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# THE MEASUREMENT OF TURBULENCE IN WATER

A Progress Report Prepared for Presentation at the
Seventh Underwater Ballistics Conference

by

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# THE MEASUREMENT OF TURBULENCE IN WATER

by

M. S. Macovsky

## INTRODUCTION

The development of techniques for measuring the turbulence of fluid media has progressed more in the study of gaseous flow than of liquid flow. The David Taylor Model Basin has recently undertaken the study of turbulence in water both for the purpose of advancing the basic understanding of the phenomenon in water, and for the purpose of applying any fruitful results to the analysis of model testing, and other hydrodynamic problems influenced by turbulence. This paper describes the techniques that have been applied to the study of turbulence in water, and the degree of progress and success of each.

Although the practical importance of fully understanding the phenomenon of turbulence in water has been recognized, progress comparable to that made in air has not been accomplished. It has been only within recent years that the meaning of turbulence in model testing, for instance, has been appreciated. Producing the proper turbulent boundary layer in ship models is essential to accurate testing. Proper model testing is but one of the many reasons which have made the necessity of measuring turbulence in water essential to the Taylor Model Basin.

A number of techniques for measuring turbulence in water have been suggested and a few of them have already been tried at TMB. Hot-wire methods similar to those used in wind tunnels, dye diffusion, and oil-drop injection techniques have been tried. Of these, the most promising is the hot wire.

Each of the techniques will be described, and the results illustrated. First, however, the basic definitions of the turbulence parameters will be reviewed.

## MEANING OF TURBULENCE

Turbulence, by definition, is a state of commotion and agitation. As applied to hydro- and aerodynamics, it is a state of fluid flow wherein random velocity fluctuations are superimposed upon the mean flow. To describe such motion, physicists resort to statistical methods.

In its simplest form turbulence, such as might occur in an open channel behind uniform rectangular wire grids, may be isotropic. Only two parameters are required to describe the degree of such isotropic turbulence, namely "scale" and "intensity".

Generally, the intensity $\sqrt{\overline{u^2}}$ is given as a percentage $\frac{\sqrt{\overline{u^2}}}{U}$ where $\sqrt{\overline{u^2}}$ is the root-mean-square of the velocity fluctuations, and U is the mean free-stream velocity. It has been found (1)* experimentally that the ratio $U/\sqrt{\overline{u^2}}$ is practically independent of U, and that it increases behind a grid nearly linearly with the distance from the grid for values of X/M between 15 and 40.

On the other hand, the scale, L, roughly defines the distance over which turbulent fluctuations are related. Strictly, it is a measure of the distance over which a correlation between velocity fluctuations exists. The correlation coefficient, R, is usually defined as $R = \frac{\overline{u_1 u_2}}{\sqrt{\overline{u_1^2}}\sqrt{\overline{u_2^2}}}$ where $u_1$ and $u_2$ are the velocity fluctuations at points 1 and 2. In isotropic turbulence this may be written $R = \frac{\overline{u_1 u_2}}{\overline{u^2}}$ since $\sqrt{\overline{u_1^2}} = \sqrt{\overline{u_2^2}}$. The scale L is then defined as $L = \int_0^\infty R\,dy$, for measurements made in some direction y. Behind grids of various sizes, it has been found that L/M, where M is the mesh size is independent of U, but that it increases with the distance from the grid.

In non-isotropic turbulence, such as the flow through a small pipe, the "intensity" and "scale" depend upon the direction under consideration and more independent parameters become necessary.

With these few remarks concerning parameters of turbulence we proceed to describe the several methods we have tried to use in measuring them.

## OIL INJECTION METHOD

Several attempts have been made at the Taylor Model Basin to devise methods of measuring L and $\sqrt{\overline{u^2}}$ in water. The first was the photographic method reported in TMB Report C-13 (2). In this test the flow of water through a lucite tube was photographed from two orthogonal planes, the flow being made visible by the injection of neutrally buoyant oil drops. Figure 1 is an example of the record. The analysis of this non-isotropic turbulence consists in measuring the turbulence velocities axially and radially, and statistically combining the results of at least 500 drops. Since the tedium involved in analyzing the data is excessive, the method is not recommendable. As yet, lack of time has prevented complete analysis of the records so obtained.

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* Numbers indicate references on page 8 of this report.

## HOT WIRE METHOD

In view of the tediousness of the oil-drop injection method, other, more direct techniques were required. The hot-wire anemometer has provided such a technique in wind tunnel turbulence measurements. Direct application of a wind-tunnel type hot wire to water has been tried, and with a fair amount of success.

Briefly, the theory of the hot wire is as follows. From the fundamentals of electricity it is a well-known fact that the resistance of a metallic wire is approximately a linear function of its temperature. With this in mind, L. V. King in 1914 (3) discovered the relationship between the resistance of a heated fine platinum wire, and the velocity of the cooling air stream in which it was placed. He found that for the wire placed normal to the stream

$$H = i^2R_e = (a + b\sqrt{V})(\theta - \theta_a)$$

where $H$ is the rate of heat lost per unit length of the wire,
$i$ is the heating current,
$R_e$ is the instantaneous wire resistance,
$V$ is the velocity of the stream,
$\theta$ is the temperature of the wire, and
$\theta_a$ is the temperature of the stream.

This relationship has since been successfully applied to measuring steady and fluctuating air velocities.

