DEPARTMENT OF ENGINEERING RESEARCH
UNIVERSITY OF MICHIGAN
ANN ARBOR

AN ANEMOMETER
FOR
A STUDY OF WIND GUSTS

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The authors are indebted to Professor C. F. Marvin, Chief of the United States Weather Bureau, and to Mr. S. P. Fergusson of the Instrument Division of the United States Weather Bureau, for suggestions and criticisms. Mr. P. O. Huss, Research Associate in the Department of Engineering Research, gave valuable assistance in the development of this instrument.

SYNOPSIS

The new type of pressure-plate anemometer described in this Bulletin was developed for use in a general program of research on the Loading and Strength of Overhead Lines. One part of this research is devoted to the study of the intensity, duration, and extent of the wind gusts occurring at the site of the experimental power line. For this purpose observations were made to determine the simultaneous values of wind velocity at a number of points, so located as to give a horizontal and a vertical cross section of the passing gusts. The gusts at this site may have a velocity in excess of 100 feet per second. It was therefore decided to use anemometers which would record accurately the average velocity over intervals of time as short as one-fourth of a second or shorter, so that a given observation might be completed before an important gust materially changed its shape and position.

Existing anemometers possess inertia errors which make them unsuitable for measuring the wind velocity over such small intervals of time. The new anemometer is equipped with a magnetic transmitter and uses an oscillograph for a recorder. The natural frequency of vibration of the pressure plate is about 115 cycles per second, and after an impulse has been given to the plate, the time required for the decay of its vibratory motion is about one-eighth of a second. The errors due to tilting of the anemometer, changes in temperature, and the angle of incidence of the wind, are negligible. The new type of anemometer can record accurately the average wind velocity over intervals of time as small as one-eighth of a second.

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General View at the Site of the Experimental Station

The anemometers on the 250-foot tower will give a vertical section of the wind gusts, while those on the 50-foot poles will give a horizontal section. All records are received in the chart-house, including the records of the forces bending the poles in the experimental line.

AN ANEMOMETER
FOR
A STUDY OF WIND GUSTS

The electric pressure-plate anemometer described in some detail in this Bulletin was developed for use in a research project which had as its main objective the measurement of the forces exerted by the wind against the conductors and poles in an electric power line. This investigation was undertaken by the Department of Engineering Research under the sponsorship of The National Electric Light Association.

Preliminary work on the project was begun in April, 1927. During the summer and autumn of that year an experimental pole line one-quarter of a mile long was built on a ridge of land about four miles from the Campus of the University of Michigan. Three commercially available anemometers were installed at the site for the purpose of obtaining records of wind velocity, together with instruments by means of which it was possible to obtain records of the forces tending to bend each of five poles near the center of the experimental line. All instruments were equipped with strip-charts driven by synchronous motors at the rate of three inches per minute so that it was possible to correlate coincidental values of wind velocities and wind forces with a time error not exceeding one-half second.

Many records were obtained with these instruments from the storms which occurred during the early months of 1929. It was found, however, that these records could not be completely analyzed without some knowledge of the characteristics of the wind gusts which occur at the site of the experimental line. This situation had been foreseen and a study of wind gusts had been included in the original program of work.

By April, 1928, preliminary studies had led to the conclusion that the available types of recording anemometers would not be suitable for this study of wind gusts since the inertia of their moving parts introduced errors of unknown amounts which could be eliminated only by taking the average recorded velocity over a relatively long period of time. It was, therefore, decided that a new type of anemometer should be designed which would be capable of following accurately the rapid fluctuations of wind velocity occurring in the larger wind gusts. It was intended that horizontal cross-sections of the wind gusts should be obtained by mounting several of these anemometers on wood poles at a height of fifty feet above the

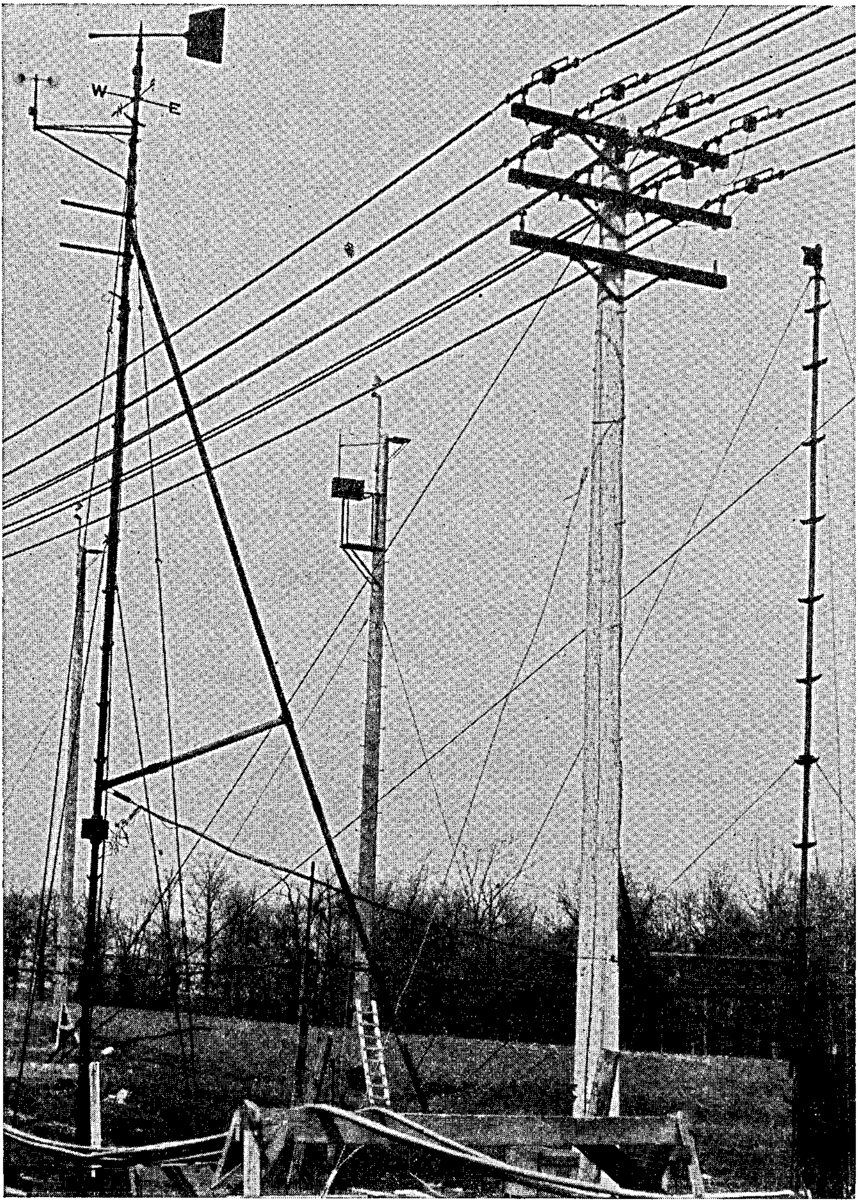

FIGURE 1. INSTALLATION OF THE CUP ANEMOMETER

The cups are installed 15 feet west of the experimental pole line at a height of 32 feet, while the new pressure-place anemometers, two of which are shown in the background, are installed 40 feet east of the pole at a height of 50 feet.

ground and with a horizontal spacing which could be changed as the experiment progressed. It was also intended that vertical cross-sections of the gusts be obtained by mounting additional anemometers at vertical intervals of fifty feet on a steel tower. From this arrangement it was expected that records would be obtained from which it would be possible to determine the variations in the horizontal and vertical extent of the wind gusts as well as the variations in their intensity and duration.

This Bulletin presents a detailed account of this new type of anemometer. After an analysis of the characteristics and limitations of commercially available anemometers, the Bulletin will discuss the design of the anemometer, the recording instrument, the electric circuit, the calibration methods, the magnitude of the instrument errors, the speed of response, and will give several typical records.

COMMERCIALLY AVAILABLE ANEMOMETERS

At the time the study of wind gusts was started three commercially available instruments were installed at the site of the experimental line, one of the revolving-cup type and two of the pressure-tube type. A description of these instruments together with typical records obtained will show why they were not adopted for use in the study of wind gusts.

The Revolving-Cup Anemometer.

The revolving-cup anemometer shown in Figure 1 is essentially the same as the three-cup type now being used by the United States Weather Bureau. It was designed by Dr. J. Patterson, Director of the Meteorological Service of Canada,[1] and Mr. S. P. Fergusson of the United States Weather Bureau. It consists of three hemispherical cups attached to short arms revolving about a central vertical spindle. At the base of the spindle is a mechanism so arranged as to give an electrical contact with the passage of each 1/60 mile of wind. The closing of the electrical contact actuates a pen in a distant chart house in such a manner that a short line is scribed on a strip chart which moves past the pen at the rate of three inches per minute. The chief difference between this and the standard Weather Bureau instrument[2] lies in the fact that the latter instrument is designed to make the electrical contact with the passage of each one mile of wind and to make its record upon a chart attached to a drum which makes one complete revolution every six hours.

[1] PATTERSON, J., The Cup Anemometer, *Trans. Roy. Soc. Canada*. Jan. 1926.

[2] *Monthly Weather Review,* pp. 216-218, April, 1924.

