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AN AUTOMATIC SPEED CONTROL FOR WIND TUNNELS

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Summary

Since 1901 it has been good wind tunnel practice to generate the air flow by some type of suction fan or screw, and to determine the air speed by means of a Pitot-static tube, or the tunnel wall pressure, or the rotational speed of the fan. Usually it is desirable to keep the air speed, or preferably the impact pressure of the stream $\rho V^2/2$, constant for some minutes consecutively, while taking observations. To maintain such constancy the fan can be held at a suitable speed either by hand control or by some automatic device. The respective advantages of constant speed and constant head were set forth by the writer in 1903 (Reference 1), in a paper explaining the inverted-cup manometer and various forms of speed nozzles.

The present article describes an automatic control that has been used in several forms, since 1921, in the wind tunnels at the Washington Navy Yard. The structural drawings were perfected in turn by Messrs. L. H. Crook and R. H. Smith, of the aerodynamics staff, and the apparatus was made in the Construction Department. In its original form it was designed by the writer for his university wind tunnel in 1902. We consider here the form now in use with the 8-foot wind tunnel at the Navy Yard.

The hand-control system.- Since the completion of this tunnel, in 1913, the air current has been generated by a 500 horsepower direct-current motor driving a Sirocco fan placed well after the working part and discharging into a return circuit. A Pitot-static tube (Figure 1), suspended 18 inches below the tunnel ceiling, in the working part, has its leads connected to an inclined tube manometer (Figure 2), on the desk of the aerodynamic balance in the observation room overhead. To keep fixed the manometer meniscus that indicates the wind strength, the operator seated at the desk, with thumb and finger on one of the small bent up reversing-switch handles, shown at the base of the manometer (Figure 6) makes the little rheostat motor (Figures 3 and 4), run forward or backward, if necessary, to adjust the field resistance in the dynamo that supplies the fan motor. Details of this reversing switch and its connections need not be given.

The automatic control.- Leads from the Pitot tube are joined also to the inverted-cup manometer shown above the rheostat at the left in Figure 3, and sectionally in Figure 5. When the sliding weight of this instrument is set to a given notch, say for 40 miles an hour, the beam tip vibrates between two electric contacts that feed the little motor. Thus when the wind is too strong or too weak the motor automatically throws the rheostat slide forward or backward. If it failed to function well the operator would notice the effect on his meniscus, and would operate the hand control by merely pressing the switch before mentioned.

The details of each mechanism may now be given.

The inverted-cup manometer.- Figure 5 presents a longitudinal section of the manometer or manometric balance shown in Figure 3. Two inverted metal cups, hung from a weighing beam, dip severally into coal-oil cisterns, each under pressure of a lead from the Pitot in the air stream.* The differential static pressure moment on the cups is balanced by a sliding weight on the beam graduated for even miles an hour. The distance of the graduations from the moment axis is proportional to the impact pressure $\rho V^2/2$, of the air stream. In practice the wind speed for the weight in any notch can be calculated from well known theory or found by experimental calibration. The dimensions of the various parts are shown by the linear scale in Figure 5.

In regular use the balance beam tip vibrates about .001 inch each way from equilibrium against two contacts giving them current of 110 volts. These transmit the current, each in opposite direction, through the small motor's double-wound field. Thus the motor runs forward with upper contact, backward with lower contact, and stands still with no contact. Dancing of the beam is prevented by the natural damping due to the constricted flow through the leads from the Pitot to the cups.

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*The third cavity lightens the casting and sometimes is used as a cistern.

The inverted-cup gauge is easily capable of indicating differential pressures of less than one millionth of an atmosphere. In the writer's use of it in 1902, one ten millionth was regularly recorded (Reference 8), without electric stops, by using as extension of the weighing beam a fine pointer playing on a millimeter scale (Figure 13). In such fine measures one needs in the cisterns a fluid whose surface tension does not hamper the displacement of the cups. For this reason coal oil instead of water is used.

The motor-driven rheostat.- When, by use of the hand switches shown in Figure 3, the fan motor is set running at some desired speed, its fluctuations are kept within narrow limits by the motored rheostat shown in Figures 3 and 4. The little rheostat motor has a worm on its extended shaft engaging a worm wheel coaxial with the rotating hand slide of the resistance box. Friction of the worm wheel, spring-pressed against the hub of the hand slide, drives the latter to right or left as needed to vary the field resistance of the dynamo supplying current to the fan motor.

