REPORT No. 127

AERONAUTIC INSTRUMENTS
SECTION III

AIRCRAFT SPEED INSTRUMENTS

IN THREE PARTS

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Bureau of Standards

REPORT No. 127.

AIRCRAFT SPEED INSTRUMENTS.

PART I.

AIR-SPEED INDICATORS.

By Franklin L. Hunt.

INTRODUCTION.

This report is Section III of a series of reports on aeronautic instruments (Technical Reports Nos. 125 to 132, inclusive) prepared by the Aeronautic Instruments Section of the Bureau of Standards under research authorizations formulated and recommended by the Subcommittee on Aerodynamics and approved by the National Advisory Committee for Aeronautics. Much of the material contained in this report was made available through the cooperation of the War and Navy Departments.

TYPES OF AIR-SPEED INDICATORS.

The air-speed indicator, as its name implies, is an instrument which shows the speed of aircraft relative to the air. It gives the speed with reference to the ground only when no wind is blowing. The ordinary air pressure type is also used as a buoyancy meter to warn the aviator when he is approaching the stalling speed at which flight can no longer be sustained, or, in rapid descent, when the air speed is becoming excessive.

The most usual forms of air-speed indicator, the Pitot and Venturi types, depend for their action on the pressure difference developed in suitably constructed pressure nozzles by their motion relative to the air. These pressures vary with the speed of the airplane in a manner which may be definitely determined for each form of nozzle.

The complete instrument consists of two parts, the pressure nozzle, which is located ordinarily on one of the outer struts of the airplane well outside of the propeller slip stream, and the indicator, in effect a sensitive pressure gage, which is fastended to the instrument board in the body of the airplane. The pressure nozzle and indicator are connected by metal tubing, which runs along the strut and the edge of one of the wings.

Pressure nozzles commonly used are of two types, (1) Pitot nozzles in which pressures greater than those of the surrounding atmosphere are developed by the impact of the air at the open end of a straight tube pointed in the direction of motion, and (2) Venturi nozzles in which pressures less than those of the surrounding atmosphere are obtained by the rush of air through the throat of a double-coned suction nozzle. In some cases the Pitot and Venturi are combined so as to add the effects of both.

The pressure developed by Pitot tubes is expressed by the relation

$$p=\frac{1}{2}\rho V^2 \qquad (1)$$

In which p is the pressure

ρ is the density of the air

and V the speed.

Numerical relationships between air speed and the pressure developed by Pitot nozzles are shown in figure 2.

Venturi nozzles are also designed to give pressures which vary as the air density and the square of the velocity over the ordinary range of airplane speeds.

The above equation may be expressed in the more general form

$$p = K\rho V^2 \tag{2}$$

The coefficient K is dimensionless, and its value is consequently independent of the system of units chosen, provided the units are consistent. In the case of Venturi tubes, however, the value of the coefficient depends upon the form of the tube, and at low speeds is also dependent upon the speed. Numerical relationships between air speed and the pressure differences developed by various types of Venturi nozzles are shown in figure 4.[1]

Since the readings of instruments of the pressure type are directly proportional to the density of the air, they read correctly for a specific density only. The standard density now commonly used in aerodynamics is .001223 gms/cm^3, corresponding to the density of dry air at a temperature of 15°.6 C. under a pressure of 760 mm. of mercury.

In practice, arrangements must also be made to determine the static pressure at the point where the Pitot or Venturi nozzle is placed. For this purpose a tube closed at its leading end and with a concentric ring of small holes or narrow slots at the side is used. This tube is pointed in the direction of motion, so that the rush of air past the openings at the side of the tube is at right angles to these openings. The static pressure within the tube is in this manner maintained the same as that of the undisturbed air without. In nozzles where both Pitot and Venturi tubes are used the static head is eliminated.

The indicator proper, or pressure-measuring element, consists ordinarily of one or more corrugated metal capsules inclosed in an air-tight case or of an air-tight case separated by a membrane of rubber or doped fabric into two air-tight chambers. The dynamic opening of the pressure nozzle is connected to the capsules, or in the rubber or doped fabric diaphragm-type to one of the air-tight chambers. The static opening is connected to the air-tight case, or in the membrane diaphragm-type to the second air-tight chamber. In Pitot-Venturi instruments the Pitot is connected to the case or one of the air-tight chambers and the Venturi to the other, no static head being used. The differential pressure developed in the pressure nozzles causes the diaphragms to expand or contract, according to the magnitude and direction of the excess pressure. This motion is carried by a suitable transfer mechanism to a pointer and indicates the corresponding speed on a dial.

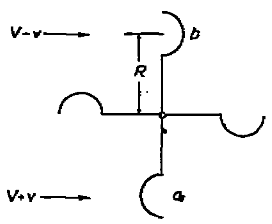
Other types of air-speed indicators have been suggested and used to a limited extent. Instruments depending on the pressure developed on a flat plate at right angles to the direction of motion have been used. In these the plate is attached to a lever whose motion is resisted by a spring. The amount of displacement of the lever, which is a measure of the air speed, is indicated by the motion of a pointer attached directly to the lever or through the intermediary of a sector and pinion. These instruments are ordinarily mounted on one of the struts of the airplane and read by the pilot at that distance. Although light and compact in arrangement and of a simple construction, they are not so accurate as the best indicators of the pressure-head type. Instruments of this type obey the ρV^2 law, for which the above-mentioned formula (2) applies.

Instruments of the anemometer type have been extensively used in Germany. In these the air speed is determined by the rate of revolution of a cup anemometer, which is attached to a tachometer or rate-of-revolution indicator. These instruments are also self-contained and are located on a strut of the airplane, from which position they are read at a distance by the pilot. Instruments of the anemometer type with distant control have also been suggested. In this form the anemometer alone is located on the strut. Wires lead from it to the indicator which is on the instrument board in the fuselage. The speed of rotation of the tachometer element of

[1] For a detailed discussion of the theory of Pitot and Venturi tubes see Annual Report of the National Advisory Committee for Aeronautics 1915, Report No. 2 by W. H. Herschel and E. Buckingham. Also see Report of National Advisory Committee for Aeronautics 1918, No. 31, on the Development of Air Speed Nozzles, by A. F. Zahm.

the indicator is maintained the same as that of the anemometer by a synchronizing commutator connected to the anemometer spindle. The energy required to drive the indicator is supplied from a battery or generator. Only the energy required to overcome friction is taken from the rotating anemometer itself.

Air-speed indicators of the anemometer type give the actual air speed at all altitudes, since their indications are practically independent of the density of the air. Their behavior may be explained in an elementary manner by assuming the motion to depend only upon the forces acting on the cups a and b, whose axes are perpendicular to the direction of motion, the effect of the cups in other positions being considered negligible.



If V is the velocity of the wind and v the linear velocity of the cups, the velocity of the air relative to cup a is evidently $V+v$ and that relative to cup b, $V-v$. Knowing the density of the air ρ, the coefficients of air resistance k_a and k_b for the cups a and b, the central cross section of the cups A, and the radius R from the axis to the center of the cups, neglecting friction, the driving couple is

$$k_b \rho A (V-v)^2 R \tag{3}$$

and the resisting couple

$$k_a \rho A (V+v)^2 R \tag{4}$$

The speed of rotation of the cups will increase until these couples are equal; that is, until

$$k_b \rho A (V-v)^2 R = k_a \rho A (V+v)^2 R \tag{5}$$

Assuming $k_a = 0.033$ and $k_b = 0.019$, as determined by Renard

$$\frac{V}{v} = 3.5 \tag{6}$$

The ratio $\frac{V}{v}$ is independent of the density of the air and hence of the altitude.

Experiments have been carried out in the Aerodynamic Laboratories at Gottingen, in Germany, which show that this ratio is practically constant over the range of velocities ordinarily experienced in airplane flight. For air densities up to an altitude of 5,000 meters and velocities above 100 kilometers per hour the variation of the ratio $\frac{V}{v}$ is considerably less than 1 per cent.

Efforts have also been made to determine air speed by the rate of flow of air through a suitably constructed flow meter. Experimental instruments of this type have been made which consist of an air-tight cylindrical chamber with a radial vane, rotatable about the axis of the cylinder. Air from a pressure nozzle similar to a Pitot nozzle is conducted into the chamber between the radial vane and a fixed radial partition so as to rotate the vane in opposition to a restraining hairspring by an amount depending on the pressure. The air flows out of the instrument by way of the clearance between the vane and the ends of the cylinder, which clearance is varied in a predetermined manner by suitable cam surfaces on the inside of the ends of the cylinder so as to give the instrument a uniform air-velocity scale.

Small propellers or helical air screws mounted on a strut of the airplane and connected to an indicating tachometer on the instrument board by electrical commutators have also been tried.

In another type the rotation of the propeller is resisted by springs, so that the resultant motion is limited to a fraction of one revolution. By a suitable transfer mechanism this motion is transmitted to the indicator, which is directly connected to the propeller support. The instrument is mounted on a strut and read by the pilot at a distance. It has also been proposed to use a propeller to operate a small magneto, the current from which is conducted by wires to an indicating galvanometer on the instrument board. The possibility of slip entering as a disturbing factor has to be considered in an instrument of this type, since an appreciable amount of energy is taken to operate the indicating element.

Hot-wire anemometers have also been designed in which the cooling effect of a stream of air on an electrically heated wire grid is taken as a measure of the air speed.[2] The amount of energy dissipated from such a grid is found to be directly proportional (1) to the temperature difference between the grid and its surroundings (2) to the square root of the velocity and (3) to the square root of the density of the air stream. Consequently if the grid is openly exposed to the full wind stream it is insensitive at the higher velocities. This difficulty has been overcome in a recently proposed device in which the grid is inclosed in a stream-line envelope provided with a perforated plug at the incident end. The velocity of the air which passes the grid is thereby greatly reduced and the sensitiveness of the instrument at high velocities mark-

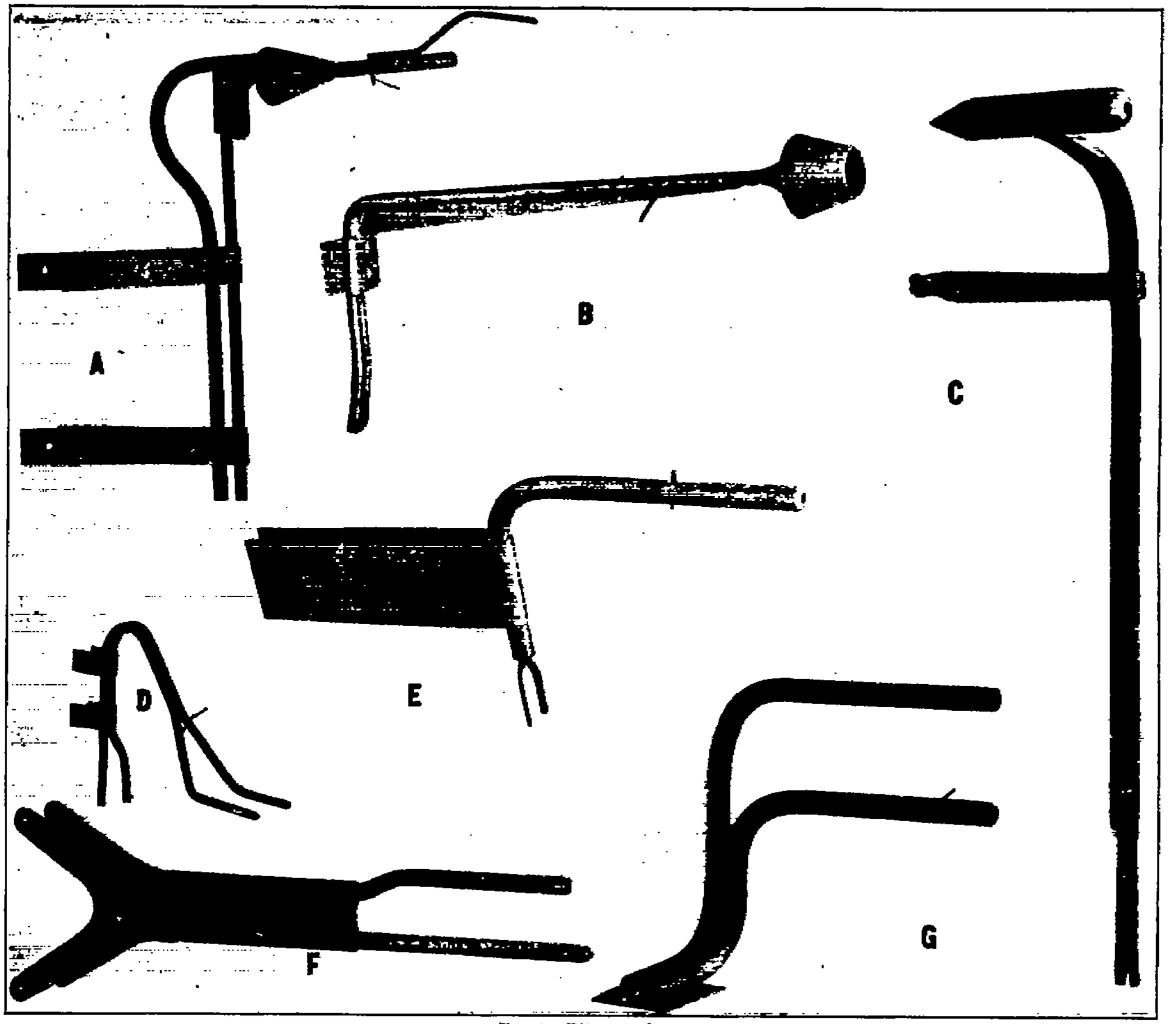


FIG. 1.—Pitot nozzles.

edly increased. By varying the size of the perforations in the plug the instrument can be made sensitive for the desired range of velocities. The grid is maintained at a constant temperature of from 200° to 300° C. above that of the air stream by balancing it on a bridge. The air velocity is found by the energy dissipated by the grid. The device is complicated and not suited for ordinary use for determining the speed of aircraft, but might be used in performance tests. Since the readings of the instrument are proportioned to the square root of the product of the density and the velocity and not of the density and the square of the velocity, the device is not a direct reading buoyancy meter as is the Pitot or Venturi meter of the ordinary type. It is also evident that a determination of the air density is necessary before the velocity can be found.

