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PIONEER WIND TUNNELS

(With 4 Plates)

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PIONEER WIND TUNNELS

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In a paper read before the Royal Society in 1759 John Smeaton presented the following very neat outline of the various methods that may be used for aerodynamic research:[1]

> In trying experiments on wind mill sails, the wind itself is too uncertain to answer the purpose; we must have recourse to an artificial wind. This may be done two ways; either by causing the air to move against the machine, or the machine to move against the air. To cause the air to move against the machine, in a sufficient volume, with steadiness and the requisite velocity, is not easily put in practice: To carry the machine forward in a right line against the air, would require a larger room than I could conveniently meet with. What I found most practicable, therefore, was to carry the axis, whereon the sails were to be fixed, progressively round in the circumference of a large circle.

Technical difficulties prevented Smeaton from using a wind tunnel and prompted him to adopt the whirling machine, invented in 1746 by Ellicott and Robins. This and other inferior methods of research were in use long after wind tunnels had been constructed and found satisfactory. Thus, Eiffel spent much time dropping plates from the tower bearing his name before adopting the wind-tunnel method; Langley and others used whirling machines, while many used natural wind, which Smeaton had already found to be unreliable.

F. H. WENHAM

The distinction of being the first to introduce the wind tunnel belongs to Francis Herbert Wenham, founder member of the Aeronautical Society of Great Britain, who read at its opening meeting his classical paper on "Aerial Locomotion". In 1871 this Society desired to undertake systematic aerodynamic experiments to obtain "data on which a true science of aëronautics can be founded". A subscription fund was established; an instrument designed by Wenham

[1] Smeaton, John, Experimental enquiry concerning the natural powers of wind and water, p. 38, London, 1794.

was approved by the experimental committee and was constructed by John Browning, an optician and member of the Society. It was set up at Messrs. Penn's Marine Engineering Works at Greenwich, where the world's first wind tunnel experiments took place.

The tunnel was a wooden trunk 18 inches square and 10 feet long. Through it was directed the blast from a fan, driven by a steam engine. The wind velocity was measured with a water gauge, various speeds up to 40 miles per hour being used. The wind was not steady, considerable fluctuations making the observations difficult. The direction of the wind was tested with a vane and said to be fairly straight, although there is no mention of a wind straightener of any kind.

The balance was exhibited and explained to the Society by Mr. Wenham. It consisted of a vertical steel spindle, supported on a hardened steel center. Through an eye at the upper end of the spindle passed a horizontal weighing beam, supported by a cross pin axle. The long end of the beam carried the testing planes which could be set at various angles of incidence while they were always kept at right angles across the current. The short end carried a sliding counterweight so as to balance the testing plane. The drag was measured by a spring steelyard connected to a lever from the vertical spindle, close to the base of the machine. The lift was read off by a vertical spring steelyard.

The balance with the testing planes was placed in front of the tunnel at a distance of 2 feet, a wooden shield covering the balance and leaving only the planes exposed to the wind. Lift and drag were measured simultaneously, two persons making the observations. Only plane surfaces were tested, the largest being 18 inches across, the same width as the tunnel. They were placed at various angles from 15° to 60°; tests on smaller angles were found to be very desirable but could not be achieved with the instrument at hand.

In spite of the crudeness of the tunnel and the shortness of the time allotted for experiments, the results were the most satisfactory of the kind obtained to that time. The experiments were very encouraging to aviation enthusiasts, as they proved that the lift at small angles exceeds the drag to a much greater extent than had previously been suspected. The desirability of a large aspect ratio and the location of the center of pressure near the leading edge were also demonstrated. The test data were published in tabular form in the Report of the Aeronautical Society. These tables were widely used and were also made the basis for actual construction, particularly by Thomas Moy for his " aerial steamer ", the first large power-driven airplane model to rise from the ground in tethered flight.[2]

Twenty-five years later Wenham expressed the wish that he might have an opportunity to build a large tunnel that would convey a current " at rates varying from a gentle breese, up to a tornado that could rip the clothes off your back, or blow you away like a feather, but no flying man should mind this effect." In 1900, at the age of 76, he actually rigged up a fan blower for experiments; it ran at 1,700 revolutions per minute and gave a current of 25 miles per hour. Apparently it was driven by hand, as he says:[3]

> I could not get beyond this as it absorbed all my strength to work it, still the current was definite and steady with proper arrangement to measure lift and drift [i. e., drag]. I attached various models in the blast, consisting of different forms of supporting surfaces. 25 miles an hour would be a sufficient speed to begin to fly with.

HORATIO PHILLIPS

Next to use a wind tunnel was another Englishman, Horatio Phillips. He produced his air current by means of a steam jet, hoping in that way to avoid the fluctuations of the wind which had marred Wenham's experiments.

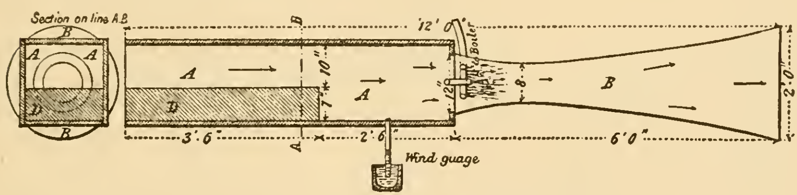

FIG. 1.—Phillips' wind tunnel, 1884.

Phillips' tunnel was 17 inches square and 6 feet long. Attached to one end was " an expanding delivery tube of sheet-iron ", which was 6 feet long, 12 inches wide where it entered the box, contracting to 8 inches, and again expanding to 2 feet. In its narrowest part was introduced a ring of iron pipe pierced with holes, through which steam was fed from a large boiler under 70 pounds pressure. This produced by suction an air current in the square part of the tunnel. In order to increase the speed of the current, the square box was partly closed by a

[2] Aeronautical Society of Great Britain, 6th Ann. Rep., pp. 75-78, 1871; 7th Ann. Rep., pp. 6-12, 1872; 9th Ann. Rep., pp. 6-7, 1874.

[3] Unpublished letters from F. H. Wenham to Octave Chanute, now in the Library of Congress.

solid packing of wood, leaving a space 10 by 17 inches in cross-section, where a speed up to 60 feet per second was obtained, as measured by a water gage.

