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## Part II. Measurements of Turbulence Intensity and Noise in the Working-Section

*By*

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*Summary.*—Measurements are given of the turbulence in the working-section together with measurements of the noise.

With all the screens fitted in the tunnel, the intensities of lateral components are of the same order as the longitudinal component and range from about 0·01 per cent to 0·03 per cent of the mean speed.

Frequency analyses have shown the longitudinal components to consist of fan frequencies and a low-frequency contribution at about 5 to 10 c.p.s. The lateral components consist almost entirely of a similar low-frequency contribution.

With all the screens in the tunnel the low level of turbulence is confined to a restricted area near the centre of the tunnel with flashes of high-intensity turbulence spreading a considerable distance from the walls.

Noise measurements with the hot-wire microphone in the middle of the working-section showed that above a tunnel speed of 150 ft/sec the longitudinal component consisted mainly of noise. Some measurements were also made with the hot-wire microphone in the turbulent boundary layer on the walls.

1. *Introduction.*—The general flow characteristics of the Royal Aircraft Establishment 4-ft × 3-ft Experimental Low-Turbulence Wind Tunnel are given in Ref. 1. This report gives the results of measurements of turbulence intensity in the working-section, together with the results of some noise measurements made with a hot-wire microphone of special design. A brief description of this instrument is given in the Appendix.

All measurements in this report were made with 3 fixed screens in the rapid expansion and 9 screens in the bulge of the tunnel. The holes of the return circuit were vented to atmosphere and the observation room was sealed.

As pointed out in Ref. 2, the measurements and the development of the apparatus have necessarily been carried on simultaneously, because the low levels of turbulence encountered have demanded equipment of very great sensitivity. As more refinements to the apparatus were made, and greater experience in making experiments was obtained, new facts emerged, which made it necessary to modify some of the results given in Ref. 2†.

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* R.A.E. Report Aero. 2412, received 21st July, 1951.

† The results of Ref. 2 are largely superseded by those given here and in subsequent work. For the sake of continuity in the R. & M. series this report is thus entitled Part II although it was originally Part III.

2. *Apparatus.*—2.1. *Amplifier.*—The measuring apparatus used is basically that described in Ref. 3 with various modifications aimed at improving the low-frequency response of the amplifier and reducing the noise level. The principal change is the introduction of a transformer between the bridge and amplifier. The first two stages have been separated from the rest of the amplifier and shielded from airborne noise by a sponge-rubber casing, and from vibration by providing soft mountings for the valves.

The frequency characteristic of the transformer plus amplifier for various values of the input resistance to the transformer is shown in Fig. 1. For the usual bridge arrangement and wire length, the input resistance is between 15 and 20 ohms. In this case there is a loss of some 30 per cent in amplifier gain at 1·5 c.p.s. and 10,000 c.p.s.

2.2. *Frequency Analyser.*—A General Radio Type 762-B Vibration Analyser was used to make frequency analyses of the hot-wire output. The frequency range of this instrument was from 2·5 to 750 c.p.s. and the band width roughly ± 1 per cent of the frequency when used on sharp sensitivity.

2.3. *Hot-Wire Mounting.*—One serious difficulty encountered in measuring low levels of turbulence is that of the vibration of the hot wire. For example a wire vibrating with an amplitude of 0·0001 in. at a frequency of 1,000 c.p.s. will produce a spurious effect equivalent to a turbulence of 0·04 per cent at 100 ft./sec. Vibration of the wires was detected with the aid of the frequency analyser as a peak in output at a definite frequency.

In previous work on low-turbulence, wire vibration has been overcome by using a sufficiently soft mounting for the hot wire, but as measurements were required at rather high wind speeds it was thought to be desirable to have a fairly stiff mounting. This was found possible as the vibration of the tunnel structure is small.

Fig. 2a shows a sketch of the type of wire holder found to be satisfactory for measuring longitudinal component. Its effectiveness depends upon the use of rather massive prongs, which are stiffer in their own plane than normal to it, set in Chatterton's compound, with some damping provided by the soft mounting of the prongs in the main body. It was confirmed by measurements in the bulge with a holder with long fine prongs that the sensitivity was not impaired by the use of the somewhat bulky wire holders. One of the authors[4] had previously used a holder in which the prongs, consisting of fine wires, were supported in tubes filled with heavy oil. This type of holder is difficult to construct and work on it was discontinued when a satisfactory holder of more simple design was found.

The final wire holders were made in a unit complete with plug pins so that hot wires could be interchanged quickly.

As regards the actual hot wire it was found better not to have this under tension but on the other hand not too slack. If the wire is attached under tension vibration is almost inevitable and also the likelihood of breakage of the wire is increased. A very slack wire distorts under the wind forces and gives spurious results. The most satisfactory wire appears to be one bent forward slightly.

Fig. 2c shows the mounting used for $u'$ measurements. Originally a 3 : 1 streamlined metal strut of 2-in. chord was used but this was found to resonate with its own eddies. The long-chord thin strut eliminated this trouble.

The lateral components were measured by the difference method using 'V' wires[5]. V wires were used in preference to the 'X'-type as being easier to construct. No loss of accuracy was suffered by using V wires because the scale of turbulence was large. As in the measurement of $u'$, trouble was encountered from vibrations of the hot wires. The damping arrangement used for the $u'$ wires was found to be unsatisfactory since the movement of the entire forward part of the holder on its rubber mounting contributed to the lateral components. The wire holder finally used is shown in Fig. 2b. The prongs were glued together except for the phosphor-bronze tips. By making these tips sufficiently rigid, vibration was eliminated, or at any rate its frequency was increased beyond the range of the amplifier. As with $u'$ wires, the wires were made slightly bent forward. With 0·0002-in. diameter platinum wire of length about 0·04-in., such wires were generally stiff enough to maintain their calibration up to speeds of 280 ft/sec.

It was also found that even when the stiff wooden strut was used to support the hot wire, there was some effect on the component normal to the span of the strut from flexural vibrations. Therefore two different struts, one horizontal and one vertical were used; the horizontal strut was used for the horizontal component measurements and the vertical strut for the vertical component.

2.4. *Calibration of Hot Wire.*—It is usual to measure the sensitivity of a hot wire by maintaining it at constant resistance by varying the heating current $i$ whilst varying the speed $U$ and determining the slope of the line $i^2$ vs. $\sqrt{U}$. It has been shown[5] that this method gives results differing from those obtained by calibrating at constant heating current and obtaining the slope $R_H/(R_H - R_0)$ vs. $\sqrt{U}$ where $R_H$ is resistance at heating current $i$ and $R_0$ is resistance at room temperature. The difference between the two methods is due to the dependence upon temperature of the constants in King's equation.

As the latter method approximates more closely to the operating condition* it has been used for determining the sensitivity. If the slope of the line is expressed non-dimensionally as

$$m = \frac{1}{2}\frac{\Delta\{R_H/(R_H - R_0)\}}{\Delta\sqrt{U}}\,\frac{\sqrt{U}}{R_H/(R_H - R_0)}$$

then the intensity of turbulence can be calculated from

$$\frac{u'}{U} = \frac{E}{miR_H(R_H/R_0 - 1)K}$$

where $u'$ is the r.m.s. value of longitudinal fluctuation of velocity

$E$ is the r.m.s. voltage output of hot wire

$K$ is the factor to allow for variation of $i$ with $R_H$. In the present bridge circuit $K$ is of the order of 0·9.

A similar method was employed for calibrating the V wires, with the variation of $U$ replaced by a variation of the incidence of the V wire in its own plane.

3. *Results.*—3.1. *Presentation.*—The root-mean-square fluctuating velocity components in the three directions, $u'$ in the stream direction, $v'$ normal to the stream direction and horizontal, and $w'$ vertical are plotted as a percentage of the local velocity $U$.

The frequency spectra are plotted as $nF(n)$ against $n$, where $n$, the frequency, is on a logarithmic scale. $F(n)$ is the spectrum function such, that $u'^2F(n)\,dn$ is the contribution to $u'^2$ of frequencies between $n$ and $n + dn$ and hence

$$\int_0^\infty F(n)\,dn = 1.$$

The advantage of this method is that it opens out the frequency scale at the lower end, whilst still permitting the integration of the areas under the curves.

For comparison with turbulence, the pressure fluctuations are expressed by the particle velocity

$$U_p' = \frac{p'}{\rho a}$$

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* Ideally the hot wire operates at constant current but in practice the heating current does depend to a small extent upon the resistance of the wire.

where $U_p'$ is the r.m.s. particle velocity

$\rho$ is the density of air

$a$ is the velocity of sound

This relation assumes sound to consist of plane waves progressing in the direction of $U_p'$.

3.2. *Turbulence.*—The intensity levels on the centre-line of the tunnel for the three components are shown in Fig. 3. Except at low speeds the lateral components are bigger than the longitudinal and $w'$ is at all speeds about 50 per cent bigger than $v'$. The frequency spectra (Figs. 4 to 7) show that nearly all the energy is contained in the low frequency fluctuations. The lateral components consist almost entirely of contributions below 20 c.p.s. except for some small peaks at 160 c.p.s. for $v'$ and 200 c.p.s. for $w'$, the frequency corresponding to these peaks is independent of wind speed but the magnitude of the peaks increases with speed. The frequency spectra of the longitudinal component are similar to those of the lateral components at low speeds, but include strong contributions from the fan* at higher speeds. As would be expected, the fan frequency is absent from the lateral components.

