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Summary. This report gives details of experimental observations on a 2-in. model jet. The observations consist of velocity distributions, root-mean-square pressure fluctuations in the field round the jet and space correlations of the fluctuating pressures in limited regions near to the jet. It is considered that the main interest lies in the space correlations which were observed by using fine-bore probe microphones and associated correlation equipment.

1. *Introduction.* Apart from the considerable academic interest of the problem, there are two main reasons for an investigation of the noise field around a jet of air, both of which arise from the fact that the jet engine is now firmly established as a propulsive unit for aircraft. Firstly, although its efficiency as a generator of sound is very low, the total energy of the efflux of a modern jet engine is so great that the fraction radiated as sound is very large on an acoustic scale. As a result, aircraft fitted with such engines are likely to give rise to protests from people who live near to the factories at which the aircraft are made and tested and the aerodromes from which they eventually operate. It is therefore very important from the manufacturer's and operator's point of view that experiments be carried out to determine the magnitude of the noise radiated from a jet and the parameters upon which the noise depends. Secondly, it has been realised for some time now that secondary structural failures noticed on the tailplanes and fuselages of modern jet-propelled aircraft are due directly to the fluctuating pressures near the jet which cause the structure to vibrate and suffer fatigue damage. If such failures are to be avoided by suitable design, then again, experimental work is called for.

These two problems call for different types of measurement. If we are concerned with the noise which is radiated from the jet we need to measure its acoustic power and the distribution of the flux of energy over the surface of a large sphere centred on the engine. Thus we have to measure only the intensity of the sound; it is to this that a human being responds, for he samples the sound field over a relatively small area. When we move nearer to the jet, the pressure fluctuations become more complicated and the term intensity is best discarded, but if we are still interested only in the reaction of a human being we can substitute a similar measurement, namely, that of the root-mean-square value of the fluctuating pressure. When, however, we come to consider the problem of the vibration of structures due to these pressure fluctuations, it rapidly becomes clear that more complicated measurements are required, for in taking from the pressure field the energy required to maintain its vibrations a structure 'samples' the distributed properties of the field and not its local properties.

A simple calculation (*see* Ref. 1) shows that the measurement which has to be made is that of the space-time correlation in the pressure field.

A considerable amount of research has been done on jet noise but on the whole this has been restricted to measurements associated with the first of the two problems introduced above, *i.e.*, measurements of the root mean square of the pressure fluctuations in various parts of the field. The main purpose of this paper is not to add to this work but to describe some experiments carried out at the University of Southampton as part of a programme of research the ultimate object of which is to measure the space-time correlation in the pressure fields around jets. At present*, the time-delay mechanism necessary for the measurement of space-time correlation is not completed and the experiments are restricted to the measurement of space-correlation.

2. *Preliminary Work.* Before the experiments on space-correlation were started some preliminary work was carried out. The purpose of this work was:

(*a*) to examine the flow from the nozzle and to track the position and spread of the jet by carrying out measurements of the velocity distribution at various stations

(*b*) to determine fairly accurately the root mean square of the pressure fluctuations near to the jet, so that apparatus for the later work could be designed.

This work was not published in detail, but since it has a bearing on the later experiments it will be briefly described here.

2.1. *Experimental Arrangements.* The jets which were used in all the work reported in this paper are produced by exhausting air stored at 150 lb/in.^{2} in a Lancashire boiler down a long pipe, in which valves to control the flow are fitted, and through a carefully designed nozzle into a laboratory,

(*a*) *Measurement of the total head and static pressure.* For these measurements a 2-in. diameter nozzle was used which was first calibrated so that the total head at exit could be deduced from a measurement of the static pressure in the pipe just upstream from the nozzle. The total head and static pressure in the jet were measured with small probes made from hypodermic tubing. These were mounted in a screw-operated traverse gear for measurements near to the jet exit, where the traverse distances were small, and in a simple sliding traverse gear for stations farther downstream where traverse distances were much larger and precise positioning less critical.

For a total head at exit of 9 lb/in.^{2}, velocity distributions were measured at 5, 10, 15, 20, 30, 40, 50, 60 and 70 diameters from the exit. Check measurements were also carried out at 3·5 lb/in.^{2} and 15 lb/in.^{2} total head.

(*b*) *Measurement of root-mean-square pressure fluctuations.* When measuring pressure fluctuation around a jet in the laboratory it is important not to attempt measurements at points too far from the jet, for it is difficult to allow for the reverberant properties of the room. After some tests had been carried out in the laboratory, it was decided to restrict noise measurements to points within two feet from the boundary of the jet; at these distances it is felt that the noise coming directly from the jet is much greater than any reflected from the walls of the laboratory. For the measurement of the r.m.s. pressure fluctuations a 4-in. diameter nozzle was used, the change to a larger nozzle being made so that the ratio of microphone size to jet diameter could be reduced†.

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* May, 1958. The time-delay mechanism has since been completed and used extensively.

† Ideally, this ratio should be small so that the microphone makes a point measurement.

The measurements were carried out using a Bruel and Kjaer condenser microphone, which was set up with its diaphragm in a plane passing through the jet centre-line. In this position the directional characteristics of the microphone are reduced. The microphone signal was taken to a Bruel and Kjaer 1/3 octave Spectrometer (which includes the microphone amplifier) and a Level Recorder. All measuring and calibrating apparatus other than the microphone was set up in a room separate from the laboratory, the microphone leads being brought in through a connecting hatch. This was done to reduce microphony due to the action of the pressure fluctuations in the laboratory on the electronic gear.

The work carried out consisted of:

(i) Measurements of the spectrum of the fluctuating pressures at various positions along lines parallel to the boundary of the jet and 1, 2, 3, 4 and 5 diameters from it. The positions on each line were, 0, 5, 10, 15 and 20 diameters from the exit plane of the nozzle.

(ii) Measurement of the overall noise at various exit speeds between 400 and 1,000 ft/sec for each of these positions.

2.2. *Results.* (*a*) *Velocity measurements.* The results required for the later work on correlation are:

(i) the spread of the jet

(ii) the decay of the mean velocity in the jet

(iii) the velocity distribution.

Fig. 1 shows the spread of the jet as defined by the perpendicular distances from the centre-line at which the velocity is one half and one tenth of that on the centre-line. It is seen that the spread is linear. In what follows the term 'jet boundary' is to be taken to mean the 1/10th velocity line.

The decay of the velocity on the centre-line and half-velocity line is shown in Fig. 2. In previous work on the decay of the mean velocity in jets (*e.g.*, Ref. 2), it has been customary to plot the reciprocal of the velocity on the centre-line and show that the result is a straight line, *i.e.*, that the velocity decays hyperbolically. Fig. 3 which is a plot of V_0/V_{max}, shows that this is true only over short distances in the jet, the full graph being a curve.