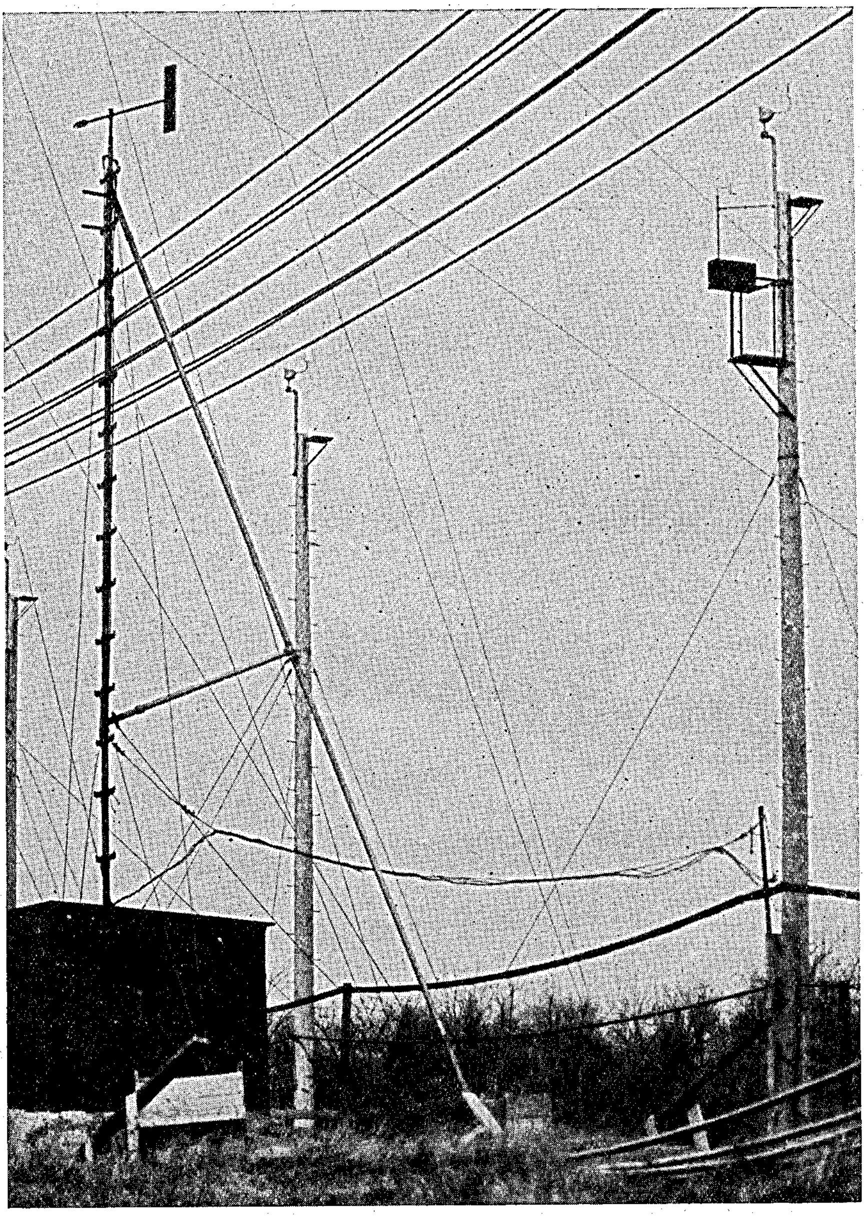

FIGURE 2. INSTALLATION OF THE SOUTH PRESSURE-TUBE ANEMOMETER

The pressure tube and its wind vane are mounted on the pipe mast shown in the left foreground. The pipes which carry the positive and negative pressures to the charthouse below emerge from the vertical stem at a point about eighteen inches below the vane. A wind direction recorder, in addition to a pressure-plate anemometer, is mounted on the 50-foot pole shown at the extreme right of this photograph. Direction recorders are mounted only on alternate poles.

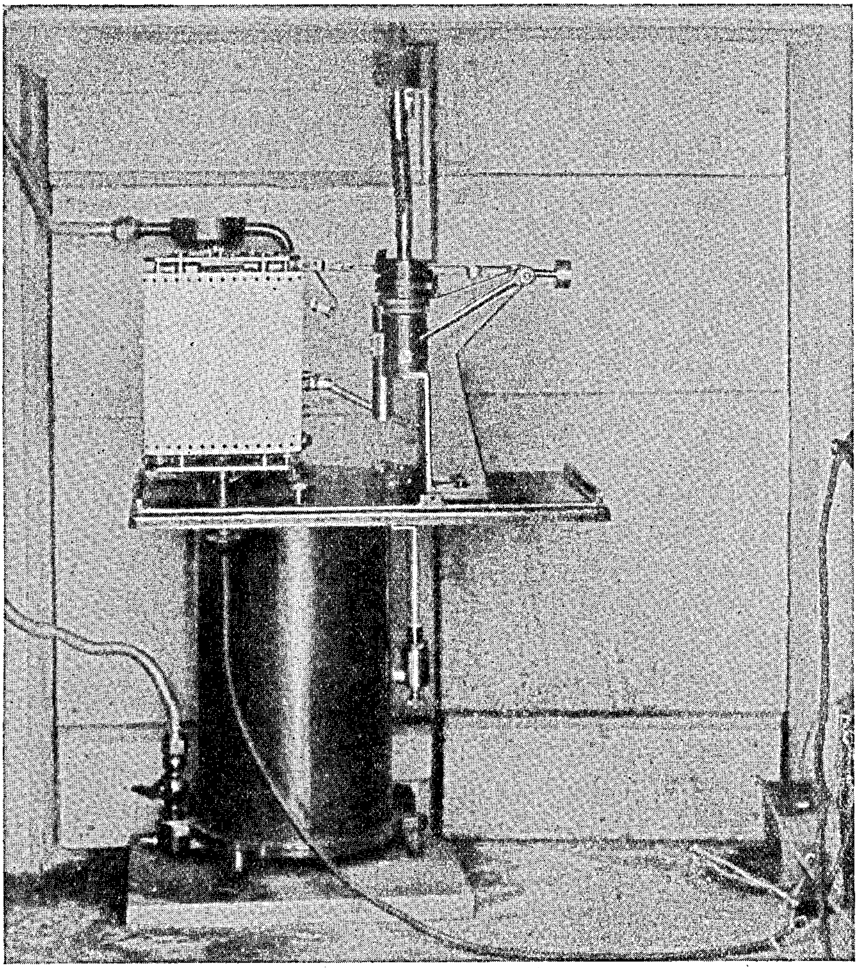

FIGURE 3. RECORDING MECHANISM FOR THE PRESSURE-TUBE ANEMOMETER

Two pens are shown bearing against the strip chart. The upper pen records wind direction while the lower one records wind pressure or velocity. The lower pen is actuated by a float immersed in liquid in the tank. A pipe transmits the total pressure from the open end of the pressure tube above to the under side of the float. Negative pressure is transmitted by a second pipe from the perforations in a vertical tube above to the inside of the tank. The height to which the float rises thus depends only on the difference in the pressures which are transmitted through the two pipes.

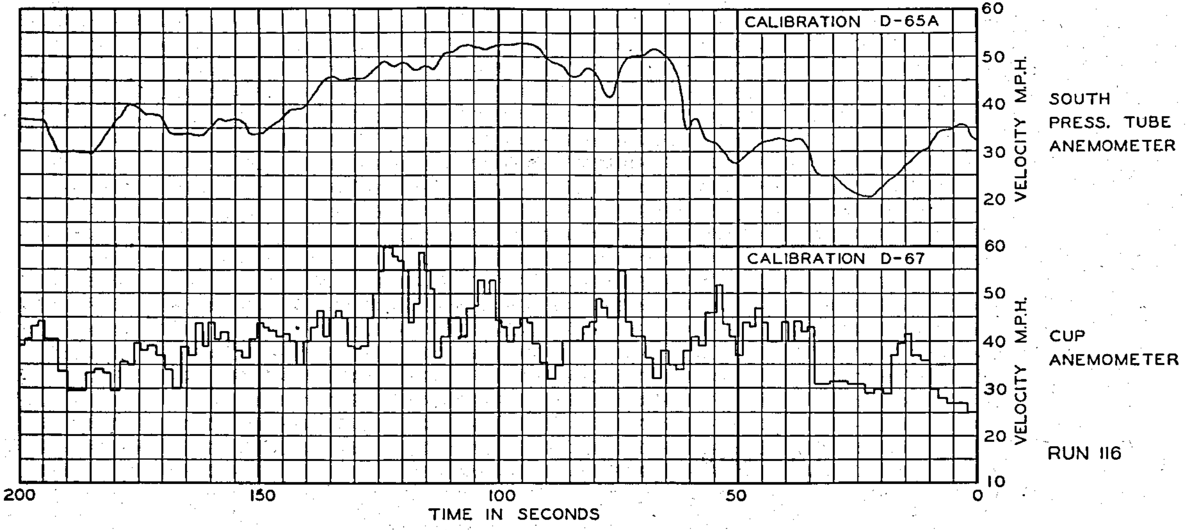

FIGURE 4. TYPICAL RECORDS FROM TWO TYPES OF ANEMOMETERS

These instruments were installed at points 250 feet apart. On all storm records the cup anemometer gave wider amplitudes and shorter cycles of fluctuation than either of the pressure-tube anemometers.

Pressure-Tube Anemometers.

The two pressure-tube anemometers are modifications of the type originally designed by W. H. Dines.[3] The installation of one of them at the site of the experimental power line is shown in Figure 2 and a view showing the recording mechanism in Figure 3.

The essential parts of this type of anemometer are the pressure tube, a suction tube, the connecting pipes, and the recording mechanism. The open end of the pressure tube is pointed into the wind by a streamline wind vane. The total pressure at the opening of the tube is transmitted through a lead pipe to the under side of a float which has the form of an inverted pail immersed in liquid. A second tube enclosing the vertical portion of the first tube is perforated with many small holes. The wind blowing past these perforations causes a decrease in pressure in the annular space between the two tubes and this decrease in pressure is transmitted through a second pipe into the tank which contains the liquid in which the float is immersed. The height to which the float rises in the liquid is thus independent of fluctuations of the air pressure within the chart house and depends only on the difference in the pressures which are transmitted through the two pipes. These pressures are functions of the wind velocity and are respectively greater and less than the static pressure near the anemometer. The action is similar to that of a Pitot-static tube.[4] The float is attached to a mechanism which actuates a pen, so that as the float moves up and down the pen scribes upon a moving strip chart a record of the variations in wind pressure. The chart has been calibrated to read velocity in miles per hour instead of pressures.

Records.

A typical record from the cup anemometer is shown in Figure 4. This record has been transcribed from the original chart and has been corrected according to a calibration curve which was established by tests in the wind tunnel for standard air-stream conditions. It was possible to obtain the average wind velocity for each 1/60 mile of wind from the original chart since the speed of the chart was known. A scale was prepared which, when used with a magnifying glass, enabled the draftsman to determine quickly the average velocity for the space between two succeeding marks of the pen and to plot this velocity on master record sheets such as are shown in the figure.

[3] DINES, W. H., Anemometer Comparisons, *J. Roy. Br. Meteorological Soc.*, July, 1892.

[4] OWER, E., *Measurement of Air Flow,* Chapters III and V (Chapman and Hall, Ltd., 199 pp., 1927).

It will be seen that there are several places on this record where a rapid fluctuation in the wind velocity occurs. Due to the mass of the revolving cups there is some question as to the accuracy of the maximum and minimum values of velocity which are here recorded. Undoubtedly, the instrument gives an accurate record only when the recorded velocity is averaged over a sufficiently long period of time to include one or more complete cycles of fluctuation. On this project it was assumed that the inertia errors due to the mass of the revolving cups were eliminated when the average velocity for an interval of 10 seconds was used. It will be seen that there are frequent instances in the record where the wind velocity has passed through both a maximum and a minimum value within a period of less than 10 seconds.