There are two principal methods of operating the hot wire. In the first, the temperature, i.e., the resistance, of the wire is maintained at a constant value. The heating current required to do this is then a function of the velocity. In the second method, the heating current is maintained constant, and the resistance allowed to fluctuate with the velocity changes. This second technique has been employed in the turbulence experiments in water.

For a rapidly fluctuating velocity field, the voltage variations of the ideal hot wire should be in phase with the velocity. Failure of a hot wire to do this arises from the existence of its time constant, M, which depends upon the size of the wire, and the operating conditions. A value of M different from zero results in a voltage output lagging in phase behind the velocity fluctuations, and a voltage output whose amplitude is diminshed with increasing velocity frequency, f, in the ratio $\frac{1}{\sqrt{1+4\pi^2f^2M^2}}$. Both of these effects, reduction in amplitude, and phase lag, can be corrected by proper compensation circuits in the amplifiers used with the instrument.

The sensitive elements used in these tests are tungsten wires 0.00031 inch in diameter, and 0.20 inch in length. Similar wires used by Schubauer at the Bureau of Standards (4) had measured time constants of approximately 0.002 second. Preliminary measurements of the same wire in water exhibit time constants in the order of 50 to 100 microseconds. The difference is probably accounted for by the fact that the thermal conductivity of water is about 25 times greater than that for air. The present tests have been conducted without compensation for thermal lag.

The hot-wire circuit shown in Figure 2 is identical with those described in Reference (1). From the theory of this circuit it is possible to measure the correlation coefficients of a turbulent stream by proper combination of the outputs of the two wires. Assuming that the velocity fluctuations are small, then the voltage fluctuations across each wire are proportional to changing velocities. By means of the reversing switch S, the voltages of the two wires can be added or subtracted before amplification. This combined output, amplified, can then be measured by a vacuum-type thermocouple and microammeter. The reading of the meter is proportional to the mean square of the voltage input. If $M_a$ is the microammeter reading for the voltages added; and $M_b$, that for the voltages subtracted, then

$$M_a = K\overline{(e_1+e_2)^2} = K'\overline{(u_1+u_2)^2} \text{ and}$$

$$M_b = K\overline{(e_1-e_2)^2} = K'\overline{(u_1-u_2)^2}$$

where $e_1$ and $e_2$ are the instantaneous voltages of the respective wires, and $u_1$ and $u_2$ the respective turbulent velocities at each. It can be shown by algebra that the correlation coefficient $R = \frac{M_a-M_b}{M_a+M_b} = \frac{\overline{u_1 u_2}}{\overline{u^2}}$ for isotropic turbulence.

For measurement of turbulent intensity, only one wire is required. It can be shown that the per cent of intensity is

$$\sqrt{\frac{\overline{u^2}}{U}} = \frac{2 R_w e'}{iF \sqrt{U} \ (\bar{R}-R\ )^2}$$

where $R_w$ is the resistance of the wire at water temperature,
$e'$ is the root-mean-square voltage fluctuation as measured by the calibrated microammeter,
$\bar{R}$ is the mean operating resistance of the wire,
$i$ is the heating current,
$F$ is the slope of the static calibration of the wire,

$R/(\bar{R}-R_W)$ vs $\sqrt{V}$ (a linear function), which is determined by comparison with a calibrated pitot in different laminar velocities.

The probe shown in Figure 3 has been used for both correlation and intensity measurements. The upper hot wire is fixed to the faired brass strut; the lower, is adjustable in the vertical plane by the micrometer screw as illustrated. Wire separation can be adjusted to a maximum of 3 inches ± 0.001 inch. The hot-wire tungsten elements are soft-soldered across two steel sewing needles which in turn are soldered to fine brass tubes connected to the lead wires. Since it is not possible to solder tungsten directly, the wire was first copper plated electrolytically except for the 0.20 inch measuring section.

## TURBULENCE MEASUREMENTS IN THE MODEL CIRCULATING WATER CHANNEL

Measurement of turbulence behind two geometrically similar grids were conducted in the 1/22-scale model of the circulating water channel at the TMB. The experimental arrangement is illustrated in Figure 4. The hot wire probe was mounted in the channel at distances of 15, 20, and 25 mesh lengths downstream from grids of ½- and 3/4-inch mesh size. At each position, both correlation and intensity measurements of the created turbulence were obtained. The speed of the channel for all tests was approximately 1.8 feet per second.

The results of the experiment are illustrated in Figures 5 through 8. In each instance it has been assumed that the turbulence was isotropic, and that the channel without the grid was nearly laminar. Actually, it is believed from preliminary measurements that a turbulence intensity of about 1% characterized the grid-free channel.

In Figure 6, correlations are compared with similar measurements made by Hall in a wind tunnel (5). Lack of close agreement between the two may be accounted for by the differences of the two media, differences in the initial turbulence of the stream, and insufficient correction of TMB results. Since these experiments are preliminary neither time constant compensation nor wire-length (1) corrections have been applied to the data.

In spite of their preliminary nature, the TMB data confirm qualitatively the law previously mentioned regarding the variation of scale with distance from the grid. Figures 6 and 7 illustrate this in the increasing area under the correlation curves for the greater distances from the grid.