Further information is contained in Figs. 8 and 9, which show respectively the correlation of $u'$ horizontally and the variation of $u'$ and $w'$ vertically across the working-section. These measurements were made at the same speeds as for frequency spectra viz. 60, 100, 160 and 180 ft/sec.

The correlation of $u'$ was measured with two wires placed symmetrically about the centre of the working-section on a horizontal line normal to the wind direction. It will be seen from Fig. 8, that the correlation coefficient, $\overline{u_1u_2}/u_1'u_2'$ is high over the whole extent of the measurements, thus confirming that the turbulence is of large scale. The correlation at 100 ft/sec is higher than at other speeds. At this speed there is a peak in the $u'$ intensity (Fig. 3), and the spectrum (Fig. 5) shows that it arises from the low frequencies.

In Fig. 9 the turbulence rises as the walls are approached. At points closer to the wall than those shown in the figure, flashes of turbulence of high intensity occur. The same observation applies to Fig. 8. Thus, from both Figs. 8 and 9 it follows that, for all but the lowest speed, on an area of 20 in. × 16 in. out of a total of 48 in. × 36 in. has the same low level of turbulence as that found on the centre-line.

3.3. *Discussion of Turbulence Measurements.*—Since the work described in the previous paragraph was completed, attempts have been made to examine the tunnel flow in more detail and to discover the reason for the peculiar turbulence characteristics described above. The results of these tests are recorded in detail in an unpublished paper, but, for the convenience of the reader, some of the later conclusions are summarized below.

(*a*) Observations of the state of the boundary layers on the tunnel walls were made using an oil film technique and these showed that at low tunnel speeds transition occurred in the working-section some distance from the end of the contraction. With increasing wind speed, the transition point moved towards the contraction and the extent of its fluctuations increased. At about 100 f.p.s. transition occurred at the beginning of the working-section and its fluctuations seemed to reach a maximum in extent. At higher speeds, the transition point moved into the contraction and here the oil film technique could not be used, because the oil would not stay on the inclined walls. Since the boundary layer in the contraction is under a considerable favourable pressure gradient, the transition point will not progress much farther with change of wind speed once it is sufficiently inside the contraction and the range of its fluctuations is likely to diminish.

(*b*) Fluctuations of transition point lead to corresponding fluctuations of displacement thickness of the boundary layer in the working-section. Thus, the effective area for the airflow in the

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* The fan has six blades so that the fundamental frequency of the noise it produces is, in c.p.s., one tenth of the fan r.p.m.

working-section is fluctuating and this produces an apparent longitudinal component of turbulence. The peak in the turbulence intensity at 100 ft/sec is explained by a maximum in the extent of the fluctuations of transition point.

(*c*) The region of high-intensity turbulence near the walls of the working-section is connected with a return flow on the walls of the bulge behind the screens and possibly also with an instability of the flow in the bulge. By reducing the number of screens in the bulge, the return flow disappears and the region of high-intensity turbulence near the walls of the working-section diminishes to an extent comparable with the spread of turbulence, which would be expected from a turbulent boundary layer. There is reason to believe that the screens are too close to a rather sudden contraction, creating conditions which ultimately produce the return flow and the accompanying unstable total-head distribution.

Although a minor detail, some reference may be made to the waviness of the intensity curves of Fig. 3. The periodic variation of $u'$ was attributed in Ref. 2 to an interference effect of the noise from the fan travelling round the tunnel circuit in opposite directions. This explanation is obviously not applicable to the lateral components to which plane waves from the fan cannot contribute directly. This is confirmed by the frequency spectra of the lateral components, which show no peaks related to fan frequencies. Further, the peak in the longitudinal component at 100 ft/sec has already found an explanation other than fan noise. There is, therefore, now less evidence that an interference effect as outlined in Ref. 2 is causing the waviness in the intensity curve of longitudinal component.

It is of interest to consider the influence of the measured turbulence on the transition of the boundary layer on a model placed in the tunnel. For a preliminary discussion it is convenient to consider a flat plate at zero incidence, since for this case the stability of the laminar boundary layer has been investigated by theory and experiment. According to the theory, which is due to Tollmien and Schlichting[6], oscillations of the boundary layer of a certain range of both frequency and wavelength are unstable. This means that once a critical oscillation of an amplitude, however small, is excited, the oscillations increase by drawing energy from the mean flow. The theory gives the boundaries between stable and unstable regions as a function of Reynolds number and it predicts the initial growth of these oscillations, but it does not explain how and when transition from these oscillations to turbulence occurs. Schubauer and Skramstad[7] used in their experiments a metal ribbon placed inside the boundary layer so that it did not influence the transition point, if it remained at rest. When this ribbon oscillated normal to the wall with a critical frequency, unstable oscillations as predicted by theory were observed; the increase in amplitude of these oscillations could be followed to a point, where transition occurred. It is interesting to see, if the conditions for a critical range of wavelength were fulfilled in these experiments. For this purpose it is more useful to introduce the wave velocity $c$ by the relation $c = \lambda n$, where $\lambda$ is the wavelength and $n$ the frequency. Fig. 26 of Ref. 7 shows that the unstable region of wave velocity $c$ is between

$$c/U_0 = 0{\cdot}2 \text{ to } 0{\cdot}4 \quad \ldots \quad (1)$$

where $U_0$ is the wind speed outside the boundary layer. Now $c$ is the velocity with which disturbances are moving in the flow and as the ribbon in Schubauer's experiments was placed inside the boundary layer, where all speeds from 0 to $U_0$ exist, the critical conditions for the wave velocity (and also the wavelength) were fulfilled. However it seems difficult to imagine disturbances outside the boundary layer with a critical wave velocity. For instance turbulence consists mainly of a slowly changing pattern, which is carried downstream with the speed of the mean flow and so far as changes in the pattern are neglected, the wave velocity is equal to the mean speed $U_0$ and, therefore, outside the critical range of values. If disturbances consist of sound, the wave velocity lies also outside the critical range for subsonic mean flow according to equation (1). Owing to experimental difficulties in creating disturbances of well-defined frequencies outside the boundary layer, Schubauer and Skramstad used only sound; they found that similar unstable oscillations of the boundary layer were excited, although agreement with theory was not so good as with the experiments with the ribbon. The experiments indicate that the transition point moved upstream as the amplitude of the applied disturbances increased*. Thus, the discussion of the experiments of Schubauer and Skramstad seems to suggest that

(i) The frequency criterion of the stability theory is more important than the wavelength (or wave velocity) criterion

(ii) The position of transition point seems to depend on the intensity of disturbances.

There may therefore be some justification for comparing in Fig. 10 the frequency spectrum of longitudinal component of this tunnel with the stability boundary of the above-mentioned theory. The relative magnitude of the abscissae for the frequency spectrum and stability boundary are, of course, arbitrary. According to this figure hardly any of the turbulent energy in the tunnel stream lies within the instability range of frequencies for a boundary layer on a flat plate at Reynolds numbers $R_{\delta^*}$ that are likely to be encountered in the tunnel. Thus these considerations seem to suggest that the influence of tunnel turbulence on transition is likely to be less than that suggested simply by the measured intensity of turbulence.

3.4. *Noise Measurements with the Hot-Wire Microphone.*—If noise consists of plane waves progressing in one direction, the relation between particle velocity and pressure fluctuations has already been mentioned in section 3.1 as

$$p' = \rho a U_p' \quad \ldots \quad (2)$$

At a sufficient distance from the source all waves can be assumed to be plane, therefore the first of the restrictions mentioned above is of little importance. However standing waves can exist in a wind tunnel. In standing waves nodes of pressure fluctuations coincide with antinodes of particle velocity. Then equation (2) is not valid as a relation between $p'$ and $U_p'$ in the same place. As will be discussed later in connection with the results of noise measurements, it is very likely that standing waves did not contribute appreciably to the total noise in this tunnel. Unfortunately a direct check has not been made by moving the microphone along the tunnel axis.

Velocity fluctuations due to turbulence are also associated with pressure fluctuations. According to investigations of Dryden and co-workers[8] turbulence behind a screen consists of a slowly changing pattern carried down with the mean speed of flow. In a free stream this applies also to turbulence from sources other than screens at a sufficient distance from its origin. Neglecting changes of turbulent flow pattern, the average pressure fluctuations for an observer at rest are equal to the average pressure fluctuations for an observer moving with mean speed. This means that the intensity of pressure fluctuations is independent of mean speed. It has been found[9] that the frequency spectrum of turbulence is independent of viscosity except for the very smallest eddies, which contribute only to a small extent to the total energy. Consequently pressure fluctuations are also independent of viscosity. Dimensional analysis then yields

$$p_t' = K.\tfrac{1}{2}\rho U_t'^2 \quad \ldots \quad (3)$$

with $U_t'^2 = u'^2 + v'^2 + w'^2$. Dashes denote root-mean-square values. The constant $K$ depends on the turbulence pattern assumed; according to calculations of G. I. Taylor[9] $K$ varied for a number of special forms of turbulence pattern from 0·6 to 1·4. Thus $K = 1$ seems to be a reasonable representative value.

