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TECHNICAL MEMORANDUMS
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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No. 508

AEROMECHANICAL EXPERIMENTATION

(Wind Tunnel Tests)

By R. Katzmayr

From Luftflotten, 1928

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AEROMECHANICAL EXPERIMENTATION.*

(Wind Tunnel Tests)

By R. Katzmayr.

Although as a result of the advanced state of theoretical aeromechanics, it is possible to solve mathematically most of the problems coming under this head, the experimental data obtained in this newest branch of technical science have nevertheless contributed much to the explanation and extension of theoretical knowledge. The purpose of the experiments, as in every other branch of science, is to test the practical value of the theories and to render accessible to the practitioner those fields in which theoretical considerations alone are insufficient.

In aviation there are two possible ways of obtaining experimental data. One is to perform the necessary experiments with a model and the other is to experiment with the object itself. The former method has long been employed in the field of aeromechanics and long before man-carrying airplanes were built, earnest investigators used very simple models for testing the correctness of their theories. The basis of the model experiments, which we will first consider, is the transferability of the results from the model to the full-size object.

*"Das aeromechanische Versuchswesen," from Luftflotten, 1928, pp. 570-580.

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Here a general solution is obtained by the consideration of the criteria adopted in the mathematical formula for the drag. This formula reads $R = \rho F v^2$, in which ρ is the air density, F the surface area, and v the relative velocity. The formula corresponds therefore to the dimensions. It is now clear that the hitherto disregarded influence of the shape and contour of the object must enter into this equation in some way, for experience shows that, other things being equal, the drag is affected by the shape of the object. This phenomenon is introduced into the mathematical formula by eliminating the apparent disagreement between theory and practice by multiplying the fundamental equation by a nondimensional quantity, hence by a pure coefficient. The fundamental law of drag accordingly takes the form $R = \xi \rho F v^2$, in which ξ is the corrective coefficient just referred to. The above formula also expresses the law of transferability from the model to the full-size object, because it indicates that the force R is directly proportional to the air density ρ , the area F and the square of the velocity v^2 . Hence, for example, the drag is thrice as great for thrice the area and decreases about half if the air density is only half as great as it was in the experiment, which is actually the case at about 6000 m (about 20,000 ft.) above sea level.

Experiments show that the coefficient ξ is not a constant and that consequently the above law of drag is not universally

applicable. If, e.g., the resistance or drag of a sphere is measured at various velocities, the ratio between the coefficient ξ and the velocity v is obtained as shown in Figure 1. At very low velocities ξ has a relatively large and very changeable value, but soon reaches, and indeed at relatively low velocities, a value which it then retains for a wide range of velocities. Here, therefore, the above-mentioned law of resistance or drag is perfectly applicable. With a further increase in velocity, the value of ξ falls quite rapidly and irregularly and then remains constant again for a wide range of velocities. Only when the velocity is still further increased, so that it approaches the velocity of sound in the given medium, 333 m (1092 ft.) per second for air, ξ begins to increase and continues to increase as the velocity increases beyond that point. Above $v = 250$ m (820 ft.) per second, it is comprehensible that ξ can no longer remain constant, due to the compressibility of the gases which can be disregarded at lower velocities. The practical aeronautical engineer seldom works, however, with such high velocities that they can be called great in comparison with the velocity of sound. At the most, only the tips of the propeller blades can approach such velocities. For such cases the model tests are no longer applicable. It is different, however, for velocities of 5-250 m (16-820 ft.) per second. It is found that the point of transition (I in Fig. 1), at which ξ falls rapidly in value, is not fixed for geo-

metrically perfectly similar bodies, but wanders. Thus, e.g., the transition point I' , for twice as large a sphere as was used in an experiment, was reached at half the velocity, and the curve in Figure 1 followed the dotted line. The experiments show further that the location of the transition points I and I' depends in like degree on the magnitude of the velocities v and of the model l . The cause of these phenomena resides in the viscosity of the fluids. The velocity distribution of a fluid in the vicinity of an obstacle and hence the flow diagram about the same depend largely on the magnitude of the friction coefficient μ of the given fluid, because it denotes the shearing forces which develop between the different fluid layers flowing past one another at different velocities. The friction coefficient itself depends, moreover, on the air pressure and temperature. We are indebted to Reynolds, the Englishman, for the above information. The relation between the different quantities, velocity v , magnitude of model l , coefficient of friction μ and fluid density ρ is called Reynolds Number, $Z = \frac{\rho v l}{\mu}$. It is a nondimensional coefficient. The coefficient ξ is a function of Z .