The balance consisted of two uprights, pivoted at the base and connected by a horizontal wire at the top. This passed through eyes on two stiff wires attached to the leading edge of the testing surface. Drag was measured by weights in a scalepan, attached to the model mounting by a string running over a pulley, and lift was measured by a weight suspended under the testing surface at the supposed center of pressure. The balance was pushed into the tunnel where the current was swiftest, so that the scalepan was outside the tunnel, and the suspended weight in a hole in the wood packing.[4]

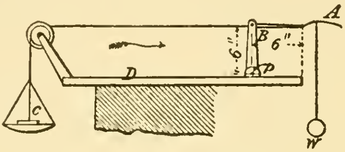

FIG. 2.—Phillips' balance.

While Wenham studied planes only, Phillips turned his attention to curved surfaces. His were the first systematic studies of cambered airfoils, a subject about which practically nothing was known before. Phillips noticed the partial vacuum above the airfoils. He patented a number of profiles, and introduced the downward curving leading edge, now in almost universal use. Several of the airfoils developed by Phillips had a maximum lift-to-drag ratio of about 10, an efficiency adequate for pioneer flying and not known to have been surpassed before the arrival of modern wind tunnels.[5]

The " Venetian blind " airplane built by Phillips, on the basis of data obtained in his wind tunnel, readily lifted itself in tethered flight, and was, with its cambered surfaces, a distinct improvement over its predecessors.

LUDWIG MACH

Dr. Ludwig Mach of Vienna in 1893 was the first to use a wind tunnel to photograph the flow of air. The tunnel had a cross section of 18 by 25 centimeters; one side was of glass and the others black on the inside. The air was sucked through by means of a centrifugal fan

[4] Engineering, vol. 40, pp. 160-161, illus., London, Aug. 14, 1885.
[5] British Patent, no. 13,768, 1884; and no. 13,311, 1891.

at the rate of 10 meters per second. A piece of wire mesh over the opening served to straighten the current. By the use of silk threads, cigarette smoke and glowing particles of iron, the flow could be observed. Streams of heated air were also introduced, invisible to the eye, but recording on a photographic plate. A series of good flow photographs was obtained.[6]

JOHAN IRMINGER AND H. C. VOGT

The first wind tunnel measurements of pressure distribution were made by Johan Irminger, and H. C. Vogt, of Copenhagen. Vogt, who was a marine engineer, had made extensive studies on sails and air propellers and had found that the partial vacuum on the leeward side was responsible for the greater part of the thrust. Phillips was first to notice a rarefaction, but did not press his investigation of this factor very far. Vogt, in conjunction with Irminger, director of the Copenhagen Gas Works, undertook a series of wind-tunnel experiments to establish this fact conclusively.

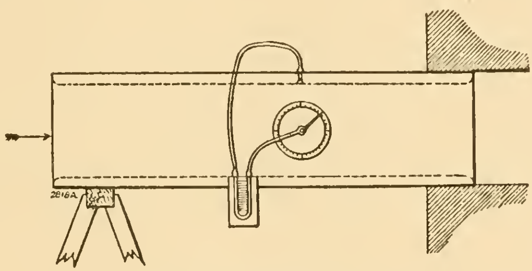

FIG. 3.—Irminger and Vogt's tunnel, 1894.

There was at the gas works a smokestack 100 feet high and 5 feet in diameter, serving a large number of gas furnaces. In order to utilize the draft in this chimney for experimental purposes, an opening was made in its side and a rectangular box inserted, 40 inches long and $4\frac{1}{2}$ by 9 inches inside cross-section. The inside of the box was polished and a shutter was used to control the speed of the air current, which ranged from 24 to 48 feet per second.

To determine the pressure distribution on plane surfaces, two pieces of sheet iron were placed 1/10 inch apart, joined along the edges to form a shallow closed box. To the interior of this a water gage was

[6] Zeitschr. Luftschiffahrt und Phys. Atmosphäre, vol. 15, pp. 129-139, pls. I-III, 1896.

connected by means of a pipe. A number of small holes were made in both surfaces, of which one at a time was opened. Two such testing planes were used; both were $1\frac{1}{2}$ inches wide, one $4\frac{1}{2}$ inches long, reaching entirely across the tunnel, the other $2\frac{1}{2}$ inches long. The testing

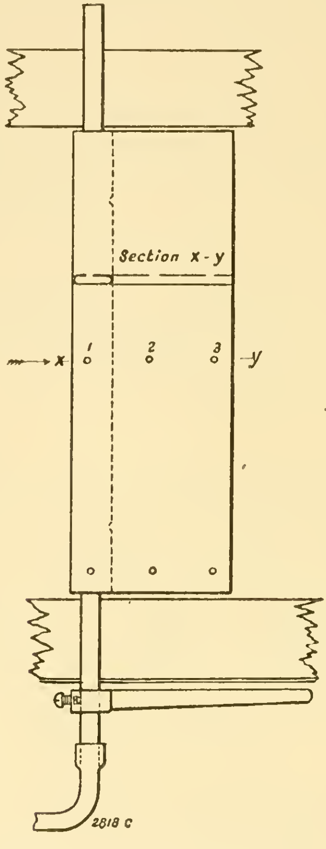

FIG. 4.—Pressure measuring apparatus used by Irminger and Vogt.

planes were placed in the middle of the tunnel and could be set at different angles that were indicated by a pointer on the outside.

Measurements of pressure distribution were also made on bodies of various shapes, as prisms, spheres, etc., and on models of buildings and gas tanks.[7]

[7] Ingeniören, p. 101, Copenhagen, 1894.
Inst. Civil Eng., Minutes of Proc., vol. 118, pp. 468-472, 1894.
Engineering, vol. 60, pp. 787-788, illus., London, Dec. 27, 1895.

CHARLES RENARD

Col. Charles Renard, constructor of the famous airship *La France*, conducted a large number of aeronautical experiments at the Établissement Militaire de Chalais Meudon, of which he was the director. Renard continued his experiments during a long period of years and employed a variety of methods and equipment. The details were secret at the time, and the information available is still meager.

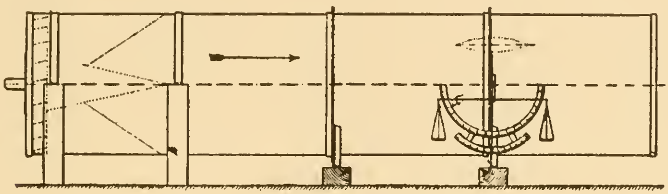

FIG. 5.—Renard's tunnel, 1896.

Some time during the latter half of the nineties a wind tunnel was used. It was cylindrical, 80 centimeters in diameter and 4 meters long. The wind was produced by a blower fan and said to be " violent ". Fourteen meters per second is given in a published chart. There is no mention of any means for straightening the wind.

