TECHNICAL NOTES.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

No. 66.

GÖTTINGEN WIND TUNNEL FOR TESTING AIRCRAFT MODELS.

By

L. Prandtl.

Taken from
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Lecture by L. Prandtl.

Gentlemen, my intention is simply to give you a brief description of the Göttingen wind tunnel. I shall first say a few words as to how such a plant came to be installed in Göttingen.

The beginning dates back to the "Motorluftschiff Studiengesellschaft" (Society for Airship Study), which was founded in 1906. On the recommendation of the Göttingen Professor of Mathematics and Physics, Felix Klein, and E. Althoff, who was the real founder of the "Motorluftschiff Studiengesellschaft," I was made a member of the Technical Committee, whereupon I called attention to the need of experimenting on models, as had long been done in connection with ship building. The idea found favor and the Motorluftschiff Studiengesellschaft appropriated, at my suggestion, the sum of 20,000 marks, with which the first small plant was begun in Göttingen in the late autumn of 1907. In 1908 it was completed and equipped. The equipment was then gradually tried out and in 1909 we were engaged in practical work. During the war we performed a large share of the experiments reported

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A more detailed description will appear later in the form of a book containing the results of the experimental work of the plant.

in the "Technische Berichte der Flugzeugmeisterei" (Technical Bulletin of the Air Service Administration). From the beginning it was of a temporary nature and could not be expected to be permanently satisfactory. It was doubtless better not to build immediately on a large scale, but to wait till the requirements had been carefully worked out. The small plant, however, considering that it was the experimental basis for an ultimate larger and more complete plant, did very satisfactory practical work.

The endeavors to obtain a second building go quite far back. I wrote the first presentation of facts in February, 1911. In 1912 we won the interest of the Emperor William Society for the Promotion of the Sciences. It was again Felix Klein who encouraged me, and it was our former chairman and present honorary member, Mr. Böttinger, who followed up the difficult negotiations with the Emperor William Society so energetically that in 1914 the project was on the point of realization.

Then came the war and our plans were brought to a standstill. We figured indeed on a short war, and no one thought at first of undertaking scientific work with increased energy. But at the beginning of 1915, when we saw that the war was going to last longer, we undertook to attain our goal by a different road, and this time with the support of the military authorities. The Emperor William Society, on the basis of a petition from me, backed by our honorary president, Prince Henry, secured from the war administration an appropriation of 200,000 marks which was afterwards increased to 300,000. Thus the way was opened for us to carry out our plans, and indeed, on a considerably larger scale than the project of 1912.

Naturally there were many obstacles to be overcome even in 1915, and still more during the actual building period. These delayed its completion, after the foundation was begun in the autumn of 1915, till the spring of 1917. Since then the plant has been in constant operation, with a permanent increase in personnel, to meet the needs of the war administration and the airplane factories. The scientific work was not neglected, however. Concerning that I had the privilege of addressing you in a theoretical lecture last year in Hamburg.

The plant finally reached a personnel of 50, including engineers, officials and workmen, though it has now been reduced to a third of that number. It is evident that such high pressure (We were then working in two daily shifts) could no longer be justified after the war, as there was no longer any necessity for it. For a long time we were anxious lest the plant would have to be closed altogether for lack of means, since it had not been running long enough during the war to earn any considerable amount of money. It received frequent generous contributions from the war administration for all uncovered expenses. We are hoping that the plant, which has thus been compelled to live from hand to mouth during the last few years, will now be set firmly on its feet. On December 3, 1919, a society was founded, with a membership fee of 1000 or more marks, which is expected to support the plant for five years. I exhort those in this assembly, who are in a position to do so, to support the plant by joining this society. The expectation is that about half of the running expenses will be paid by the government, while the remaining half will be furnished by the Emperor William Society, by the Göttingen Society for the Promotion of Applied Mathematics and Physics, and by this new supporting society. On this basis, we hope to continue the work during the next few years at least as efficiently as during the past year.

Fig. 1 shows the old 9 x 11 m. plant. In the sectional plan is shown the cylindrical tunnel in which a rotary fan V generates an air current as indicated by the arrows. Various devices serve to keep the air current as free from disturbances as possible. An airship model is shown in the experiment room (M).

In the sectional elevation of the building there is again shown the experiment room with the model, while half of the left side shows the fan and the other half the so-called honeycomb (G_1), a system of parallel cells designed to eliminate diagonal currents.

The old plant was taken down in 1918. The new plant is a substantial building with a hall of reinforced concrete, containing the apparatus, while the front part of the building contains the office, work-room and watchman's room. The restored and improved old building is added to the rear end.