The decay law of intensity, and its independence of Reynolds number are illustrated in Figure 8. Comparison of the

TMB results with those obtained by Hall (5) and Schubauer (1) shows that the data for water are not only in agreement with the slope of the decay curve, but also in order of magnitude. Differences between Hall's curve and Schubauer's curve have been attributed (5) to differences in initial wind-tunnel turbulence.

## PRINCIPAL DIFFICULTY OF THE HOT WIRE IN WATER

It has been found in wind tunnel applications of the hot-wire anemometer that frequent brushing of the wire is compulsory for maintainance of a constant calibration. The rate of dirt accumulation in water, even drinking water, is many times that for air and the calibration of the wire changes within a matter of minutes in water. Constancy of calibration is accomplished only by very frequent brushing. Consistency of results where a constant calibration is required, such as in the measurement of intensity, can only be obtained by observing data immediately after the wire has been cleaned. In measurement of correlation, however, it was assumed that both wires were accumulating dirt at approximately the same rate, and hence, changing calibration at the same rate. Although their sensitivities were gradually diminishing, the wires could still measure correlation provided their response characteristics remain nearly alike. Even in the correlation measurements, however, the two wires were frequently cleaned.

## APPLICATION OF HOT WIRES TO TURBULENT BOUNDARY-LAYER INVESTIGATIONS

Turbulence in boundary layers has been a subject for investigation for some time in wind tunnel work. Only recently, however, has research been undertaken at TMB to investigate the nature of the boundary layer on ship models. Not only is it of importance to know the characteristics of the laminar and turbulent regions, but locating the region of transition from laminar to turbulent boundary layer is essential in estimating frictional resistance.

Locating the region of transition under variable operating conditions, therefore, was the first phase of the investigation undertaken with the hot wire. Preliminary tests have been conducted on a wood friction plane 6 feet long, 12 inches wide, and 0.50 inch thick with ends tapering to a thickness of 0.04 inch. The plane, fitted with 6 fixed hot wires, was towed in the deep water basin at Carderock. The hot wires were platinum; 0.0015 inch in diameter and 0.25 inch in length. The normal distance of the wires from the surface was measured, and the average distance was 0.016 inch which was well within the laminar boundary layer at the wire locations.

A simple series heating circuit similar to that of Figure 2 was used to heat the wires. A current of 1.0 ampere was maintained, and the fluctuating voltage output of the wires was amplified and recorded by a string oscillograph. No compensation for thermal lag was used.

Definite evidence of transition was detected on one of the two wires located at the midlength of the plane. A sample of the record is given in Figure 9. The record which may be expected from mixed or transitional flow is typified by Figure 9(c). At higher speeds it is seen that the flow was turbulent, being characterized by higher frequency and the expected smaller amplitude fluctuations resulting from lack of compensation.

Similar experiments have been conducted on a ship model with equal success. The hot wire, therefore, can be used in this manner to distinguish qualitatively between laminar and turbulent flow. Measurement of scale and intensity of the turbulence in boundary layers in being considered, and such results should provide significant information regarding the accuracy of present methods of artificially creating turbulent boundary layers by various size rods placed ahead of the model being towed.

## DYE DIFFUSION METHOD OF MEASURING TURBULENCE

A third method of measuring turbulence intensity, which depends upon the diffusion by turbulence of a dye injected into the stream, has been tried in the model channel. A fine brass rod replacing one of the strands of a ½-inch mesh, and bent in the form of an L extending 15 mesh lengths downstream was used as an injector of a water solution of red dye.. A similar rod attached to a pipette served as a sampler probe. With the channel operating at a speed of about 1 knot, cross-stream surveys by sampling the water were made at distances of ½, 3/4, and 1 inch from the nozzle of the injector. The concentration of the samples of each survey was compared with the original concentration of dye by means of an electrophotometer. The boundary of the diffusing dye wake, defined as the standard deviation of the cross-stream distribution of dye concentration was determined at the three stations. The slope of the boundary so determined was applied to determine the value of the turbulence intensity in the region of the dye injector nozzle. In Figure 8 the result of the experiment is seen to agree, in order of magnitude, with the hot wire results. Since the experiment was carried out in a rather crude fashion, better agreement was not expected.

## CONCLUSION

Since the measurement of turbulence in water is still in its preliminary stages, it is impossible to discuss any real deviations from the laws describing the phenomenon in air. First appearances would indicate that the same laws hold in both media. With further development of the hot-wire technique, and possibly the dye-diffusion technique, it may be possible in the near future to confirm or amend the laws of turbulence as they apply to air to describe the situation in water. Aside from its use in investigation of fundamental properties of turbulence, the hot-wire has already shown that it will be a valuable tool for the investigation of boundary layers of ship models, a study which, as is becoming increasingly apparent, is necessary for improving prediction of full-scale performance.

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2. "The Development of Facilities and Photographic Methods of the Study of Turbulence in Water," by P. Eisenberg, M. S. Macovsky, and C. E. Lemich, TMB CONF Report C-13, Sept. 1947.

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4. "Theory and Application of Hot-Wire Instruments in the Investigation of Turbulent Boundary Layers," by G. B. Schubauer, and P. S. Klebanoff, NACA, ACR No. 5K27, March 1946.

5. "Measurements of the Intensity and Scale of Turbulence," by A. A. Hall, Aero. Res. Com., Rep. and Memo. No. 1842, August 1938.

