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Measurements of the Free Stream Turbulence in the R.A.E. Bedford 13ft. x9ft. Wind Tunnel

By

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SUMMARY

The r.m.s. fluctuation level in the longitudinal direction was found to be 0·02% at 50 ft/sec, rising to 0·04% at 200 ft/sec; in the vertical and horizontal (transverse) directions, 0·02% rising to 0·10% for the same speed range. These results are given together with a short description of the tunnel and of the technique and apparatus used.

Introduction

R.m.s. intensity measurements were made for all three component fluctuations, together with frequency spectra from 16 c/s to about 1 000 c/s. Tape recordings of the wire signals were used later to produce spectra extending down to 2 c/s to test for the presence of low-frequency peaks, the existence of which could be important in oscillatory derivative work.

Some intensity and spectral measurements were made off the centre line of the tunnel both in vertical and horizontal displacement.

Apparatus

The wires were of 0·00015 in. diameter tungsten and approximately 0·02 in. long. Single-wire probes were used to measure the longitudinal component of turbulence, and cross-wire probes were used for the vertical and horizontal transverse components. All wires were calibrated in mean speed, and the cross-wire probes calibrated in yaw, in the potential core of a 2 in. diameter jet.

The wires were mounted in the tunnel at any one of three heights above the floor on a strut of aerofoil section built around a 5 in. x $2\frac{1}{2}$ in. 'U' channel fitted vertically between the roof and floor of the tunnel. The hot-wire elements were approximately 6 in. (i.e., one half chord) upstream of the strut.

Constant-current/

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Constant-current hot-wire equipment was used throughout the experiment. A simplified diagram of the circuitry following the hot-wire is shown in Fig.1. The wire signal is fed to a transformer and a D.C. amplifier in parallel. The transformer and its associated high-pass filter $C_1 - R_1$ act as an amplifier with a gain of 20 and extremely low noise for signals between 400 c/s and 20 kc/s, while the D.C. amplifier and its low pass filter $R_2 - C_2$ have a gain of 20 for signals below 400 c/s: the transformer and amplifier signals are added in a Tektronix 122 amplifier to give a characteristic which is flat from D.C. to 20 kc/s. The Tektronix 122 amplifier incorporated both high- and low-pass filters. For the purpose of this experiment these filters were set to provide a bandwidth of 0·2 c/s to 1 000 c/s. It was necessary to employ the relatively low high-frequency cut-off point so as to filter out wire vibration at frequencies of the order of 4 kc/s or so. The Tektronix 122 amplifier output was fed to a resistance-capacitance compensating circuit. Two hot-wire channels, each as described above, were used with the cross-wire probes, the difference of the output signals giving a signal proportional to the lateral component of turbulence. The compensated signal was then fed to the spectrometer where appropriate, squared in an electronic multiplier and then electronically integrated so as to eliminate the necessity of averaging fluctuating galvanometer readings by eye.

The spectrometer mentioned above was a Bruel and Kjaer 2111 analyser with a frequency range of 16 c/s to 31·5 Kc/s covered in $\frac{1}{3}$ -octave steps. Details of the compensator, difference unit, multiplier and integrator are given in Ref.1.

The overall frequency response of each hot-wire channel used was 0·3 c/s to 1 000 c/s; the frequency response of the multiplier was 2 c/s to 100 Kc/s and so the equipment as a whole had a bandwidth of 2 c/s to 1000 c/s. Noise in the equipment was found to be equivalent to about 0·003% turbulence. This figure was the result of cutting off at 1 000 c/s, as most of this noise had its source in the Tektronix amplifier. Had the upper limit of the amplifier been set to 10 Kc/s, the equivalent turbulence would have been 0·006%; and 0·009% for a setting of 40 Kc/s. Spectrum measurements showed, however, that most of the turbulent energy was contained in the lower frequencies and so the high frequency cut-off at 1 000 c/s had negligible effect on the results.

The spectra are plotted in the form $f\overline{[u(f)]^2}/\overline{u^2} \equiv Ff$ against log f, so that the area under the curve between two frequencies is proportional to the energy contained in that frequency interval, as

$$\int Fdf = \int (Ff)d(\log f)$$

where $F\delta f$ is the energy in the band f, $f + \delta f$.

Turbulence signals were recorded on an Ampex 306-2 tape recorder at 6 in./sec, and later cut into 75 ft loops and played back at 62·5 in./sec. This signal was then analysed in a Bruel and Kjaer 3330 analyser which has a lower frequency limit of 20 c/s, and so it was possible to investigate the distribution of energy below the range of the B. and K. 2111 analyser.