In Fig. 2 is shown a plan and a sectional elevation through the laboratory and tunnel. The laboratory is traversed by a 4-ton hand travelling crane. The wind tunnel makes a complete circuit. Its cross-section varies however and it is interrupted in the testing room. The open testing room was copied from the Eiffel laboratory. We recognize the Eiffel entrance cone and collector, but in contrast with the Eiffel tunnel (which begins at the entrance cone and terminates behind the blower, because there must be an airtight room for the experimenter on account of the partial vacuum at the testing point), we have enclosed the return current and are therefore able to make the testing room perfectly accessible. We can enter the testing room with the crane and we can run the testing apparatus (which is provided with wheels) in on tracks. The location of the tracks is shown in the plan. In order to obtain more room for the apparatus, two bays were built, one on either side of the main hall. If, after an aerofoil experiment, a propeller test is to be made, the latter can be prepared in one of the bays and then run in when everything is ready. This is one great advantage of this plant. Another advantage consists in the smoothness and uniformity of the air current resulting from the series of curved streamlined deflectors in each corner.

Still another advantage lies in the fact that the width of the cross-section behind the blast gradually increases and is then greatly reduced shortly before the measuring place. Thus we have a cross-section of 20 sq.m. back of the entrance cone and of only 4 sq.m. at the testing point. This increases the speed fivefold and the momentum twenty-fivefold, from which it follows that the irregularities ensuing from the inflow only relate to values of 1/25 of the momentum previously obtaining. Thus, without special adjustment, uniformity is assured in the experimental cross-section to within 4% of the momentum, and 2% of the speed. Since the uniformity in the inflowing current is fairly good to start with, it is very satisfactory in the experimental section. In contrast with the former plant, where we could obtain uniformity only through tedious adjustments which, in the course of time often had to be repeated, we here obtained a satisfactorily uniform current at the very outset.

A great saving of power is effected by the arrangement in the new plant. In the old tunnel, with its uniform cross-section, there was a great loss of energy in eliminating the eddies. We have therefore put the straightening device, a honeycomb with cells of only about an inch diameter, in the position of least velocity, thereby causing only a small loss of energy. The energy emerging from the entrance cone, aside from the losses in the open stretch, is utilized in the further circulation, since the whole stream is again collected. In this way the kinetic energy of the air stream in the experimental section is nearly 1 1/2 times the energy of the blast at the driving shaft of the blower. This is made possible by the fact that the kinetic energy is partially recovered in the collector. Hence only about 2/3 of the air energy needs to be furnished at the blower shaft.

In Göttingen we have an alternating current which renders the regulation of the r.p.m. difficult. Consequently, we have installed a motor-generator set (consisting of an induction motor which drives a dynamo) by which the blower motor is driven. The power plant also includes a smaller dynamo for driving the propeller-testing device and an exciting dynamo.

Both dynamos are so-called Ward-Leonard dynamos which can be run at different voltages, so that the blower may be driven at any desired speed from 50 to 1100 r.p.m. In this connection, there is a regulation system, consisting of a coarse and a fine regulator, which influences the field excitation of the dynamos. The fine regulator is operated automatically by a pressure balance or regulator.

Fig. 3 is a diagram of the pressure regulator. It is quite complicated, and I will not try to explain all its details here. The essential points are as follows: The excess pressure in the entrance cone, where the contraction from 20 sq.m. to 4 sq.m. takes place, is communicated by a pipe to the inside of a movable cylinder inverted in a stationary cylinder containing some sealing liquid. The diagram shows how the pressure makes the level of the liquid lower inside than outside the movable cylinder, thereby exerting an upward force corresponding to this difference in level, against the horizontal balance arm H. The equilibrium of the balance is restored by placing weights on the pan at the bottom, these weights being of such values as to give air speeds of 10, 15, etc., up to 50 m. per sec. In the new plant this device is perfectly automatic, while in the old plant a coarse hand adjustment was necessary. In fact, it is only necessary to press a button to set the whole machinery in motion, which automatically adjusts itself to the speed at which the balance arm is horizontal. The whole machinery is stopped by pressing another button.

The maximum power at the blower shaft is about 300 HP. With such a small electric power plant as that of Göttingen, care must be exercised not to make great load increases too suddenly. The automatic regulator takes care of this.

In Fig. 3 the coarse regulator is shown above the balance arm. It is provided with a special system of springs under compression, so that contacts can only be made when the balance is very unevenly loaded. As soon as an approximate adjustment is made, the coarse regulator is switched off and the work is taken up by the fine regulator, which is shown below the balance arm. It is so arranged that the fine regulator, after reaching its limit, switches the coarse regulator a step further and then another step and does this gradually, so that as soon as the coarse adjustment is made, the fine regulator resumes its work.

In this regulation there was the difficulty that it could not be made, as in the case of a steam engine, for a fixed r.p.m.

but must proceed by air speeds from 5 to 50 m. per sec., thus covering a range of 1:10. Such a requirement is made of no engine regulator. Consequently, we were obliged to invent devices (as, for example, the stabilizing of the balance arm by means of the rods C and T) which, I am free to confess, consumed considerable time. This makes the balance arm slower in its movements as more weights are added. When there are no weights on the pan, it is so balanced by the weight U over the pivot, that the balance arm swings almost astatically.

There are many other details not shown on the diagram and which I have not the time to describe, as, for example, a device for preventing over-regulation and an adjustable device for damping the oscillations, etc.