For the same velocity fluctuations, the ratio of associated pressure fluctuations for noise and turbulence is derived from (2) and (3) with $K = 1$

$$\frac{p'}{p_t'} = \frac{2a}{U'}$$

if $U' = U_t' = U_p'$ and $a$ equals the speed of sound. At subsonic speeds, this ratio is greater than 1000 : 1 for velocity fluctuations of 0·01 per cent of the mean velocity. It is therefore possible

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* Actually Fig. 35 of Ref. 7 proves that the intensity of boundary-layer oscillations at a fixed point depends on the amplitude of the vibrating ribbon and, if this is sufficiently high, transition occurs. This clearly suggests a dependence of the transition-point position on the intensity of the applied disturbance.

to distinguish between noise and turbulence by comparison between measurements made with a hot wire and with a pressure sensitive instrument.

A hot-wire microphone was used here to avoid certain objections (*see* Appendix) against Badcoe's[10] earlier measurement with a moving-coil microphone placed flush with the tunnel wall. A description of the hot-wire microphone is given in the Appendix.

In Fig. 11 the particle velocity as measured with hot wires and microphones of the two types is plotted against speed. That the total turbulence $\sqrt{(u'^2 + v'^2 + w'^2)}$ in the middle of the tunnel is so much more than the particle velocity due to noise can be explained by the absence of any appreciable noise in the lateral components; they are almost entirely composed of low frequencies for which the associated wavelength would be much bigger than the dimensions of the working-section (4 ft × 3 ft), so that sound waves of these frequencies could not exist. Only a small contribution at 170 and 220 c.p.s. (*see* Figs. 6 and 7) could be standing waves, as half their wavelength corresponds to the lateral dimension of the cross-section, but the pressure waves would have a node in the middle of the tunnel and consequently no contribution would arise there. Thus noise contributes almost entirely to the longitudinal component of turbulence. A comparison between the corresponding curves in Fig. 11 shows that the longitudinal component above 150 ft/sec is mainly due to noise and below 150 ft/sec is mainly due to fluctuations of transition point of the boundary layer on the tunnel wall as already mentioned. This is confirmed by the frequency spectra of noise Figs. 12, 13 and 14 at 100, 160 and 180 ft/sec. All contain a high peak at the fan fundamental frequency ($\frac{1}{10}$ of the fan speed in revolutions per minute for a fan of six blades) and its second harmonic. The frequency spectra of noise and longitudinal component of turbulence look very similar at 180 ft/sec (compare Fig. 14 with top picture of Fig. 7), agreement is poor at 160 ft/sec (Figs. 13 and 6) and there is hardly any similarity at 100 ft/sec (Figs. 12 and 5).

In previous measurements[10] of noise a moving-coil microphone mounted in the tunnel wall had been used. Measurements with this arrangement resulted in a particle velocity roughly twice as high as that measured with the hot-wire microphone in the middle of the tunnel. The corresponding frequency spectra look completely different as a comparison between Fig. 14 and the dotted line in Fig. 15 shows. For comparison, the hot-wire microphone was also moved into the boundary layer on the tunnel wall. The intensity was now increased about 2 to 3·5 times (*see* Fig. 11) compared with the centre of the tunnel and the frequency spectrum (full line in Fig. 15) differs by a big contribution of frequencies above 50 c.p.s. (Fig. 14). The obvious conclusion is that within the boundary layer, pressure fluctuations exist which are associated with turbulence and are propagated outside only with a considerably reduced intensity.

Any sound generated by pressure fluctuations in the turbulent boundary layer should contribute to the lateral components of turbulence. The frequency spectra of lateral components of turbulence (Figs. 12, 13 and 14) show very little energy within those frequencies, which contribute almost all the energy to the pressure fluctuations within the boundary layer (Fig. 15).

From these measurements two conclusions can be drawn:

(*a*) If a microphone is mounted in a tunnel wall, where a turbulent boundary layer exists, it will record not only the sound in the tunnel, but also pressure fluctuations associated with turbulence, which are propagated outside the boundary layer only to a limited extent. Therefore the mounting of a microphone in a tunnel wall is usually not suitable for measurement of noise inside the tunnel.

(*b*) Pressure fluctuations within the turbulent boundary layer on the tunnel wall did not contribute noticeably to the noise in the middle of the tunnel.

All the noise in the working-section seems to consist of waves in the direction of the tunnel axis and to originate in parts of the tunnel other than the working-section. Besides noise at the fan fundamental frequency and its higher harmonics which are of course generated by the fan, there is noise of continuous frequency distribution; it probably originates from separation of flow, wakes and also vibrations of the tunnel structure.

The discrepancy between measurements with the moving-coil microphone and the hot-wire microphone in the boundary layer needs some explanation. The discrepancy relates to intensities and frequency spectra as is seen in Figs. 11 and 15*. The explanation is a drop in sensitivity of the moving-coil microphone at both ends of the frequency range. The low sensitivity at low frequencies is peculiar to this type of instrument; at high frequencies it is due to the pressure fluctuations being associated with eddies, whose size is small compared with the diaphragm of the instrument, which was about 1 in. in diameter.

We return now to the question of whether standing waves are present in the working-section. Standing waves are usually connected with resonances and these result in peaks in the frequency spectrum at a number of fundamental frequencies and their higher harmonics, which depend on the geometry of the tunnel. Now the noise spectra show peaks only at the fan fundamental frequency or its second harmonic and these frequencies change continuously with wind speed. The noise intensity increases also continuously with wind speed, so that there seem to be no peaks at discrete frequencies. Thus, it is unlikely that standing waves contribute appreciably to the total energy.

## LIST OF SYMBOLS

| | |
|---|---|
| $a$ | Speed of sound |
| $c$ | Wave velocity in boundary layer |
| $E$ | r.m.s. voltage output of hot wire |
| $F(n)$ | Frequency spectrum function |
| $i$ | Hot wire heating current |
| $K$ | Hot wire bridge correction factor |
| $m$ | Hot wire sensitivity parameter |
| $n$ | Frequency |
| $p'$ | r.m.s. pressure fluctuation |
| $R_0$ | Hot wire resistance at room temperature |
| $R_H$ | Hot wire resistance at heating current $i$ |
| $U_0$ | Mean wind speed |
| $u'$ | r.m.s. value of longitudinal velocity fluctuation |
| $v'$ | r.m.s. value of horizontal lateral velocity fluctuation |
| $w'$ | r.m.s. value of vertical velocity fluctuation |
| $U_t'$ | $= \sqrt{(u'^2 + v'^2 + w'^2)}$ |
| $U_p'$ | Particle velocity of sound waves |
| $\frac{\overline{u_1 u_2}}{u_1' u_2'}$ | Correlation coefficient of longitudinal velocity fluctuations between points 1 and 2 |
| $\lambda$ | Wavelength |
| $\rho$ | Density |
| $\nu$ | Kinematic viscosity |

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* The ordinate in Fig. 15 is $(U_p'/U_0)^2\, n\, F(n)$; it is different from those in Figs. 12 to 14 in order to allow direct comparison at every frequency between the two curves.

## REFERENCES

| No. | Author | Title, etc. |
|---|---|---|
| 1 | H. B. Squire, and K. G. Winter | The R.A.E. 4-ft × 3-ft Experimental Low-Turbulence Wind Tunnel. Part I. R. & M. 2690. February, 1947. |
| 2 | H. Schuh and K. G. Winter .. | The R.A.E. 4-ft × 3-ft Experimental Low-Turbulence Wind Tunnel. Part II: Measurements of longitudinal intensity of turbulence. R.A.E. Report Aero. 2285. A.R.C. 11,829. August, 1948. |
| 3 | R. H. James and J. H. Mitchell.. | Turbulence Measuring Apparatus. R.A.E. Tech. Note Inst. 949. A.R.C. 9885. March, 1946. (Unpublished.) |
| 4 | H. Schuh .. .. .. .. | Windschwankungsmessungen mit Hitzdrähten. Gottingen Monographs D1 4.3. |
| 5 | H. Schuh .. .. .. .. | Determination of the sensitivity and the time constant of hot wires for turbulence measurements. A.R.C. 10,046. August, 1946. |
| 6 | C. C. Lin .. .. .. .. | On the stability of two-dimensional parallel flows. Part III. Stability in a viscous fluid. *Quart. App. Math.* Vol. III, No. 4. January, 1946. |
| 7 | G. B. Schubauer and H. K. Skramstad. | Laminar Boundary Layer Oscillations and Transition on a Flat Plate. N.A.C.A. A.C.R. April, 1943. A.R.C. 6777. (Unpublished.) |
| 8 | H. L. Dryden, G. B. Schubauer, W. C. Mock and H. K. Skramstad. | Measurement of intensity and scale of wind-tunnel turbulence and their relation to the critical Reynolds number of spheres. N.A.C.A. Report 581. 1937. |
| 9 | G. I. Taylor .. .. .. | Some recent developments in the study of turbulence. Proceedings of the Fifth International Congress for Applied Mechanics. |
| 10 | S. R. Badcoe .. .. .. | Preliminary investigation of noise in wind tunnels. R.A.E. Tech. Note Rad. 415. A.R.C. 11,518. January, 1948. (Unpublished.) |
| 11 | H. Billing .. .. .. | A sensitive hot-wire microphone of small diameter and especially low sensitivity to vibrations. R. & T. 229. October, 1946. |
| 12 | S. R. Badcoe .. .. .. | Calibration of a hot-wire microphone by a cavity method. R.A.E. Tech. Note Rad. 471. A.R.C. 13,057. December, 1949. |

## APPENDIX I

### *Description of the Hot-Wire Microphone*

It was considered that in a wind tunnel with low noise level a microphone mounted in the tunnel wall would not measure the noise in the middle of the tunnel but would include also pressure fluctuations in the turbulent boundary layer on the tunnel wall. A microphone was therefore required which could be mounted in the middle of the tunnel free from any interference from a boundary layer. Further requirements of the microphone were:

(*a*) To respond only to static-pressure fluctuations,

(*b*) To be sufficiently small to avoid reflection of acoustic waves of the frequencies encountered,

(*c*) To have good response down to very low frequencies.

