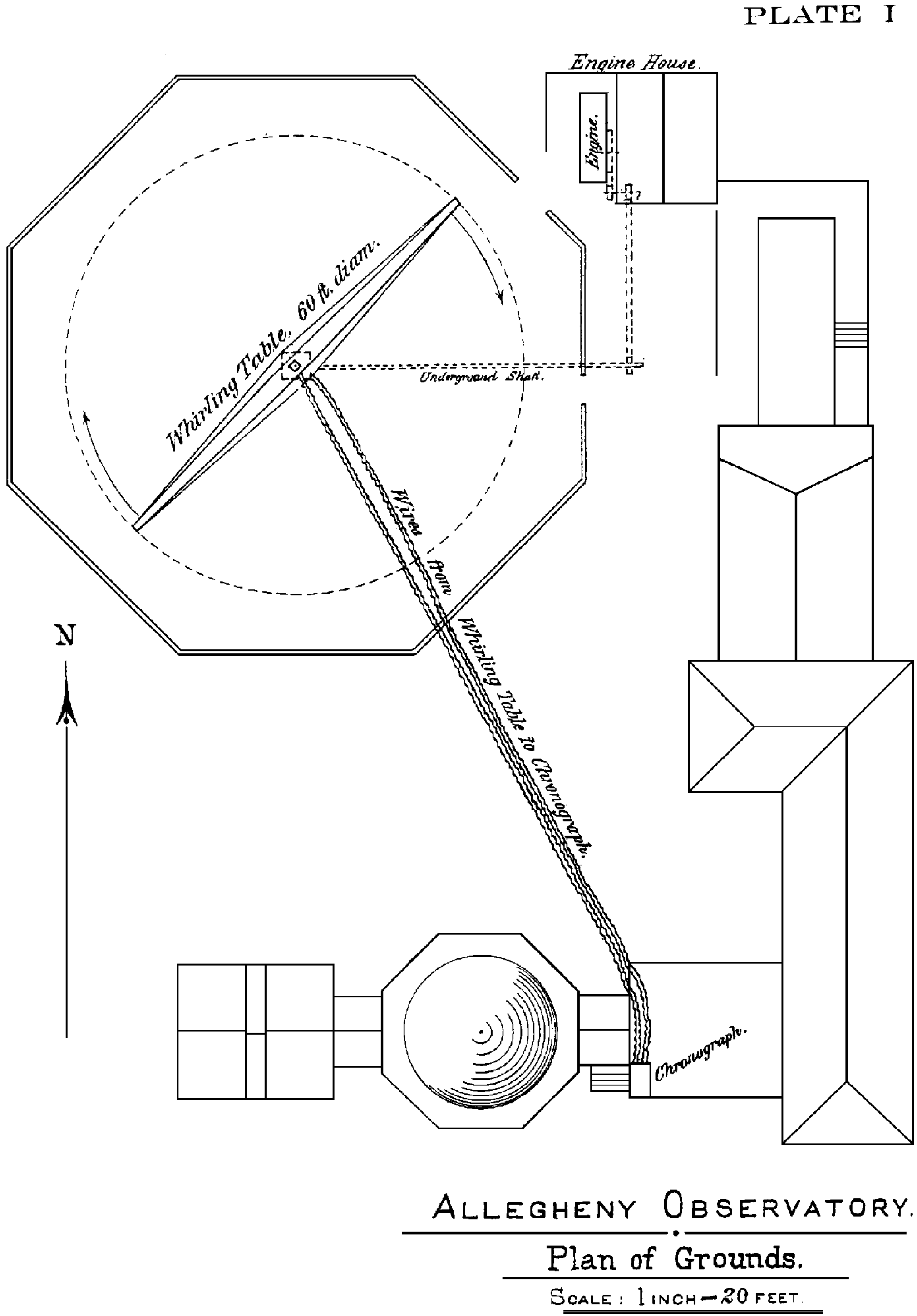

Fig. 3 Langley's whirling-arm device (original figure from Ref. 6).

whirling arm; even in today's modern aerodynamics it is difficult to see how they could be properly mitigated and/or accounted for without much undue effort. It is no wonder that whirling arms quickly fell out of favor for aerodynamic research at the beginning of the 20th century. In spite of these difficulties and potential sources of error, the 19th century investigators using whirling arms—Cayley, Lilienthal, and Langley, for example—somehow obtained data that were meaningful in their own right in their own time. We elaborate on this thought later.

In interpreting his data, Langley made an assumption that had nothing to do with the inadequacies of a whirling arm and which was plainly wrong. He neglected the influence of friction on his aerodynamic force measurements. By the end of the 19th century, the calculation of skin friction drag was unreliable.[5] Even the basic physical mechanism was a mystery; there was a constant debate about the applicability of the no-slip condition at the surface, i.e., the assumption of zero velocity of the air adjacent to the surface relative to the surface. Was this the actual case, or not? Langley expresses an opinion about this—the correct opinion. He states in a footnote in *Experiments in Aerodynamics*[6]:

> There is now, I believe, substantial agreement in the view that ordinarily there is no slipping of a fluid past the surface of a solid, but that a film of air adheres to the surface, and that the friction experienced is largely the internal friction of the fluid—i.e., the viscosity.

Note that Langley explicitly uses the words "no slipping"; the source of the term "no-slip condition" goes back at least to the

19th century. Langley goes on to make a calculation of skin friction drag using a friction formula given by Clerk Maxwell. He compares the resulting friction drag on a plate at zero angle of attack with the pressure drag on the same plate at 90-deg angle of attack, and concludes the former to be negligible compared to the latter. Of course, this is comparing apples and oranges, and this author is amazed by Langley's uncharacteristically faulty logic here. As we see, Langley's intentional neglect of skin friction compromised his interpretation of his data for plates at small angle of attack.