Fig. 4 is an accurate representation of the entrance cone, which can be turned slightly up or down and to the right or left. This is necessary for accurately adjusting the direction of the air current. The forces acting on the balance are resolved into vertical and horizontal. In adjusting this balance, its weight has an influence, for one hangs weights on the balance and observes the deflection of the horizontal and vertical arms. When the air current is not horizontal there is an inaccurate resolution of the components and, since the drag is relatively small and the lift large, an error in the drag, through a lift component, is very important. We accordingly make control measurements: One with the convex side of the aerofoil up, and the other with it down. If both measurements are not the same, the cone is not properly adjusted.

Fig. 4 shows an arrangement which we have employed (especially at first, before our experimental arrangements were entirely completed) in measuring simple resistances. The model hangs on vertical wires. The wire underneath, with the weight, serves to hold the measuring wire taut. The latter branches, in the cone, into two wires, whereby the resistance to be measured is resolved into two forces in these directions. One wire goes to a balance above the cone where the force can be measured. We have employed this device especially for hanging full-sized objects in the air current and measuring their resistance. Various published data were obtained in this manner.

The entrance cone is made of wood, lined with sheet-iron and supported externally by a light iron framework, with which the diagonal adjusting rods are connected. The larger end of the cone is supported by a cast-iron rim in the wall. Excepting the part between the entrance cone and the blower, which is made of wood and iron, the tunnel is made of reinforced concrete, which has proved very satisfactory. Even the deflectors are made of reinforced concrete and simply brought into position with a crane and walled in.

A measuring device serves for measuring the speed distribution in the air current, for testing its uniformity, on the one hand, and for determining the speed in the vicinity of the object, on the other hand. This device is comparatively new and only a few tests have yet been made with it. Otherwise, I would have shown you a diagram of the uniformity of the air current. The reason I do not do so is chiefly because our recording manometer must be reconstructed, in order to do really accurate work. I expect, however, to be able to do so at our next meeting. On a car which can run horizontally on the wooden rails, there is a tower on which a second car runs in a vertical direction. Through the latter runs a rod on the end of which is a pressure gage. Thus all points can be reached. By means of a pressure recording device, a line is drawn for either the horizontal or vertical direction.

Fig. 5 shows a device that is located under the floor of the experiment room. (In Fig. 4 this space is left empty, corresponding to its condition at the beginning of 1917.) This is a very noteworthy object, consisting of a turntable with floats and a trap. When the experimental apparatus is wheeled in, it can not be left on wheels, but must rest on stationary supports, since only thus can accurate weighings be made. Hence it is necessary to have some special provision for supporting the heavy apparatus which weighs from 500 to 1500 kg. We have hit upon the expedient of lowering the central portion of the track on four spindles. These may be either outside the turntable or even on the turntable, if necessary, whereby the entire measuring apparatus can be swung through a moderate angle (so that, for example, a propeller can be tested in an oblique position with reference to the air current.)

In addition to the fact that it can turn on a circular track a, the device has the further peculiarity that a part of it can float. Fig. 5 shows large pots g of which there are four. When water is poured into these pots, the so-called float frame c is supported by the floats. By pouring water into the pots, a lift of 0 to 2000 kg. may be generated, so that the heaviest objects can be floated. The purpose of the floats is to enable a horizontal motion in all directions, so that when we attach one or more scales to the object, we can measure the forces without trouble from friction.

Fig. 5 shows, for example, an object held by stay wires with its axis vertical, ready to be subjected to the blast. Since it is all mounted on a turntable, any side may be turned toward the air current. Thus far provision has only been made for measurements of drag, but it is intended to provide also for lift measurements.

Fig. 6 is a diagram of the measuring device, the so-called 3-component balance, which has been chiefly used for measuring lift, drag and moment. It has been built on the plan of the very satisfactory device employed in the old plant, with some structural improvements, and also for greater forces. The aerofoils are usually hung bottom up, so that the lift stresses the wires instead of slackening them. In the contrary case, it may happen that the model, when it is not sufficiently weighted, is lifted and the wires are broken. By the above-indicated method, however, nothing can happen. When the model is not heavy enough to withstand a negative lift, a few additional weights are hung on span wires.

The model is suspended by three sets of wires: On the leading edge, by a set of three wires (a, b, c); in the rear by two wires (d, e); and also in front by a horizontal wire (f) against the air current. This suspension is statically determined, which is essential in order that all measurements may proceed smoothly. The static determination of any such weighing device is indispensable for a reliable multicomponent balance and is taken into consideration in the construction of all the balance joints. In the construction of the knife edges, a number of new devices have been invented.

The front system of wires hangs from a bridge G_1 and the rear system from another bridge G_2. The points of attachment to the bridges may be varied at will. These bridges hang, in turn, from balance arms, joined in pairs by shafts, to which the bridges are parallel. On the front end, the balance arms have extensions (H_1, H_2) to which the rods A_1 and A_2 are attached. The scales for reading are intentionally omitted in the drawing. In reality, they are located about where the letters stand.

The drag wire f, as in Fig. 4, transfers its force to two other wires g and h, the latter being attached to the arm of the balance W (Fig. 6).