In Fig. 4 are shown a few of the velocity distributions at stations where the so-called 'fully-developed' velocity profile is established.

These four graphs are plotted from the results of the experiments in which the total head of the jet at exit was $9 \cdot 0$ lb/in.^{2} (*i.e.*, exit velocity = 888 ft/sec). Check measurements at $3 \cdot 5$ and 15 lb/in.^{2} revealed no substantial differences.

(*b*) *Root-mean-square pressure measurements.* The results of the measurements of the overall level at each point as a function of speed were plotted and from each graph the level corresponding to an exit velocity of 1,000 ft/sec was read off. These results were then used to construct contours of equal level. Fig. 5 shows the contours, the numbers on the curves being the r.m.s. level in decibels relative to a datum of $0 \cdot 0002$ dynes/cm^2. The principal result from this Figure is that between 5 and 10 diameters from the exit each contour bends and becomes roughly parallel to the jet boundary.

3. *Measurement of Space-Correlation.* If in a given region the pressure is a function of space (denoted by the vector x) and time, $p(x, t)$, the space-correlation function is defined as:—

$$r(x_1, x_2) = \overline{p(x_1)\, p(x_2)} \tag{1}$$

where the bar indicates a time average over an interval long enough for representative samples of $p(x_1, t)$ and $p(x_2, t)$ to have been obtained. Thus to measure the space-correlation two microphones are used, one at the reference position x_1 and the other at some point x_2 in the field, their signals multiplied and the product integrated over a certain interval of time. This is repeated for a sufficient number of values of x_2 for the correlation pattern in the field to be revealed. Frequently it is more convenient to work in terms of the space-correlation coefficient, which is obtained by dividing equation (1) by the product of the root-mean-square values of $p(x_1)$ and $p(x_2)$, *i.e.*,

$$\rho(x_1, x_2) = \frac{\overline{P(x_1, t) \, . \, P(x_2, t)}}{\sqrt{\{\overline{P^2(x_1, t)}\}}\sqrt{\{\overline{P^2(x_2, t)}\}}}$$

This coefficient is a number which will always lie between -1 and $+1$.

3.1. *Experimental Arrangements.* For the experiments to be described a linear traversing technique was adopted, *i.e.*, one microphone was placed at the selected reference point and the second traversed past it along a straight line, observations being made at regular separations. About 20 to 25 readings were required to define satisfactorily a correlation curve for such a traverse and in order to prevent the experiment from becoming excessively long it was decided to use a 2-in. diameter nozzle, so as to conserve the air supply and provide a longer running time on one boilerful of air.

From purely dimensional considerations, confirmed by some correlation work already reported[3], it was expected that the correlation coefficient would vary rapidly in distances of the order of one diameter. This meant that the Bruel and Kjaer condenser microphones as used earlier were unsuitable, for, quite apart from the consideration of the size of the microphones, the correlation would vary appreciably over their diaphragms, thus rendering any measurement inaccurate*. It was decided that with a jet of exit diameter 2 in. it might be necessary to have the microphone separation as small as $\frac{1}{8}$ in. for some measurements and so the development of a small-bore probe attachment for the condenser microphones was initiated[4]. As a result of this development it was possible to produce probe attachments which, after being carefully matched to two particular microphone capsules, resulted in a pair of microphones whose responses differ by not more than 0·5 dB over their working range, 40 to 7000 c.p.s. The probe tube is of hypodermic tubing of 0·030-in. inside diameter. As developed, the microphones have response characteristics with a fall of 6 dB per octave. To compensate for this a microphone amplifier with the inverse characteristic was designed and constructed.

For the correlation measurements the traversing microphone was mounted on a screw-operated traversing gear. The difficulties inherent in traversing one microphone past the other are solved by the fact that, being so small, the microphones are non-directional. Thus the fixed microphone was arranged horizontally and the moveable one mounted vertically in the traversing gear. A photograph of the microphones and traversing gear set up alongside the jet is given in Fig. 6.

As in the measurements described in Section 2 only the microphones and their cathode-followers were mounted in the laboratory, the leads from the cathode followers being taken away to an adjacent instrument room in which the readings were taken. After amplification the microphone signals were passed to the computer. This computer was designed by K. R. McLachlan of the

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* This also applied to r.m.s. measurements, of course. *See* footnote to Section 2.1(*b*).

Electronics Laboratory as a general-purpose machine covering the frequency range zero to 10,000 c.p.s. It will be described fully elsewhere[5], and so only brief details will be given here.

The computer consists of a quarter-squares multiplier incorporating a biased-diode function generator, followed by a pair of modified Bootstrap integrators. An integrator integrates the multiplier output over an interval of 10 sec after which its result is fed to an analogue-to-digital converter and thence to a digital register. This conversion process takes roughly 2 sec and during the next 8 sec the integrator is error-corrected by a servomechanism. At the end of a 20-sec period from the start of the previous integration, the integrator again starts to integrate the multiplier output. Thus each integrator works on a cycle of 20-sec period and the two are staggered so that the output of the multiplier is continuously integrated, the results of the separate integrations being added on the digital register. In this way an integration time of any multiple of 10 sec up to 100 sec and any multiple of 100 sec up to 1,000 sec is possible with very small errors.

The result of the integration appears on the digital register as a number, subsequently referred to as the 'count'. In the experiments to be described it was proposed to work with the correlation coefficient and so an overall calibration of the computer was not necessary. Initially an integration time of 20 sec was used but it soon became clear that 10 sec was quite adequate and a change was made in the interests of running time. The procedure was:

(i) Integration of the product of the signals in channels 1 and 2

(ii) Integration of the square of the signal in channel 1

(iii) Integration of the square of the signal in channel 2.

Details of the actual measurements taken are given in the next Section.

3.2. *Details of Measurements, and Results.* (*a*) *Single traverses.* For a given position of the fixed, or reference microphone, the space-correlation is a function of the position of the second microphone relative to the reference microphone. Further, in a complicated pressure field, this dependence is likely to be different when the position of the reference microphone is changed. Thus the first question to be settled is the choice of what we may call co-ordinate axes. There are two principal ways in which the second microphone may be moved relative to the first, *viz.*, along a straight line or around a circle centred on the first microphone. In the present work it was decided to use a linear traverse, but this still leaves open the question of the orientation of the traverse lines, for we could traverse parallel to the jet axis, parallel to the jet boundary, at right angles to the jet boundary or along lines radiating from the centre of the jet exit.

For very close measurements traverse lines parallel to the jet axis involve the risk of running the moving microphone into the jet, and so this direction was rejected. After consideration of the problem of setting up the microphones it seemed that the simplest traverse lines were those parallel to the jet boundary and those at 90 deg to the jet direction forming a horizontal plane through the centre-line of the jet. These will be referred to respectively as a longitudinal and a lateral traverse.