In his tunnel Renard studied the stability and critical speed of airships.[8] Most of his equipment—balances, testing models, etc.—are preserved in the aeronautical museum at Chalais Meudon.

SIR HIRAM MAXIM

For the construction of his giant airplane, Sir Hiram Maxim realized the necessity for scientific data and utilized a number of testing devices. Among these was a wind tunnel which was in operation in 1896. Maxim's tunnel was a wooden box 12 feet long and 3 by 3 feet inside cross-section, connected with a shorter box 4 feet square. Two airscrews on the same shaft, placed in the wider section and driven by a 100-hp. steam engine, blew the air through the tunnel. To straighten the airstream a number of wooden slats were placed in the tunnel horizontally, vertically, and diagonally. The objects to be tested were

[8] C. R. Acad. Sci., vol. 138, p. 146, June 6, 1904.

Aerophile, vol. 12, pp. 153-155, July 1904.

IV congres internationale d'aeronautique, Nancy 1909. Proces-verbeaux, rapports et memoires, p. 241.

Aeronautique, vol. 6, p. 84, illus., Paris, April 1924.

placed in front of the tunnel and the balance measured both lift and drag.

Sir Hiram tested airfoils, struts, and airplane parts in his wind tunnel, and also the efficiency of steam condenser pipes.[9]

PAUL LaCOUR

Two wind tunnels were used by Paul LaCour, of Askov, Denmark, for windmill research. Both were made of sheet iron, cylindrical, 2.2 meters long; one was 1 meter in diameter and the other ½ meter. The wind was produced by electric blower fans and straightened by radial fins inside the tunnels. A speed of 10 meters per second was used, and this was kept constant by controlling the fan speed, which was read from a tachometer. The testing surfaces and windmill models were placed 1 meter out in front of the tunnel.[10]

ETIENNE MAREY

Etienne Marey, of Paris, famous for his chronophotographic studies of animal locomotion, in 1899 turned his attention to obtaining photographs of air in motion. This was achieved by the use of narrow bands of smoke in a small, vertical wind tunnel.

The tunnel was 20 by 30 centimeters in cross-section, with front and sides of plate glass and the back covered with black velvet. The air was drawn down through the tunnel by a small suction fan and straightened by passing through fine silk gauze of very even weave.

Smoke was supplied through a row of fine tubes at the top of the tunnel and descended in straight bands, clearly showing the flow past small models that were inserted. Photographs were taken by means of a magnesium flash, burnt in a ventilated box close to one side of the tunnel.

Among the scientists that were interested in these experiments was Samuel P. Langley. He provided funds from the Smithsonian Institution for their continuance, and the next year Marey built a new and improved tunnel. This was 20 by 50 centimeters in cross-section, and the smoke tubes, 60 in number, could be made to vibrate laterally 10 times a second.

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[9] The Aeronautical Annual, 1896, pp. 50-61, illus., Boston.

Maxim, Hiram, Artificial and natural flight, pp. 50-61, illus., New York and London, 1908.

[10] LaCour, Paul, Forsögsmöllen, pp. 14-15, Copenhagen, 1900.

Ingeniören, no. 10, Copenhagen, 1897.

The speed of the air at any point was indicated by the undulations of the smoke bands caused by these vibrations. Judging from some of the photographs where the measuring rod is seen, the speed was about 30 centimeters per second.

A number of very beautiful flow photographs were obtained by Dr. Marey.[11]

A. F. ZAHM

The first complete wind-tunnel laboratory, equipped for a wide range of aerodynamical experiments and with instruments capable of exact measurements, was devised by Dr. A. F. Zahm and erected on the grounds of the Catholic University of America in the winter of 1901.

This laboratory was made possible by Hugo Mattullath, inventor of a giant flying boat, Dr. Zahm having agreed to become, during his spare time, the consulting engineer of Mattullath's company.

The laboratory building was a one-story frame structure 30 by 80 feet and housed a wooden tunnel 6 feet square in cross-section and 40 feet long, with windows in the ceiling and walls. The wind was drawn through at a speed of 27 miles per hour by a 5-foot suction fan, driven by a 12 hp. electric motor. The intake end was covered with one or two screens of cheese cloth or wire mesh to straighten the wind. The air speed was held constant within a fraction of 1 percent by a boy with a tachometer and a rheostat, controlling the fan speed. For some researches movable liners were introduced in the main tunnel, making the current contract trumpetwise to gain speed, then run straight in a narrower stream, and finally discharge as an open jet in the after part of the main tunnel. The testing model was placed either between the parallel sides, where the wind speed was greatest, or in the center of the current where it entered the experimental chamber.

The wind tunnel was equipped with a variety of instruments invented by Dr. Zahm for showing the character of the air flow and its action on the models.

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[11] C. R. Acad. Sci., vol. 131, pp. 160-163, July 16, 1900; vol. 132, pp. 1291-1296, June 3, 1901.

Ann. Rep. Smithsonian Inst., 1901, pp. 14, 332, 337-340, pls., 1902.

Journ. phys. theroique et appliquée, 4th ser., vol. 1, pp. 129-135, illus., 1902.

Scientific American, n. s., vol. 86, pp. 75-76, illus., Feb. 1, 1902.

Nogues, P., Recherches expérimentales de Marey sur le mouvement dans l'air. France. Min. de l'air. Publ. sci. et techn., pp. 94-97, illus., 1933.

The air speed was measured with a pitot-static tube, connected with an extremely sensitive manometer.[12] This consisted of two thin metal cups, inverted over coal-oil and supported from opposite ends of a weighing beam. Two tubes, one from underneath each cup, were joined respectively to the inner and outer tubes of the speed nozzle. To test the accuracy of this instrument a " balloon anemometer " was devised. A toy balloon floating downstream intersected on its way two thin pencils of light focussed on the moving plate of a long camera constructed for that purpose. This was an adaptation of the ingenious chronograph previously invented by Dr. Zahm for his researches on the speed of bullets.[13]

The manometer was also used for the study of pressure distribution.

Several aerodynamic balances were developed, among them the wire suspension balance, now in general use, and the bell crank balance, now often called the N. P. L. balance. It was called the " universal pressure balance " in 1902, and consisted of a bell crank with horizontal axle mounted on knife edges above the tunnel, having a graduated horizontal arm with scalepan and sliding weights, and a vertical arm running down through a streamline wind shield to hold the models in the air stream.

