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Summary. A recent suggestion in an earlier report by the authors that a relationship exists between the auto-correlation of the fluctuating pressure near to a jet and the space-correlation along lines parallel to the boundary of the jet is examined and confirmed. The ideas involved are used to account for the fact that the longitudinal space-correlation curve is independent of jet speed, and this is illustrated by a simple calculation and an experiment. The explanation is then expanded to demonstrate the possibility of similarity between model and full-size experiments, and this possibility is confirmed by a comparison of the present work with similar full-scale work carried out at the Royal Aircraft Establishment.

1. *Introduction.* Recent work at Southampton University on the fluctuating pressures close to a model jet[1] suggested that there is a simple relationship between the space-correlation along lines parallel to the boundary of the jet and the auto-correlation of the pressure at the reference point. This possibility has been examined in a short series of experiments at the Royal Aircraft Establishment, Farnborough, in which measurements were carried out using one of the engines of a *Comet* aircraft.[2] If allowance is made for the fact that in these experiments some of the low-frequency energy of the pressure fluctuations was missed because of the limited low-frequency response of the apparatus, then the conclusion to be drawn is that the suggestion is confirmed. In order to be sure of this conclusion, it was decided to carry out identical measurements on a model jet at Southampton University, for by decreasing the size of the jet the spectrum of the pressure fluctuations is moved to higher frequencies and the difficulty of the low-frequency response of the apparatus overcome. Further, it was felt that such work might also reveal useful information about similarity between 'model' and full-scale tests. The main purpose of the present paper is to report the results of these, and other, experiments and to compare them with the results of the measurements made at the R.A.E. Before presenting these results, a brief re-statement of the physical ideas involved will be given.

If, relative to a given reference point close to a jet, space-correlation measurements are made of the pressure fluctuations along two lines, one parallel to and one perpendicular to the boundary of the jet, the resulting curves are quite different (Fig. 1). For the longitudinal traverse, *i.e.*, the traverse parallel to the boundary of the jet, the space-correlation curve falls rapidly and oscillates slightly before dying out; for the lateral traverse the curve falls much more slowly and dies away without oscillating. The difference is such as to suggest that the frequency spectra of the pressure fluctuations were quite different for the two curves, but since the conditions under which the measurements were taken were the same, this cannot be so. When it is remembered that the longitudinal traverse is made in a direction roughly parallel to the direction of the mean velocity in the jet and the lateral traverse in a direction perpendicular to it, it seems possible that the difference between the curves is due to something like the Doppler effect. It might be supposed that this idea could be checked by experiments at different jet speeds, but for reasons which will be discussed later (Section 3 below) such experiments apparently fail to yield useful results, for the longitudinal correlation curve is found to be almost independent of jet speed over quite a large range of velocities. Further consideration of the problem, however, leads to experiments of much greater interest.

A turbulent volume of fluid such as a jet may be divided into eddies, an eddy being defined as a volume around a given reference point throughout which the velocity is strongly correlated with that at the centre. The pressure fluctuations recorded by a microphone placed near to a jet are associated with the turbulent velocities within the jet, and therefore with the eddies, and may be considered to be composed of two components, a hydrodynamic or Bernoulli-type component (sometimes referred to as 'pseudo-sound'), and an elastic or acoustic component. Very near to the jet the hydrodynamic component is very large and much greater than the acoustic component, but as the distance between the jet and the microphone is increased the hydrodynamic component falls off rapidly. Thus it seems likely that when a microphone is placed close to the boundary of a jet the major part of the signal is due to the hydrodynamic pressure fluctuations associated with a relatively small number of eddies in the near vicinity of the microphone. Now the eddies in the jet are known to move downstream and, further, if the assumption is made that the fluctuations within the eddies are slow when compared with their speed of convection, they will retain their 'identity' for some distance. This being so, then if two microphones are placed on a line parallel to the boundary of a jet a distance ξ apart and if the mean convection velocity of the eddies is u, a group of eddies opposite the upstream microphone at time t will be opposite the downstream microphone at a time $(t + \xi/u)$. If changes within the eddies are very slow then the signal from the downstream microphone will be almost identical to that from the upstream microphone except for a time-shift of ξ/u. Thus the variation of separation distance ξ in the longitudinal space-correlation measurement is equivalent to a variation of the delay time ξ/u between the two signals and it should be possible to deduce the space-correlation curve from a measurement of the auto-correlation of the signal from the reference microphone.

2. *The Relationship between the Space-Correlation and Auto-Correlation Curves.* (*a*) *Details of the Measurements; Calculations and Results.* The experiments to be described in this Section were carried out on a 2-in. diameter cold air-jet in the Low-Speed Aerodynamics Laboratory at the University of Southampton. The two probe microphones used in the measurements are fitted with standard Bruel and Kjaer condenser microphone capsules which connect directly to their cathode followers. To reduce the effects of microphony, the leads from the cathode followers were taken away into a separate room and there connected to the microphone amplifiers and the correlator. For spectrum measurements the output of the microphone amplifier was fed to a Bruel and Kjaer Spectrometer and the spectra recorded with its associated Level Recorder. Full details of the experimental rig can be found in Ref. 1.

Details of the reference positions and traverse lines are given in Fig. 2, from which it will be seen that four traverses were made along two lines roughly parallel to the jet boundary. These positions are scale reproductions of the positions chosen for the work of Ref. 2. The jet speed at exit was 710 ft/sec for all four traverses, as it was in the full-size experiments.

The results of the correlation measurements are given in Fig. 3 where the space-correlation coefficient $\rho(\xi)$ is plotted as a function of the distance ξ between the microphones. All four traverses gave systematic curves with little scatter of the results.

Since at the time that these experiments were done the time-delay unit for the correlator was not yet complete, it was necessary to calculate the auto-correlation coefficient from the power spectrum of the microphone signal. Figs. 4a to 4d give the frequency analysis of the signal from a microphone at each of the four reference positions. From these curves, which give the level of the output from the 1/3 octave filters of the spectrometer in dB relative to some arbitrary datum, an approximation to the normalised power spectral density may be calculated in the following way:

If n_i is the level (in dB, relative to the arbitrary datum) of the output from the ith filter, the central frequency of which is f_i, then the overall level N is given by

$$\text{antilog}\left(\frac{N}{10}\right) = \sum \text{antilog}\left(\frac{n_i}{10}\right).$$

Thus the normalised filter level is given by

$$\nu_i = n_i - N$$

and the arbitrary level becomes unity.

The filter level may be reduced to normalised spectrum level (in dB per cycle per second) by the approximate method of subtracting $10 \log (\Delta f)_i$, where $(\Delta f)_i$ is the bandwidth of the ith filter. The result is

$$\text{Normalised spectrum level} = 10 \log F(f_i) = n_i - N - 10 \log (\Delta f)_i .$$

The normalised spectral density is now

$$F(f_i) = 2\pi\, F(\omega_i) = \text{antilog}\,[n_i - N - 10 \log (\Delta f_i)] .$$

Having $F(\omega)$, the auto-correlation coefficient may be calculated from the familiar transform relationship

$$\rho(\tau) = \int_0^\infty F(\omega) \cos \omega\tau \, d\omega ,$$

the integral being evaluated either analytically after assuming a suitable approximate form for $F(\omega)$, or (as in this paper) numerically.

The results of calculations carried out in this way on the spectra measured at positions 1, 2 and 4 are given in Fig. 5.

As in Refs. 1 and 2, the assumption was now made that the average speed of the eddies in the jet was half the maximum mean velocity. The time-delay in the auto-correlation may now be scaled to an equivalent separation,

$$\xi = u\tau = 355 \times 12\tau = 4260\tau \text{ in.}$$

Fig. 6 shows comparisons of the auto-correlation curves scaled in this way and the measured space-correlation curves. It will be seen that, particularly for the traverse in the upstream direction, the agreement for positions 1 and 2 is good. For position 4 the agreement is poor; since it may be expected that the agreement will also be poor for position 3 (which is on the same traverse line as 4), calculations were not carried out for that point.

(*b*) *Discussion of the Results.* The curves of Fig. 6 confirm the tentative conclusions of Ref. 2, namely, that for longitudinal traverses close to the boundary of a jet, the space-correlation may be approximated to by scaling the auto-correlation curve. Further, the curves for position 2 support the statement made in Ref. 2 that the poor agreement in that paper for position 2 was due to the fact that a significant proportion of the energy in the spectrum was below 40 c.p.s., the lowest frequency at which measurements could be made.

It will have been noticed from Fig. 6 that the agreement between the measured and calculated curves becomes poor at large separations. This is probably due to a combination of two effects:

(i) When calculated numerically the auto-correlation coefficient becomes inaccurate at large values of τ.

(ii) The eddies in the jet are changing as they move downstream and these changes become more serious as the separation distance is increased. Thus for large separations the assumption on which the relationship between the space-correlation and auto-correlation curves depends, becomes incorrect.

3. *The Effect of Jet Speed on the Longitudinal Space-Correlation Curve.* It has been found experimentally[1, 3] that the space-correlation curve for longitudinal traverses is almost independent of jet speed over quite large ranges of speed. This is illustrated by Fig. 7 (taken from Ref. 1) which shows the results of two longitudinal traverses taken along a line 0·5 diameter from the boundary of a 2-in. diameter jet relative to a reference point 5 diameters from the exit, one for a jet speed of 343 ft/sec and the other for a speed of 888 ft/sec. The differences are quite small. If the results of the previous Section are accepted, it is quite easy to show that this independence of speed is to be expected.

