EXPERIMENTAL STUDY OF THE FLOW FIELD DOWNSTREAM OF A SINGLE TUBE ROW

By

CHENG MINTER

B.S. Mechanical Engineering Department
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Mechanical And Aerospace Engineering
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APPROVED BY :

Committee Chairman : ______________________

Committee Member : ______________________

Committee Member : ______________________

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ABSTRACT

This report describes the investigation of the flow phenomena at various positions downstream of a tube row having a pitch-to-diameter ratio of 1.3, using a Pitot tube, a Kiel probe, and a hot-wire anemometer. The flow through this row of parallel cylinders can be considered as a number of two-dimensional jets passing through the gaps of the cylinders. The experimental results show that the flow is unstable at these conditions. The instability results in the jets tending to coalesce in random groups immediately after their exit from the tube row, resulting in strongly eddying flow. The jets turn one way or the other because of the Coanda effect. The remarkable observation is that the flow downstream of a closely spaced tube row has multiple stable configurations, which are maintained irregularly for long periods.

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NOMENCLATURE

C_p – dimensionless pressure coefficient

D – tube diameter

E – hot-wire anemometer bridge voltage

I – hot-wire anemometer bridge current

P – surface pressure

P_s – undisturbed stream static pressure

Q – rate of heat transfer

R – hot-wire anemometer bridge resistance

Re – Reynolds number

S – Strouhal number based on the undisturbed mean velocity

S′ – Strouhal number based on the mean gap velocity

U – mean-flow velocity

U_g – gap velocity

ρ – mass density

CHAPTER 1

INTRODUCTION

Rows of tubular cylinders subjected to cross flow are used in a variety of heat exchanger equipment. In recent years, there has been a trend toward much larger heat exchangers with increased shell-side flow velocity to improve heat transfer. In some cases, this has resulted in the occurrence of strong vibrations in the tube banks, accompanied by intense noise. The large amplitude of the heat exchanger tubes can lead to fatigue and fretting failures. These vibration problems must be taken into account when designing highly rated heat exchangers. Heat exchanger designers need to know when the flow-induced vibrations will occur and how to suppress them. In order to get a deeper insight of this question, one must understand the mechanism of vibration involved.

The flow through tube banks with the tube axes normal to the gas flow is highly turbulent, containing numerous vortices of different sizes and intensities. The buffeting forces can be either random or periodic in nature depending on the flow phenomenon involved.

When a flow passes a single cylinder or a series of parallel ones, vortices will be formed in the wake after the cylinder within a certain range of the Reynolds number. It is reasonable to consider that the flow through a row of parallel cylinders is made up of a number of two-dimensional jets passing through the gaps of the cylinders. These jets are separated by a series of wakes behind the cylinders. In certain cases the flow downstream of a closely spaced row of parallel cylinders is unstable. The instability results in the jets tending to coalesce in random groups. This flow instability behind a tube row is of importance in the vibration problems of heat exchangers.

This paper includes the investigation of this flow phenomenon at various distance downstream of a tube row having a pitch-to-diameter ratio of 1.3, in a cross-flow of Reynolds number equal to 100,000 (based on the gap velocity Ug), using a Pitot tube, a Kiel probe, and a hot-wire anemometer. It is found that :

1.) The flow is unstable downstream of a tube row with a pitch-to-diameter ratio of 1.3.
2.) Two or more jets merge together immediately after the tube row due to the Coanda effect.
3.) The unstable flow phenomenon is caused by the flow itself, not by mechanical irregularities of the tube row.
4.) The flow has multiple meta-stable configurations which are maintained irregularly for a long time.

5.) The maximum turbulence intensity was in the shear layer, for a short distance behind the tube row. At further downstream positions, the shear layer developed, and the turbulence filled up the whole jet.

6.) No characteristic frequency in the wake of the tube row was identifiable by means of spectral analysis, under these circumstances.

The problem has been simplified in the present instance to an ideal model, this model consists of a single row of circular cylinders mounted normal to the airstream. The tube bank heat exchanger can be usually considered as a series of tube rows arranged in a rectangular duct. It is believed that the investigation of this simple tube row serves as a basic step to the investigaiton of multi-rows of tube bank. The time available for preparing and performing the experiments was too short for a thorough investigation of all cases of the flow, but it was hoped to obtain some basic ideas for further research.

CHAPTER 2

LITERATURE SURVEY

There has been a numerous papers about flow across a single cylinder, but for a tube row there are only a few reports available.

R. Gran Olsan (1936) dealt with the flow phenomenon behind a row of rods having a pitch-to-diameter ratio of 4.0 and found no instability for this case. His work was mainly concerned with mixing in fully developed turbulent flow, and the flow was not truly two-dimensional in his experiments. G. Cordes (1937) investigated essentially the same problem as Gran Olsan did, and no instability was found in his experiment also.

J. G. von Bohl (1940) succeed in obtaining both stable and unstable cases by varying the open area ratio of a grid. He conducted his experiments by using flat sharp-edged wooden slats set normal to the airstream and obtained " pitch-to-diameter " ratios of 2.7 and 2.2, corresponding to stable and unstable flow conditions respectively. This is the first complete theoretical and experimental investigation of this problem.

A thorough investigation of the stability of two-dimensional flow through a row of parallel rods was made by S. Corrsin [1]. He conducted his experiments by using a row of non-circular brass rods having a " pitch-to-diameter " ratio of 1.20. By using a hypodermic-needle total-head tube, he measured total head distribution at a series of positions downstream of the row of rods. His principal experimental result was the observed instability of the system of two-dimensional jets issuring from the slots in a grid made up of a row of parallel rods having a " pitch-to-diameter " ratio 1.20. The phenomenon was nonstationary in the sense that the same pair of adjacent jets did not always unite first. He explained that the physical mechanism of this coagulation of the jets appeared to depend upon the entrainment of air by individual jets from the wakes between them. His explaination for the mechanism of instability is as follows : " The entrainment reduces the static pressure between jets, tending to force them together. As a jet spreads out downstream, it behaves like a diffuser, so that its center-line static pressure increases downstream. The pressure difference between the jets and the air between them is balanced by divergent curvature of the jets streamline. Thus, for a series of jets, the wider the spacing between them, the greater the diffusion angle between the individual jets before adjacent jets combined with one another; and when the spacing between the jets is sufficiently great (i.e., the open area ratio of the screen is small), the necessary angle is prohibitively large, resulting in a breakdown or instability of the flow. ". It would appear that, for given flow conditions, there might be a critical opening ratio for the screen below which the instability of the flow might be expected and above which the flow might be regarded as completely stable. Bohl's measurements gave an approximate confirmation of this hypothesis. He dealt with only one case, a pitch-to-diameter ratio of 1.20, and observed definite instability. He also found that at small distance downstream of the row of rods, the turbulence maxima coincided with the velocity minima, which were the regions between jets. In the same paper, he presented two possible methods to prevent instability.

P. G. Morgan [2] reviewed the instability of the flow through screens of low opening ratio, considered the case of a two-dimensional grid composed of parallel rods equally spaced and made some suggestions concerning possible mechanism for it. He also investigated the three-dimensional flow across screens made of wire gauze and perforated plate. In his measurements of static and total pressure behind various screens, instability of the flow was observed in the form of sudden changes in pressure after a period of apparent steadiness. He found that, in general, the larger the opening area ratio of the screen the less time was required for the static pressure tapping readings to settle down to a steady value. The perforated plates showed few signs of instability of flow over a wide range of flow conditions and different opening area ratio. On the other hand, for wire mesh screens of opening area ratio below 0.5 instability was observed. He concluded that this instability may be caused not only by the gradual entrainment of air flow , but also by irregularity in the spacing of the wires of the screen.

P. Bradshaw [3] produced an excellent photograph of the flow through a row of parallel cylinders. The flow has been visualized by a smoke tunnel showed a series of similarity sized and spaced jets coalesced in pairs behind a high blockage, two-dimensional cascade, in such a fashion that it strongly influenced the steady drag force on the components of the cascade. Its pitch-to-diameter ratio was about 1.7 and the Reynolds number was 1,500. He pointed out, such a pairing was quite stable in any one of two bi-stable states. This pairing arrangement seemed to be applicable for only a short distance behind the cascade. At larger distance downstream the velocity profile varied, as von Bohl's experiments indicated, in a somewhat random fashion. He inquired as the effect to Reynolds number on the flow through the cascade from 2 * 10^4 to 2 * 10^5 and found there occurred no change in the general flow structure.

A. R. J. Borges [4] discussed the problem of vortex shedding from single row of parallel circular cylinders of equal diameter set normal to an airstream. His experimental results showed that the Strouhal number S' based on the mean gap velocity was nearly constant for single row down to a pitch-to-diameter ratio of 2.0, and its departure from the value corresponding to the isolated cylinder was hardly significant. Beyond this range of pitch-to-diameter ratio, he stated that the flow became unstable. The remarkable observation during his experiments was the appearance of a very intense high frequency signal at the pitch-to-diameter ratio of 1.33 corresponding to values of S′ in between 3 and 8, the exact values depending apparently on Reynolds number.

Seikan Ishigai and Eiichi Nishikawa [5] used the Schlieren method to visualize the flow pattern passing through a single column, a single row, and double rows tube banks, disclosing the vortex formation region, and that the Coanda effect had a dominant effect on the structure of the gas flow in these three types of tube banks. They described the structure of the vortex flow after a tube row as the result of a complex synthesis of Karman vortices generated by each tube in the tube row. The gap flow between adjacent tubes normal to the flow behaved as a two-dimensional jet. It always formed that in some tube spacing, the jets coalesced with each other due to the Coanda effect, and in an extreme case unstability was observed in the bulk flow. The pitch-to-diameter ratio of their experiment of single row was from 1.2 to 3.0 and the Reynolds number was from 4,000 to 33,000 with the velocity Ug at the minimum flow area as the representative velocity. From the Schlieren photograph they obtained, they found the basic properties and the size of the vortex formation region depended largely on the tube spacing and the Coanda effect. The size of the vortex formation region was the same as a single tube when pitch-to-diameter ratio greater than 2.5. For pitch-to-diameter ratio less than 2.5, a larger wake and a smaller wake took place in a strictly alternate order one after another. When pitch-to-diameter ratio less than 1.5, the vortex formation region occurred only behind the tube having smaller wakes. The vortex shedding frequency was strongly depended on the tube spacing. Two different Strouhal numbers were obtained in the range of pitch-to-diameter ratio greater than 2.5 due to the deflection phenomenon. When pitch-to-diameter ratio less than 1.5 the shedding frequency was somewhat irregular. They mentioned when pitch-to-diameter ratio less than 1.5 the anemometer caught the periodic velocity fluctuation due not to the Karman vortex but to unknown reasons.