It seemed to be difficult to fulfil these requirements with a conventional microphone even of miniature type ('buttonhole' microphone). It was thought that a hot-wire microphone built in the form of a static-tube would be suitable. It should be made clear that the hot wire responds to velocity fluctuations only. In a hot-wire microphone the pressure fluctuations at the holes of the instrument are transformed into velocity fluctuations in the throat inside the instrument, where the hot wire is placed.

The hot-wire microphone used is similar to Billing's[11] design. A sketch is given in Fig. 16. The external pressure is fed in through six pressure holes each 0·06-in. diameter, which lead to the throat formed by two glass plates 0·02 in. apart. The hot wire is mounted in the middle of this gap. Next to the gap comes a cavity, which together with the throat, forms a Helmholtz resonator; this serves to improve the response of the instrument at high frequencies. In order to avoid frequency distortions an additional constant airflow is maintained through the throat. These distortions occur, because the law relating the rate of cooling of a hot wire to the wind speed is not linear and because the hot wire is completely insensitive to reversal of flow. The airflow is supplied by a compressed-air bottle and enters through an inlet near the rear of the instrument, passes through a cotton wool filter to remove any dust and then goes through a capillary tube into the cavity of the resonator. The pressure drop through the capillary is sufficiently large to maintain a constant airflow independent of exit pressure. A fabric screen is fitted in the cavity to diffuse the flow entering from the capillary tube. The hot wire is kept straight by phosphor-bronze needles, which are connected to the brass plug pins.

The pressure holes are two diameters behind the head of the microphone. This distance is a compromise between the normal six diameters recommended for static-tubes, and the requirement that the boundary layer on the microphone at the holes should be laminar and free, for speeds up to 300 ft/sec, from any amplified oscillations preceding transition. It is considered that the holes are sufficiently far back to ensure that the pressure measured at the holes includes only a small proportion of the free-stream dynamic head.

The frequency characteristic of the instrument itself is of course far from flat; however the amplifier has suitable circuits to compensate for the deficiency of the instrument, so that the response of the combination of both instrument and amplifier is reasonably uniform.

The microphone was calibrated by inserting the head just beyond the pressure holes into a box in which a known pressure fluctuation could be produced by means of a telephone receiver. This device has been described by Badcoe[12]. It covered a frequency range of 80 to 1000 c.p.s. The result of the calibration of the microphone and fully compensated amplifier is given in Fig. 17.

Unfortunately there was no means of calibrating the instrument below 80 c.p.s. The rise in the response of the instrument near 80 c.p.s. (see Fig. 17) is explained by a change in velocity distribution in the throat. For low frequencies the velocity profile is the same as for steady flow (parabolic), but with increasing frequency inertia forces become more important and the velocity profile changes to a form where the velocity is constant over most of the cross-section with peaks near the walls*. The effect of this change in velocity profile was estimated and found to change the sensitivity of the instrument by a factor of 1·5 in the neighbourhood of 90 c.p.s. This unevenness in sensitivity has not been compensated by the amplifier. It has however, been taken into account in the evaluation of sound intensity measurements.

This hot-wire microphone was a first attempt. It was quite satisfactory for the experiments dealt with in this report but it could be improved, both in frequency range and in sensitivity, if more work were devoted to its development.

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* *See* Goldstein: *Modern Developments in Fluid Dynamics.* Vol. I, p. 187.

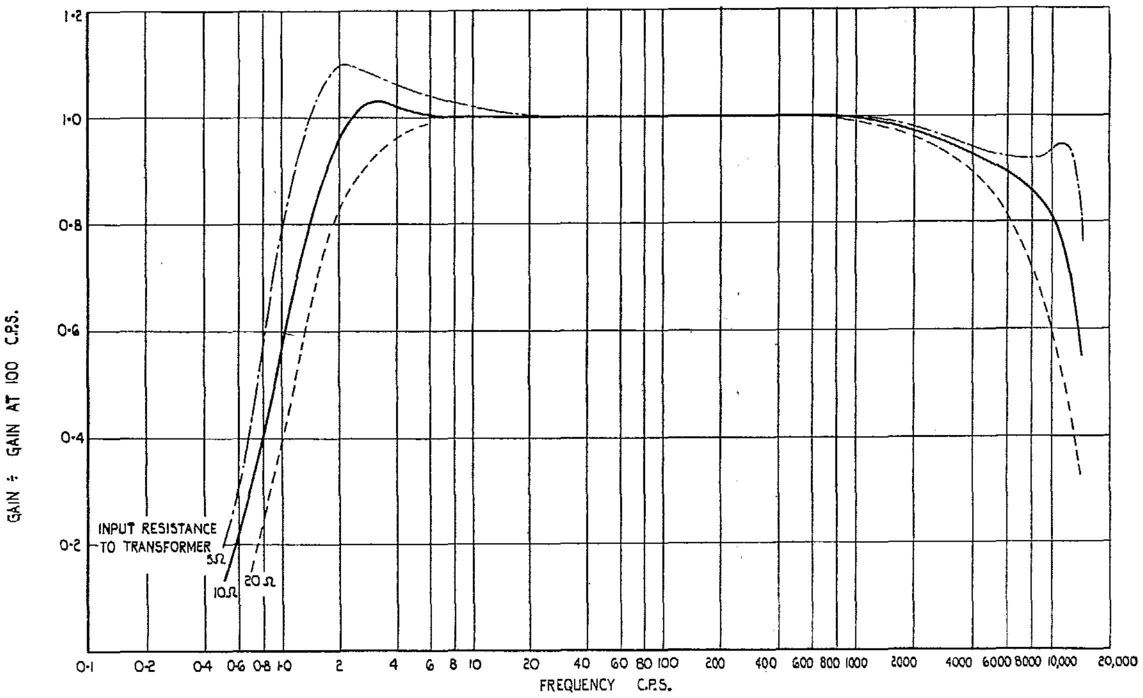

FIG. 1. Frequency characteristics of amplifier plus transformer.

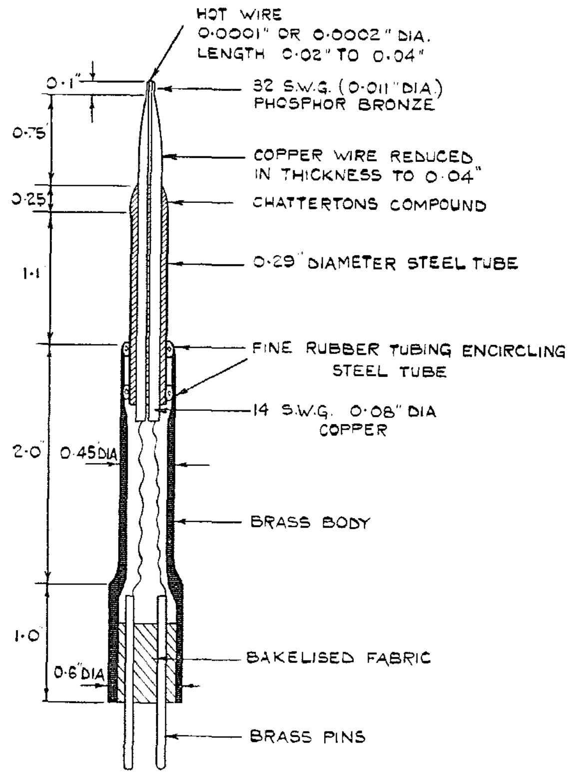

FIG. 2a. Hot-wire holder for u′.

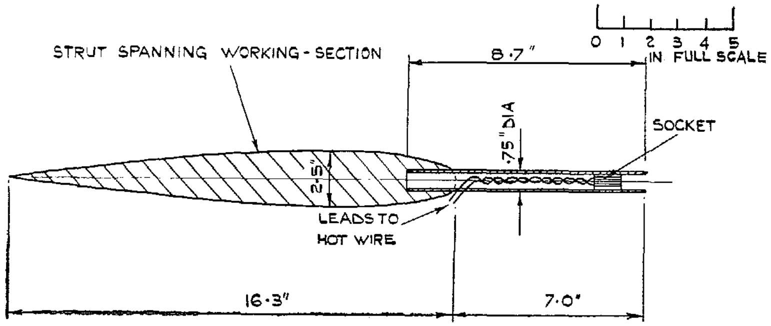

FIG. 2c. Hot-wire mounting.