The Tunnel

A diagram of the R.A.E. 13ft × 9 ft tunnel is given in Fig.2. The contraction ratio is 16 : 1 and the power factor is approximately 0·22.

Vortex generators are fitted in the first diffuser, which has rather thick entry boundary layers and a rather large area ratio, to prevent separation.

It was at first feared that particles of dust from the tunnel would break the wires or at least affect their calibrations during runs at the higher speeds, say at 200 ft/sec or over. At no stage did foreign matter break the wires, but it was found that after about ten hours' running the wires collected a very fine form of tarry deposit. It was thought that this substance originated from previous smoke experiments performed in the tunnel. Although this was not serious, it meant that the mean speed calibration of the wires varied with time. Efforts to remove this deposit with organic solvents were only partly successful but the difficulty was largely overcome by making calibration checks at two or three tunnel speeds during a turbulence-measurement run, and comparing these points with the original calibration. If necessary the calibration was modified, and the new figures used to calculate the turbulence values.

Results

The intensity measurements and spectra taken on the tunnel centre line were compared with those taken 2 ft above the central position and with those measurements made with the strut moved 3 ft to one side. No significant difference was found between the three sets of measurements, and so only those made on the centre line are given here.

The variation of the longitudinal r.m.s. intensity with tunnel velocity is shown in Fig.3. The v-component (vertical) and w-component (horizontal) curves are given in Figs.4 and 5 respectively. The two curves in Fig.3 show only relatively small discrepancies between those measurements made with a cross-wire probe and those made with the single wire probe. The cross-wire u-component turbulence values shown here are calculated from a v-component run, the results of which are shown in Fig.4 and so provide a useful check on both sets of results.

As might be expected from the 16 : 1 contraction ratio, the u-component fluctuation is lower than the v- and w-fluctuations for all speeds. Comparison of Figs.4 and 5 will show that the w-component is a little higher than the v-component for all speeds. This was also the case for other stations in the tunnel. Bearing in mind the expected accuracy of the experiment, the author considers this difference just significant.

Figs.6, 7 and 8 show spectra for the u-, v- and w-component fluctuations respectively at a tunnel speed of 200 f.p.s. The curves have not been drawn through points that are unconnected with the tunnel turbulence; viz., hum-pickup, strut vibration etc., although all points are shown. The crosses on these curves at the low frequency ends are the points supplied from analyses of the tape recordings. Peaks at 40 c/s and 200 c/s are evident on the v- and w-spectra; the former is certainly due to strut vibration; examination of tape recordings at different tunnel speeds all show peaks at 40 c/s. Rough calculations were made to determine the frequency of vibration in the fundamental mode of the strut, (a) assuming it to be clamped at both ends, and (b) assuming it to be freely pinned at both ends. These gave 72 c/s and 20 c/s respectively. As in practice the strut mounting must lie between these two extremes, a vibration frequency of 40 c/s is quite plausible on this basis. The peaks at 200 c/s in the v- and w-spectra are most probably due to vortex shedding behind the strut aerofoil which had a chord of one foot.

Disregarding/

Disregarding, then, these spurious effects and also the peaks at 50 c/s which were due to hum pickup, the following points are worthy of note:-

(a) a small, but noticeable contribution in the u-spectrum at the fan-blade frequency, i.e., 20 c/s. This is absent from the v- and w-spectra;

(b) distinctly more energy in the medium frequency band is present in the u-spectrum than in the other two; in fact, it contains approximately three times as much energy, expressed as a fraction of the mean square value in the interval 100 c/s to 500 c/s; and

(c) the intensity fall-off at the low-frequency end of each of the v- and w-spectra is more rapid than in the case of the u-spectrum. To a certain extent this may be due to contributions from low-frequency surgings in tunnel speed.

Examination of tape analyses at intermediate tunnel speeds show only one other interesting point, the presence of a noticeable peak in the u-spectrum at 2·8 c/s at a tunnel speed of 150 ft/sec. The height of this peak is 3 dB above the rest of the curve in the neighbourhood of 3 c/s, that is, a factor of two on the vertical scale in Figs.6-8.

Conclusion

The v- and w-component intensities are about what would be expected if the r.m.s. turbulence levels ahead of the screens were approximately 5% - a plausible value. The theoretical attenuation factor for each of the five tunnel screens is 0·54, and that of the contraction is 0·2. At the lower tunnel speeds natural decay of the turbulence is expected to be appreciable. The u-component intensity, according to the same theories, would be negligibly small; some redistribution of energy clearly takes place, and low-frequency surgings in the tunnel speed must also contribute to the measured intensity.