The preceding statements accordingly show that the above-mentioned law of drag is perfectly applicable only when the Reynolds Number Z is the same for the model as for the full-size object, because only then are the flow diagrams and the interaction of object and fluid perfectly alike. This knowl-

The following is a list of the names of the persons who were present at the meeting held on the 15th day of October, 1910, at the residence of Mr. J. H. Smith, located at No. 123 Main Street, in the City of New York.

Present: Mr. J. H. Smith, Mr. W. L. Brown, Mr. C. D. Green, Mr. E. F. White, Mr. G. H. Black, Mr. I. J. Gray, Mr. K. L. Blue, Mr. M. N. Red, Mr. O. P. Yellow, Mr. Q. R. Purple, Mr. S. T. Orange, Mr. U. V. Silver, Mr. W. X. Bronze, Mr. Y. Z. Iron, Mr. A. B. Steel, Mr. C. D. Lead, Mr. E. F. Tin, Mr. G. H. Zinc, Mr. I. J. Nickel, Mr. K. L. Copper, Mr. M. N. Aluminum, Mr. O. P. Magnesium, Mr. Q. R. Potassium, Mr. S. T. Sodium, Mr. U. V. Calcium, Mr. W. X. Barium, Mr. Y. Z. Strontium, Mr. A. B. Rubidium, Mr. C. D. Cesium, Mr. E. F. Francium, Mr. G. H. Actinium, Mr. I. J. Radium, Mr. K. L. Polonium, Mr. M. N. Bismuth, Mr. O. P. Antimony, Mr. Q. R. Arsenic, Mr. S. T. Selenium, Mr. U. V. Tellurium, Mr. W. X. Iodine, Mr. Y. Z. Bromine, Mr. A. B. Chlorine, Mr. C. D. Fluorine, Mr. E. F. Oxygen, Mr. G. H. Nitrogen, Mr. I. J. Carbon, Mr. K. L. Hydrogen, Mr. M. N. Helium, Mr. O. P. Neon, Mr. Q. R. Argon, Mr. S. T. Krypton, Mr. U. V. Xenon, Mr. W. X. Radon.

Respectfully,
J. H. Smith, Secretary.

edge leads to making such arrangements for the model tests as to satisfy the above condition.

Inspection of the quantities in the function $\xi = f\left(\frac{\rho v l}{\mu}\right)$ shows how the test arrangements must be made, in order to be sure from the beginning that the results of the model tests will be transferable to the full-size object with the smallest possible errors. Hence, it is obvious that, by enlarging the model (l) and the velocity (v), or both simultaneously, we will continually come nearer to the natural flow diagram. However, with a considerable increase in the value of v , we would finally approach the velocity of sound where, as already shown, the Reynolds Number would not apply.

In addition to l and v , however, the function of ξ also contains ρ and μ . Since, as already mentioned, aeronautical engineers deal chiefly with velocities which are small in comparison with the velocity of sound, so that the development of the forces is not affected by the compressibility of the gases, model tests can also be made in absolutely incompressible fluids, like water, for example. In this case, with a model 0.1 full size, only about 0.7 of the velocity of the object in the air would be necessary in order to obtain a perfectly equivalent Z . However, this is quite a high value, because, at flight speeds of 40 m (131 ft.) per second, it gives a velocity of about 28 m (92 ft.) per second in water, which is not easily attainable in practice. We would, however, have

The first part of the document discusses the importance of maintaining accurate records of all transactions. It emphasizes that every entry should be supported by a valid receipt or invoice. The second part outlines the procedures for handling discrepancies between the books and the actual cash on hand. It states that any variance must be investigated immediately and reported to the appropriate authority. The third part provides a detailed breakdown of the monthly financial statements, including the balance sheet, income statement, and cash flow statement. Each statement is accompanied by a brief explanation of the items included and the methods used for their calculation. The final part of the document contains a summary of the overall financial performance for the period and offers recommendations for future improvements.