The combination of cup manometer and motor rheostat tends to counteract the fan fluctuations; but, if ungoverned, actually over controls them and begets "hunting"; viz., propels the slide too far forward, then too far backward, incessantly. To prevent this excessive sweep, limiting stops carrying circuit breakers stand guard to right and left of the slide. These stops are small brass posts (Figure 4) planted on the lugs or jaws of two bakelite disks coaxial with the rheostat slide, and pressed by it against the main supporting slate, so as to rotate jointly to right or left with a little friction. A spacer fixes the jaws at any desired distance apart.

When the slide strikes either guard post it opens a circuit by bending the leaf-spring contact shown pressing the post, thus stopping the motor. Presently, with change of wind speed, the slide sweeps toward the other post, and either strikes it or halts on the way. In either case it loiters to and fro between the posts, and thus holds the fan at the speed predetermined by the manometer loading. Heating of the tunnel air or the various electric circuits may require the pair of posts to move to a new part of the rheostat arc. This occurs by creeping of the pair toward the side receiving the most knocks, each of which causes a little sliding of the joined pair. Thus the rheostat slide automatically moves to the proper place to hold the air stream at the designed impact pressure $\rho V^2/2$.

The step-tube manometer.- The manometer shown in Figs. 2, 6, and 7, was designed, for sake of compactness and convenience of reading, to replace a single alcohol tube having a 1 to 10 slope and a length of 32 inches, needed to indicate air speeds up to 80 miles an hour. The 10 glass tubes seen in Figure 6 have a common slope of 1 to 10 and a clear exposed length of 5.5 inches. Their left ends are joined by rubber sleeves to a single internal groove closed at the top and extended at its bottom into an alcohol cistern in the base of the main casting. Their right ends are joined to a like groove with lower end closed and upper end coupled to the static lead of the Pitot tube. The impact lead exerts pressure in the cistern. As the alcohol, under this differential pressure, rises in the left groove, it runs toward the right in the glass tubes successively, so that a meniscus is always visible. The glass tubes are embedded in accurately parallel wall slots and secured with metal gibs. The upper side of each slot beetles over the glass so as to grip it, as seen in Figure 7. Graduations on the outer face of the metal holding these tubes indicate air speeds up to 80 miles an hour.

Further details are shown in Figure 7. A float in the alcohol is adjusted with a screw to set the meniscus at zero on the lower glass tube when the differential pressure is zero. Leveling screws at the base of the casting serve to ensure correctness of slope of the glass tubes. An increment in their common slope causes their ends all to rise equally; hence an error in slope affects the upper tubes relatively much less than if they formed a single straight tube.

The Pitot-static tube.- The instrument shown in Figure 1, known as the British NPL Pitot-static tube, is a standard speed nozzle which in a given air stream delivers to its gauge the same differential pressure as the carefully calibrated Navy Pitot-static tube. This equality was accurately established for all speeds up to 160 miles an hour, as described in Reference 2, where data and working drawings are furnished.

Special tests with an exploring Pitot have shown that the air speed at any point in the working part of the 8-foot tunnel bears a fixed ratio to the speed where the permanent Pitot is mounted. Hence after a preliminary exploration of that region of the tunnel where the models are to be studied, the manometer connected with the permanent Pitot, fixed farther upstream, is graduated to indicate the speed of standard air flowing undisturbed in the model region. Thus all determinations of air force or pressure distribution automatically apply to air of standard density, without correction for temperature and barometric pressure. This method, first described by the writer in Reference 1, seems now to be standard in all wind tunnels.

Usefulness of automatic control.- During working hours the 8-foot wind tunnel operates almost continuously through the year, and for the most part at a fixed speed of 40 miles an hour. Without an automatic device the wind tunnel observers would have to make by hand frequent adjustment of the air speed, when their attention is needed for measuring and note taking. The automatic adjustment not only saves the operator's time, but controls continuously and rather more closely. The instrument therefore has been adopted as a permanent installation. It is not so perfect as might be wished, but has proved to be a valuable auziliary. At the usual test speed of 40 miles an hour it keeps the mean impact pressure $\rho V^2/2$, constant to within one-half of one per cent.

History.- It seems desirable to have a general survey of the methods of wind tunnel control, comprising their history, principles and practical working. Such survey is beyond the scope of this paper, which treats of a single scheme. Some historical items, however, bearing on the present speed control elements may be added.

Prior to 1902 the Pitot and static parts of present-day Pitot-static nozzles were located on separate parallel tubes. Figure 10 by W. M. White (Reference 3), is an example. In 1902 coaxial tubes (References 1, 4) were used: one devised by the writer in early spring, one by Admiral D. W. Taylor, U.S.N., and one by Messrs. Gregory and Maltby, in the autumn. The latter (Figure 11), closely resembles the British N. P. L. standard Pitot-static tube (Figure 12), developed nearly ten years later (Reference 5). All these forms were found to give, to within a fraction of 1%, the true static and impact pressures when headed into a uniform stream of air or water. Hence for a differential pressure Δp, the stream velocity is $v = k\sqrt{2g\,\Delta p/\rho}$, where k differs from unity by less than 1%.