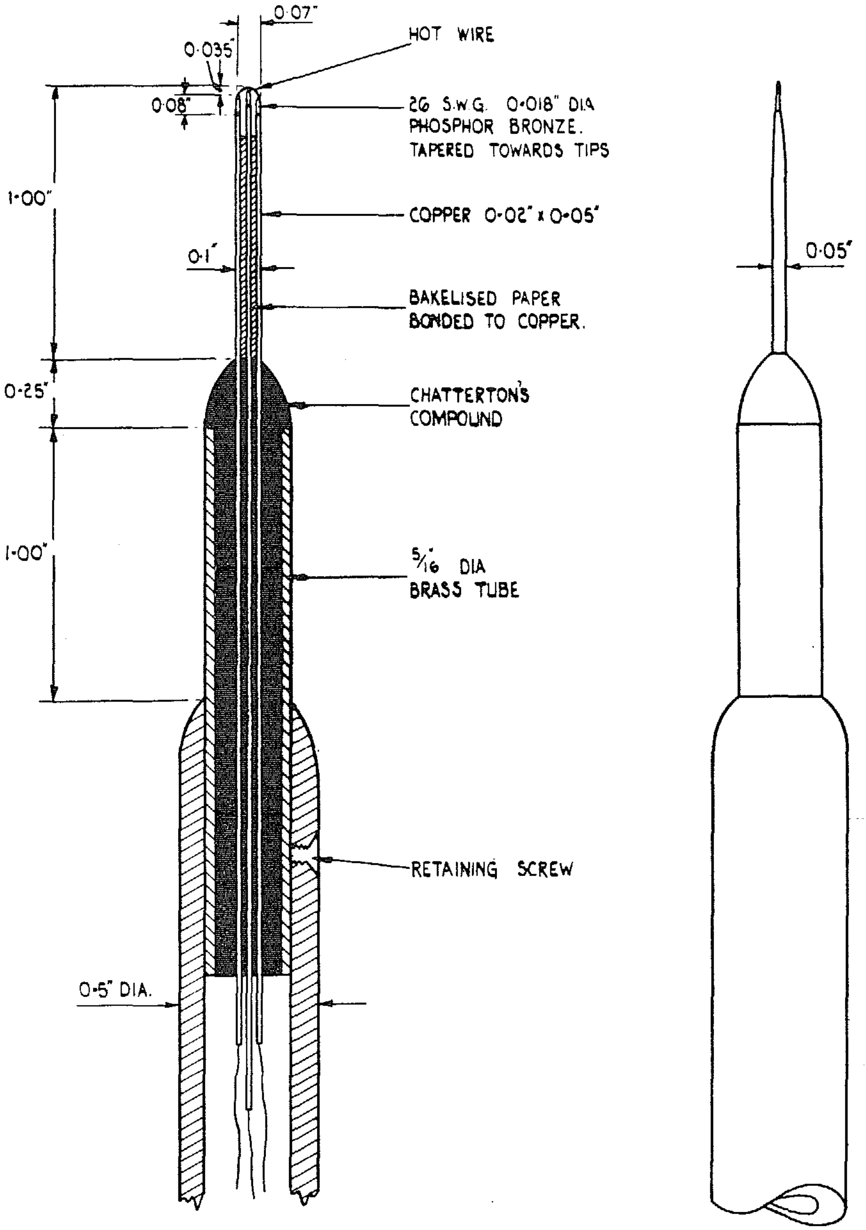

FIG. 2b. V-type wire holder.

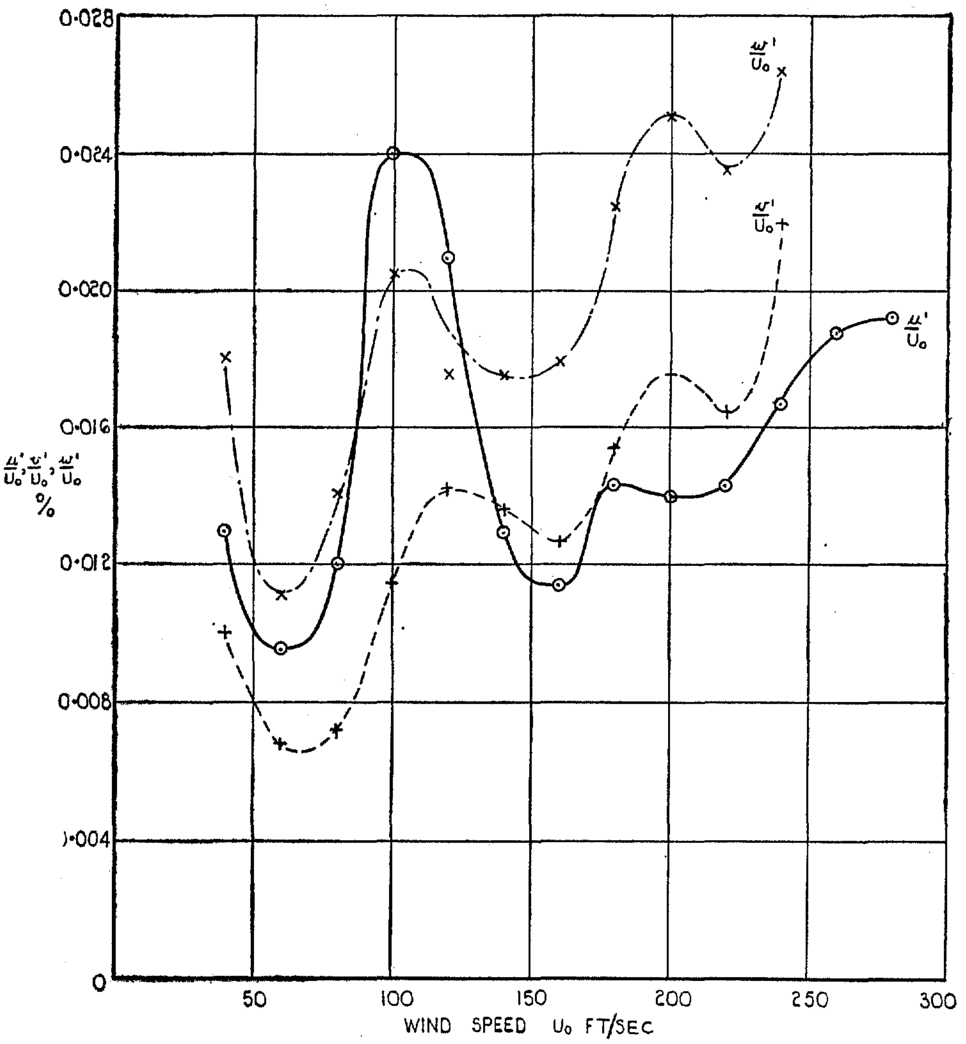

FIG. 3. Turbulence components in working-section : 3 + 9 screens. Measurements made on the tunnel centre-line.

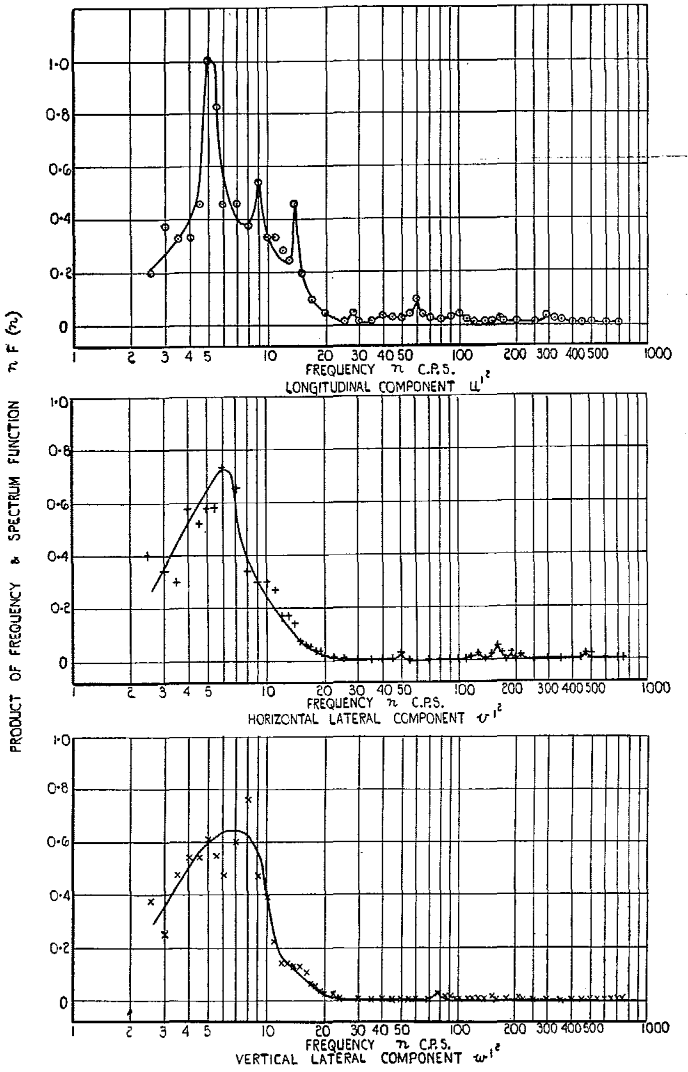

FIG. 4. $U_0$ =60 ft/sec. Fan speed = 140 r.p.m.