Acknowledgements

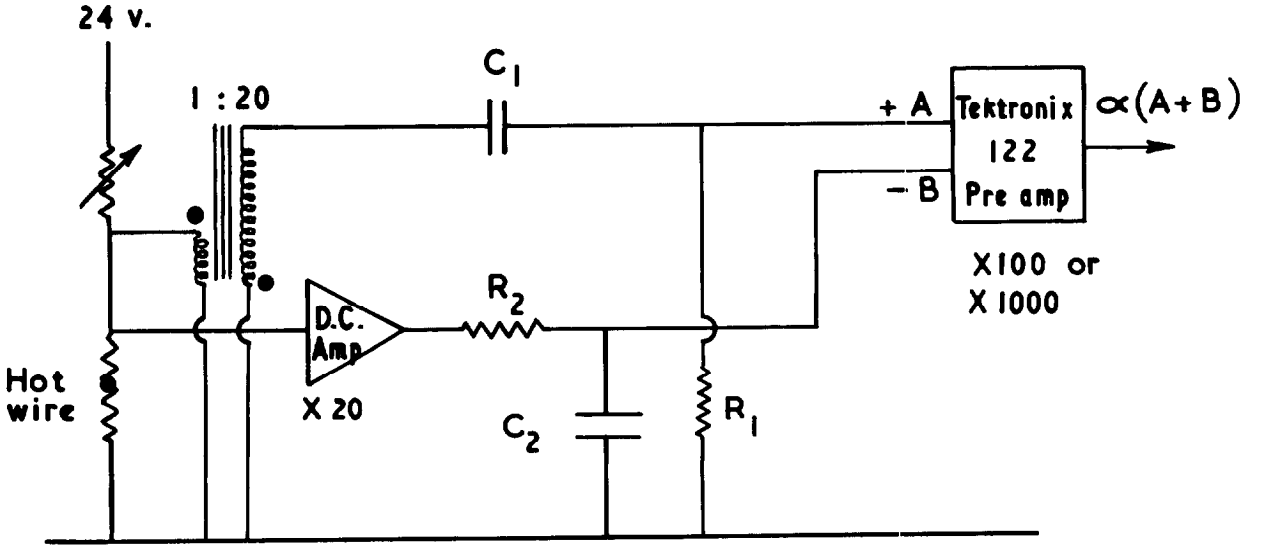
The author wishes to acknowledge the assistance of Mr. P. Bradshaw in planning the experiment, and the help given by Messrs. K. W. Stuart and G. K. Knight with the tunnel work. He would also like to thank Mr. T. B. Owen of R.A.E. Farnborough for the loan of the tape recording equipment and for processing the tapes.

Reference

No.	Authors	Title, etc.
1	P. Bradshaw and R. F. Johnson	National Physical Laboratory Notes on Applied Science, No.33. Turbulence measurements with hot-wire anemometers.