Fig. 7 shows the results of a longitudinal traverse in which the reference microphone was placed at a point 6·2 diameters from the exit plane of the jet and 0·5 diameter from its boundary. The jet speed at exit was roughly 490 ft/sec. The curve is quite well defined except where the correlation coefficient falls below 0·1 when the results scatter a little.

Fig. 8 shows the results of a lateral traverse in which the position of the reference microphone and the speed of the jet were the same as for Fig. 7. The results are more scattered than in Fig. 7

and it is fairly certain that this is due to the rapid fall in the signal from the second microphone; the r.m.s. pressure level falls off very rapidly in this direction (*see* Fig. 5) and at this stage of the work the microphone amplifiers were fitted with coarse attenuators*. However, the curve is defined clearly enough for the considerable difference between the longitudinal and lateral traverses to be evident. This difference is such as to suggest that the high-frequency content of the signals was greater for the longitudinal traverse than for the lateral one. Since the running conditions and the position of the reference microphone were the same in both runs, this may be due to an apparent frequency shift arising from the fact that in Fig. 7 the traverse is made roughly parallel to the direction of the mean velocity in the jet and in Fig. 8 at 90 deg to this direction. Thus the phenomenon is rather like the Doppler effect.

It seems natural to try to check this by carrying out longitudinal traverses at various speeds. This was done with the fixed microphone 5 diameters from the exit plane of the jet and $0 \cdot 5$ diameter from the boundary for three different speeds: 900, 340 and 120 ft/sec, roughly. The results are shown in Fig. 9 and it will be seen that there is little difference between the curves. The reason for this could be that the frequency spectrum of the pressure fluctuations also changes with the jet speed in such a way that the effects cancel one another, but a more likely explanation is suggested below and investigated (Section 3.2 (*c*)).

(*b*) *Variation of the space-correlation over a surface.* In the above experiments attention has been given only to the variation of the space-correlation along a line. For the problem of structural vibrations information about the spatial variation is required. Here again the problem of co-ordinate axes arises and it is difficult to decide on what surfaces to take measurements in order to accumulate the data most economically. With the problem of the variation in the space-correlation of the pressures on an aircraft fuselage in mind, it was decided in the present work (which is essentially of a preliminary nature) to take measurements on a plane surface parallel to and $0 \cdot 5$ diameter from the jet boundary. The reference microphone was placed 5 diameters from the jet exit and the jet velocity was set at 815 ft/sec. Five traverses were made, details of which are given in the sketch which accompanies Fig. 10, and the results plotted so that contours of equal correlation coefficient could be drawn. These contours are given in Fig. 10.

The contours of iso-correlation coefficient plotted in Fig. 10 are rather curious in shape, although they do confirm the difference between the longitudinal and lateral traverses shown in Figs. 7 and 8. Their irergularities could be due to either of two reasons: (i) because of inaccuracies in setting up the microphones, for the microphone signal varies very rapidly as the distance from the jet is increased (as can be seen in Fig. 5 or, better, in Fig. 11, which shows the variation in the count† from one microphone during a lateral traverse); (ii) because of the choice of surface on which the measurements have been taken. As a result of these doubtful points, the measurements were for the moment restricted to only one quadrant of the plane.

(*c*) *Relationship between space-correlation and auto-correlation.* Returning to the question of the difference between the correlation curves obtained with longitudinal and lateral traverses, the possibility of a simple relationship between the longitudinal space-correlation and the auto-correla-

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* These were later augmented with two finely stepped attenuators and the difficulty was eliminated.

† The count in this case is a number proportional to the mean-square pressure fluctuation.

tion coefficient of the signal from the reference microphone arises. The pressure fluctuations recorded by the microphones are associated with the turbulent eddies in the jet and these are known to move downstream. When the microphones are very close to the jet it is probable that the pressure fluctuations which are sensed are mainly due to a small number of eddies quite near to the microphone. In a longitudinal measurement, then, the signal recorded by the downstream microphone at any instant will be very similar to that recorded a short time earlier by the upstream microphone, for if the eddies move with a velocity u and the distance between the two microphones is ξ, those eddies opposite the upstream microphone at time t will be opposite the downstream microphone at time $(t + \xi/u)$. If during this interval the pressure distribution around the eddies has changed very little, the signals from the two microphones will be almost the same except for the time shift. Thus if the space-correlation is changed to an equivalent auto-correlation by dividing its abscissae by the velocity u, the resulting curve should be similar to the auto-correlation of the signal from either of the two microphones. The velocity u is of course unknown, unless space-time velocity correlation measurements are carried out, but from previous work on jets and boundary layers it seems not unreasonable to take it as half the maximum speed of the jet, at the cross-section where the reference microphone is situated, this being based on the rather crude picture of the eddies acting as rollers between the fluid at the centre of the jet and the surrounding fluid.

This idea has been pursued. Since the time-delay unit for the correlator was not completed it was necessary to calculate the auto-correlation of the signal from the reference microphone from its power spectrum. Fig. 12 shows the spectrum of the signal as measured with the Bruel and Kjaer Spectrometer and Level Recorder. For this measurement the microphone was placed at the position occupied by the reference microphone for the traverse shown in Fig. 7. The spectrum was first normalised and then corrected for bandwidth to give an approximation to the power spectral density $F(\omega)$, the result being plotted in Fig. 13. Using this curve the auto-correlation coefficient was calculated from the familiar relationship

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

the integral being evaluated numerically. The resulting auto-correlation curve is shown in Fig. 14.

In Fig. 15 this auto-correlation curve is compared with both the positive and negative halves of the space-correlation curve of Fig. 7 scaled to equivalent auto-correlations using the half-speed of the jet. In carrying out this scaling, account was taken of the variation of velocity with axial position by using the curves of Fig. 2.

The agreement in this one case is good particularly when it is noted that the computation of the auto-correlation coefficient becomes inaccurate at the larger delay-times.

4. *Conclusions.* The main results of the experiments reported above are considered to be:

(1) the velocity distributions

(2) the space correlations of the fluctuating near field pressures

(3) the possibility of a relationship between the longitudinal space-correlation and the auto-correlation for points near to the jet boundary.

The velocity distributions provide information on the spread of the jet which is useful in determining where the microphones should be placed in the near field (*e.g.*, in the experiments reported above; parallel and perpendicular to the jet boundary). The velocity distributions may also be of use for estimating the speed of convection of pressure disturbances within the jet.

The space correlations, whilst being limited in extent, reveal some interesting facts. It is apparent that for longitudinal traverses parallel and close to the jet boundary that the space-correlation coefficient curve is constant over a wide range of jet exit velocities (*see* Fig. 9).