As a final preliminary, we note that Langley made many measurements of the aerodynamic force on flat plates over a large range of angles of attack, including 90 deg, i.e., with the plate oriented perpendicular to the flow. From these 90-deg results, he readily calculated values for Smeaton's coefficient k, defined from

$$p = kV^2 \tag{1}$$

where p is the average pressure on the plate and V is the velocity. For p in units of lb/ft^2 and V in units of miles per hour, Langley measured a value of $k = 0.003$ for Smeaton's coefficient. This value is very close to the modern, 20th century value of $k = 0.0029$ established by the Royal Aeronautical Society. It is also a far cry from the earlier accepted value of 0.005 obtained from Smeaton's tables published in the 18th century—a value that has been shown by several investigators over the past two centuries to be too high (see the discussion of Smeaton's coefficient elsewhere[5]). Hence, Langley's measurement is quite accurate—a testimonial to the accuracy of his experiments for these conditions.

Direct Aerodynamic Force Measurements

Langley was a master instrument designer. In contrast to the simple weight, pulley, and spring mechanisms developed by Otto Lilienthal in Germany for his aerodynamic force measurements, Langley designed rather sophisticated electromechanical instruments for measuring various types of forces. For example, he developed his resultant pressure recorder, which measured both the direction and the magnitude of the resultant aerodynamic force on the flat plate; both the recorder and the flat plate were mounted at the end of the whirling arm, and both moved in unison. Extremely detailed descriptions of all of his measuring devices, with elaborate mechanical drawings of the same, are included in *Experiments in Aerodynamics*.[6] Langley reported his force results in both tabular and graphic form. In the same spirit as Lilienthal, Langley referenced his force measurements to the measured force on the flat plate at 90-deg angle of attack; hence, his recorded ratios are simply the resultant force coefficient C_R,

$$C_R = P_\alpha / P_{90} \tag{2}$$

where P_α is the force at a given angle-of-attack α and P_{90} is the force at $\alpha = 90$ deg. Assuming the drag coefficient for the flat plate at $\alpha = 90$ deg is unity, then Eq. (2) is simply equal to the modern resultant force coefficient, defined as

$$C_R = \frac{R}{\frac{1}{2}\rho V^2 S} \tag{3}$$

Otto Lilienthal was the first to use aerodynamic force coefficients; however, Langley was not far behind. Lilienthal published his data in 1889, and Langley's *Experiments in Aerodynamics* was published in 1891. It is clear that the impact that both men had on future aerodynamic investigators served to establish the use of aerodynamic force coefficients as part of the way of doing business in applied aerodynamics.

Langley's first major measurements were those on a 1-ft^2 flat plate, wherein the magnitude and direction of the resultant aerodynamic force were measured with the resultant pressure recorder over a range of angles of attack from 5 to 90 deg. The linear translational velocity of the center of the flat plate ranged from 4.5 to 11.1 m/s for various different tests. Of course, the results presented in force coefficient form were independent of velocity—a fact that is clearly demonstrated by the entries in Langley's tables. These square-plate results, obtained over the period from August to October of 1888, are represented by the curve labeled "12 × 12 inch plane" in Fig. 4. (This figure is essentially Fig. 10 in *Experiments in Aerodynamics*,[6] except that the present author has added some of Lilienthal's data points, to be discussed later.) From Langley's point of view, the main value of these measurements is that they dispelled the Newtonian sine-squared law. At the beginning, Langley explicitly states that he desires to "investigate the assumption made by Newton that the pressure on the plane varies as the square of the sine of its inclination." By this time in the late 19th century, such a matter appears to be an unnecessary obsession with Langley, because Cayley and others in Europe had already pointed out that the sine-squared variation did not hold. Rather, Langley simply added his own data to the existing evidence that the aerodynamic force varied linearly with angle of attack at low angles—a result clearly demonstrated by his 12 × 12 in. plate results plotted in Fig. 4. Indeed, at the end of this series of experiments, Langley comments about the results: "The principle deduction from them is that the sustaining pressure of the air on a 1 foot square, moving at a small angle of inclination to a horizontal path, is many times greater than would result from the formula implicitly given by Newton." Langley pointed out, for example, that at a 5-deg angle of attack, the experimental results gave a resultant force 20 times that predicted from the Newtonian sine-squared law. Although Langley was not the first to point out such a comparison, the results were especially important to him because the practicability of sustained, powered flight hinged in part on such a result.

Also shown in Fig. 4 are Langley's measurements for two other flat plates, each with different aspect ratios. All three curves, taken together, illustrate the strong effect of aspect ratio on the resultant aerodynamic force. In the angle-of-attack range below 20 deg (which is the range for practical flight), Langley's data show that the highest-aspect-ratio plate (30 × 4.8 in., aspect ratio of 6.25) gives the highest values of C_R and that the lowest-aspect-ratio plate (6 × 24 in., aspect ratio of 0.25) gives the lowest values of C_R. The data for the 1-ft^2 plate (aspect ratio of 1) lies between the other two extremes. The variation in Langley's data due to aspect ratio is qualitatively correct. Langley performed other experiments that even more clearly point out the superiority of high-aspect-ratio wings; we discuss these results under "Plane-Dropper Experiments."

Finally, in regard to Fig. 4, for the sake of comparison, this author has superimposed Lilienthal's whirling-arm data for a square flat plate; these data are given by the solid squares in Fig. 4. At low angles of attack, on the order of 5 deg or less, Lilienthal's measurements are in agreement with an extrapolation of Langley's measurements. This is important because practical cruising flight normally occurs at such low angles of attack. However, at higher angles of attack, there is some discrepancy between the two sets of data, with Lilienthal's data falling about 20–25% below those of Langley. This most likely is due to deficiencies in Lilienthal's particular whirling-arm setup—deficiencies that Lilienthal himself suspected and that drove him to an alternative setup measuring aerodynamic force on a stationary device in the natural wind.[5] Lilienthal's data for cambered airfoils obtained in the natural wind consistently gave higher force coefficients than those measured with his whirling arm—on the order of 20%—which is essentially the difference shown in Fig. 4. Lilienthal did not report any flat-plate data from his natural-wind experiments; had he done so, it is safe to expect that they would have been higher than those obtained from his whirling arm, and hence would have been in closer agreement with Langley's data than that shown in Fig. 4. In any event, the comparison shown in Fig. 4 illustrates the precarious nature of whirling-arm experiments, and is an example of the reasons for the eventual demise of this type of aerodynamic test facility.