A. S. Ramamurthy, P. M. Lee, and G. P. Ng [6] investigated boundary interference associated with flow past single row of cylinders and symmetric equilateral prisms. The tests were limited to examine the characteristics of vortex shedding frequency of single row of bluff bodies. The vortex shedding frequency of the row of bodies were determined from the wake surveys conducted with the help of a hot-wire anemometer. The Strouhal number S, which based on the undisturbed mean velocity U as the reference velocity, increased with the blockage. In the lower range of blockage, the S′ based on the mean gap velocity Ug was nearly constant for the single row of cylinders. As blockage was increased to 0.5, vortex shedding for single row of cylinders occurred at more than one frequency.

CHAPTER 3

EXPERIMENTAL AND MEASUREMENT SETUP

The present experiments are performed in the 40 HP low-speed open-circuit wind tunnel which is available in the Department of Mechanical And Aerospace Engineering of Oklahoma State University. The tunnel has a closed test section and is driven by a centrifugal fan located downstream of the test section. The rectangular test section is 28 inches length with a height of 16-1/8 inches and a width of 24-1/2 inches (a detailed description of the wind tunnel see Fig. 1).

3.1 Single Cylinder

A preliminary experiment was carried out with a single cylinder. The cylinder model used was a 24-1/2 inches length of plexiglass tube with an outside diameter of 1 inch and mounted in the test section of the wind tunnel spanned the width of the tunnel, giving the length to diameter ratio of 24-1/2 and the blockage ratio, defined as the cylinder diameter divided by the working section height, of 1/16.

The velocity at the entrance to the test section was measured with the help of a Pitot tube and a manometer. Thus, enabled one to determine the mean velocity U at the center line on the model. From this velocity the Reynolds number was calculated. A static pressure tap (1/32 inch of diameter) was drilled at the midspan of the tube to measure the cylinder surface pressure (a detailed setup see Fig. 2).

The cylinder could be turned around its longitudinal axis from $\theta = 0^\circ$ (stagnation point) to $\theta = 180^\circ$. The difference of surface pressure and undisturbed stream static pressure was measured by a manometer (Dwyer Instmts. Inc.). The results of measurement were presented in terms of the dimensionless pressure coefficient Cp, where

$$Cp = [P(\theta) - Ps] / 0.5 \rho U^2$$

$P(\theta)$ is the mean static pressure at the perpherical angle θ on the cylinder surface. Ps is the undisturbed stream static pressure and ρ is the mass density of the fluid.

3.2 Single Tube Row

The wind tunnel used in this experiment was essentially the same one as was used in the test of a single cylinder. The experimental setup comprised a row of nine parallel 24-1/2 inches length 1 inch schedule 40 PVC pipes having a pitch-to-diameter ratio of 1.3, mounted in the test section, spanned the width of the tunnel, normal to the free stream in order to give a row of parallel two-dimensional jets. The tubes were rigidly mounted on the end plates to prevent the tube motion (a detailed setup see Fig. 3). The velocity to the entrance of the test section also be measured by a Pitot tube. Pitot tube and Kiel probe were used to measure the pressure distribution at various positions downstream of the tube row, a hot-wire anemometer was used to measure the velocity profiles and the vortex shedding frequencies in the wakes in this experiment.

3.2.1 Pitot tube

A Pitot tube was installed downstream of the tube row to measure the pressure distribution of the flow field. The position of the Pitot tube could be changed longitudinally every 0.5-D from 1-D to 4.5-D after the tube row and traversed in steps of 1/16 inch. Based on the length limitation of the probe itself, it could be traversed from 4-9/16 inches to 14-7/8 inches reference to the bottom of the test section. A manometer was used to measure the stagnation and static pressure difference of the Pitot tube. (a detailed setup see Fig. 4)

3.2.2 Kiel probe

A Kiel probe was also used to measure the pressure distribution downstream of the tube row. The position could be changed longitudinally every 0.5-D from 0.5-D to 4.5-D after the tube row and traversed in steps of 1/16 inch from 1/16 inch to 15-1/2 inches reference to the bottom of the test section. For Kiel probe, it was only for measuring the total pressure, a reference static pressure tap was chosen on the side wall of test section three tube diameters after the tube row. A static pressure probe was used to measure the traverse static pressure distribution at same position as the reference static pressure tap and found that the maximum pressure difference between the values measured from static pressure probe and the reference pressure tap was 0.3 inch of water column, so we could assume the reference static pressure was accurate. A manometer was also used to measure the total and reference static pressure difference at each measuring point (a detailed setup see Fig. 5).

3.2.3 Hot-Wire Anemometer

A hot-wire anemometer was used to measure the velocity profiles, turbulence intensities downstream of the tube row and the vortex shedding frequencies in the wakes. The position of the hot-wire could be changed longitudinally every 0.5-D from 0.5-D to 2.5-D after the tube row and traversed in steps of 1/16 inch from 8-3/8 inches to 15-1/8 inches reference to the bottom of the test section (a detailed setup see Fig. 6).

The use of hot-wire for measurments of flow velocity relies on laws governing convective heat transfer. These laws are generally too complicated to permit a theoretical calculation of the relation between the flow velocity and the heat flux from the probe and the relation must therefore be found experimentally, using laws of similarity. A theoretical solution to the heat transfer problem of a uniformly heated cylinder in a two-dimensional, incompressible, potential and non-viscous flow was formed by L. V. King in 1914. But in practice, the heat transfer is of a more complex nature, so direct calibration is therefore necessary.

For conditions of thermal equilibrium, the rate of heat loss Q from the hot-wire must be equal to the heating power generated by the electric current, that is, it must be equal to $I^2 * R$. From a view-point of anemometer, we are primarily interested in the relation between flow velocity and electrically generated heating power. For a hot-wire probe operated at a specific overheating ratio, in a specific fluid, at a specific temperature, the relation can be expressed by the equation

$$E^2 = A0 + A1 * U^{0.5} + A2 * U,$$

where E is the output of anemometer bridge voltage,

U is the flow velocity,

A0, A1, A2 are constants.

In the present experiments, a DISA Type 55M01 Constant Temperature Anemometer Standard Bridge and a hot-wire, DISA Type 55P11, were used to measure the velocity. A digital multimeter (DMM) was used to read the output signal of time-mean (mean) and root-mean-square (rms) vlotage. A spectrascope (Spectral Dynamics SD-345) and a video printer (AXIOM EX-850) were used to record the output voltage fluctuation and frequency spectrum.

The hot-wire was calibrated on a small air jet before the experiments. The facility consists of a compressed air line, a pressure regulator, a rotameter and a standard converge type nozzle with a 3.5 cm diameter throat. The calibration data as shown in Fig. 7. We can use equations of

$$[E(mean)]^2 = A0 + A1 * [U(mean)]^{0.5} + A2 * U(mean)$$

$$E(rms) = \left(\frac{\partial E(mean)}{\partial U(mean)}\right) * [U(rms)]$$

to derive the equations for calculating the mean velocity and the root-mean-square velocity, which is the turbulence velocity, then we can obtain turbulence intensity by using

$$\text{Turbulence Intensity} = U(rms) / U(\infty) \quad ,$$

where $U(\infty)$ is the entrance velocity of the test section.

CHAPTER 4

RESULTS

4.1 Single Cylinder

This was the preliminary measurement of mean surface-pressure distribution around a circular cylinder at five different Reynolds numbers from 23,140 to 69,260. The surface pressure was measured over one side of the model only. No correction has been made for blockage effect.

The distribution of the surface pressure was measured in steps of $\theta = 5^\circ$ around a half of circumference from $\theta = 0^\circ$ to $\theta = 180^\circ$. Fig. 8 showed the relationship of the surface pressure distribution and Reynolds numbers. The results of the dimensionless pressure coefficient at different Reynolds numbers and the theoretical value, which is

$$Cp = 1 - 4 * (\mathrm{SIN}\ \theta)\hat{}2,$$

were plotted versus the perpheric angle θ of the cylinder. In this figure, Re1 = 23,140, Re2 = 39,800, Re3 = 49,540, Re4 = 61,400, Re5 = 69,260. These five different conditions were before the transition into the critical region, which begins at Re = 3.5 * 10^5 [7], the boundaries still separated laminarly.

4.2 Single Tube Row

The principal experimental result was the observed instability of the system of two-dimensional jets issuring from a row of parallel tubes having a pitch-to-diameter ratio of 1.3. The instability consisted of a grouping together of adjacent jets immediately after their exit from the tube row, resulting in strongly eddying flow. Adjacent groups then joined, and at a very short distance from the tube row, the flow was no longer identifiable as having originated from a regular row of tubes.

Fig. 9 showed a series of pressure profiles at various positions downstream of the tube row measured by a Pitot tube. In this case, the flow started out at six jets, a short distance after, the pressure difference of jets decreased and adjacent jets grouping together. Finally at 4.5-D after the tube row, all the jets coalesced together, the flow looked as if it had originated from a single jet.

At 2-D downstream of the tube row, two experiments of the same conditions were conducted at two different times. The results were compared in Fig. 10, it was seen that at the same position but conducted at two different times obtained different results. It seemed a wake shift one tube diameter upward. The jets grouping patterns of those two tests was shown in Fig. 11. It was believed that the phenomenon was caused by the Coanda effect, this fact also showed that the phenomenon was not caused by mechanical imperfections in the tube row but caused by flow itself.

Fig. 12 showed a series of pressure profiles at various positions downstream of the tube row measured by a Kiel probe, it traversed whole range of the test section. In this case the flow started out as eight uniform, almost equally spaced jets. At 1-D downstream of the tube row, jet 2 was closed to jet 3, jet 4 was closed to jet 5, and jet 6, 7, 8 were closed together. At 1.5-D downstream of the tube row, it had 1-3-2-2 combination. At 2-D after the tube row, initial eight jets coalesced into three main jets. At 2.5-D after the tube row, the two closed jets were combined together. At 3-D after the tube row, the flow just looked as initially two separated jets, and those two jets were far apart so they were not coalesced together for further downstream positions. It was believed that if the two final jets were closed sufficiently, they would be coalesced together, and the flow field looked as if it had originated from a single jet. Comparing the flow field configurations at 0.5-D and 1.5-D after the tube row, the pattern of jets was as shown in Fig. 13; it could be seen that an initial 8 jets rapidly coalesced into 3 groups after the tube row.

At 3-D and 3.5-D downstream of the tube row, four points for each position in the regions of pressure difference increasing, decreasing, positive, and negative were chosen to find out the Kiel probe directional sensitivity (as shown in Fig. 14 and 15), it was found that at both negative reading regions the readings were almost remained constant by rotating the Kiel probe from -90° to $+90^{\circ}$. It was shown that at negative reading region, which was in the wake, the flow was either very turbulent or had a very large angle corresponding to the measuring head of the Kiel probe. At other three regions, readings of the Kiel probe were not changed by rotating Kiel probe from about -30° to $+30^{\circ}$.