Contours of iso-correlation coefficients have been plotted on one quadrant of a vertical plane parallel to the jet boundary and 0·5 diameter from it. Measurements were carried out in one quadrant only because it is felt that, in this preliminary stage of the work, it is advisable to examine the variation on different surfaces rather than to complete the contours for the whole plane, for there is a possibility that there are surfaces on which the correlation contours are simpler in shape.

Finally the possibility of a relationship between the longitudinal space-correlation and the auto-correlation at the reference point has been examined on the hypothesis of the convection of a rigid pattern of pressure past the microphones. At one point 0·5 diameter from the boundary of the jet an approximate relationship exists.

These experiments have suggested two lines of approach, both of which are being pursued. These are:

(1) a much more exhaustive treatment of the space correlations in the near field

(2) the examination of the connection between space-correlation and auto-correlation at more points along the jet boundary and at different jet exit velocities.

The second of these forms the subject of a further report shortly to be completed which examines this idea in a more theoretical manner and suggests the possibility of full-scale estimations from model tests in limited regions in the near field.

5. *Acknowledgements.* The authors wish to express their sincere thanks to K. R. McLachlan of the Electronics Laboratory of the Engineering Department, who was responsible for the design and construction of the computer and gave much-appreciated help in the task of taking measurements, and to Prof. E. J. Richards for his advice and encouragement.

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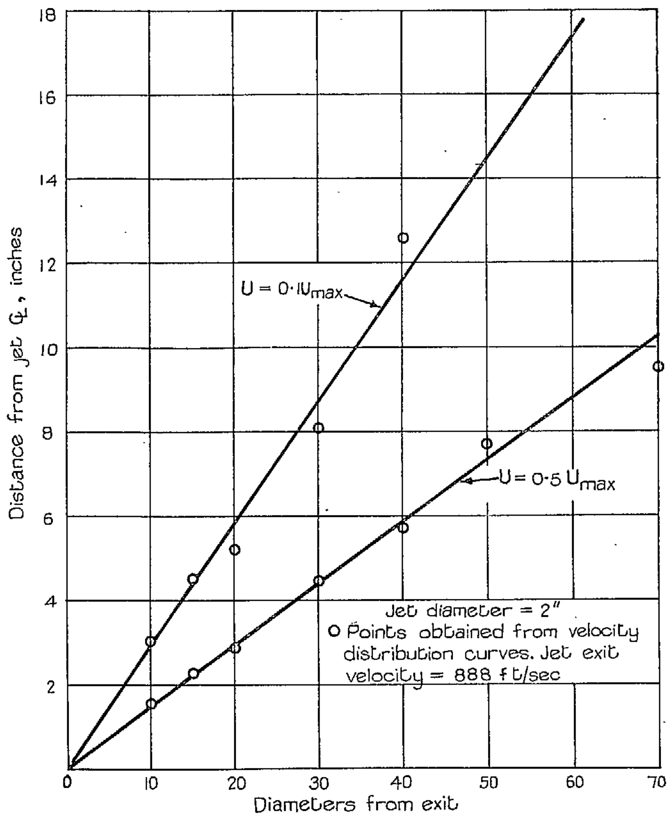

FIG. 1. Spread of the small-scale jet.

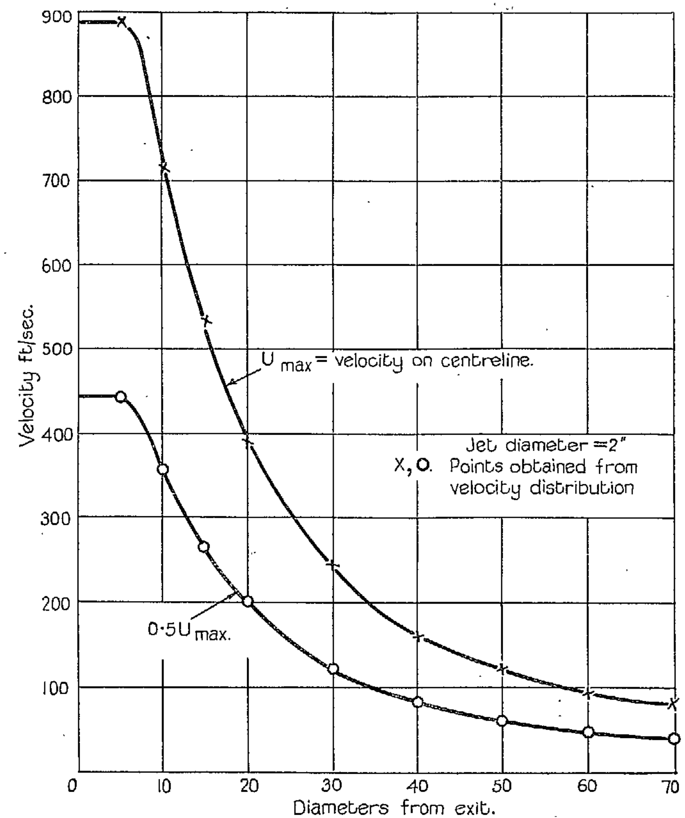

FIG. 2. Decay of velocity in the small-scale jet.

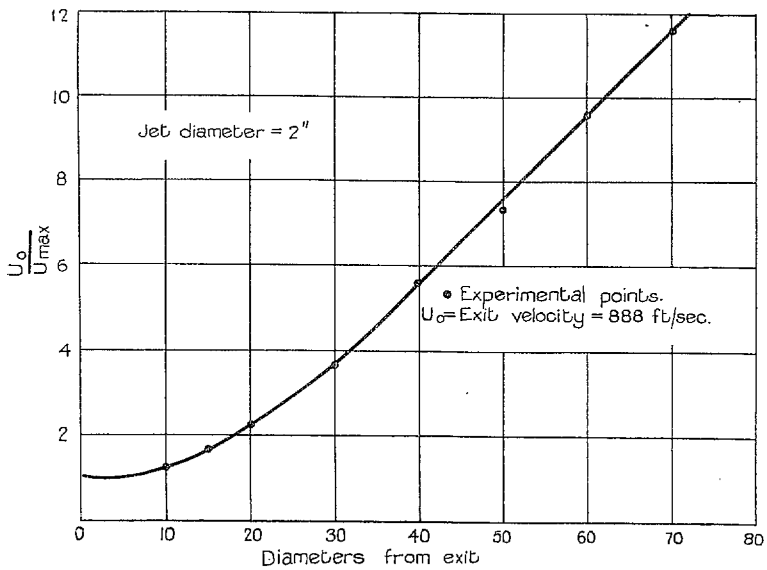

FIG. 3. Decay of velocity in the small-scale jet.

