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STRAIN-GAGE ANEMOMETER FOR ANALYZING VARIOUS CHARACTERISTICS OF WIND TURBULENCE

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ABSTRACT

This article describes an apparatus composed of a strain-gage assembly, electrical amplifier, and recording oscillograph for measuring characteristics of wind turbulence of velocity-fluctuation frequencies up to 120 cy per sec. All parts but the strain-gage assembly are available commercially.

Fluctuations of wind pressure and velocity were recorded along the x, y, and z axes for different wind velocities and various heights above surfaces of certain degrees of roughness in a wind tunnel and in the field, and the recorded data were analyzed to check the adaptability of the apparatus.

Analyses indicated the presence of uniformly turbulent flow in the wind tunnel, but records from the field indicated a variably turbulent flow in which the larger scales of turbulence were superimposed on the smaller ones. No matter what type of turbulent flow, analyses indicated that the velocity fluctuations along the x, y, and z axes some distance above the ground were statistically distributed to fit the normal curve. The fit was reasonably good for various drag velocities, axes, and magnitudes of surface roughness. Close to the ground, on the other hand, both pressure and velocity curves for x and y axes did not fit the normal curve but velocity fluctuations along the x axis reasonably fit the normal curve.

Records indicated that the relative intensity of turbulence, which is a measure of the velocity fluctuation at some particular height in proportion to the mean velocity at that height, was greatest nearest the surface and decreased in arithmetic proportion with height. The relative magnitude of turbulence, which is a measure of fluctuation of velocity at a particular height in proportion to the drag velocity, on the other hand, was lowest nearest the surface, increased with height depending on roughness of surface, then decreased with height. The scale of turbulence, which denotes the relative size of eddies, was smallest nearest the ground and increased as the logarithm of height.

The turbulence factor, which denotes how much greater the maximum impulse forces of turbulent flow are over those of uniform flow of equal mean velocity, was greatest and had a mean value of 2.71 very close to the surface and decreased rapidly with height. It remained virtually constant for different degrees of surface roughness and drag velocities of the wind.

1. Introduction

Many agricultural and industrial problems are related to turbulence of the air. This phenomenon has major implications in the erosion of soil by wind, the diffusion of dust and smoke through the atmosphere, the scattering of pollen and seeds, the transfer of heat from the earth's surface to the atmosphere, and the evaporation of water from land and sea.

As defined by Sutton (1955), "turbulence is the eddying of the fluid as a diffusion process." It is manifested in rapid, random fluctuations of velocity. Turbulence of the atmosphere is often referred to as gustiness. Scrase, as reported by Sutton (1955), divided turbulence of the atmosphere into large, intermediate, and small scales. He defined large scale turbulence as that manifested over an interval of one hour, the intermediate as that covering a period of one minute, and the small as that characterized by velocity fluctuations having a period of a fraction of a second. Dryden (1934), on the other hand, asserted that comparatively slow velocity fluctuations which can be detected by ordinary measuring instruments, such as a pitot tube and manometer or a vane or cup anemometer, are generally not included in the concept of turbulence. Only those are included that have periods shorter than one per second. Turbulent flow as demonstrated by the classical experiment of Reynolds is manifested by velocity fluctuations ranging from about 5 to 5000 cy per sec (Sherwood, 1946). Direct measurement of turbulence (*i.e.*, small-scale turbulence) therefore requires a very sensitive instrument.

Since an instrument of a high degree of sensitivity was not available to the authors in their investigations on the capacity of wind to transport soil materials, an anemometer consisting of strain gages, electrical amplifier, and magnetic oscillograph capable of recording air-pressure impulses of frequencies up to 120 cy per sec was developed. The anemometer appears to have advantages over other instruments by virtue of its simplicity combined with a high degree of sensitivity. All parts but the strain gage assembly are available commercially. The anemometer is based on the principle of change in electrical resistance caused by mechanical strain exerted on a conducting wire. As changes occur in the resistive

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value of the strain-gage wire attached to a small pressure plate, they are recorded in direct proportion to the change. The magnitude of pressure on the plate is converted to fluid velocity on the basis of $P_1 - P_2 = \frac{1}{2}\rho v^2$ in which P_1 and P_2 are pressures per unit area on the fore and lee parts of the plate, respectively, ρ is the density of the fluid, and v is its velocity. According to Middleton and Spilhaus (1953), the above equation is only approximately correct so that a correction factor is involved. In this study, it was assumed the error is small and no attempt was made to go through an elaborate procedure to determine what it might be. The anemometer was calibrated simply by applying known pressures on the plate and recording the magnitude of pen deflections for various attenuator factors of the oscillograph.

2. Review of literature

Of the several instruments devised to measure turbulence, the hot-wire anemometer improved by Dryden and Kuethe (1929) is perhaps the most sensitive. Fage and Townend (1932) used an ultra-microscope to observe the motion of fine particles as indicators of fluid turbulence. Taylor (1927) used a bi-directional vane that measured vertical and horizontal fluctuations at right angles to wind direction. Schmidt (1935) used light-weight plates that oscillated forward and backward with respect to the general wind direction. From 25 to 75 plates mounted on a frame were photographed every 0.2 sec to record the oscillations.