To calibrate such nozzles various methods have been used.

White, in 1901, carried his tubes in a boat through still water, as had been done by Duchemin many decades earlier (Reference 6). At the British National Physical Laboratory, in 1912, the speed nozzle during calibration was borne at the end of a 32-foot long whirling arm in a closed shed 80 feet square, careful correction being made for the air swirl induced in the room by the moving apparatus. The writer, in 1902, (Reference 1), calibrated Pitot-static tubes in a wind tunnel having a uniform stream of air whose speed was determined with a balloon anemometer. That is, a toy balloon, released just aft of the intake, drifted with the air and, at two points of its path, interrupted thin pencils of light crossing the tunnel and coming to focus on the sensitized plates of an oscillograph camera. White and others also calibrated pressure tubes in water streams of known speed. All these methods, and various others, can be used to graduate such nozzles to within less than 1% of the true speed. Indeed, the careful calibration described in Reference 5 seemed to be accurate to 0.1% at the test speeds, ranging from 2000 to 3000 feet per minute.

The inverted-cup* gauge (Figure 13), joined to suitable pressure collectors, was devised and used by the writer in 1902, first to measure the pressure difference in various parts of the tunnel air stream, then to find the pressure distribution about models

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*The cups may also dip in the liquid as floats with their bottoms closed, if the leads from the pressure nozzle convey liquid, as in hydraulic experiments. A pressure difference in the leads then causes, as before, a moment in the cup balance beam (e.g., Reference 9). In one or other of these forms the cup manometer is now standard equipment for studies in fluid dynamics.

therein suspended. Later in various laboratories it was adapted to govern the rheostat controlling the tunnel motor. A well-known instance is its application in the Göttingen wind tunnel (Reference 7).

Another way to steady the air speed, devised and used at that date, was to place relief valves on the walls of the tunnel, weighted like a steam-escape valve. These were long narrow flaps hinged at their upper edges, and overlapping liberal cracks cut in the tunnel wall. It is clear that if the wall pressure fore and aft of the working segment of an air tunnel is fixed, or if the differential pressure on its two ends is kept constant, the air will traverse the segment at constant speed. At that time, however, there was little need for either form of automatic control, because a boy with a tachometer and rheostat held the fan speed constant, while others read the Pitot manometer and weighed the air forces with the wire balance or bell-crank balance. Further details of these tunnel equipments are given in References 1, 8.

Comparison of the control methods.- Figure 14 shows an apparatus improvised to record the tunnel wind force respectively, with no speed control, with hand control, and with automatic control. An inch square balsa wood stick held at the tunnel axis by fine transverse piano wires, as shown, has at the upstream end a drag body, at the rear a pen recording on a chronograph drum its displacement due to the wing drag deflecting the wires. To obviate much turbulence the drag member is made of brass fly net one yard square soldered at its corners to the front wires. Lead riders are placed on the stick to damp the oscillations, and removed to allow them free play. The whole vibrating system weighs 7.39 pounds; the leads alone aggregate 6.93 pounds. The piano wires are .013 inch thick; the fly screen wires .009 inch thick, and 1/16 inch between centers. One inch displacement requires about 2.1 pounds.

Figure 15 shows brief sample records, taken with the leads on, of the displacement against time, at 40 miles an hour, before the rheostat system attained its final temperature; Table I gives data scaled from faired lines through the records. With no wind the drag pen rests accurately on the upper line of the time record and, if tapped lengthwise of the rotating drum, traces a damped harmonic of about one cycle per second, as shown at the left of the figure.

In a 40-mile wind the displacement, disregarding structural tremor, wavers slowly above and below its mean value by a fraction of 1%, as shown in the table. This slow swell, unapparent to the eye viewing the record, is clearly disclosed in columns 3 and 5. The wavy tremors, of 2 to 3 cycles a second, are negligible. They are too weak and rapid to affect the manometer or usual readings on the massive aerodynamic balance. Besides they can be made anything one chooses, by altering the free period of the suspension system, the character of the wind object, and the type of honeycomb that affects the smoothness of the general air stream.

As a net result, Table I shows that the mean variation from the faired drag record, in the present test, is .30% with no control; .15% with attentive hand control; .06% with normal automatic control. As is well known, the mean variation of percentage speed is half that of the drag.