[2] See also, On some proposed electrical methods of recording gas flow in channels and pipes based on the linear hot-wire anemometer, by L. V. King, Journal Franklin Institute, August, 1916, p. 191.

DESCRIPTION OF TYPICAL INSTRUMENTS.

Nozzles.—A group of typical Pitot nozzles is shown in figure 1. A is an early type of British nozzle and B an early type nozzle of American manufacture. The dynamic openings are at the extreme outer ends of the tubes. Each is provided with a hood, behind which the static tube terminates. A slight suction is produced by these hoods, so the tubes are strictly speaking not simple Pitot tubes. C is a German Pitot nozzle. This consists of a tube about seven-eighths of an inch in diameter and 5 inches long. The dynamic opening is at the rounded end. The nozzle tapers sharply at the trailing end. The static openings are in the depressed ring or groove in the side of the tube about 1 inch back from the open end. The tubing which connects the nozzle to the indicator is closed in a stream-line casing. D is an American nozzle in which the dynamic and static heads are separate tubes about one-fourth inch in diameter. These are bent upward at a sharp angle to prevent the accumulation of water in the tubes. The static head has a series of fine concentric holes in the side of the tube. E is a Pitot nozzle of British design in which the dynamic and static tubes are concentric, the dynamic tube being inside of the static tube. The dynamic opening is at the extreme end of the tube. The concentric ring of holes in the static tube can be seen at the side about 2 inches from the end. F is a standard British Pitot nozzle. The static head in this case has 4 concentric rings of holes about one-fourth of an inch apart along the side of the tube. G is a Pitot nozzle in which an annular series of slots are provided in the static head instead of the small round holes which are usually used. Experiments indicate that small round holes are in general a more reliable means of determining the static pressure.

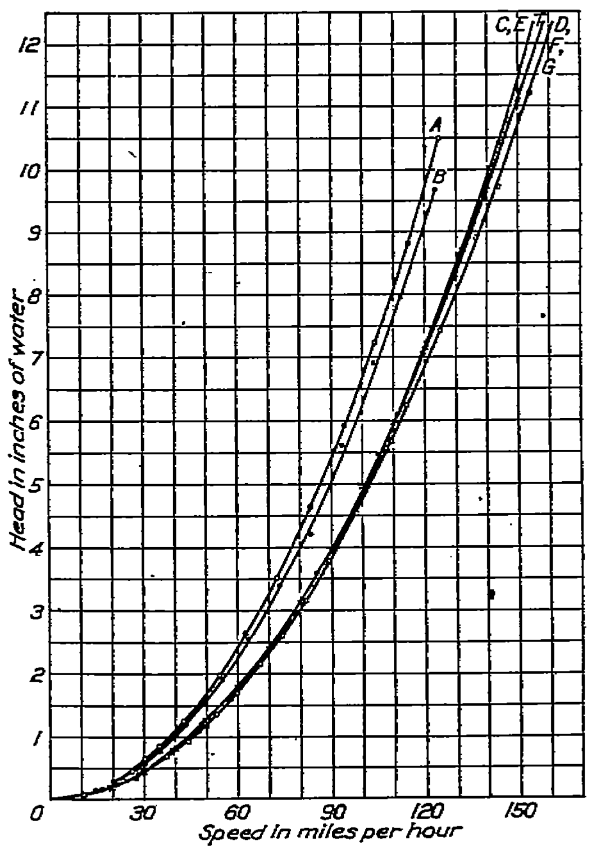


Fig. 2.—Calibration of Pitot nozzles shown in fig. 1.

The pressures developed by these nozzles for the ordinary speed range of airplanes is indicated in figure 2.[3] The curve marked T represents the theoretical values computed by the ρV^2 law. The larger differential pressures developed by nozzles A and B are due to the slight suction caused by the hoods. Nozzles C and E developed pressures which are the same within the experimental error. Nozzles D, F, and G are also practically identical in performance. With the exception of nozzles A and B the values agree closely with the theoretical curve, which shows that Pitot nozzles may differ considerably in the details of construction and still follow closely the ρV^2 law.

A series of nozzles of the Venturi and Pitot-Venturi type are shown in Fig. 3. A represents a single Venturi nozzle of French design. At the side of the tube about two-thirds of the distance from the forward end can be seen an annular row of holes which constitute the static openings. In this nozzle the suction and static tubes are concentric. B is a German double Venturi nozzle and C a French double Venturi nozzle. In both of these a small Venturi tube is located at the throat of the large Venturi tube and concentric with it. A greater differential pressure is thereby obtained than with the single nozzle. In these nozzles no static connection is used. D and G are Pitot-Venturi nozzles made from the design of Dr. A. F. Zahm for use

[3] These results and those on Venturi tubes which follows were obtained in cooperation with the Wind Tunnel Staff of the Bureau of Standards.

on naval aircraft. D is of electroplated copper and G of cast aluminum. These have both a pressure and a suction nozzle. The suction nozzles are distinguished by the long protruding cones and the Pitot nozzles by the short orifices on the supporting arm of the Venturis. By their combined action these nozzles develop a larger differential pressure than either the Pitot or Venturi alone, but they are rather large and heavy. They are attached to one of the outer struts of the airplane with the supporting arm inclined downward at an angle of 45° to prevent water choking the tubes.

Another form of Pitot-Venturi nozzle similar to the Zahm but much smaller and equally effective as regards the differential pressure developed is shown in E. This nozzle was developed

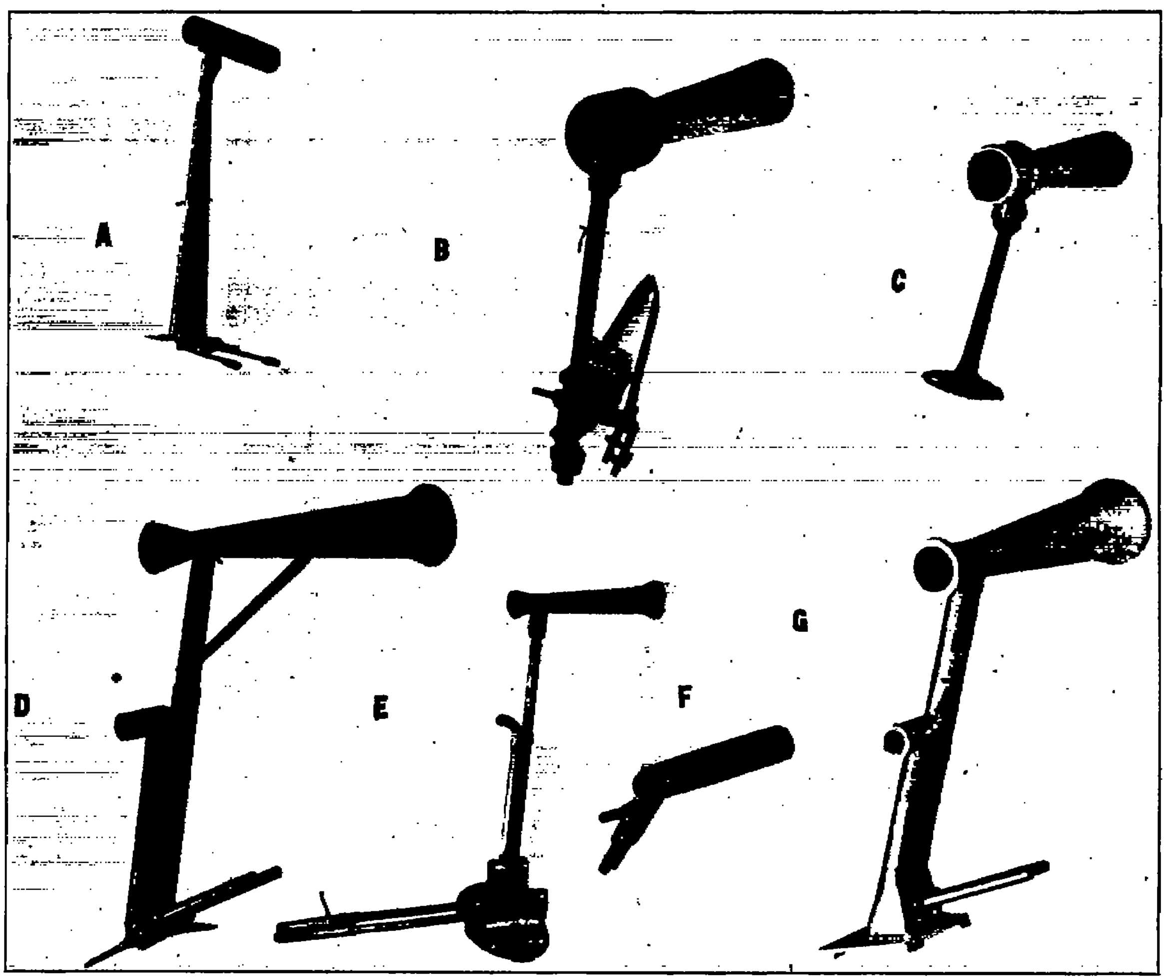


FIG. 3.—Venturi and Pitot-Venturi nozzles.

at the Bureau of Standards in collaboration with the Bureau of Aircraft Production. F is a double Venturi nozzle of French design. The Venturi tube, which is the upper of the two shown in the illustration, is stream lined on the outside. This nozzle was designed for use with the Toussaint-Lepère recording air speed indicator shown in figure 21.

Venturi nozzles have the advantage of developing much greater differential pressures than Pitot nozzles, so that more rugged indicators can be used with them, which is a consideration in view of the vibration and other unfavorable conditions to which the indicator is continuously subjected in use. On the other hand slight differences in the size and shape of Venturi nozzles introduce large changes in the pressures developed so that it is difficult to manufacture Venturi nozzles of required uniformity, while Pitot nozzles are insensitive to wide variations of dimensions and shape. At present Pitot nozzles are used almost entirely in England and Venturi nozzles are generally used in France. During the recent war American nozzles were almost entirely of the Pitot-Venturi type. Most German nozzles are Venturis.

Calibration curves of the above Venturi nozzles are shown in figure 4. The performance of the American Pitot-Venturi nozzles D, E, and G is represented by curve D. E. G. They are all designed to develop the same differential pressures. The French Pitot-Venturi F gives slightly larger values for the differential pressure, but not quite so large values as the single French Venturi A with static connection. At corresponding speeds the two double Venturi nozzles B and C give practically three times the differential pressure developed by any of the other instruments.

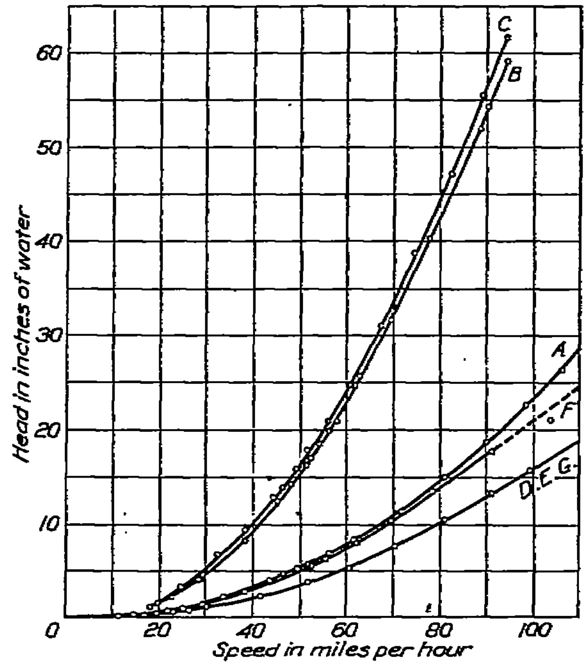


FIG. 4.—Calibration of Venturi and Pitot-Venturi nozzles shown in fig. 3.

Indicators.—The mechanisms of representative air speed indicators of the Pitot and Venturi type are shown in accompanying photographs. Figure 5 is an early Foxboro indicator of American manufacture for use with the Pitot nozzle shown in figure 1B. The nozzle is connected to two batteries of small metal diaphragms D. In addition to the elastic resistance of the diaphragms themselves to the internal pressure developed by the nozzle, small coiled springs S are provided, which connect all of the units of each battery. The motion of the diaphragms is transmitted by the levers L to the sector K which engages a pinion on the pointer shaft. The reservoir R which is inserted between the nozzle connection and the diaphragms is provided to damp the oscillations which would otherwise be set up by momentary fluctuations in the nozzle pressure. This indicator is much larger and heavier than the later types used during the recent war. The scale is also not uniform, being considerably compressed at the low speed end.

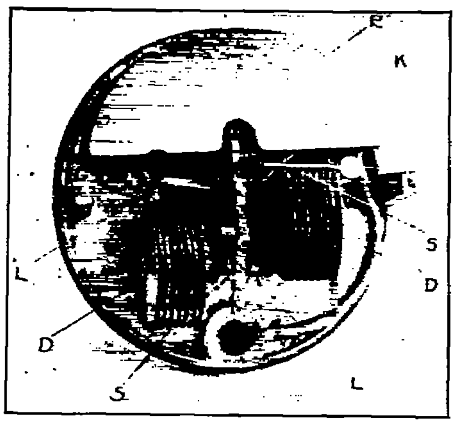


FIG. 5.—Foxboro air-speed indicator, Pitot type.

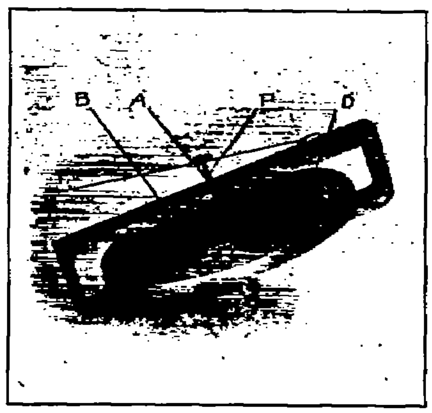


FIG. 6.—Sperry air-speed indicator.

The Sperry instrument shown in figure 6, of American manufacture, is provided with a single corrugated metal capsule D. It is used in connection with the Pitot nozzle shown in figure 1E. The diaphragm D presses against the steel pin P which has a helical groove in its outer surface. A screw A in the frame B engages the groove. The indicating pointer is fixed to the upper end of the steel pin P and as the diaphragm expands the pin P is forced out axially and rotated simultaneously by the action of the spiral groove thereby indicating through the displacement of the pointer, the magnitude of the deflection of the diaphragm. This transfer mechanism is simple, but friction effects are larger than in instruments of the sector and pinion type, and, moreover, it is not practicable to vary the pitch of the spiral groove sufficiently to make the scale uniform.