Sherlock and Stout (1931) devised a pressure-plate anemometer capable of measuring up to four wind-velocity cycles per second. Einstein and El Samni (1949) used a Trimount pressure cell with AC-generator and amplifier and magnetic oscillograph capable of recording fluid pressure fluctuations up to 50 cy per sec.

Dryden (1931) and Sherwood (1946) used the resistance of a sphere as an indicator of turbulence. This procedure is based on the principle that drag on the sphere drops sharply when fluid turbulence sets in.

3. Description and measurement of various characteristics of turbulence

Kalinske (1943) showed that fluid-velocity fluctuations at any distance above the ground are distributed according to the normal error law of distribution; hence the standard deviation σ of velocity fluctuation describes the relative spread of velocity around its mean and was therefore adopted as a measure of the intensity of turbulence. He called the ratio $\sigma/\bar{v}$, in which $\bar{v}$ is mean velocity, the *relative intensity of turbulence*. It is a measure of velocity fluctuation at some particular height in proportion to the mean velocity at that height.

The relative intensity of turbulence fails to describe the actual magnitude or range of velocity fluctuation. If velocity fluctuations are distributed according to the normal error law, nearly all (99.73 per cent) of the velocity range is included within $\bar{v} \pm 3\sigma$. Therefore, for practical purposes 6σ may be regarded as a measure of the magnitude of velocity fluctuation and $6\sigma/\bar{V}_*$, in which $\bar{V}_*$ is the mean drag velocity of the wind, reflects a measure on a dimensionless basis of the *relative magnitude of turbulence*. The relative magnitude of turbulence is a measure of fluctuation of velocity *at a particular height* in proportion to the drag velocity which characterizes the whole velocity profile of the fluid boundary layer. The relative measure of turbulence varies directly as 6σ since it is a relative measure of range of velocity fluctuation at a particular height. The 6σ are divided by the value of drag velocity to give the same values of relative magnitude of turbulence regardless of the kind of units of measure that may be used.

Another characteristic of turbulence is the size of eddies which Kalinske (1943) termed the *scale of turbulence*. This was determined by measuring from records of velocity fluctuation the number of velocity cycles in a given time interval. Dividing the velocity, or the distance the fluid has traveled in that time interval, by the number of cycles in that interval gave a length factor which was taken as a relative measure of eddy size.

Many problems of transport of soil materials by wind and water are dependent on maximum impulses of turbulent flow, although only average pressure and velocity computed from pressure can be measured with ordinary instruments. It is important, therefore, that some idea of magnitude of maximum impulses in proportion to mean pressure is obtainable. Since no distinct maximum pressure exists for a turbulent fluid, the value $\bar{P} + 3\sigma$ was taken as the maximum pressure, and the ratio $(\bar{P} + 3\sigma)/\bar{P}$, in which $\bar{P}$ is mean pressure and σ as standard deviation of $\bar{P}$, may be termed the *turbulence factor*. The turbulence factor determined with the apparatus described herein indicates approximately how much greater the maximum impulse forces of turbulent flow are over uniform flow of equal mean velocity.

4. Description and qualitative performance of the apparatus

The apparatus consists of a small plate A (fig. 1) mounted on one end of a thin shaft B whose other end is attached to plate C which in turn is cemented to the loose ends of four active strain gages D. This arrangement permits measurement of small magnitudes of dynamic pressure exerted against plate A registered as changes in electrical resistance of the strain gages. The gages are composed of a flat grid

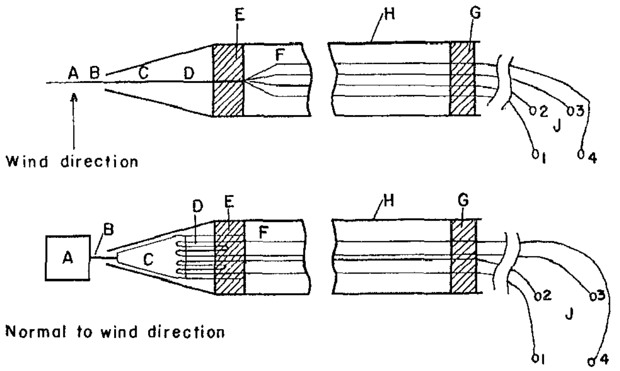

Fig. 1. Diagram of apparatus for measuring fluid turbulence, shown oriented to measure turbulence along the x axis.

of constantan filament wire cemented to a thin paper base. A pair of gages is cemented together side by side and another pair back to back of the first pair. The constantan wire gage having minimum hysteresis and high fatigue life appears to give a good measure of dynamic (fluctuating) strain. Iso-elastic wire gages might be even more satisfactory.

The base ends of the gages are held firm by block E (fig. 1) and are connected to fine copper wires F held in place by blocks E and G inside a metal tube H. The wires lead through the wall of a wind tunnel or, if in the open, directly at some distance to circuit bridge J on an amplifier connected with a recording oscillograph. The amplifier in use has a maximum sensitivity of one microvolt per chart line of the recording oscillograph.

