without having in mind a specific airplane to which the results are to be applied, or they may be conducted on a scale model of an existing or proposed airplane with a view to predicting the performance and flying qualities of the full-scale airplane.

Tests of the first class usually involve systematic changes in the model configuration and routine measurements of the forces and moments acting on the model. The model might for example represent a horizontal tail surface consisting of the stabilizer and a movable elevator. Systematic changes could be made in the elevator nose-shape, and the investigation could be extended by testing each nose-shape with each of several elevator hinge-line positions. The data accumulated from such a series of tests would be of value to an airplane designer because it might turn out that one of the combinations of elevator nose-shape and hinge-line locations tested had just the characteristics he requires, but whether this were true or not, the data would enable him to predict, probably with considerable accuracy, the characteristics of a new and untried combination.

Even though the airplane designer makes use of many data of the sort just described, he must still resort to tests of the complete airplane in order to make sure that the final design meets all requirements. A scale model of the airplane is built which reproduces very accurately all the details of the external shape of the airplane. The internal structure of the airplane is not reproduced in the wind tunnel model, since the forces measured by the wind tunnel balances are caused solely by the flow of air over the model. In addition to including such details as gun turrets, bomb-bay doors, retractable landing gears, etc., wind tunnel models have movable flaps and control surfaces, and are frequently tested with running propellers driven by small electric motors contained within the model. From the point of view of design, it is necessary to know not only the forces and moments acting on the complete airplane, but also the increment added by each part of the airplane separately. For this reason, the model is built so that the wing alone may be tested without the fuselage, nacelles, or tail surfaces. The model may be built up by adding the fuselage, nacelles, tail surfaces, gun turrets, etc., in turn, so that the effects of each component of the airplane on the characteristics of the airplane as a whole may be investigated. Thus it is possible to trace the origin of good or bad characteristics and to determine details of the design which require revision to effect improvements.

With the development on the one hand of airplanes of very large size, and on the other of airplanes with extremely high speeds, it has become necessary to build wind tunnels of greater and greater complexity in order to enable the testing of models under conditions which correspond closely to those met by the full-size airplane.

The Cooperative Wind Tunnel is capable of producing an air stream of very high speed and it is anticipated that tests will be carried out at air speeds up to the speed of sound (750 miles per hour). Such tests will provide much useful information regarding the so-called "compressibility effects" which play such a large part in the flight of a high-speed airplane, but concerning which there is much to be learned.

Aerodynamic theory demonstrates, and it may be observed experimentally, that under identical conditions a small scale model does not possess exactly the same characteristics as the full-size airplane, so that the forces and moments measured by the wind tunnel balances do not correspond exactly to those which affect the motion of the full-size airplane. However, the small scale of the wind tunnel model may be compensated for by increasing the density of the air stream in which it is tested. It is for this reason that the Cooperative Wind Tunnel is of the variable-density type, capable of testing models at air pressures up to four times atmospheric pressure (58.8 pounds per square inch absolute). The tunnel may also be operated under reduced pressures down to approximately 0.1 of atmospheric pressure (1.5 pounds per square inch absolute). An advantage of this arrangement is that at low pressures, less power is required to produce a high-speed air stream than is required at atmospheric or higher pressures.

STRUCTURAL FEATURES

THE geometry of the Cooperative Wind Tunnel is similar to that of other well-known wind tunnels now in operation, such as the Wright Field 20-foot tunnel, the Wright Brothers Memorial Wind Tunnel at Massachusetts Institute of Technology, and the Boeing Tunnel at Seattle. Since there are great advantages in being able to control the pressure of the air in the duct, the Cooperative Wind Tunnel was designed so that air could be maintained at any desired pressure between approximately 1.5 pounds per square inch absolute and 58.8 pounds per square inch absolute.

Since the duct acts as a pressure vessel, it was designed in accordance with standard practice for such vessel. The duct is constructed of steel plate approximately one inch thick and is arc welded. Approximately 3,000,000 pounds of steel were used in the fabrication and erection of the tunnel. Approximately 17 miles of electric arc welding were required. Large sections of the duct were prefabricated in the shops of the Consolidated Steel Corporation in Maywood, California, and trucked from there to Pasadena, where they were erected by the company's field force.

The tunnel is supported on eight columns, as indicated in *Fig.* 3. The general construction is shown in *Fig. 4.* These columns have spherical ends so that each is the equivalent of a portion of a sphere 18 feet in diameter. The tunnel is free to "roll" on the eight columns—at least so far as the columns are concerned. The tunnel is restrained from moving horizontally (in any direction) by a pin which is located midway between columns three and four and engages a plate welded to the tunnel. The tunnel is restrained from rotating about this pin by a link which connects the tunnel and the base of column seven. Thus the tunnel is restrained horizontally in a statically determinate manner. It can expand or contract without restraint.

After the tunnel was completed (structurally) the distribution of the weight between the eight columns was measured and then redistributed to conform to design assumptions. The load in each column was measured by mounting a special (20-foot) extensometer on each column. The zero reading was determined by jacking the tunnel up so as to take the weight off the columns (four at a time). It was found that column three was carrying about 50 per cent more than its design load and that column four was correspondingly unloaded.

The problem of transferring the concentrated loads from the columns to the shell in such a manner as to avoid unduly high stresses is a complicated one. The basic theory can be found in Timoshenko's *Theory of Plates and Shells.* Herman Schorer in an article entitled "Design of Large Pipe Lines," published in *Transactions of the A. S. C. E. 1933,* clearly illustrates the application of the theory.