Figure 7 is the mechanism of a Munroe Pitot indicator of British manufacture which has a single diaphragm made of silver. This diaphragm is connected by a short lever arm to the arbor A. At the end of the arbor is a pin P which terminates at the slot S. The expansion of the diaphragm causes the arbor A to rotate and the pin P to slide along the slot S, thereby dis-

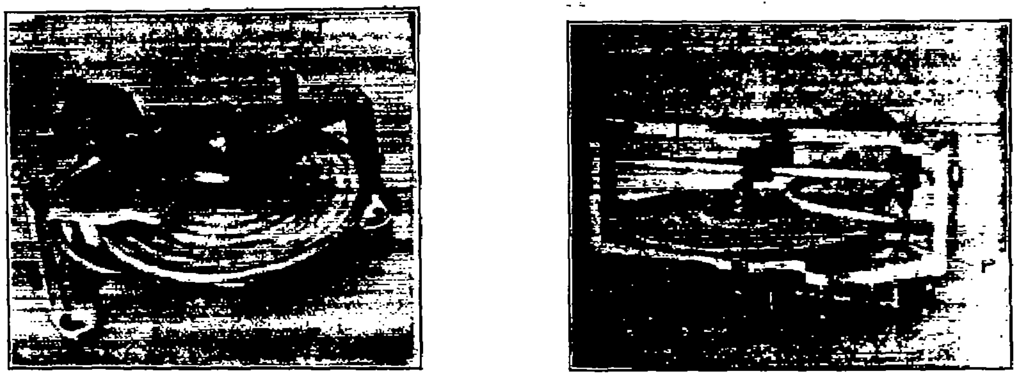


FIG. 7.—Munroe air-speed indicator.

placing the sector T. This sector meshes with a pinion on the shaft of the indicating pointer I. The sliding contact at the slot is used to make the scale more nearly uniform by regulating the direction of the slot relative to the sector so as to increase the relative deflection for the lower velocities. A hairspring is attached to the pointer shaft to prevent backlash.

Figure 8 represents a Smith indicator of the Pitot type. It is of British manufacture. The two corrugated metal diaphragms D which are offset, are connected by a lever mechanism to opposite sides of the arbor A. Otherwise the transfer mechanism is the same as that of the indicator just described. Both were designed for use with a nozzle of the type F, figure 1.

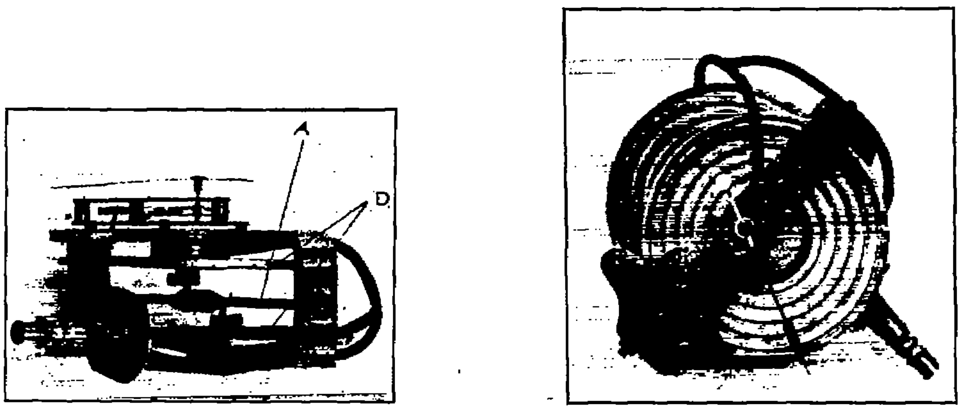


FIG. 8.—Smith air-speed indicator.

The instrument shown in figure 9, an Ogilvie instrument, also British, is provided with a diaphragm D of rubber, the tension of which is regulated to conform to the range of pressures to be measured. It is used in connection with a Pitot tube. The transfer mechanism is very simple. A silk fiber F attached to the center of the diaphragm passes over a small idler M and is wound around the pointer stake T. The pressure nozzle of the Pitot tube is connected to the chamber on one side of the rubber diaphragm and the static connection to the other. The differential pressure thus obtained causes the diaphragm to expand, thereby unwinding the fiber from the pointer stake and indicating a deflection depending upon the pressure developed. The back of the instrument is cup shaped. With increasing pressure the diaphragm expands until it comes in contact with the back, thereby protecting the diaphragm from injury under excessive pressure. This instrument is simpler in construction than any of the others of the same type, but is difficult to readjust if thrown out of adjustment. This indicator was designed for use with nozzle E, figure 1.

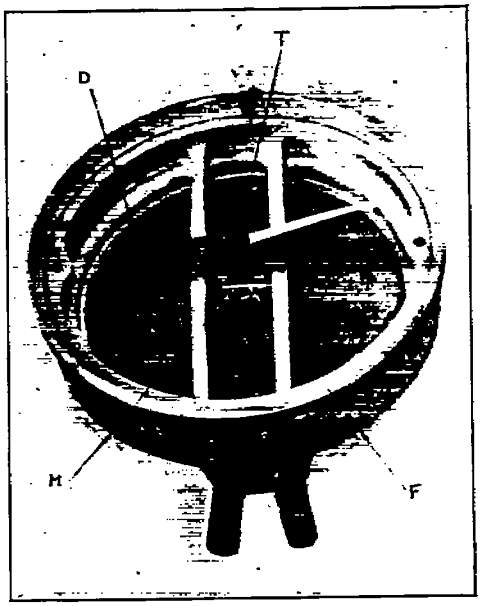


FIG. 9.—Ogilvie air-speed indicator.

Figure 10 shows a Clift instrument which has a diaphragm of doped silk, D. It is of British manufacture. The center of the diaphragm is covered by a metallic disk K at the center of which is a pin P. The pin is in contact with the spring S. A lever L attached to an arbor A rests against the spring S. At the end of the arbor is a pin which engages a slot attached to the sector T in the usual manner. In this instrument the spring S is the elastic member which takes the place of the corrugated diaphragm in the instruments previously described. The air-tight chamber on one side of the doped silk diaphragm is connected to the pressure tube of a Pitot nozzle; that on the other side, to the static tube. As a result of the differential pressure developed the pin P is pressed against the spring S which in turn operates the indicating mechanism by means of the lever L. Nozzle G, figure 1, was designed to use with this indicator.

An Atmos Pitot indicator of German manufacture with doped silk diaphragm is shown in figure 11. A pin attached to the plate P in the center of the diaphragm presses against the

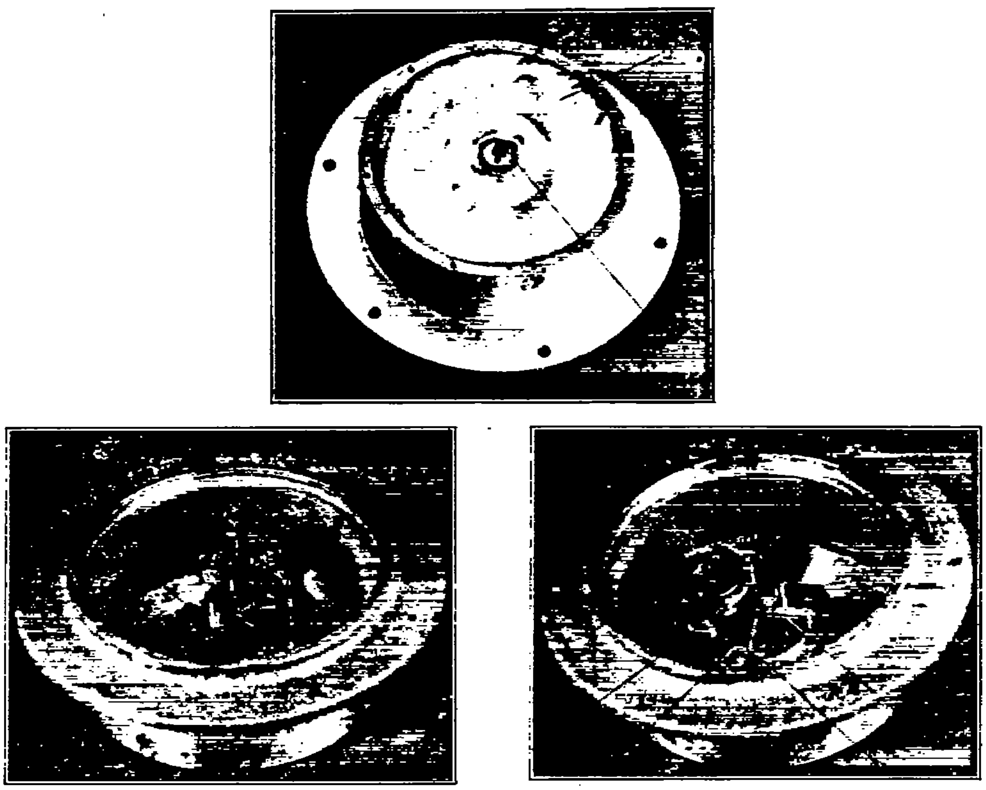


FIG. 10.—Clift air-speed indicator.

spring S which is in contact with the steel ball B at the end of the adjustable lever L which in turn is attached to the arbor A. The pin T also attached to the arbor A supports the fine fiber F which is wound around the stake of the pointer. The expansion of the diaphragm presses the spring S against the ball lever L, thus rotating the arbor A and causing the fiber F to unwind and move the pointer. Above the spring S is a second spring S′ supported at both ends and depressed near the center by an adjustable set screw K. The lower spring S conforms to the curved surface of the upper spring S′ which is adjustable, thus making it possible to vary the openness of the scale. The lever L also provides an additional means of adjustment. This indicator was designed for use with nozzle C, figure 1.

Pitot nozzles are sometimes used with liquid manometer indicators. Figure 12 shows such an indicator, the Pioneer, of American manufacture, designed for use with the nozzle

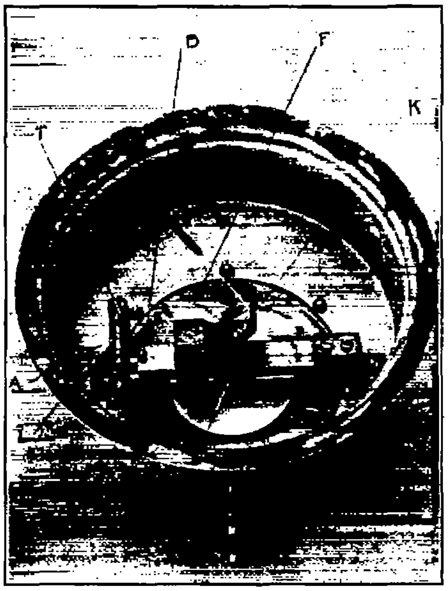


FIG. 11.—Atmos air-speed indicator.

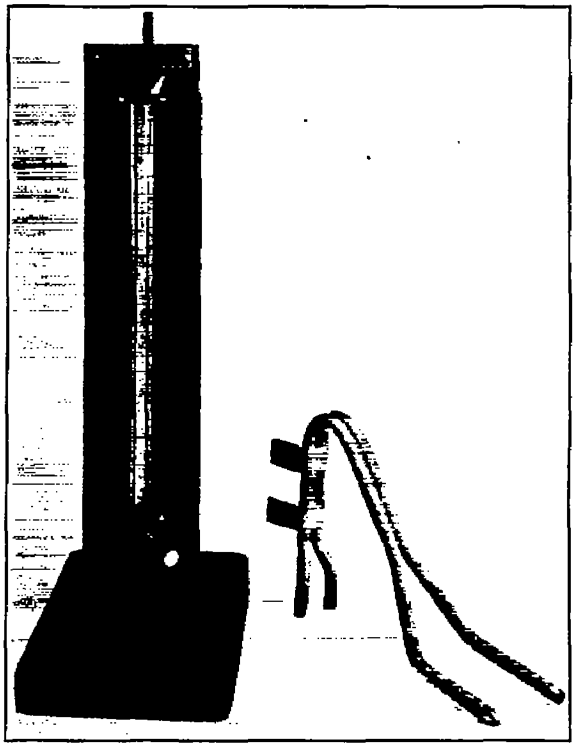


FIG. 12.—Pioneer air-speed indicator, liquid type.

shown and also in figure 1, D. The reservoir at the base is of large diameter compared with that of the column of liquid which indicates the air speed, so that practically all of the motion of the liquid is in the tube. The velocity is read directly from the scale which is graduated in miles per hour. A similar device, the Elliott, of British manufacture, is shown diagrammatically in figure 13. In this case instead of a single large reservoir at the base of the indicator tube two narrow reservoirs A and B are provided, one on each side. There are also safety traps C and D between the indicator and the nozzle connections to prevent the loss of the indicating liquid in case the instrument is inverted. The scale is adjustable for zero correction. The liquid type of indicator is not much used at present. Aside from the possibility of loss of liquid which would give erroneous readings, and also tilting errors the scale of the instrument is not uniform, being excessively compressed at the low velocity end. Moreover, it is the general opinion that a dial with an indicating pointer is much more easily read at a glance than a liquid column so that the former type of indicator is preferred by most aviators.