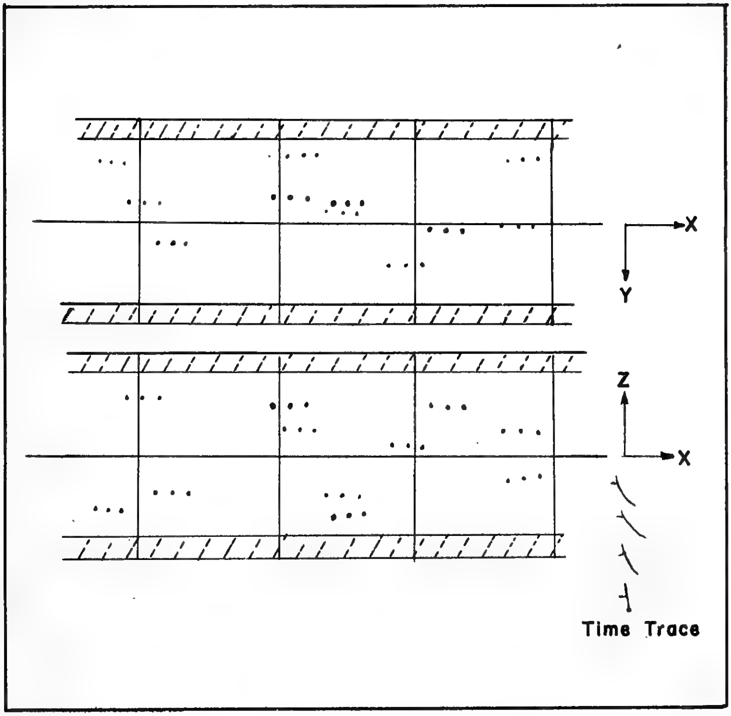

FIGURE 1 COPY OF PHOTOGRAPH OF OIL-DROP METHOD FOR MEASURING TURBULENT FLOW THROUGH A LUCITE TUBE AT A MEAN VELOCITY OF 10 FT./SEC.

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OCTOBER 1948

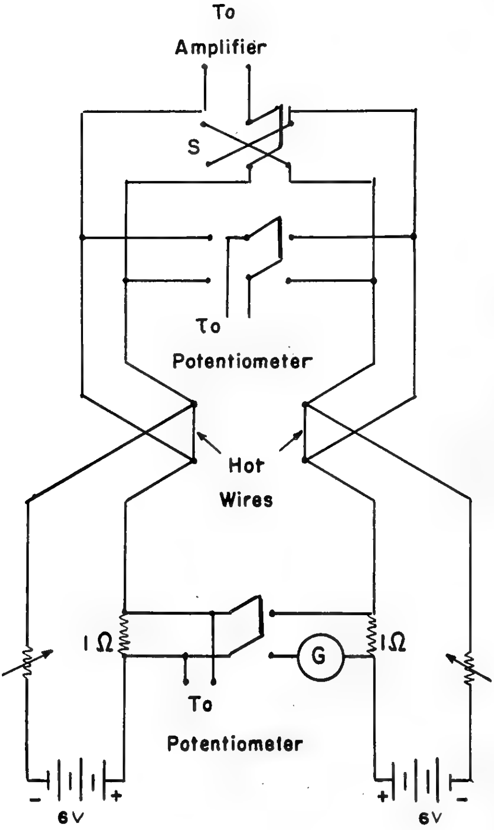

FIGURE 2. HOT WIRE CIRCUIT USED IN MEASURING CORRELATION BETWEEN VELOCITY FLUCTUATIONS.

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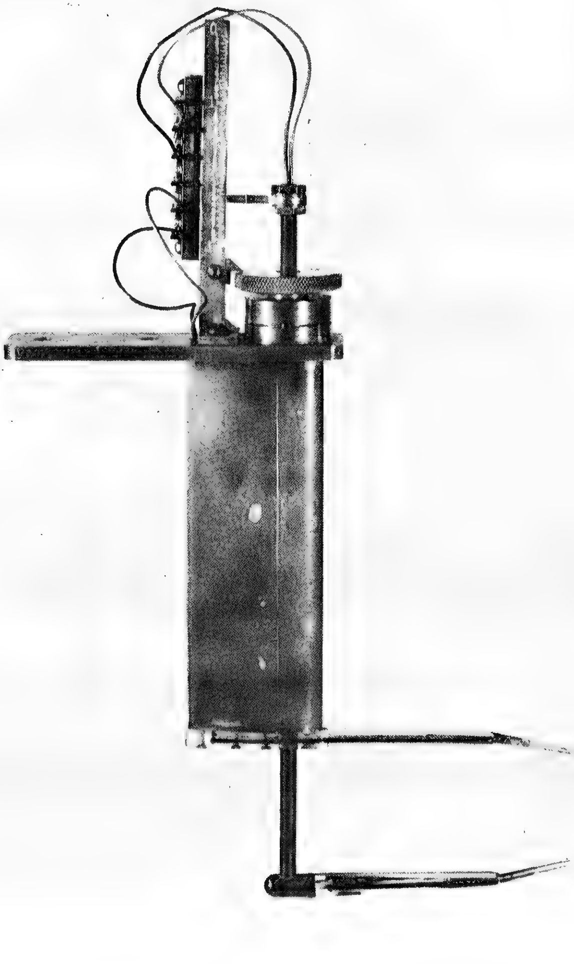