Fig. 16 showed the velocity profiles of the flow field from 0.5-D to 2.5-D downstream of the tube row measured by a hot-wire anemometer, the hot-wire was installed horizontally normal to the flow. In this case the flow started out as four uniform, almost equal velocity jets. At 1-D after the tube row, three jets were closed together. At 2.5-D after the tube row, initial four jets were coalesced together, the flow looked as if it had originated from a single jet.

At 0.5-D downstream of the tube row, two tests of the same conditions were conducted at two different times. The results were compared in Fig. 17. It was shown that the configurations were almost the same. Since the hot-wire was installed horizontally normal to the flow, it measured the combination of u and v components of the velocity, so the directional change of the flow would not have significant effect on the output reading of hot-wire anemometer of those two different time experiments.

Comparing the profiles of mean velocity and turbulence intensity at same postiton (as shown in Fig. 18), we could show that, as expected, the maximum turbulence intensity was in the shear layer, for a short distance behind the tube row. At further downstream positions, the shear layer developed, and the turbulence filled up the whole jet.

The remarkable observation during this experiment was at 2-D downstream of the tube row; the flow switched from one stable state to another stable state (as shown in Fig. 19); about thirty minutes later it switched back to its original stable state. This proved that the flow downstream of a closely spaced tube row has multiple stable configurations, which are maintained irregularly for a long time.

Fig. 20 showed the noise frequency spectrum of the background, and Fig. 21 showed the frequency spectrum in the wake. It was seen that there was no identifiable characteristic frequency in the wake of tube row, under these circumstances, and much intense singal occurred at low frequency region (0 to 30 KHZ). The peak at 52,500 HZ was the noise of the background.

CHAPTER 5

DISCUSSIONS AND CONCLUSIONS

5.1 Single Cylinder

1.) When we measured the pressure distribution and calculated the dimensionless pressure coefficient, we assumed the flow around the cylinder was steady state. This was not true exactly, because of the alternating eddy separation. Therefore the measured surface pressure values are the time-mean values.

2.) The experimental results from various sources for a two-dimensional circular cylinder vary owing to the differences in experimental conditions. The test facility turbulence characteristics, the cylinder length to diameter ratio, the tunnel blockage ratio, the model end conditions, the degree of the cylinder surface smoothness, and the inaccuracy of measuring instruments differ, therefore it is difficult to make an exact comparison of the existing results. It is only possible to say that the results of this experiment match the trend of previously published works at subcritical Reynolds numbers.

5.2 Single Tube Row

1.) The flow was unstable downstream of a tube row with a pitch-to-diameter ratio of 1.3, which agrees with the results of previous authors.

2.) The results obtained by a Pitot tube, a Kiel probe, and a hot-wire anemometer were not quite same. The readings of Pitot tube were affected by both turbulence level and variations in mean-flow direction. Kiel probes can obtain accurate total pressure readings when the angle between flow direction and probe axis is less than 30°. The hot-wire anemometer was sensitive to the orientation of the hot-wire, temperature change, and turbulence level. So the numerical values in the results of this report did not have consistent meanings. This report covers mainly qualitative studies of flow patterns.

3.) In many regions of measuring pressure distribution, " impact pressures " less than static pressure were recorded. These were the regions of lateral or reverse flow occurred.

4.) From the continuity of the pressure profile after the tube row, some previous authors concluded that the configuration was maintained if its upstream and downstream did not change or it could be maintained for a long enough time to provide at least one traverse or longer. In my experiment, it was shown in Fig. 19 that the flow configuration did change during one test and its patterns maintained irregularly for various periods.

5.) Bradshaw pointed out that the jets always coalesced in pairs for a short distance behind a high blockage two-dimensional cascade. Based on the results obtained from my experiments (as shown in Fig. 13), it was seen that the groups of jets were not always in pairs, two or more jets could merge together immediately after the tube row, and the same group did not always unite first.

6.) No characteristic vortex shedding frequency in the wake of the tube row was identifiable by means of spectral analysis, with a pitch-to-diameter ratio of 1.3 at this Reynolds number, and more than one frequency was observed in the low-frequency region.

7.) The physical mechanism of the instability of the flow field downstream of a closely spaced tube row was based on the entrainment of air by the individual jets from the wakes between them. The jets turned one way or the other based on the Coanda effect.

8.) Since two tests at the same conditions, conducted at different times, obtained different results, it was shown that the unstable flow phenomenon downstream of a closely spaced tube row was not caused by mechanical irregularities in the tube row but caused by the flow itself.

9.) It was found in these experiments (as shown in Fig. 18) that the maximum turbulence intensity was in the shear layer, for a short distance behind the tube row. At further downstream positions, the shear layer developed, and the turbulence filled up the whole jet.

This experiment dealt with only one case. Several methods were used to determine the flow phenomena downstream of a closely spaced tube row. These two-dimensional investigations showed the nature of the problem and the difficulties associated with mesurement.