Figure 14 represents a Badin instrument of French manufacture designed for use with the double Venturi nozzle shown in figure 3C. A single corrugated metal capsule is used. The transfer mechanism is essentially the same as that of the Pitot instruments just described. The motion of the diaphragm D rotates the arbor A and presses the pin P against the sector T, which engages a pinion on the pointer shaft S. The indicator shown is for use with a Venturi tube. Instruments of this design are also used with Pitot tubes. In this case a knife edge projects from the sector T beyond the pivot V. The pin P makes contact with the knife edge on the opposite side of the pivot from that shown in figure 14 so that the direction of the motion

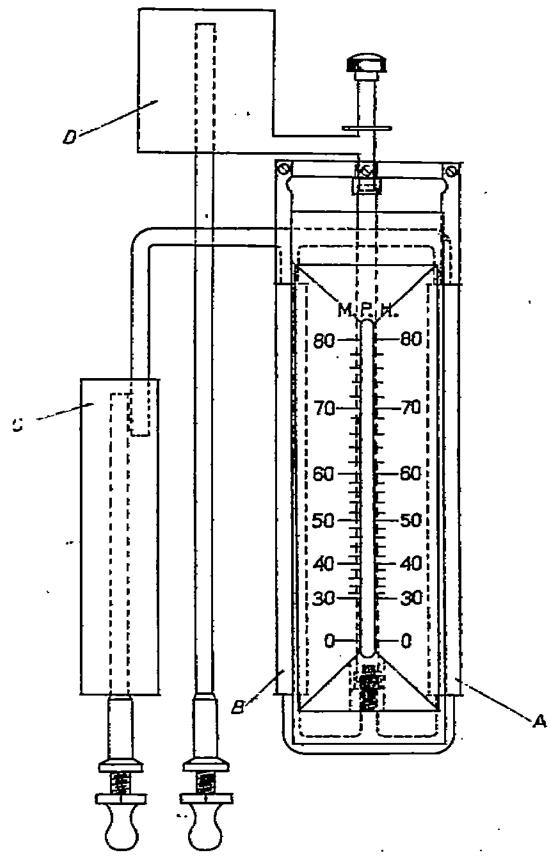


FIG. 13.—Elliott air-speed indicator, liquid type.

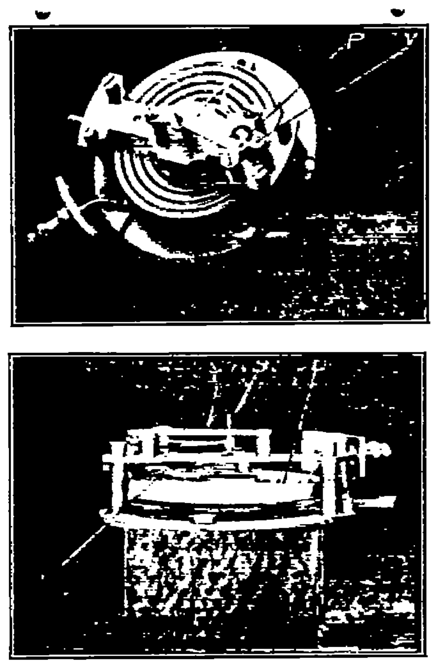


FIG. 14.—Badin air-speed indicator.

of the pointer is the same in both Pitot and Venturi instruments, although in the former case the diaphragms expand and in the latter contract.

Figure 15 shows an improved type of Badin mechanism. A small contact disk P attached to the diaphragm pushes against the jewel J at the end of the short counter balanced lever L

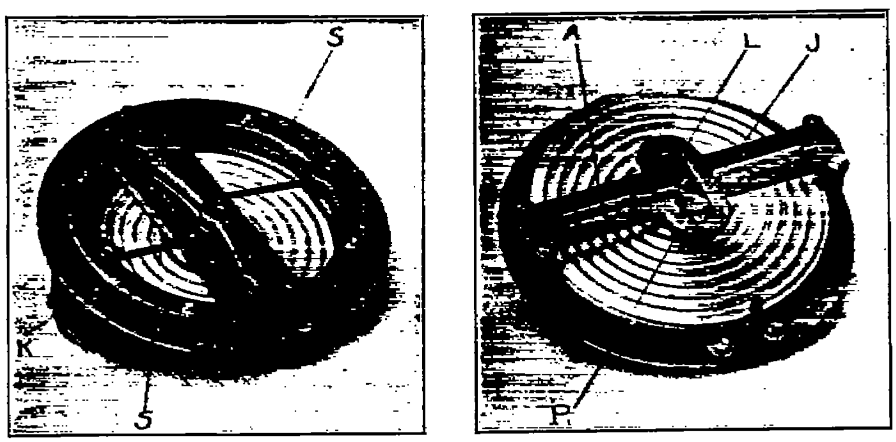


FIG. 15.—Badin air-speed indicator, improved type.

attached to the arbor A. The pin K operates the sector S which meshes with the pinion attached to the pointer. The sector S′ serves as a counterbalance for the sector S. Jeweled bearings are used throughout except those of the arbor A.

The Bruhn indicator shown in Fig. 16 is of German manufacture and was designed for use with the nozzle shown in figure 3B. The mechanism consists of a single bronze diaphragm which contracts, thereby rotating the sector S by means of the connecting strip T. The sector engages a pinion on the stake of the pointer.

Figure 17 represents a Bristol instrument of the Pitot-Venturi type of American manufacture designed for use with nozzles shown in figure 3 D, E, and G, all of which develop the same differential pressure It is provided with two superposed diaphragms. Their motion under the differential pressure of the Pitot-Venturi nozzle is transmitted by the lever L to the arbor A and thence by the pin P to a movement of the sliding contact type identical in principle to those previously described. A coil of capillary tubing C is inserted between the diaphragms and the nozzle connection to dampen the vibration of the pointer under the action of wind gusts encountered in flight. The same result is also sometimes obtained by inserting baffle plates in the connecting tubes. The baffle plates consist of disks of thin metal perforated with small holes. Still another method of damping vibration is to connect the case instead of the diaphragm to the suction nozzle, thereby increasing the volume of air displaced, which tends to neutralize momentary fluctuations in pressure.

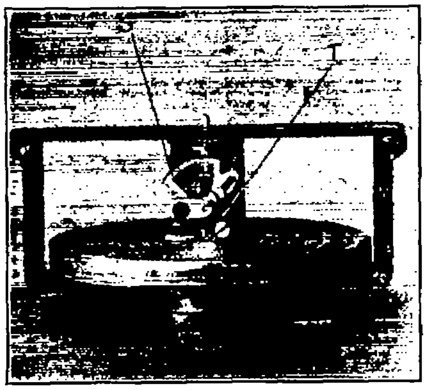


FIG. 16.—Bruhn air-speed indicator.

Figure 18 is a Foxboro instrument of the Pitot-Venturi type, which is made by the same American manufacturer as the Pitot instrument shown in figure 5. It is designed for use with the Pitot-Venturi nozzles shown in figure 3 D, E, and G. The indicator is similar in construction to the Pitot instrument except that in the Pitot-Venturi form the diaphragms contract instead of expanding under the resultant differential pressure. The levers from the diaphragms to the sector are connected so as to make the pointer rotate in the same direction in both instruments. The Pitot-Venturi instrument is also provided with adjustable springs T which are used to give a uniform scale by constraining the motion of the diaphragms when the differential pressure has become sufficient to bring the pins P in contact with the springs T, thus increasing the resistance to motion for the larger velocities for which the differential pressures are proportionally greater.

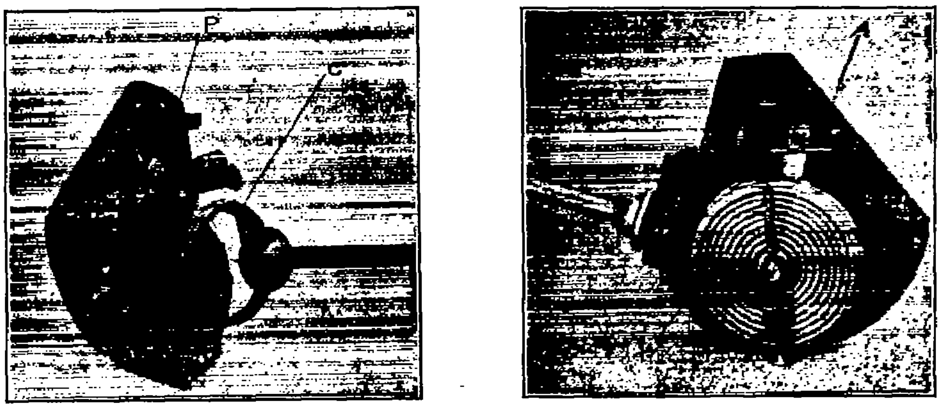


FIG. 17.—Bristol air-speed indicator.

The Precision instrument shown in figure 19, an American instrument of the Pitot-Venturi type designed for use with nozzles D, E, and G, figure 3, is provided with three superposed metal diaphragms. The ball and slot transmission is used but differs from those previously described in that the slot is curved instead of straight. By properly choosing the curve of the cam the scale of the instrument can be made practically uniform. The transfer mechanism is statically balanced by a small weight W attached to the arbor A. The yoke Y is provided with adjusting screws.

Figure 20 shows a King instrument, also of American manufacture, designed for use with the Pitot-Venturi nozzle shown in figure 3 D, E, and G. The motion of the diaphragms is transmitted to the arbor A, at the end of which is fastened a hairpin B of stiff wire which makes sliding contact with a second wire C attached to the sector S. The instrument is adjusted by bending the wire C and the hairpin B. A wide range of adjustment is in this way possible. On the other hand, a slight roughness or corrosion of the wire or hairpin greatly increases the friction errors and slight accidental bending of the wires seriously affects the calibration.

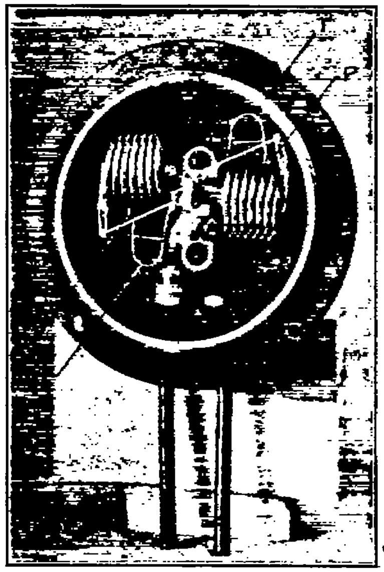


FIG. 18.—Foxboro air-speed indicator, Pitot-Venturi type.

Figure 21 is a Toussaint-Lepère recording air speed indicator of French manufacture. It is also of the Pitot-Venturi type and designed for use with the nozzle shown in figure 3 F. It is provided with two rubber diaphragms which are inclosed in the chambers C and C′. These diaphragms are built up of annular stampings of rubberized fabric which are cemented together in the form of cylindrical bellows. The diaphragms are attached to the connecting rod R which in turn actuates the lever system L and the pen P. The elastic resistance member is the spring S. This in conjunction with the lever system provides a practically uniform scale. The Pitot nozzle is connected to the chamber C and the Venturi to the chamber C′. The record is made on a graduated chart K which is fastened to a drum operated by clockwork.

Figure 22 is a Colombel instrument of French manufacture in which the combined air-speed indicator and altitude readings are obtained on a single chart. The air-speed indicator element is shown at A. It consists of a simple corrugated metal diaphragm element which is connected by a lever system L to the pointer P. It is designed for use with a Venturi nozzle.

A French device of the pressure plate type is shown in figure 23. The displacement of the square plate B under the air pressure developed is opposed by the spring S. The amount of the displacement is a measure of the air speed. This is indicated by the motion of the pointer P.

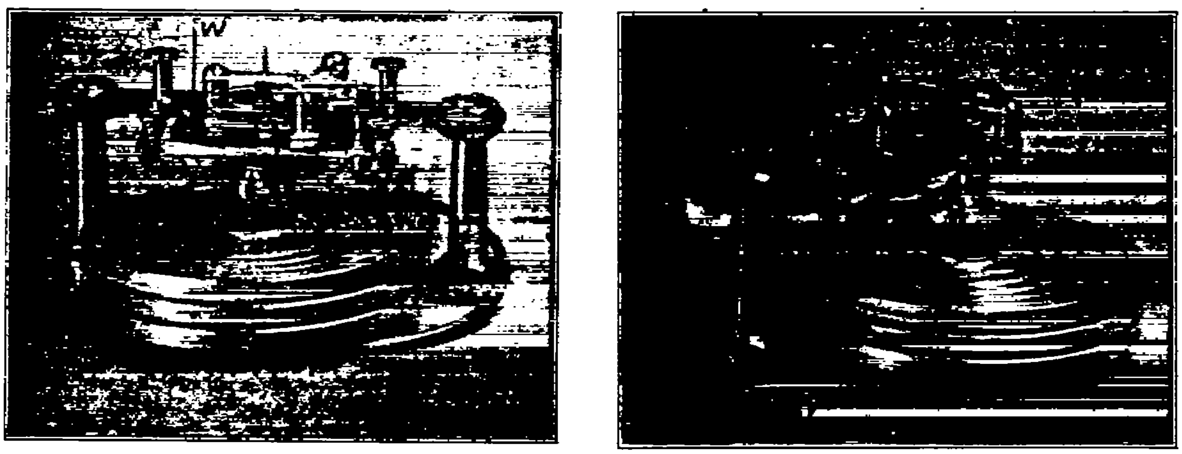


FIG. 19.—Precision air-speed indicator.

The magnitude of the excursion can be regulated by the adjustment of the leverage of the arm A and the tension of the spring at K.

Another instrument of the pressure-plate type, the Pensuti, is shown in figure 24. It is of Italian manufacture and was extensively used on Italian airplanes during the recent war. A small circular aluminum plate P is attached to the lever L. This moves the sector S which

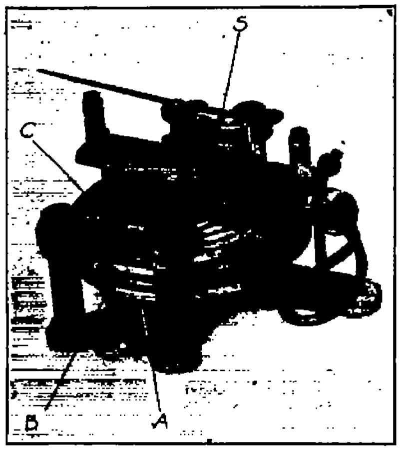


FIG. 20.—King air-speed indicator

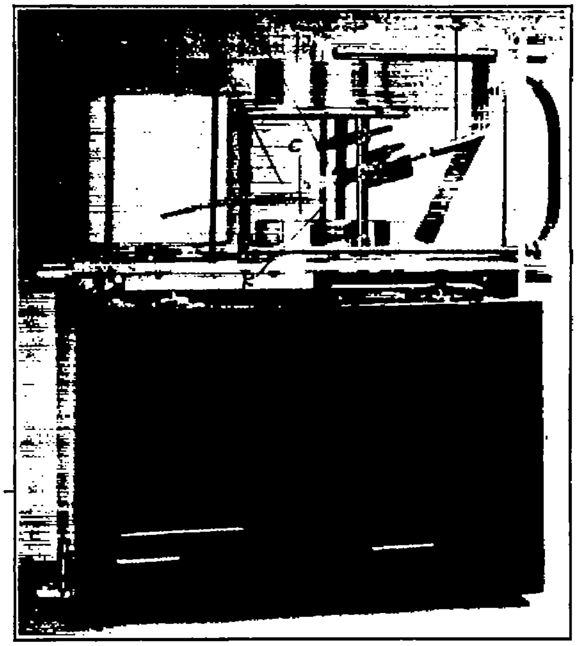


FIG. 21.—Toussant-Lepère recording air-speed indicator.