FIGURE 3 HOT WIRE PROBE FOR TURBULENCE MEASUREMENTS
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TMB 30259 11 OCTOBER 1948

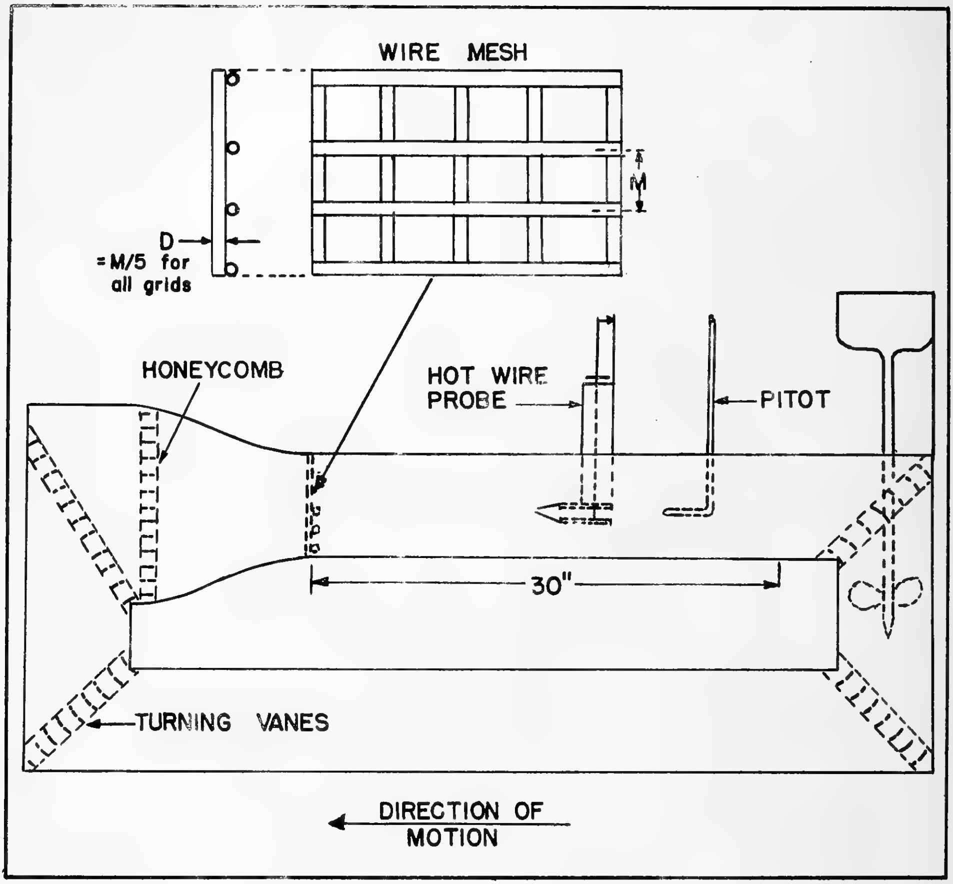

FIGURE 4 SCHEMATIC DIAGRAM OF THE EXPERIMENTAL ARRANGEMENT IN THE 1/22-SCALE MODEL OF THE CIRCULATING WATER CHANNEL

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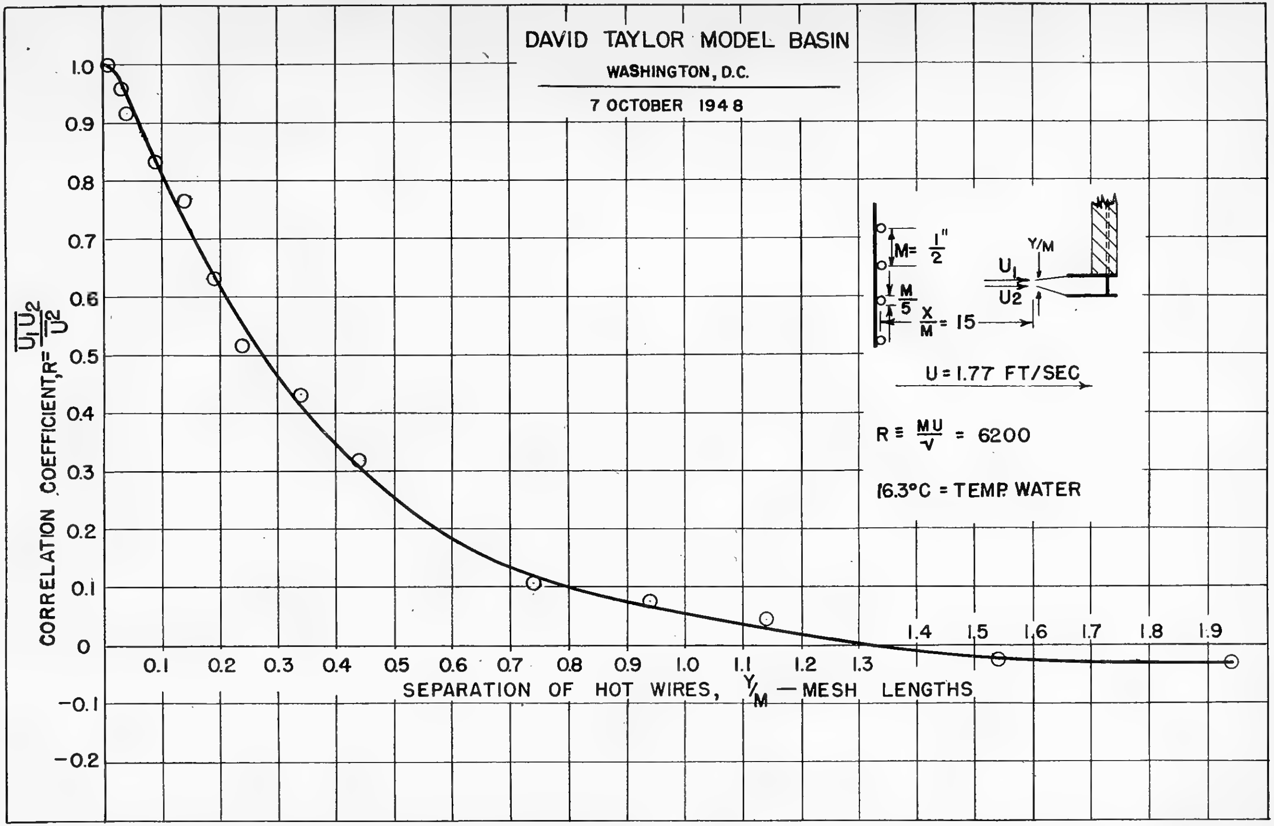