The following table shows the monthly sales figures for the past year. The data indicates a steady increase in sales over the period, with a notable peak in the fourth quarter. The reasons for this growth are attributed to the implementation of new marketing strategies and the expansion of the product line. The table also includes a comparison of sales against the budget, showing that the company has consistently exceeded its targets. This success is a result of the hard work and dedication of the entire team. The document concludes with a statement of appreciation for the support and cooperation of all stakeholders.

to change ρ and μ by taking, instead of a liquid, some other gas than air, e.g., carbon dioxide (CO_2) under a high pressure and at a low temperature. Lastly, we can make the model tests in very highly compressed air. The last two methods have been developed since the war. There is now in America a wind tunnel in which the air is subjected to an additional pressure of about 20 atmospheres, and which gives values of Z agreeing perfectly with the values obtained in full-size tests.

If we consider the course of the function $\xi = f Z$ (Fig. 2), we do not find it at all necessary to make the test conditions such as to yield values of Z equal to those obtained in full-size tests. The course of the function ξ , after the drop from its high initial values, is nearly constant for a wide range of Z , this constancy extending far beyond the values obtained in the full-size tests. It is therefore permissible to experiment at considerably smaller Z values, but we must make sure that we are not experimenting in the region of transition I. This is easily done by comparing the results of two successive tests to see whether they both yield the same value for ξ . Experience shows that satisfactory results are generally obtained with Z values of the order of magnitude of 4-6 m^2/s . (13.1-19.7 sq. ft./sec .)

The turbulence of the air affects the test results in a way which has not yet been quantitatively explained. This is due to the fact that no standard of value for the turbulence

has yet been established. The qualitative effect of the turbulence is evidenced by the fact that it not only lessens but also affects the direction of the drag. Its effect is similar to that produced by increasing the Reynolds Number. The simplest assumption is that the force required to propel an object through a turbulent fluid is smaller than that required in a fluid whose molecules maintain the same relative positions, because the separate parts do not need to be accelerated in like degree.

The law of relativity, which says that the dynamic interaction of two bodies depends only on the relative state of motion, and that the results are therefore the same whether the body moves through quiet air or the air moves against the fixed body, affords two possible methods of experimentation. By the first method, the model is driven forward at a given velocity in quiet air, and the air resistance or drag is measured. This is done in so-called "towing plants," which have long been used. There are two kinds, one with a straight track and the other with a curved track (generally circular). To the former belong, for example, the mechanism for the falling experiments conducted by Eiffel from the second platform of the tower built by him in Paris. These experiments were performed in 1903 on a vertically stretched cable. Von Parseval rigged up a towing car in a balloon hangar. This car could be operated like an overhead travelling crane. No sufficiently large Reynolds Numbers could be

obtained by the Eiffel method, because of the smallness of the models and their low falling velocity. The Parseval method enabled the use of larger models, but their velocity was greatly restricted by the shortness of the hangar. The French built at Saint Cyr a government experimental station including a long towing track with an electrically driven test carriage. The models to be tested were relatively large and were towed through the air at a height of 5-6 m. (16-20 ft.) above the ground. The great length of the track enabled a higher velocity than the Parseval plant, though not much over 60 km (37 miles) per hour. During the war a similar towing car was used by the German war department, this car being towed by an ordinary steam locomotive. The car carried a 10-meter (33-foot) tower, to which a full-size airplane could be fastened, but the ordinary railroad track near Berlin allowed no high speed, so that no large values could be obtained for Z , despite the large size of the model. This was not the only reason, however, for the abandonment of such towing devices. The most important reason was the uncertainty in the determination of the velocity and direction of motion of the model with respect to the air, for the latter is equal to the towing velocity only when the air is perfectly still, which is seldom the case in the open. Moreover, it is difficult to install the various instruments in the car and protect them from shocks. It is only during a very small part of time that conditions are satisfactory for using automatic

recording instruments. Furthermore, the results are impaired by the nearness of the model to the surface of the ground.

Towing experiments can also be performed on circular tracks, as already mentioned. Due to their small peripheral velocity and the size of the model, they have given mostly only small values of Z . Their chief disadvantage, however, lies in the creation of a whirling motion of the air and centripetal accelerations, which cause considerable errors in the determination of the relative velocity.