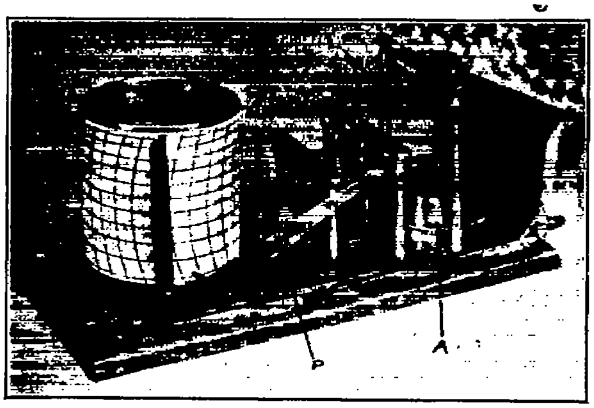


FIG. 22.—Colombel combined recording air-speed indicator and barograph.

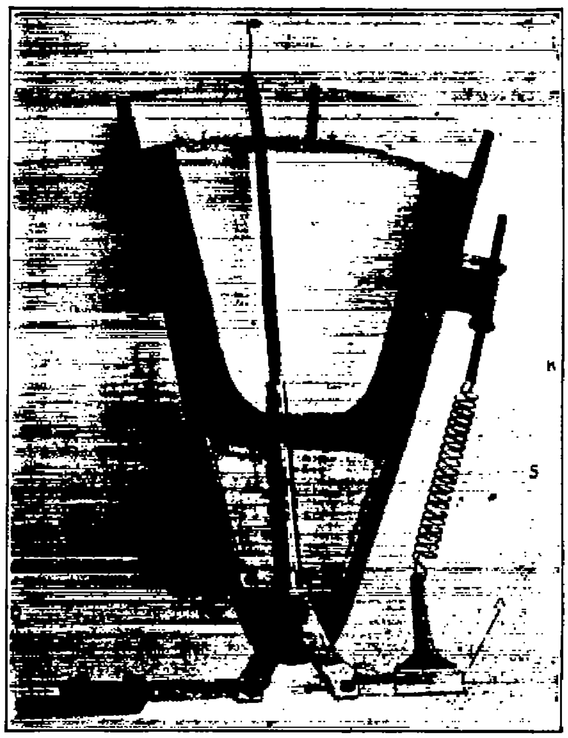


FIG. 23.—Eteve air-speed indicator.

meshes with a pinion on the pointer shaft. The motion of the lever under the air pressure is resisted by a spring R. The amount of the displacement of the lever and the resultant motion of the pointer is a measure of the air speed of the airplane. The dial is marked to indicate minimum, maximum, and ordinary speed, but is not graduated in units of speed. The brass buttons shown on the dial are adjustable, so that the minimum, maximum, and ordinary speed can be

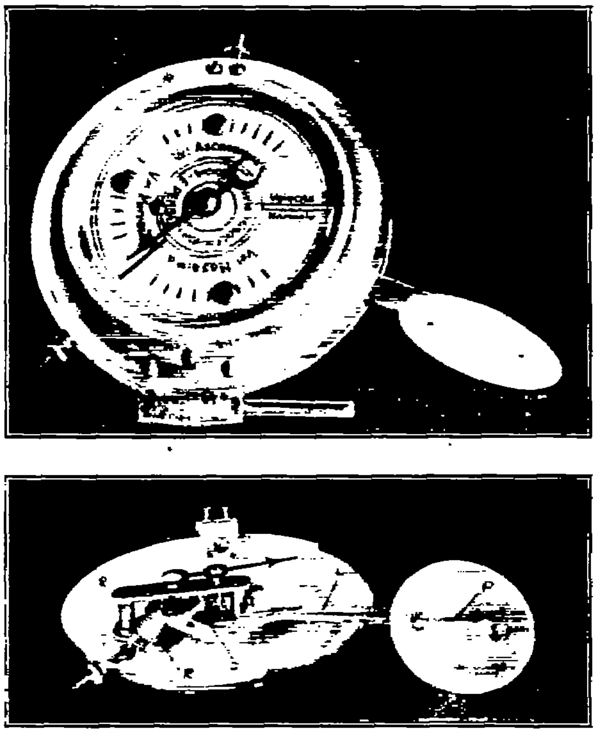


FIG. 24.—Pensuti air-speed indicator.

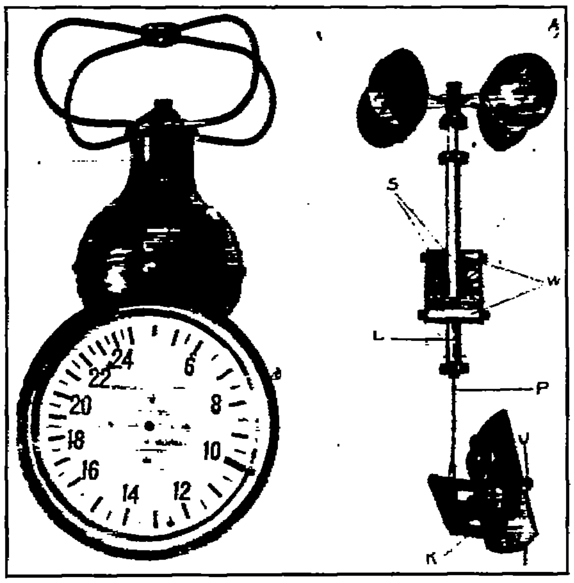


FIG. 25.—Morell air-speed indicator.

changed according to the plane on which the instrument is mounted. The indicator is located on a strut, or in planes of the pusher type near the front of the fuselage.

Figure 25 shows a Morell instrument of the anemometer type, of German manufacture. The rotation of the cup anemometer A forces the weights W of the centrifugal tachometer to which it is attached out from the axis of revolution in opposition to the springs S. This displacement lifts the pin P through the action of the lever L. The lower end of the pin is attached to the sector K which meshes with a pinion on the pointer shaft. The amount by which the pointer is displaced is proportional to the displacement of the weights W which in turn depends upon the rate of revolution of the cups and thus on the speed of the airplane. This instrument is also self-contained and is located on a strut of the airplane or elsewhere away from the propeller slip stream, from which position it is read at a distance by the pilot.

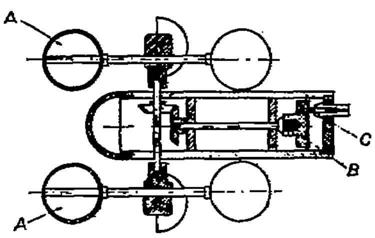


FIG. 26.—Favre-Bulle air-speed indicator.

Figure 26 shows the indicating element of a Favre-Bulle distant reading anemometer air-speed indicator. It has two pairs of cups A connected to a synchronizing commutator B. This commutator converts direct current from a battery or generator into three-phase alternating current which is supplied through bushes C to the field coils of a synchronous motor attached to the indicating element of a centrifugal tachometer on the instrument board. The frequency of the alternating current and consequently the rate of rotation of the tachometer motor depends on the rate of rotation of the commutator.

GENERAL SPECIFICATION AND PERFORMANCE REQUIREMENTS.

Under the conditions of use air-speed indicators are subjected to wide variations of temperature and pressure, to vibration and exposure to the weather. The instruments must, therefore, be carefully designed, and constructed, and made to conform to rigid specifications which from the manufacturer's point of view is difficult because of the inherent delicacy of construction.

The mechanism is ordinarily made of brass to minimize corrosion and the diaphragms, if of metal, of bronze, German silver, or similar alloys. Steel and silver diaphragms have also been used. The dial should be of metal, and adequately thick to prevent warping under service conditions. The case is generally made of aluminum or light aluminum alloy. The entire indicator need not weigh more than 1½ pounds.

The dial graduations should preferably be concentric with the case. Important figures such as 30, 60, 90, 120, and 150 should be about 8 millimeters high to be easily read, and ordinarily are made luminous with radium paint. The scale should be approximately equally divided. The pointer should be counterbalanced, and it is ordinarily illuminated on the indicating end. The bushing should be of brass or other noncorrosive material so that the pointer can be easily removed for resetting. The pointer should be free to swing past the zero point. No stop at zero should be used. It is generally necessary to dampen the movement of the pointer of instruments of the Pitot and Venturi type by inserting a coil of fine copper tubing inside the case between the diaphragms and the suction connection or to insert in the tubing small baffle plates perforated by fine holes.

For convenience of replacement all the parts should be made with sufficient accuracy to insure interchangeability with corresponding parts of any other instrument made to the same specifications.

The relation between the pressure developed at the pressure nozzle and the corresponding air speed should be given by a table or formula, and the indicator required to be accurately calibrated in conformity therewith. For ordinary Pitot nozzles this relation is

$$V=45.18\sqrt{h} \quad (7)$$

For the Pitot-Venturi nozzle designed by Dr. A. F. Zahm and at present used by the United States Aviation Service

$$V=17.89\sqrt{h} \quad (8)$$

where V is the velocity in m. p. h. and h the corresponding differential pressure in inches of water.

It is practicable to make air-speed indicators so that the scale errors at room temperature do not exceed 1 per cent of the total scale range at any part of the scale. When calibrating, readings are usually taken with the dial vertical while tapping the indicator to eliminate friction errors, and with both increasing and decreasing scale readings. Indicators should be calibrated at low and high temperature as well as at room temperature since a wide variation of temperature is experienced in flight. The maximum scale errors over a temperature range from −10° C to +40° C should not exceed 2 per cent of the total scale range at any part of the scale, when readings are taken both with increasing and decreasing scale readings and with tapping.

To test the effect of continued vibration such as is experienced in use, the indicators are subjected in the laboratory to vibration on a suitably constructed vibration stand for several hours. During vibration they are generally maintained at approximately half scale deflection in which condition the pointer should not oscillate appreciably, certainly not more than 1 per cent of the total scale range. After vibration for at least five hours, the errors at no part of the scale should exceed 1 per cent of the total scale range.

To test the effect of changes of position, readings should be taken in laboratory tests when the indicators are changed from a vertical to a horizontal position and when rotated laterally to the right or left through an angle of 90°. The differences should not amount to more than

1 per cent of the total scale range. The pointer should move smoothly under a uniformly increasing pressure sufficient to give full scale deflection in not less than 15 seconds. As a further test of friction the difference in readings before and after tapping is taken. This should not exceed 1 per cent of the total scale range.

The elastic properties of the diaphragms may be tested by subjecting the indicators for at least one minute to a differential pressure approximately 50 per cent greater than that required to produce full scale deflection. Not more than five minutes after the release of the pressure the pointer, with tapping, should return to zero within the linear equivalent of one per cent of the total scale range. While under this pressure diaphragms and case may be tested for leaks. As a further indication of the elastic behavior of the diaphragms the indicators may be subjected for several hours to a pressure sufficient to give full scale deflection. After the release of this pressure the pointer should return, with tapping, within five minutes to approximately zero.

The pointer should have sufficient quickness of response to return to rest within one second after the release of a pressure corresponding to a deflection of approximately 100 miles per hour, and after a sudden change of pressure, corresponding to approximately 10 miles per hour, the pointer should assume its new position within one second.

RESULTS OF TESTS ON AIR-SPEED INDICATORS AT THE BUREAU OF STANDARDS.

The results [4] of tests conducted recently at the Bureau of Standards on Pitot-Venturi instruments are given in Table 1. The instruments are grouped according to the manufacturer as indicated in column 1. Column 2 gives the number of instruments subjected to the tests indicated in the succeeding columns, with the exception noted at the bottom of the table. In column 3 are the average scale errors in miles per hour computed by first finding the average of the errors without regard to signs for each instrument and then the average of these averages for each make of instrument. In column 4 are the average differences of readings with increasing and decreasing deflection computed in the same manner; in column 5, the average difference in reading before and after tapping the instruments; in column 6, the average change in reading due to maintaining the instruments at full scale deflection continuously for five hours; in column 7, the average change in reading due to subjecting the instruments momentarily to a pressure 50 per cent greater than that corresponding to full scale deflection. The instruments of groups B and C were made by the same firm, but those in group C, which represent an improved model, were so much better than the previous samples as to warrant placing them in a separate group. The improvement between groups B and C is representative of the development in air-speed indicators of American manufacture during the recent war.

TABLE 1.—*Results of tests of air-speed meters.*

BY THE BUREAU OF STANDARDS.

Manufacturer.	Number of instruments.	Errors in miles per hour.				
		Average scale error.	Average hysteresis.	Average friction.	Average drift.	Average over-pressure.
A	19	1.19	0.79	1.28	*0.93	0.65
B	18	4.03	3.78	0.94	+2.09	4.02
C	29	1.05	1.11	0.75	±1.10	0.44
D	17	2.05	1.59	•0.66	1.30	1.96

*Average of 16 instruments.
+Average of 14 instruments.
±Average of 22 instruments.
•Average of 16 instruments.

[4] The author is indebted to Mr. H. O. Stearns, formerly of the Bureau of Standards, for the compilation of these data.

ALTITUDE EFFECT ON AIR-SPEED INDICATORS.

Since the pressure developed by Pitot and Venturi nozzles [5] is proportional to the density of the medium with reference to which they are moving and the square of the speed, the pressure developed by such nozzles for a given velocity is less at high altitudes than at the surface of the earth (at 20,000 feet approximately one-half as great). Consequently an air speed indicator which depends upon dynamic pressure for its velocity indication and is calibrated for air at sea level density will show readings at high altitudes which are too low. This does not affect the use of the instrument as a buoyancy meter, however, since the buoyancy effect will be the same for a given speed reading whatever the altitude, although the airplane must be flying faster at high altitudes to produce a given reading.