DR

FIG. 1



$$C_1 R_1 = C_2 R_2 = \frac{1}{2\pi f_o} \quad . \quad f_o = 400 \text{ c/s}$$

Constant-current hot-wire channel

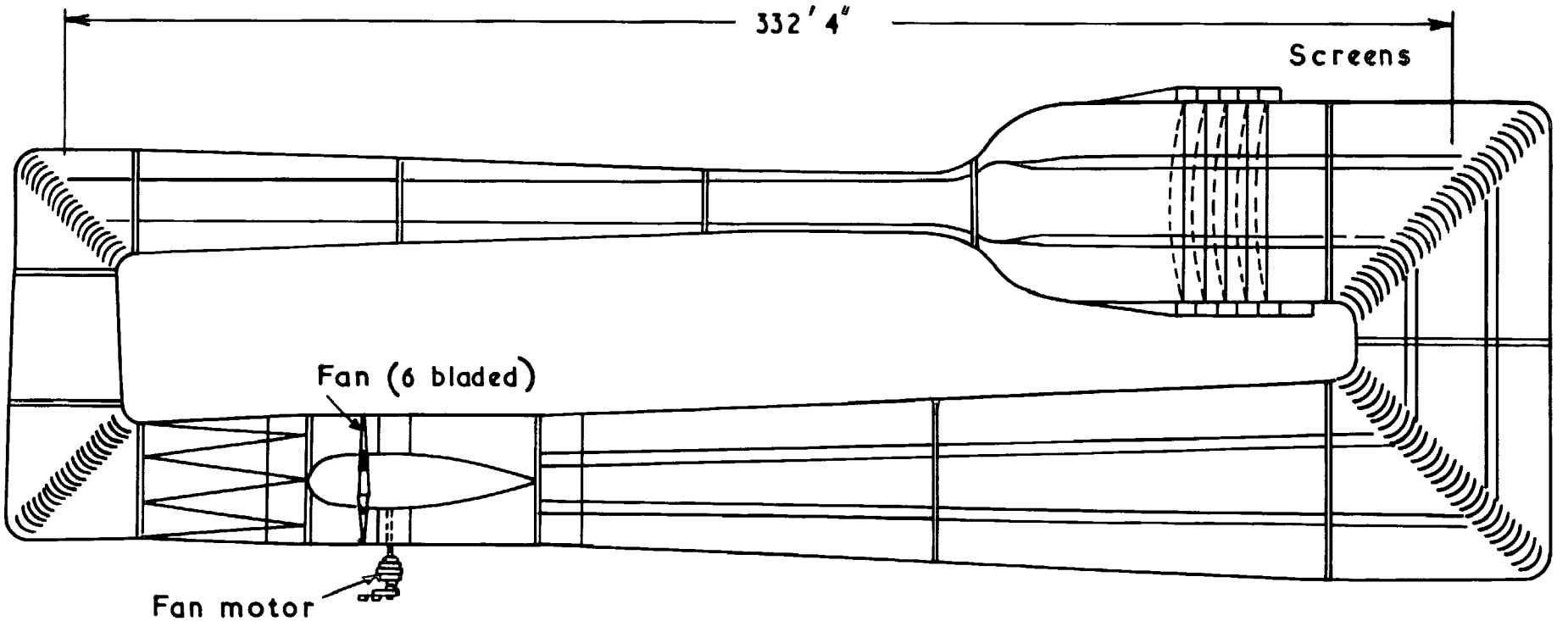


FIG. 2

RAE 13 ft x 9 ft tunnel (1954)