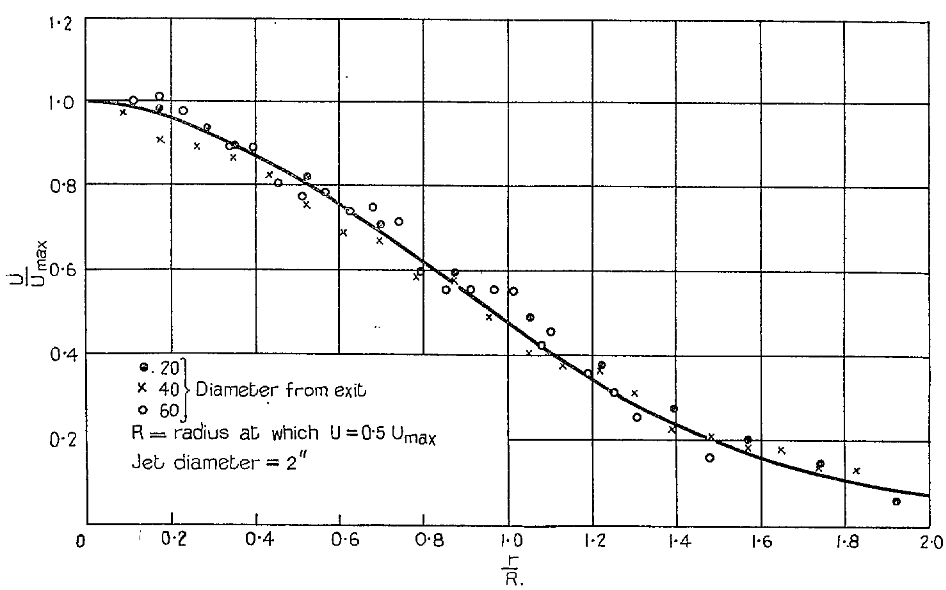

FIG. 4. Experimental velocity distributions in the small-scale jet.

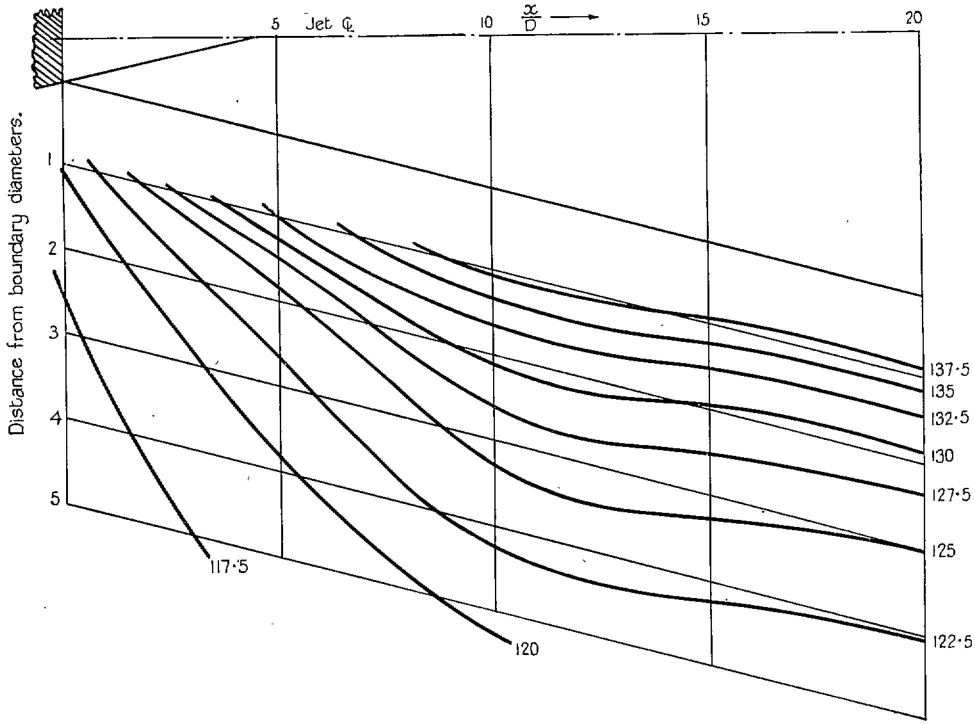

FIG. 5. Contours of equal r.m.s. pressure near a 4-in. diameter jet. Exit velocity = 1000 ft/sec. Numbers on curves give level in *dB* re 0·0002 dynes/cm^2.

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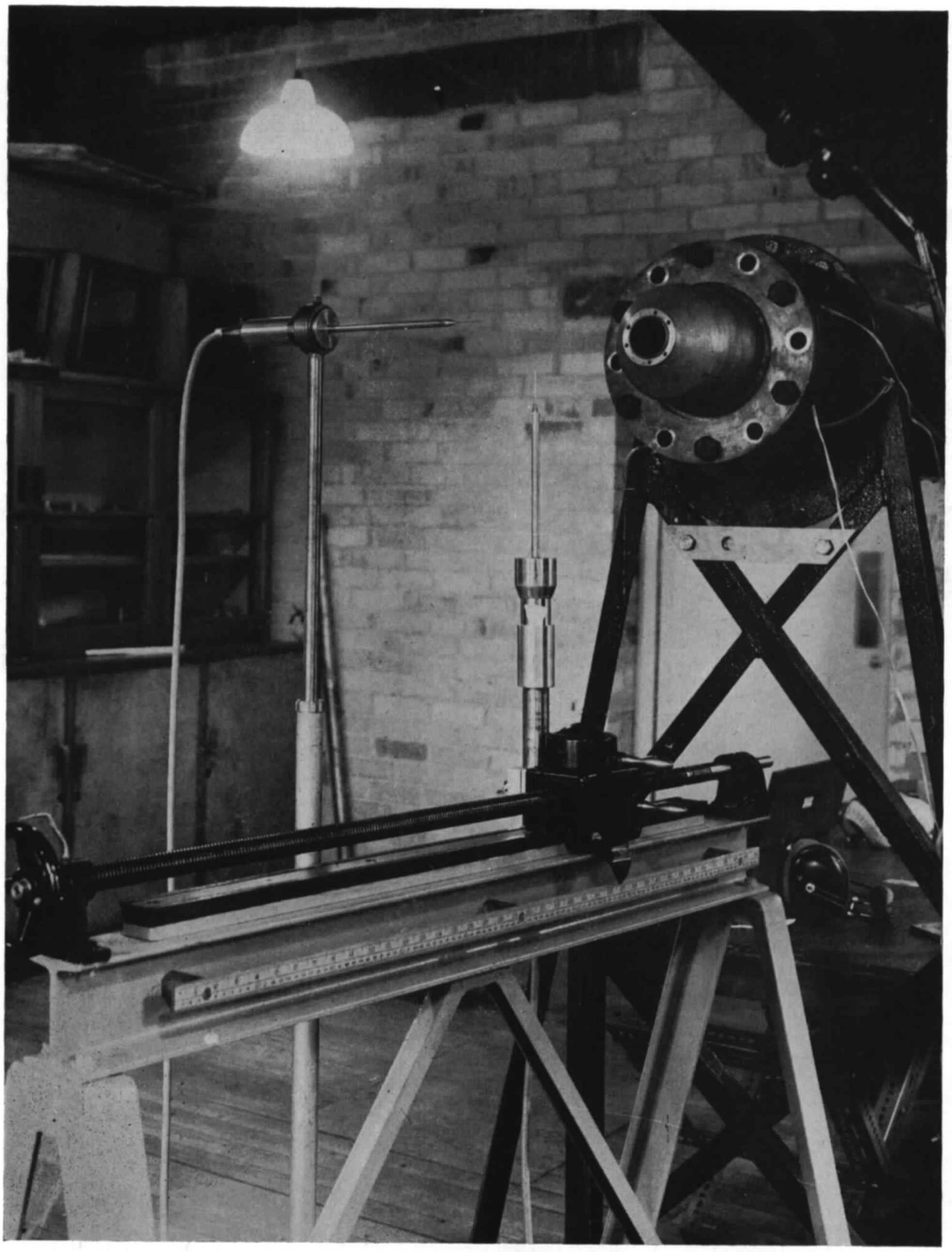