Figure 4 also contains a portion of one of the transcribed records from the south pressure-tube anemometer after calibration corrections had been made. The effect of the inertia of the moving parts of the instrument in damping out rapid fluctuations in the record is even more noticeable here than it is in the record for the cup anemometer. No method was devised for determining the amount of this effect but it was assumed that the instrument gives an accurate record when the velocity is averaged over an interval of 10 seconds or more. It will be seen that there are numerous instances in this record also where the velocity fluctuates so as to include both a maximum and a minimum value within a period of less than 10 seconds. There is no doubt that the fluctuations in velocity which are shown in this record do not give the true amplitude of the fluctuations which actually occurred in the wind velocity and that many important minor gusts occurred which are not recorded at all.

An exact comparison of the sensitivity of these instruments can not be made since they were installed at points 240 feet apart. Nevertheless, on all storm records the cup anemometer gave wider amplitudes and shorter cycles of fluctuation than either of the two pressure-tube anemometers in spite of the fact that the topography of the ground at the cup anemometer is more favorable for the preservation of smooth air currents than it is at either of the pressure-tube anemometers.

Other Types of Anemometers.

There are several other commercially available anemometers, none of which, however, were believed to be sufficiently free from inertia errors to be satisfactory in this study of wind gusts. One type, which has been designed for use at industrial plants and airports, consists of a Robinson cup anemometer with the rotor of a small electric generator attached to the vertical spindle. The voltage which is generated by the rotor is indicated or recorded by a voltmeter which may be graduated to read velocity instead of volts. These instruments are probably less accurate in gusty winds than the cup anemometer which was used in this study, since, in addition to the inertia errors of the revolving cups, there are also the errors due to the electrical drag of the generator, the inertia of the generator, and the inertia of the swinging pen. Another type is the vane or windmill anemometer which is available commercially for such uses as the measurement of wind velocities in air ducts, mines, and tunnels. This instrument is especially valuable for measuring low velocities but its use is not advocated for gusty winds.[5] There appear to be possibilities of making a satisfactory instrument of this type in which the "windmill" is constructed of balsa wood and is sufficiently large so that its torque will be too great to be appreciably affected by the inertia and the electrical drag of a small generator. There is reason to believe that such an instrument, using an oscillograph instead of a voltmeter, would give an accurate record of changes in wind velocity occurring at very rapid rates, provided that it was equipped with an efficient vane to keep it pointed into the wind.

It was evident early in this research that none of the instruments which have just been described would be satisfactory for use in a study of wind gusts because of the indeterminate nature of the inertia errors which they contain. These errors could be partly eliminated by using for each observation the average velocity over an interval of time which is at least as long as the shortest interval in the records during which there occurred a complete cycle of velocity changes. The records show this interval to be from three to ten seconds long, during which time a gust would have traveled hundreds of feet and no record of its structure would have been obtained except its average velocity. It was clearly desirable to develop instruments which would be more quickly responsive to changes in wind velocity.

DESIGN OF THE NEW ANEMOMETER

The anemometer which is described in this Bulletin was designed to give accurate records of wind velocity for intervals of time as small as one-quarter of a second. It was expected that this degree of sensitivity would be ample to show all the characteristics of wind gusts which are of interest in this study. The pressure plate was adopted as the actuating element because, with the proper type of electric transmitter, it would be possible to restrict

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[5] Ower, E. *Measurement of Air Flow,* Chapter VII (Chapman and Hall, Ltd., 199 pp., 1927).

the motion of the plate to a few thousandths of an inch and thus reduce the momentum of the oscillating plate to such a low value that the inertia errors would be negligible. When a force is applied to the plate it is pushed back from its neutral position and produces elastic deformations within the electric transmitter. When the force is wholly or partially removed, the plate tends to return to its neutral position, the speed of response depending upon the rigidity of the elastic parts and the inertia of the moving parts. If, due to small mass in the moving parts or to the small amplitude of oscillation, the natural period of vibration is short, then the return toward the neutral position will be accomplished rapidly and the plate will quickly assume a condition wherein it can respond freely to another impulse.

During the early stages of the development of this new anemometer, experiments were conducted to determine the suitability of stacks of carbon discs as the electrical transmitting elements. This principle was discarded in favor of the magnetic principle because of the difficulty of controlling the calibration of the carbon stacks.

An assembly drawing of the pressure-plate anemometer is shown in Figure 5 which is attached to the back cover of this Bulletin. This figure contains a sectional elevation, a sectional plan, and the front view of the instrument.

The pressure plate of the anemometer contains one-half of a square foot of exposed area. It is nine inches high and eight inches wide. It is attached near the bottom to the frame of the anemometer by means of two pairs of flexible hinges. At the center of the plate a rod is attached which passes back to the transmitter in such a way that any pressure against the plate tends to rotate it about the flexible hinges and to transmit the pressure through the pusher rod to the back prong of the magnetic transmitter. The back prong of the transmitter is provided with a flexible hinge about which it rotates as pressure is applied to the plate. This modifies the air gap between two sets of iron laminations, one of which is attached to the back prong of the transmitter. The details of the transmitter are shown in Figure 6. It will be seen that one set of laminations is E-shaped and that a coil of wire surrounds its center prong. The transmitter operates on the change of inductance in the coil which accompanies a change in the size of the air gap. In the drawing the various details for the adjustment and insulation of the laminations are self-explanatory.

The wires from the coil are carried to slip rings located on the vertical axis of rotation of the anemometer. By means of the slip rings, it is possible for the anemometer to make any number of complete revolutions about its vertical axis without twisting the wires which pass from the transmitter through the vertical shaft to the central chart house. Ball bearings are used to insure freedom of motion of the anemometer in responding to changes in the direction of the wind.

The transmitting mechanism is enclosed in a thin brass cover which is arranged so that it may be easily removed for inspection and adjustment of the transmitter. The pressure plate is provided with flanges which extend back beyond the front of the cover but do not touch it at any point. A space of about 1/16 of an inch is provided all around between the flanges and the brass cover for the purpose of clearance and to permit free ventilation of the space inside the cover. No attempt was made to have the shape of the cover conform to a theoretical streamline profile. It was merely made large enough to enclose the mechanism and was given a symmetrical shape in plan and in elevation.

The pressure plate is braced against distortion by a hard aluminum casting into which the pusher rod is screwed and to which the flexible hinges are attached. The thin aluminum plate is attached to the casting by means of screws which draw the plate into the countersunk holes in the casting to such a depth that the flat head screws are flush with the face of the pressure plate. The slots in the screws are filled with foundry cement. The plate is then given a satin texture by burnishing it with a wire buffing wheel.

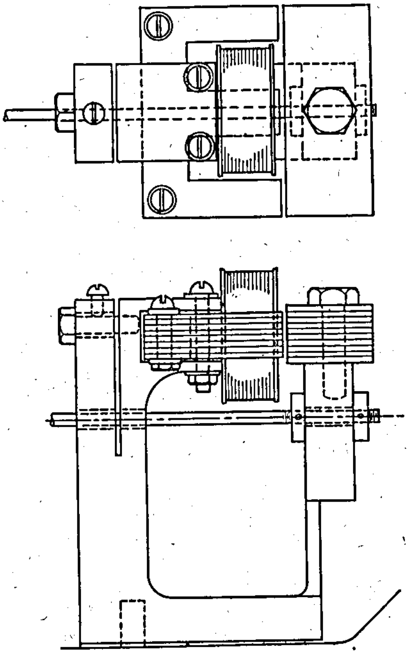

FIGURE 6. DETAILS OF THE MAGNETIC TRANSMITTER

The pressure plate is kept normal to the direction of the wind stream by a streamline vane, which is located 16 inches back of the pressure plate. The center of the vane is located 12 inches above the center of the pressure plate. The best position for the vane was determined experimentally in the wind tunnel by placing vanes singly and in pairs at various positions above, below, and to the side of the horizontal axis of the anemometer and observing its behavior in the air stream. With the vane placed in the position which was finally adopted, it was found that, in a wind having a velocity of 30 m.p.h., the tail could be turned normal to the wind stream and upon being released would return to a steady position on the fourth beat of oscillation. This degree of dynamic stability was considered to be satisfactory.

When the instrument was rotated so as to simulate the effect of a sudden change in wind direction, centrifugal forces were transmitted to the pusher rod by both the pressure plate and the back prong of the transmitter. These forces oppose each other so that it is possible to balance them and thus to remove their effect upon the size of the air gap. It was found by trial that one-half pound of lead on the back of the pressure plate was sufficient to establish the desired dynamic balance. The addition of the lead weight also had the effect of reducing the natural frequency of vibration of the pressure plate to about 115 cycles per second.

THE RECORDING INSTRUMENT

A TWELVE-ELEMENT OSCILLOGRAPH

It was decided to use an oscillograph as a means for recording the wind variations. The oscillograph was chosen instead of a graphic meter primarily for its greater speed, though there was the secondary consideration that one oscillograph could take the place of a number of graphic meters, which would make the installation more compact, and the records more simple to correlate.

Description of the Oscillograph.

The oscillograph selected was of the twelve-element, permanent-magnet type, and was sufficiently different from the standard instrument that it seems desirable to give a description of its more important features. The moving element consists, as in other oscillographs, of a coil of fine wire with a single turn, having the two sides of the coil very close together. The construction is shown in Figure 7. One end of the wire is fastened to a terminal at the top, passes over an upper bridge member, a lower bridge, around a small pulley, then back over the bridge pieces to the other terminal. The pulley is fastened to a spring strip, so that the stringing wire is kept in tension. Across the wires at a point midway between the bridges is cemented a small mirror. The element is so supported that the portion between the bridges is between the poles of a strong permanent magnet. When current is passed through the element, passing downward in one wire and upward in the other, one wire is pushed to the front, and the other to the rear, and the mirror is thus deflected from its zero position. Light from a small incandescent lamp shines on the mirror, from which it is reflected back either to a ground glass viewing-screen or to a photographic film, giving a spot of light on the screen or film. The concentration of the light to a small spot is aided by two lenses, one close to the mirror, the other a cylindrical lens near the screen. When the mirror is deflected the spot of light is displaced, the amount of displacement being dependent on the strength of the current passing through the element. If the photographic film is moved with uniform speed in a direction at right angles to the motion of the spot of light, there results a curve with rectangular coördinate axes, one axis representing time, the other current. The relation between wind velocity and current is known from the anemometer calibration, so that this curve can be interpreted as a record of wind velocity plotted against time. A sample record is shown in Figure 19, page 32.