It is perhaps unnecessary to state that the axes are not really supported by ordinary bearings, but on carefully constructed knife edges. The bearings are shown in the drawing only for the sake of simplicity and clearness. As in the old plant, the whole balance may be raised or lowered so as to change the attacking angle of the model. This is accomplished by means of the lever at the lower right-hand corner, which may be set at different heights.

Balance W gives the drag. Balances A_1 and A_2 give the lift. Of course all the balances must first read (or tared and brought to zero) without wind and then read with wind, when the difference in the two readings will give the force of the wind. Models of any desired weight may be used. Most of our models are made of plaster of Paris with a sheet-iron covering.

Fig. 7 shows a model rear view with its suspension wires, as seen from the collector, or blower end. We can recognize the front system of wires (a, b, c) and the rear system (d, e). The drag wire f does not show, but the vertical wire h does. The bottom wire k (Fig. 6) holds the whole system under tension by means of a weight. A small pressure gage is attached at the upper left and extends into the upper part of the tunnel. The air current is so uniform that the gage does not need to be moved back and forth.

As shown in Fig. 2, the air is led from the collector to the blower by a cylinder, which was located here to enable the introduction of fresh air from out-doors through the basement through a second cylinder to the blower, in order to perform experiments (with radiators, for example,) requiring a constant supply of fresh air. The latter cylinder has not yet been built.

Fig. 8 is a diagrammatic representation of a balance for measuring the six power components, namely, the three forces, lift, drag and drift, and the three moments about the X, Y, Z, axes. This balance is practically finished. It has not yet been used, because we did not have the leisure during the war to make the final adjustments.

I will only try to give you a general idea of it here. The model is again suspended by six wires, but they are here attached to a rigid triangular board. The forces are resolved not by the model but by this board. The rods which transmit the six components are only indicated here by arrows. Rods 1 and 2 together give the lift and in their difference give the moment about the longitudinal axis. 3 and 4 give drag and the moment about the lateral axis. 5 and 6 give the lateral force and the moment about the vertical axis. With these rods there is connected still another system of levers, whereby the resolution of the forces and moments is effected and the center of the moments is located in the middle of the air current.

This complicated system of levers saves us all calculations and we immediately read on six scales, which in this case work automatically, the results, namely, the three forces and the three moments already calculated for us. Naturally, however, the allowances for the resistance of the wires themselves must be subsequently calculated. This was a difficult task which long delayed the completion of the balance.

Fig. 9 shows the propeller testing device, which has also been constructed from a new point of view. All such devices must give the torque and thrust of the propeller. For the torque, in the ordinary devices, a coupling with a longitudinal motion is required. The couplings heretofore employed generate a moment in the structure, which interferes with accurate weighing. They usually have ball bearings. The balls finally wear into the ball race and impair the accuracy of the measurement. The contact surfaces would frequently have to be reground or replaced. Here, instead of the longitudinally moving coupling, the whole mechanism is mounted on the float frame, which is shown at the bottom of the figure. Since the whole mechanism floats horizontally, we can now simply attach the thrust balance to the float frame and thus eliminate the longitudinal coupling. The torque is so measured that a balance indicates the couple at which the float is in neutral equilibrium.

The propeller is driven by a 50 HP electric motor by means of a bevel gear. All the driving parts are protected from the air current. Otherwise the latter would exert a force on the mechanism, which would cause an error in the thrust reading. This propeller testing device has not yet been tried, because the machine works has had to remake the chrom-nickel-steel gear wheels several times, on account of some defect in casting or workmanship. The propellers which will have a diameter of one meter, will probably be driven at a speed as high as 5000 r.p.m. for the purpose of studying the influences of the compressibility of the air.

The new tunnel is designed for an air speed of 54 m/sec. and it will probably be possible to reach 60 m/sec., corresponding to an air efficiency of about 800 HP. I believe that this plant (so far as indicated by the reports from enemy countries), at least until very recently, was the largest and most powerful of its kind. For the possibility of making it, we must thank the generosity of our military administration.

I would not conclude any lecture without emphasizing the fact that I could not have carried the matter through without the devoted and intelligent assistance of my Göttingen fellow-workers. I wish to make special mention of Dr. Betz, who is chiefly responsible for the wind tunnel, which he had previously tested in model form, and which, when set in operation, gave exactly the wind pressure we had calculated. I must also mention Dr. Wieselsberger for the construction of various fine apparatus. Much was worked out in common. For instance, we all helped on the pressure regulator. Dr. Betz also had a large share in constructing the balances. I must also make honorable mention of my constructing engineer from the beginning of my work. Dr. Thoma, who originated the ideas of building the tunnel of reinforced concrete and of giving it the vertical position. This was a great advance over our former method of construction. There are many others whose names

I shall not mention, but all of whom I wish to thank.

REMARKS.

Professor Parseval inquired whether the balance would not lack sensitiveness on account of the four floats. He thought this would result from the great difference in lift, if a float went down on one side while the opposite float went up.

In this connection, Dr. Prandtl claims that the center of gravity of the floating portion of the propeller testing device is quite elevated and that, by suitable water filling, the lateral metacenter may be brought as near as desired to the center of gravity. For this purpose, the side floats are of comparatively small cross-section in the vertical direction. Hence, the fears of Prof. Parseval can be disregarded.