The mean variation is used here only for comparison, not to display the steadiness of the wind force. To determine whether any control is needed, one may examine column 5. This shows that with no control the drag sometimes varies for a considerable period as much as .9%, which is not permissible. After the rheostat heating attains equilibrium the drag may remain constant to less than half of one percent for long periods without either hand or automatic control.

TABLE I.

Wind Drag Versus Time with Three Types of Control.
Wind speed = 40 M.P.H.

Time from start t sec.	Interval of constant air speed Δ t sec.	Drag displacement s in.	Weight of same s Δ t	Percentage variation 100(s-mean s) / mean s %	Weight of same absolute % × Δ t
			No Control		
2	2	3.14	6.28	-.3	.6
5	3	3.13	9.39	-.6	1.8
10	5	3.15	15.75	0	0
16	6	3.13	18.78	-.6	3.6
28	12	3.14	37.68	-.3	3.6
38	10	3.13	31.30	-.6	6.0
44	6	3.12	18.72	-.9	5.4
56	12	3.13	37.56	-.6	7.2
71	15	3.12	46.80	-.9	13.5
83	12	3.13	37.56	-.6	7.2
90	7	3.14	21.98	-.3	2.1
97	7	3.13	21.91	-.6	4.2
102	5	3.15	15.75	0	0
114	12	3.14	37.68	-.3	3.6
121	7	3.13	21.91	-.6	4.2
137	16	3.15	50.40	0	0
148	11	3.14	34.54	-.3	3.3
157	9	3.15	28.35	0	0
162	5	3.16	15.80	+.3	1.5
193	31	3.15	97.65	0	0
206	13	3.14	40.82	-.3	3.9
213	7	3.15	22.05	0	0
226	13	3.14	40.82	-.3	3.9
233	7	3.17	22.19	+.6	4.2
257	24	3.16	75.84	+.3	7.2
286	29	3.15	91.35	0	0
310	24	3.16	75.84	+.3	7.2
316	6	3.17	19.02	+.6	3.6
331	15	3.15	47.25	0	0
339	8	3.17	25.36	+.6	4.8
352	13	3.16	41.08	+.3	3.9
380	28	3.15	88.20	0	0
423	43	3.17	136.31	+.6	25.8
429	6	3.16	18.96	+.3	1.8
453	24	3.15	75.60	0	0
480	27	3.16	85.32	+.3	8.1
	480		480/1511.80		480/142.2
			mean s=3.15		mean %=.30

TABLE I (Cont.)

Wind Drag Versus Time with Three Types of Control.
Wind speed = 40 M.P.H.

Time from start t sec.	Interval of constant air speed Δt sec.	Drag displacement s in.	Weight of same s Δt	Percentage variation $\frac{100(s - \text{mean } s)}{\text{mean } s}$ %	Weight of same absolute % × Δt
Attentive hand control					
40	40	3.15	126.00	-.3	12.0
60	20	3.16	63.20	0	0
100	40	3.15	126.00	-.3	12.0
125	25	3.16	79.00	0	0
140	15	3.15	47.25	-.3	4.5
160	20	3.16	63.20	0	0
180	20	3.15	63.00	-.3	6.0
190	10	3.16	31.60	0	0
200	10	3.17	31.70	+.2	2.0
220	20	3.16	63.20	0	0
230	10	3.15	31.50	-.3	3.0
260	30	3.16	94.80	0	0
270	10	3.17	31.70	+.2	2.0
320	50	3.16	158.00	0	0
370	50	3.17	158.50	+.2	10.0
410	40	3.16	126.40	0	0
420	10	3.18	31.80	+.5	5.0
460	40	3.17	126.80	+.2	8.0
480	20	3.16	63.20	0	0
490	10	3.17	31.70	+.2	2.0
500	10	3.18	31.80	+.5	5.0
560	60	3.17	190.20	+.2	12.0
575	15	3.16	47.40	0	0
590	15	3.17	47.55	+.2	3.0
	590		590/1865.5 mean s=3.16		590/86.5 mean %=.15
Automatic control					
50	50	3.21	160.50	0	0
60	10	3.22	32.20	+.3	3.0
90	30	3.21	96.30	0	0
105	15	3.20	48.00	-.2	3.0
155	50	3.21	160.50	0	0
160	5	3.19	15.95	-.6	3.0
170	10	3.20	32.00	-.2	2.0
180	10	3.22	32.20	+.3	3.0
232	52	3.21	166.92	0	0
235	3	3.22	9.66	+.3	.9
240	5	3.21	16.05	0	0
	240		240/770.28 mean s=3.21		240/14.9 mean %=.06