FIG. 6. Photograph of probe microphones and traversing gear. The microphones are here set up for one of the traverses from which the iso-correlation contours of FIG. 10 were obtained.

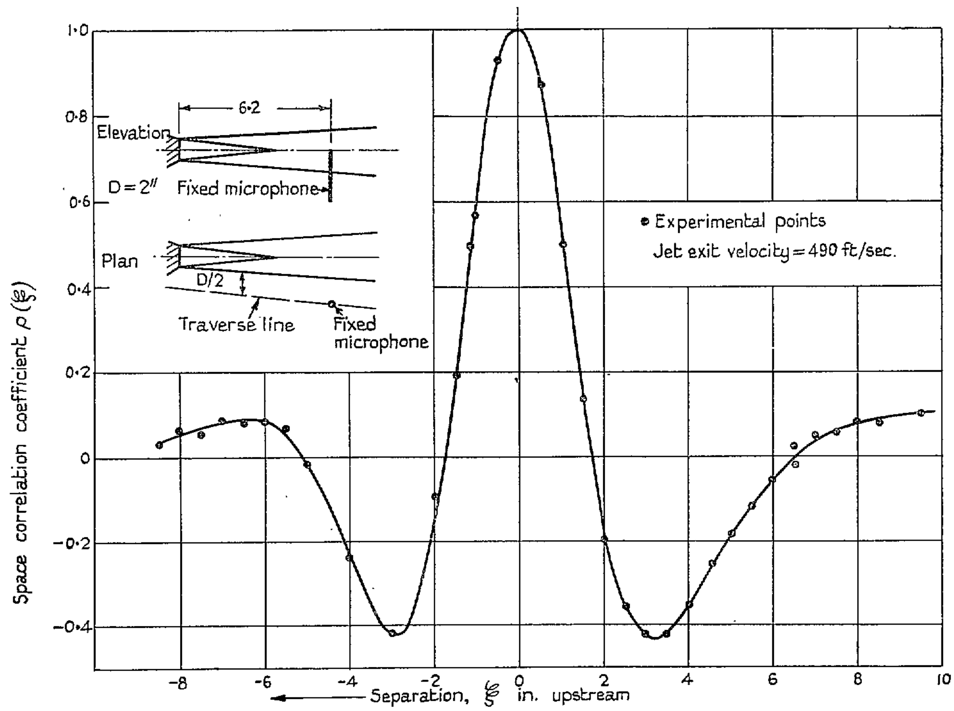

FIG. 7. Space-correlation coefficient of pressures.—Longitudinal traverse on small-scale jet.

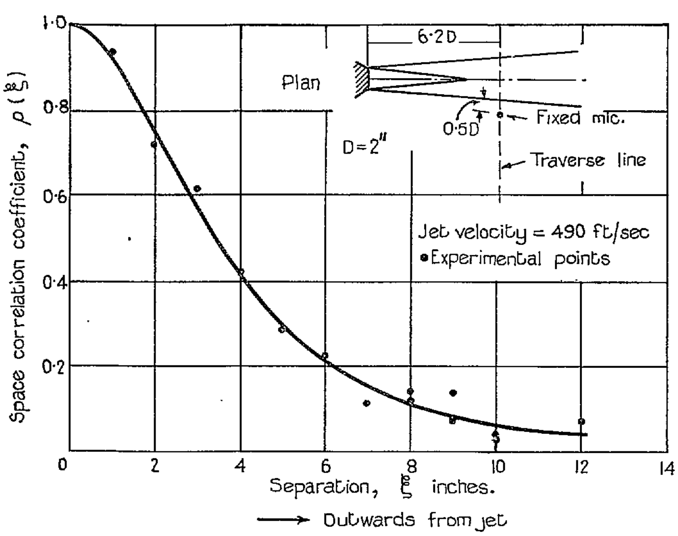

FIG. 8. Space-correlation coefficient of pressures.—Lateral traverse on small-scale jet.

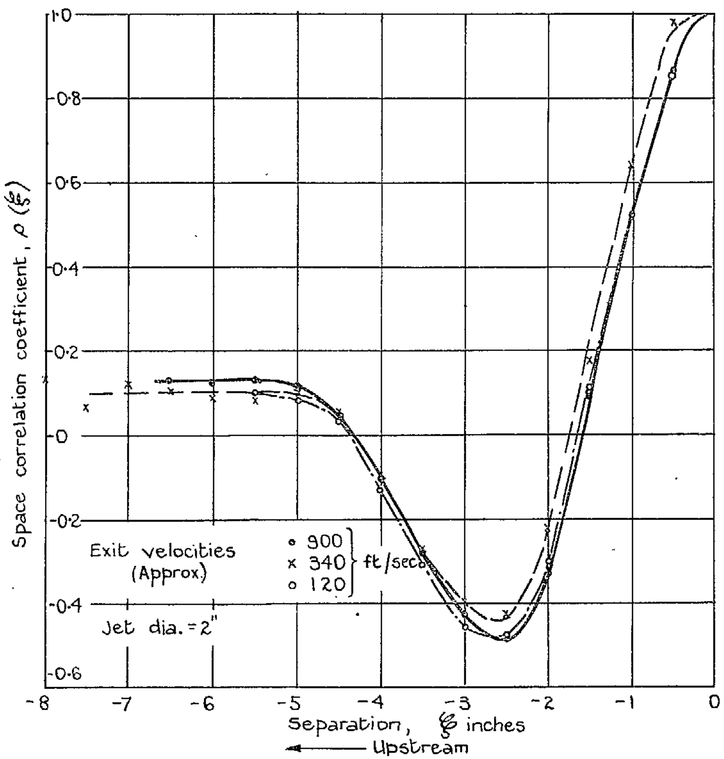

FIG. 9. Variation of longitudinal correlation curves with jet speed.—Reference microphone 5 diameters from exit, 0·5 diameter from boundary of the small-scale jet.