Engineer Gsell suggested that possibly the Eiffel tunnel might be more favorable in its power consumption than the Göttingen tunnel and that the loss of power at the exit of the former might be smaller than in the return current of the Göttingen tunnel; also that, in the Göttingen arrangement, power might be further conserved by gradually increasing the cross-section behind the experiment place into a "diffuser" before the beginning of the return current.

Prof. Prandtl answered that in fact the Eiffel tunnel appears to be from 5 to 10% more economical than the Göttingen tunnel. The cross-section of the Göttingen tunnel continually increases from the experiment place through the blower and return cylinder as far as the entrance cone. There is a loss of about 15% of the air pressure at each turn. There are, however, other more important grounds for this arrangement than that of a small improvement in economy. The main losses in the return tunnel come from its relatively small cross-section (about 10 sq.m.) at the first two bends, a compromise with the building cost, which would be correspondingly increased by lengthening the tunnel. Eiffel required no turns and saved some power thereby, but he has the disadvantage that his air current returns in all sorts of irregular ways through the hall to the intake place and thereby brings with it all sorts of eddies and cross currents. The fact that Eiffel, in addition to the honeycomb shown in his book, subsequently added another in the entrance cone, leads one to the conclusion that he previously found his air current too uneven. By the closed air current circuit, we have the advantage of a very uniform current at the testing place, aside from the convenience of the open space for manipulating the apparatus by means of tracks and cranes, etc.

Professor Junkers stated that, in connection with the theoretically correct widening of the tunnel behind the entrance cone, he had experienced the difficulty that the aerofoil deflected the air stream so that it did not completely fill the widened tunnel, which impaired the effect of the widening. He considered the Göttingen arrangement better than the Eiffel.

Professor Karman agreed with the latter view and added that, if one had an empty airship hangar at his disposal, he might obtain good results even with the Eiffel arrangement.

Professor Prandtl, in his closing remarks, emphasized the fact that, with reference to the cost of building, which plays quite an important role, the maximum economy had been foregone. If he were to build again, he would stick to the same system, though improvements might be made in some of the details.

Translated by the National Advisory Committee for Aeronautics.

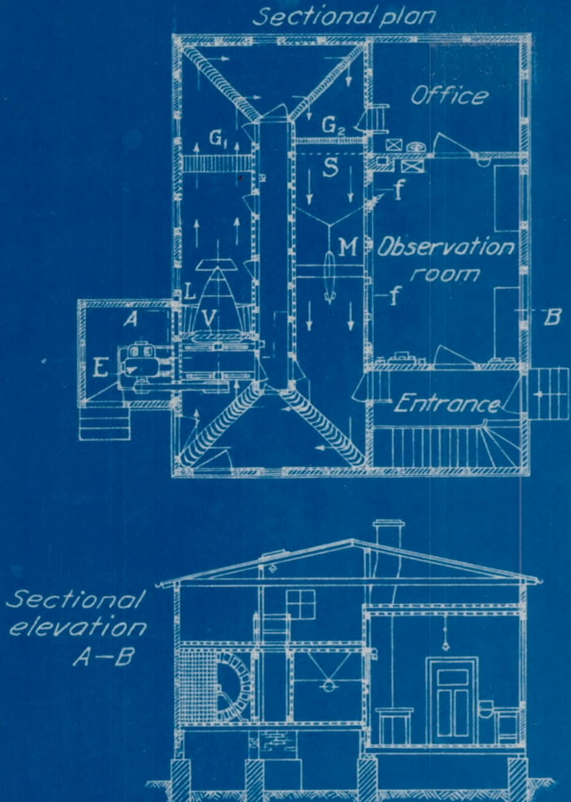


Fig. 1 Old wind tunnel building
G_1 and G_2 = Coarse and fine honey combs
E = Motor   L = Directing device   f = Window
M = Model   S = Sieve   V = Fan