References

1. Zahn, A. F. : Measurement of Air Velocity and Pressure. "Physical Review," Dec., 1903.

2. Zahm, A. F. and Smith, R. H. : Comparison of United States and British Pitot-Static Tubes. N.A.C.A. Technical Report No. 81. (1920)

3. White, W. Munroe : The Pitot Tube; Its Formula. "Journ. Assoc. Eng. Societies," August, 1901.

4. Gregory, W. B. : The Pitot Tube. "Trans. A.S.M.E.," 1903, Vol. 25.

5. Bramwell, F. H., Relf, E. F. and Fage, A. : On a Determination on the Whirling Arm of the Pressure Velocity Constant for a Pitot (velocity head and static pressure) tube; and on the absolute measurement of velocity in aeronautical work. British Advisory Committee for Aeronautics Reports and Memoranda No. 71. (Dec., 1912)

6. Duchemin, Col. : "Recherches Experimentales sur les Lois de la Resistance des Fluids." (1842)

7. Prandtl, Prof. L. : "Ergebnisse der Aerodynamischen Versuchsantalt zu Göttingen," 1921, Vol. I.

8. Zahm, A. F. : Atmospheric Friction on Even Surfaces. "Philosophical Magazine," July, 1904.

9. Ermish, H. : "Abhandlungen aus dem Aerodynamischen Institut an der Technischen Hochschule," Aachen, Heft 6, 1927.

Fig.1 Pitot-static tube in working part of 8 - foot tunnel

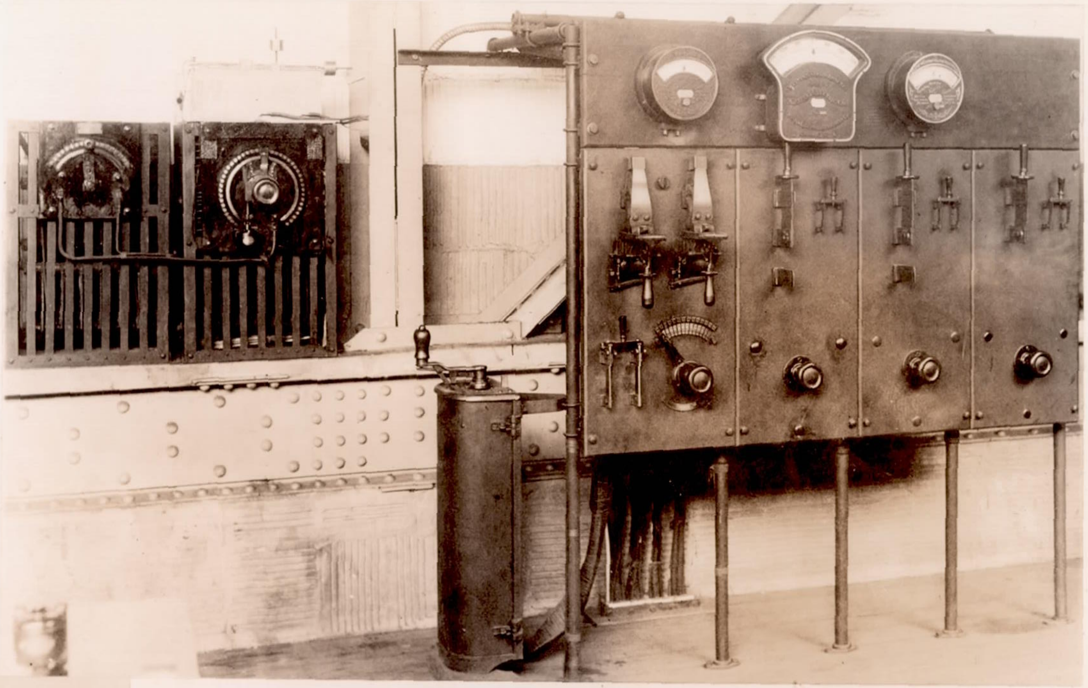

Fig.3 Switch board with motored rheostat at left

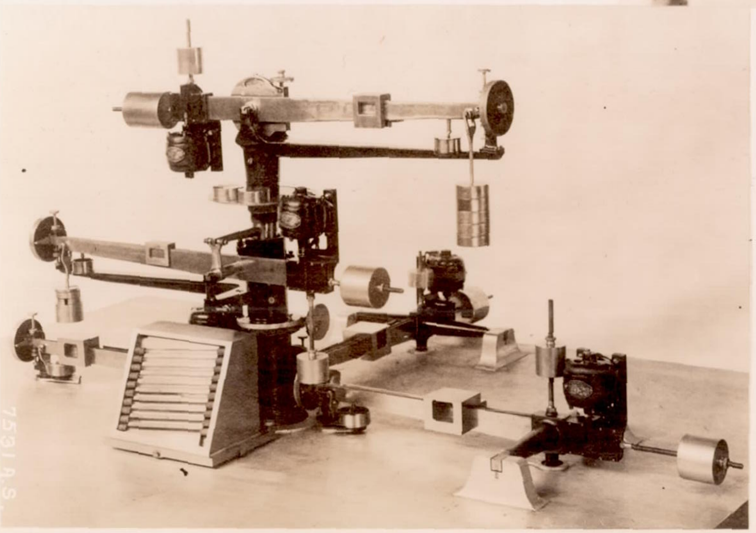

Fig.2 Step-tube manometer on desk of 6 - component wind balance

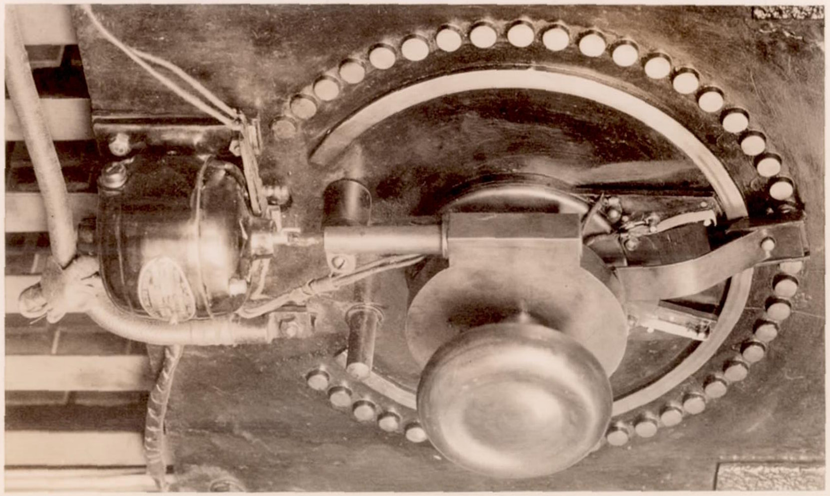

Fig.4 Close-up view of motor-driven rheostat