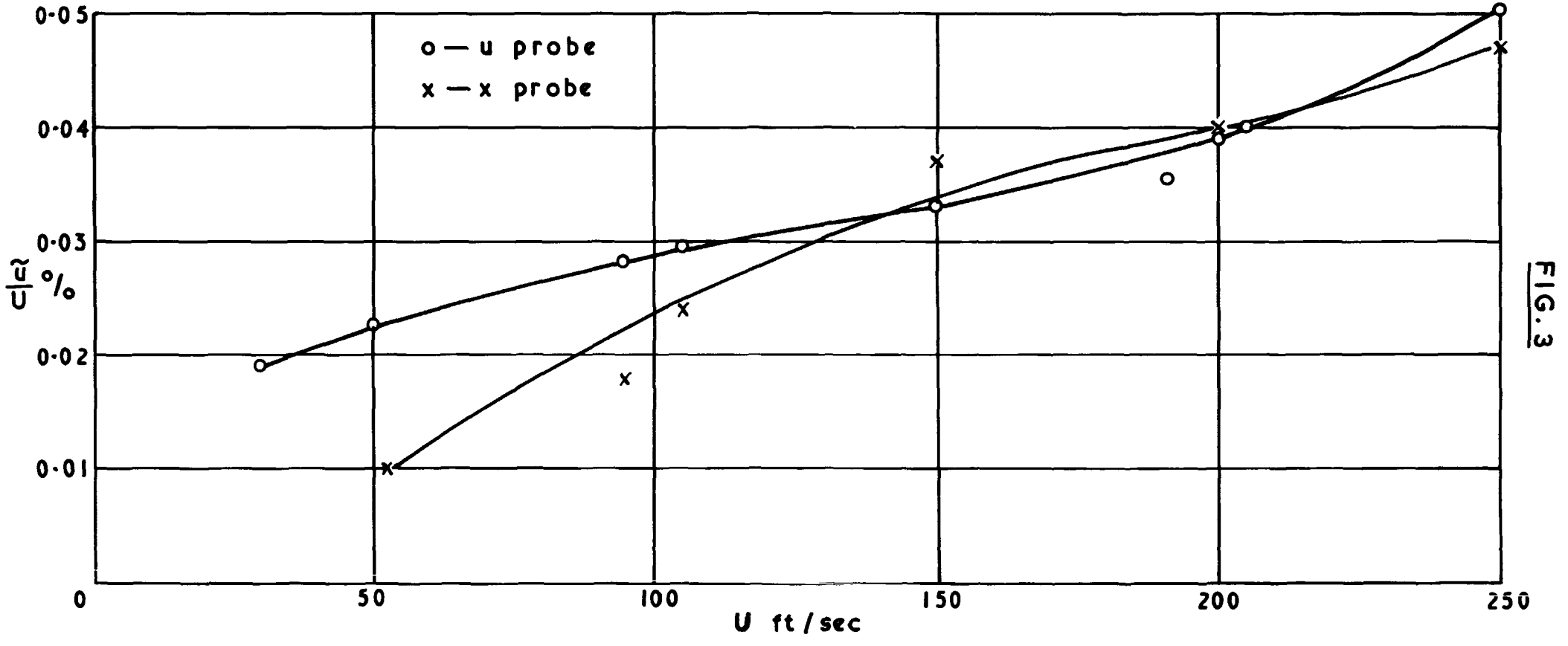


FIG. 3

u-component r.m.s. intensity

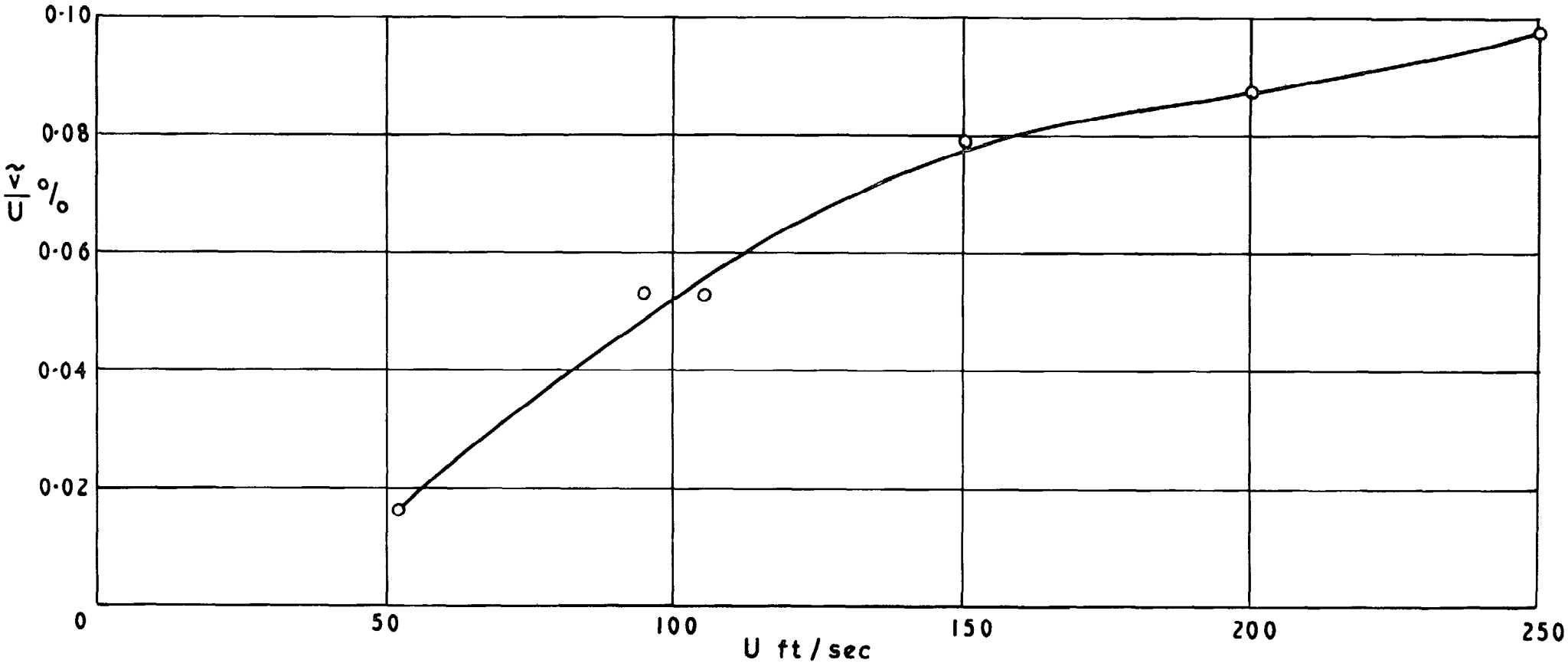