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FIGURES

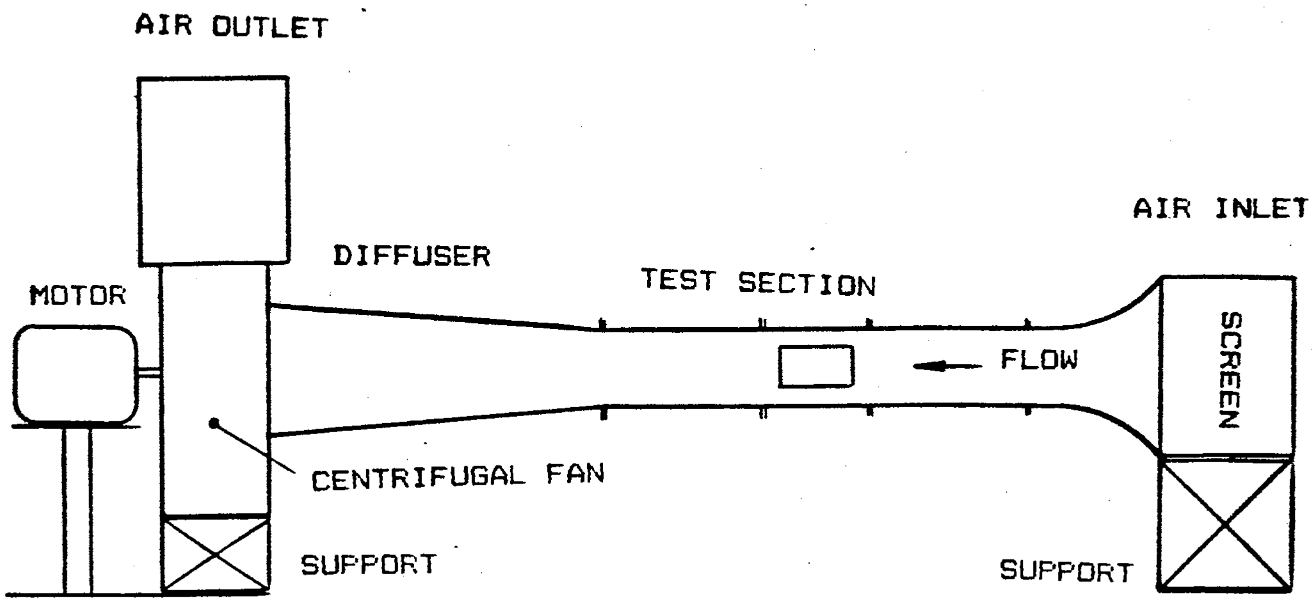


Fig. 1 Wind Tunnel Setup

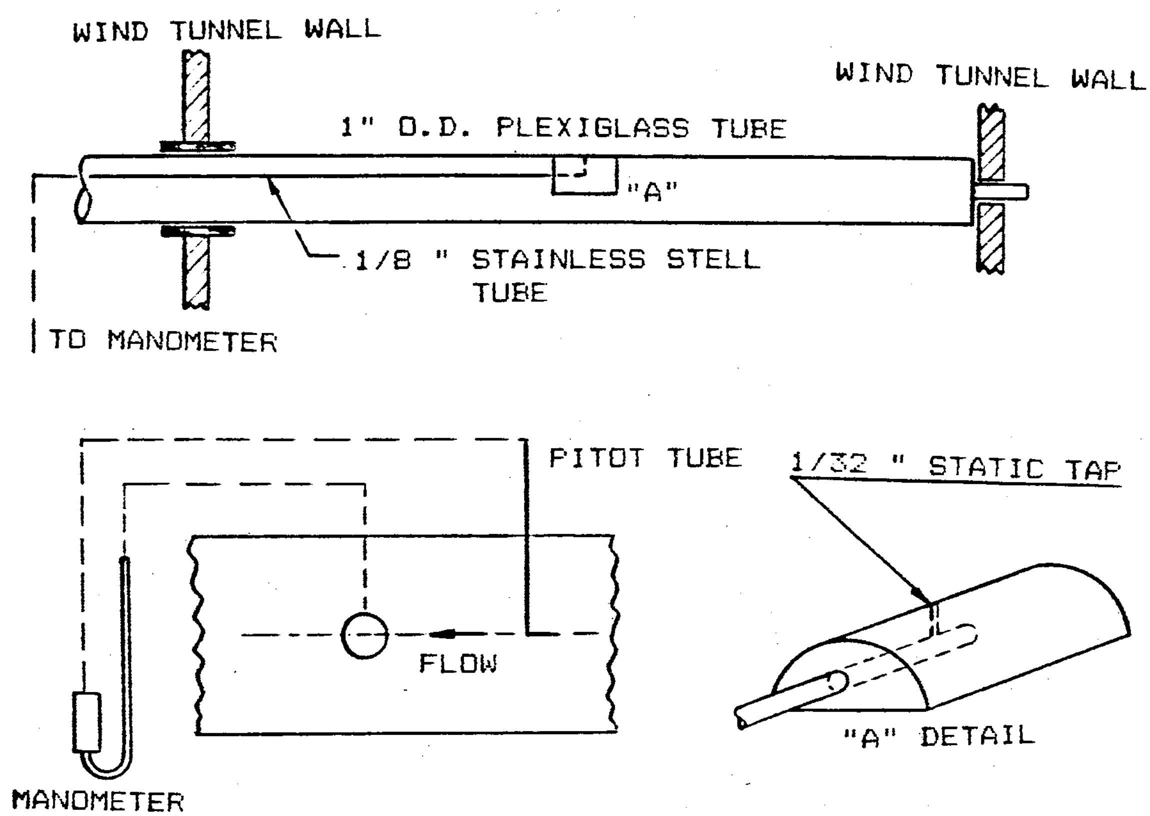


Fig. 2 Single Cylinder Setup

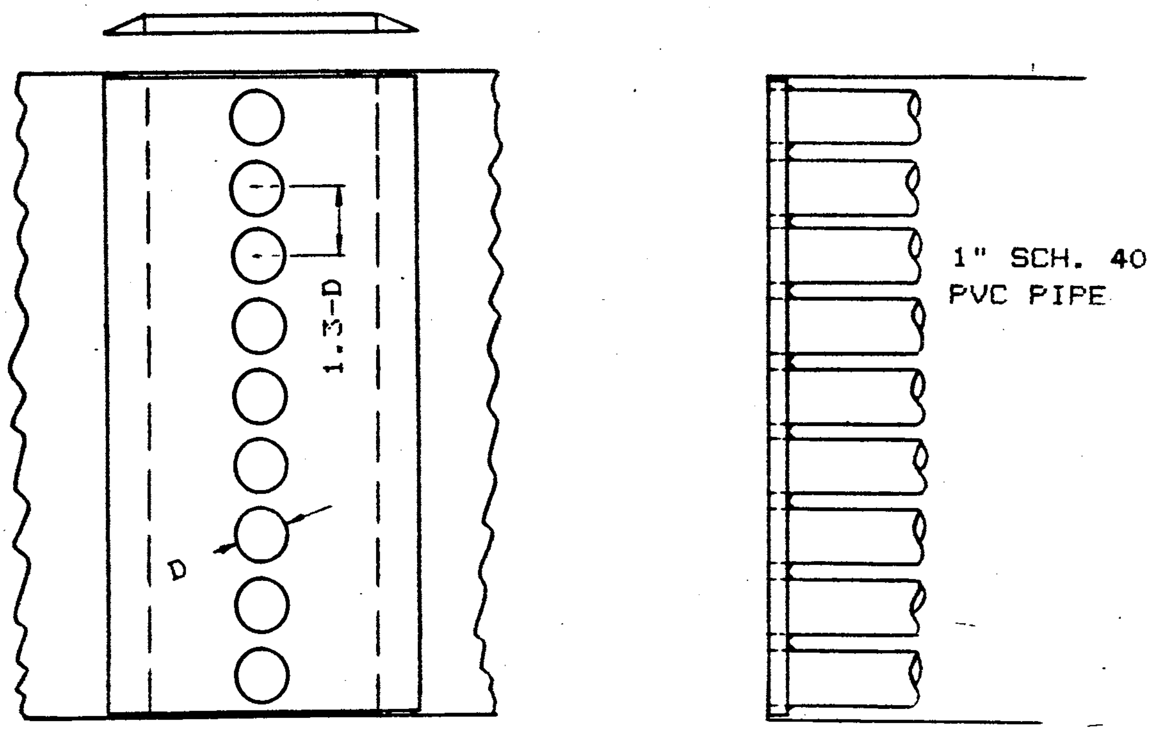


Fig. 3 Tube Row Setup

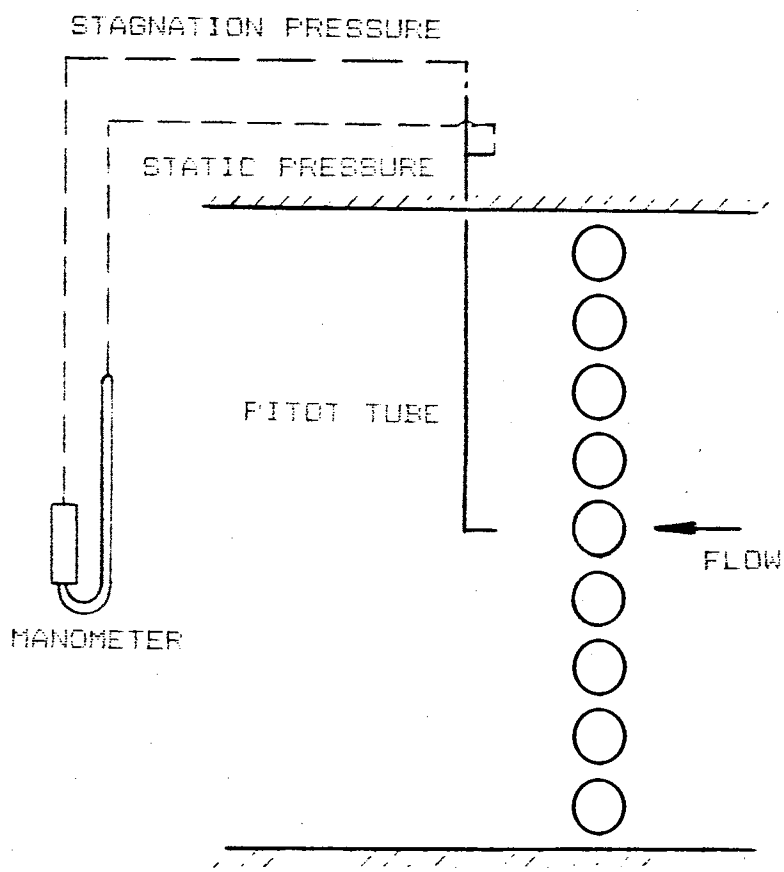


Fig. 4 Pitot Tube Setup

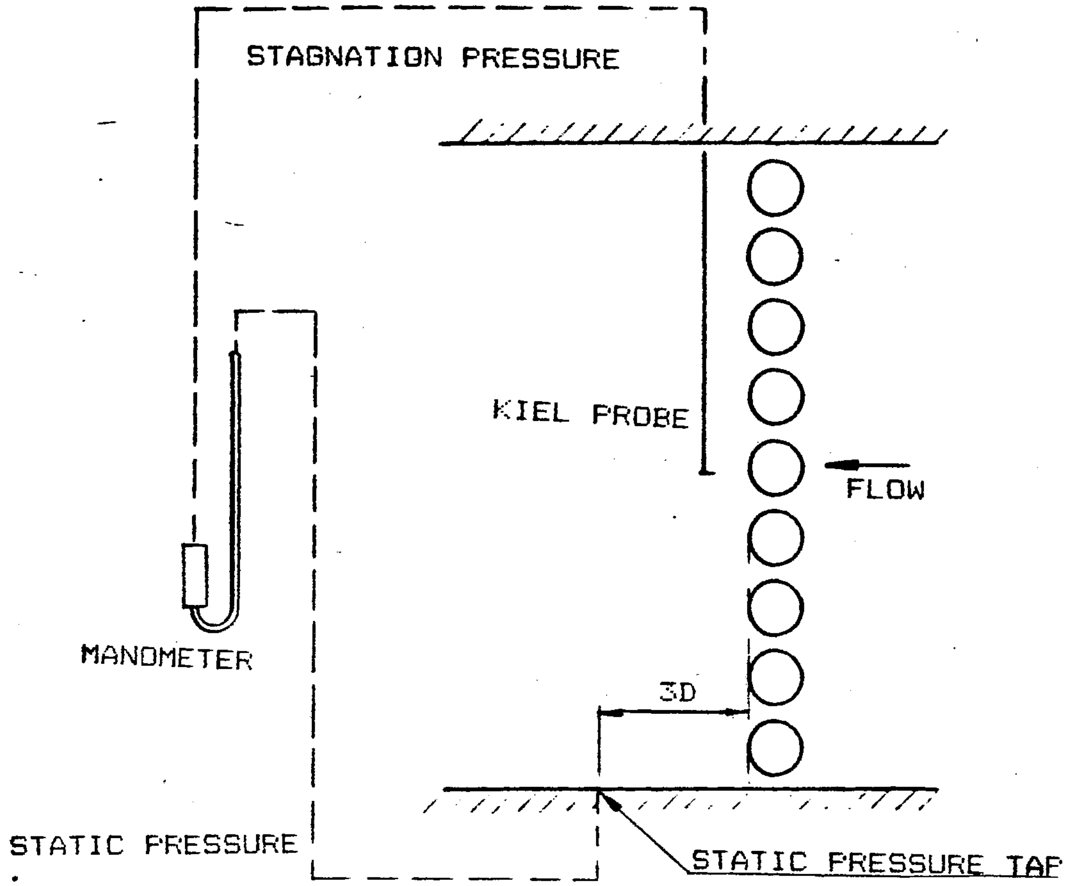


Fig. 5 Kiel Probe Setup

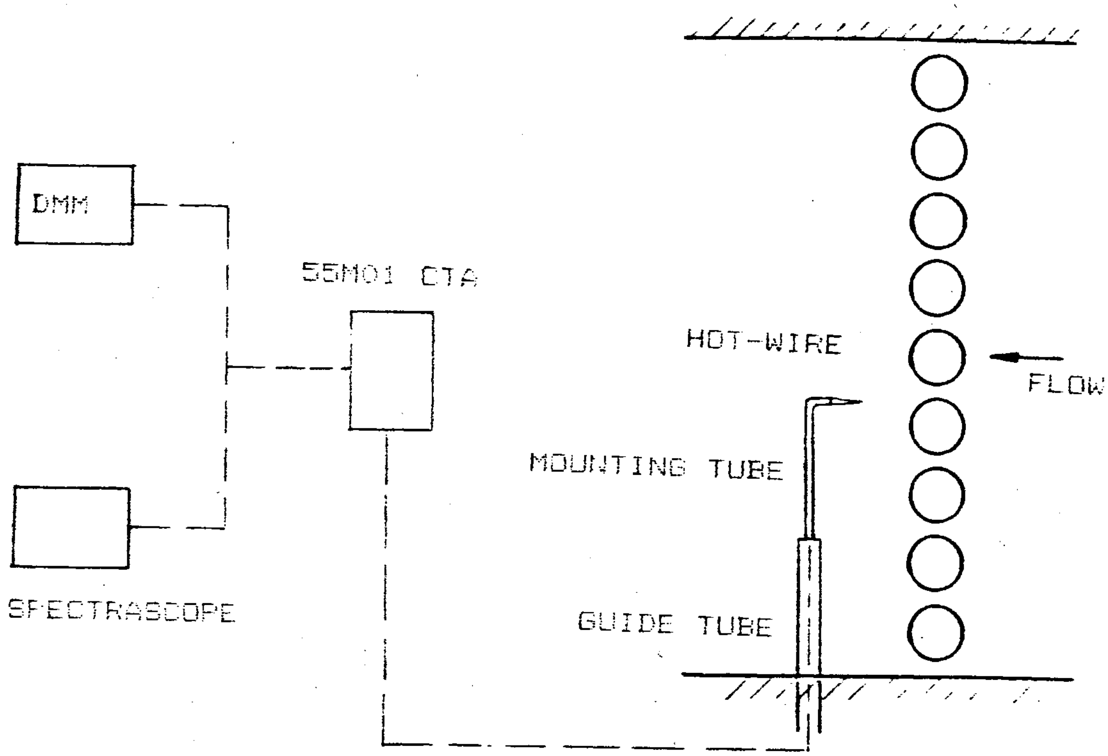


Fig. 6 Hot-Wire Anemometer Setup

V-VELOCITY CALIBRATION CONSTANTS

OCT. 9, 1985 TIME 14.35

M.T. CHENG

ATMOSPHERIC PRESSURE = 740 MM HG

A0 = 7.18069288
A1 = 3.64101722
A2 = -.142401354

E^2 = A0 + A1 * V^0.5 + A2 * V

E (PRED.)	E (ACTUAL)	ERR (VOLTS)
3.07573873	3.070975	-4.76373173E-03
3.25347164	3.26246166	8.99001863E-03
3.39193973	3.39069338	-1.24634895E-03
3.49338452	3.50151699	8.13246146E-03