It is obvious that, in general, the towing devices do not meet the fundamental requirements of aerodynamic experiments. It has been found that towing experiments in water are well adapted to show flow phenomena and to enable their photographic preservation. Professor Ahlborn of Hamburg has rendered valuable service in this connection.

In the second method, a stream of air is directed against a stationary model. There are two ways of doing this. One is to suspend the model in a closed tunnel through which air is driven. The other is to suspend the model in an open space between the two closed parts of the tunnel, which is said to be of the "open-jet" type.

There are many ways of applying these two principles. The earliest tunnels (mostly cylindrical) had a fan or propeller b at one end, which removed the air by suction (Fig. 3). This air entered a large room c and returned to the tunnel entrance d ,

thus completing the circuit. The model was suspended at *m*. One of the earliest of these tunnels was built for Professor Joukowski in Koutchino (1906).

The first tunnel (Fig. 4) in which the air from the propeller did not enter the room, but was returned to the model through closed channels (*c* and *d*), was erected at Teddington by the British National Physical Laboratory. The old Göttingen wind tunnel, most of the English and many of the American wind tunnels were built on this plan.

Open-jet tunnels have come into general use in France, Italy, Austria and now also in Germany. There are two different types. Figure 5 represents the one first used by Eiffel, in which, due to the negative pressure produced by the propeller *b*, the open jet enters the test chamber through the entrance cone *a*. Thence the air stream is drawn into the exit cone *f* and passes through the propeller *b* into the room *c* in which the whole plant is located. In a tunnel of this type, it is essential to maintain negative pressure in the test chamber. Figure 6 represents the second open-jet type first used by Professor Knoller in the Vienna Aeromechanical Laboratory. It differs from the Eiffel type in that the test chamber is under atmospheric pressure, which in itself is of great advantage. The air flows from the large room *g* through the cone *a* against the model *m* and through the test chamber *e* into the exit cone *h*. It then passes through the tunnel *i* into

the room k, from which it is driven by the propellers b through the shafts l to the room g. Accordingly there is the greatest positive pressure in room g, while only about half of room k is under positive pressure. The new Göttingen open-jet tunnel built during the war and the Zeppelin wind tunnel are both of this type, although, instead of the advantageous very large rooms g and k, they have only return channels and small pressure rooms, whereby moreover the symmetry of the plant was destroyed. This symmetry is especially important, because it produces a uniform velocity distribution over the whole cross section of the air stream, which is an indispensable condition for such wind tunnels. Another just as important condition is that the velocity of the air stream remains constant after being once established. This is accomplished by means of more or less complex devices for regulating the electric propeller motors.

In accordance with the above-mentioned need of the greatest possible Reynolds Number, the recent wind tunnels were built with the greatest possible air-stream cross section, up to 3.25 m (10.66 ft.), in order to enable the use of the largest possible models. The air velocities have also been considerably increased, so that velocities of 30-50 m (98-164 ft.) per second may be regarded as normal.

Margoulis proposed a carbon dioxide wind tunnel in 1919, but this idea has not yet been put in practice. The tunnel was

to be like Figure 4. The American variable pressure wind tunnel, designed by Dr. Munk, functions at a maximum pressure of 20 atmospheres and an air velocity of 25 m (82 ft.) per second. Its diameter is 1.6 m (5.25 ft.).

All wind tunnels naturally have devices for determining all the quantities requisite for a complete description of the effects of the air force. Accordingly the magnitude and direction of the drag and its relation to the model can be measured. A description of the very interesting instruments and accessories would require too much space. In every wind tunnel it is possible to measure the air velocity very accurately. Generally it is also possible to determine the distribution of the air pressure over the surface of the model. This gives information regarding the best shape of the airfoils. There are also devices for making visible and photographing the streamlines about the obstacle..

Experiments may be tried with separate parts of airplanes or with models of whole airplanes, with propellers and with anything else which comes into contact in any way with moving air. Thus, for example, one can determine the wind pressure against buildings, sail-boats, railway and street vehicles, windmills, etc. Even the more recent theory of water turbines avails itself with advantage of wind tunnels, thus showing the intimate relation between gases and liquids.