FIG. 4

v – component r.m.s. intensity

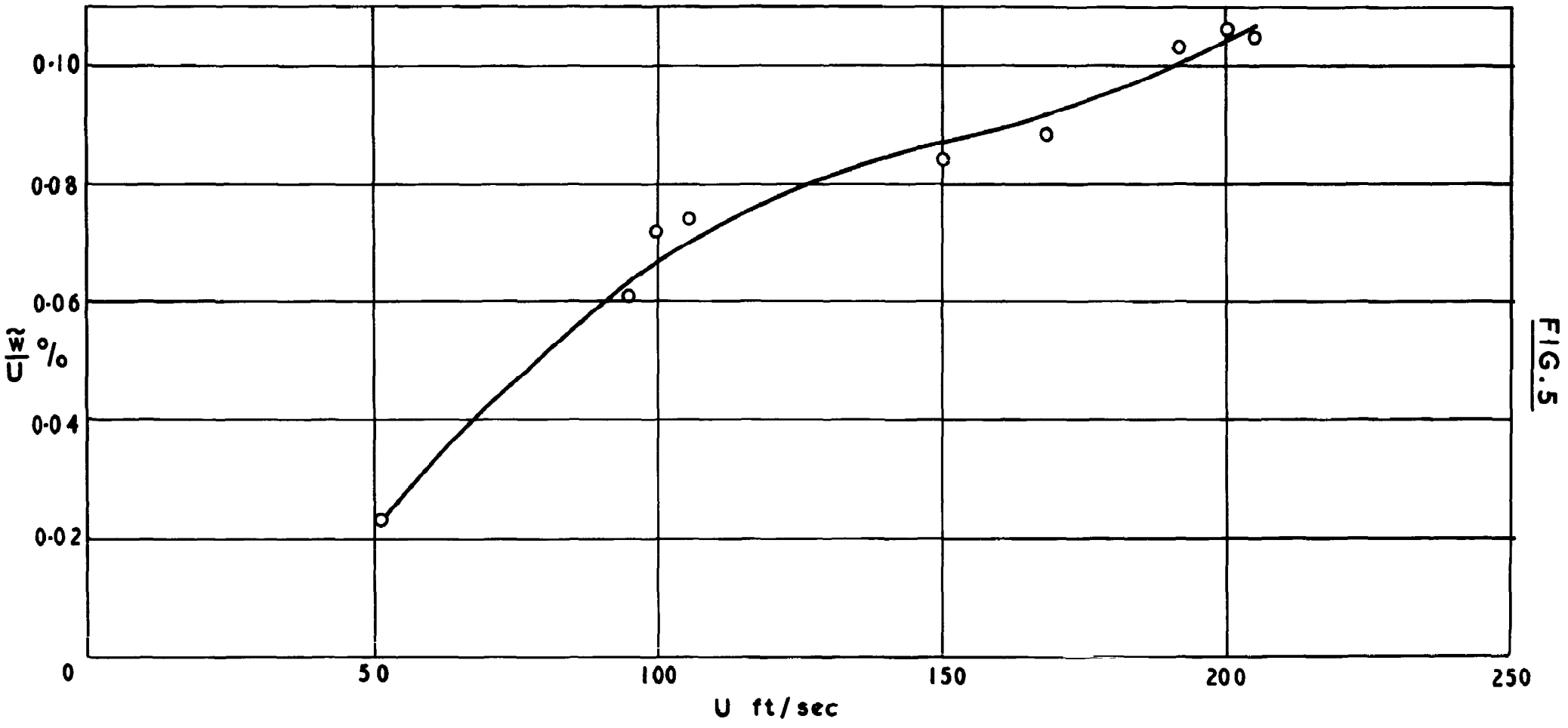


FIG. 5