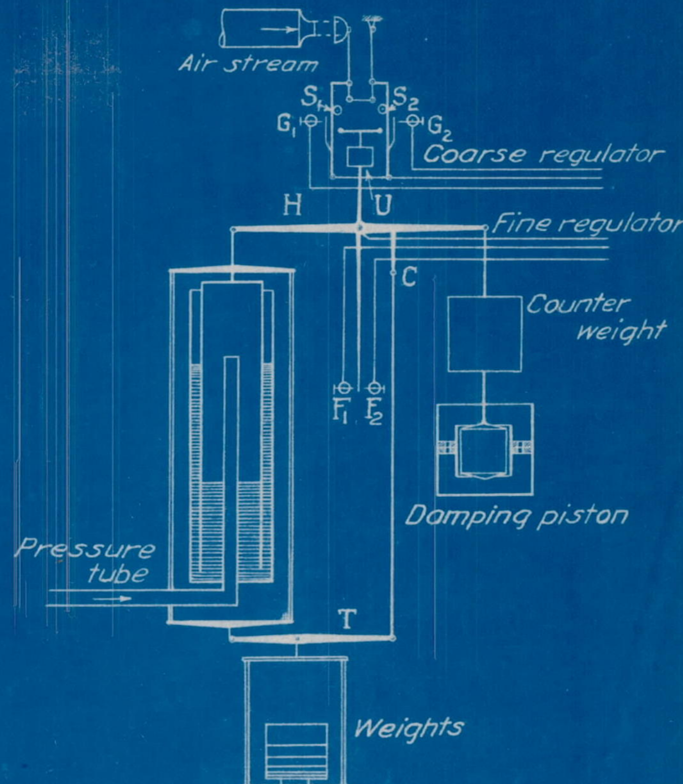


Fig. 3 Diagram of pressure regulator
H = Balance arm
F_1 and F_2 = Fine regulator contacts
G_1 and G_2 = Coarse " "
S_1 and S_2 = Stop pins
U = Astatic weight