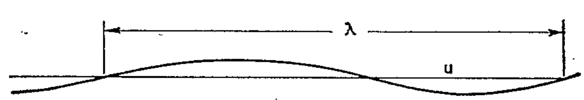
It will be recalled that the auto-correlation may be expressed as the Fourier cosine transform of the power spectral density in frequency. In a similar way, the space-correlation may be interpreted as the transform of a power spectrum in wave-number. Thus:

$$\rho(\xi) = \int_0^\infty G(k) \cos k\xi \, dk \, , \tag{3.1}$$

where $k = 2\pi/\lambda$, the wave-number.

When proposing that a relationship between the space-correlation and auto-correlation curves exists it is assumed that the eddies in the turbulence are unchanged as they are convected downstream. This is equivalent to assuming that the pressure field around the jet is fixed in (relative) space and convected downstream with a certain velocity, say u. A component of this pressure field of wavelength λ will produce at a point an apparent frequency of:

$$f = \frac{u}{\lambda} \cdot$$



Thus

$$\frac{f}{u} = \frac{1}{\lambda} \text{ or } \frac{2\pi f}{u} = \frac{\omega}{u} = \frac{2\pi}{\lambda} = k \, .$$

With this assumption, the integral of equation (3.1) may be rewritten as

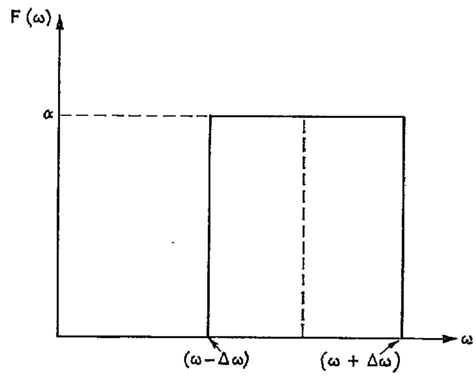
$$\rho(\xi) = \int_0^\infty G\left(\frac{\omega}{u}\right) \cos\left(\frac{\omega}{u}\right) \xi d\left(\frac{\omega}{u}\right). \tag{3.2}$$

Now, for a given jet, the ratio (ω/u) is proportional to $(\omega D/U)$, the Strouhal number, and it is known that the Strouhal number varies only slowly with Reynolds number (*see*, for instance, the discussion in Ref. 4, p.580). Thus the space-correlation is seen to be the integral of a function which will vary only slowly with Reynolds number and so, for a given jet, it will be almost independent of jet speed.

A rough calculation will illustrate further the principles involved:

Assume that most of the energy in the pressure fluctuations at a point near a jet is contained within a band of frequencies of width $2\Delta\omega$ around a central frequency ω_0 when the exit speed is U_0. As the speed of the jet is changed so the central frequency will change, but if it is assumed that the Strouhal number remains constant, then the central frequency ω at a speed U is given by

$$\omega = \left(\frac{\omega_0}{U_0}\right) U. \tag{3.3}$$



Now, referring to the accompanying sketch, since

$$\int_0^\infty F(\omega)\, d\omega = 1.$$

We have

$$\int_{\omega-\Delta\omega}^{\omega+\Delta\omega} \alpha\, d\omega = 2\alpha\, \Delta\omega = 1.$$

Therefore

$$\alpha = \frac{1}{2\Delta\omega}. \tag{3.4}$$

The auto-correlation is given by

$$\rho(\tau) = \int_0^\infty F(\omega) \cos \omega\tau\, d\omega = \frac{1}{2}\int_{\omega-\Delta\omega}^{\omega+\Delta\omega} \frac{\cos \omega\tau\, d\omega}{\Delta\omega} = \frac{\sin \Delta\omega\tau}{\Delta\omega\tau} \cos \omega\tau \tag{3.5}$$

and on using (3.3) this becomes

$$\rho(\tau) = \frac{\sin \Delta\omega\tau}{\Delta\omega\tau} \cos\left(\frac{\omega_0}{U_0}\right) U\tau. \tag{3.6}$$

The zeros of this are at

$$\left(\frac{\omega_0}{U_0}\right) U = \frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}, \text{ etc.,}$$

or

$$\tau = \left\{\frac{\pi(2n+1)}{2} \frac{U_0}{\omega_0}\right\} \frac{1}{U}, \qquad n = 0, 1, 2, \ldots, . \tag{3.7}$$

From this it is seen that the auto-correlation curve will contract as the jet speed is increased. On the other hand, the space-correlation curve is given by

$$\rho(\xi) = \rho(a\, U_T)\,, \tag{3.8}$$

where a is a constant assumed in the previous Section to be $\frac{1}{2}$. The zeros of $\rho(\xi)$ will be at

$$\xi = aU_T = \left\{\frac{\pi(2n+1)}{2}\frac{aU_0}{\omega_0}\right\}, \qquad n = 0, 1, 2, \ldots. \tag{3.9}$$

and so the space-correlation is independent of jet speed.

The statements made above are easily checked by experiment. Fig. 8 shows the frequency analysis of the signal from the reference microphone at the point 0·5 diameter from the jet boundary and 5 diameters from the exit for the two speeds of 343 and 888 ft/sec. The shift of the spectrum to higher frequencies as the speed is increased is apparent in this Figure, but it is even more apparent in Fig. 9a which shows the normalised power spectral densities derived from the frequency analysis (*Note*, too, that the shape of power spectrum assumed in the calculation above is not an unreasonable one, particularly for the lower speed). Fig. 9b shows the calculated auto-correlation curves and illustrates the contraction of the curve with increase in speed. Finally, Fig. 10 shows the two auto-correlation curves scaled to 'equivalent' space-correlation curves assuming, as in Section 2, that the constant a in equation (3.6) is $\frac{1}{2}$. If these curves are compared with those of Fig. 7 it will be seen that the calculation reproduces the slight variation in the space-correlation curve brought about by the change in speed.

4. *Comparison of Model and Full-Size Results.* If it can be assumed that the flow pattern in a model jet is geometrically similar to that in a full-size jet, then the pressure fields around the jets may also be similar. In this case, the wavelength λ in the pressure field around a model jet of diameter D will correspond to a wavelength λ_0 in the pressure field around a jet of different diameter D_0, and will be given by

$$\lambda = \frac{\lambda_0}{D_0} D\,.$$

When the conditions for the relationship between space-correlation and auto-correlation curves hold, a wavelength λ in the pressure field around the model jet will produce, at a point, an apparent frequency of

$$f = \frac{u}{D}\frac{D_0}{\lambda_0}\,.$$

Whence

$$\frac{\omega D}{u} = \frac{2\pi\, D_0}{\lambda_0} = k_0\,.$$

Thus the integral of equation (3.1) may be written in the non-dimensional form

$$\rho\left(\frac{\xi}{D}\right) = \int_0^\infty G\left(\frac{\omega D}{u}\right) \cos\left(\frac{\omega D}{u}\right)\frac{\xi}{D}\, d\left(\frac{\omega D}{u}\right). \tag{4.1}$$

The quantities under the integral sign are now functions of the Strouhal number and since this number varies only slowly with Reynolds number, then the value of the integral should be almost independent of the jet velocity and the jet size. If the conditions are correct, it should be possible to compare directly the space-correlation curves from tests on model jets and on full-size engines.

As a first check on this the non-dimensional power spectral density $G(\omega D/U)$ can be calculated for the model and full-size results and compared to see if the curves match. This calculation will also serve as an additional check on the loss of low-frequency data in the tests on the full-size engine. The power spectrum is calculated in a similar way to that described in Section 2 and using the same notation, the result is:

Normalised non-dimensional spectrum level

$$= 10 \log G\left(\frac{\omega_i D}{U}\right) = n_i - N - 10 \log \frac{2\pi \, \Delta f_i \, D}{U} .$$

This has been calculated for both the full-size and the model experiments and the results are plotted in Figs. 11a to 11d. In general the results are good, the discrepancies being due to:

(i) spurious noise; this accounts for the peculiar peak in the full-size results at $(\omega D/U) = 3$, which is possibly due to compressor whine,

(ii) poor low-frequency accuracy due to the use of too rapid a scanning rate when taking the level recordings; this applies to the full-size results of Fig. 11c.

A direct comparison of the longitudinal space-correlation curves obtained from 'model' and 'full-scale' experiments is given in Figs. 12a to 12d.

For the positions 1 and 2 (*see* Fig. 2) the agreement is good. These positions are within approximately one diameter from the jet boundary. The two outer positions (3 and 4) do not show good agreement. These positions are about two diameters from the jet boundary and it is considered that this is too far from the jet boundary for the hypothesis of a convected field past the microphones to hold.

It is felt that the convection hypothesis can be used for longitudinal traverses within one diameter of the jet boundary and that, with this restriction, scaling from 'model' longitudinal space-correlations to 'full-scale' can be done.

5. *Conclusion.* On the basis of the experimental evidence reported here, it is considered that the pressure field within roughly one diameter of the jet boundary is a convected field and, as a consequence of this, that the space-correlation in the longitudinal direction (parallel to the jet boundary) may be scaled from the auto-correlation at that point.