The laboratory was built and equipped early in 1901 and a description was communicated to the American Association for the Advancement of Science June 30, 1932, and was privately printed (200 copies) in a small pamphlet which is now a great rarity.[14]

Mattullath died in December 1902, and the flying-boat project was abandoned, but the scientific work in the laboratory went on intermittently until 1908. Money grants for special researches were made by the Smithsonian Institution and the Carnegie Institution in 1904 and 1905. Results of the investigations were communicated to scientific journals and societies. The most important of these was Dr. Zahm's

[12] Exhibited before the Washington Philosophical Society, May 24, 1902; described in Phys. Rev., vol. 17, pp. 410-423, December 1903. In this paper, p. 417, the term " wind tunnel " is used for the first time.

[13] The resistance of the air determined at speeds below one thousand feet a second, with description of two new methods of measuring projectile velocities inside and outside the gun. Thesis, Johns Hopkins Univ., 46 pp., illus., 1898.

[14] New methods of experimentation in aerodynamics; outline of some experiments made by H. Mattullath and A. F. Zahm, at the Catholic University of America. Paper communicated to the meeting of the American Association for the Advancement of Science, at Pittsburgh, June 30, 1902. 12 pp., illus., signed A. F. Zahm, Washington, D. C., 1902.

epoch-making paper on "Atmospheric Friction",[15] read before the Philosophical Society of Washington, February 27, 1904.

This paper disclosed for the first time the fact that skin friction is responsible for the major part of the total drag. The tests were made in the wind tunnel on carefully constructed boards up to 16 feet long suspended on the wire balance.

Tests were also made on various spindle- and fish-shaped bodies, establishing the best form for airship hulls and giving, for the first time, the reason why the now universally accepted torpedo shape is preferable. The resistance of wires, struts, wings, and other airplane parts was also studied.

The tunnel was also used for instruction at the University, several students taking part in the experiments. Occasionally, special tests were made for other investigators; for instance, Octave Chanute sent a stuffed buzzard for lift and drag measurements, and Emile Berliner had a monoplane model tested.

WRIGHT BROTHERS

The Wright Brothers' gliding experiments at Kitty Hawk in 1901, although they seemed successful to other observers, were very disappointing to the Wrights themselves, as the new glider did not at all perform according to their calculations based on the aerodynamic tables of Lilienthal. On returning to Dayton in August, they decided to find out by laboratory methods what was wrong.

Their first testing machine consisted of a bicycle wheel mounted horizontally on a spar projecting from the front of a bicycle. The relative aerodynamic efficiency of various surfaces was found by mounting them on this wheel, balancing one against the other and riding the bicycle at a fairly constant speed.

Next they sent the blast from a fan through a square tube and mounted their surfaces as blades on a vane in the stream, balancing a curved surface against a plane surface.

By the middle of October 1901 a small wind tunnel was completed. It was 16 inches square inside and about 6 feet long, with a glass top. The wind was forced through by a blower fan, and passed through a

[15] Atmospheric friction with special reference to aeronautics, pp. 237-276, diagrs., 1904. From Bull. Philos. Soc. Washington, vol. 14, 1904.

Also printed in England: Atmospheric friction on even surfaces, with commentary note by the Rt. Hon. Lord Rayleigh, F. R. S. Reprinted from the Philos. Mag., July 1904, pp. 58-67, diagrs.

honeycomb wind-straightener. The air speed was estimated to be 40 feet per second.

The balance was based on the principle of using the normal pressure on a plane surface to measure the lift of an airfoil. The wing model and the normal plane were mounted on separate horizontal cross-stream bars so linked together that the wind lift on the model

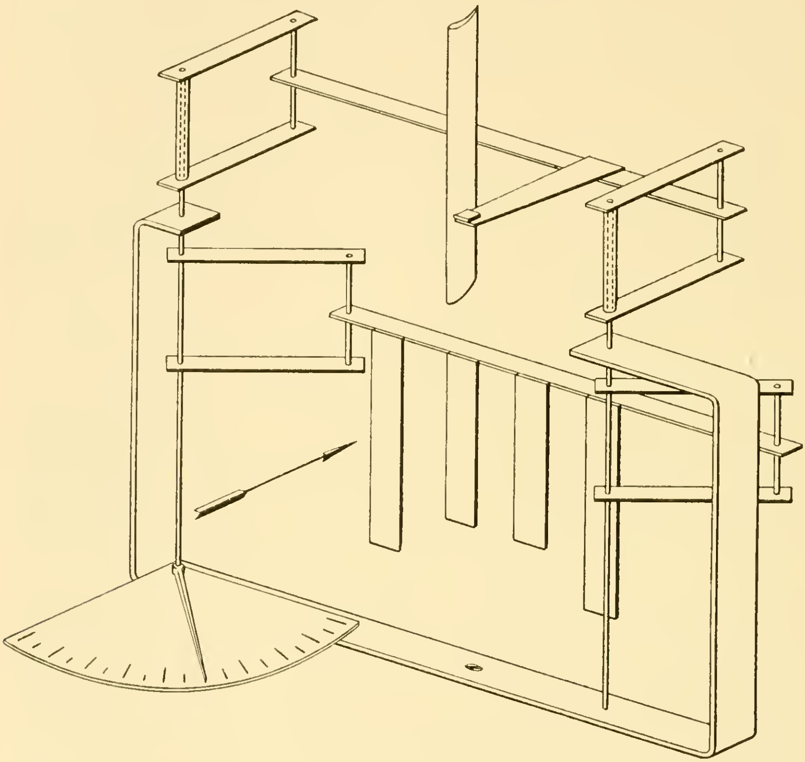

Fig. 6.—Schematic drawing of the Wright Brothers' balance, based on a photograph.

tended to move it across stream. The drag on the normal plane would tend to resist this movement. When the two were exactly balanced, the ratio of lift to the resistance of the normal plane was indicated by a pointer.

A balance of similar construction was later used by Orville Wright in his wind tunnel in Dayton.[16]

[16] Warner and Norton, Wind tunnel balances. U. S. Nat. Adv. Comm. Aeronautics, Rep. no. 72, pp. 39-40, 1920.

About 200 wing models made of sheet metal were tested in the wind tunnel. Each model was tested at 14 different angles of incidence, varying from 0° to 45°. Tests were also made to ascertain the effect of varying the aspect ratio, of superposing surfaces, etc. Great care was taken in making the tests; no one but the observer was allowed near the tunnel while it was in operation, and he kept the same position during the extent of the test, in order not to disturb the air current. The results were meticulously noted, and when completed they formed a valuable collection of aerodynamic tables which were later used by the Wrights as the basis for their design. Around Christmas 1902 these experiments came to an end, and the apparatus was taken down.[17]

This construction and the Wright Brothers' investigations therewith formed one of the chief factors leading to their success at Kitty Hawk on December 17, 1903.