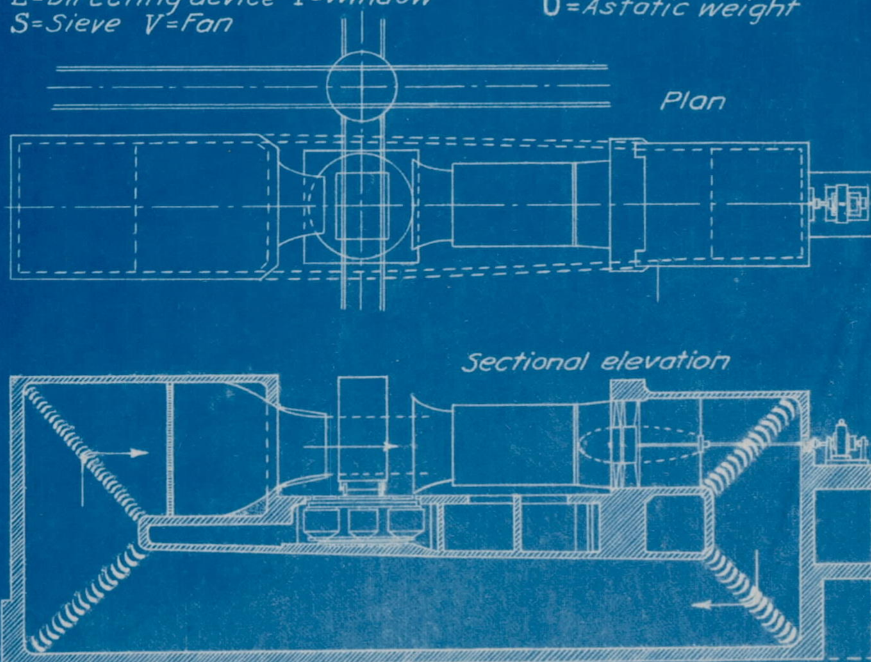


Fig.2 New wind tunnel

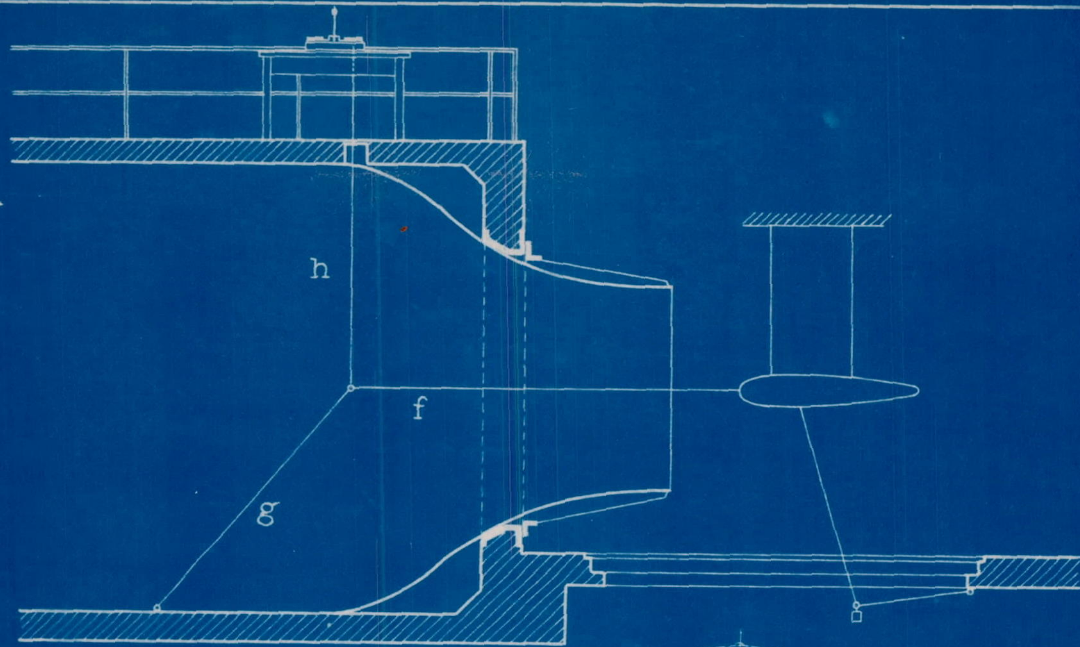
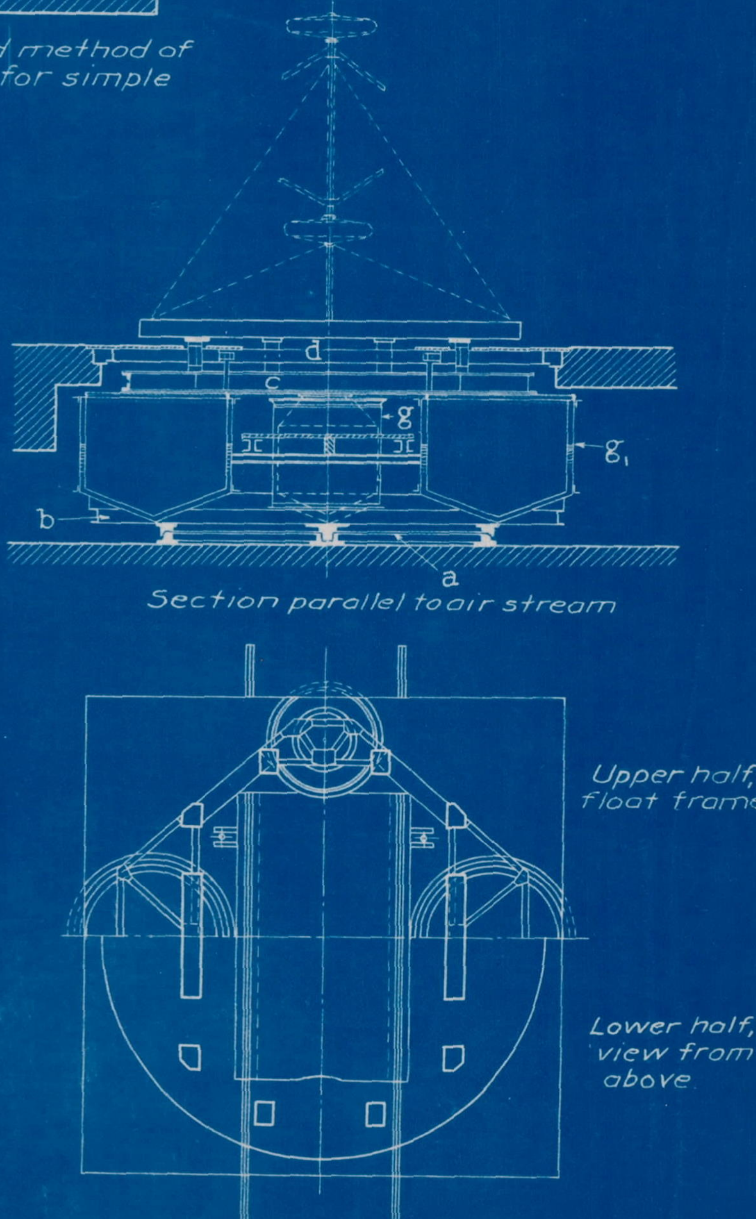
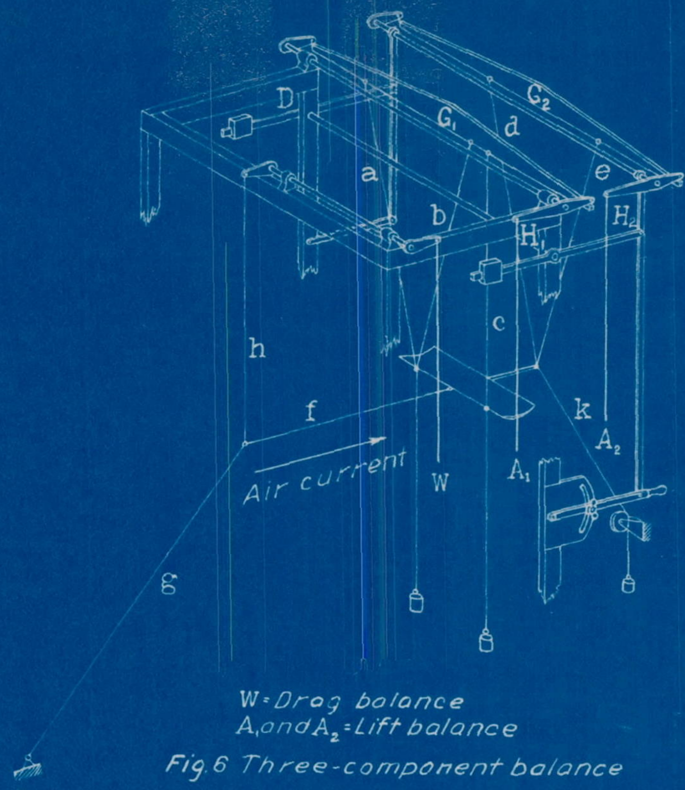


Fig. 4. Entrance cone and method of supporting model for simple drag tests

a = Circular tracks for turntable
b and d = Frame for revolving part
c = Float frame
g and g_1 = Water tanks containing floats

Fig. 5.
Turntable with floats.