If P is the pressure developed by the nozzle, V_s the speed of the airplane, V the reading of the instrument, K a constant depending upon the construction of the nozzle, ρ the density of the air, and ρ_o the standard density for which the instrument was calibrated

$$P = K\rho V_s^2 = K\rho_o V^2 \tag{9}$$

Assuming that the density of the air is proportional to the barometric pressure and the absolute temperature

$$\rho = \rho_o \frac{BT_o}{B_oT} \tag{10}$$

where B is the barometric pressure and T the absolute temperature of the air.

Substituting in Eq. (9)

$$V_s = \sqrt{\frac{B_oT}{BT_o}}\, V \tag{11}$$

or

$$V_s = FV \text{ where F is the multiplying factor} \sqrt{\frac{B_oT}{BT_o}} \tag{12}$$

The change in air-speed indicator readings at different altitudes and for different temperatures are shown in Fig. 27, from data computed at the Bureau of Standards,[6] on the basis of this formula and the assumption that the readings of the instrument are independent of compressibility and viscosity. The pressures in millimeters of mercury are plotted as abscissæ and the factor by which the observed indicator reading must be multiplied to give the correct velocity with reference to the air at various altitudes and for different temperatures as ordinates. The altitudes were computed by the altitude pressure relation:

$$H = 62900 \log_{10} \frac{759.6}{p} \tag{13}$$

Where H is the altitude in feet and p the barometer pressure in millimeters of mercury.

An instrument for computing this correction, known as the Appleyard air-speed computer, has been devised. It solves the expression

$$V_s = V\sqrt{\frac{B_o}{B}} \tag{14}$$

and hence corrects the indicated air speed V only for changes of pressure. If the air temperature is known, further correction can be made by subtracting 1 per cent of the air speed as determined by the computer for each 5.5° C. below 16° C.

The instrument consists of two concentric circular scales rotatable relative to each other. Air speeds are graduated on the inner scale and altitudes on the outer. The indicated air speed is set against the altitude and the corrected air speed is read opposite.

[5] The limitations of this statement are discussed in Report No. 110, National Advisory Committee for Aeronautics, 1920.

[6] Prepared by Mr. H. N. Eaton, of the Bureau of Standards.

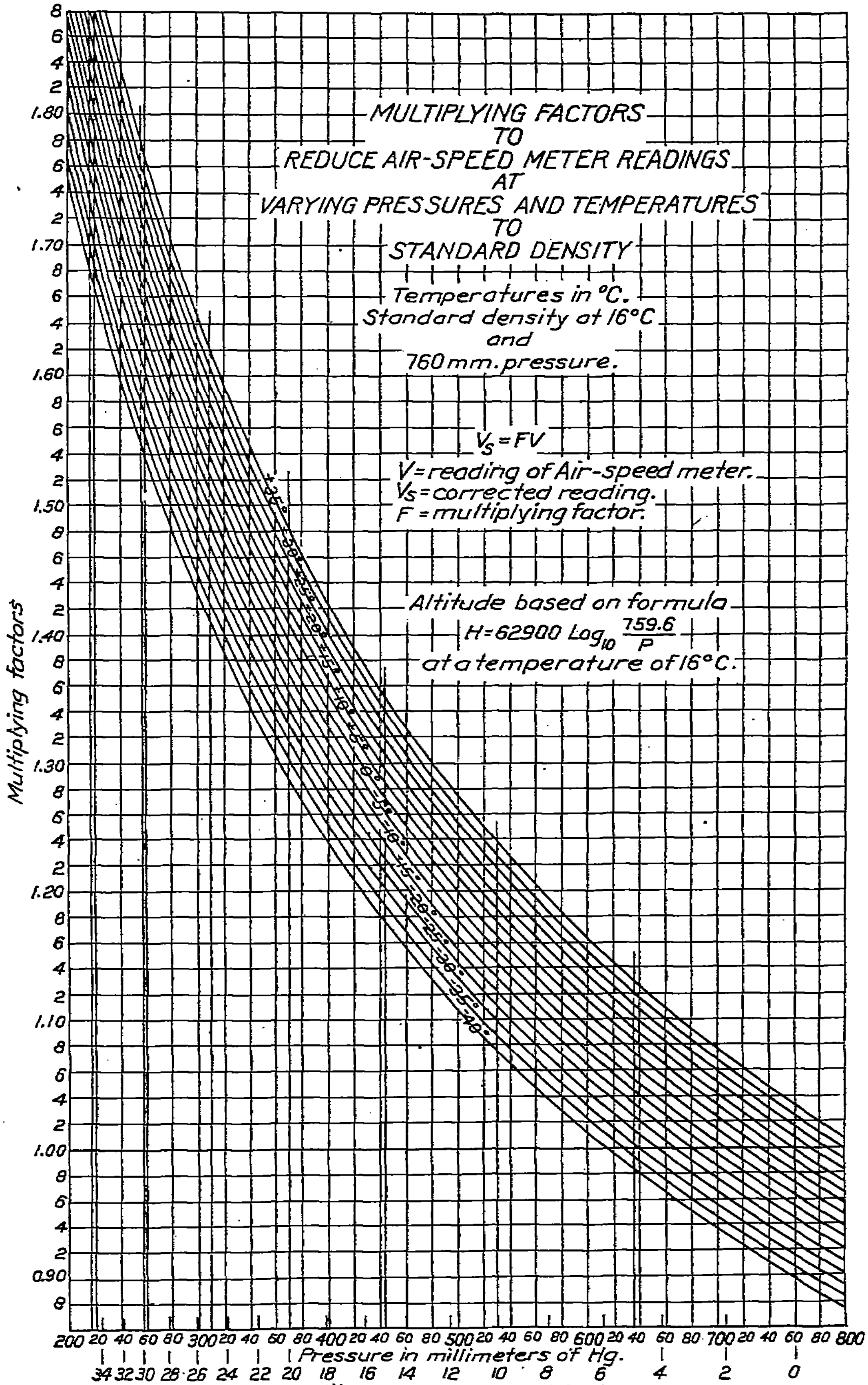

MULTIPLYING FACTORS
TO
REDUCE AIR-SPEED METER READINGS
AT
VARYING PRESSURES AND TEMPERATURES
TO
STANDARD DENSITY
Temperatures in °C.
Standard density at 16°C
and
760 mm. pressure.
$V_S = FV$
V = reading of Air-speed meter.
V_S = corrected reading.
F = multiplying factor.
Altitude based on formula
$H = 62900 \log_{10} \frac{759.6}{P}$
at a temperature of 16° C.
Multiplying factors
Pressure in millimeters of Hg.
Altitude in thousands of feet

Fig. 27

REPORT No. 127.

AIRCRAFT SPEED INSTRUMENTS.

PART II.

TESTING OF AIR-SPEED METERS.

By H. O. Stearns.

INTRODUCTION.

There are three types of tests which may be made to determine the accuracy of air-speed meters; flight tests, wind tunnel tests, and static or laboratory tests. The flight test requires that the instrument be installed in an airplane and that a measured course be chosen. A test of this kind when properly carried out gives the most complete corrections, for it includes not only the errors in the instrument and pressure head, but also a correction due to the location of the pressure head. Ordinarily, however, owing to varying atmospheric conditions, a number of corrections must be made to the data taken to obtain the desired result. The wind tunnel tests give the correct performance of the combined indicator and pressure nozzle under conditions which can be regulated with a considerable degree of accuracy. The wind tunnel is also the most convenient means by which the errors of the pressure nozzle alone can be determined, but the error due to the position of the pressure nozzle can not be found in this manner. For an exact determination of this free flight tests are necessary. The method of combining wind tunnel and static tests will be discussed later.

The static tests are applied simply to the indicating part of the instrument, which is treated for this purpose as a delicate pressure gage. This is an accurate method of determining the errors assuming the pressures delivered by the pressure nozzle to be correct. The static tests are those to which the Aeronautic Instruments Section of the Bureau of Standards has given special attention, and a more complete description of these will be given here than of the other tests.

LABORATORY APPARATUS FOR STATIC TESTS.

The apparatus necessary for testing various types of Pitot and Venturi air-speed meters includes manometers with suitable regulating valves, a vacuum pump, or some source of reduced pressure, pressure pump, temperature chamber, and vibrating board.

For the tests a vacuum equivalent to 12 or more inches of mercury should be available. The pressure does not need to be greater than 4 to 5 inches of mercury. Since the tests are static, a large capacity is not necessary in the exhaust system. The most essential part of the equipment is the manometer and there are two types which are in general use—the U tube and the single-tube manometer. By changing the density of the liquid the lengths of these manometers can be varied over a wide range. For the manometers, tubing at least a fourth of an inch in diameter should be used in order to reduce as much as possible the effect of capillarity.

The standard manometer used at the Bureau of Standards is a single-tube water manometer with 100-inch column. It carries a scale graduated in inches and in miles per hour, also a scale in knots for calibrating Navy instruments. The miles per hour scale was taken from the calibration chart of the Zahm pressure head as determined in the Washington Navy Yard wind tunnel, for which the corresponding formula is $V = 17.89\sqrt{h}$, where V is in miles per hour and h in inches of water. Another single-tube water manometer is used for calibrating indicators to be used with Pitot pressure heads. This has a scale graduated in cm. and another in miles per hour according to the formula $V = 45.18\sqrt{h}$ for the units above mentioned. A U-tube water manometer (see fig.1) is used for most of the testing, since it is more convenient than the longer single-tube manometer.

To facilitate the rapid testing of instruments a control valve is used with the test apparatus which makes it possible to set the instruments at a predetermined reading in a comparatively

FIG. 1.

short time. This is a four-way valve which controls the flow of the air to or from the instruments at any desired rate.

Instruments are tested in a temperature chamber to determine the effects of temperature on the working parts. The chamber used at the Bureau of Standards is about 4 feet long and 3 feet deep (fig. 2). It is double-walled and has a 3-inch space between the inner and outer wall filled with heat-insulating material. The front is closed by a sliding double plate glass window so that the instruments can be read from outside. At the back of the chamber a cooling coil is located which has a radiating surface of about 26 square feet. With ammonia-cooled brine a temperature of $-10°$ C. is thus obtained. Electric heaters are attached to the upper part of the chamber, as shown in figure 2. With both of these connected a temperature of 60° C. can be maintained. Two 8-inch variable speed fans are used to keep the air in circulation. The rack shown in figure 2 is used to hold the instruments while under test. This rack is equipped with a tapping device by which the instruments are tapped before each reading. It is operated electrically from outside of the chamber.

A vibrating board is used to determine the effect of vibration such as is experienced on an airplane, and also to see if the pointer of the instrument vibrates under conditions approximating those of actual flight. The upper part of the board is arranged to hold the instrument rigidly in place during vibration. Below the horizontal board is a motor for producing the vibrations. In figure 3 can be seen the board and an automatic device for stopping the motor at any desired time. To the motor is attached an eccentrically loaded flywheel. The position

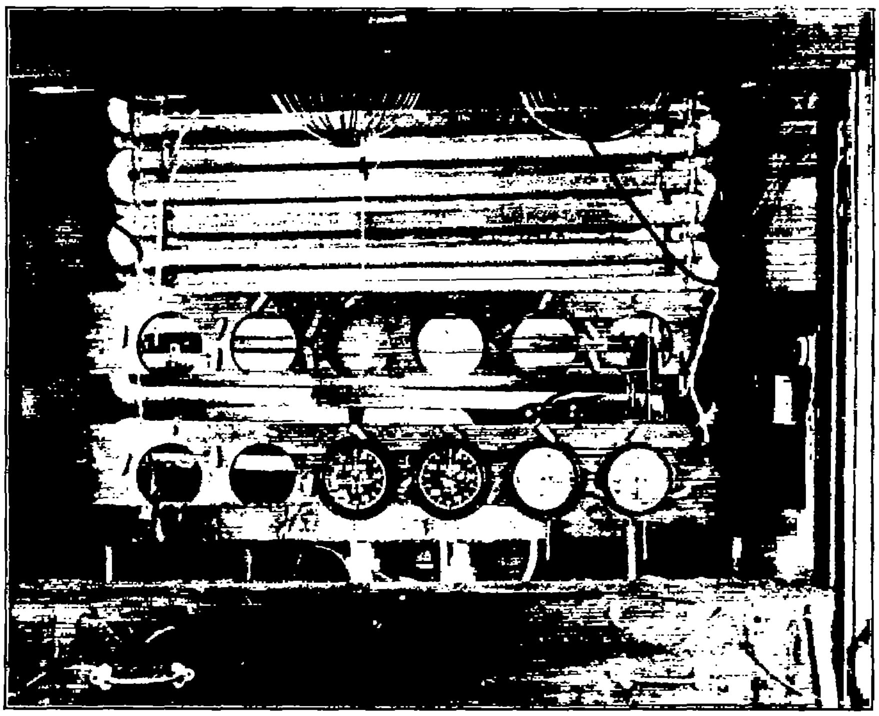


FIG. 2.

of the load can be varied, thus making it possible to change the character of the vibrations for any given voltage on the motor. Lamps and rheostats can be so arranged as to secure any required speed for the motor. For a given location of the load on the flywheel, and a given speed, the amplitude of vibration depends on the inertia of the board. Hence, the desired amplitude should be secured by making final adjustments after the instruments are in place.

PROCEDURE OF TESTS.

Before beginning a test the valves of the testing apparatus are adjusted so that both arms of the manometer are open to the air. The zero reading is then noted, and if necessary readjusted. It is advisable to run the manometer to a full scale reading and back before beginning a test. This wets the tube and prevents irregular capillary effects. Instruments of the diaphragm type are then subjected to the following tests:

Zero reading.—Before any strain has been put on the diaphragms of an instrument its zero reading should be taken.

Tests for leaks.—After all the connections have been made a differential pressure sufficient to give a 60-mile per hour deflection should be applied and held for 10 to 15 seconds to test for leaks. It has been found convenient in making connections with rubber tubing to use glycerin to insure tight joints and also to enable the connections to be made easily.