Plane-Dropper Experiments

Another novel device designed by Langley was his plane-dropper apparatus. This was an iron frame mounted vertically at the end of his whirling arm, on which was mounted an aluminum falling piece that ran up and down on rollers. He attached his flat-plate lifting surfaces to this falling piece, where the lifting surface was oriented horizontally to the ground. With the lifting surface locked into its highest position, the whirling arm was started, and when the desired

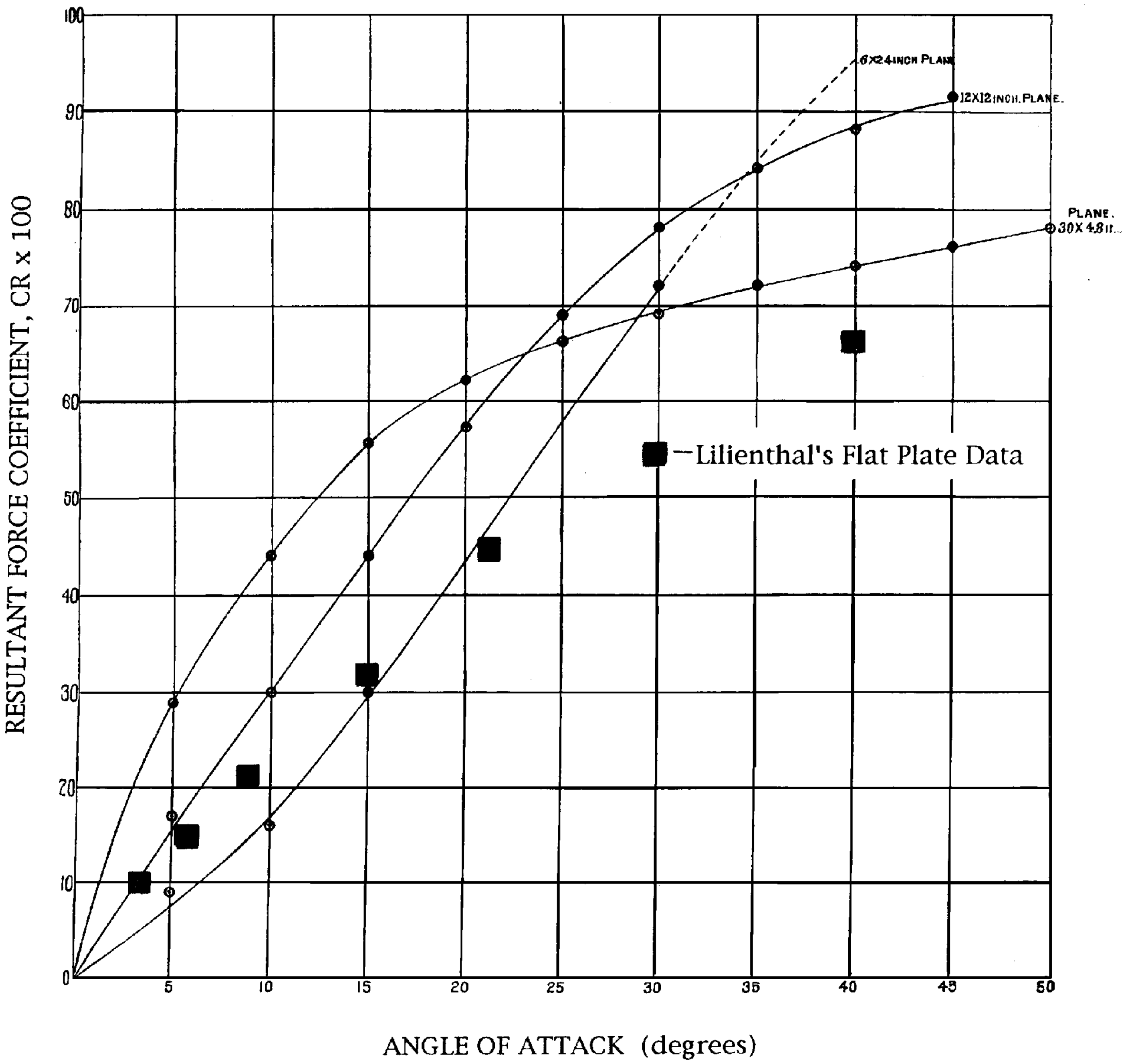

Fig. 4 Resultant force coefficient for a flat plate; comparison of Lilienthal's and Langley's data (original figure with addition, from *Experiments in Aerodynamics*[6]).

airspeed over the plate was reached, the plate was released. It would then proceed to fall a maximum distance of 4 ft (as allowed by the height of the iron frame). The time it took the plate to fall this distance was recorded by Langley. When lift was produced, it acted counter to the weight of the falling plate, and hence the plate took a longer time to fall the distance of 4 ft. The more lift, the longer the time. Hence, a measurement of the time required to fall the distance of 4 ft is an index of the lifting capacity of the plate.