Plate A is tempered aluminum 7.2 mm square and 0.07 mm thick, shaft B is tempered steel 0.2 mm in diam, and each gage has a wire grid 1/4 in long and 5/64 in wide.

Tube H with the strain-gage assembly is mounted on a carriage equipped with a linear scale for convenient measurement of height above the ground or the tunnel floor. The tube is mounted horizontally as shown in fig. 1 for measuring the impulses along the x axis—*i.e.*, parallel with general motion of the fluid and the surface. For measuring impulses along the z axis—*i.e.*, normal to the general direction of fluid motion and the surface, the tube remains in a horizontal position but is rotated 90 deg so that the edge of the plate squarely faces the wind and the flat side of the plate is parallel with the surface. For measuring impulses along the y axis—*i.e.*, normal to fluid motion and parallel with the surface, the tube is positioned vertical to the tunnel floor or the ground and oriented so that the flat sides of the plate are vertical to the ground and parallel with the general direction of the wind.

An extremely important feature of the strain-gage assembly is that pressure, if any, against the edge of plate A transmits to the gages strains and stresses that balance each other out and therefore produce zero reading on the oscillograph. It is necessary to recognize that the apparatus records only the degree the bridge is unbalanced by strains and stresses that are applied. It is also necessary to recognize that the circuit bridge is unbalanced in proportion to the difference in the strains of gages located in adjacent arms and in proportion to the sum of the strains of gages located in opposite arms. Thus, if gages (a) and (b) are cemented back to back and (c) and (d) also back to back with (a) and (c) on one side of plate C and (b) and (d) on the other, the proper connection to the circuit bridge J would be gage (a) to bridge arms 1 and 2, gage (b) to arms 2 and 3, gage (c) to arms 3 and 4, and gage (d) to arms 4 and 1. To deflect the oscillograph needle in the opposite direction, it is necessary only to rotate all gage connections one-quarter turn in some one direction.

Attenuator factors used with the apparatus determine the degree of sensitivity at which the amplifier is set. Attenuator factor of 1, designated for convenience as A1, is the most sensitive setting. The sensitivity decreases directly with the attenuator factor. For example, 10 lines of deflection of the pen from its reference position at A1 setting is equivalent to 5 lines of deflection at A2, 2 lines at A5, 1 line at A10, *etc.* The attenuator factor that should be chosen depends on the magnitude of dynamic force on the strain gages. That attenuator factor is chosen which maintains the pen oscillations of the recording oscillograph within the limits of the chart on which the records are made. It is possible, by adjusting the pen-zero position of the dynamic strain off the chart paper, to measure the static component and to magnify and record on the chart the magnitude of the dynamic component. The chart used has 50 equidistant lines on which the dynamic component may be recorded. In many cases, it was not necessary to have the pen-zero position off the chart paper.

Two performance characteristics of the apparatus for measuring dynamic strain are essential. First, the weight of the rapidly oscillating plate and the length of shaft B that holds the plate must be reduced to the minimum; otherwise, plate oscillations due to inertia of the plate would be set up and superimposed on plate oscillations produced by fluctuations of fluid pressure. Effects of inertia in the apparatus described are virtually zero. Pressure of a pencil point suddenly released from the plate (at points indicated by arrows of fig. 2) causes the pen point of the oscillograph to swing back instantaneously to zero but not beyond this position. This and the statistical analysis of the oscillograms indicates no appreciable inertial effects of the plate. Maximum plate displacement along the x axis is about 0.5 mm for a 40-mph mean wind velocity.

Secondly, the pressure-recording apparatus has to

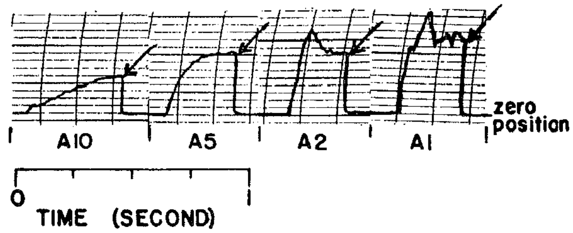

FIG. 2. Four portions of oscillograms with attenuator factors of 10, 5, 2, and 1 showing no perceptible inertial influences of the pressure plate as pressure against the plate was suddenly released at points shown by arrows.

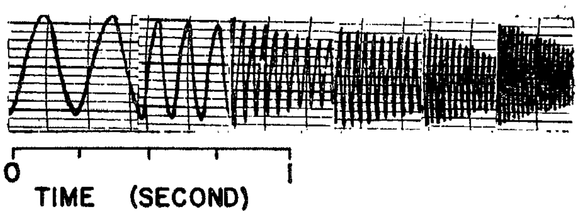

FIG. 3. Frequency response of the pressure-recording apparatus.

register rapid fluctuations of pressure without distortion. The analyzer used is claimed by the manufacturer to have a frequency response of 100 cy per sec without distortion. Response of the apparatus to known frequencies up to 65 cy per sec was found to be perfect (fig. 3). No lag in response to the pressure impulses was detected.