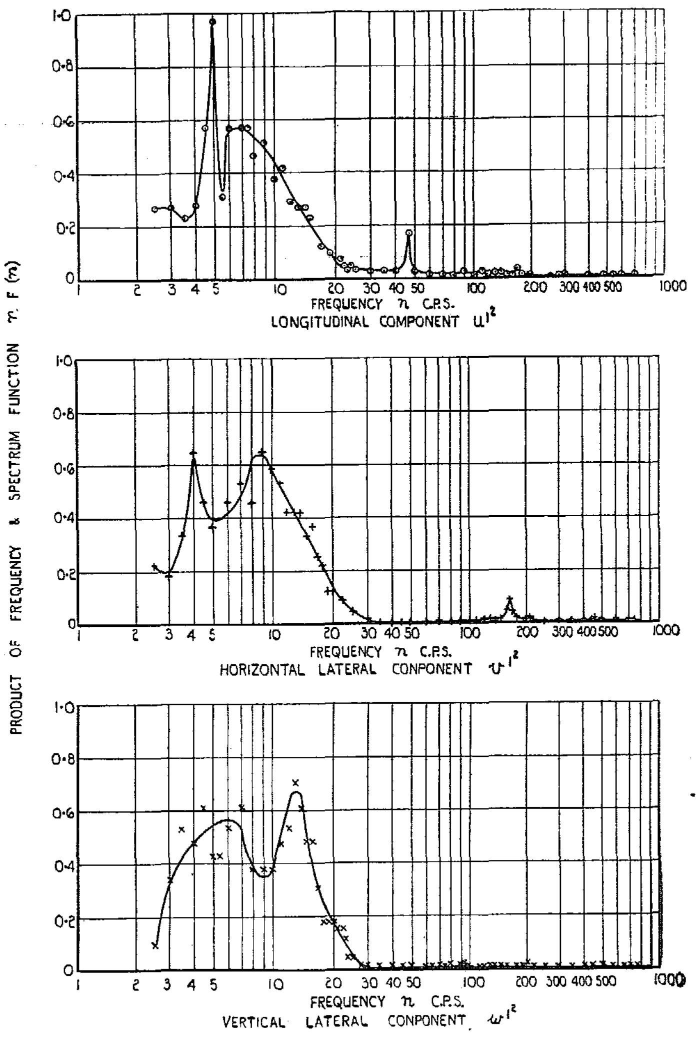

FIG. 5. $U_0$ = 100 ft/sec. Fan speed = 230 r.p.m.

FIGS. 4 and 5. Frequency spectra of the three turbulence components on the centre-line of the tunnel.

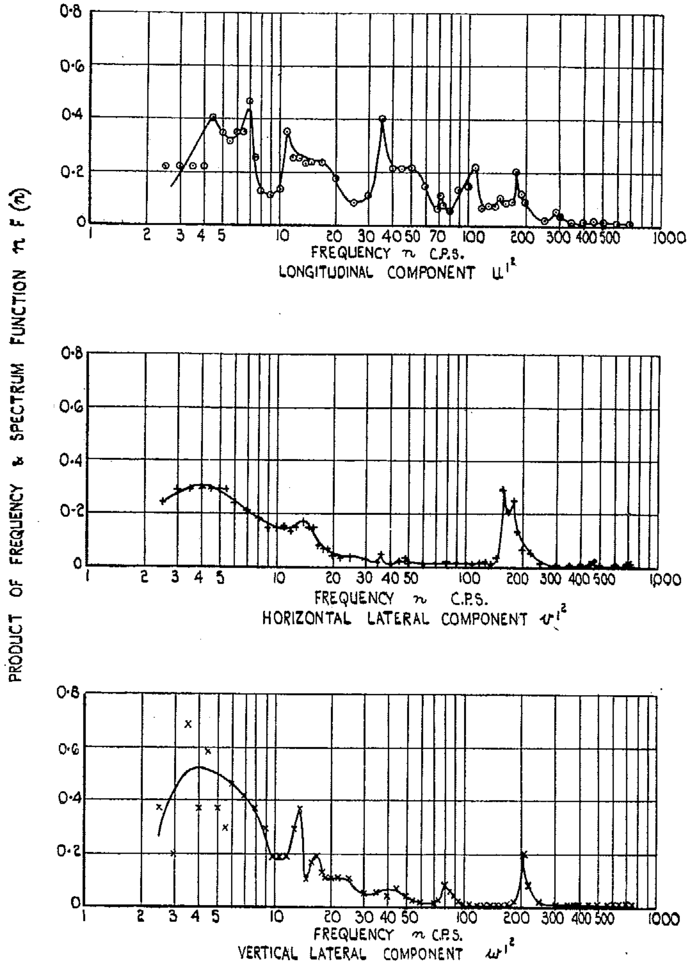

FIG. 6. $U_0 = 160$ ft/sec. Fan speed $= 360$ r.p.m.

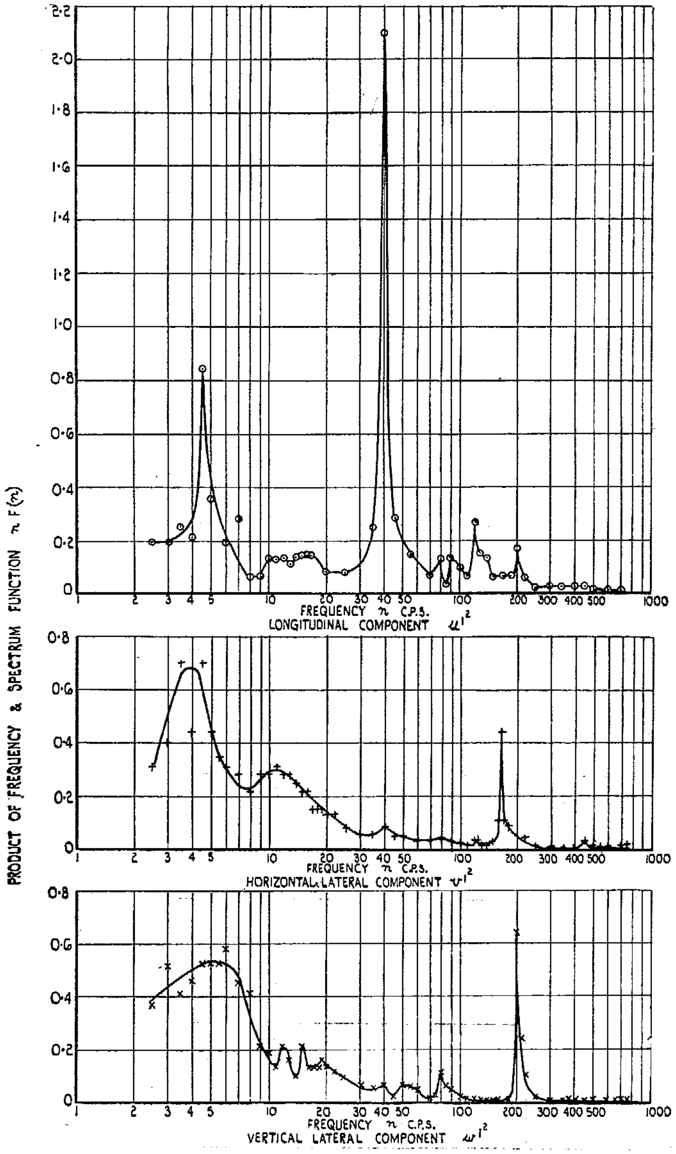

FIG. 7. $U_0 = 180$ ft/sec. Fan speed $= 400$ r.p.m.

FIGS. 6 and 7. Frequency spectra of the three turbulence components on the centre-line of the tunnel.