FIGURE 5 HOT-WIRE OBSERVATIONS OF CORRELATION COEFFICIENTS IN ISOTROPIC TURBULENT FLOW IN WATER BEHIND A GRID OF 1/2-INCH MESH

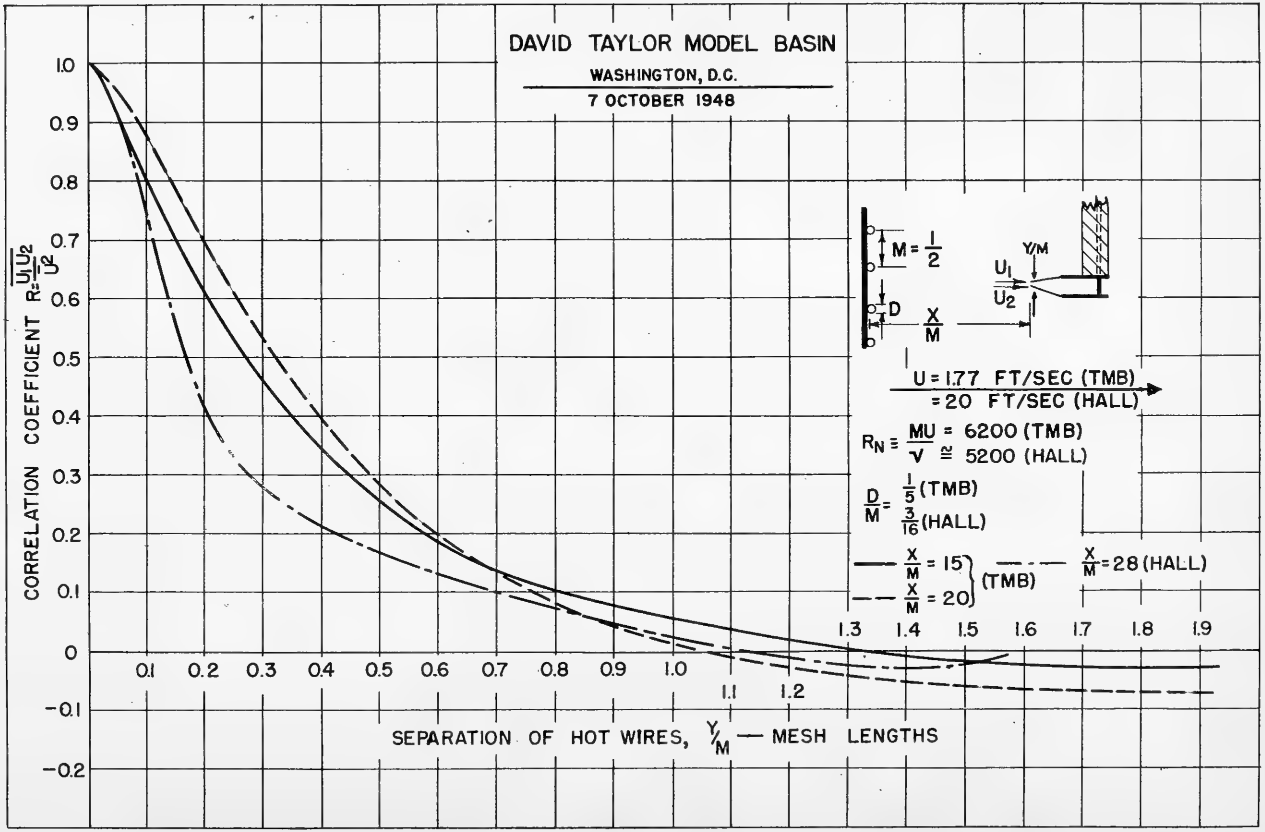


FIGURE 6 HOT-WIRE OBSERVATIONS OF CORRELATION COEFFICIENTS IN ISOTROPIC TURBULENT FLOW IN WATER BEHIND A GRID OF 1/2-INCH MESH COMPARED WITH SIMILAR WIND TUNNEL DATA