5. Results of measurement of various characteristics of turbulence

Fluctuations in wind pressure and velocity were recorded along the x, y, and z axes for different drag velocities of the wind and at various heights above a gravel surface of various degrees of roughness in a wind tunnel and in the open field. Recorded data were analyzed from the standpoint of various characteristics of turbulence to check the adaptability of the apparatus.

Portions of velocity records in the wind tunnel and in the open field for comparable height and surface roughness are given in fig. 4. The record taken in the wind tunnel shows what may be termed a *uniformly turbulent flow* in which only the small scale (microscopic) turbulence is operative. The record taken in the field, on the other hand, indicates a *variably turbulent flow* in which the larger scales of turbulence are superimposed on the smaller ones. It was not possible to record the smallest and the largest scales of turbulence using the same attenuator factor in both cases shown in fig. 4. If the smallest factor was used, much smaller scales of turbulence would have been indicated, but the recording pen in (a) would have run off the chart periodically. Also, a record of only 3 sec duration in (a) was too short to indicate gusts of longer duration. It was necessary, therefore, to make several records with different attenuator factors and periods of time to indicate the various scales of turbulence. Fig. 5 indicates the smallest scale of turbulence that could be recorded with the apparatus. The smallest recorded scale of turbulence in the wind tunnel and in the field indicated velocity fluctuation cycles having a period of 0.008 to 0.012 sec. The number of velocity cycles, therefore, was approximately 120 to 80 per sec.

Analyses of both uniformly and variably turbulent flow indicated that velocity fluctuations along the x, y, and z axes some distance above the ground were statistically distributed according to the normal error law. Curves of velocity and pressure plotted on an arithmetic probability scale for two different heights

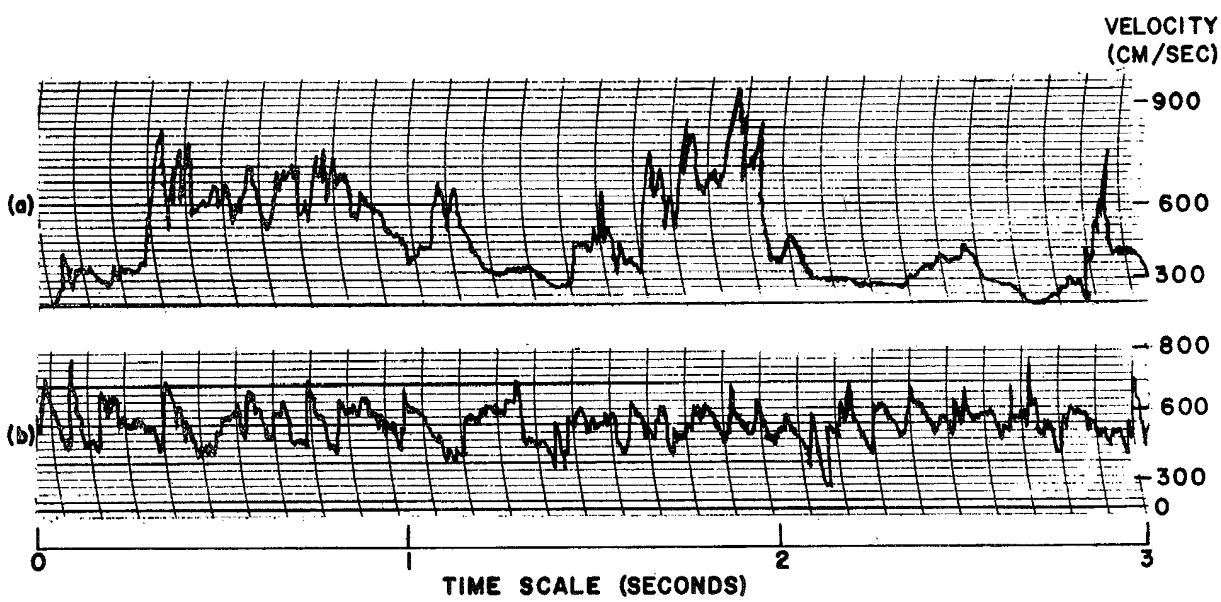

FIG. 4. Oscillograms with attenuator factor of 10 indicating magnitude of velocity fluctuation along the x axis of wind having the same mean velocity (a) in the field as (b) in the wind tunnel, both at 9 cm height above a smoothed ground surface.