The most substantive data from Langley's plane-dropper tests is that wings with high aspect ratio produced more lift than wings with low aspect ratio. This is clearly seen in Fig. 5, taken from *Experiments in Aerodynamics.*[6] Here, the time required to fall 4 ft is plotted vs the horizontal velocity for three plates of equal weight and surface area but different aspect ratio. Clearly, at any given velocity, the higher the aspect ratio, the longer the falling time. Although Langley was not the first to appreciate the aerodynamic efficiency of high-aspect-ratio wings (the Englishman Francis Wenham in 1866 was the first to point out this effect), he was the first to produce an organized set of definitive experimental data that clearly proved the superiority of such wings. Moreover, Langley later put these data to use in the design of his aerodromes. Note that the highest-aspect-ratio model shown in Fig. 5 is that consisting of two 18 × 4 in. planes; here, the aspect ratio of each plane is 4.5—a fairly high value for the state of the art at that time. Influenced by these results, Langley later designed his successful aerodrome no. 5 with a relatively high aspect ratio of 5.

Soaring Experiments (and the Component Pressure Recorder)

The final category of Langley's experiments in aerodynamics to be examined here is characterized by yet a different experimental technique and a different measuring instrument. The technique involved the "soaring" of his flat-plate models, and the measuring instrument was his specially designed component pressure recorder. This instrument was essentially a balance arm that was supported in the middle on a knife-edge bearing; however, in addition to being able to move up and down vertically about this knife edge, the arm also could oscillate horizontally about a vertical axis. A flat-plate lifting surface was mounted at one end of the balance arm, and the plate angle of attack was mechanically set to a specified angle. The whole apparatus was moved through the air at the end of Langley's whirling arm. The speed of the flat plate through the air was adjusted so that, for the given angle of attack, the lift generated by the plate exactly equaled the weight of the plate; in this situation, the plate was "soaring," to use Langley's term. Also, in this situation, the

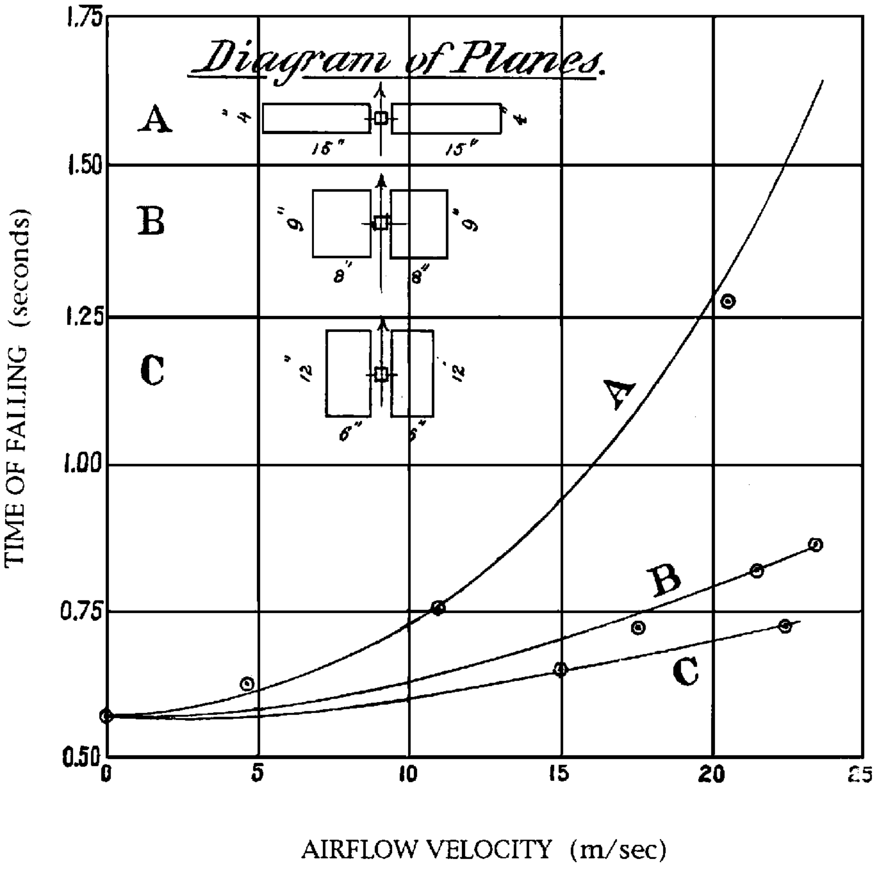

Fig. 5 Data from Langley's plane-dropper experiments (original figure from Ref. 6).

measuring arm of the component pressure recorder was balanced exactly in the horizontal position, i.e., the arm was level to the horizontal. However, the drag force on the plate tended to rotate the balance arm about the vertical axis of the recorder. The drag ("horizontal pressure" in Langley's terms) was measured by the extension of a spring that resisted the horizontal oscillation. The component pressure recorder was designed to record a measurement only when the lift of the plate balanced the weight; when this situation existed, an electrical contact was joined, and the horizontal force (drag) was recorded. In short, the component pressure recorder was an ingeniously designed device that measured the drag on the plate for the flight condition when the lift exactly equaled the weight. For the fixed angle of attack of the plate, this flight condition was obtained only for one particular translational velocity of the plate through the air. This velocity was found by simply varying the rotational speed of the whirling arm. By repeating a series of these tests, each for a different angle of attack α, the variation of both lift and drag coefficients with α could be plotted.

Langley found that his force measurements obtained with his soaring experiments agreed within 2% (at worst) with his data from the resultant pressure recorder experiments described earlier. Considering the state of experimental aerodynamics at the end of the 19th century, this is incredible! Here we have two sets of experiments obtained at different times with different apparatus using different techniques, and excellent agreement is obtained.

The consistency of Langley's measurements of C_R between these two totally different sets of experiments tends to lend validity to his results. It speaks highly of Langley as a master instrument designer, and as a consummate organizer of careful experiments. However, this consistency does not tell us about the validity of Langley's whirling-arm data in general, because both sets of data were obtained with the same whirling arm. Hence both sets were subject to the same experimental uncertainties characteristic of a whirling-arm device. It has been argued already that such uncertainties are responsible for the discrepancies between Langley's data and those of Lilienthal, as shown in Fig. 4.