The experiments with models are preferably supplemented by

experiments with full-size objects. The latter are often very important, especially when the velocity of the air approaches that of sound. Airplane flight tests are much more difficult and expensive than wind-tunnel tests with models. Unfortunately the results obtained in the former way are still relatively inaccurate. Even the determination of the simplest quantities, like the relative velocity or the attitude of the airplane with respect to the direction of the wind, meets with considerable difficulties. These difficulties are increased by the fact that, in the open, it is very difficult to maintain a steady motion, which is a relatively simple matter in wind-tunnel tests. There is also the variation in the air density at different altitudes, which must be reckoned from the readings of the barometer, thermometer, and hygrometer, or at least requires the observing of a special densimeter. Even the installation of the many instruments in an airplane is no easy task. In order to relieve the observer, much use is made of self-recording instruments, whose accuracy, however, is relatively poor. Recently this source of error has been eliminated by taking motion pictures of the indicating instruments.

It was very natural, therefore, to try to make most of the observations from the ground, and various measuring devices were developed for this purpose, including a photogrammetric method combined with a method for the local illumination of the photographic plates.*

*"Flugbahnanalyse mit Hilfe der Photogrammetrie," R. Katzmayer in Der Motorwagen, 1920, p. 46.

Some phenomena can be tested only during actual flight, such, e.g., as the unsteady motions of an airplane. For this purpose, special accelerometers have been constructed. Moreover, all stress measurements of the structural parts of an airplane must be made during flight, as likewise those experiments whose results give an insight into the interaction of the propeller and airplane.

It has always been endeavored to test propellers in their natural size, because of the inaccuracy of the results obtained with models. The oldest arrangements enabled only the so-called "stand tests," which, of course, do not correspond to actual flight except at the moment of taking off. Measurements were made of the thrust, torque and the number of revolutions per minute (R.P.M.). In order to extend the tests to a moving propeller, the test stand was mounted on wheels which ran on a track. The first device of this kind was probably that of Professor Prandtl at the Frankfort International Aeronautic Exposition in 1909. It showed the same faults as all towing plants in the open air. Subsequently, propellers were tested on airplanes during flight with the aid of dynamometer or measuring hubs. Attempts were also made to solve the problem by mounting the whole engine on a movable support. It was found possible, however, to make all these measurements with a fixed propeller in a wind tunnel by directing an air stream against it. The plant proposed by Professor Knoller was erected

at Fischamend near Vienna during the war and was first used in the beginning of 1918. It consisted of a 27-meter (88.58-foot) tunnel as shown in Figure 7. The full size propeller b stood in the middle of the test chamber c, which had a diameter of 6 m (19.68 ft.), and was driven by a 300 HP. electric motor. It is noticeable that no special blower is used to generate an air flow in the tunnel. This is not necessary because the propeller, which is being tested, itself produces the requisite pressure difference in the chamber c to cause the air to enter through the cone e and leave through the cone f. Another noteworthy feature of this plant is that the whole tunnel a is mounted on four pairs of wheels and can be moved away from the propeller, thus enabling the stand test. The Italian Government wished to remove the whole plant to Rome, but the size of the separate parts rendered this impracticable.

I will conclude this report by mentioning that, of course, not only the wings but also the power plant (the engine) require thorough investigation. Engines are tested principally on the stand. In order to learn the behavior of engines at high altitudes, they were first tested on high mountains. Subsequently, only the carburetor and exhaust pipe were subjected to negative pressure. Even during the war several negative-pressure chambers were completed, in which the whole engine could be installed and in which any desired negative pressure can be maintained, so that the engine can be tested under al-

most the exact conditions actually existing at high altitudes. In order to determine the effect of low temperatures on the engine output, a free balloon of 9300 m³ (328,425 cu.ft.) gas capacity is being fitted out in Germany, in the basket of which a complete test stand for explosion engines is to be installed.