3.58916627	3.58626781	-2.89845653E-03
3.66594158	3.66214924	-3.79233714E-03
3.7379635	3.73040233	-7.56117608E-03
3.8054514	3.80048943	-4.96197678E-03
3.86117341	3.8633822	2.20878609E-03
3.92406208	3.92340413	-6.57952391E-04
3.98384255	3.97287078	-.0109717706
4.02829925	4.03299063	4.69138101E-03
4.07693966	4.08458408	7.64441676E-03
4.13093472	4.13923586	8.30114074E-03
4.19735881	4.19576298	-1.59583427E-03
4.24388138	4.25213165	8.25026445E-03
4.30497415	4.30241122	-2.56292149E-03
4.36631354	4.35657436	-9.73917917E-03
4.41526359	4.41774531	2.48172134E-03

Fig. 7 Hot-Wire Calibration Data

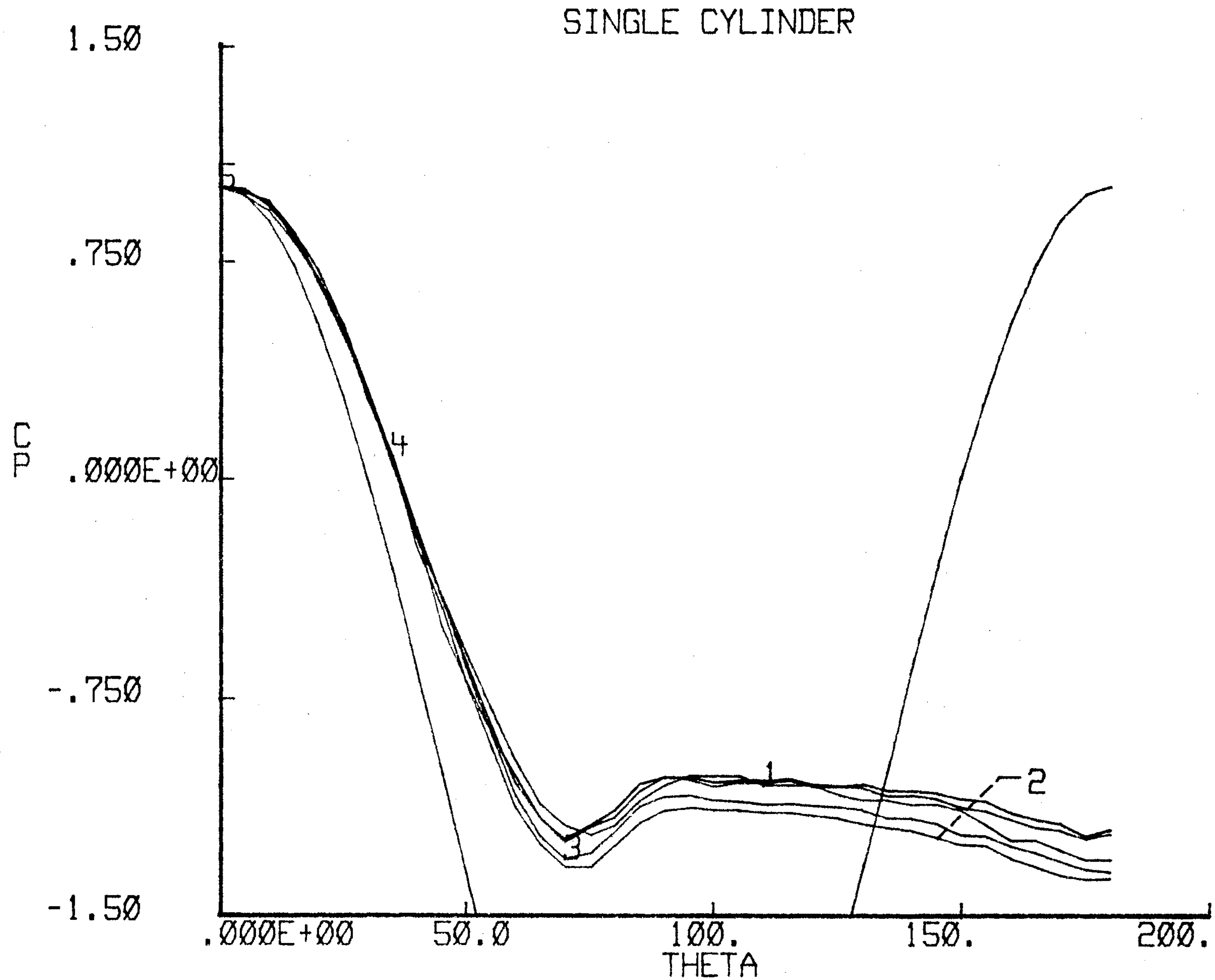


Fig. 8 Pressure Distribution on A Circular Cylinder

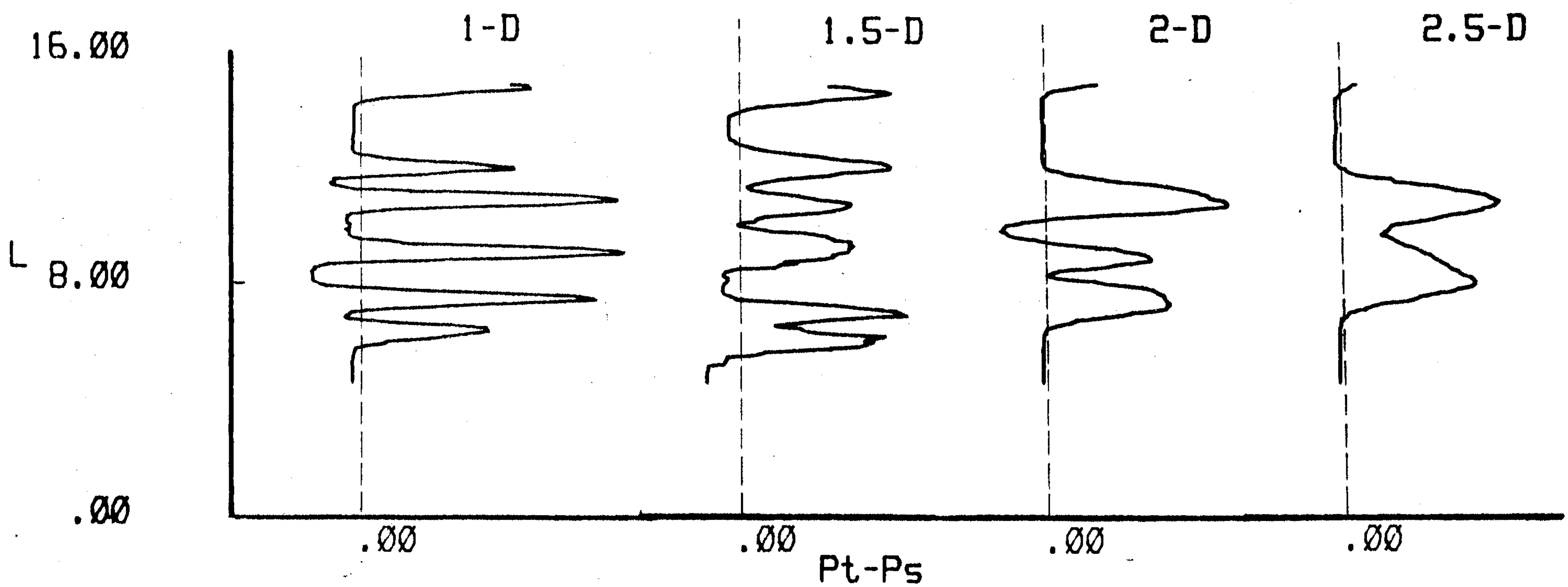


Fig. 9 Pressure Profiles Measured By A Pitot Tube

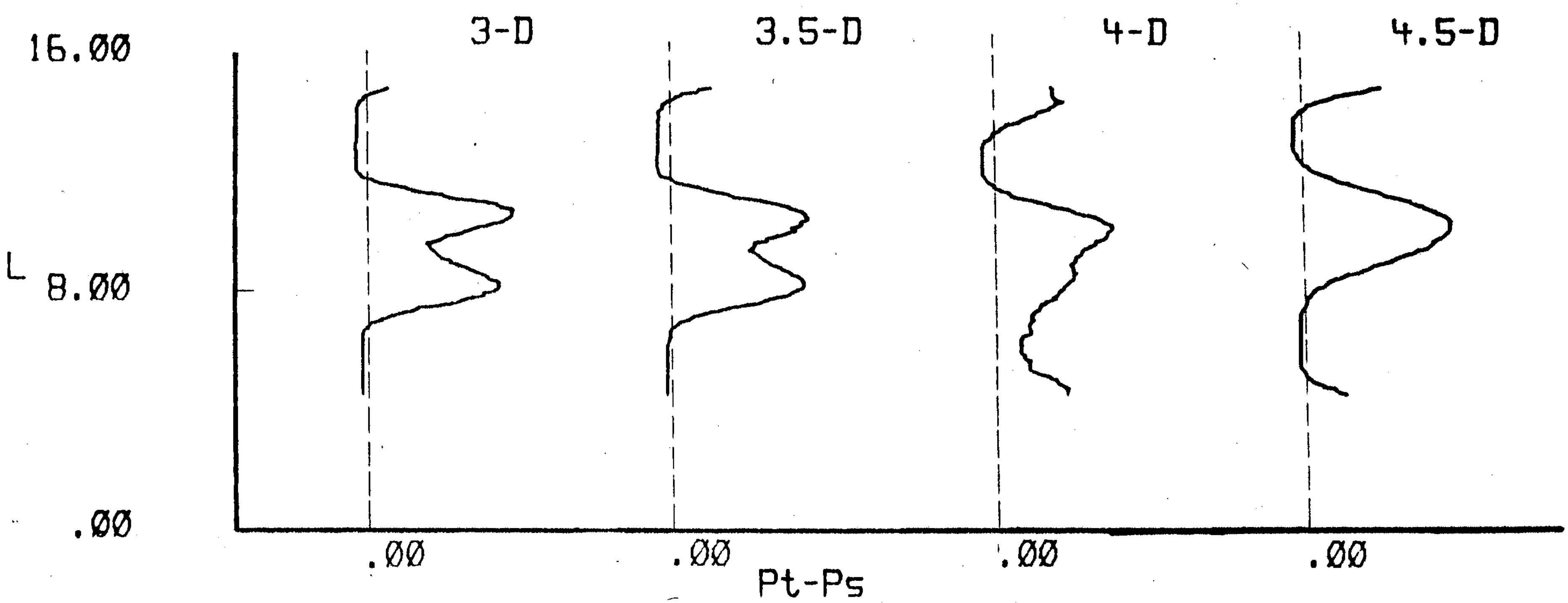


Fig. 9 (continued)