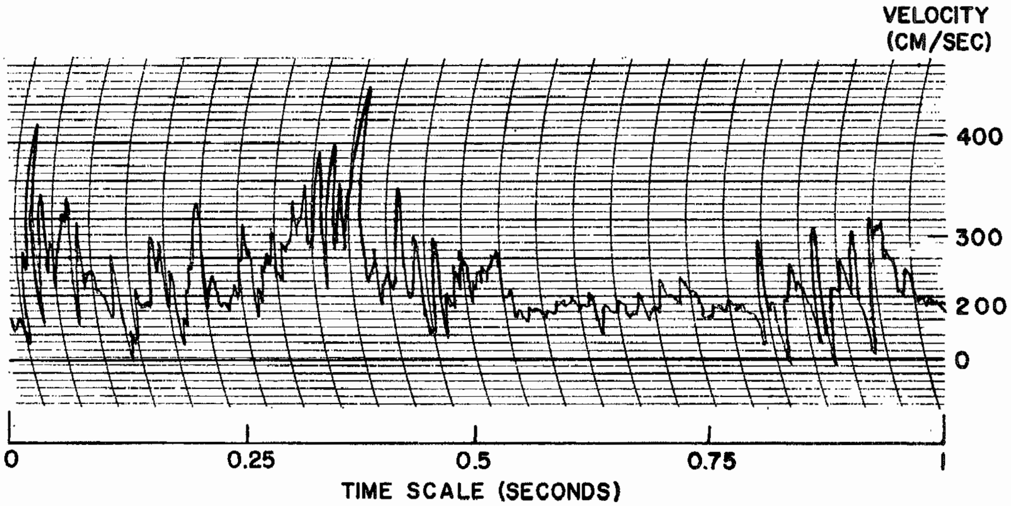

FIG. 5. Oscillogram based on attenuator factor of 2 indicating magnitude of velocity fluctuation along the x axis of wind in the tunnel at a position half way between the top and the bottom of gravel ridges 2.5 cm high and 10 cm apart.

above one type of surface are shown in fig. 6. A perfect fit of velocity or pressure data to the normal curve would give a straight line. It will be noted that at some distance above the surface the velocity distribution rather than pressure more nearly fits the normal curve. Very close to the surface, both velocity and pressure do not fit the normal curve.

Kalinske (1943) asserted that frequency of occurrence of various velocities of water in the Mississippi River at least 1.5 ft above the bottom fits the normal curve of distribution. Einstein and El-Samni (1949) showed that pressure rather than velocity frequencies of water against a rough surface fit the normal curve. Since pressure varies as the square of velocity within the common range of conditions, it follows for a given set of conditions that frequencies of occurrence of various magnitudes of both pressure and velocity cannot fit the normal curve.

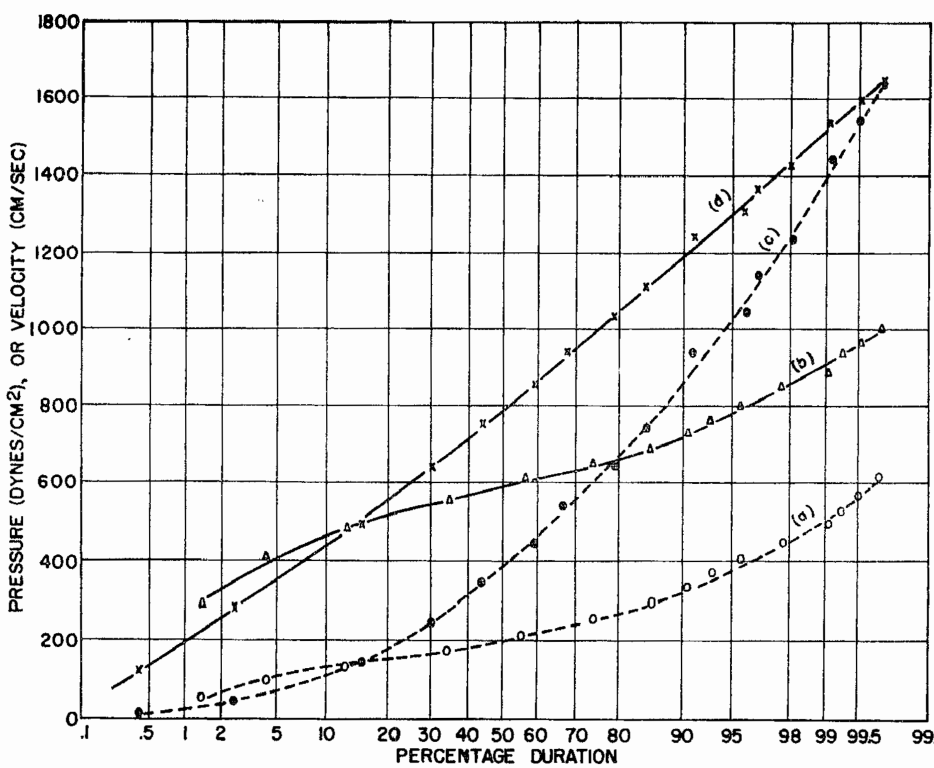

FIG. 6. Curves of pressure and velocity duration along the x axis plotted on an arithmetic probability scale for two different heights above gravel ridges 10 cm high, 40 cm apart at right angles to wind, (a) pressure at mean surface half way between the ridges, (b) velocity at same position as (a), (c) pressure at 10 cm above mean surface, and (d) velocity at 10 cm above mean surface.