The foregoing discussion lays no claim to completeness. Many things could be only mentioned, while many more had to be omitted altogether. I have endeavored to show that aeromechanical experimentation has become an important aid to theory. It constitutes a science in itself and means should be provided for work of this kind in Austria.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

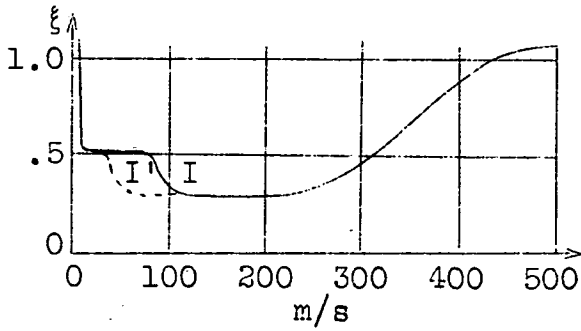
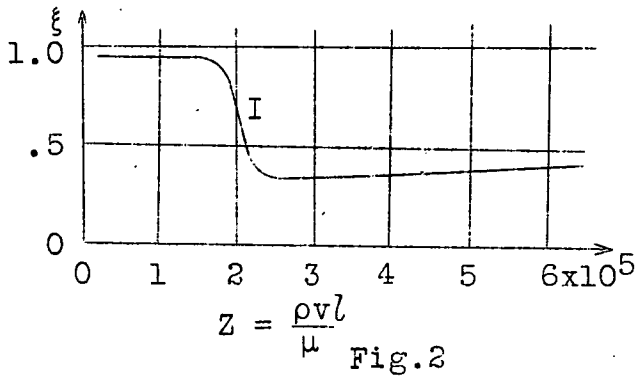


Fig.1



$z = \frac{\rho v l}{\mu}$ Fig.2

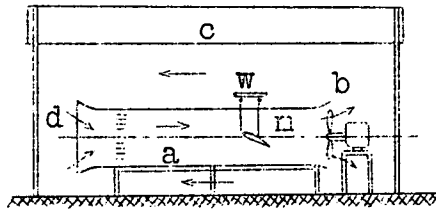


Fig.3

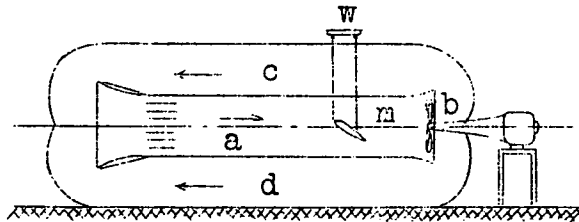


Fig.4

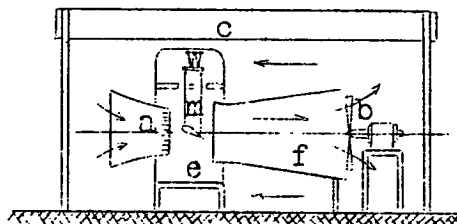


Fig.5

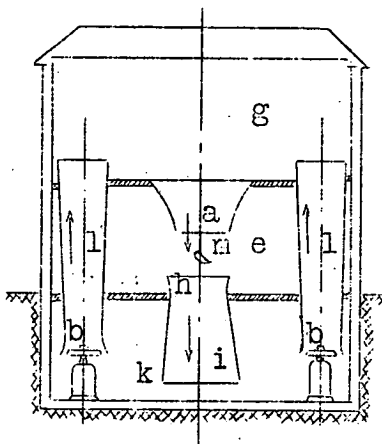


Fig.6

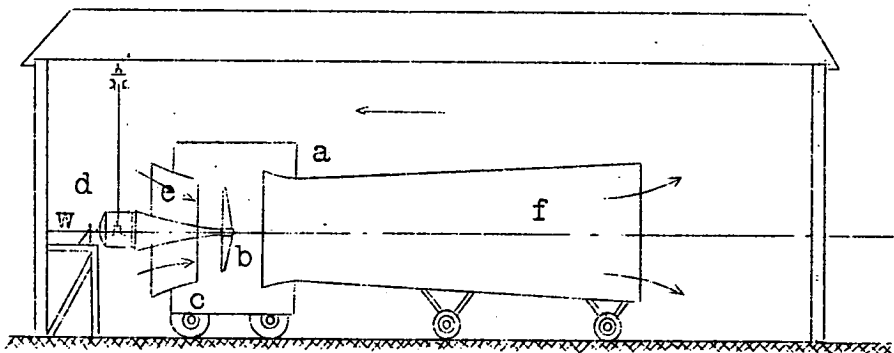


Fig.7