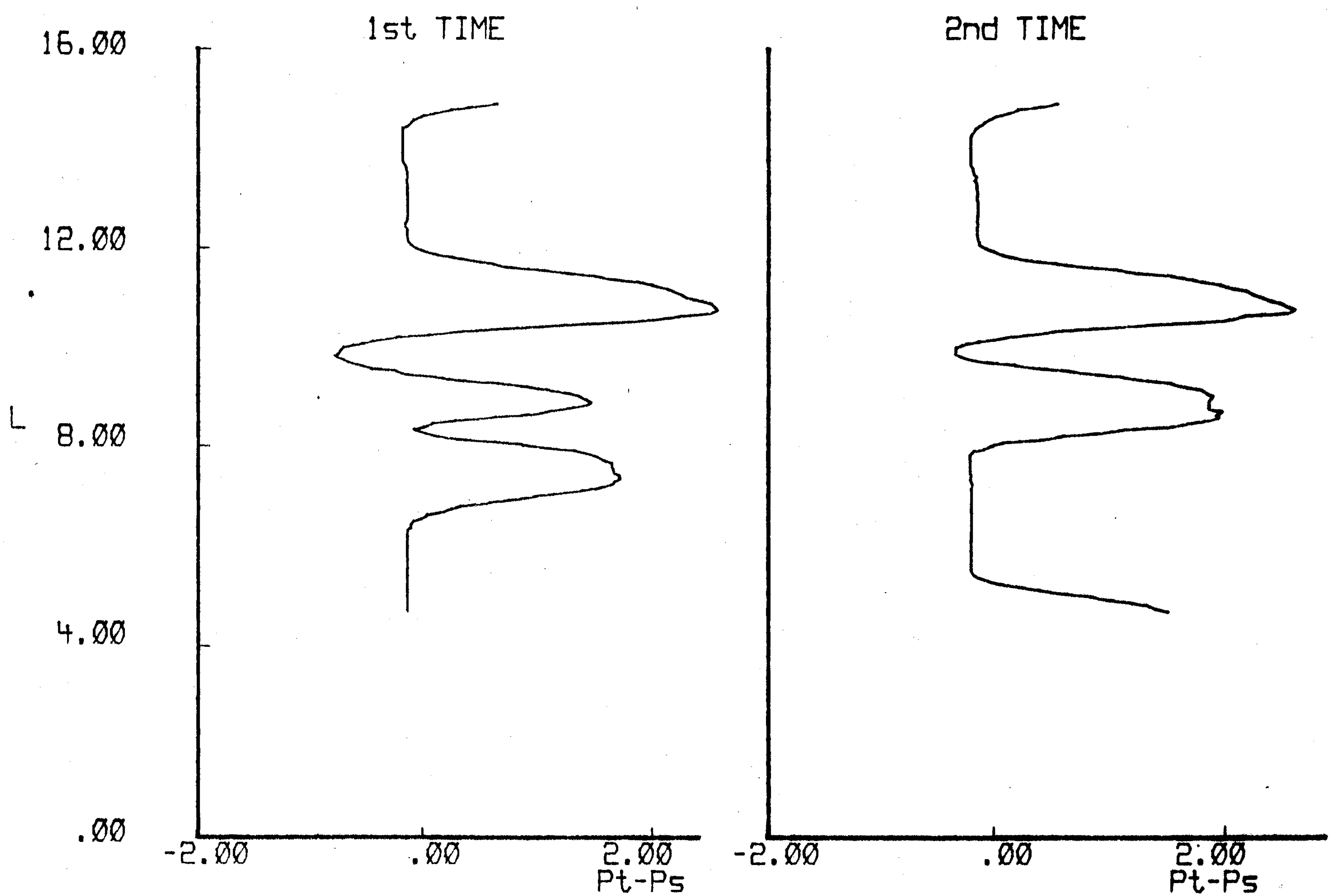


Fig. 10 Comparison of Two Tests of the Same Conditions

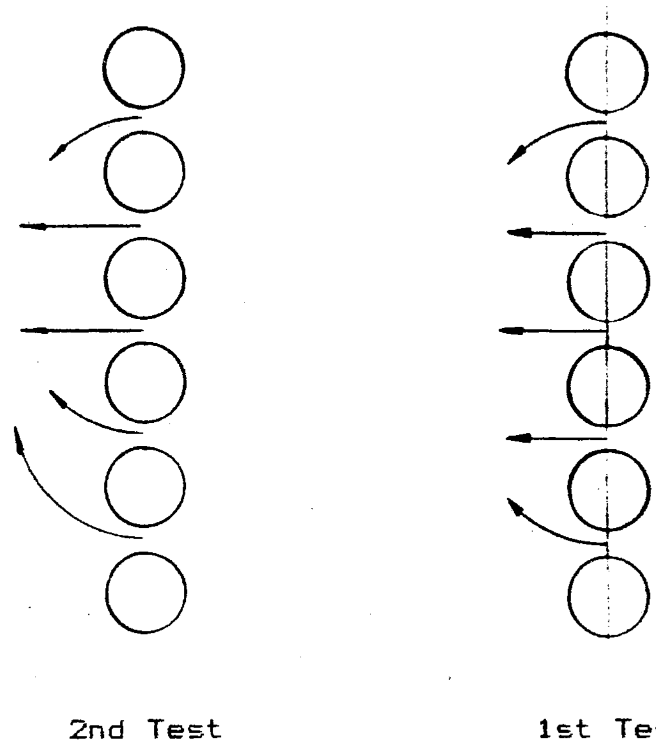


Fig. 11 Jets Grouping patterns of Two Tests of the Same Conditions

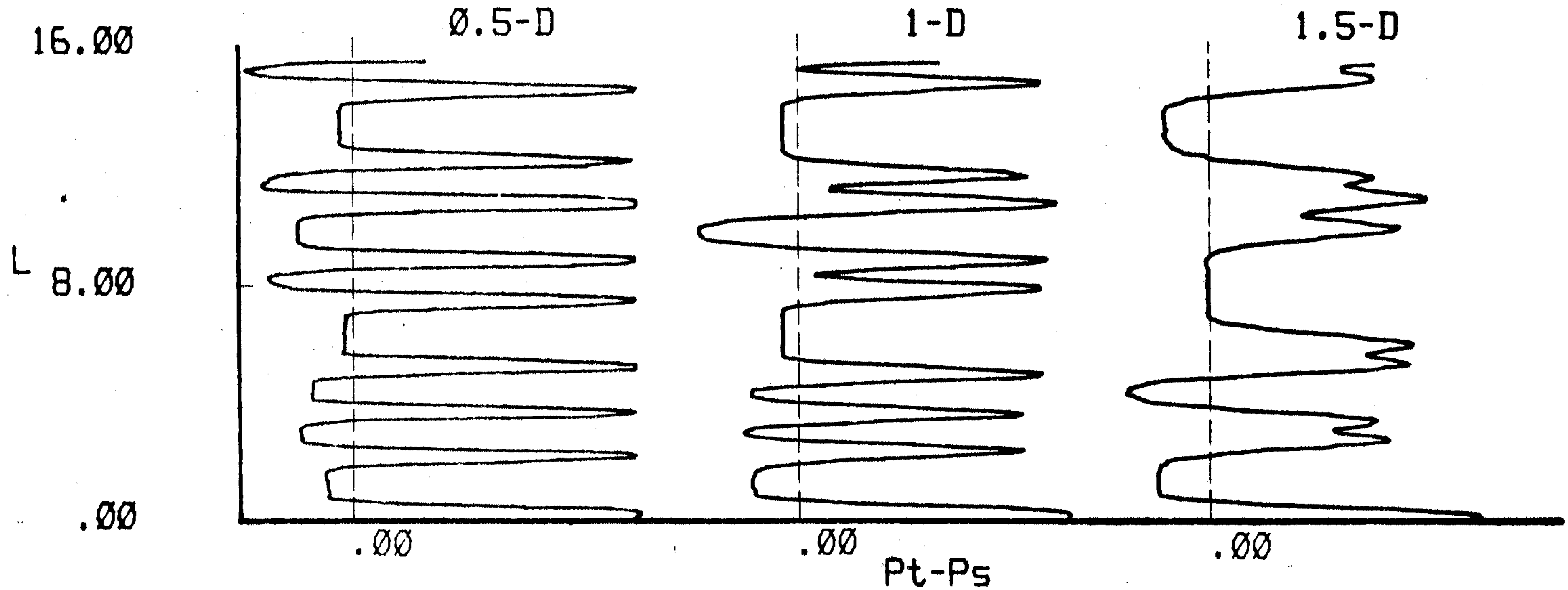
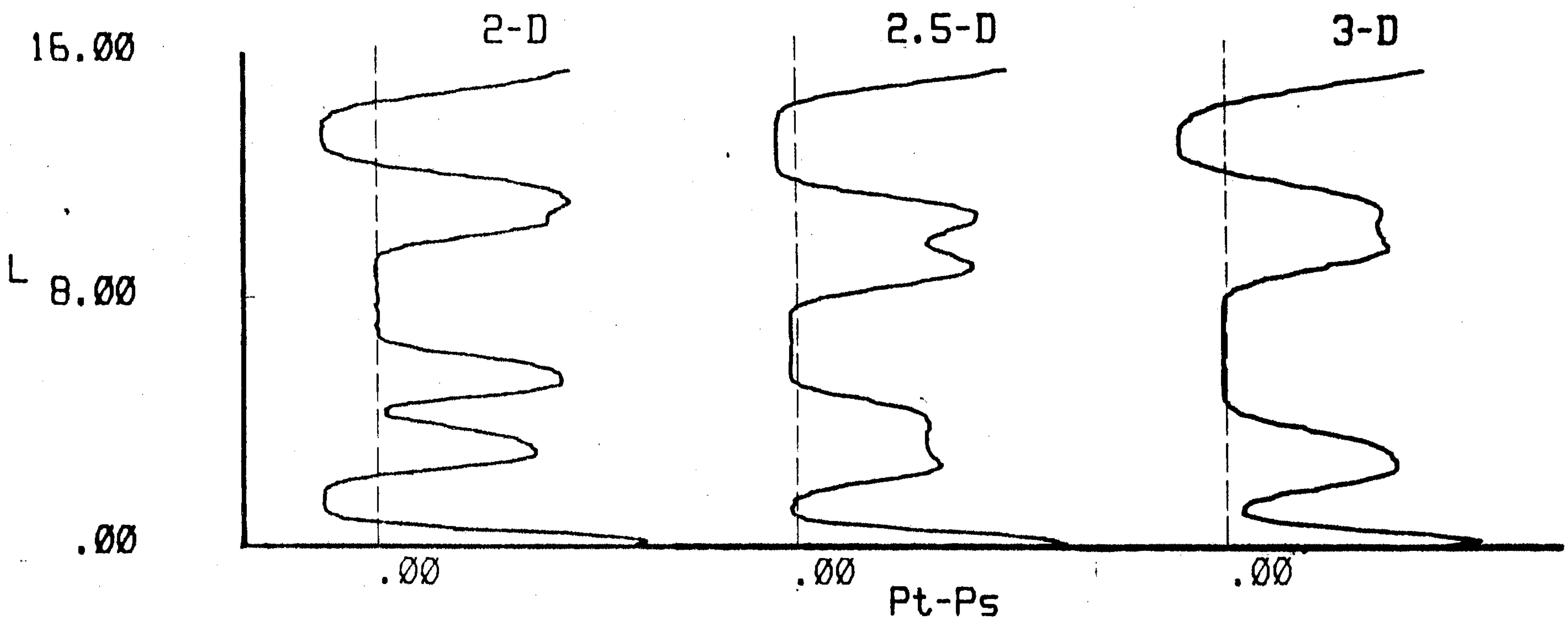