The convection idea is used to explain the independence of the longitudinal space-correlation curves with jet velocity (Fig. 7). An extension is made to include the effect of jet diameter and it is found that, if the space correlation curves are plotted on a non-dimensional ξ/D basis, good agreement is obtained between model and full-scale results.

These results are of interest for structural response calculations where the structure lies parallel and close to the jet boundary.

6. *Acknowledgements.* The authors tender their thanks to Professor E. J. Richards for his encouragement and interest in the problem, and to K. R. McLachlan of the University of Southampton for several interesting discussions and for help in taking the measurements.

The full-scale data used in Section 4 form part of some work carried out by R. E. Franklin during a Vacation Consultancy at the Royal Aircraft Establishment, Farnborough, and the authors wish to express their thanks to the Ministry of Supply for permission to include these results.

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No.	Author	Title, etc.
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APPENDIX

The convection hypothesis suggested above may also be used to explain some of the results of an earlier investigation of space-correlation near to a jet reported in Ref. 3. In this work, correlation traverses were made along the boundary of a full-size jet and so the hypothesis may be expected to hold.

The first point to be noted is that the value of the separation distance at which the first zero crossing of the space-correlation curve occurs was found to increase as the reference point was moved downstream. Now it has been found that the frequency of the pressure fluctuations near a jet decreases as the distance from the exit is increased and, on referring to equation (3.9), it will be seen that if the central frequency of the spectrum (ω_0) is reduced, the value of the separation distances for the zeros of the space-correlation curve must increase.

The second question is concerned with the effect of filtering the microphone signals before measuring the correlation. For a given reference position and jet speed it was found that when the microphone signals were passed through filters with a fixed mid-frequency, the band width of the filters had little effect on the separation for zero correlation. As the band width about the central frequency was reduced the zero crossings were unaltered, the only effect being that the value of the space-correlation at the second maximum was increased.

Starting from the equation for the non-dimensional space-correlation

$$\rho\left(\frac{\xi}{D}\right) = \int_0^\infty G\left(\frac{\omega D}{u}\right) \cos\left(\frac{\omega D}{u}\right)\frac{\xi}{D}\, d\left(\frac{\omega D}{u}\right) = \int_0^\infty G(S) \cos S\frac{\xi}{D}\, dS$$

and recalling that filtering the microphone signals through a filter with a pass-band from $(\omega - \delta\omega)$

to $(\omega + \delta\omega)$ is equivalent to 'filtering' the function $G(S)$ from $(S - \delta S)$ to $(S + \delta S)$, a calculation similar to that in Section 3 gives

$$\rho_{2\delta S}\left(\frac{\xi}{D}\right) = \frac{\sin \delta S(\xi/D)}{\delta S\,(\xi/D)} \cos S\frac{\xi}{D}. \tag{A.1}$$

From this it is clear that for bandwidths which are not too large the first zeros are governed by S and are independent of δS. However, reduction of δS results in an increase of the factor $\{\sin \delta S\,(\xi/D)/\delta S(\xi/D)\}$ and so the amplitudes of the oscillations of the correlation curve will be increased.

The situation is altered when instead of keeping the mid-frequency constant and changing the bandwidth (as in the last paragraph), the bandwidth is kept constant and the central frequency is changed. Since this is equivalent to selecting different wave-numbers it is to be expected that the separation for the first zero crossing will change. If this separation is ξ_1, then from equation (A.1):

$$S\frac{\xi_1}{D} = \frac{\pi}{2}$$

or

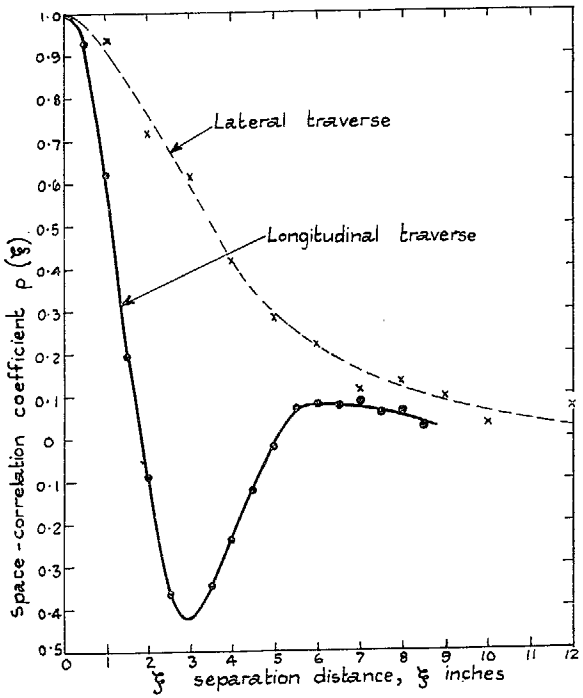
$$\frac{\xi_1}{D} = \frac{\pi}{2S} = \frac{\pi}{2}\frac{u}{\omega D} = \frac{\pi}{2}\frac{aU}{\omega D}$$

Thus

$$\log\frac{\xi_1}{D} = \log\frac{\pi a}{2} - \log\frac{\omega D}{U}$$

$$= \log\frac{a}{4} - \log\frac{fD}{U}$$

and it is seen that a logarithmic plot of (ξ_1/D) against (fD/U) should give a straight line of slope -1.



Reference point 6·2 dia. from jet exit, 0·5 dia. from boundary. Jet exit diameter, 2 inches. Longitudinal traverse made in upstream direction. Jet exit velocity = 710 ft/sec.

FIG. 1. Comparison of longitudinal and lateral space-correlation curves for pressure near to a model jet.

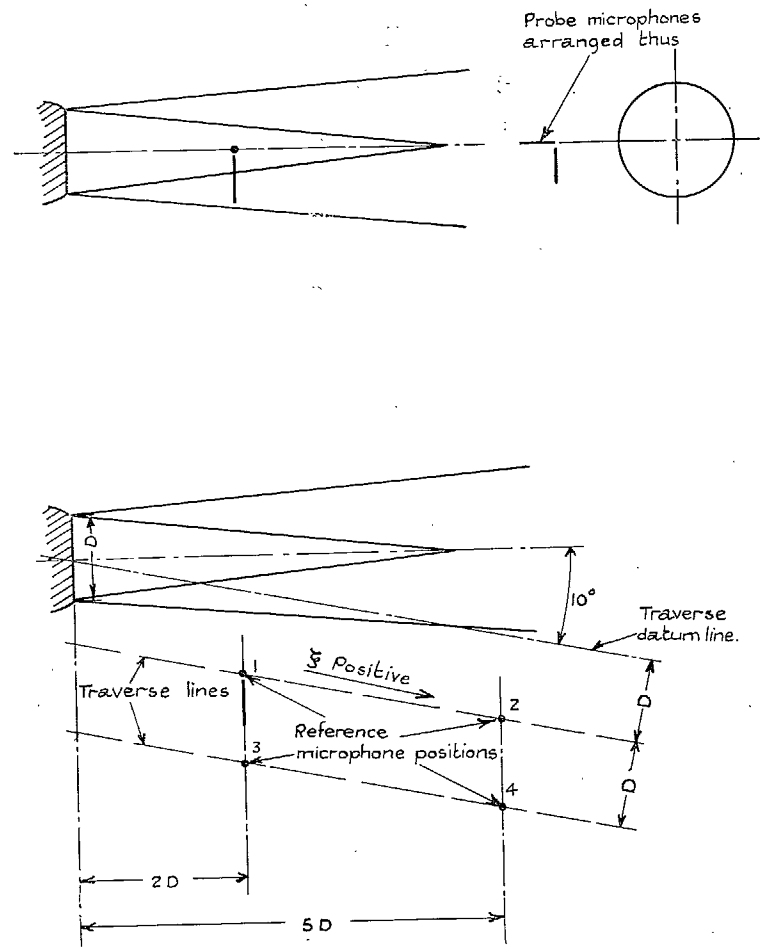


FIG. 2. Diagram giving details of reference points and traverse lines. Microphones shown at positions 1.