T. E. STANTON

The first wind tunnel at the National Physical Laboratory in London was set up several years before aeronautics became a subject of research at that institution. This predecessor of the great modern N. P. L. tunnels was built in 1903 by Dr. Thomas E. Stanton, for investigation of wind pressure on surfaces and structures.

Stanton's tunnel was vertical, the upper part a cylinder 2 feet in diameter and 4½ feet long, terminating in a square box 4 by 4 feet, and 1 foot 3 inches deep where the balance was inserted. Underneath this, connected by a shorter length of pipe of the same diameter as the upper part of the tunnel, was the fan chamber. The fan, which produced the wind in the tunnel by suction, was driven by an electric motor and could be regulated to give air speeds from 5 to 30 feet per second.

The balance comprising a horizontal lever carried on knife edges, had a sliding scale, and a scalepan with a dashpot for damping the vibrations. It was inserted in the center part of the tunnel, so that the model projected into the cylindrical section. The long arm of the lever was hollow and could be connected with a sensitive manometer

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[17] Aeronautical Journ., vol. 20, pp. 73-74, July-Sept. 1916.

Unpublished letters of Wilbur Wright to Octave Chanute, now in the Library of Congress.

for measurement of pressure. The speed of the current in various parts of the tunnel was measured by a pitot-static tube connected to the manometer.

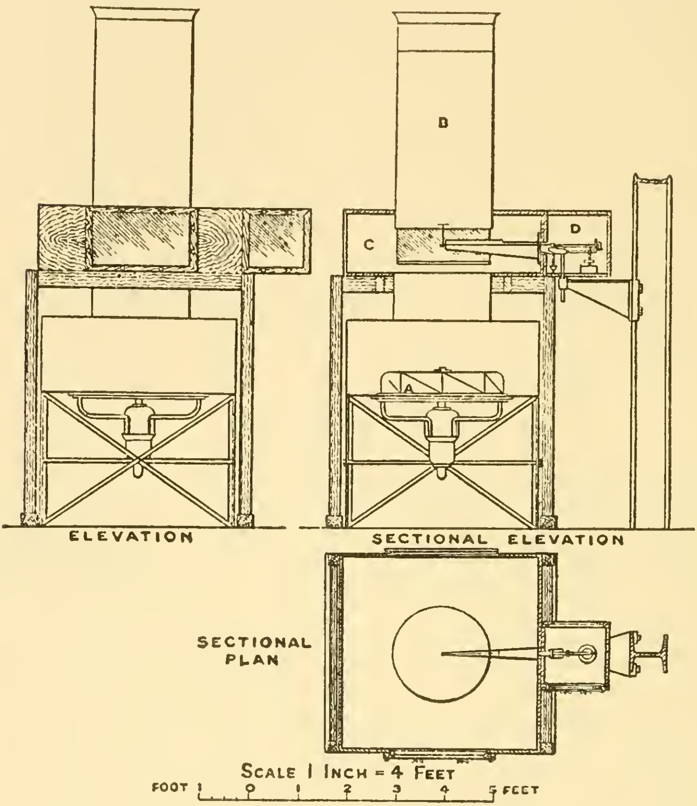

Fig. 7.—Stanton's tunnel, 1903.

Experiments were made in this very carefully constructed little tunnel to determine the resultant pressure and the distribution of pressure on round, square, and rectangular thin plates, normal and inclined to the current, on lattice work, cylinders, and finally on model roofs and bridges. The tunnel was still in use at the time when the 4-foot N. P. L. tunnel was constructed.[18]

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[18] Inst. Civil Engineers, Minutes of Proc., vol. 156, pp. 78-139, illus., 1904. Great Britain Adv. Comm. Aeronautics. Rep. 1909-10, p. 14.

G. A. CROCCO

In the fall of 1903 an aerodynamical laboratory was established near Rome by the "Brigata Specialisti" of the 3rd Italian Engineer Corps. The laboratory was built under the direction of Lieutenant, now General, Gaetano Arthuro Crocco. It was well equipped with research apparatus, including, as the most prominent part, a wind tunnel of novel construction.

By means of a 2.5-meter centrifugal fan and a 30-hp. electric motor, air was driven into a large cylindrical chamber like a gasometer, 5 meters in diameter and 3.5 meters high, which served to overcome turbulence and fluctuations. From here the wind was conveyed through a tunnel, the end of which was inserted in the laboratory wall, fan and air tank being outside. The cross-section of the mouth of the tunnel was 1 by 1 meter square; also a cross-section of 80 by 80 centimeters was used, and cylindrical mouthpieces of smaller diameter.

The tests were made in the open jet, balance and models being mounted on a support on the floor, on a light carriage, or sometimes on floats swimming in water. The principal balance, constructed by Crocco in 1904, was an improvement on the dynamometric balance of Renard.

For some researches the part of the laboratory where the air entered, was closed off to form a second air-straightening chamber, and the wind continued through a tunnel within the laboratory building. This tunnel was 8 meters long and 0.85 by 1.50 meters in cross-section.[19]

The investigations at the laboratory of the Brigata Specialisti were chiefly concerning air propellers and the resistance and stability of airships. The construction of the first Italian military airship in 1907 was based on these tests.

Results of the investigations were also presented in several important papers by Crocco, published in various places, and reprinted in his "Problemi aeronautici, degli albori fino alla guerra." 524 p., illus., 27 pls. (Roma, A. Stock, 1931).

D. RIABOUCHINSKY

Through the efforts of D. Riabouchinsky, a wealthy patron of science and himself a scientist, Russia took its place in the front rank with regard to pioneer aerodynamic research.

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[19] Boll. Soc. aeronautica ital., vol. 2, p. 209, illus,, Nov.-Dec. 1905.
Marchis. Le Navire aerien. Appendix, pp. 122a-127a, illus. Paris, 1909.