Film is used where high sensitivity to light is required, that is, in case of fast film motion. Where the motion is less rapid it is possible to record directly on sensitized photographic paper. For the anemometer records taken so far a chart speed of six inches per minute has been used. At this speed the paper gives satisfactory records, and is used in preference to film

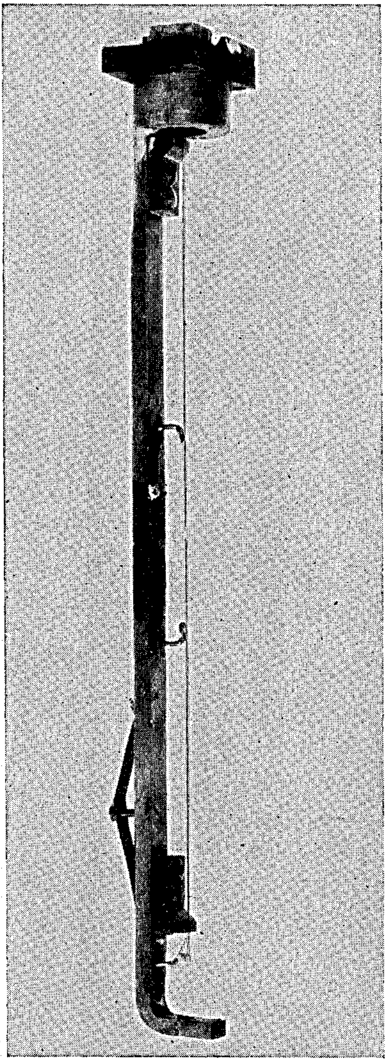

FIGURE 7. AN OSCILLOGRAPH ELEMENT

The small mirror is cemented to the stringing wires midway between the loops of wire each of which contains a drop of damping oil. Full size.

on account of lower cost and of greater ease in making marks on the record. The paper for this twelve-element oscillograph is a strip twelve inches wide, and comes in rolls one hundred feet long.

Damping.

Any system possessed of inertia and spring effects, as in the oscillograph element, exhibits a natural frequency of vibration. If the element is disturbed electrically, or jarred mechanically, it will vibrate at its natural rate. If an electric current varying at a frequency near that of the element be passed through it, the resulting record will be of greatly distorted amplitude. To prevent blurring and distortion of the record by this rapid natural vibration it is necessary to provide some form of damping.

In the oscillograph which has been used so far in this study two rings of wire are supported near the element wires, and a drop of oil is placed in each ring as shown in Figure 8. The oil drop envelops the wires, and provides the desired damping. This form of construction is in interesting contrast to the type used in the standard oscillographs, in which the entire element is immersed in a well of oil, with a window for the light to reach the mirror. The open construction has the advantage of simplicity. Moreover no light is absorbed by the oil between window and mirror. On the other hand, it has some serious objections. The exposed oil drop may, in time, form a hard crust, or it may creep away along the stringing wires or along the oil ring support. Also, dirt finds its way to the oil ring and to the mirror. Small magnetic particles adhere to the pole pieces, and prevent free movement of the element. A great deal of attention is required to maintain this particular type of oscillograph in satisfactory working order.

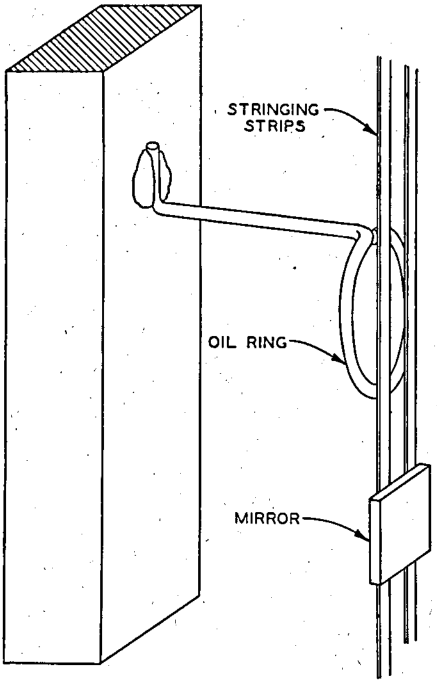

Figure 8. Enlarged Sketch of the Damping Device on the Oscillograph Element

The stringing strips are made of round copper wire rolled flat.

Sensitivity and Speed.

This oscillograph, as is shown in Figure 7, due to the relatively long distance between bridge pieces and to the light stringing wire used, has a greater sensitivity than the standard oscillographs, giving a deflection of two inches with a current of 7 to 12 milliamperes. As another consequence of the more flexible stringing, the natural frequency is only 600 cycles per second according to the manufacturer's data, which is considerably lower than for the standard instruments.

THE ELECTRIC CIRCUIT

As explained earlier in this Bulletin, the force of the wind on the pressure plate causes a change in the length of the air gap between the two sets of iron laminations. The stationary set of laminations is E-shaped, and has a coil around the middle prong. The movable set is straight, and bridges the openings of the E, leaving a short air gap between the end of the prongs and the straight piece. With zero wind force the air gap is approximately .007 inch long, and with a 7-pound wind force, approximately .012 inch long.

Principle of Operation.

The change of air gap causes a change in the inductance or inductive reactance of the system. If an alternating voltage of constant frequency and meter value is impressed on the coil, the magnitude of the current flowing through the coil is dependent on the length of the air gap. As the gap is increased the coil current increases, and can thus be used as a measure of gap length. If it were desired to use the instrument for visual observation only, the coil current values could be observed by means of an A.C. milliammeter. For recording purposes the current could be passed through an oscillograph element, giving as a record an alternating current of varying amplitude. The desired record would be obtained by following the outline, or envelope, of the A.C. waves. A record of this nature is shown by the lower curve of Figure 18, page 30. The maximum and minimum values of amplitude depend on the maximum and minimum gap lengths.

The method of recording coil current directly has been used in some cases,[6] but has two objections for the purpose of this instrument. First, the useful deflection is only a part of the total amplitude, thus compressing the scale of the useful part. Second, the method of using the envelope of the

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[6] SODERBERG, C. R. The Vibration Problem in Engineering. *Elec. Jour.*, p. 71, Feb., 1926.

A.C. waves would cause an inadmissable overlapping and confusion where 12 records are placed on a film 12 inches wide. The first objection has generally been overcome by using some method of subtracting the minimum current from all readings, thus permitting the instrument scale to be spread over the used gap variation. This has been accomplished in a number of ways, the best known of which are several types of bridge circuits.[7] In this instrument the second objection is removed by the use of a rectifier and filter, giving a single-line record instead of the modulated A.C. wave, or wave envelope.

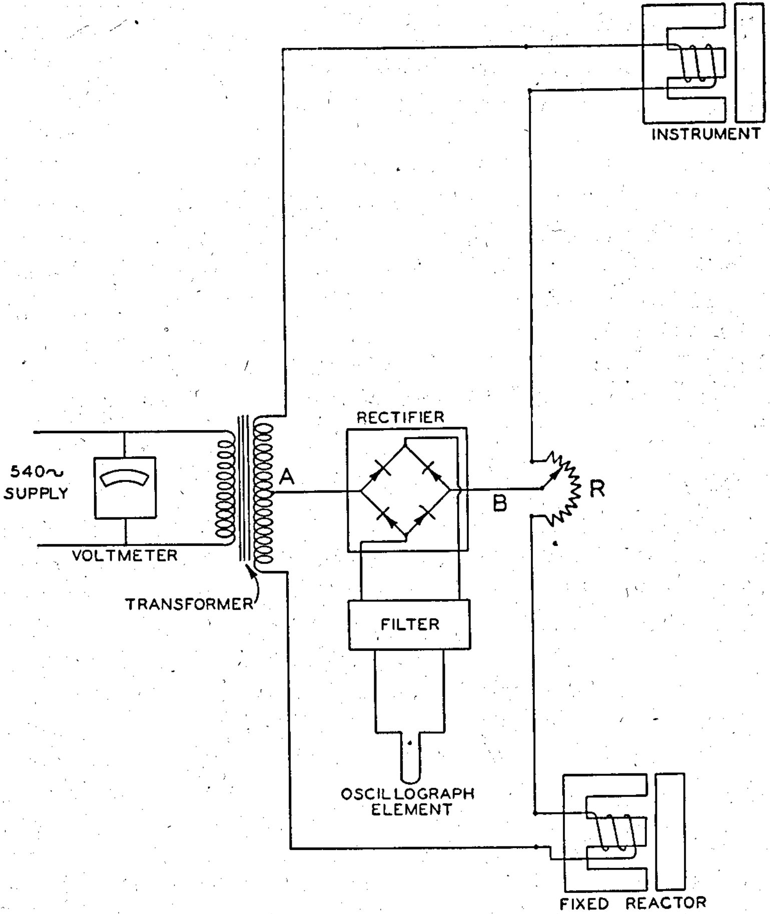

FIGURE 9. CIRCUIT DIAGRAM

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[7] MERSHON, A. V. Vibration Recorder, *Trans. A.I.E.E.*, p. 1007, June, 1926.

The Bridge Circuit.

Preliminary experiments with several types of bridge connections led to the adoption of the form shown in Figure 9 as being most sensitive and most simple. In it a fixed reactor is used, as shown in Figure 10, similar to the instrument coil and laminations, but having a fixed but adjustable gap. The instrument and reactor form a series circuit, fed from the secondary of a transformer. The indicating circuit is connected from the midpoint A of the transformer to the point B between the instrument and the reactor.

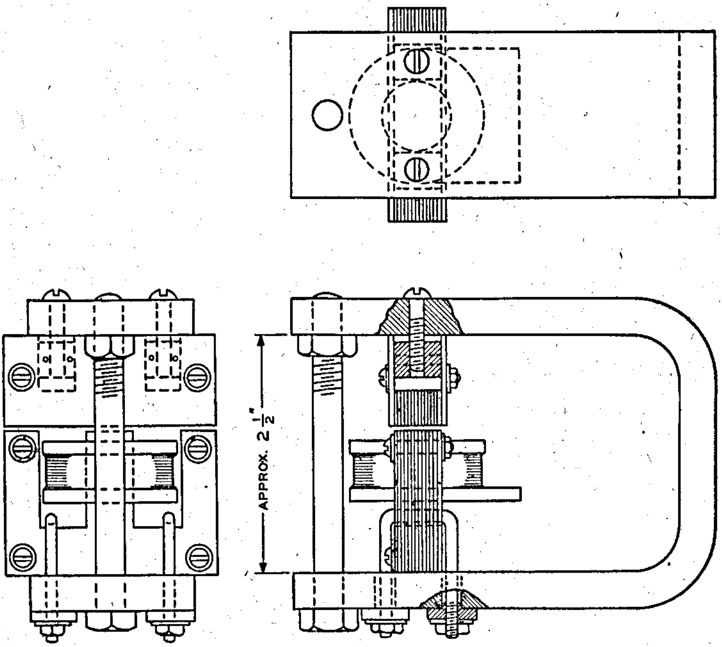


FIGURE 10. DETAILS OF THE FIXED REACTOR

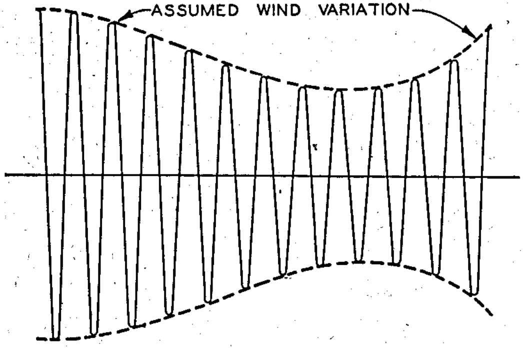
It can be seen that if both coils have identical characteristics, the circuit is balanced and no current flows in the connection A-B. If, however, the instrument gap is changed, the balance is destroyed, and current flows through the oscillograph, the magnitude being dependent on the amount of gap unbalance. The inductances of the two coils can be balanced at the zero position by adjustment of the reactor gap. The variable resistor R is included, as it is impossible to get perfect circuit balance unless the two sides of the circuit are equal in resistance as well as in inductance. The power supply for the instrument is a 540-cycle-per-second generator driven by a synchronous motor running from the 60-cycle supply line.