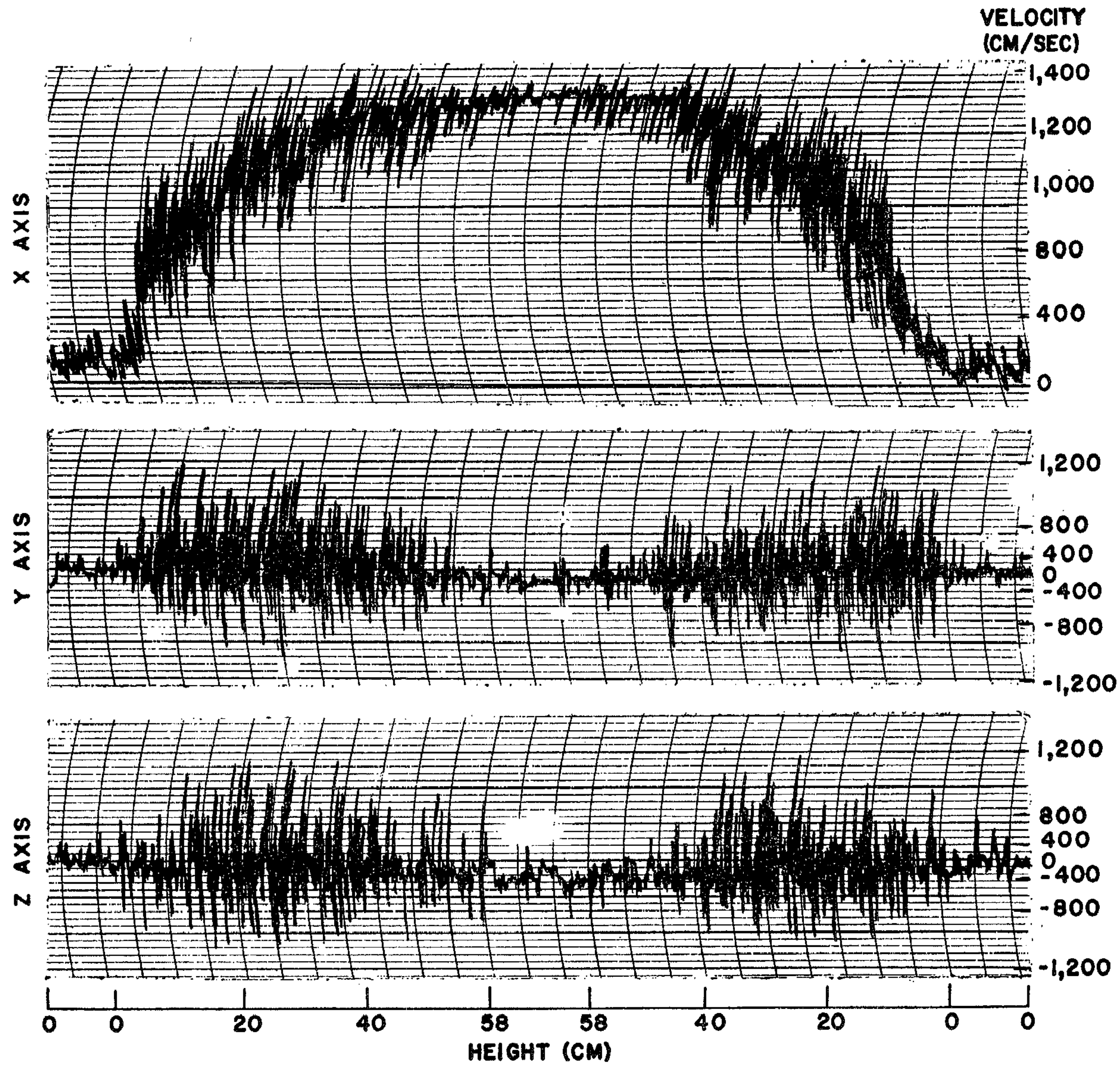

FIG. 7. Velocity and velocity fluctuation along the x, y, and z axes at various heights (shown in duplicate) above gravel ridges 10 cm high and 40 cm wide in the wind tunnel.

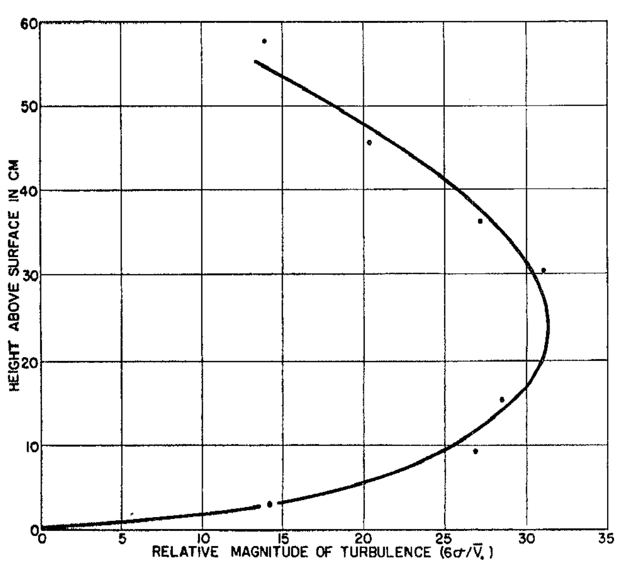

FIG. 8. Variation of magnitude of turbulence along the x axis with height above surface composed of gravel ridges 10 cm high and 40 cm wide.