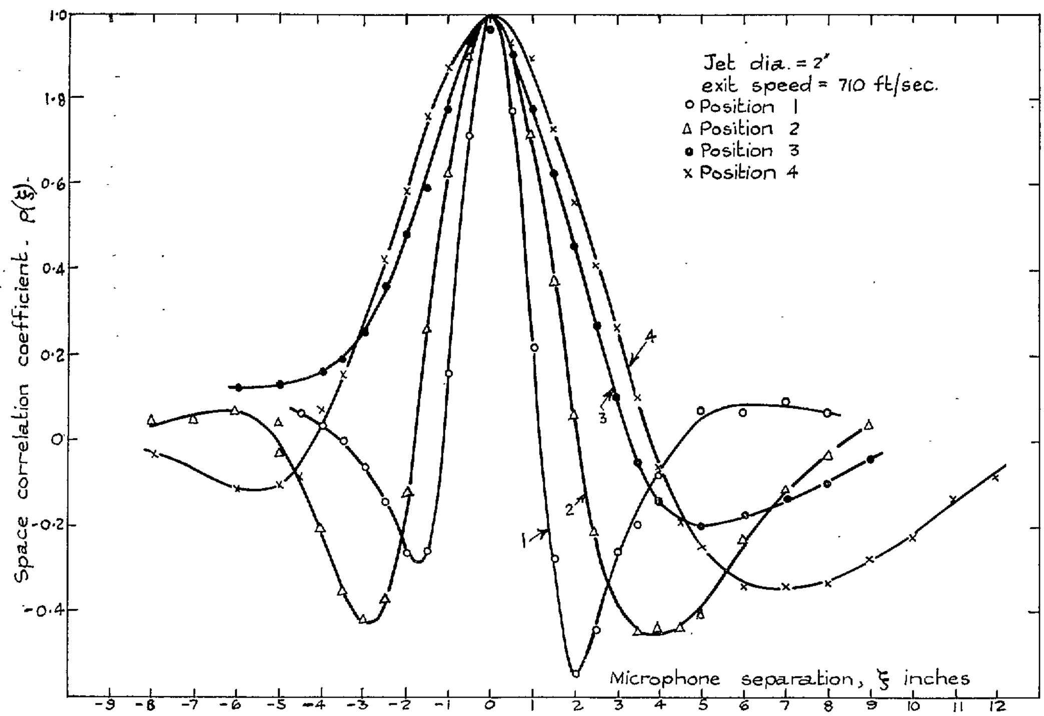
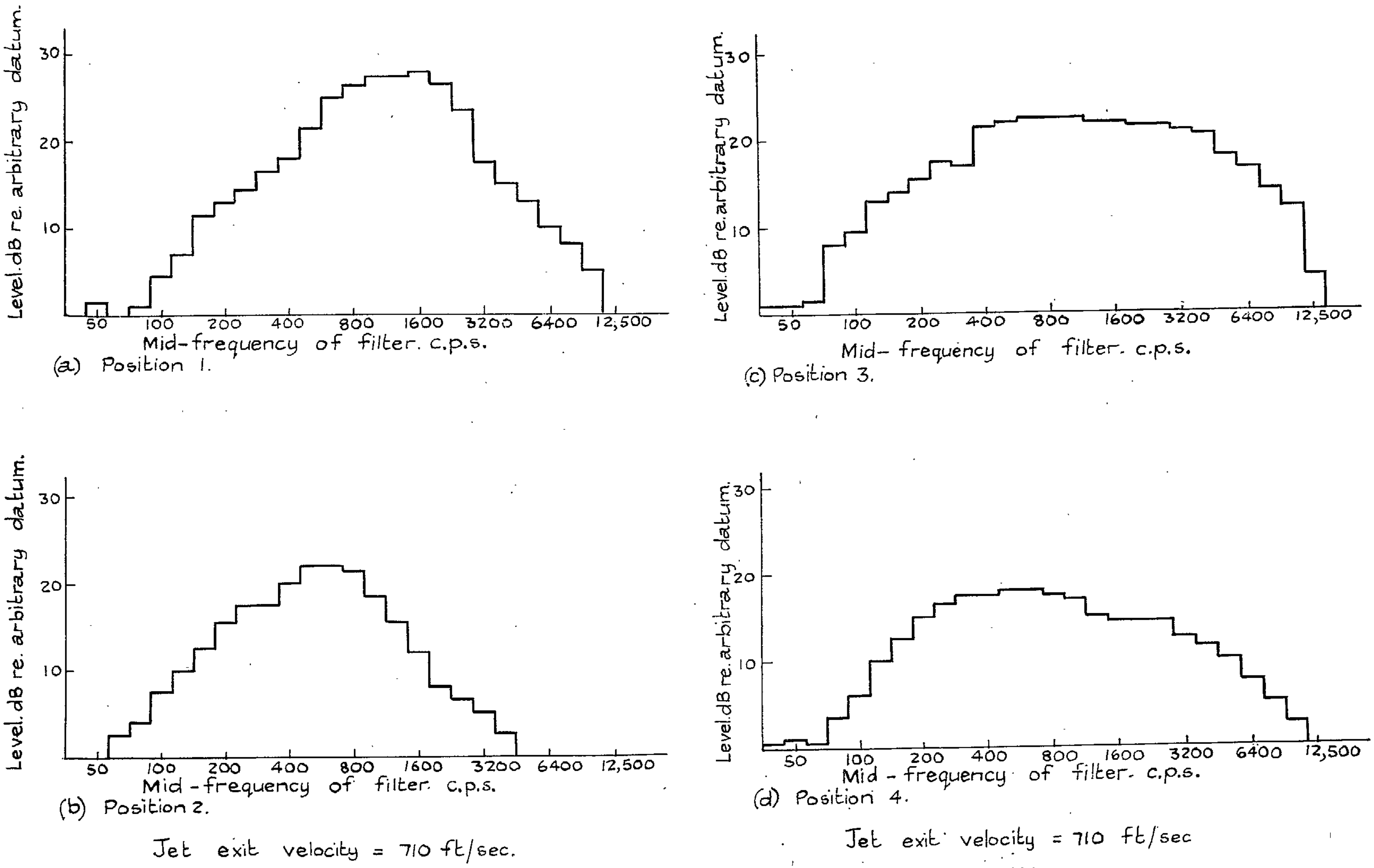
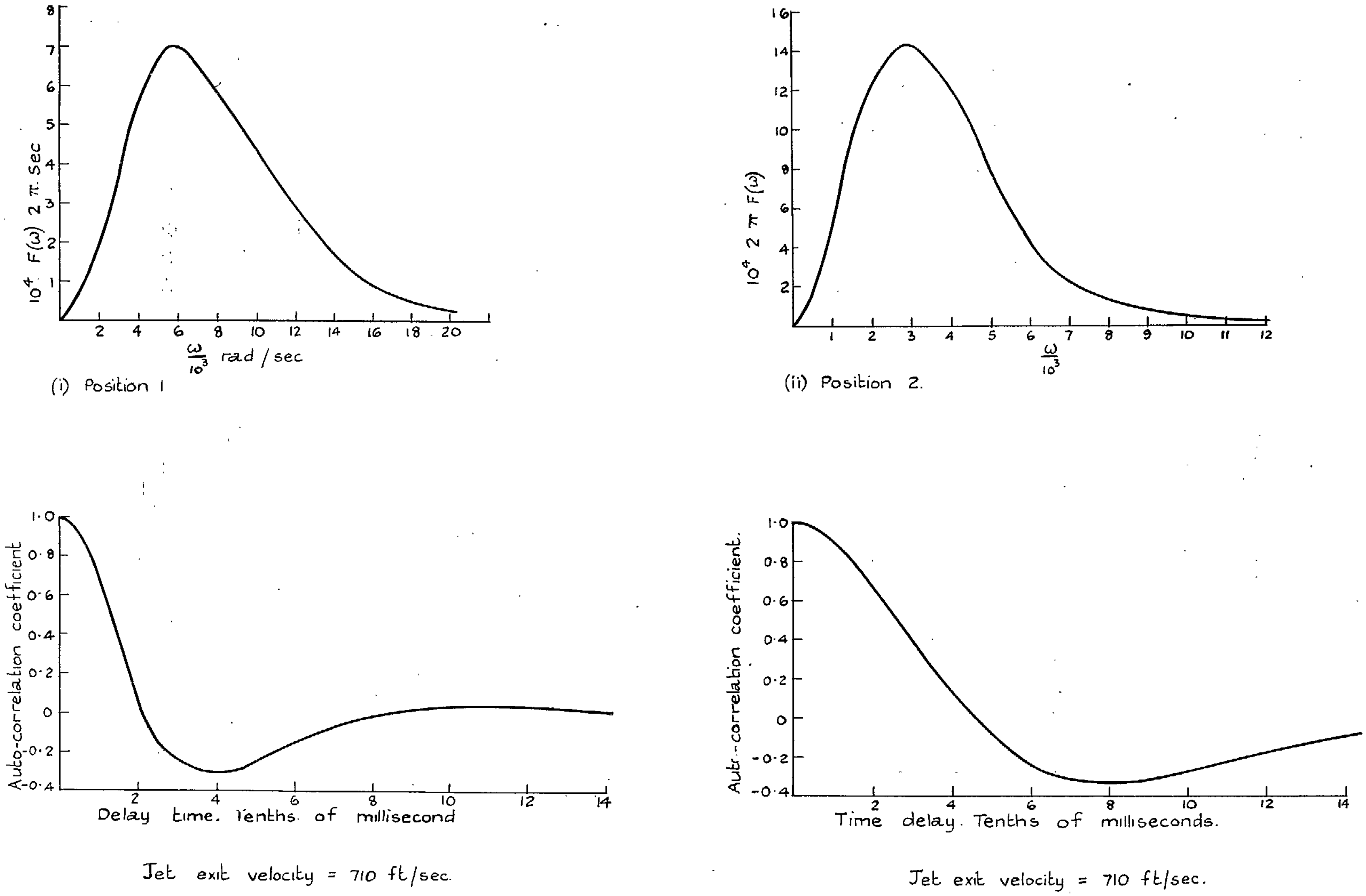


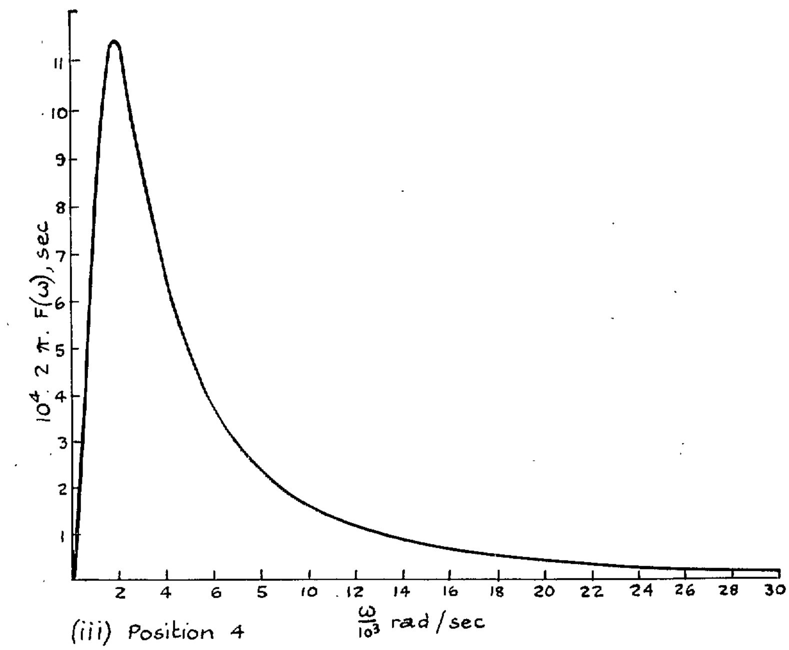
FIG. 3. Space-correlation curves for positions 1, 2, 3 and 4 on model jet.