w-component r.m.s. intensity

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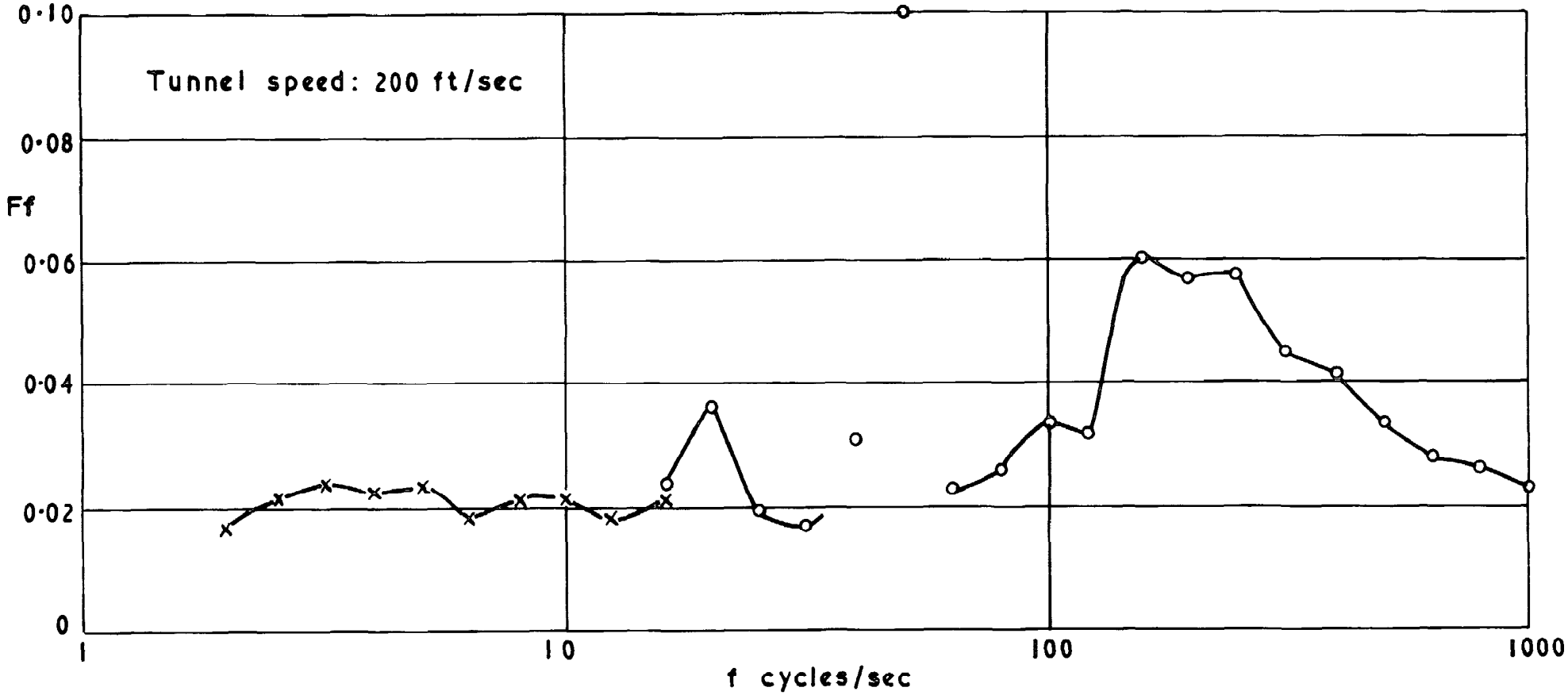