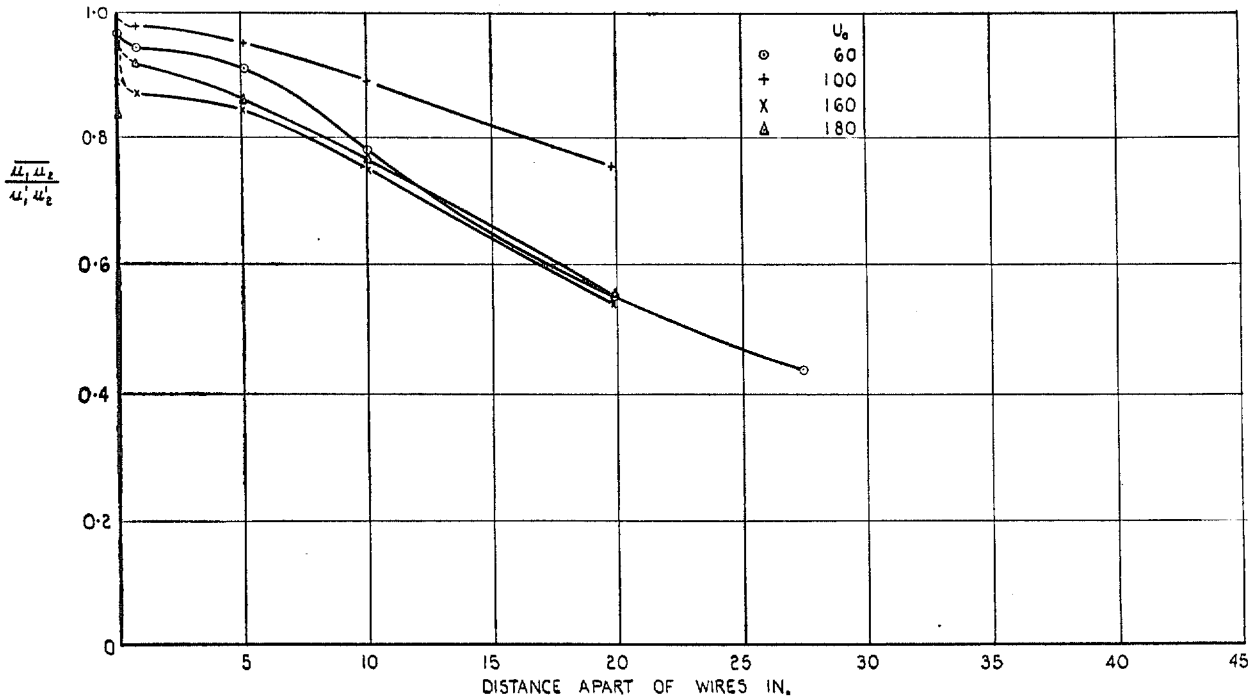

FIG. 8. $u'$ correlation across width of working-section.

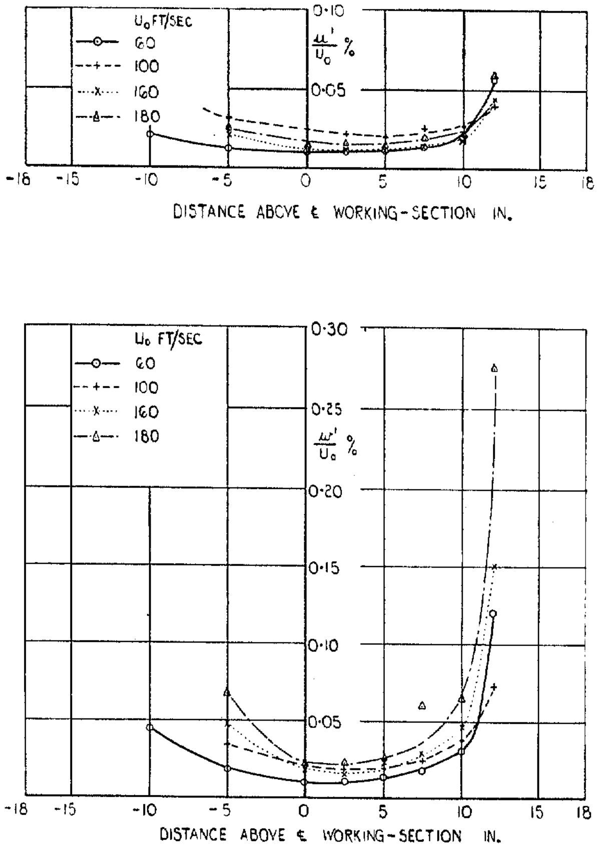

FIG. 9. Variation of turbulence intensity with distance from centre-line of working-section.

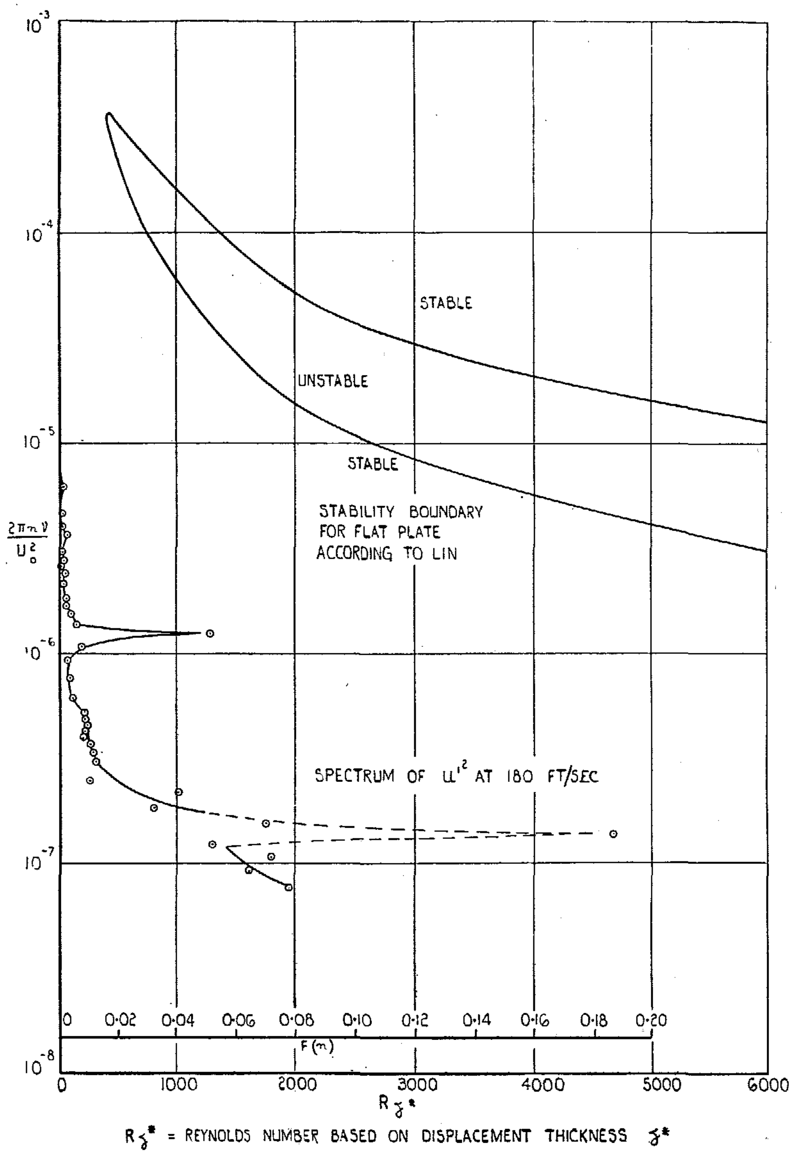

FIG. 10. Comparison of energy spectrum of longitudinal component of turbulence with stability boundary for flow along a flat plate.

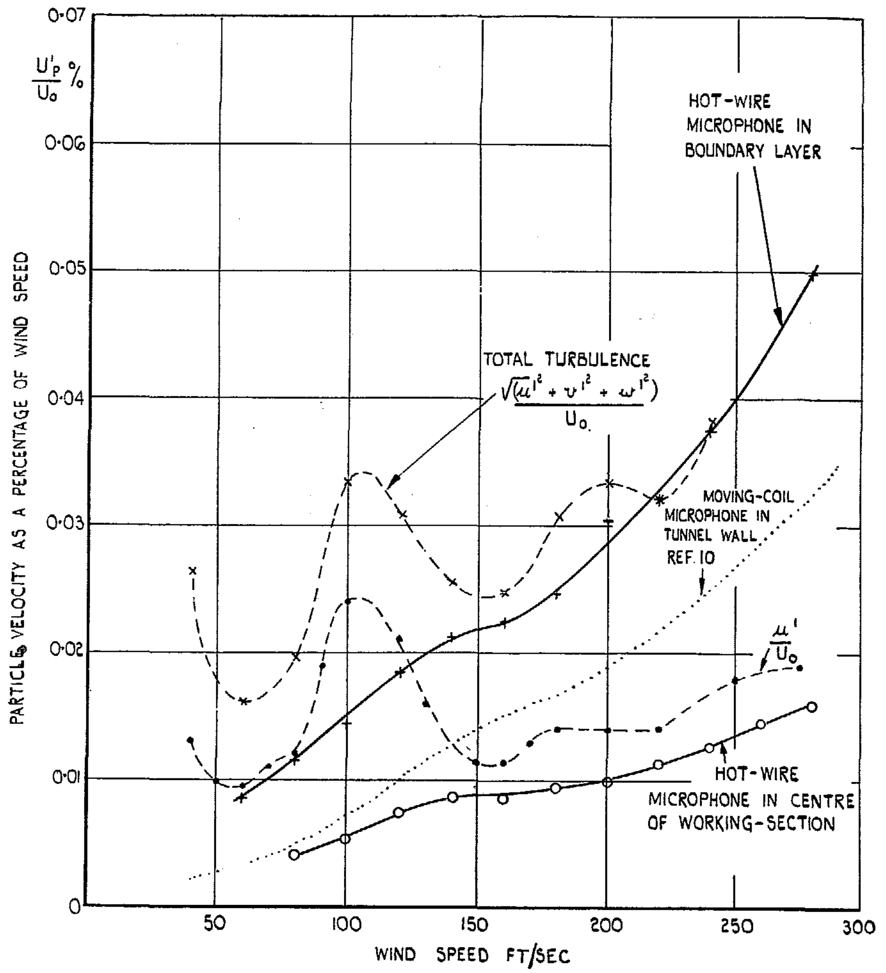

FIG. 11. Apparent turbulence from noise measurements.