The Rectifier.

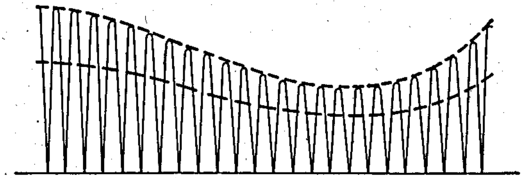
The rectifier which is used to change the alternating current to a unidirectional current is of the copper oxide type.[8] It consists of four groups of copper discs connected in the well-known bridge type circuit for full-wave rectification. The copper oxide rectifier was adopted on account of its compactness, simplicity, and the absence of battery requirements. It is known to vary in behavior to some extent with change of temperature,[9] though published material on this point is meager. After some measurements, it was decided to eliminate this difficulty by placing the rectifier in a constant-temperature box for all readings.

The Filter.

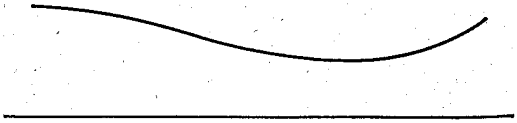
The pulsating unidirectional current coming from



(a) ALTERNATING CURRENT IN ARM A-B



(b) RECTIFIED CURRENT



(c) OSCILLOGRAPH CURRENT

FIGURE 11. DIAGRAMS OF THE 540-CYCLE ALTERNATING CURRENT, RECTIFIED AND FILTERED

The pulsating unidirectional current coming from the rectifier is filtered before it is passed through the oscillograph in order to remove variations due to the 540-cycle supply frequency, and leave only variations caused by the wind.

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[8] GRONDAHL, L. O., and GEIGER, P. H. A New Electronic Rectifier, *A.I.E.E.*, p. 357, Feb., 1927.

[9] SANTINI, D. and SMITH, I. R. The Rectox Rectifier—Its Application to Industrial Control, *Elec. Jour.*, p. 416, Sept., 1929.

the rectifier is filtered before passing it through the oscillograph in order to remove variations due to the 540-cycle supply frequency, and leave only variations caused by the wind. The action of the rectifier and filter are illustrated by the diagram of Figure 11. Curve (a) shows the form of the 540-cycle alternating current in the connection A-B of Figure 9 due to an assumed form of wind variation. Curve (b) shows the effect of the rectifier, in somewhat idealized form, in changing all current flow to the same direction. Curve (c) shows the oscillograph current, which follows the average value of Curve (b) with the rapid variations removed due to the action of the filter.

With perfect full-wave rectification of a 540-cycle wave the filter would need to remove variations of 1080-, 2160- and higher-cycle frequency, and accordingly, a low-pass filter cutting off below 1080 cycles would be satisfactory, though it is safer to cut off below 540 cycles, as otherwise imperfections of the rectifier may cause some of this frequency to appear. The anemometer itself has a natural frequency of about 115 cycles per second, as shown in Figures 17 and 18. For this reason it was considered advisable to have the cut-off below this value so that instrument peculiarities should not appear on the record. Moreover, as the present chart speed is six inches per minute (0.1 inch = 1 second), it was not desired to show on the chart any very rapid fluctuations that may occur in the wind, since at this chart speed the rapid fluctuations would not be distinguishable, but would merely cause a blurring of the record. Accordingly, a simple low-pass filter has been used consisting of a single section, and giving a cut-off frequency of about 50 cycles per second, though the cut-off is of course not sharply defined. The oscillogram, Figure 18, shows that it requires about 0.15 second for the record to indicate completely an instantaneous change of wind velocity from 84 m.p.h. to zero, most of this lag occurring in the filter. The response could be made more rapid by decreasing the inductance of the filter, but as the present speed is considered ample for this project, and in view of the considerations outlined above, it was decided that the present arrangement is more desirable.

CALIBRATION METHODS

The intensity of the pressure exerted against an object in a wind stream may be expressed as the product of the density of the air, the square of the wind velocity, and a coefficient whose value depends chiefly on the shape of the object. The pressure which will be exerted against a thin flat rectangular plate by any given wind velocity can be computed in advance by the use of a coefficient whose validity has already been established so well experimentally that it is now in common use.[10] In the case of this anemometer, however, the presence of the metal cover behind the pressure plate makes it necessary to establish a new coefficient which is characteristic of the plate when used in this particular arrangement.

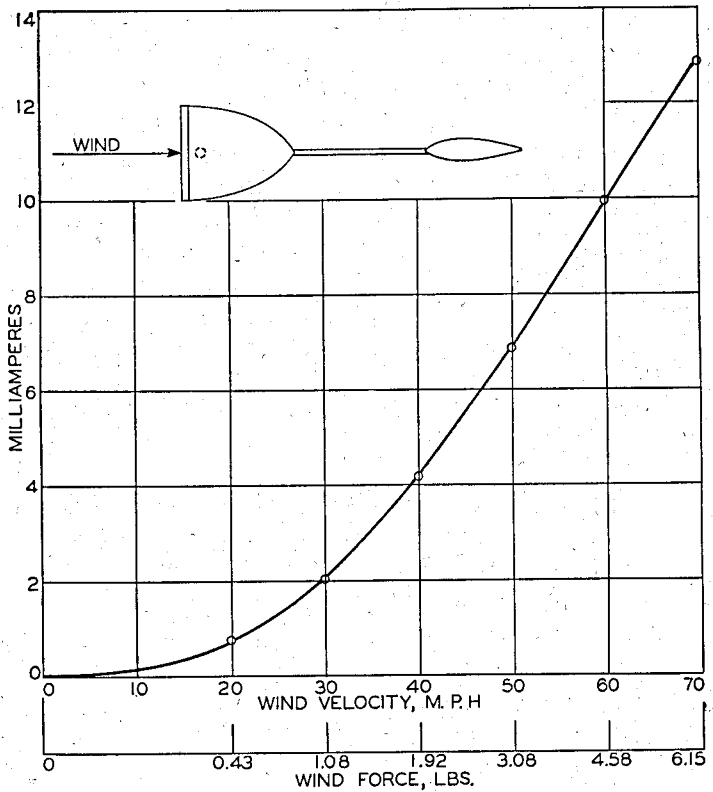

FIGURE 12. WIND TUNNEL TESTS OF ANEMOMETER No. 8

The wind forces corresponding to the various wind velocities were determined by applying known forces to the pressure plate and observing the electrical indication. The forces were applied by means of the device shown in Figure 13.

The necessary calibration was made in the wind tunnel and in addition to this a device was perfected whereby the behavior of the recording mechanism could be checked from time to time by the use of weights.

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[10] EIFFEL, G. *La Resistance de l'Air et l'Aviation*, pp. 39-43 (Paris, 1911).

Calibration in the Wind Tunnel.

For the purpose of establishing the relationship between true wind velocity and electrical indication each of the anemometers was mounted in the wind tunnel and tested in wind velocities varying from 20 m.p.h. to 70 m.p.h. The diagram in Figure 12 shows the calibration curve which was obtained for Anemometer 8 with the wind normal to the pressure plate. It will be seen that as the wind velocity increases the indication in milliamperes varies nearly as the ordinates of a parabola. This curve is typical of those obtained for the other anemometers, although no two of them coincide exactly. The velocities indicated have been corrected according to the calibration of that portion of the tunnel in which the instrument was mounted.

The wind velocity in the tunnel was measured by a standard Pitot-static tube and an inclined manometer. These instruments do not indicate the *true* velocity of the wind in the tunnel but they indicate that velocity which, in a *standard* atmosphere, would produce the same pressure in the manometer. The standard atmosphere has a temperature of 15°C. and a barometric pressure of 760 mm. of mercury. The Pitot-static tube measures the velocity head or the impact pressure, the value of which is expressed by the formula

$$q = 1/2\ \rho\ V^2,$$

where ρ is the density and V is the velocity of the air. It is evident that a constant value of pressure will indicate a constant value of the velocity only in those cases in which the density is the same. Since the density is affected by changes in temperature and barometric pressure, it is not convenient to compute its value for each set of pressure readings and thus to obtain the true value of the wind velocity. It is more convenient to assume a standard value for the density and thereby to obtain the value of wind velocity which would produce the same pressure in a standard atmosphere. This procedure can be followed with this pressure-plate anemometer without error since it likewise measures the impact pressure of the wind. It may be said, therefore, that the velocity indications of the pressure plate anemometer have been reduced to standard atmosphere.

Calibration by Weights.

It was found advisable to check the calibration of the instrument from time to time in the field to determine any changes which might occur in it. For this purpose a special calibration device was designed to apply measured forces to the pressure plate. By means of the device shown in Figure 13, it was possible to apply known forces to the center of the pressure plate and to observe the corresponding electrical indication. Immediately after the anemometer had been tested in the wind tunnel, it was tested with the pressure device so as to determine the pressures which correspond to the various wind velocities. The results of these observations are plotted horizontally in Figure 12. By means of this system it is necessary to calibrate an instrument only once in the wind tunnel and all calibrations thereafter can be made by means of forces applied directly to the pressure plate.