FIGS. 4a to 4d. Frequency analysis of signal from reference microphone.
Filter bandwidth = 1/3 octave.—Model jet.



FIGS. 5(i) and 5(ii). Normalised power spectral density and auto-correlation coefficient.—Model jet.



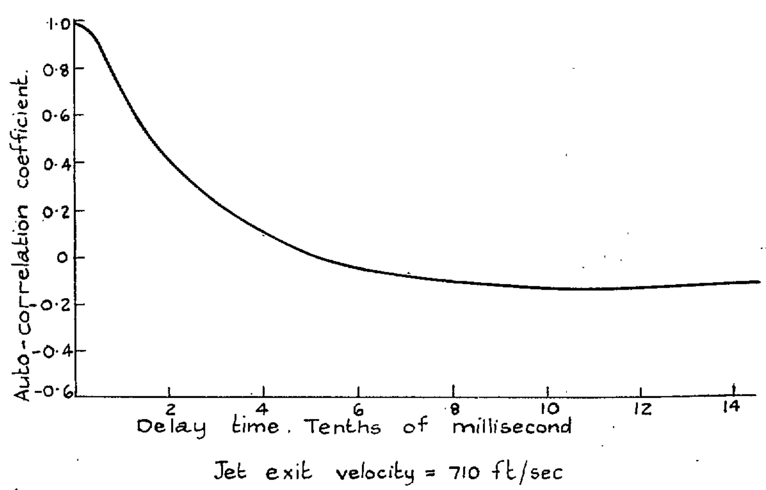


FIG. 5(iii). Normalised power spectral density and auto-correlation coefficient.—Model jet.

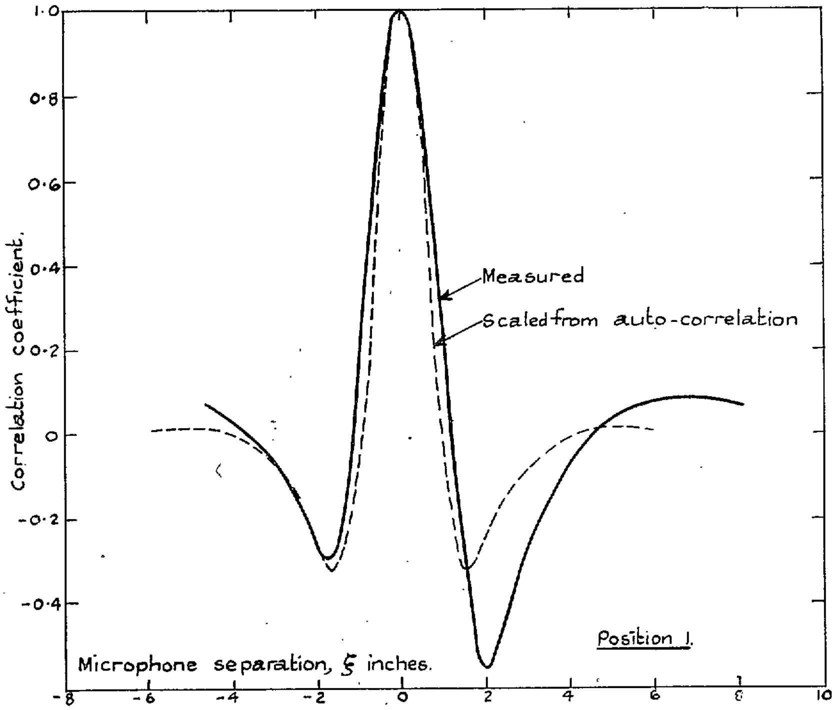


FIG. 6a. Comparison of measured space-correlation and scaled auto-correlation.—Model jet. Jet exit speed = 710 ft/sec.

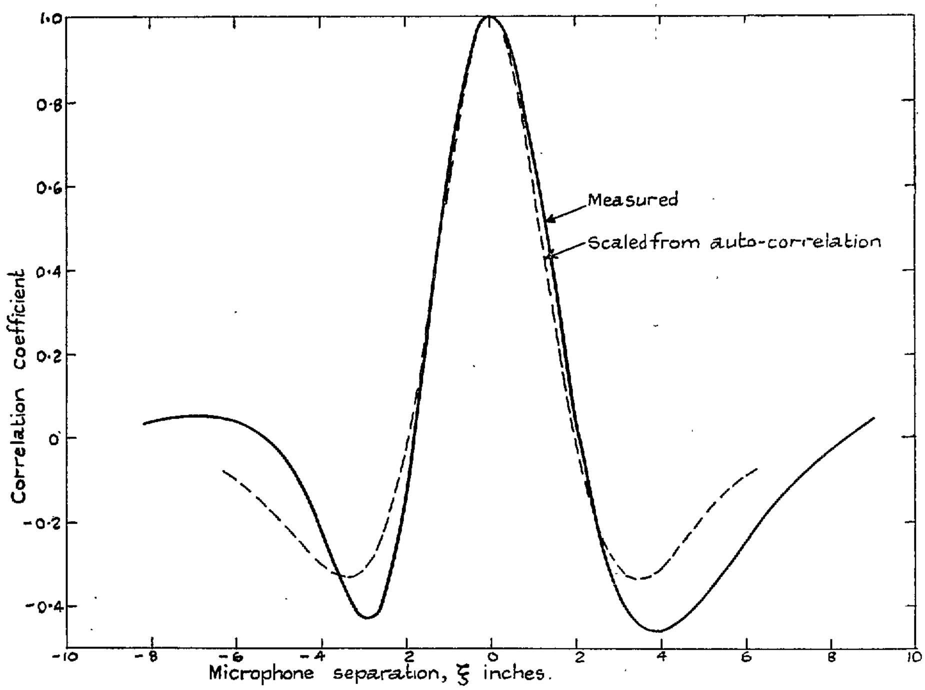


FIG. 6b. Comparison of measured space-correlation and scaled auto-correlation.—Model jet. Jet exit speed = 710 ft/sec (Position 2).

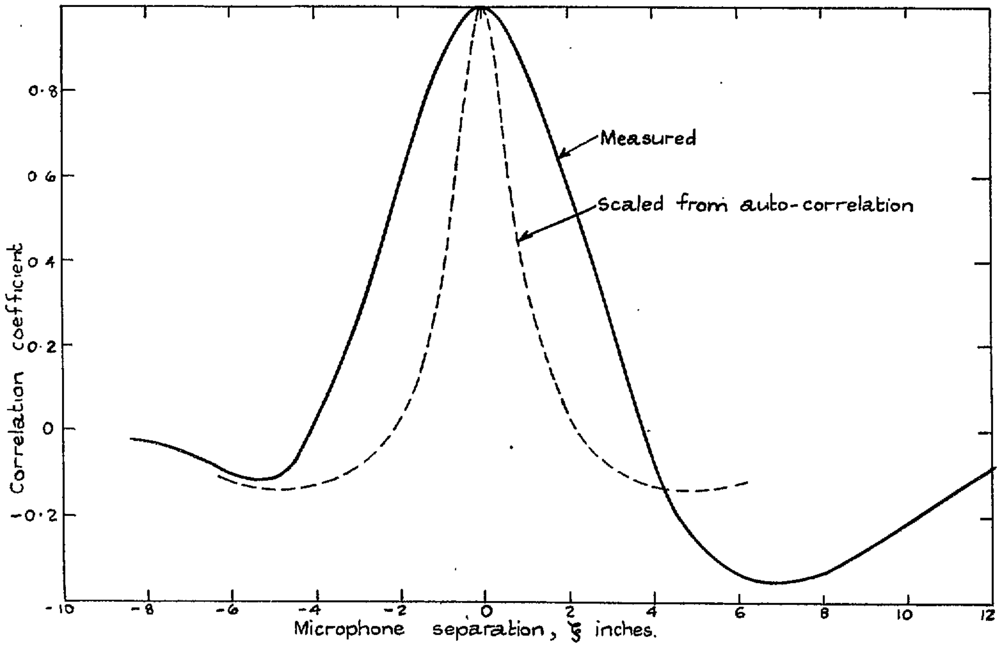


FIG. 6c. Comparison of measured space-correlation and scaled auto-correlation.—Model jet. Jet exit speed = 710 ft/sec (Position 4).