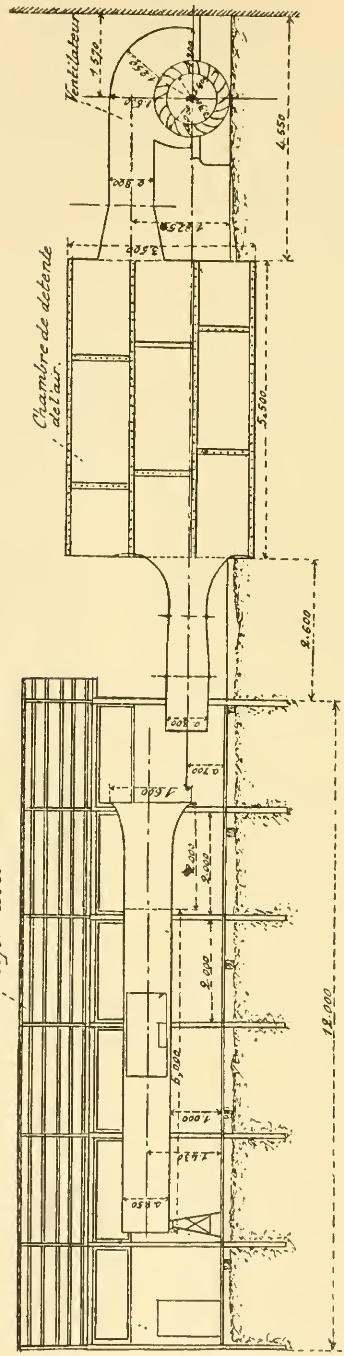

FIG. 8.—Crocco's tunnel, 1903.

At Koutchino, not far from Moscow, Riabouchinsky erected, at his own expense, a complete aerodynamic laboratory with several buildings and an adequate staff. According to a suggestion by Prof. N. E. Joukovsky, the laboratory was equipped with a cylindrical wind tunnel, 14.50 meters long and 1.20 meters in diameter. Wind was produced by a suction fan, driven by an electric motor. Great pains were taken to render the wind uniform. After several experiments that did not give satisfactory results one end of the tunnel was enclosed in a cylindrical hood 2.2 meters in diameter and 3.5 meters long, coaxial with the tunnel itself. This admitted the air in such a way that a sufficiently even current was obtained. The testing section, in the middle of the tunnel, was provided with windows, from which the action of models could be observed.

A great variety of aeronautical and hydrodynamical subjects were studied. Among the researches in the wind tunnel, the experiments with propellers, particularly lifting propellers were important. A bulletin was published by the laboratory in six large issues, the last in 1920.[20]

LUDWIG PRANDTL

With the construction of the first wind tunnel at Göttingen we are approaching modern times. This was the first return-flow tunnel, built by Dr. Ludwig Prandtl for Motorluftschiffstudiengesellschaft and completed in July 1908.[21]

This tunnel was superseded in 1916-17 by a much larger tunnel with open jet and return flow, which is now called the Göttingen type.

A. RATEAU

With the aid of the Société d'Études de Locomotion Aérienne, A. Rateau built a wind tunnel in Paris in 1909. A 4-foot propeller blew the air into a rectangular chamber, 1.60 meters in cross-section, with an outlet contracting to a nozzle 70 centimeters square. The current was straightened by passing between a number of wooden

[20] Institut aérodynamique de Koutchino. 8 pp., 17 pls., St. Petersbourg, 1905.
Institute aérodynamique de Koutchino, 1904-1914. Moscow, 1914.
Bulletin de l'Institut aérodynamique de Koutchino. Fasc. 1-6. Moscow, 1909-1920.

[21] Motorluftschiffstudiengesellschaft m. b. h. Berlin, Jahrbuch 1907/08-1912/13.
Zeitschr. Ver. deutsch. Ingenieure, vol. 53, pp. 1711-1719, Oct. 16, 1909.

slats, and the nozzle made possible speeds of up to 35 meters per second.[22]

GUSTAVE EIFFEL

Gustave Eiffel built his first wind tunnel on the Champ de Mars in 1909. It was the open-jet nonreturn tunnel with an airtight testing chamber, known as the Eiffel type. The air current was cylindrical, 1.5 meters in diameter, later enlarged to 2 meters.[23]

In 1911 Eiffel moved to Auteuil and built a new and larger laboratory, which he later turned over to the French Government.

NATIONAL PHYSICAL LABORATORY

The N. P. L. built its first large wind tunnel in London in 1910. It was 4 by 4 feet in cross-section and was supported inside another tunnel 8 by 8 feet. The space between the walls of the two tunnels was a return passage for the air, which was drawn through the 4-foot tunnel by a Sirocco fan, driven by a 15 hp. engine.[24]

This tunnel was not very satisfactory and was replaced in 1912 with a closed-jet nonreturn flow tunnel.

The tunnels of Prandtl, Eiffel, and the N. P. L. have been very briefly described, as their main features are generally known, and full descriptions are readily available.[25] They end the pioneer period and begin a new era in wind-tunnel history. Before these three laboratories were established, powered flight had become a proved fact, and airships had met with considerable success. The necessity for reliable laboratory research soon became universally recognized and wind-tunnel laboratories were built and maintained by governments and institutions, as well as by private agencies.

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[22] Aérophile, vol. 27, pp. 266-268, illus., June 15, 1909.

Soc. ingenieurs civils France, Mém. et C. R. Traveaux, vol. 65, pp. 61-78, illus., July 1912.

[23] Eiffel, Gustave, Installation d'un laboratoire d'aérodynamique. Paris, 1910. La résistance de l'air et l'aviation, experiences effectuées au Laboratoire du Champ de Mars. Paris, 1910. The resistance of the air and aviation, experiments conducted at the Champ de Mars Laboratory. Translated by Jerome C. Hunsaker. London and Boston, 1913.

[24] Great Britain Advisory Committee for Aeronautics, Rep. 1909-10, pp. 14-15, 2 folded plates.

Flight, vol. 2, pp. 226-227, March 26, 1910.

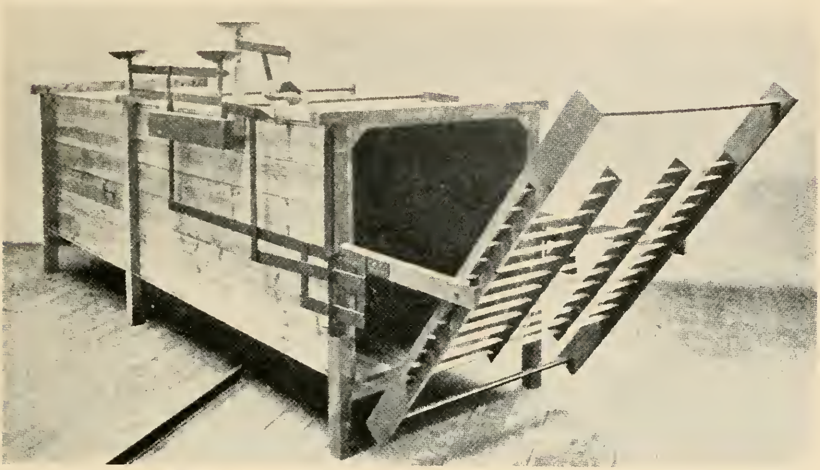
[25] Zahm, A. F., Report on European aeronautical laboratories, Smithsonian Misc. Coll., vol. 62, no. 3, 23 pp., 11 pls., 5 figs., 1914.