Langley was well aware of the role of thrust for a flying machine, namely to overcome drag. Moreover, he knew that the power required to drive a flying machine through the air is equal to the product of drag times velocity. Thus, to make estimates of how large an engine is needed to power a flying machine, he needed reliable estimates for aerodynamic drag. For this reason, he placed particular attention on the actual measurements of drag from his soaring experiments. Specifically, Fig. 6 is a plot from Langley's *Experiments in Aerodynamics*[6] showing the measured variation of drag with angle of attack for the 30 × 4.8 in. flat plate at soaring speeds.

Langley was well aware of the difficulties in measuring the small values of drag that prevail at low angles of attack. In regard to the data shown in Fig. 6, he commented:

> The horizontal pressures on the inclined planes diminish with decreasing angles of elevation, and for angles of 5° and under are less than 100 grammes. Now, for a pressure less than 100 grammes, or even (except in very favorable circumstances) under 200 grammes, the various errors to which the observations are subject become large in comparison with the pressure that is being measured, and the resulting values exhibit wide ranges. In such cases, therefore, the measured pressures are regarded as trustworthy only when many times repeated.[6]

Here, Langley is explicitly expressing his concern about the accuracy of the drag measurements at low angle of attack, and properly so. His understanding of this matter is another example of his seemingly natural ability to carry out and interpret experimental observations. However, in one aspect of the graph shown in Fig. 6, Langley falters. He comments:

> On the 30 × 4.8 inch plane, weight 500 grammes, fifteen observations of horizontal pressure have been obtained at soaring speeds. These values have been plotted in (Fig. 6), and a smooth curve has been drawn to represent them as a whole. For angles below 10° the curve, however, instead of following the measured pressure, is directed to the origin, so that the

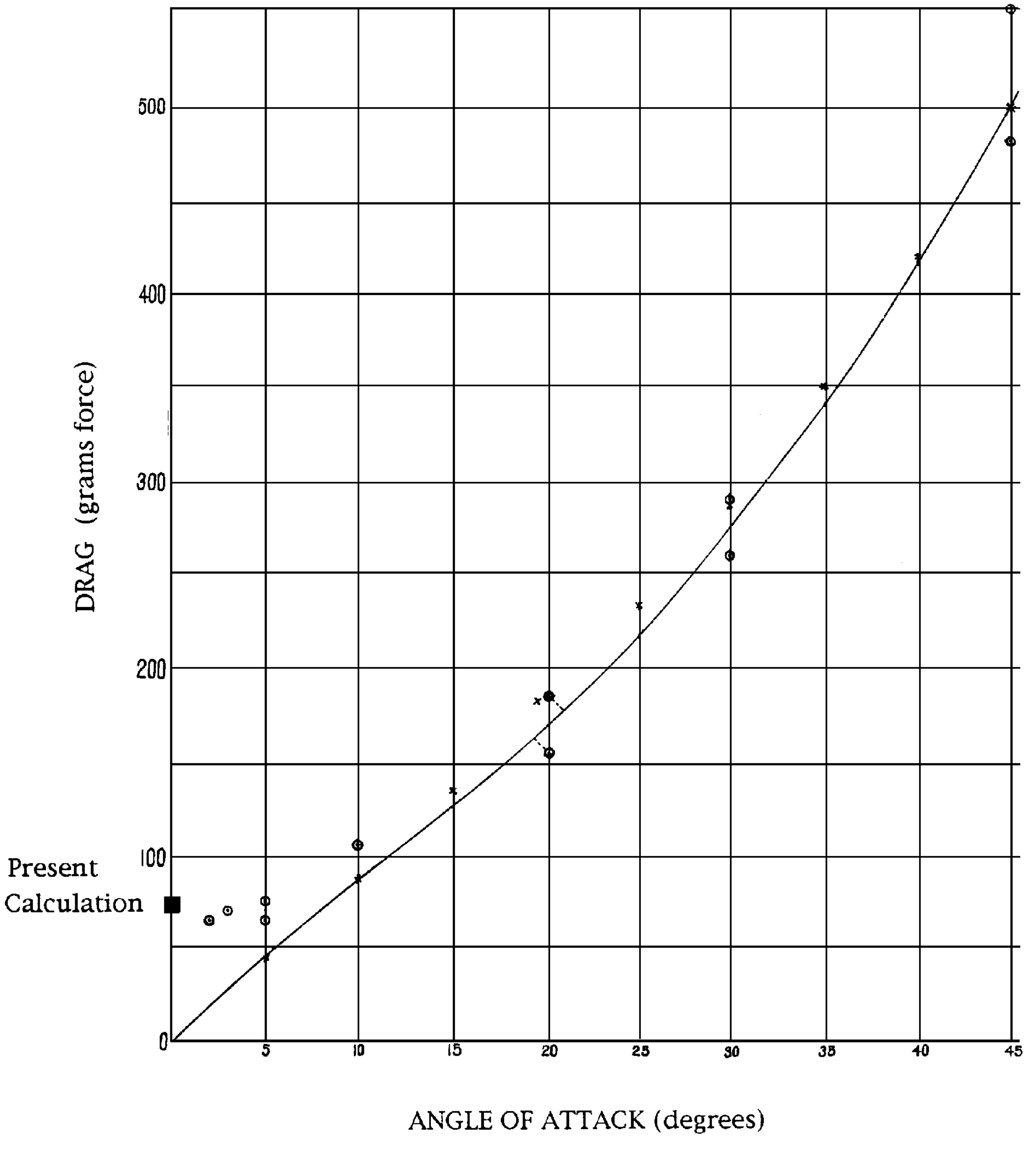

Fig. 6 Langley's data for the drag coefficient for a flat plate, and comparison with the present calculations (original figure, with addition, from Ref. 6).

