TECHNICAL MEMORANDUMS

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 508

AEROMECHANICAL EXPERIMENTATION

(Wind Tunnel Tests)

By R. Katzmayr

From Luftflotten, 1928

Washington
April, 1929

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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 ob-
tained in this newest branch of technical science have never-
theless 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 in-
sufficient.

In aviation there are two possible ways of obtaining ex-
perimental 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 test-
ing the correctness of their theories.  The basis of the model
experiments, which we will first consider, is the transfera-
bility of the results from the model to the full-size object.

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 $\rho$ 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 $\xi$ 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 $\rho$, 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 $\xi$ 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 coeffi-
cient $\xi$ and the velocity  v  is obtained as shown in Figure 1.
At very low velocities $\xi$ 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 re-
sistance or drag is perfectly applicable.  With a further in-
crease in velocity, the value of $\xi$ falls quite rapidly and ir-
regularly 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, $\xi$ begins to increase and
continues to increase as the velocity increases beyond that
point.  Above  v = 250 m (820 ft.) per second, it is compre-
hensible that $\xi$ can no longer remain constant, due to the com-
pressibility of the gases which can be disregarded at lower ve-
locities.  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 veloci-
ties.  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 $\xi$ 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 dia-
gram about the same depend largely on the magnitude of the
friction coefficient  $\mu$ 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 pres-
sure and temperature.  We are indebted to Reynolds, the English-
man, for the above information.  The relation between the dif-
ferent quantities, velocity  v,  magnitude of model  $l$,  coef-
ficient of friction  $\mu$ and fluid density  $\rho$  is called Reynolds
Number,  $Z = \dfrac{\rho\,v\,l}{\mu}$.  It is a nondimensional coefficient.  The
coefficient  $\xi$ 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-

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

Inspection of the quantities in the function $\xi = f\left(\dfrac{\rho\,v\,l}{\mu}\right)$ 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 $\xi$ also contains $\rho$ and $\mu$. 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

to change $\rho$ and $\mu$ 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 $\xi$, 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 $\xi$. Experience shows that satisfactory results are generally obtained with $Z$ values of the order of magnitude of 4-6 m²/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 en-
abled 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 locomo-
tive. 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 val-
ues could be obtained for  Z,  despite the large size of the
model. This was not the only reason, however, for the abandon-
ment 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

Joukowsky in Koutchino (1906).

The first tunnel (Fig. 4) in which the air from the propel-
ler 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 differ-
ent types.  Figure 5 represents the one first used by Eiffel,
in which, due to the negative pressure produced by the propel-
ler  b,  the open jet enters the test chamber through the en-
trance 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 cham-
ber.  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 advan-
tage.  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 tun-
nel are both of this type, although, instead of the advantage-
ous 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 indispensa-
ble condition for such wind tunnels.  Another just as important
condition is that the velocity of the air stream remains con-
stant after being once established.  This is accomplished by
means of more or less complex devices for regulating the elec-
tric 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 considera-
bly 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 tun-
nel, 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 direc-
tion of the drag and its relation to the model can be measured.
A description of the very interesting instruments and accesso-
ries would require too much space.   In every wind tunnel it is
possible to measure the air velocity very accurately.   Gener-
ally it is also possible to determine the distribution of the
air pressure over the surface of the model.   This gives infor-
mation regarding the best shape of the airfoils.   There are
also devices for making visible and photographing the stream-
lines 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.*

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*"Flugbahnanalyse mit Hilfe der Photogrammetrie," R. Katzmayr 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 pro-
peller, which is being tested, itself produces the requisite
pressure difference in the chamber  c  to cause the air to en-
ter through the cone  e  and leave through the cone  f. An-
other 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) re-
quire 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. Sub-
sequently, 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 en-
gine 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 aeromechan-
ical 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,
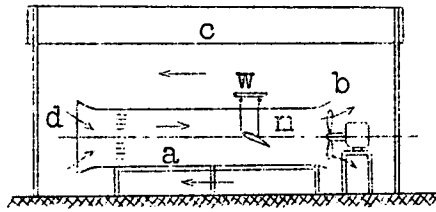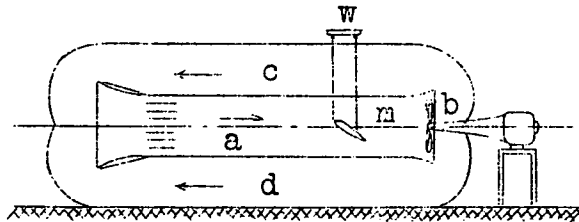National Advisory Committee
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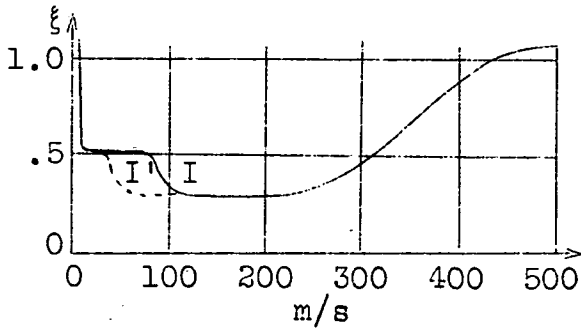
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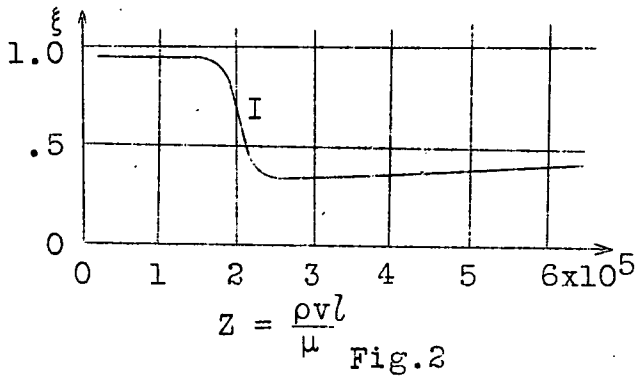


$$Z = \frac{\rho v l}{\mu}$$ Fig.2



Fig.3



Fig.4

Fig.5



Fig.6



Fig.7