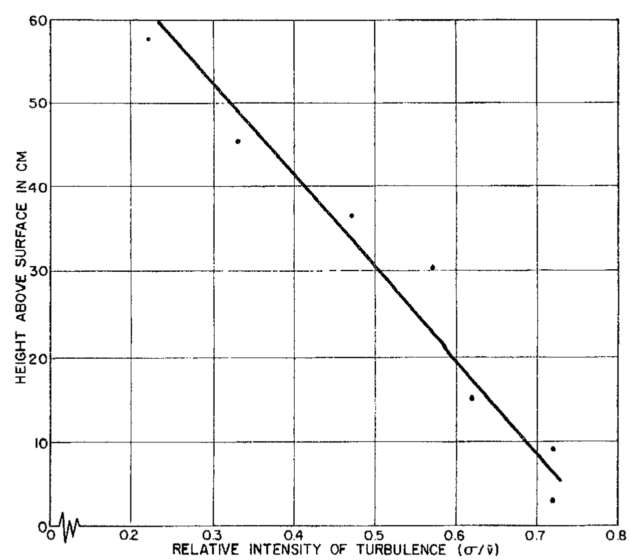

FIG. 9. Variation of relative intensity of turbulence aolng the x axis with height above surface composed of standard ridges 10 cm high and 40 cm wide.

TABLE 1. Characteristics of wind turbulence for various heights, surface roughness, drag velocities, and axes.

Surface roughness	Height of measurement, cm	Mean drag velocity $\overline{V}_*$, cm/sec	Axis	Mean velocity $\bar{v}$, cm/sec	Standard deviation σ of velocity fluctuations, cm/sec	Number of velocity fluctuations n, cy/sec	$\sigma/\bar{v}$	$6\sigma/\overline{V}_*$	$\bar{v}/n$, cm
Smoothed gravel 2–6.4 mm in diam	0.2	83	x	395	290	88	0.73	21.0	4.5
	9.1	83	x	1180	455	80	0.38	32.9	14.8
	30.4	83	x	1450	195	87	0.13	14.1	16.7
Smoothed gravel 2–6.4 mm in diam	0.2	83	y	310	187	102	0.60	13.5	3.0
	9.1	83	y	1180	340	98	0.28	24.6	12.0
	30.4	83	y	1450	212	98	0.15	15.3	14.8
Smoothed gravel 2–6.4 mm in diam	0.2	83	z	283	187	88	0.67	13.5	3.2
	9.1	83	z	1180	293	80	0.25	21.2	14.8
	30.4	83	z	1450	157	104	0.10	11.3	13.9
Ridges 2.5 cm high, 10 cm apart at right angles to wind	0.6	71	x	168	128	74	0.77	10.8	2.3
	9.1	71	x	660	345	81	0.52	29.2	8.1
	36.5	71	x	900	147	100	0.17	12.4	9.0
Ridges 2.5 cm high, 10 cm apart at right angles to wind	0.6	86	x	248	191	73	0.77	13.3	3.4
	9.1	86	x	810	445	93	0.55	31.0	8.7
	36.5	86	x	1100	200	84	0.18	14.0	13.1
Ridges 2.5 cm high, 10 cm apart at right angles to wind	0.6	111	x	312	240	79	0.77	13.0	3.9
	9.1	111	x	1060	555	89	0.52	30.0	11.9
	30.4	111	x	1490	325	83	0.22	17.6	18.0
	36.5	111	x	1550	219	76	0.13	11.8	20.4
Ridges 2.5 cm high, 10 cm apart at right angles to wind	0.6	111	y	312	219	73	0.73	11.8	4.1
	9.1	111	y	1060	399	74	0.37	21.6	14.3
	30.4	111	y	1490	325	74	0.22	17.6	20.1
	36.5	111	y	1550	219	72	0.13	11.8	21.5
Ridges 2.5 cm high, 10 cm apart at right angles to wind	0.6	111	z	312	240	117	0.73	13.0	2.8
	9.1	111	z	1060	377	114	0.35	20.4	9.3
	30.4	111	z	1490	234	98	0.15	12.6	15.2
	36.5	111	z	1550	190	117	0.12	10.3	12.8
Ridges 10 cm high, 40 cm apart at right angles to wind	2.9	162	y	540	368	103	0.67	13.6	5.4
	9.1	162	y	1010	540	103	0.53	20.0	9.8
	57.8	162	y	1740	320	95	0.18	11.9	18.3
Ridges 10 cm high, 40 cm apart at right angles to wind	2.9	162	z	540	361	96	0.65	13.4	5.7
	9.1	162	z	1010	520	91	0.52	19.3	11.1
	57.8	162	z	1740	293	73	0.17	10.9	23.8

Oscillograms, shown in duplicate in fig. 7 to show that results are reproducible, indicated that the relative magnitude of velocity fluctuation along the x, y, and z axes was lowest very near the surface of the ground and at some distance above the surface. The zone of maximum magnitude of velocity fluctuation (maximum magnitude of turbulence) in the wind tunnel was at a height of 5 to 40 cm for standard ridges 10 cm high, 5 to 20 cm for ridges 2.5 cm high, and 2 to 15 cm for a smoothed surface of gravel 2 to 6.4 mm in diam.