> results will show a zero horizontal pressure for a zero angle of inclination. This, of course, must be the case for a plane of no thickness. . . .[6]

Here, Langley is committing a sin that is characteristic of many scientific investigators since the dawn of science, namely, the intentional fairing of a curve to exhibit what the investigator thinks is the right answer, even though the data show otherwise. In Fig. 6, for angles of attack less than 10 deg, Langley ignores his data and fares his curve to go through the origin even though the experimental data clearly are converging to a finite drag at zero angle of attack. In fact, incredibly, his measured data at low α is converging to the right value in spite of the experimental uncertainty discussed earlier. A modern calculation of the drag at zero α for Langley's conditions is given in Appendix A. This calculation predicts a total drag force of 76 g at zero angle of attack. This calculated result is shown as the shaded rectangle in Fig. 6. Note that Langley's experimental measurements are very nicely converging to the computed result. (Once again we remark on the apparent accuracy of Langley's measurements.) There are two physical phenomena that contribute to the finite drag at zero angle of attack: 1) the flat plate in the experiment had a finite thickness of $\frac{1}{8}$ in., and when at zero angle of attack, the blunt face of the front edge perpendicular to the flow is responsible for pressure drag; and 2) the viscous shear stress exerted over the top and bottom surfaces parallel to the flow is responsible for skin friction drag. To Langley's credit, he was well aware of the pressure drag. In fact, let us complete the last sentence of Langley's statement quoted earlier, in regard to the matter of zero drag at zero angle of attack.

> This, of course, must be the case for a plane of no thickness, and cannot be true for any planes of finite thickness with square edges, though it may be and is sensibly so with those whose edges are rounded to a so-called "fair" form.

Indeed, Langley goes on to state that his own calculation shows that the pressure drag due to plate thickness is responsible for most of the drag at low angle of attack, and when this calculated pressure drag is subtracted from his experimental data, good agreement then is obtained with the faired curve. Langley is partially correct in this assessment because the calculation in Appendix A for zero angle of attack estimates a pressure drag of 61 g-force and a friction drag of 15 g-force; clearly, the pressure drag in this case is a large percentage of the total drag. On the other hand, equally clearly the friction drag is not trivial and should not be ignored. It is in this respect that Langley is wrong. Throughout all of his aerodynamic work, Langley consistently and intentionally ignores friction drag. He blatantly makes the following statement near the beginning of *Experiments in Aerodynamics*[6]: "Most of the various experiments which I have executed involve measurements of the pressure of air on moving planes, and the quantitative pressures obtaining in all of the experiments are of such magnitude that the friction of the air is inappreciable in comparison." Once again, we should not blame Langley too much for this wrong impression. In 1891, no reliable theory existed for the accurate calculation of friction drag. On the other hand, Langley's outright neglect of friction simply reinforced the perception of others that friction played no practical role in the net aerodynamic force; this was a disservice to the next generation of aerodynamicists.

The "Langley Law"

Perhaps the most interesting, and the most controversial conclusion made by Langley on the basis of his experimental data is the Langley law, which simply states that the power required for a vehicle to fly through the air decreases as the velocity increases. Langley considered this to be one of his most important contributions. It is immediately stated in *Experiments in Aerodynamics*, right up front on page 1:

> These new experiments (and theory also when reviewed in their light) show that if in such aerial motion, there be given a plane of fixed size and weight, inclined at such an angle, and moved forward at such a speed, that it shall be sustained in horizontal flight, then the more rapid the motion is, the less will be the power required to support and advance it. This statement may, I am aware, present an appearance so paradoxical that the reader may ask himself if he has rightly understood it.

This conclusion is repeated no less than three other times in his book, twice in italics. For example, in summarizing his soaring experiments with the component pressure recorder, he states: "The most important conclusion may be said to be the confirmation of the statement that *to maintain such planes in horizontal flight at high speeds, less power is needed than for low ones*."

This conclusion flies in the face of intuition, which is why Langley labeled it as "paradoxical." It was considered to be misleading at best by some contemporaries and outright wrong by others. Crouch[3] states that Lilienthal and the Wright brothers rejected this conclusion outright. In a meeting of the British Association for the Advancement of Science at Oxford in August 1894, Langley presented a short paper summarizing his work and conclusions; he was criticized and taken to task by both Lord Kelvin and Lord Rayleigh—formidable opposition to say the least. Indeed, Langley has been derided for this power law to the present day.

However, Langley's conclusion was based on his experimental data, and these data consistently supported it. Moreover, in *Experiments in Aerodynamics*,[6] he gives a theoretical "proof" of this law. To make an assessment of the validity of Langley's conclusion, this author has made a calculation of the power required curve for Langley's flat plate in soaring flight. This calculation is described in Appendix B. *It clearly shows that all of Langley's experimental data were obtained on what today is called the back side of the power curve—the region where the power required for steady, level flight indeed decreases with an increase in velocity.* The calculated powered required curve is shown in Fig. 7; it pertains to a flat plate of aspect ratio 6.25, planform area of 1 ft^2, and a weight of 500 g-force. The shape of this curve is like that for all conventional flight vehicles. It has a local minimum point, for minimum power required. In Fig. 7, this local minimum occurs at a velocity equal to about 22 m/s. At velocities below and above this point, the power required increases. The higher velocity side of this curve, that part to the right of the minimum point, is dominated by parasite drag, which increases essentially as the square of the velocity. The lower velocity side, that part to the left of the minimum point, is dominated

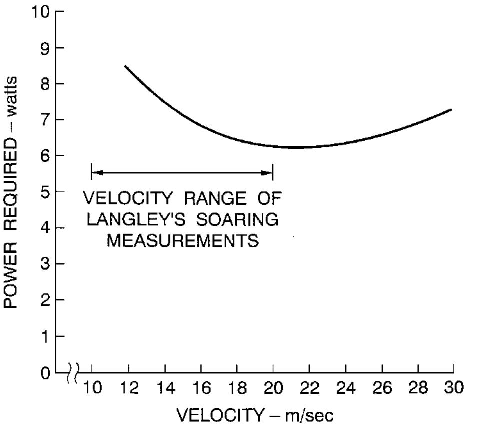

Fig. 7 Power required for Langley's flat plate.