Calibration before vibration.—An initial calibration is made to determine the condition of the instruments as received and to form a basis for studying later the effect of other tests. The instruments are connected to the test apparatus previously described and the pressures required for a series of scale readings determined first with increasing scale readings to full scale deflection and then immediately afterwards with decreasing scale readings back to zero. If a single instrument is to be tested, it is often best to adjust the pressure until the pointer of the instrument stands at a predetermined mark on the scale. If, however, several instruments are to be tested, it is more convenient to set the manometer and then read the instruments. The errors during this test at no part of the scale should be greater than 1 per cent of the total scale

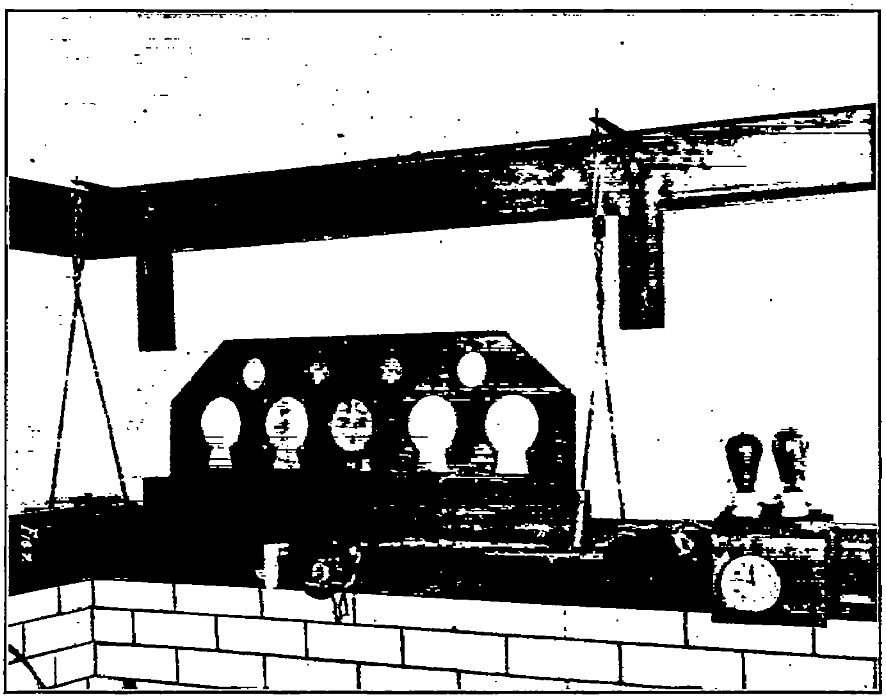


FIG. 3.

range either with increasing or decreasing readings. Instruments are always tapped immediately before reading.

Vibration.—For this test the vibrating board previously described is used. The instruments are vibrated for several hours. During vibration the pointer should not oscillate at any part of the scale more than 1 per cent of the total scale range.

Calibration after vibration.—The object of this calibration in which the procedure is the same as that made before vibration is twofold: To determine if the vibration has injured the instrument, and to give a room temperature calibration with which to compare the subsequent temperature tests. The error due to vibration for several hours should not exceed 1 per cent of the total scale range if the instrument is to perform satisfactorily under the actual conditions of use.

Temperature tests.—The instruments are placed in the temperature chamber and the temperature raised to about 50° C. After the instruments have been given time enough to come to practically the same temperature as the air in the chamber, they are calibrated as in the previous calibration. The error during this run should not at any time exceed 2 per cent of the total scale range. This also applies to the cold run. For the cold test the procedure is the same as in the hot test, except that the temperature is lowered to −10° C.

Friction and inclination tests.—These two tests are run at the same time. The instruments are slowly brought up to a given reading which is noted. The instruments are then tapped, and the reading again noted. The difference between these two readings constitutes the friction error. After recording the second reading the instruments are turned into a horizontal plane, tapped, and the reading noted. The difference between the third and second readings is known as the inclination error. Neither of these errors should exceed 1 per cent of the total scale range.

Drift.—For this test a differential pressure sufficient to produce nearly full scale deflection is applied to the instrument for several hours. The change of reading during this time is called the drift. This should not exceed 1 per cent of the total scale range.

Overpressure.—A differential pressure 100 per cent greater than that required for full scale deflection is applied for one minute. If the pointer returns approximately to zero, it is assumed that no damage has been done. A study has been made of the effect of overpressure on the calibration curve, from which it was found that in some cases a permanent displacement occurs, thus changing the calibration of the instrument.

The results of tests on a representative instrument of Pitot-Venturi type of American manufacture are given below. It was calibrated at room temperature before and after subjection to vibration similar to that experienced in actual flight and at −7° C. and +47° C. by applying measured differential pressures to the instrument. Readings were taken at approximately equal intervals up the scale to full scale deflection and then immediately afterwards back to zero. The corresponding speeds in miles per hour were found from the pressure velocity chart previously referred to which was prepared at the Washington Navy Yard wind tunnel for use with the Zahm pressure nozzle.

In column 1 of Table I are the readings of the instrument in miles per hour. In the even-numbered columns are the additive corrections for increasing differential pressure, and in the odd-numbered columns, after column 1, the same for decreasing differential pressure.

TABLE I.—*Airspeed-Indicator Calibration.*

SERIAL NO. 137. IDENT. NO. 2.

Instruments reading, miles per hour.	Corrections at +25°C., before vibration.		Corrections at +25° C., after vibration.		Corrections at −7° C., cold run.		Corrections at +47° C., hot run.	
	Up.	Down.	Up.	Down.	Up.	Down.	Up.	Down.
1	2	3	4	5	6	7	8	9
30	+4.0	+2.0	+3.0	+1.7	+3.3	+2.3	+2.5	+0.5
60	+2.4	+1.0	+2.0	+0.8	+2.7	+1.5	+1.5	+0.2
90	+2.0	+0.3	+1.7	+0.3	+2.2	+1.4	+1.0	−0.2
120	+1.3	+0.4	+1.2	+0.4	+2.2	+1.4	+0.5	−0.6
140	+1.0	+0.3	+0.6	+0.4	+1.7	+1.4	0.0	−0.6
160	+1.0	+1.0	+1.0	+1.0	+1.5	+1.3	0.0	0.0

SUMMARY OF RESULTS.

Effect of temperature.—The readings of the instrument at −7° C. are lower than the room-temperature readings on the average by about 0.5 mile per hour, whereas the readings at +47° C. are higher by about the same amount.

Effect of vibration.—A slight decrease of the additive correction in the middle scale readings resulted from vibrating the instrument for five hours.

Friction test.—Readings taken before and after tapping in no case show differences exceeding 1 mile per hour. There was a slightly irregular motion of the pointer under gradually applied pressure.

Inclination test.—Readings taken with the instrument vertical and horizontal showed a maximum difference of 2.5 miles per hour at the 30 miles per hour point. This should be less than 1 mile per hour.

Drift.—The error caused by the elastic fatigue of the diaphragms was determined by applying for five hours a differential pressure sufficient to produce a scale reading of 155 miles per hour. This error was 1.3 miles per hour.

Overpressure.—An increase in reading amounting to about 1 mile per hour resulted from applying for 1 minute a pressure of 130 inches of water.

The results are shown graphically in figure 4.

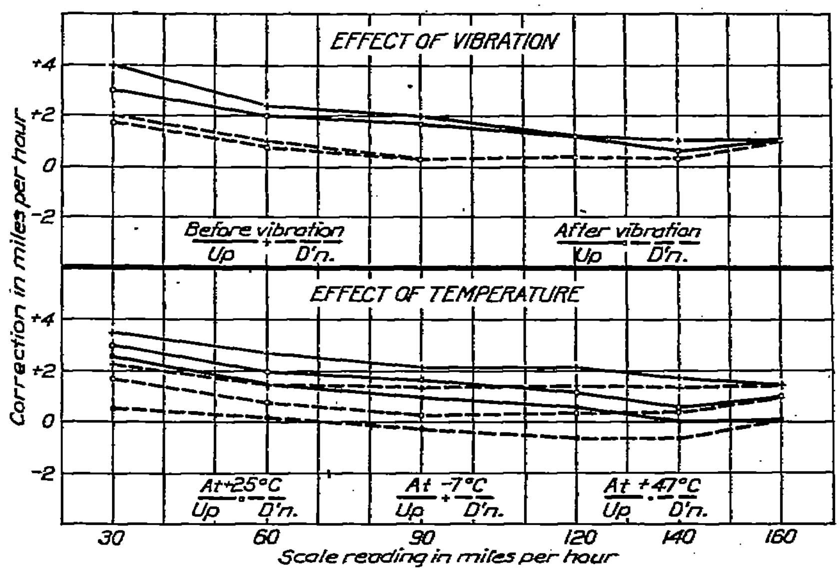


FIG. 4.—Effect of vibration and temperature on an air-speed indicator.

METHODS OF COMBINING WIND TUNNEL TESTS WITH STATIC TESTS.

The purpose in this section is to indicate briefly the method of obtaining the calibration curve of a given pressure head and indicator by combining the results of wind tunnel and static laboratory tests. In general the procedure is as follows:

A wind tunnel test is made on the pressure nozzle in which the relation between the pressure developed by the nozzle and the velocity of the corresponding air stream is directly determined. The results of this test are plotted on logarithmic paper, with the air speed as one axis and the pressure as the other. This curve will be a straight line within the ordinary range of airplane speeds if the pressure head follows the ρV^2 law. The differential pressures corresponding to a series of indicator readings are then found in the laboratory with a manometer in the usual manner. The speeds corresponding to these pressures are computed from the logarithmic plot and the corrections found by subtracting (algebraically) the instrument reading from the true reading. A plot of these points is made, and the smoothed curve drawn through these points is the calibration curve. An example of this procedure is seen below in some tests made on Venturi air-speed meters by the Bureau of Standards in cooperation with the Washington Navy Yard, where the wind tunnel tests were made.

TABLE II.—*Wind tunnel data.*

DOUBLE-THROAT VENTURI.

Speed in miles per hour.	Suction in inches of water.
20	1.89
25	3.07
30	4.87
35	7.06
40	9.10
45	12.15
50	14.90
55	18.20
60	22.30
65	26.55
70	29.60

From the above a curve was plotted on logarithmic paper. With suction in inches of water as ordinates and speeds in miles as abscissas this curve is shown in figure (5).

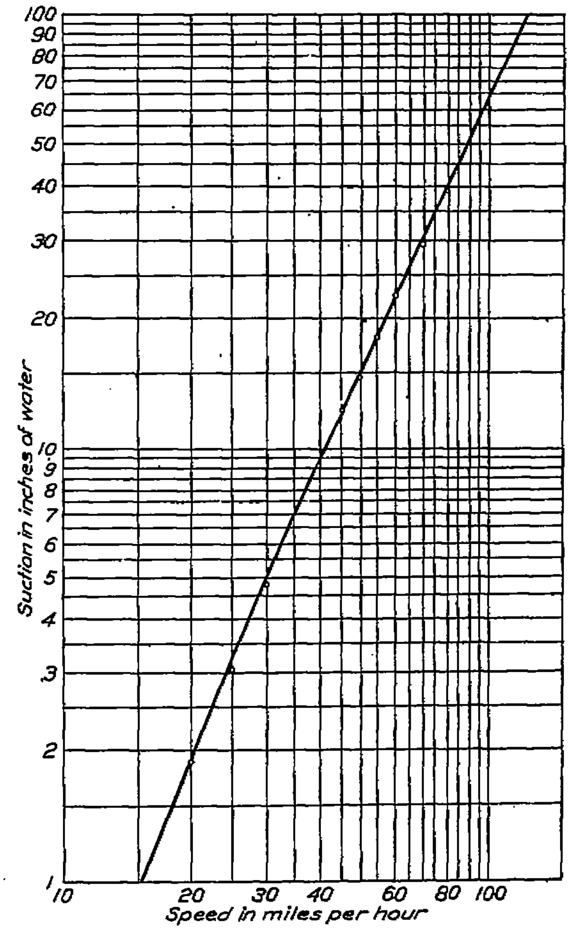


FIG. 5.

In Table III are shown the data of a static test on the indicator and the corrections computed from the above calibration of the nozzle.

TABLE III.—*Static tests.*

READING TAKEN WITH INCREASING SUCTION.

Suction in inches of water.	Reading, miles per hour.	True speed, miles per hour.	Correction, miles per hour.
7.34	33	36	−3
11.88	48	45	−3
14.88	53	52	−1
17.81	57	54	−3
21.10	61	58	−3
31.59	73	70	−3
46.20	86	83	−3
63–10	98	96	−2
82.0	111	108	−3
84.0	113	109	−4

READING TAKEN WITH DECREASING SUCTION.

Suction in inches of water.	Reading, miles per hour.	True speed, miles per hour.	Correction, miles per hour.
6.26	40	34	−6
10.80	50	44	−6
15.95	57	52	−5
22.3	64	60	−4
32.6	76	72	−4
47.5	89	85	−4
63.3	100	96	−4

In Table IV are shown the results of wind tunnel and static tests[7] on a series of instruments. The fact that the average discrepancy between the tests is less than 1 mile per hour is noteworthy, considering the errors which may enter.

In the static tests the errors are largely due to the difficulty of reading the instrument. An accuracy exceeding 0.2 mile per hour is rarely attained since the manometer can only be read to about this degree of accuracy. In wind tunnel tests the rapid fluctuations of the manometer reading introduce more serious errors. When the results of the two tests are combined there may be a further error due to interpolation.

TABLE IV.—*Comparison of wind tunnel tests with static calibrations.*

Instrument.	Instrument No.	Reading, miles per hour.	Static calibration corrections.	Corrected scale reading.	Scale reading corrected for Venturi error.[1]	Standard Pitot reading.	Difference.
F	110	75	−7.8	67.2	65.0	66.3	−1.3
F	225	76	−8.2	67.8	65.6	66.3	−0.7
F	83	77	−4.5	72.5	70.3	66.5	[2] +3.8
F	324	67	+1.2	68.2	66.0	66.6	−0.6
F	345	67.5	+1.0	68.5	66.3	67.7	−0.4
B	25	65.5	+1.8	67.3	65.1	67.3	−2.2
B	9	67.5	+0.8	68.3	66.1	67.5	−1.4
B	9	49.8	+0.2	50.0	47.8	53.6	−5.8
B	71	70.5	+0.1	70.6	68.4	67.5	+0.9
B	282	70.1	+0.5	70.6	68.4	67.5	+0.9
B	261	68	+1.7	69.7	67.5	67.4	+0.1
P	5	72	−0.9	71.1	68.9	67.5	+1.4

[1] Pitot-Venturi No. 138–B used with all instruments. At 65.6 miles per hour by Bureau of Standards Standard Pitot, 138–B reads 67.8 miles per hour, which gives a correction of −2.2 miles per hour.
[2] The difference between up and down readings at this point amounts to 3 miles per hour.