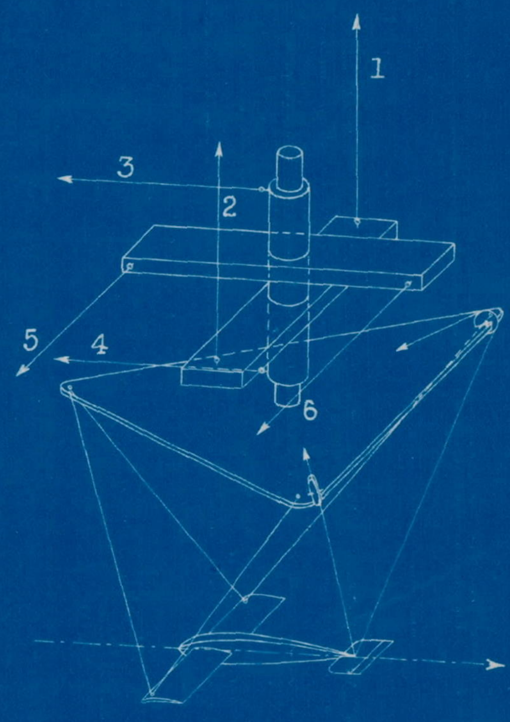




W = Drag balance
A_1 and A_2 = Lift balance

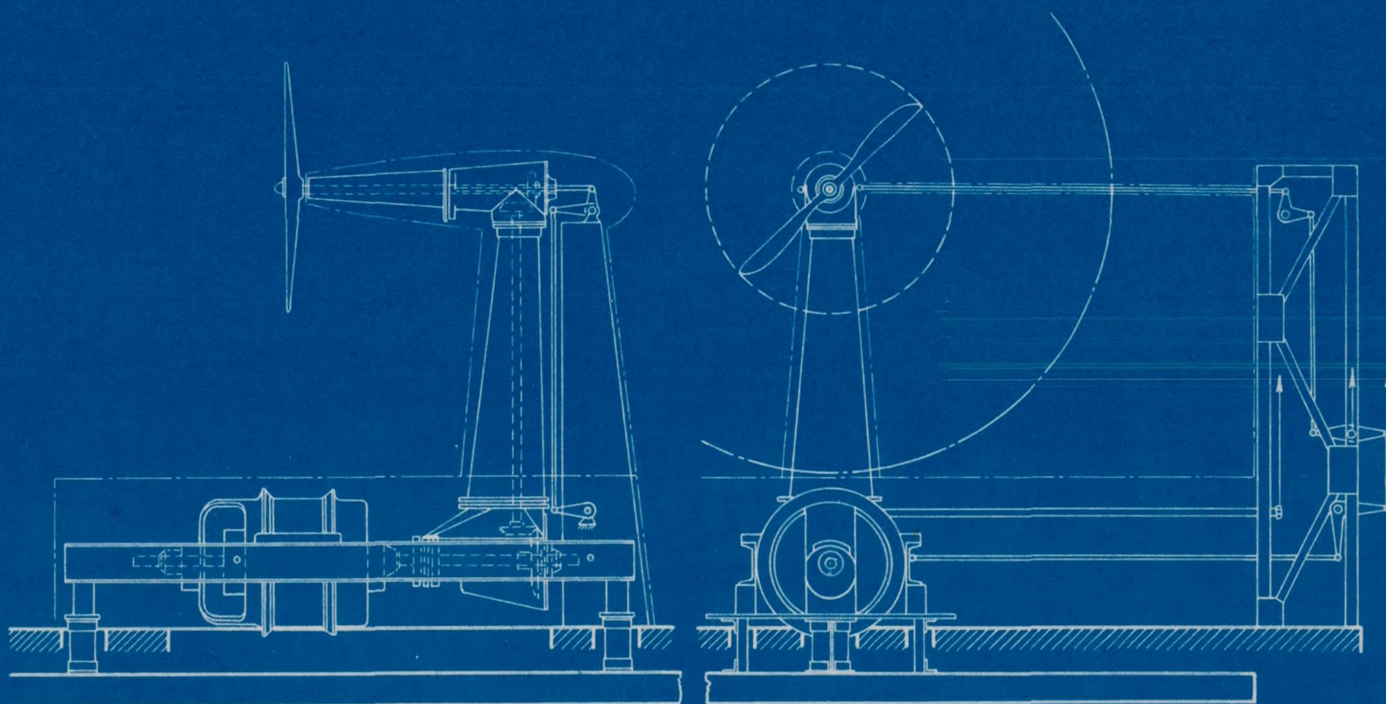
Fig. 6 Three-component balance

Fig. 7 Method of connecting model (rear view) with three-component balance, looking toward entrance cone.



Rods 1 & 2 give lift and rudder movment
Rods 3 & 4 give drag and elevator movment
Rods 5 & 6 give lateral force and movment

Fig 8 Six component balance



Below is float frame on which driving gear rests

Fig. 9. Propeller testing devise.

Fig. 9.