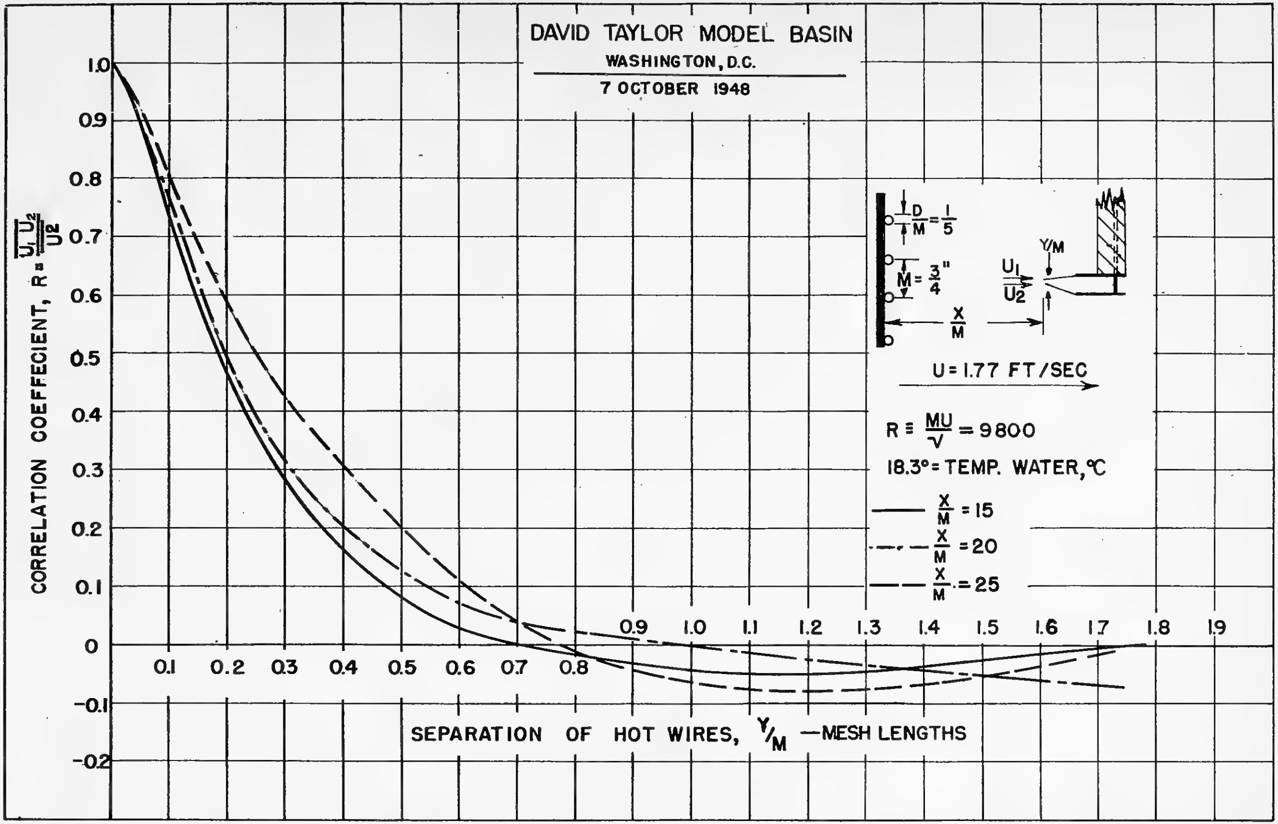


FIGURE 7 HOT-WIRE OBSERVATIONS OF CORRELATION COEFFICIENTS IN ISOTROPIC TURBULENT FLOW IN WATER BEHIND A GRID OF 3/4-INCH MESH