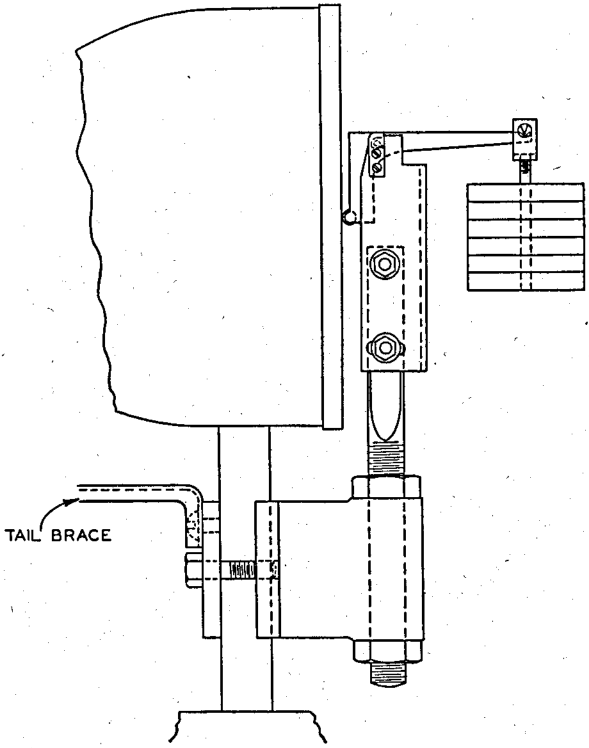

FIGURE 13. ANEMOMETER TESTING DEVICE

Known forces were applied to the pressure plate by hanging weights on the bell crank. The tail brace prevents rotational movement of the anemometer while forces are being applied.

MAGNITUDE OF THE INSTRUMENT ERRORS

In any instrument there are certain sources of error which cannot be entirely eliminated, but which can be controlled so that the magnitude of the errors are known. In this anemometer all of the known sources of error produce effects which are so small that they may be ignored. Three of the most important sources of error are due to the angle of incidence of the wind, the temperature effects, and the effects of tilting.

Angle of Incidence of the Wind.

The changes in electrical indication as the angle of incidence of the wind is changed are shown by a family of curves in Figure 14. A different curve is shown for each of four different velocities varying from 30 m.p.h. to 60 m.p.h. It will be seen that the curves all have the same typical shape. As the angle of incidence changes from the normal, there is a decrease in the indication, which becomes most pronounced at about 5 degrees. The greatest decrease amounts to about 2½ per cent and occurs at 30 m.p.h. In general, the curves show the same indication at 7 degrees angle of incidence as at zero degrees, after which the indication increases rapidly and reaches a peak at about 17 degrees, where the increase of indication is about 15 per cent.

No method has been devised whereby a record may be obtained of the degree of accuracy with which the anemometer follows changes in the direction of the wind. Some basis for forming an opinion, however, was obtained by observing the angle which the axis of the anemometer made with the direction of a string, one end of which was allowed to float freely in the wind stream. This was accomplished in the following manner.

About ten inches above the top of the anemometer a triangular sheet of thin aluminum was mounted in a horizontal plane on a wire frame attached to the anemometer. The triangular sheet had a length of ten inches and an angle of 20 degrees at the vertex which was pointed into the wind. This vertex was placed directly above the center of rotation of the anemometer, and supported a short piece of wire to the top of which the string was attached. When the axis of the anemometer was parallel to the wind direction, the string bisected the 20-degree angle, but when the axis deviated from the wind direction by an angle of 10 degrees, then the string was directly above and parallel to one edge of the triangle. By sighting upward with field glasses from a position on the ground it was possible to observe the position of the string with reference to the triangular sheet and to estimate the maximum deviation of the anemometer from the wind direction.

The greatest deviation from normal incidence which was observed in a natural wind of about 30 m.p.h. did not exceed 10 degrees. By far the largest number of oscillations away from normal incidence was not greater than 5 or 6 degrees, as nearly as could be estimated by visual observation. The curves in Figures 12 and 14 show that, between zero and 7 degrees angle of incidence, the observed wind velocity is always less than the true velocity, the maximum error amounting to about 0.5 m.p.h. Between 7 and 10 degrees the curves show that the observed velocity is greater than the true velocity, the error at 10 degrees amounting to 1¼ m.p.h.

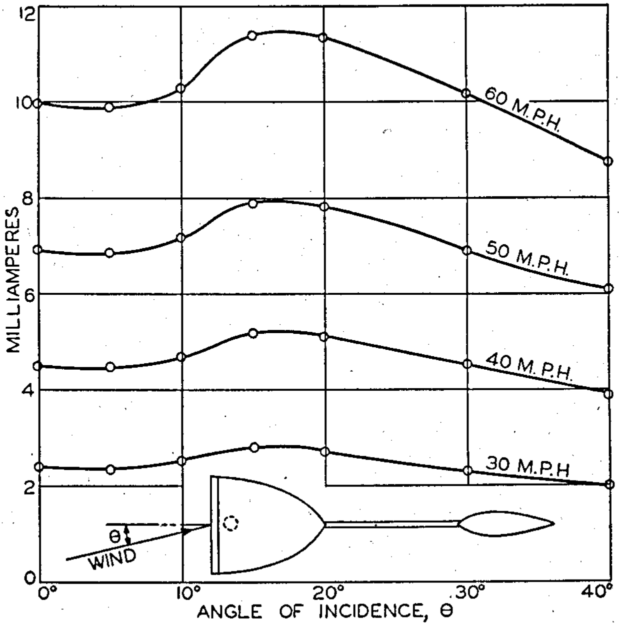

FIGURE 14. CALIBRATION CURVES FOR INCLINED INCIDENCE OF THE WIND

The curves in this figure were obtained in the wind tunnel. Observations made in the field showed that by far the largest number of observed deviations from normal incidence in a natural wind was less than 5 or 6 degrees, but an occasional deviation approached 10 degrees.

The true wind direction may lie on either side of a line normal to the pressure plate, and its direction at any distant, within the limits of error stated above, is purely a matter of chance. If, therefore, a continuous record of the angle of incidence were obtained, it would be possible to find the most probable angle for any single case by taking the average for a large number of cases. The corresponding correction in the wind velocity would give the most probable value of the true wind velocity for any single observation. In the absence of any such investigation it may be stated, on the basis of visual observation, that any single observation of velocity probably will be less than the true velocity by an amount not exceeding 0.5 m.p.h., but that occasionally a single observation will be more than the true velocity by an amount not exceeding 1.25 m.p.h.

In this study of wind gusts the errors arising from this source are not of sufficient importance to justify the use of statistical methods of correction. On a project in which greater accuracy is desired the errors from this source could be reduced by redesigning the instrument to obtain a lower rotational moment of inertia and by using a larger vane placed closer to the instrument as in Figure 15.

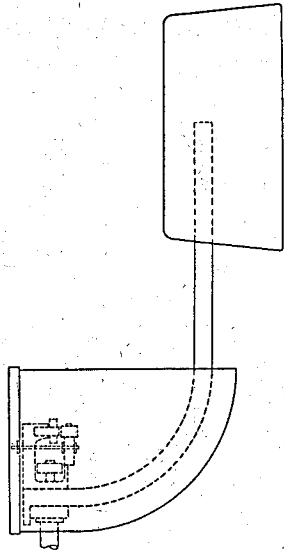

FIGURE 15. SUGGESTED MODIFICATION IN THE ARRANGEMENT OF THE ANEMOMETER VANE

By placing the magnetic transmitter on the vertical axis of rotation of the anemometer, the rotational moment of inertia would be reduced. If, in addition, the tail were made shorter and the vane larger, the instrument would be still more responsive to changes in the direction of the wind.

Temperature Effects.

Two series of observations were used to determine the effect of temperature changes upon the electrical indication of Anemometer 8. In the first series the instrument was placed in an insulated box and a number of observations were made at room temperatures, with applied forces on the pressure plate ranging from zero to seven pounds. This range of pressures corresponds to a range of velocities from zero to 75 m.p.h. The box was then closed, the temperature was raised about 35°C. above the room temperature, and the observations were repeated. Readings were obtained for six cycles of temperature change.

In the second series the observations were made at room temperature and the instrument was then moved into a cold room, where, after an interval of several hours, the observations were repeated at temperatures about 45°C. below room temperature. Readings were obtained for six cycles of temperature change.

Table I shows the average change in electrical indication for a 10° (Centigrade) rise in temperature. Each value shown in the table is the average of readings obtained during six cycles of temperature change. In all cases the changes are so small that they are not appreciable at the scale used on the field charts. It appears that a different effect is produced at high temperatures than at low temperatures, but this is not definitely established since, in either case the change is too small to permit accurate determination.

TABLE I

Anemometer No. 8
Rise in Milliamperes for
10°C. Rise in Temperature

Applied Force		Hot Box		Cold Room	
Pounds	Equiv. velocity m.p.h.	Change in ma.	Equiv. change m.p.h.	Change in ma.	Equiv. change m.p.h.
0	0	.039		–.025	
1	29	.050	0.25	–.005	–0.03
2	40.5	.045	0.18	–.008	–0.03
3	49.5	.045	0.15	.026	0.08
4	56.5	.065	0.21	.016	0.05
5	63.0	.058	0.19	.035	0.11
6	69.0	.073	0.24	.024	0.08
7	75.0	.083	0.27	.025	0.08

Effects of Tilting.

If the anemometer is not mounted with its axis vertical, an error is introduced into the reading. If, for example, the anemometer is tilted forward, there is a component of the weight of the plate and rear laminations acting along the pusher rod, tending to decrease the air gap between the two sets of laminations, and hence to decrease the meter indication. Quantitative measurement of this effect was made by mounting the anemometer on a base board 24 inches long, and tilting it by blocks placed under one end of the base. The blocks used varied in thickness by ½ inch increments up to two inches, which gave a maximum tilt of 4° 46′ either forward or backward from a true vertical position. Observations were made by applying pressure to the plate in increments of one pound up to a total of seven pounds. A complete cycle of pressure was applied for each increment of tilting. It was found that the change of meter indication was 0.09 milliampere per degree of deviation of the anemometer axis from the vertical. This represents about 0.5 per cent of full scale meter value.

In order to obviate errors from this source, the leveling device shown in Figure 16 was designed and built for field use in checking the installation of the anemometers. This device snaps around the upright of the anemometer and can be rotated to any desired position. With this instrument it is possible to detect deviations from the vertical of much less than one degree. From experience it is felt that, in spite of the difficulties of mounting the instrument in the field, the deviation should always be materially less than one degree, and hence in field use the error in current reading from this source should always be within the limit of 0.5 per cent of full-scale value. The corresponding error in velocity indication would be about 0.3 m.p.h. in a wind velocity of 60 m.p.h., and about 0.45 m.p.h. in a velocity of 30 m.p.h.