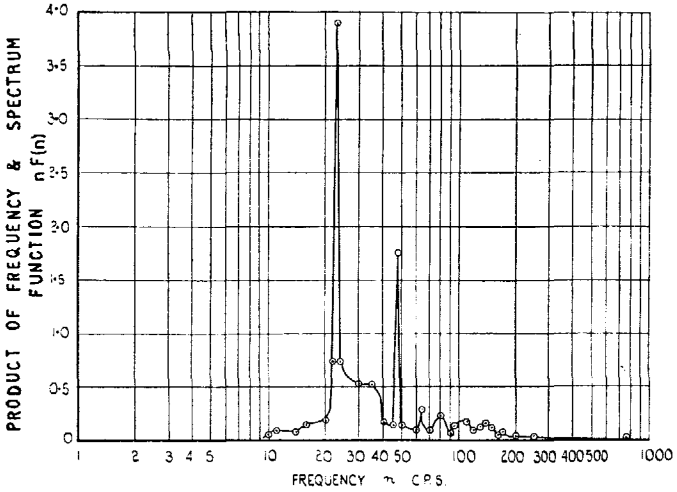

FIG. 12. $U_0 = 100$ ft/sec. Fan speed = 230 r.p.m.

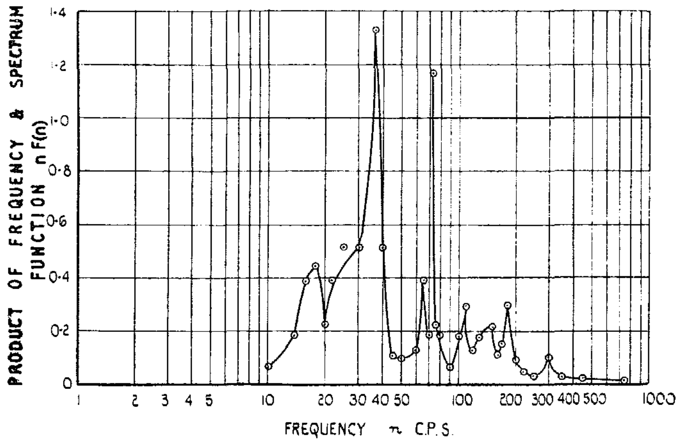

FIG. 13. $U_0 = 160$ ft/sec. Fan speed = 360 r.p.m.

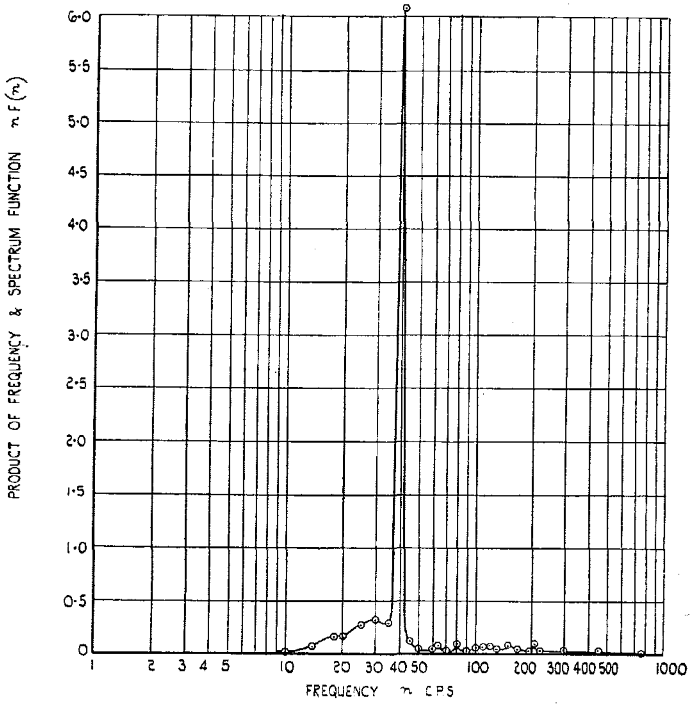

FIG. 14. $U_0 = 180$ ft/sec. Fan speed = 400 r.p.m.

FIGS. 12, 13 and 14. Frequency spectra of noise in centre of working-section.

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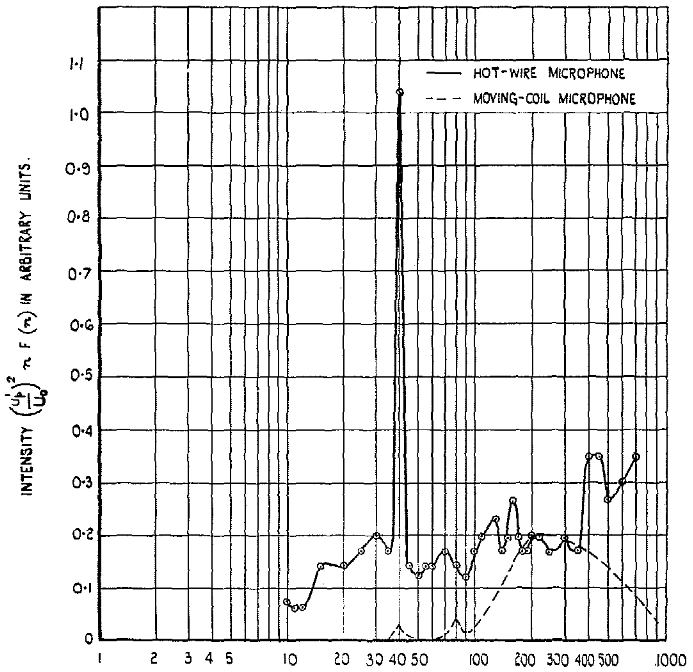

FIG. 15. Frequency spectrum of 'noise' in boundary layer on tunnel wall. $U_0 = 180$ ft/sec. Fan speed $= 400$ r.p.m.

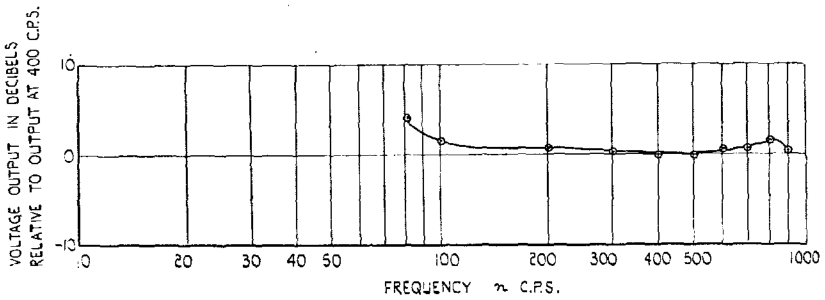

FIG 17. Frequency calibration of hot-wire microphone.

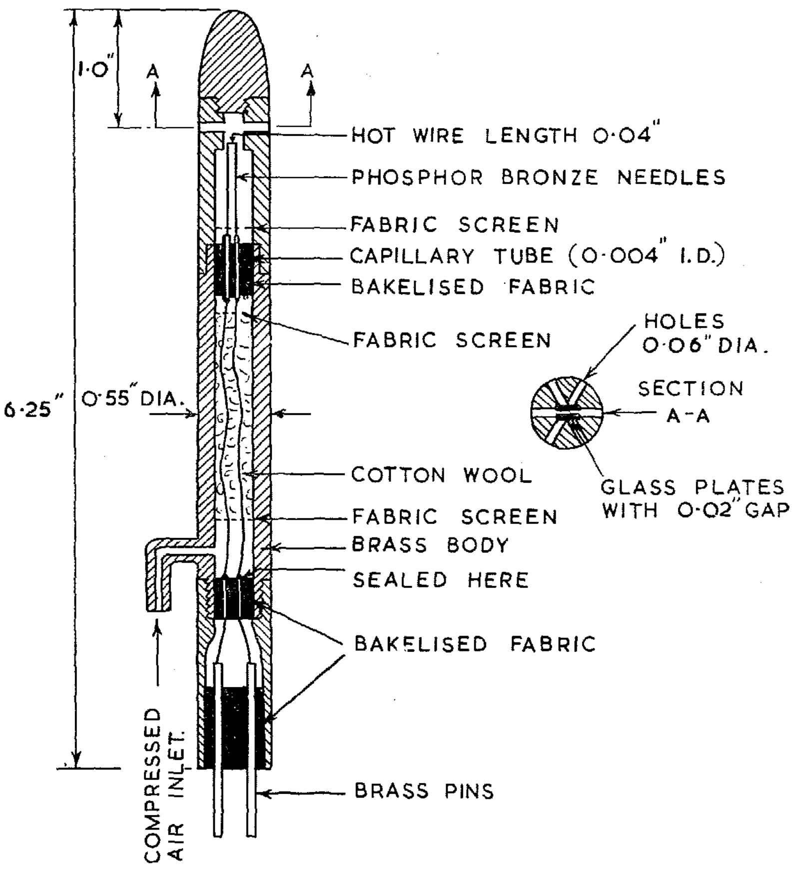

FIG. 16. Hot-wire mircophone.

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