FLIGHT TESTS.

Flight tests on air-speed indicators involve determining simultaneously the readings of the instrument during flight and the speed of the airplane itself relative to the air by an independent method, which usually consists of measuring the time of flight of the airplane over a measured course. In general such observations are made from the ground, although it is also possible with suitable arrangements to determine without the use of an ordinary air-speed indicator the air speed of an airplane from the airplane itself. One of the difficulties encountered in all of these measurements of air speed is that of eliminating the effect of the wind

[7] These results were obtained in cooperation with the Wind Tunnel Staff of the Bureau of Standards.

which, in general, is not constant either in magnitude or direction for any considerable length of time.

The method most usually adopted is to conduct the experiments when no wind is blowing or to select a measured course in the direction of the wind and have the airplane fly back and forth across this course with and against the wind. At each end of the course an observer is stationed who notes with the aid of sighting wires the exact moment at which the airplane passes the designated point. The time intervening between these observations is determined either by the use of synchronized stop watches or preferably a chronograph and from this and the known length of the course the speed of the airplane can be calculated. The mean of the measurements with and against the wind gives the true air speed of the airplane. Comparison of these observations with those obtained from the readings of the air-speed indicator on the plane itself make it possible to determine the errors in the speed indicator. If stop watches are used some method of signaling between stations such as a telephone must be provided. At the exact moment when the airplane passes the first station the observer starts his stop watch and signals to the second station, who also starts his watch. When the airplane reaches the second station on signal from the second observer both stop watches are simultaneously stopped. The average of the readings of the two watches is taken as that of the time of transit of the airplane over the course. If a chronograph is used it is provided with two recording pens. One is connected to a standard clock which makes a mark on the chronograph record each second; the other, connected electrically to the stations of the measured course, records the time when the airplane passes the observers, each of whom presses a key to make a mark on the chronograph strip. The interval between the two marks as determined by the series of one-second marks on the chronograph record makes it possible to obtain within 0.1 second the true time of transit of the airplane. These observations, together with those made on the air-speed indicator during the flight, provide the necessary data for computing the corrections of the air-speed indicator itself. If the course is not exactly in the direction of the wind the magnitude and direction of the latter must be determined by meteorological methods and a suitable correction applied. Because of the variability of the wind this is ordinarily a troublesome and uncertain factor.

The speed of the airplane can also be found from the airplane itself by the use of a measured course or of two objects on the ground a known distance apart by determining with a suitable sighting device and stop watch the time required for the airplane to fly back and forth between the selected points, which should be in the direction of the wind. The air speed is determined, as in the previous case, by taking the average of the observations with and against the wind and this value compared with the average of a series of readings taken simultaneously on the airspeed indicator.

The disturbing effect of the wind can also be eliminated by flying over a selected triangular course, the distances between the three points which determine the triangle having been carefully measured. From the time required to fly over each of the known distances the effect of the wind can be determined.

It is also possible to calibrate air-speed indicators by determining the position of an airplane in flight at frequent intervals with the use of theodolites or camera obscuras located on a base line of known length. The speed of the plane at the various positions at which observations are taken can then be computed and the air-speed indicator calibrated by comparing these speeds with those read at corresponding times on the air-speed indicator carried on the airplane. These methods will not be considered here at length because they pertain to investigations relating to the performance of the airplane itself rather than to the calibration of air-speed indicators.

Additional data sufficient to determine the temperature of the air and the barometric pressure are also required for flight tests of air-speed indicators because the readings of the instruments depend on the density of the air. This is particularly true in the case of the last-mentioned method, where observations at varying altitudes are made.

REPORT No. 127.

AIRCRAFT SPEED INSTRUMENTS.

PART III.

PRINCIPLES OF GROUND-SPEED MEASUREMENT.

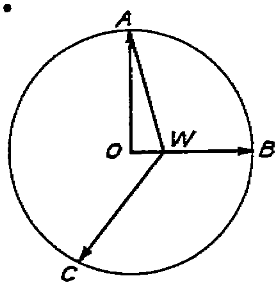
By Franklin L. Hunt.

MEASURING GROUND SPEED FROM THE GROUND.

The measurement of the speed of aircraft relative to the ground is of great importance in long-distance flying, in bombing operations, and in connection with aircraft performance tests. The problem of finding suitable methods for the purpose has been given much thought, but as yet no entirely satisfactory solution has been found.

Methods which have been considered may be divided into two classes: (1) Those applicable essentially to aircraft performance tests in which the speed of the aircraft is measured from the ground and (2) the much more important class in which the ground speed is determined from the aircraft itself.

Of the former methods, the one most commonly used is that of measuring the speed of the aircraft over a measured course. The principal difficulty in this case is that the wind may introduce errors which are difficult to eliminate. This can best be done by selecting a course exactly in the direction of the wind. By determining the time required to fly over such a course first in one direction and then in the other, the effect of the wind can be eliminated assuming that the speed of the aircraft is constant, by taking the average of the velocities with and against the wind. When ground speed is determined by this method an observer is ordinarily stationed at each end of the measured course to note with a stop watch or record on a chronograph the time of transit of the airplane. Telephonic or telegraphic communication is provided between the stations to coordinate the time data.



Another possibility is to select a triangular course and to determine the time required for the aircraft to fly over each of the three legs. The effect of the wind can then be determined graphically as follows: If WA, WB, and WC represent in magnitude and direction the three velocities attained on the triangular course the radius OA of the circle drawn through the points A, B, and C will represent the velocity of the airplane and WO the velocity and direction of the wind.

The difficulty here is that it is almost impossible if there is a strong side wind to fly exactly over the corners of the course.

Another method essentially of a military nature and applicable only where bombing areas are available is to fly twice over a chosen course, once exactly with the wind and again exactly against it and to drop each time two bombs at a definitely determined time interval. From the time intervals and the distance between the spots where the bombs strike the effect of the wind can be eliminated the speed of the aircraft found. Here again it is also possible to eliminate the effect of the wind by making three flights in different directions and from the three values of the velocity and the directions of the flights to eliminate the effect of the wind by the graphical method previously described. To obtain the necessary accuracy by this method the interval at which the bombs are dropped should be at least from 5 to 10 seconds.

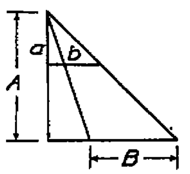
It is also possible to determine the speed of aircraft from the ground by the use of theodolites. If only one instrument is available the ground speed can be found by using it in conjunction with a barograph by making a series of azimuth and altitude observations with the theodolite at known time intervals and determining from the barograph the corresponding altitudes. More accurate determinations can be made by using two theodolites located one at each end of a measured base line. This base line should if possible be at least a mile in length. In this case altitude and azimuth observations are made at known time intervals with each instrument, from which, with the length of the base line, the ground speed of the aircraft can be determined. Telegraphic and telephonic communication between the two stations is provided to coordinate the time data. In a recent instrument of this type photographic records of the readings of the instruments are obtained by the use of an especially constructed film camera attachment. The shutter of the camera is operated electrically and the film is advanced automatically after each exposure. A chronograph is also provided which records the time when each observation is made. This instrument has the advantage that an observer is not required to record the settings. Moreover, since the settings are recorded instantaneously they can be made at more frequent intervals, which increases the accuracy of the results. It is also possible by suitable electrical connections to record the settings of the instrument at both ends of the base line simultaneously, in which case the observer at each theodolite must keep his instrument trained constantly on the aircraft. A further refinement would be to provide the theodolites with telescopes having cameras attached and in this way obtain simultaneously records of the readings of both instruments and the positions of the aircraft in the telescopic fields.

Another method, the same in principle, is to place camera obscuras at the ends of a measured base line and plot the position of the aircraft at definite time intervals. The plots obtained, together with the optical constants of the cameras, and the length of the base line, provide the necessary data for computing the ground speed of the aircraft.

MEASURING GROUND SPEED FROM AIRCRAFT.

The methods of determining ground speed from the aircraft itself are also subject to classification according or not as they depend upon seeing the ground. The former are essentially optical, the latter dynamical or electrical.

If a sighting telescope is available the ground speed can be determined from the airplane by flying over either a straight or triangular measured course or between any two objects on the ground of known distance apart and noting the time required. This method is essentially one previously described where observations are made from the ground. The statements made in regard to the effect of the wind and methods of eliminating it apply equally in this case.



The type of optical ground-speed indicator most commonly used on aircraft, the type ordinarily seen on bomb sights, depends upon determining with a stop watch the time required for some object on the ground to pass between two sighting points on the ground speed indicator in a horizontal line longitudinal with reference to the aircraft. The ground-speed is calculated from (1) the ratio of the distance apart of the two sighting points, (2) the distance from the horizontal line defined by them to a third sighting point at the observer's eye, and (3) the altitude of the aircraft. The principle may be demonstrated as follows:

Let a = distance from line b to the eyepiece.

b = distance between the two sighting points.

A = the altitude.

B = the distance traversed by the aircraft while the object appears to move between the two sighting points.

t = time in seconds required.

S = speed of the aircraft.

Then by geometry

$$\frac{a}{A}=\frac{b}{B}$$

But B = St

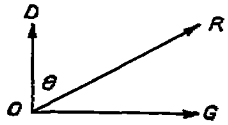
$$\therefore S = \frac{A}{a}\frac{b}{t}$$

$$= \text{Const.}\ \frac{A}{t}$$

It is also possible by a suitable optical arrangement to neutralize the apparent motion of objects on the ground as viewed through a telescope or to cause some reference point in the telescopic field to move at the same rate as the image of the object on the ground. If then the rate at which the telescope or the image in the telescopic field is moving is determined and the altitude of the aircraft is known the ground speed may be found. A number of devices of this kind have been invented.

Another method is to introduce by means of a rotating telescope or similar device an artificial drift at right angle to the actual drift relative to the ground. From the direction of the resultant apparent drift and the magnitude of the artificial drift the ground speed can be computed. The principle may be illustrated graphically as follows:

Let OG represent the ground speed of the aircraft the magnitude of which is to be found and the direction of which is shown by the use of some drift device; OD the known artificial drift introduced at right angles to the ground speed OG by the rotating telescope or other device OR will then represent the resultant apparent drift as seen through the rotating telescope and if the angle θ between the artificial drift and the resultant apparent drift is measured the magnitude of the ground speed can be calculated by the relation



$$OG = OD \tan \theta.$$

Considering now the dynamical methods, it is theoretically possible to obtain the speed of an aircraft by determining the time integral of the accelerations to which it is subjected. It has been proposed to do this by supporting a mass between springs so that it is free to move in a horizontal plane in a fore and aft direction. The displacement of the mass under these circumstances will be proportional to the acceleration of the aircraft. The time integral of this displacement may be obtained mechanically and shown on a direct reading dial, but the inherent friction of the integrating mechanism and the inevitable accumulation of errors in integration seriously limits the practicability of such a device. Moreover it is necessary that the mass move only in a horizontal plane to prevent accelerations of the mass due to gravity which can apparently be brought about only by gyroscopic stabilization.

The principle involved may be demonstrated as follows:

Let M = mass supported by the springs.
x = displacement of mass M due to the acceleration of the aircraft.
v = velocity of the aircraft.
C = constant of proportionality depending on the strength of the springs.
t = time.

The force exerted on the mass M due to the acceleration of the aircraft is

$$F = M\frac{dv}{dt}$$

This force is also proportional to the displacement of M since the reaction is due to the resistance of the springs, hence

$$F = Cx$$

Equating

$$M\frac{dv}{dt} = Cx$$

and integrating

$$v = \frac{C}{M}\int x\,dt$$

i. e., the velocity is proportional to the time integral of the displacement of the mass M which in turn is proportional to the acceleration of the aircraft.

Ground speed may also be determined by observing the displacement of a mass in opposition to a resistance proportional to the velocity of the mass. Such a resistance might be either of mechanical or electrical origin. An experimental model made at the Bureau of Standards[a] to illustrate this principle consists of a metal ball free to move along a horizontal glass tube filled with oil. Owing to the viscosity of the oil the ball experiences a resistance proportional to its velocity. The principle is as follows:

Let m = the mass of the ball.

v = its velocity with reference to the viscous medium.

v_0 = its absolute velocity in space.

R = resistance which it experiences.

x = the displacement of the mass in time t.

c = a constant of proportionality.

Then $R = -cv$ since the resistance is proportional to the velocity.

But also $R = m\frac{dv_0}{dt}$ by the laws of motion.

Therefore

$$\frac{dv_0}{dt} = -\frac{c}{m}v$$

Integrating

$$v_0 = \frac{c}{m}x$$

and since v_0 does not differ appreciably from the ground speed of the aircraft, the displacement is evidently a measure of the ground speed. This device would also require stabilization, which in this case presents the special difficulty that the movement of the ball displaces permanently the center of gravity of the stabilized system.

The recent development of directional wireless telegraphy methods has presented another possibility for ground-speed measurement. With a suitable receiving apparatus, the position of the aircraft at successive intervals of time with reference to two sending stations of known distance apart may be determined and from these observations the ground speed computed.

It has also been suggested that methods of determining the potential differences set up electromagnetically in conductors on the aircraft by their motion through the earth's magnetic field might be developed and applied to the measurement of the speed of the aircraft with reference to the earth. The practical difficulty is to avoid the equal opposing electromotive force set up by the return wire of the electro-magnetic circuit. Moreover, varying static potential differences in the atmosphere encountered by the aircraft in flight might easily introduce troublesome disturbances of such magnitude as to swamp the main effect. No practical device of this kind has thus far been made.

SUMMARY.

Of the methods of determining ground speed from the ground, the measured speed course is the most exact. Of the methods from the aircraft itself the optical methods mentioned are practicable and reasonably precise but troublesome to the aviator because they require that observations be made at frequent intervals. Of the methods not depending upon the earth being visible, the wireless triangulation method appears most likely to yield practical results.

[a] Suggested by M. D. Hersey.