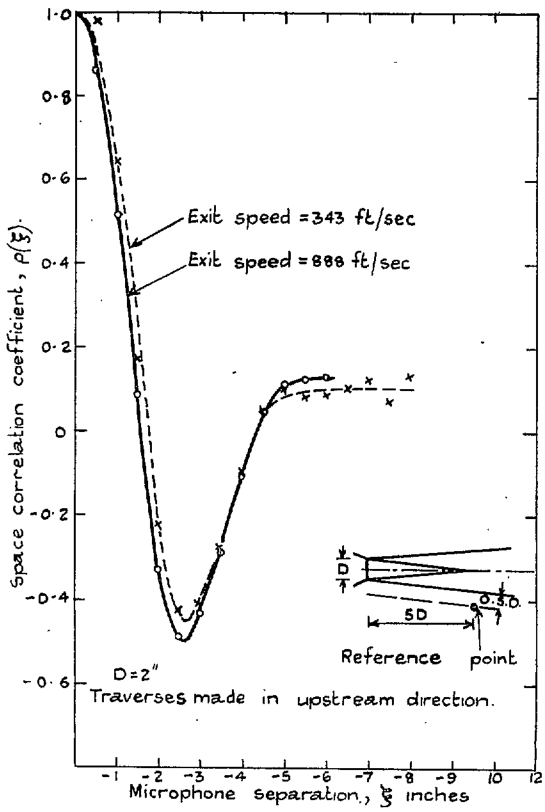
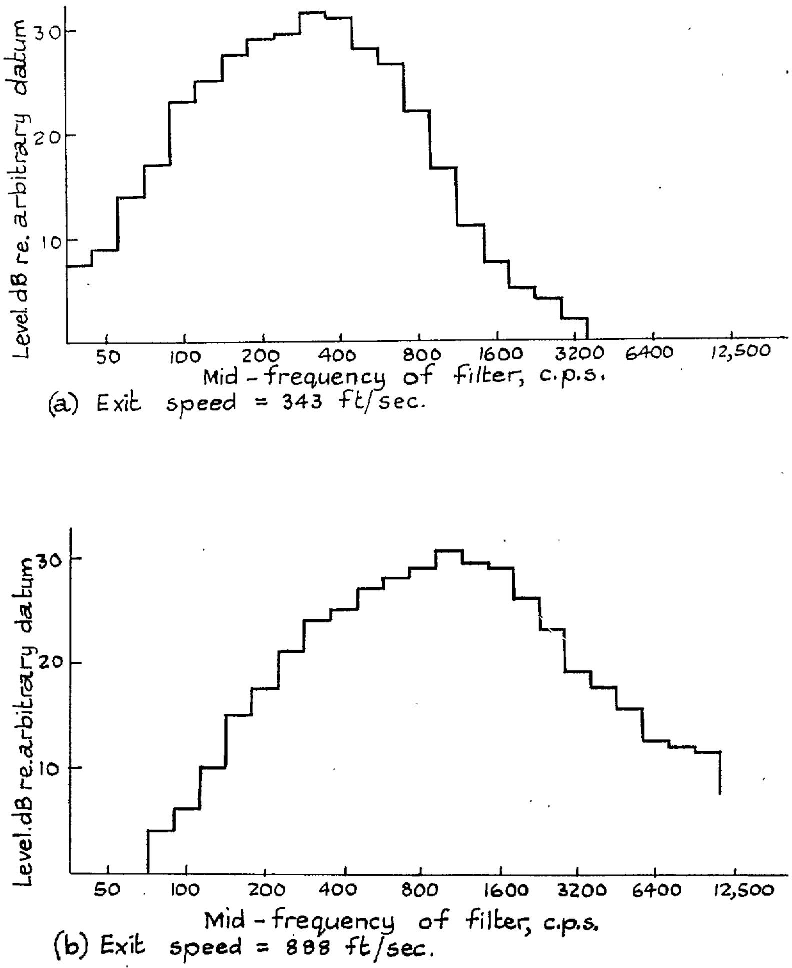


FIG. 7. Effect of exit speed on longitudinal space-correlation curve.—Model jet.



FIGS. 8a and 8b. Frequency analysis of signal from microphone at point 0·5 diameter from boundary, 5 diameters from exit. Filter bandwidth = 1/3 octave.—Model jet.

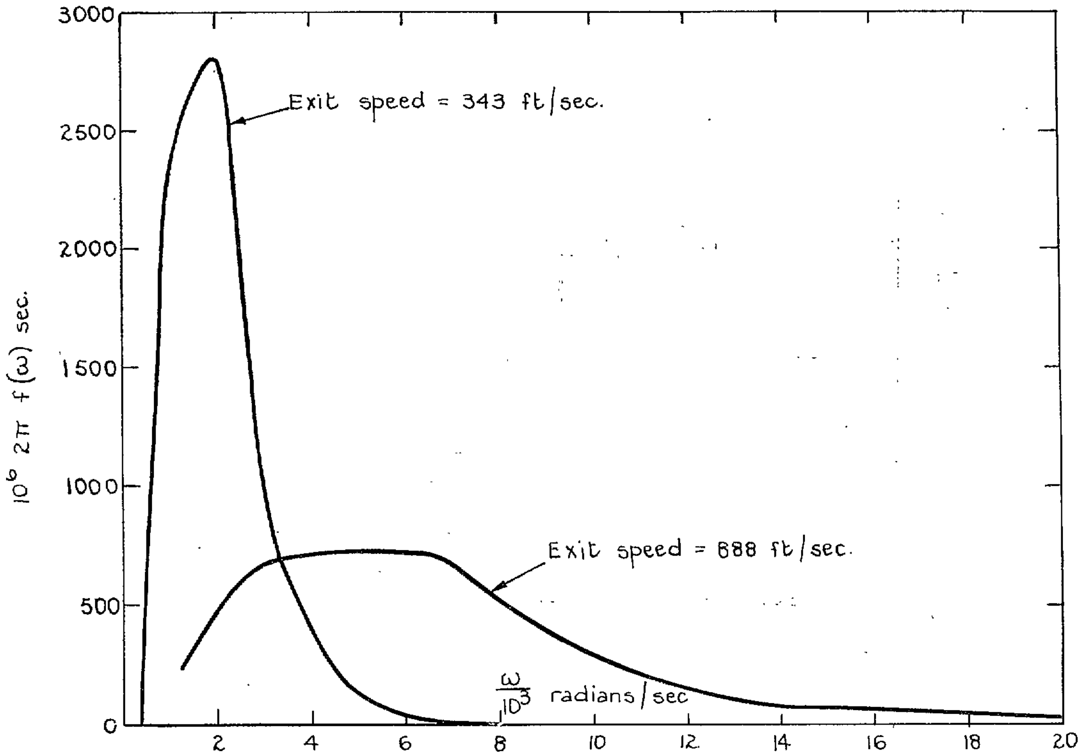


FIG. 9a. Normalised power spectral density at point 0·5 diameter from boundary, 5 diameters from exit.—Model jet.

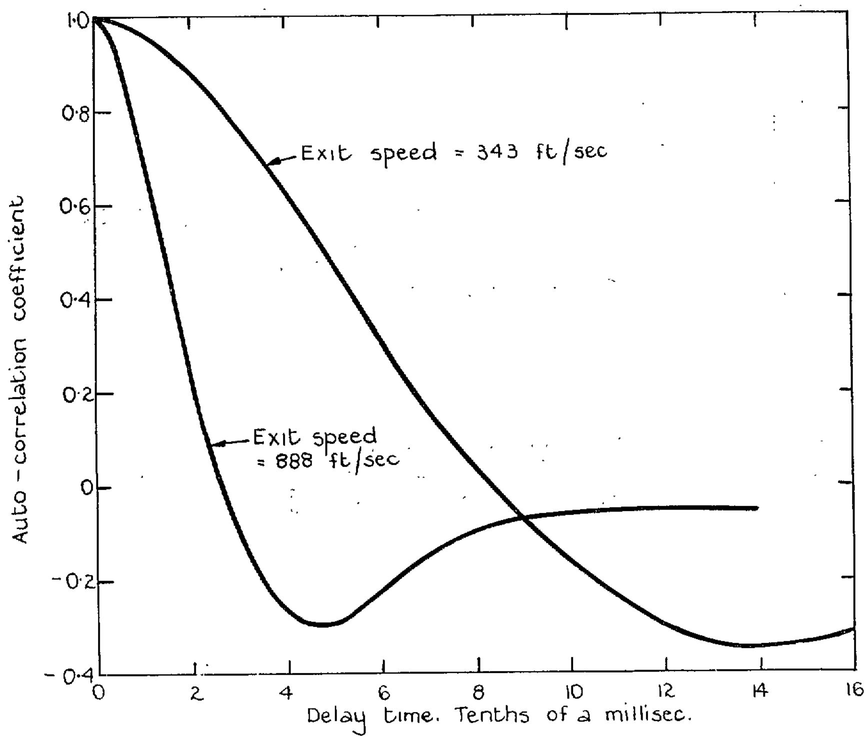


FIG. 9b. Auto-correlation coefficient at point 0·5 diameter from boundary, 5 diameters from exit.—Model jet.