by the "drag due to lift," i.e., the pressure drag that is associated with the pressure difference that creates the lift. The drag due to lift actually increases as the velocity decreases; one can associate this trend with the rapidly increasing angle of attack as the velocity decreases—the increase in α is necessary to sustain the lift equal to the weight as the velocity decreases. Examining all of Langley's data, we note that they were all taken at velocities of 20 m/s or less. This range of velocity is identified in Fig. 7. *Clearly, all of Langley's data were obtained on the back side of the power curve.* Hence, his conclusions that led to the Langley power law were correct for his range of test velocity. It is interesting to note that had his whirling arm allowed testing at velocities greater than 22 m/s, Langley would have noted a reversal in his data trend, and most likely the Langley power law would never have existed.

Parenthetically, we note that Langley offered "theoretical proof" of the Langley law in *Experiments in Aerodynamics*[6]—a short derivation covering only one-half page. The reader who examines this proof will see that his reasoning is sound, except that he uses for his drag expression $D = W \tan\alpha$, where W is the weight of the plate and α is its angle of attack. In this expression, Langley is ignoring friction, consistent with his earlier flawed argument that friction is negligible. From Appendix B, we note that the proper drag expression is

$$D = D_f + W \tan\alpha$$

where D_f is the friction drag and $W \tan\alpha$ is the drag due to lift (recalling that for soaring flight $W = L$). It is the presence of D_f in the above drag equation that results in the increase in power required at higher velocities. Ironically, Langley's neglect of friction drag limited his "theoretical proof" to the back side of the power curve. Of course, Langley did not realize this—given the state of the art of aerodynamics at that time, it is no surprise.

Conclusions

In retrospect, the major substantive contributions made to the state of the art by Langley's aerodynamic experiments can be summarized as follows:

1) He measured an accurate value of Smeaton's coefficient—within 3% of the modern accepted value.

2) He made extensive use of aerodynamic coefficients and legitimately shares with Lilienthal the credit for introducing the concept of lift, drag, and resultant force coefficients to the applied aerodynamics community.

3) His data are the first substantive proof of the aerodynamic superiority of high-aspect-ratio wings over those with low aspect ratio; it is curious that Langley is not widely recognized for this important contribution.

Langley's work was the first meaningful aerodynamic research in America, and because of his world-class prestige, he was responsible for shifting the epicenter of aerodynamic investigation slightly west of its late 19th century location in Europe.

On the other hand, in regard to the question as to what major practical contributions Langley's experiments made to the design of flying machines, we have to answer—very little. In *Experiments in Aerodynamics*,[6] all of his data pertain to flat plates, and other than the three contributions listed previously, these data were, for the most part, of academic interest only. Especially counterproductive was Langley's emphasis of the Langley power law. Although we have shown that the Langley law was an appropriate conclusion from his data, it pertains only to the back side of the power curve, which is avoided as much as possible in real flight. In any event, the Langley law was against intuition, and criticism of Langley on this account tended to diminish the credibility of the bulk of the rest of his findings in the eyes of many.

In the final analysis, however, we agree with Crouch,[3] who states about Langley's aerodynamic experiments: "Still, the work did serve a very useful purpose. The fact that a man of Langley's stature believed in the possibility of the flying machine was enough to convince most laymen that aeronautics was no longer the pastime of fools." Moreover, Langley was a master instrument designer, and a careful organizer of well-thought-out experiments. His data were all internally consistent from one type of experiment to another, and the accuracy of his results is good in light of external checks using modern aerodynamic knowledge. Although his unique measuring instruments were not used by anyone else, and although the whirling arm quickly disappeared as an aerodynamic testing device, Langley's experiments as related in *Experiments in Aerodynamics*, by the power of the intellect embodied in them, should serve as an inspiration even today for experimental aerodynamicists.

Appendix A: Calculation of Drag for Langley's Flat Plate at Zero Angle of Attack

Samuel Langley's data for flat-plate drag obtained from his soaring experiments is shown in Fig. 6. For low-speed incompressible flow, the laminar friction drag coefficient for a flat plate, including both the top and bottom surfaces of the plate, is

$$C_{D,f} = \frac{2.656}{\sqrt{Re}} \tag{A1}$$

where the Reynolds number is defined as

$$Re = \frac{\rho_\infty V_\infty c}{\mu_\infty} \tag{A2}$$

For the conditions of Langley's experimental data given in Fig. 6, the sea-level density and viscosity coefficient are $\rho_\infty = 1.23\ \mathrm{kg/m^3}$ and $\mu_\infty = 1.7894 \times 10^{-5}\ \mathrm{kg \cdot m^{-1}\ s^{-1}}$. The chord length of the plate was $c = 4.8\ \mathrm{in.} = 0.1219\ \mathrm{m}$. Hence, from Eqs. (A1) and (A2), we have

$$C_{D,f} = \frac{2.656}{[(1.23)(0.1219)V_\infty/(1.7894 \times 10^{-5})]^{\frac{1}{2}}} = \frac{0.029}{(V_\infty)^{\frac{1}{2}}} \tag{A3}$$

In Eq. (A3), V_∞ is in m/s. For the experimental data given in Fig. 6, Langley measured a soaring velocity at low angle of attack (i.e., at $\alpha = 2$ deg) of 20 m/s. For this velocity, the value of $c_{D,f}$ from Eq. (A3) is

$$C_{D,f} = \frac{0.029}{\sqrt{20}} = 0.00648 \tag{A4}$$

The drag force due to skin friction is given by

$$D_f = \tfrac{1}{2}\rho_\infty V_\infty^2 S C_{D,f} \tag{A5}$$

In Eq. (A5), S is the planform area of the plate, equal to $0.929\ \mathrm{m^2}$. Hence, from Eq. (A5),

$$D_f = 0.148\ \mathrm{N} = 15\ \text{g-force}$$

[We note that the Reynolds number for these conditions is 1.6758×10^5—certainly low enough to justify the assumption of laminar flow and hence the use of Eq. (A1).]