Fig. 12 Pressure Profiles Measured By A Kiel Probe



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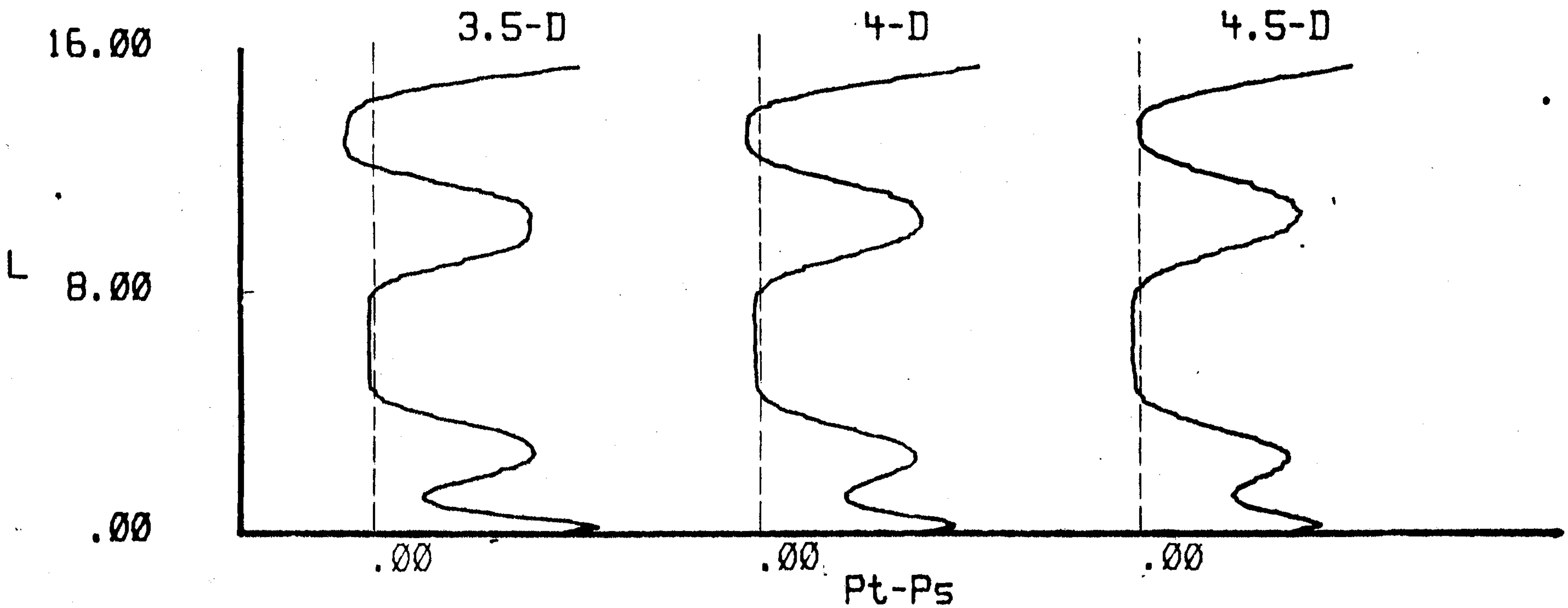

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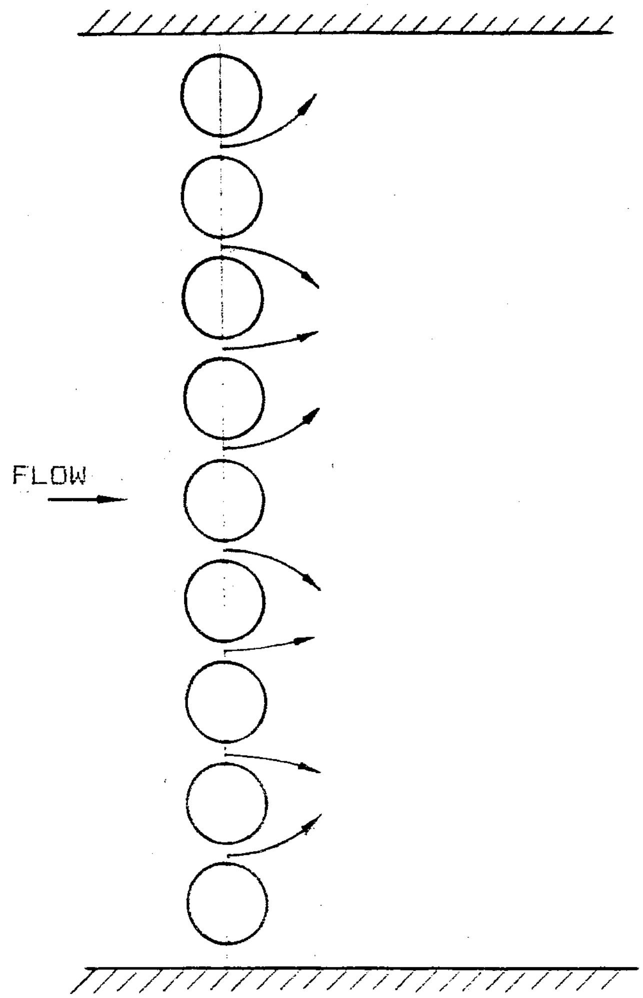


Fig. 13 Flow Field Pattern Measured By A Kiel Probe

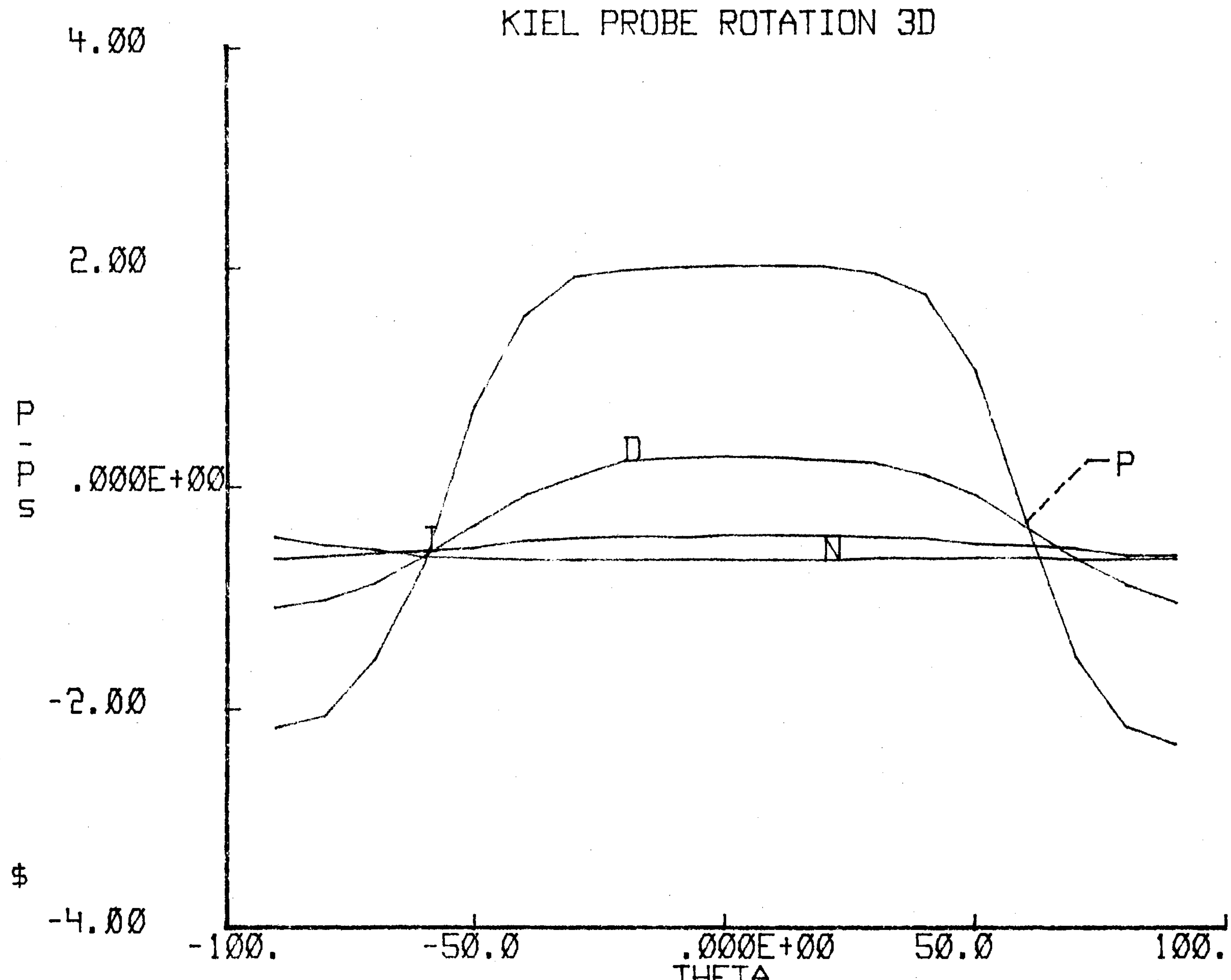


Fig. 14 Kiel Probe Directional Sensitivity (3-D)