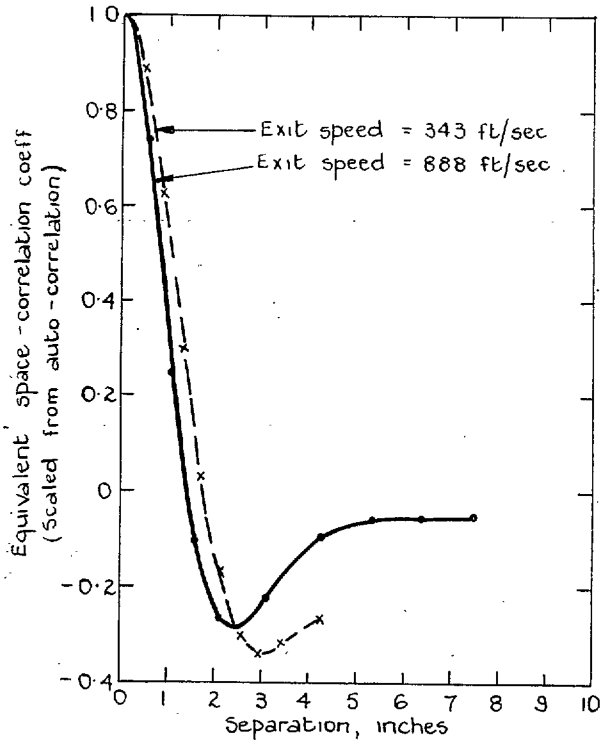
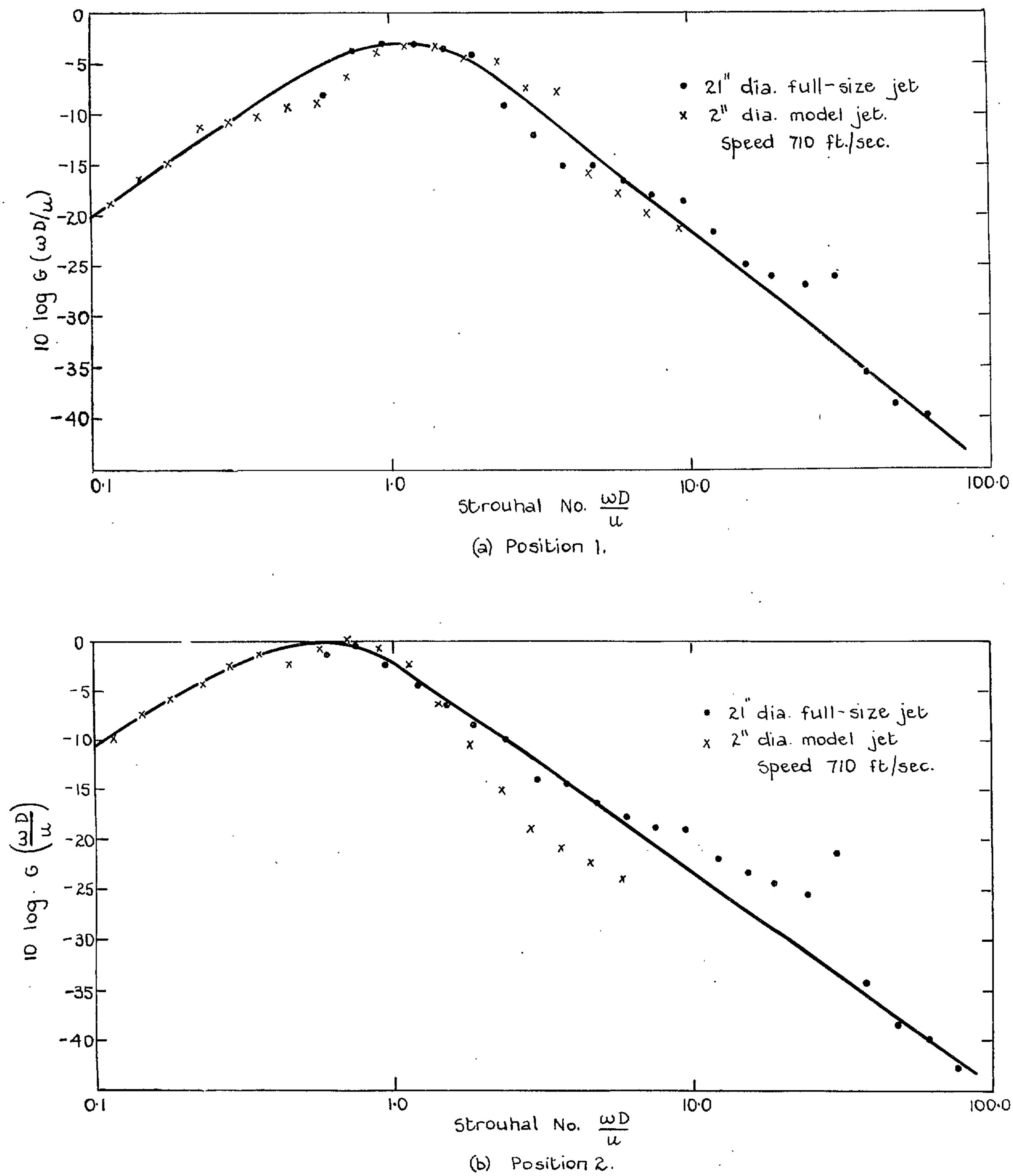
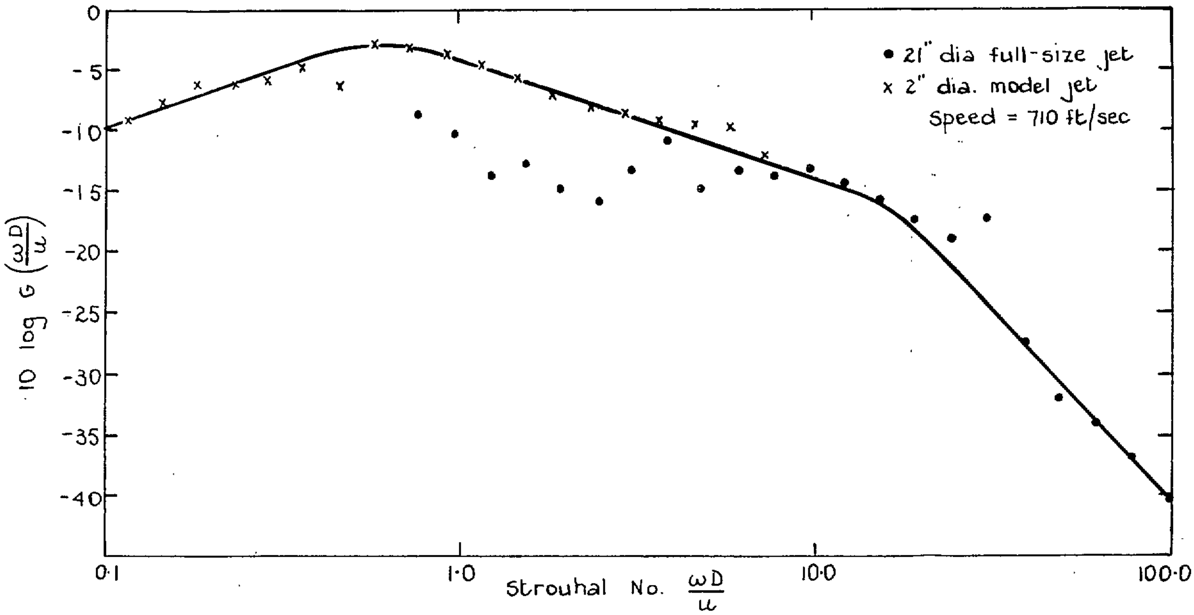


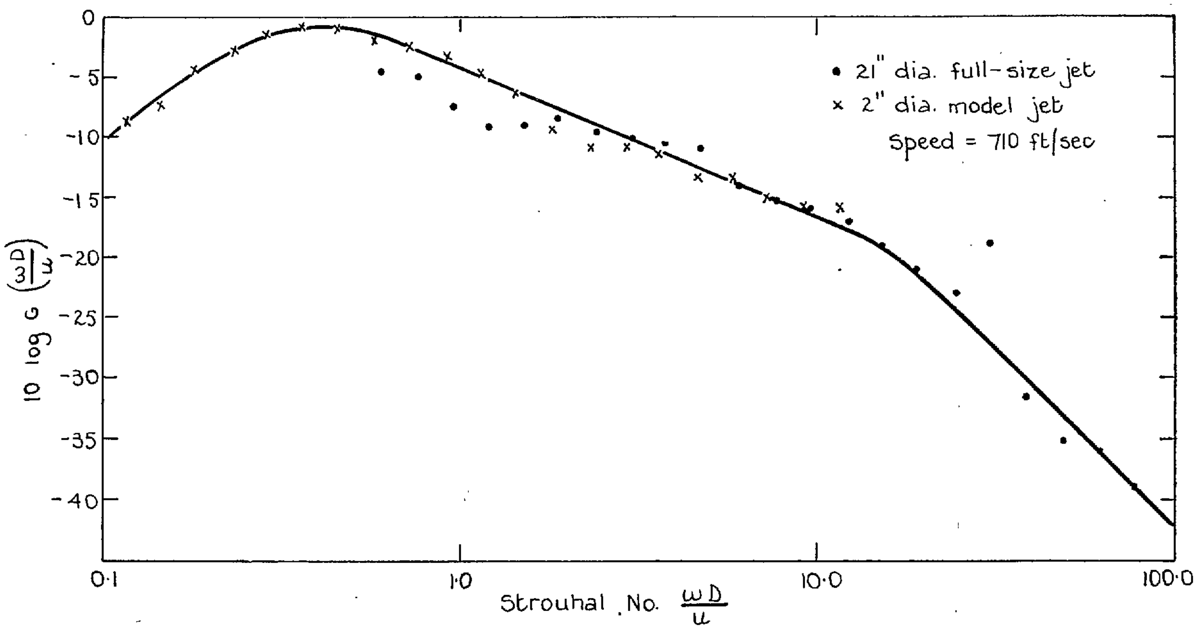
FIG. 10. Auto-correlation curves for point 0·5 diameter from boundary, 5 diameters from exit, scaled to 'equivalent' space correlation curves (*cf.* FIG. 3(1)).—Model jet.