FIG. 6

u-component spectrum

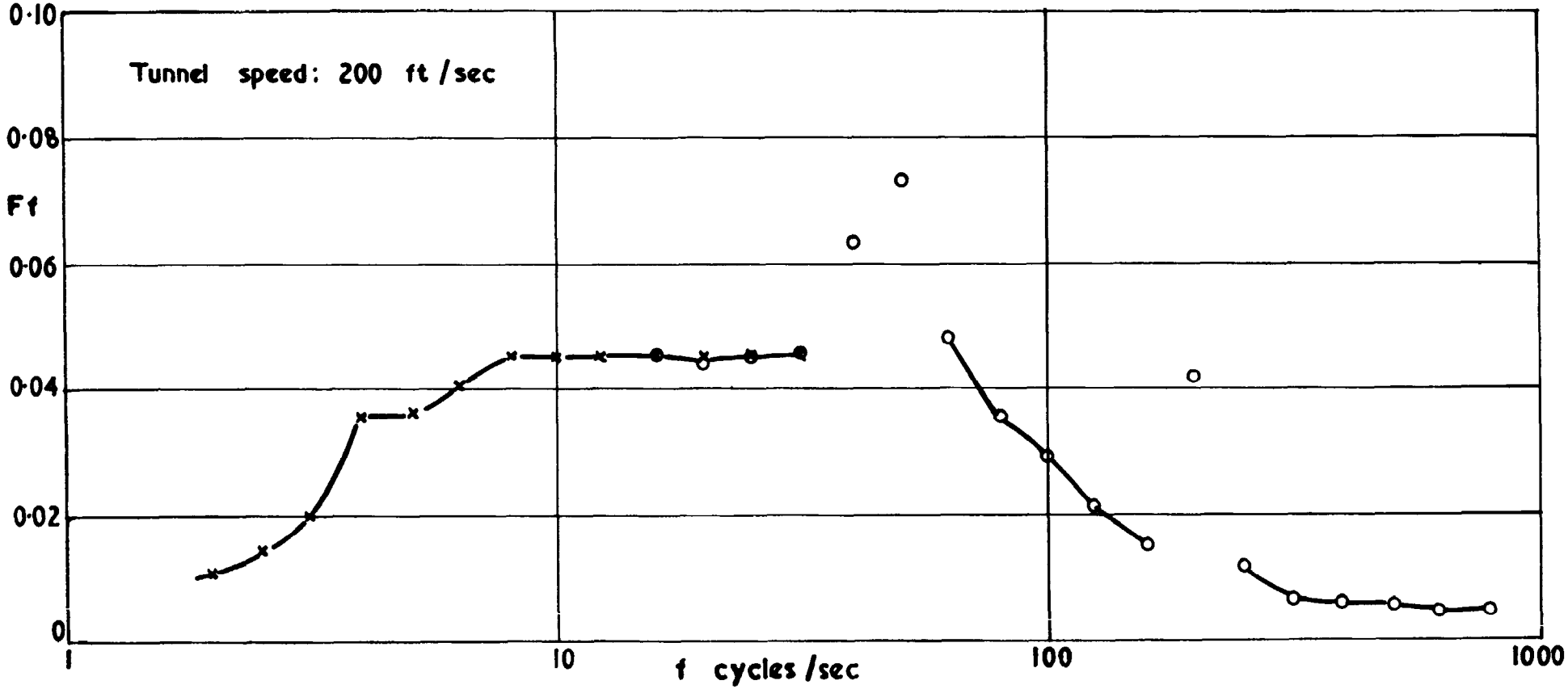

FIG.7.

V – component spectrum

D 548/Wt.51 K.4 3/64 XL & GL

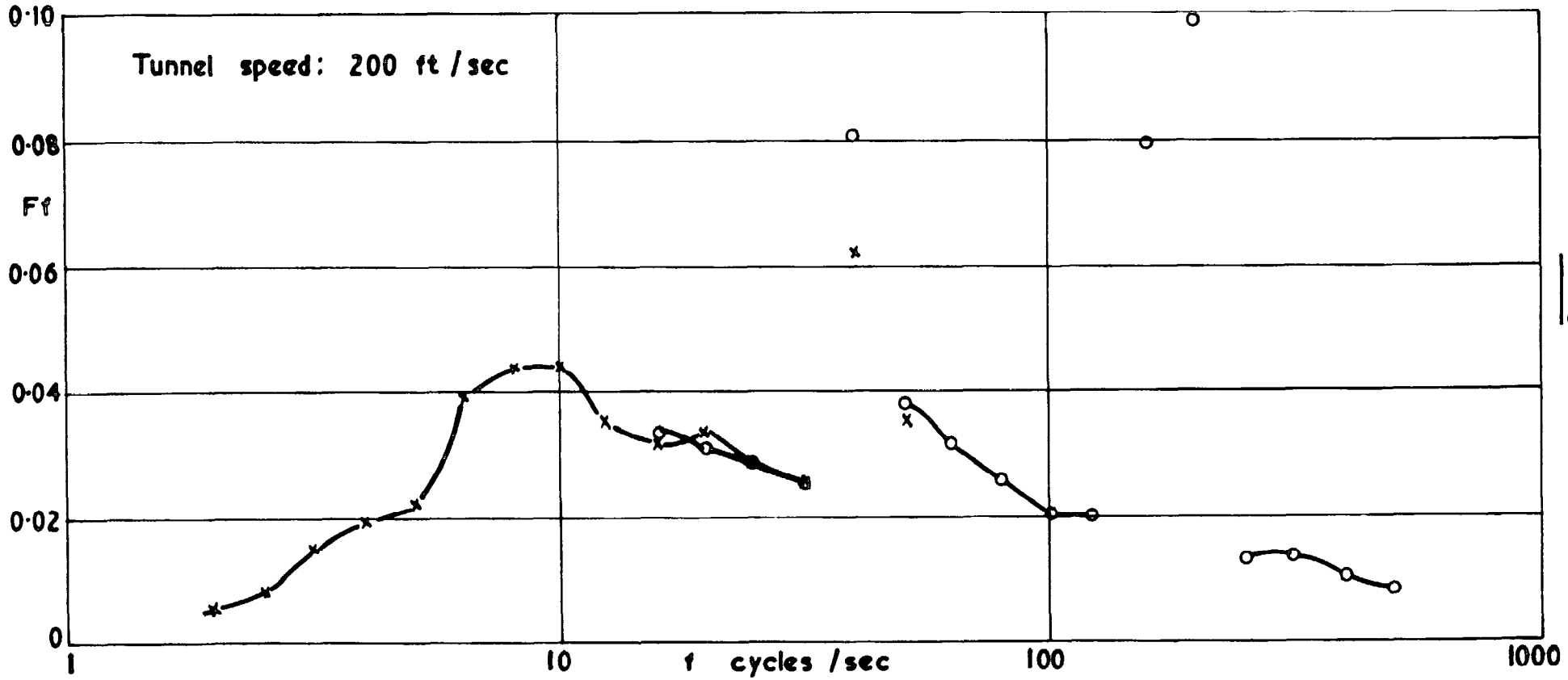

FIG. 8

w — component spectrum

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