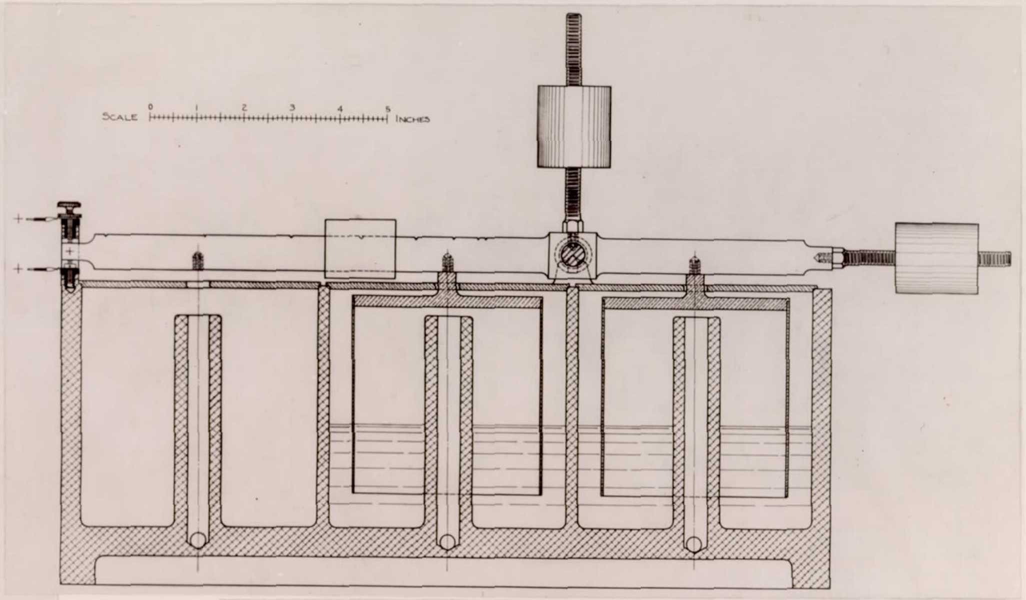

Fig.5 Longitudinal section of inverted-cup manometer

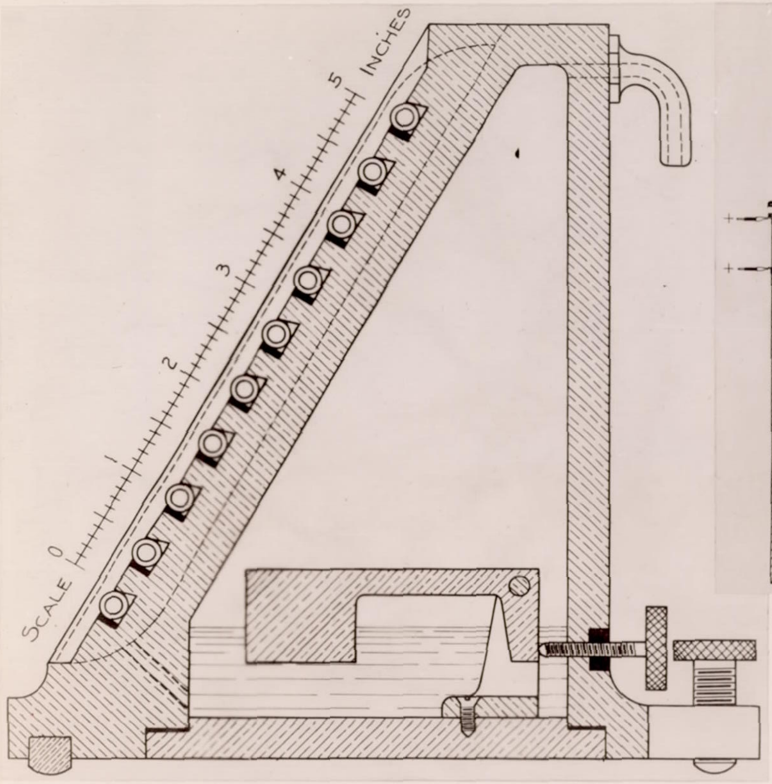

Fig.7 Cross-section of step-tube manometer

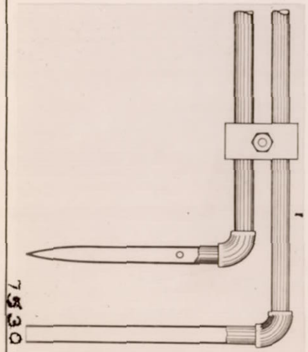

Fig.10 Separate Pitot and static tubes of W.M.White, 1901

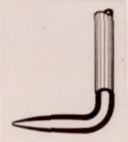

Fig.8 Original form of Pitot tube invented by Pitot in 1730.

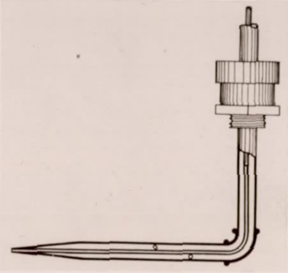

Fig.11 Combination Pitot-static tube of Gregory & Maltby, 1902

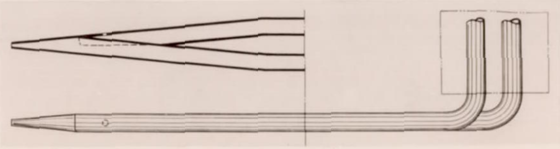

Fig.9 Pitot-static nozzle of M.H.Darcy and M.H.Bazin, 1865

Fig.6 Close view of step-tube manometer

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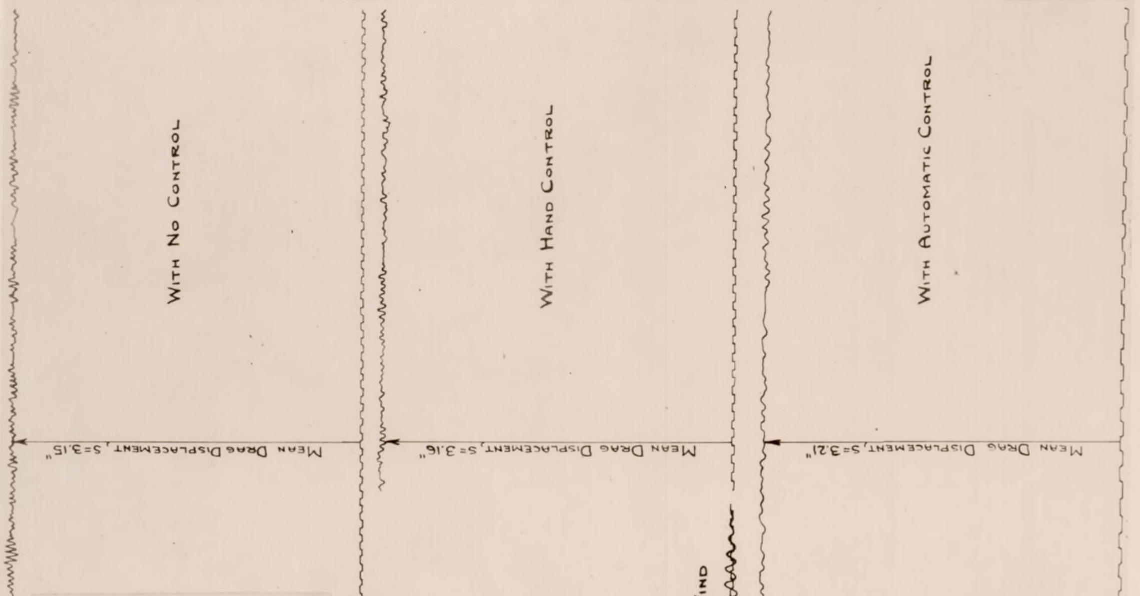