The corners of the tunnel contain turning vanes for efficiently turning the air (see *Figs. 5 and 6*). These are mounted in an elliptical section about three feet long, which is inserted between the ends of the cylindrical shells. The forces acting on the elliptical ring are the following:

(a). Dynamic air forces on the vanes.
(b). Air pressure on inside of elliptical ring.
(c). Loads due to stresses in shell plate wherever it is intersected by the elliptical ring.

Loads (a) and (b) are fixed and do not depend on the elastic properties of the elliptical ring. Loads (c) are known if the elastic properties of the elliptical ring correspond to those of the cylinder which has been cut away. This relationship, however, is very difficult to establish.

Two types of construction were considered:

1. The ends of the vanes to be fastened to the elliptical ring so as to act as stay bolts.
2. The ends of the vanes to be fastened through slip joints so that no axial loads could be transmitted to the vanes.

Both types of construction had been used previously for wind tunnels, but no data were available on which a choice could be based. The staff of the Cooperative Tunnel selected method (1) above, because in their opinion it saved considerable material, eliminated a lot of "dirty" expansion joints and provided a much more rigid elliptical ring, thus being much more satisfactory so far as carrying loads (c) above. A typical corner may be seen at the right of *Fig. 4*.

A design of the elliptical ring was made on the basis of statics, neglecting bending stresses in the ring and assuming that the loads due to stresses in the shell were not changed because of the elastic properties of the ring. These assumptions seemed reasonable, but it was felt that some further substantiation was necessary; so a scale model was constructed (six feet in diameter—approximately one-fifth scale). Because of the materials available, the dimensions of the model were such that a pressure of 53 pounds per square inch on the model caused the same unit stresses as would a pressure of 47 pounds per square inch in the tunnel. The model is shown in *Fig. 7*.

The stresses in the model were measured by using Huggenberger strain gages on the elliptical rings and shell, and dial gages on the vanes. The results showed that the model had not been built with sufficient accuracy to secure the results ultimately desired, but nevertheless they showed that the design assumptions were satisfactory. After the stress measuring program had been completed, the model was proof-tested as this practice is defined in the A.P.I.-A.S.M.E. code. This test consisted of painting the surface of the model with whitewash and then gradually raising the pressure until flaking of the whitewash indicated yielding of the material. The pressure in the model reached 175 pounds per square inch before any flaking of the whitewash was detected. The pressure was then gradually increased to 225 pounds per square inch. At this pressure the distortion was large over the entire model and there seemed to be no reason for carrying the pressure higher.

The decompression sphere was designed on somewhat the same basis as the corner structures. A model of this section was also built and tested in a similar manner. In general the model test results indicated satisfactory behavior.

The fan for the 10 foot *Galcit** tunnel until quite recently has been equipped with wooden blades. During approximately 15 years of operation a number of wooden fan blades have been wrecked and on one occasion the loose blades broke through the comparatively thin concrete shell surrounding the fan. The fan blades for the cooperative tunnel are aluminum alloy, so that there is every reason to believe that the danger of losing a fan blade is negligible; nevertheless an attempt has been made to provide for that contingency. The fan shaft and bearing supports are strong enough to resist the unbalanced certrifugal force occasioned by the loss of one-half of the blades—all on one side of the hub. The shell surrounding the fan section is twice as thick as required by pressure considerations. It is further reinforced by a steel cone, filled with concrete, surrounding the shell at each fan.

The shell and the reinforcement of openings, etc., conform to the A.P.I.-A.S.M.E. code. The stiffening rings, which prevent the shell from collapsing because of external pressure, were designed so as to buckle under an external pressure of 60 pounds per square inch. The design formulae can be found in Timoshenko's *Strength of Materials* or *Theory of Elastic Stability*.

MAIN DRIVE POWER PLANT AND CONTROLS

THE fan system in the Cooperative Wind Tunnel is driven by a two-element electric motor set with a peak rating of 12,000 *hp*. The basic unit of this set is a variable speed direct current motor supplied through a separate motor-generator, which is made up of a variable voltage direct current generator directly coupled to and driven by an alternating current motor of the synchronous type. These three machines, comprising the direct-current system, have a top rating of approximately *2,000 hp* at from 300 to 570 *rpm*. Power requirements beyond the capacity of the direct current system are supplied by an alternating current, adjustable speed, induction motor provided with a wound rotor and slip rings and carrying a short time rating of 10,000 *hp*. The speed and torque of this alternating current machine are controllable by means of a slip regulator of the liquid rheostat type, involving movable electrodes immersed in an electrolyte solution. Both motors are separately forced air cooled and are assembled as a three-bearing set, driving the fan propeller shaft directly through flexible couplings. A portion of the power room is shown in *Figs. 8 and 9*. One of the power panels is shown in *Fig. 10*.

This split system of drive motors was devised to take advantage of standard developed machines in a combination providing flexibility and reliability at moderate cost. The particular combination selected, in conjunction with a controllable pitch propeller fan system, is calculated to permit comparatively high efficiency operation over the complete speed and power range and at the various air densities attainable. This is possible since a substantial portion of the high air speed region may be operated at approximately full shaft speed, thus effecting low slip losses in the induction motor secondary resistive device. The reader is reminded that appreciable losses are inherent in the operation of such an induction motor substantially below its designed top speed. Full advantage is taken of the wind tunnel characteristic that power requirements at various speeds are essentially proportional to the cube function of the comparative speeds, so that at one-half the maximum air speed only one-eighth, or roughly 1500 *hp*, is required to drive the fan.

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