FIGS. 11a and 11b. Comparison of model and full-size results.—Non-dimensional power spectrum.

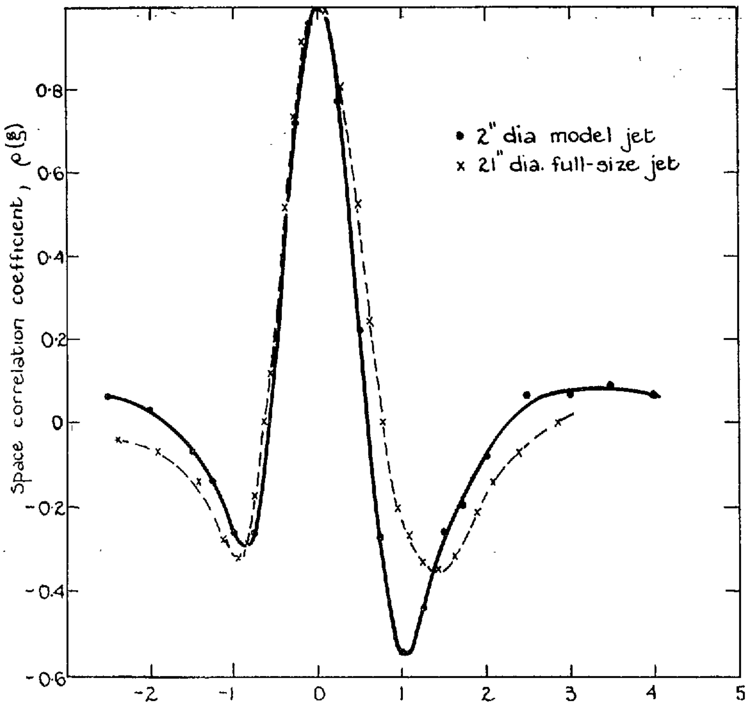


(c) Position 3.

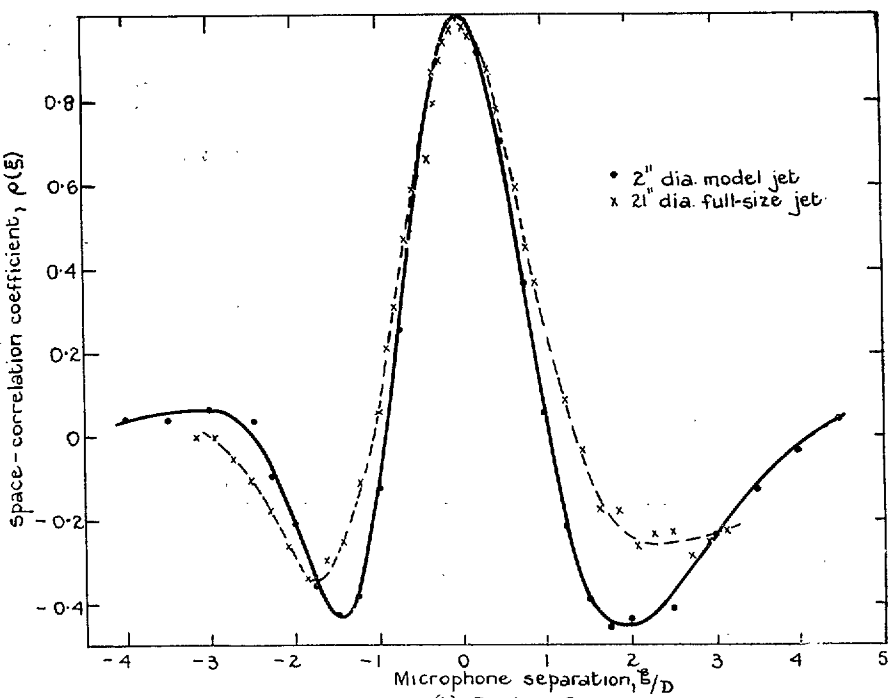


(d) Position 4.

FIGS. 11c and 11d. Comparison of model and full-size results.—Non-dimensional power spectrum.

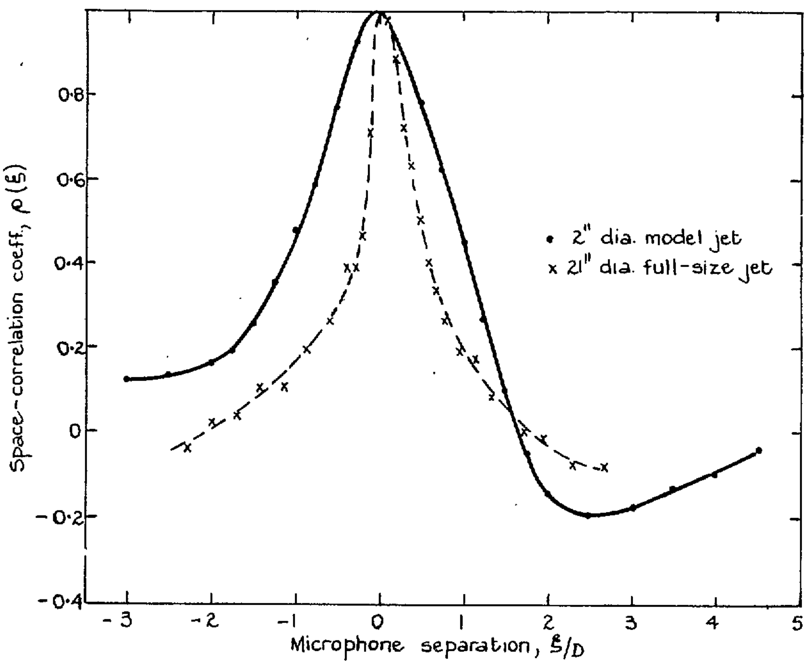


(a) Position 1.

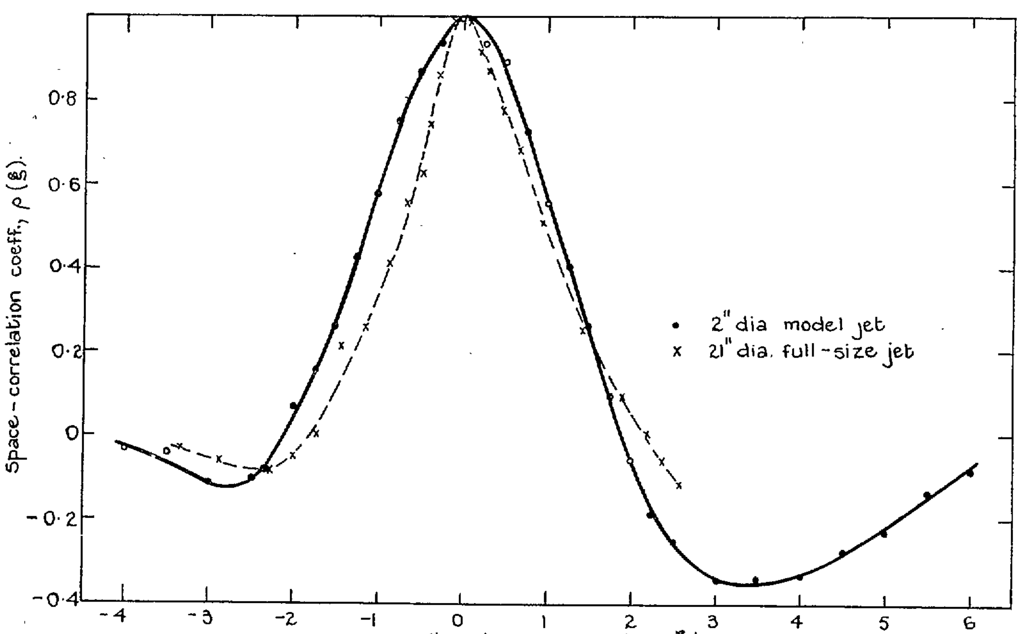


(b) Position 2

FIGS. 12a and 12b. Comparison of model and full-size results.—Space-correlation plotted on a non-dimensional basis.



(c) Position 3.



(d) Position 4.

FIGS. 12c and 12d. Comparison of model and full-size results.—Space-correlation plotted on a non-dimensional basis.

(78799) Wt. 54/8210 K.5 10/60 Hw.

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