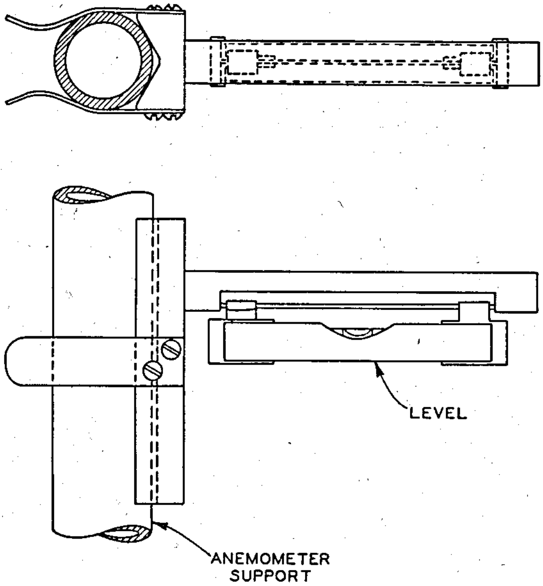

FIGURE 16. ANEMOMETER LEVELING DEVICE

Used when the instruments are being installed in the field or tested in the laboratory.

SPEED OF RESPONSE

The smallest interval of time for which an accurate observation of wind velocity can be made is indicated by Figure 17. This is an oscillogram which was made for the purpose of determining the natural frequency of vibration of the pressure plate and the rapidity with which impulses to the pressure plate can be made to follow one another without interference.

The upper curve of the oscillogram is a timing wave each complete cycle of which represents 1/60 second. The lower curve is a 540-cycle-per-second wave which was produced by the alternating current after it had passed through the coil in the magnetic transmitter. Any fluctuation in the size of the air gap accompanying vibrations of the pressure plate produced a fluctuation in the amount of current drawn through the coil with a corresponding fluctuation of the amplitude of the 540-cycle wave. Vibrations were produced in the pressure plate by striking it sharply with the handle of a screw driver. No external force was acting on the plate during this period and it was therefore free to vibrate with its natural frequency. By comparing the vibrations of the plate with the 60-cycle timing wave it will

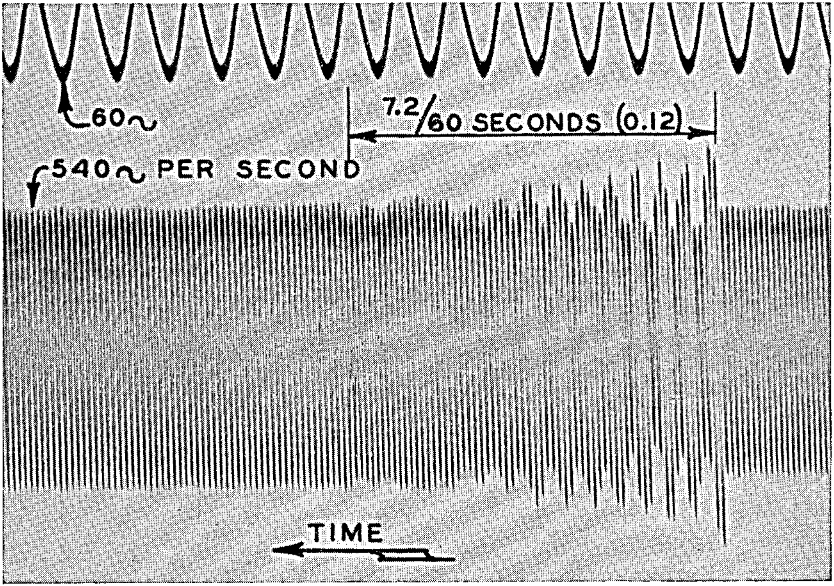

Figure 17. Oscillogram Showing the Natural Frequency of Vibration of the Pressure Plate and the Time Required for the Decay of the Vibratory Motion

The vibrations were induced in the plate by striking it with the handle of a screwdriver. The 540-cycle wave was produced by current which had passed through the coil of the magnetic transmitter but had not passed through the rectifier and filter.

be seen that the natural frequency of vibration was about 115 cycles per second. The time which is required for the decay of the vibratory motion of the plate as here recorded is about 0.12 of a second. The small ripples along the edge of the 540-cycle wave before and after the interval during which vibration takes place are the result of peculiarities in the motor generator set and are not characteristic of the anemometer.

It is not to be inferred from this test that the anemometer is capable of recording accurately wind gusts occurring as rapidly as 115 times a second. Knowledge of the natural frequency of the instrument is useful, however, as it makes possible the computation of the accuracy of indication of such slower gusts as appear on the record. The behavior can be explained by a study of the mechanical principles involved.

Any system possessing mass in its moving parts, as does the pressure plate, and spring effects, as found in the prong of the transmitter, exhibits a natural frequency of vibration. This natural rate is the one shown by the parts if they are displaced from the rest position, released, and allowed to vibrate freely without external hindrance. If a regular alternating force of maximum value P is applied to the system, the amplitude of the resulting motion, assuming no damping force, is given by the expression

$$A = kP\left(\frac{1}{1-(f/f_n)^2}\right)$$

where k is a constant of the spring, f the frequency of the applied force and f_n the natural frequency. If it were not for the inertia effects of the mass, the observed amplitude would always be proportional to the applied force; that is,

$$A = kP,$$

irrespective of the frequency. The factor in parentheses thus represents the amplitude of the actual record in comparison with the value it would have if there were no inertia errors present. By evaluation of this factor it is found that if the frequency to be recorded is one tenth of the natural frequency, the recorded amplitude is larger than it should be by the amount of 1%. If f/f_n is .2, the over-indication becomes 4%. It can be concluded, therefore, that the pressure plate of this anemometer is capable of recording pulsating pressures up to 11.5 cycles per second in frequency with an error not exceeding 1%, and up to 23 cycles per second, with an error not exceeding 4%. In both cases the error will be slightly less, due to the presence of some damping force.

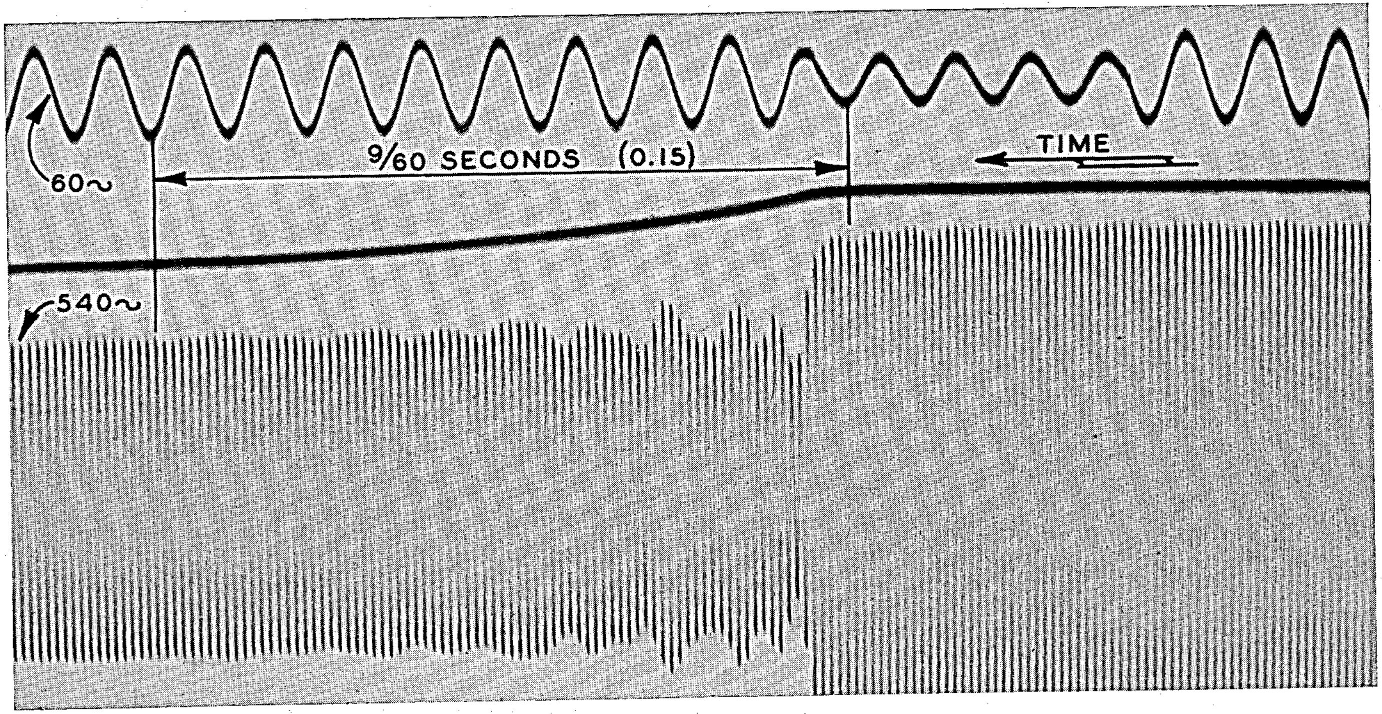

FIGURE 18. OSCILLOGRAM SHOWING THE SPEED OF RESPONSE OF THE RECORD

A force of 8.5 pounds was suddenly released from the pressure plate. The oscillograph had fully recorded this change in 0.15 of a second.

The analysis just presented applies to the action of the pressure plate under the effect of a regular alternating force. A different condition exists in the case of a single impulse, or sudden change of load. While the natural frequency does give an idea of the rapidity of response under such conditions, it does not give a complete picture of the behavior of the instrument and its circuit. Accordingly, to obtain experimental evidence of the accuracy of the anemometer in recording rapid load changes another test was made simulating the effect of a sudden decrease in wind force.

Figure 18 shows three curves which were obtained when the instrument was connected in the same type of circuit as is used for the taking of field records. A 60-cycle timing wave appears at the top of the oscillogram. A 540-cycle wave, which was obtained from the current drawn through the coil of the magnetic transmitter, appears at the bottom. Between these two curves is a third curve which was obtained from the electric current after it had passed through a rectifier and a filter and was in its final form for making records.

A force of 8.5 pounds was applied to the pressure plate by the calibration device in the usual manner, except that the weights were suspended from the bell crank by a short length of fuse wire. The current which was passed through the fuse wire was taken from the same source as the current for the timing wave, so that when the switch was closed to pass current through the fuse, the amplitude of the timing wave was reduced until the fuse wire had melted. The melting of the fuse wire released the load from the pressure plate, thus causing a change in the air gap of the transmitter with a corresponding change in the amount of current drawn through the coil in the transmitter. The amplitude of the 540-cycle wave is proportional to the current. It will be seen that following the release of the load this amplitude passes through a number of cycles of variation which correspond to the cycles of vibration in the pressure plate. It required less than 1/120 of a second for the decrease in load to become fully effective at the pressure plate, after which it required about .13 to .15 of a second for all evidence of vibration to disappear.