Velocity impulses were not randomly distributed at all heights and on all axes. Impulses very near the surface were predominantly forward and upward. They were more or less randomly distributed in the zone of maximum magnitude of turbulence, but above this zone they were predominantly in the direction opposite to those near the surface.

The curve of fig. 8 and additional data in table 1 indicate that the lowest relative magnitude of turbulence in the wind tunnel occurred nearest the surface of the ground and at some distance above the surface. The depth of zone characterized by greatest magnitude of turbulence increased directly though not proportionately with the roughness of surface. The relative intensity of turbulence, on the other hand, was greatest nearest the surface of the ground and decreased in arithmetic proportion with height (fig. 9). The scale of turbulence, which denotes the relative size of eddies, was smallest nearest the surface of the ground and increased as the logarithm of height (fig. 10).

Data in table 1 indicate that relative intensity, magnitude, and scale of turbulence were approximately the same along the x, y, and z axes. Relative intensity and magnitude of turbulence remained about the same for different drag velocities of the wind and different degrees of surface roughness. They varied appreciably only with height above the surface. The relative scale of turbulence appeared to

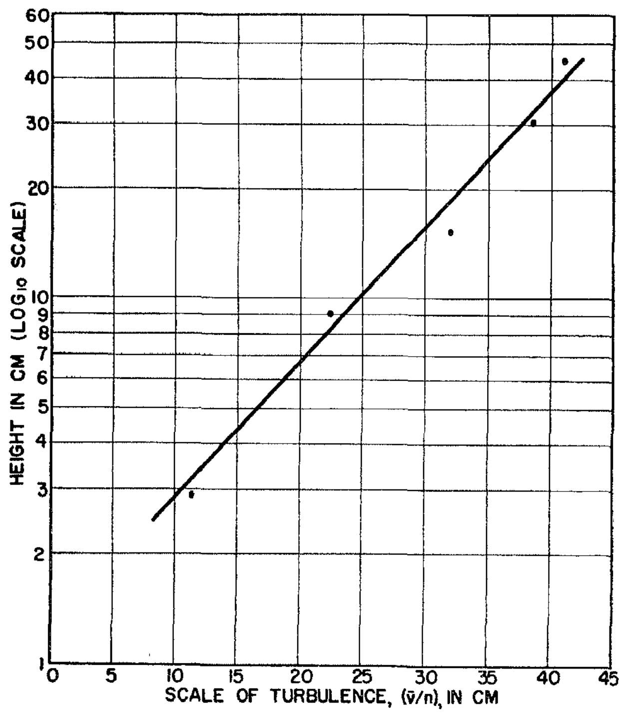

FIG. 10. Variation of scale of turbulence along the x axis with height above surface composed of gravel ridges 10 cm high and 40 cm wide.

increase slightly with drag velocity of the wind but remained virtually constant with changes in surface roughness.

The turbulence factor in the tunnel was greatest at the surface of the ground and decreased as the height was increased till its value was nearly one (table 2). A factor of one would indicate zero pressure fluctuation and consequently zero magnitude and intensity of turbulence. The mean value of the turbulence factor very close to the surface of the ground was 2.71. It remained virtually the same for different degrees of surface roughness and drag velocities of the wind.

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TABLE 2. Turbulence factor for various degrees of surface roughness, height, and drag velocities along the x axis in a wind tunnel.

Surface roughness	Height of measurement, cm	Drag velocity, cm/sec	Mean pressure $\bar{P}$, dynes/cm²	Standard deviation σ of $\bar{P}$, dynes/cm²	Turbulence factor $(\bar{P}+3\sigma)/\bar{P}$
	0.2	83	94	51	2.63
Smoothed gravel 2–6.4 mm in diam	9.1	83	840	126	1.45
	30.4	83	1280	23	1.05
	0.6	111	59	35	2.78
Ridges 2.5 cm high, 10 cm apart at right angles to wind	9.1	111	680	187	1.82
	30.4	111	1350	64	1.14
	36.5	111	1460	29	1.06
Ridges 2.5 cm high, 10 cm apart at right angles to wind	0.6	86	37	22	2.78
	9.1	86	400	120	1.90
	36.5	86	730	24	1.10
Ridges 2.5 cm high, 10 cm apart at right angles to wind	0.6	71	17	10	2.76
	9.1	71	260	72	1.83
	36.5	71	490	13	1.08
	2.9	162	170	90	2.59
	9.1	162	610	315	2.55
Ridges 10 cm high, 40 cm apart at right angles to wind	15.2	162	950	360	2.14
	30.5	162	1340	428	1.96
	36.5	162	1460	326	1.67
	45.6	162	1620	178	1.33
	57.8	162	1810	85	1.14