The frontal cross-sectional dimensions of the plate are $(30) \times (\frac{1}{8})$ in., giving an area of $2.4384 \times 10^{-3}\ \mathrm{m^2}$. Assuming a vertical flat-plate drag coefficient of 1.0, the combined pressure drag due to the front and back edges of the plate being perpendicular to the flow is

$$D_p = \tfrac{1}{2}\rho_\infty V_\infty^2 S C_D = \tfrac{1}{2}(1.23)(20)^2(2.4384 \times 10^{-3})(1)$$
$$= 0.6\ \mathrm{N} = 61\ \text{g-force}$$

Hence, the net predicted drag on the plate at zero angle of attack is

$$D = D_f + D_p = 15 + 61 = 76\ \text{g-force} \tag{A6}$$

This is the value shown as the shaded rectangle in Fig. 6.

Appendix B: Calculation of the Power-Required Curve for Langley's Flat-Plate Models

This appendix gives the calculations for the power-required curve plotted in Fig. 7.

The Reynolds number associated with Langley's 30×4.8 in. plates (chord length = 4.8 in.) for the velocity range from 10 to 20 m/s is 8.4×10^4 to 1.68×10^5—low enough to safely assume that Langley's data were obtained for laminar flow. For laminar flow, the flat-plate skin friction coefficient is given by Eq. (A3) from Appendix A, accounting for skin friction on both the top and bottom surfaces of the plate. However, at even small angles of attack, the flow over a flat plate readily separates from the top surface, creating a low-energy dead-air region over the top surface. Therefore, at angle of attack, only the bottom of the plate experiences an attached flow, and this is where the major influence of skin friction will be felt. Hence, for the present calculation, we use for the skin friction drag coefficient one-half the value given by Eq. (A3), i.e.,

$$C_{D,f} = \frac{0.0145}{\sqrt{V_\infty}} \tag{B1}$$

The pressure acts perpendicular to the plate surface. Ignoring the thickness of the plate, i.e., ignoring the pressure acting on the front and rear edges (which have a very small surface area compared to the planform area), at angle of attack the resultant pressure force is essentially perpendicular to the plate. Hence, the pressure drag is related to the lift via

$$D_p = L \tan\alpha \tag{B2}$$

or in coefficient form,

$$C_{D,p} = C_L \tan\alpha \tag{B3}$$

The total drag coefficient due to both the shear stress and pressure distributions exerted over the plate is given by the sum of Eqs. (B1) and (B3):

$$C_D = \frac{0.0145}{\sqrt{V_\infty}} + C_L \tan\alpha \tag{B4}$$

This is the drag polar for Langley's flat-plate model.

The procedure for calculating power required for steady, level flight, given the drag polar, is described elsewhere.[7] For the present calculation, it is as follows:

1) Specify V_∞.
2) Calculate C_L from

$$L = W = \tfrac{1}{2}\rho_\infty V_\infty^2 S C_L$$

or

$$C_L = \frac{2W}{\rho_\infty V_\infty^2 S} = \frac{2(0.5)9.8}{(1.23)(0.0929)V_\infty^2} = \frac{85.76}{V_\infty^2} \tag{B5}$$

In Eq. (B5), the mass of the plate is 0.5 kg, standard density is 1.23 kg/s, the planform area is $0.0929\ \mathrm{m^2}$, and 9.8 is the acceleration of gravity in meters per second squared necessary to convert the mass in kilograms to weight in newtons.

3) For the value of C_L calculated previously, obtain the corresponding angle of attack α as follows:

Using the standard correction to lift slope due to finite aspect ration from Prandtl's lifting line theory, we have[8]

$$\frac{\mathrm{d}C_L}{\mathrm{d}\alpha} \equiv a = \frac{a_0}{1 + (57.3a_0/\pi e \mathrm{AR})} \tag{B6}$$

Table B1. Calculation of power required

V_∞ m/s	C_L [Eq. (B5)]	α deg [Eq. (B7)]	C_D [Eq. (B4)]	P_R [a] [Eq. (B9)]
12	0.596	7.84	0.0863	8.5
14	0.4376	5.76	0.0480	7.5
16	0.335	4.41	0.0295	6.89
18	0.265	3.49	0.0194	6.45
20	0.2144	2.82	0.0138	6.29
22	0.177	2.33	0.0103	6.25
24	0.149	1.96	0.00806	6.35
26	0.127	1.67	0.0065	6.51
28	0.109	1.43	0.00546	6.83
30	0.095	1.25	0.00472	7.26

[a]The power required from this tabulation is plotted vs V_∞ in Fig. 7; this is the power-required curve for Langley's flat-plate model.

where a is the lift slope of the finite wing, a_0 is the infinite wing lift slope taken as 0.1 per degree, e is a span efficiency factor taken as 0.943, and AR is the aspect ratio, given as 6.25. Hence, from Eq. (B6) we have $a = 0.076$ per degree, and the angle of attack pertaining to the lift coefficient calculated in step 2 is

$$\alpha = \frac{C_L}{a} = \frac{C_L}{0.076} \text{ (in deg)} \tag{B7}$$

4) Calculate C_D from Eq. (B4).

5) Calculate power required from

$$P_R = DV_\infty = \tfrac{1}{2}\rho_\infty V_\infty^2 S C_D V_\infty \tag{B8}$$

For the values of ρ_∞ and S pertaining here, Eq. (B8) is written as

$$P_R = 0.057 V_\infty^3 C_D \tag{B9}$$

where P_R is in watts.

Some values from this calculation are given in Table B1.

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A. Plotkin
Associate Editor