Fig.15 Wind drag vs. time with three types of control. Wind speed, 40 M.P.H. Each segment of time record = 1/2 second.

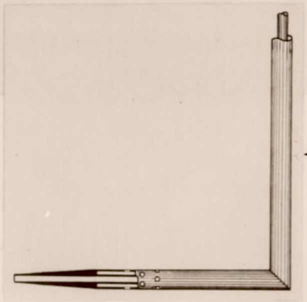

Fig.12 British standard Pitot-static tube, 1912

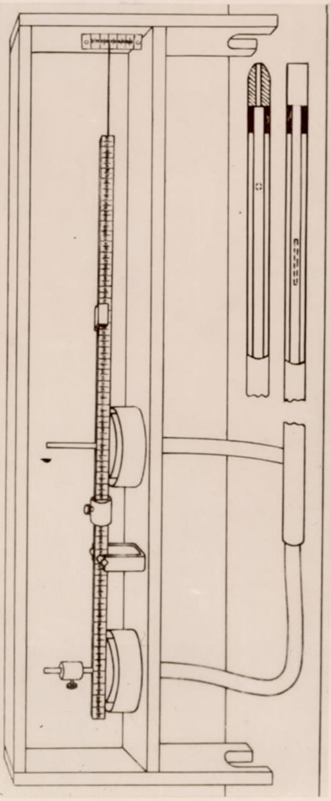

Fig.13 A.F.Zahm's micromanometer joined to leads of Pitot-static tube, 1903, with two types of pressure nozzle. Length of balance beam equals one meter.

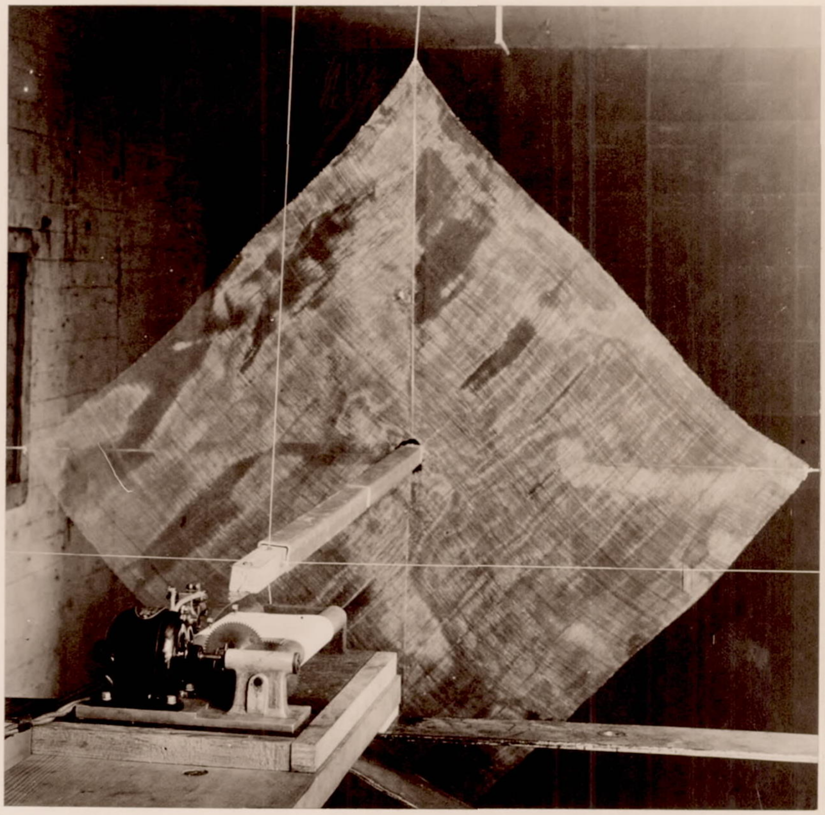

Fig.14 Apparatus for recording wind force against time, used to compare three types of air-speed control. Wire net, less meshes, had a frontal area equal to 1/25 of the tunnel cross section and was mounted 5 feet upstream from the chronograph

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