Specifications of Pioneer Wind Tunnels

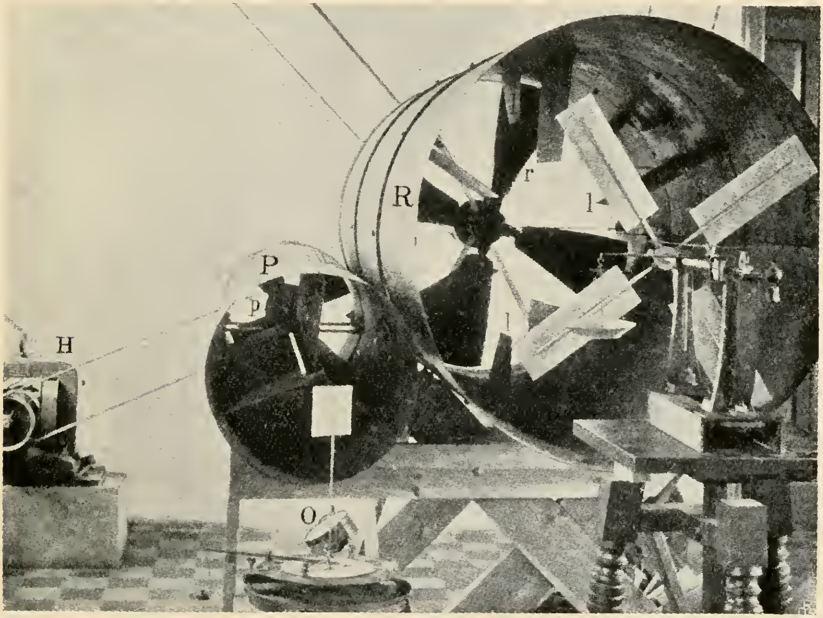
Date	Name	Cross-section	Air speed	Impeller and engine	Subject of research
1871	Wenham	18 x 18 in. 0.26 x 0.26 m	40 miles per hr. 18 m per sec.	Blower fan Steam engine	Lift and drag of plane surfaces
1884	Phillips	10 x 17 in. 0.25 x 0.43 m	41 miles per hr. 18 m per sec.	Steam jet 70 lbs. pressure	Forces on airfoils
1893	Mach	7 x $9\frac{3}{4}$ in. 0.18 x 0.25 m	22 miles per hr. 10 m per sec.	Suction fan Gas engine	Flow visualization
1894	Irminger and Vogt	$4\frac{1}{2}$ x 9 in. 0.115 x 0.23 m	34 miles per hr. 15 m per sec.	Chimney draft	Pressure distribution
1896	Renard	Diam. 31 in. Diam. 0.80 m	31 miles per hr. 14 m per sec.	Blower fan	Stability and critical speed of airships
1896	Maxim	3 x 3 ft. 0.91 x 0.91 m	49 miles per hr. 22 m per sec.	Blower fan Steam engine 100 hp.	Airplane parts and condensers
1897	LaCour (2 tunnels)	$19\frac{1}{2}$ & 39 in. diam. 0.5 & 1 m diam.	22 miles per hr 10 m per sec.	Blower fan Electric motor 2 hp.	Windmills
1899	Marey	8 x 12 in. 0.20 x 0.30 m	$\frac{2}{3}$ miles per hr.	Suction fan	Flow visualization
1900	Marey	8 x $19\frac{1}{2}$ in. 0.20 x 0.50 m	0.30 m per sec.	Electric motor	

Specifications of Pioneer Wind Tunnels

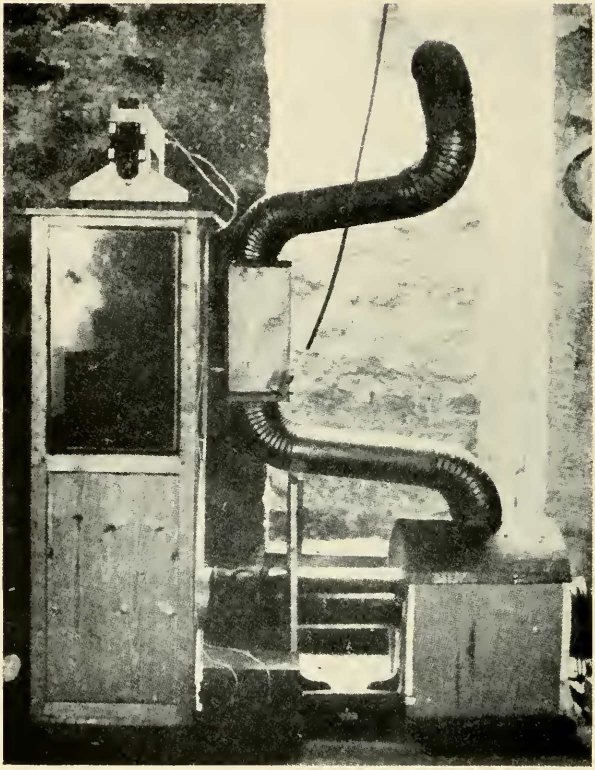
Date	Name	Cross-section	Air speed	Impeller and engine	Subject of research
1901	Zahm	6 x 6 ft. 1.83 x 1.83 m	25 miles per hr. 11 m per sec.	Suction fan Electric motor 12 hp.	Skin friction, air force on wings, struts, hulls, etc.
1901	Wright	16 x 16 in. 0.40 x 0.40 m	27 miles per hr. 12 m per sec.	Blower fan Gasoline engine 2 hp.	Lift and drag. Effect of aspect ratio, etc.
1903	Stanton	24 in. diam. 0.61 m diam.	20 miles per hr. 9 m per sec.	Suction fan Electric motor	Wind pressure on structures
1903	Crocco	39 in. 1 x 1 m	65 miles per hr. 29 m per sec.	Centrifugal blower fan Electric motor	Airship models. Propellers, etc.
1905	Riabouchinsky	4 feet diam. 1.2 m diam.	$14\frac{1}{2}$ miles per hr. 6.50 m per sec.	Suction fan Electric motor	Airscrews and general aerodynamic research
1908	Prandtl	$6\frac{1}{2}$ x $6\frac{1}{2}$ ft. 2 x 2 m	22 miles per hr. 10 m per sec.	Suction fan Electric motor 34 hp.	Airship models and general aerodynamic research
1909	Rateau	$27\frac{1}{2}$ x $27\frac{1}{2}$ in. 0.70 x 0.70 m	78 miles per hr. 35 m per sec.	Blower fan Electric motor 25 hp.	Airfoils. Propellers
1909	Eiffel	5 x 5 ft. 1.5 x 1.5 m	44 miles per hr. 20 m per sec.	Suction fan Electric motor 68 hp.	Airfoils and general aerodynamic research
1909	N. P. L.	4 x 4 ft. 1.2 x 1.2 m	30 miles per hr. 13 m per sec.	Centrifugal suction fan Electric motor 15 hp.	General aerodynamic research