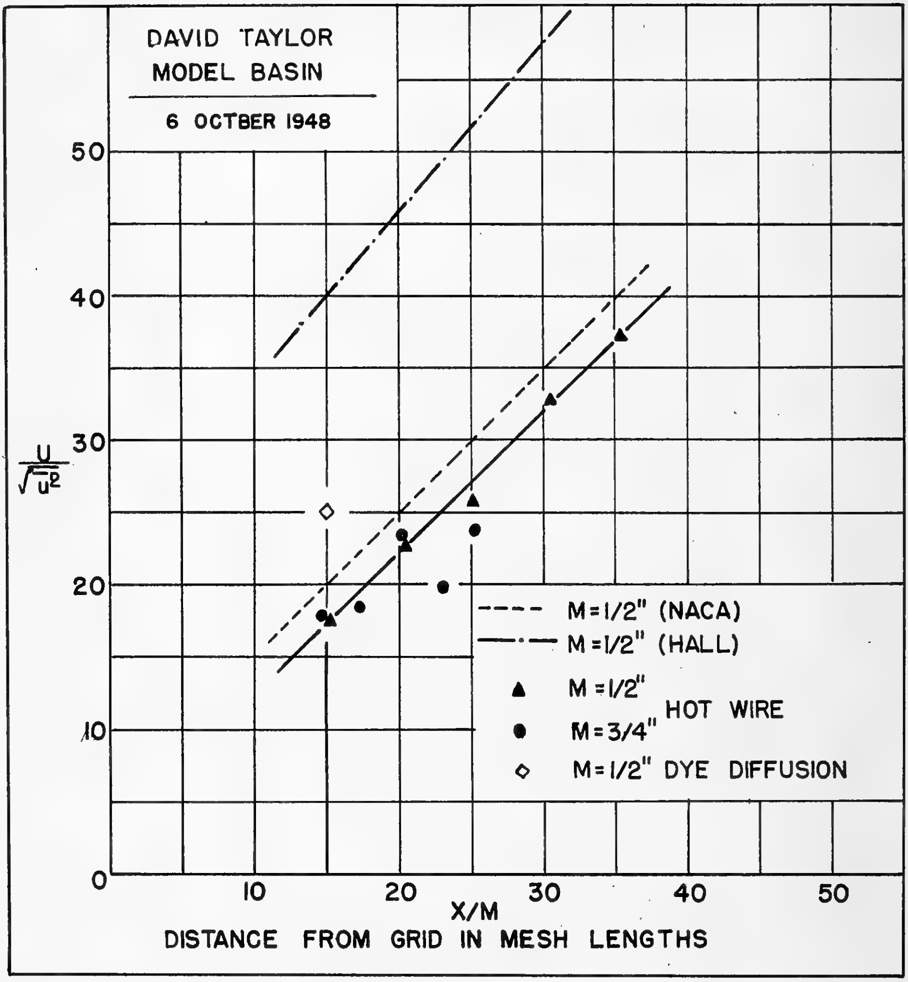
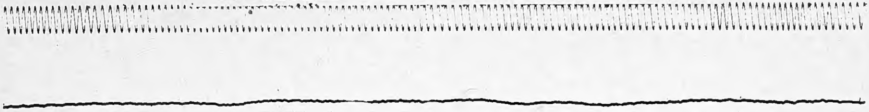
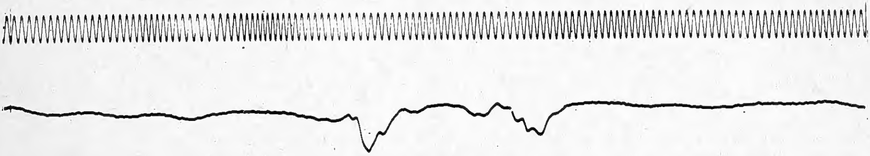


FIGURE 8 HOT-WIRE OBSERVATIONS OF DECAY OF ISOTROPIC TURBULENCE IN WATER COMPARED WITH SIMILAR WIND TUNNEL DATA

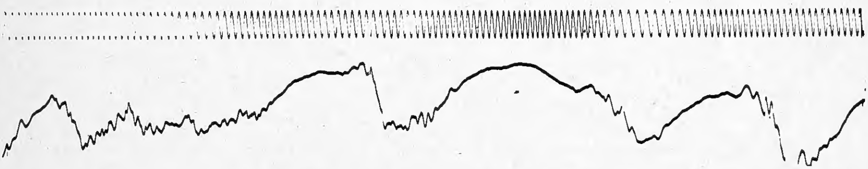
60 CYCLES PER SECOND TIMING TRACE



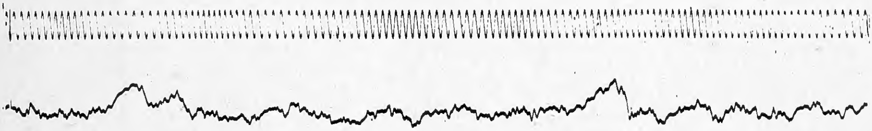
(a) SMALL LAMINAR OSCILLATIONS; TOWING SPEED V = 1.25 KNOTS X-REYNOLDS NUMBER, $R_x = 5.16 \times 10^5$



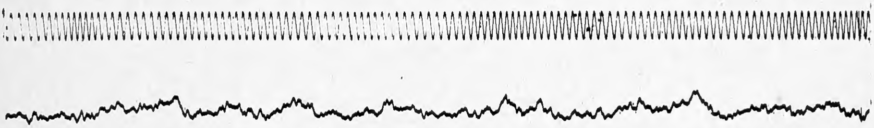
(b) INCEPTION OF TRANSITION; V = 1.49 KNOTS, $R_x = 6.15 \times 10^5$



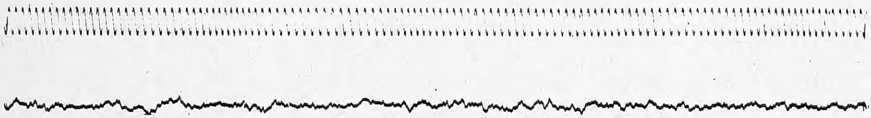
(c) TRANSITIONAL FLOW; V = 1.74 KNOTS; $R_x = 7.18 \times 10^5$



(d) TURBULENT LAYER; V = 1.99 KNOTS; $R_x = 8.21 \times 10^5$



(e) TURBULENT LAYER; V = 2.25 KNOTS; $R_x = 9.29 \times 10^5$



(f) HIGH FREQUENCY TURBULENCE; DECREASE IN AMPLITUDE IS PARTLY CAUSED BY LAG EFFECT OF HOT WIRE WHICH WAS NOT COMPENSATED; V = 3.50 KNOTS; $R_x = 1.44 \times 10^6$

FIGURE 9: OSCILLOGRAPH RECORDS OF HOT WIRE RESPONSE TO VELOCITY FLUCTUATIONS IN THE BOUNDARY LAYER OF A THIN, FLAT PLATE TOWED IN WATER. HOT WIRE WAS LOCATED 3 FEET AFT OF FORWARD EDGE OF PLATE.

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