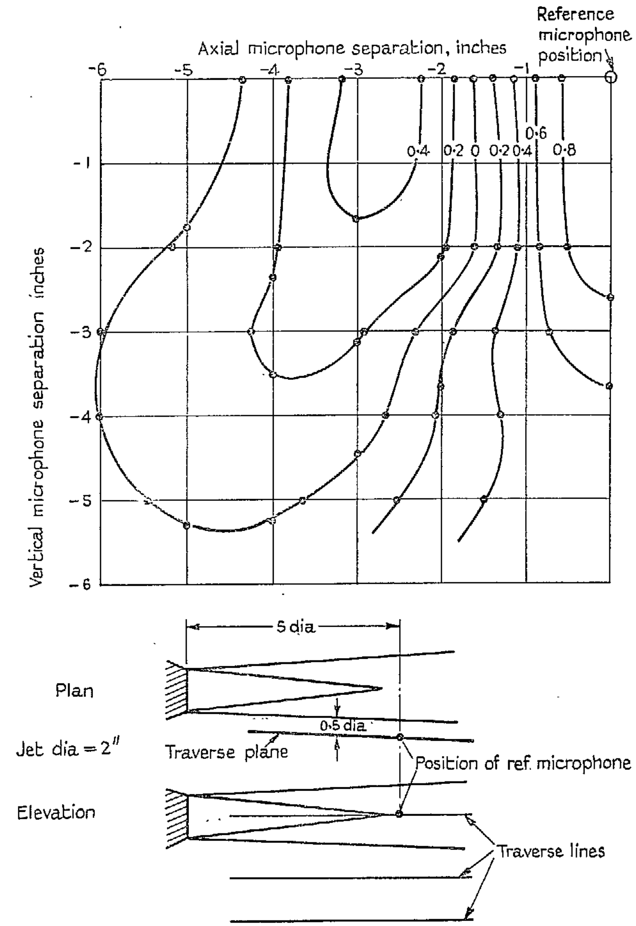

FIG. 10. Contours of iso-correlation coefficient on small-scale jet.—The reference point as shown.

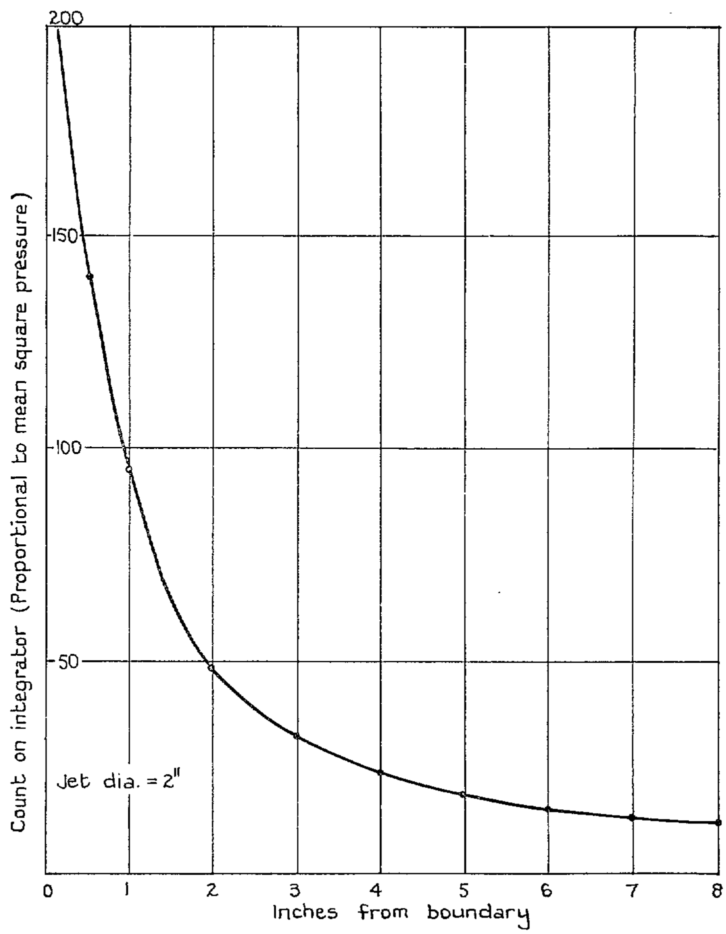

FIG. 11. Variation in signal from traversing microphone during lateral traverse

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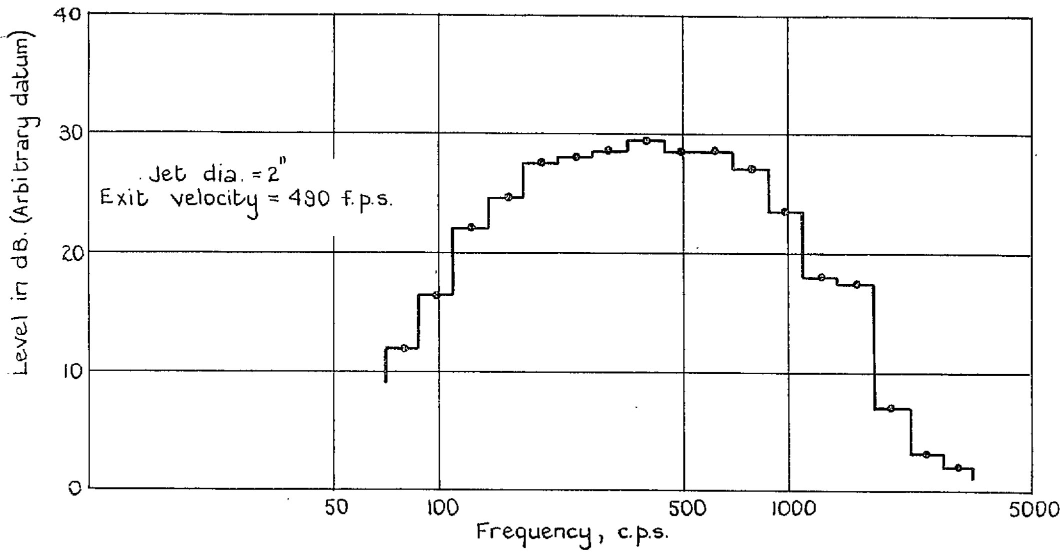

FIG. 12. Spectrum of signal from reference microphone 6·2 diameters downstream, 0·5 diameter from boundary on small-scale jet.