When the load was released from the pressure plate, the middle curve, corresponding to the record produced in a natural wind, was deflected to a new position which it reached in about .15 of a second. The length of time that is required for the curve to reach its new position depends chiefly on the strength of the electric filter. However, improvement in the responsiveness of the instrument cannot be continued indefinitely merely by changing the design of the filter unless a corresponding change is effected

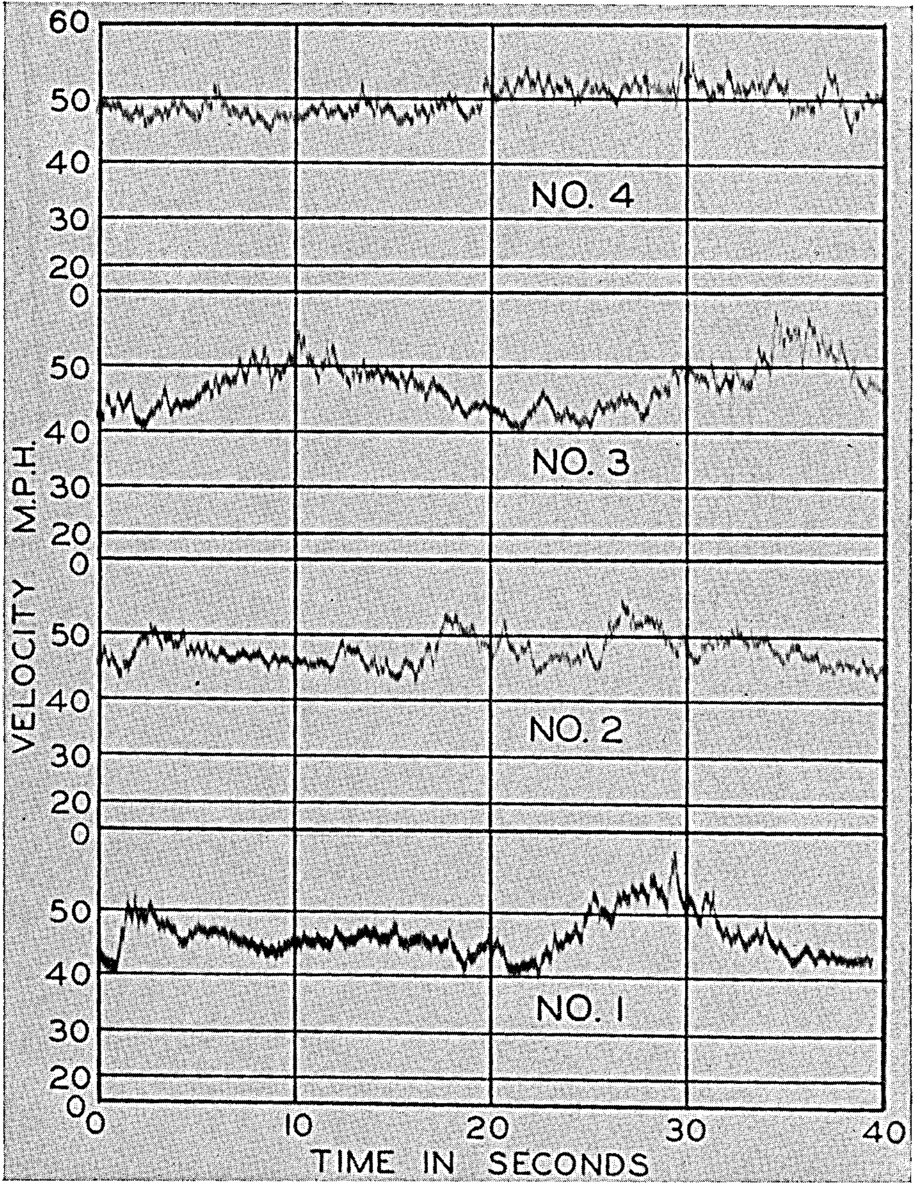

Figure 19. Sample Records of a Natural Wind

Anemometer located 200 feet above the ground.

in the length of time required for the decay of the vibrations, since the effect of the vibrations would otherwise begin to show in the records. The time required for the decay of vibrations could be reduced through the use of a lighter pressure plate and a heavier flexible hinge in the transmitter.

The record obtained in Figure 18 corresponds to the record which would be obtained by a sudden change in the wind velocity from 84 m.p.h. to 0 m.p.h. in 1/120 of a second. This is a very extreme condition and one that probably would never occur in a natural wind. Under this condition, however, the records show that there will be a complete recovery of the instrument from the applied impulse within a period of about 0.1 to 0.15 of a second. In other words, within 1/10 second after a change has occured in the wind velocity the record of the change will have been completed and the instrument will be ready to record a new change without appreciable error.

TYPICAL RECORDS

The records of wind velocity shown in Figure 19 were obtained during a storm of moderate intensity which occurred at Ann Arbor on the night of September 26, 1930. Four records are shown, all of which were made by Anemometer 11, located at a height of 200 feet above the ground. Each record covers a period of 40 seconds at different times during the storm. The time and velocity scales were added after the sensitized paper carrying the record had been developed and dried. The zero reference line is established once every two or three minutes by opening the switch between the anemometer and the oscillograph element. The entire group of records is match-marked for correlation of time by opening and closing a master switch.

Record 1 in Figure 19 shows wind velocities varying from about 40 m.p.h. to about 58 m.p.h. Near the beginning of this record a gust is noted in which the wind velocity increased from 40 m.p.h. to 51 m.p.h. in less than one-half second and did not again decrease to 40 m.p.h. for about 18 seconds. Another gust began at 22 seconds and ended at about 35 seconds from the beginning of the record. Numerous minor gusts occurred within each major gust. On the original record sheet it is possible with the aid of a magnifying glass to distinguish fluctuations as rapid as 10 cycles per second. Faster fluctuations than this merely tend to blur the record. Records 2 and 3 exhibit a variety of fluctuations in the wind velocity while Record 4 shows a fairly uniform velocity near 50 m.p.h.

SUMMARY

This new electrical recording anemometer was developed because it was found that the available types of anemometers possess inertia errors which make them unsuitable for use in a study of wind gusts.

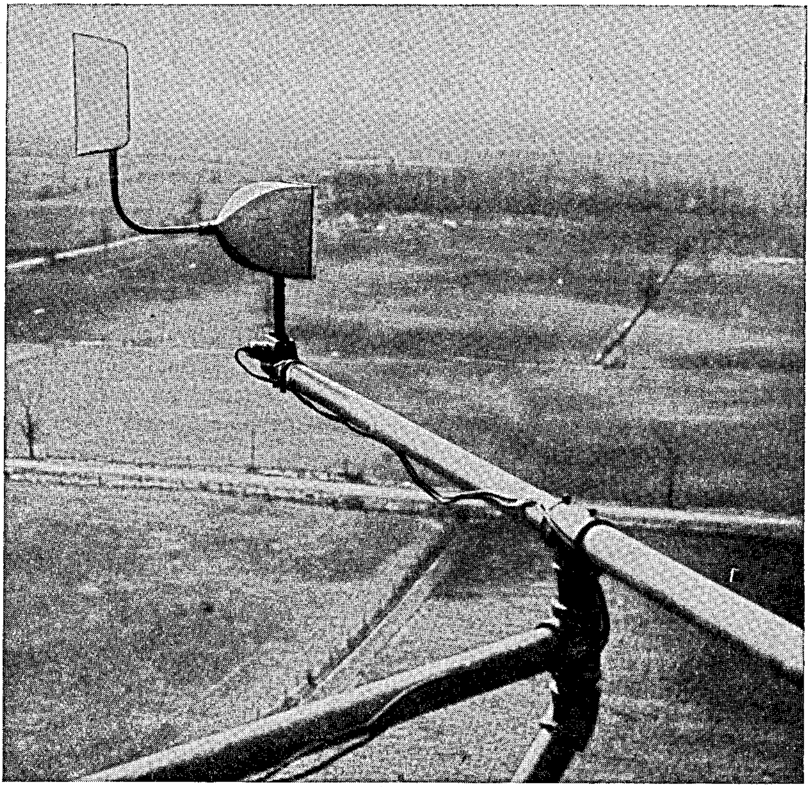

FIGURE 20. ANEMOMETER INSTALLED AT THE 150-FOOT LEVEL OF THE TOWER

The actuating element is a pressure plate having an area of one-half square foot. A magnetic transmitter is used which operates on the change of inductance in a coil as the air gap between two sets of laminations is modified by the wind pressure against the plate. The record is made by an oscillograph upon a strip chart of photographic paper.

The pressure plate has a maximum movement of about .005 of an inch and the moving parts of the instrument have a natural frequency of vibration of about 115 cycles per second. From .10 to .15 of a second is required for the instrument to complete its response to an impulse against the pressure plate and be ready to receive a new impulse without interference in the records.

Calibrations were made in a six-foot wind tunnel and a special device was developed for checking the calibration in the field by the use of weights.

Tests showed that the maximum errors which will ever arise due to changes in temperature, tilting of the anemometer, and changes in the angle of incidence of the wind against the pressure plate are, respectively, 0.27 m.p.h., 0.45 m.p.h., and 1.25 m.p.h.

The various parts of the instrument have been proportioned to give a calibration curve which can be conveniently used for wind velocities above 30 miles per hour. Below that velocity the curve is so flat that a small error in observing the electrical record produces a large error in the observed velocity. If it is desired to produce an instrument which is sensitive over the lower range of wind velocity, it would be necessary to increase the flexibility of the hinge in the magnetic transmitter to such an extent that the full range of gap size, which, in the present design, is produced by velocities up to 70 m.p.h. would, in the revised design, be produced by velocities up to 30 m.p.h. This would cause an increase in the natural period of vibration of the mechanical system with a consequent decrease in the responsiveness of the instrument. In order to restore it to its present speed of response it would be necessary to reduce the weight of the moving mechanical system. This could be accomplished by moving the transmitter closer to the pressure plate and thus reducing the load which must be added to the plate to produce dynamic balance about the vertical axis of rotation. For any project which requires greater speed the responsiveness of the instrument could be still further improved by reducing the weight of the plate and by redesigning the electric filter.

This instrument was designed for use on this particular research project and no attempt was made to simplify it or its accessory equipment so as to make it suitable for routine field use. Reliable records will be obtained with this type of instrument only when the calibrations have been made and the records taken in collaboration with one who understands the electrical principles involved in the design or with an electrician who is following a carefully prepared list of precautions to be observed.

For this project twelve of these anemometers have been mounted in the field on supports which have been rigidly braced with steel guys. Five of the instruments are on a steel tower 250 feet high and seven of them are

50 feet above the ground on wooden poles. It is intended that, in studying the changes which occur in the horizontal and vertical cross sections of wind gusts, the records shall be divided into intervals of one second or one-half second each, and that each observation shall be the average velocity for one interval at one anemometer. This method will insure an ample margin of accuracy, since, in one second, the pressure plate is capable of responding to about ten impulses without interference between the records of the separate impulses.

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