1. MAXIM'S TUNNEL, 1896

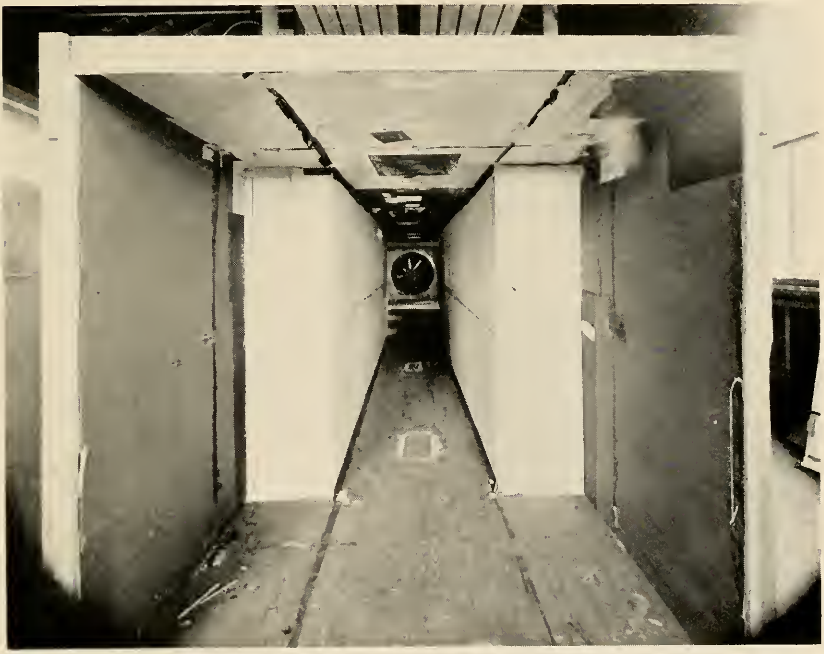


2. LA COUR'S TWO TUNNELS, 1897

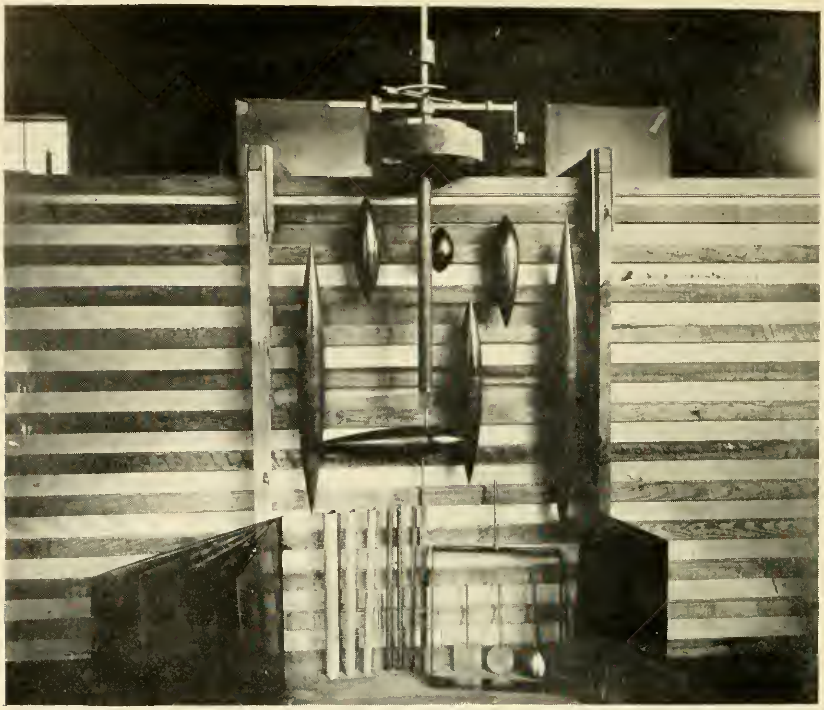


MAREY'S TUNNEL, 1900

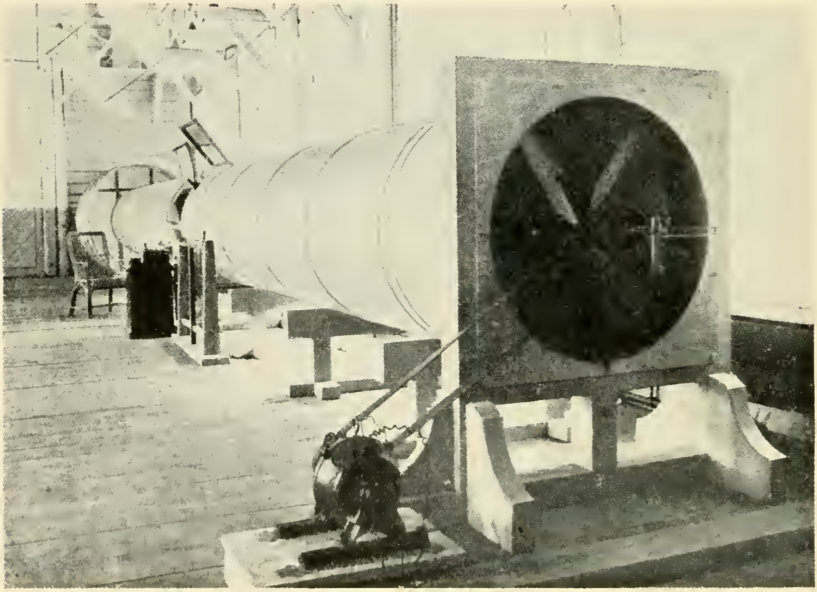
1. A. F. ZAHM'S AERODYNAMIC LABORATORY, 1901



2. ZAHM'S TUNNEL WITH INTAKE CONE REMOVED



BALANCE AND GROUP OF TEST MODELS USED IN ZAHM'S TUNNEL



RIABOUCHINSKY'S TUNNEL, 1905