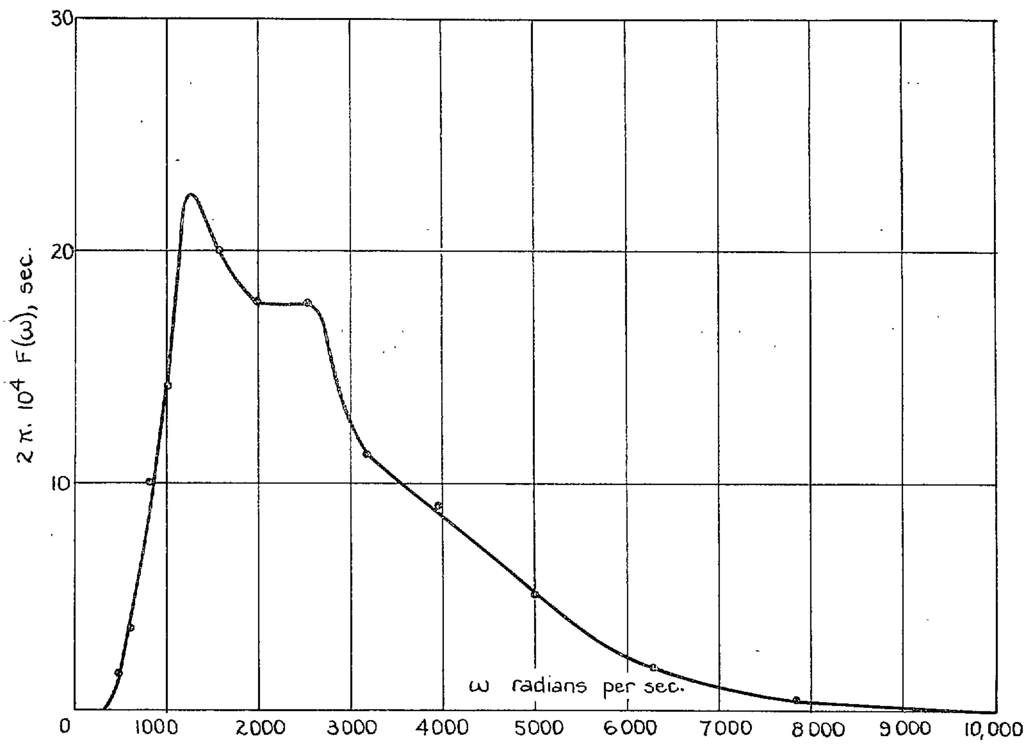

FIG. 13. Power spectral density calculated from Fig. 12.

(78823) Wt. 54/8210 K.5 9/60 Hw.

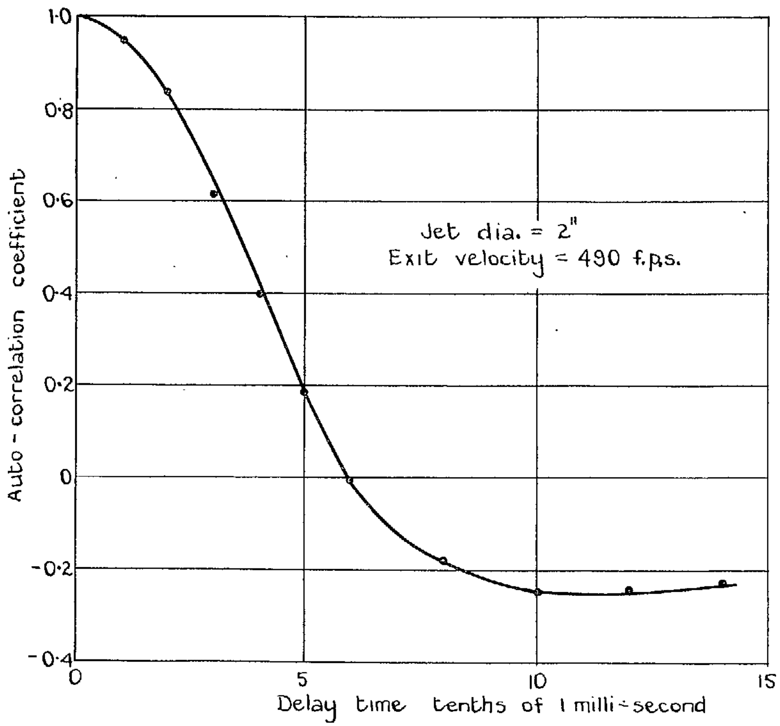

FIG. 14. Auto-correlation coefficient for pressure measured at point 6·2 diameters from exit, 0·5 diameter from boundary.—This curve was computed by taking the Fourier cosine transform of the power spectrum (FIG. 13).

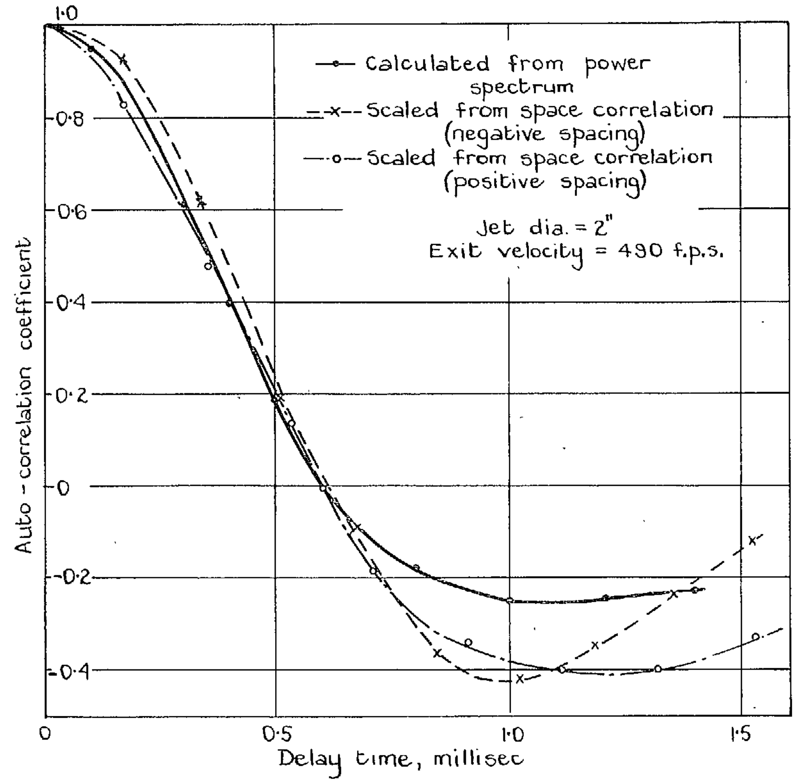

FIG. 15. Auto-correlation coefficient compared with scaled space correlation (Space-correlation curves taken from FIG. 7).

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