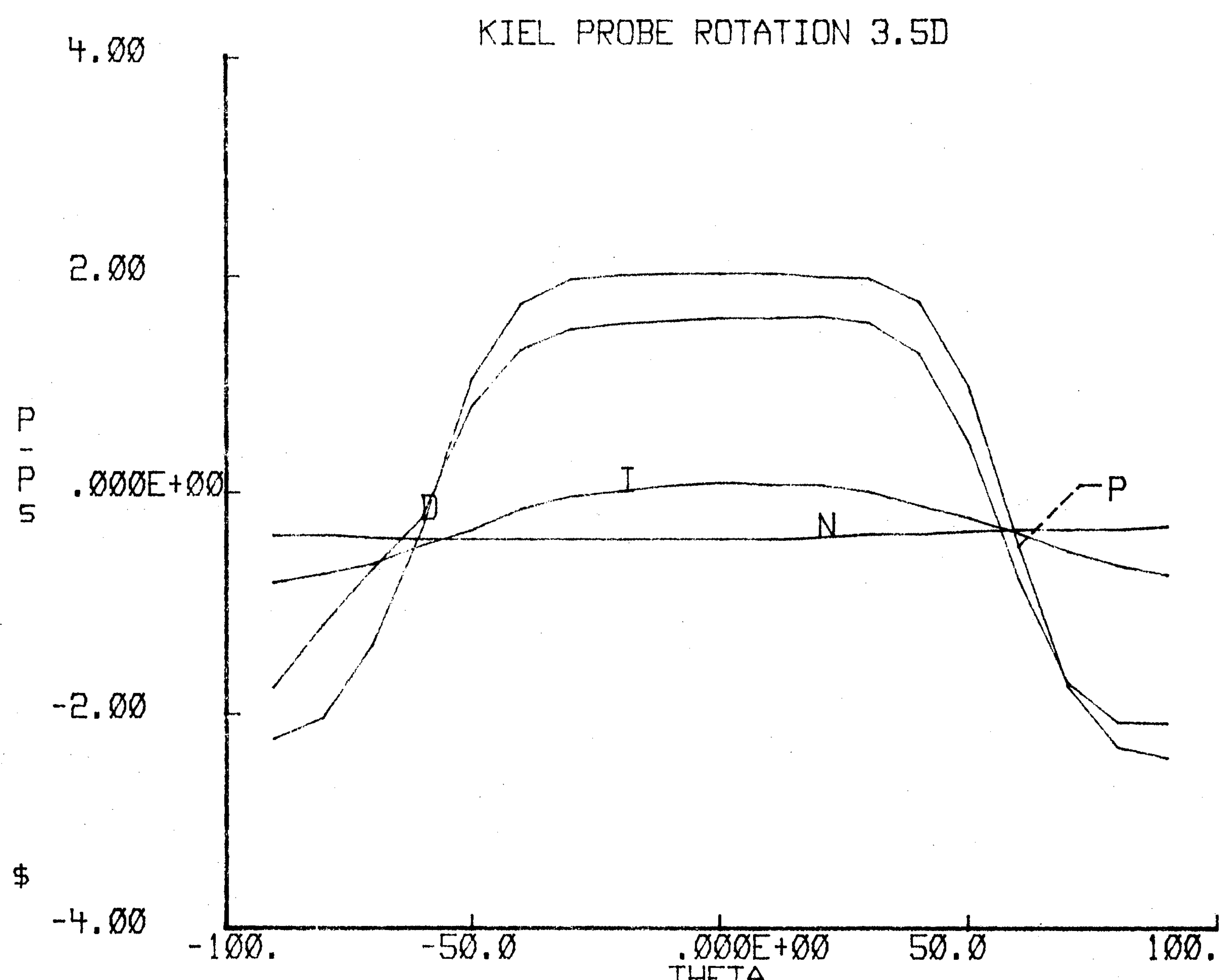


Fig. 15 Kiel Probe Directional Sensitivity (3.5-D)

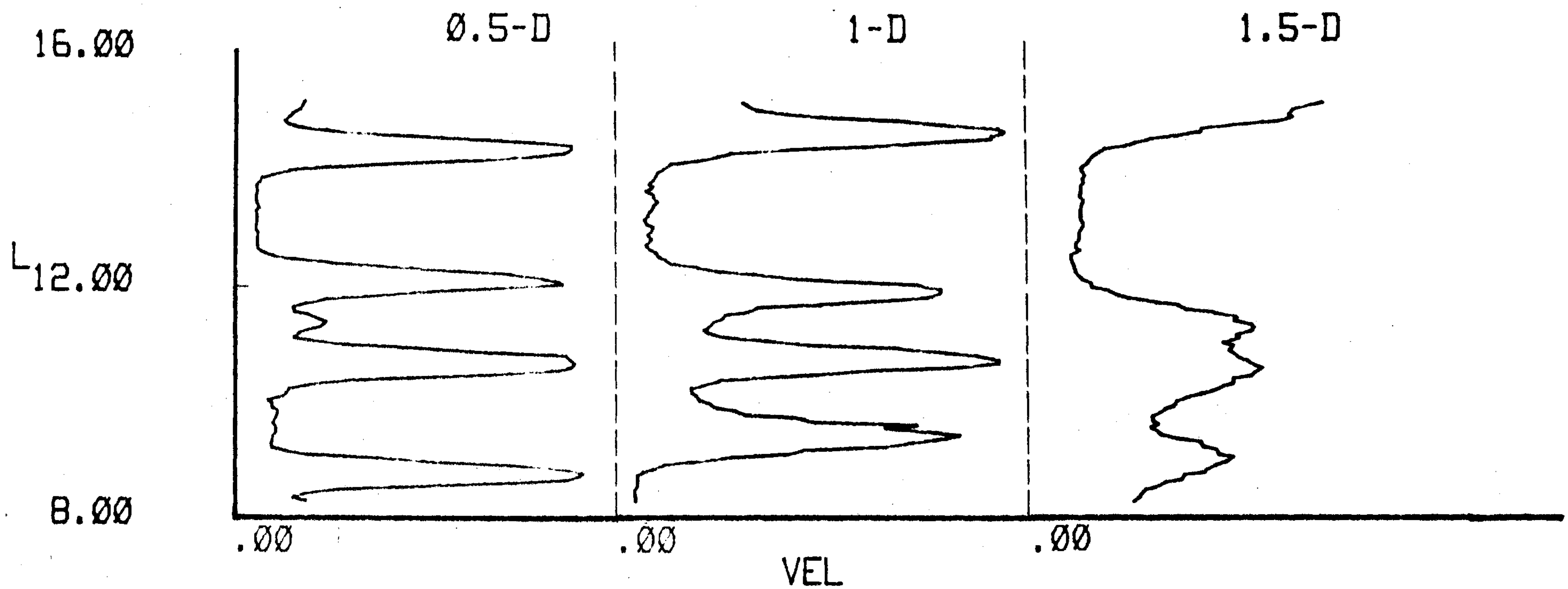
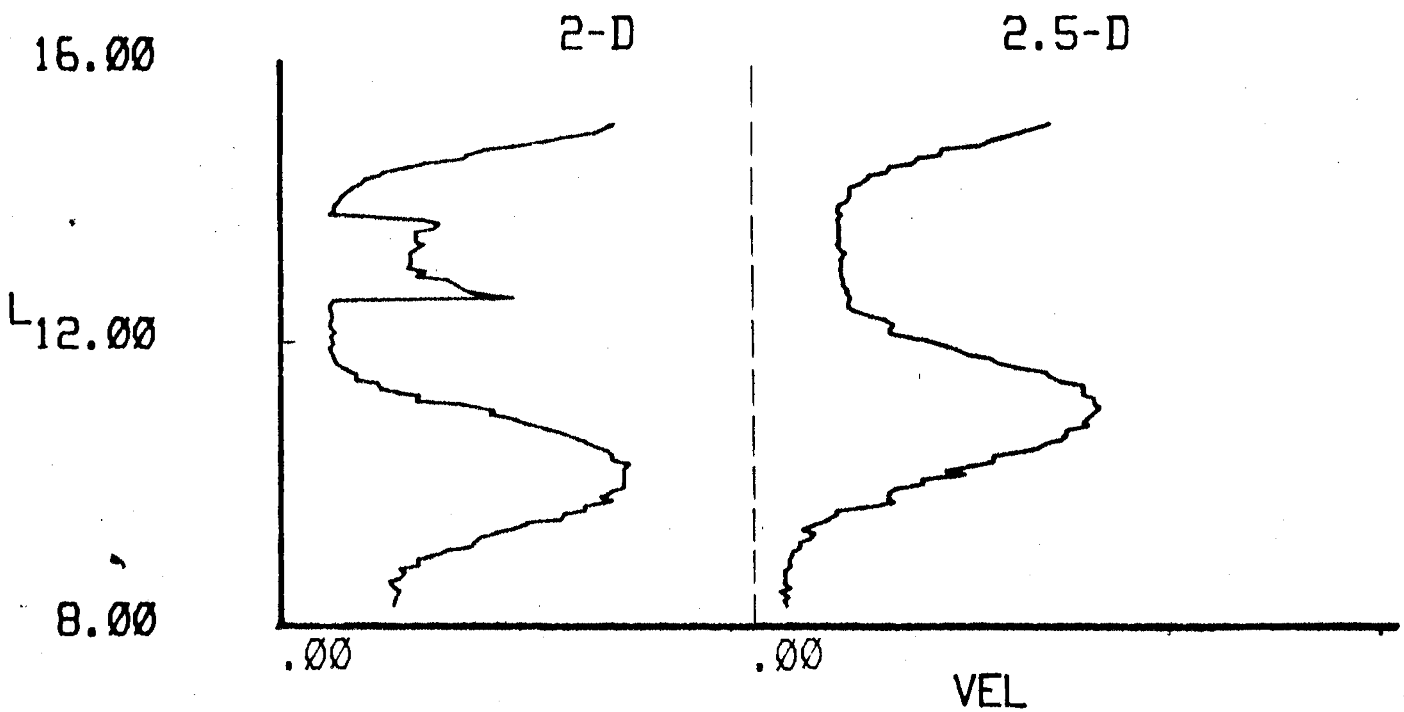


Fig. 16 Velocity Profiles Measured By A Hot-Wire Anemometer



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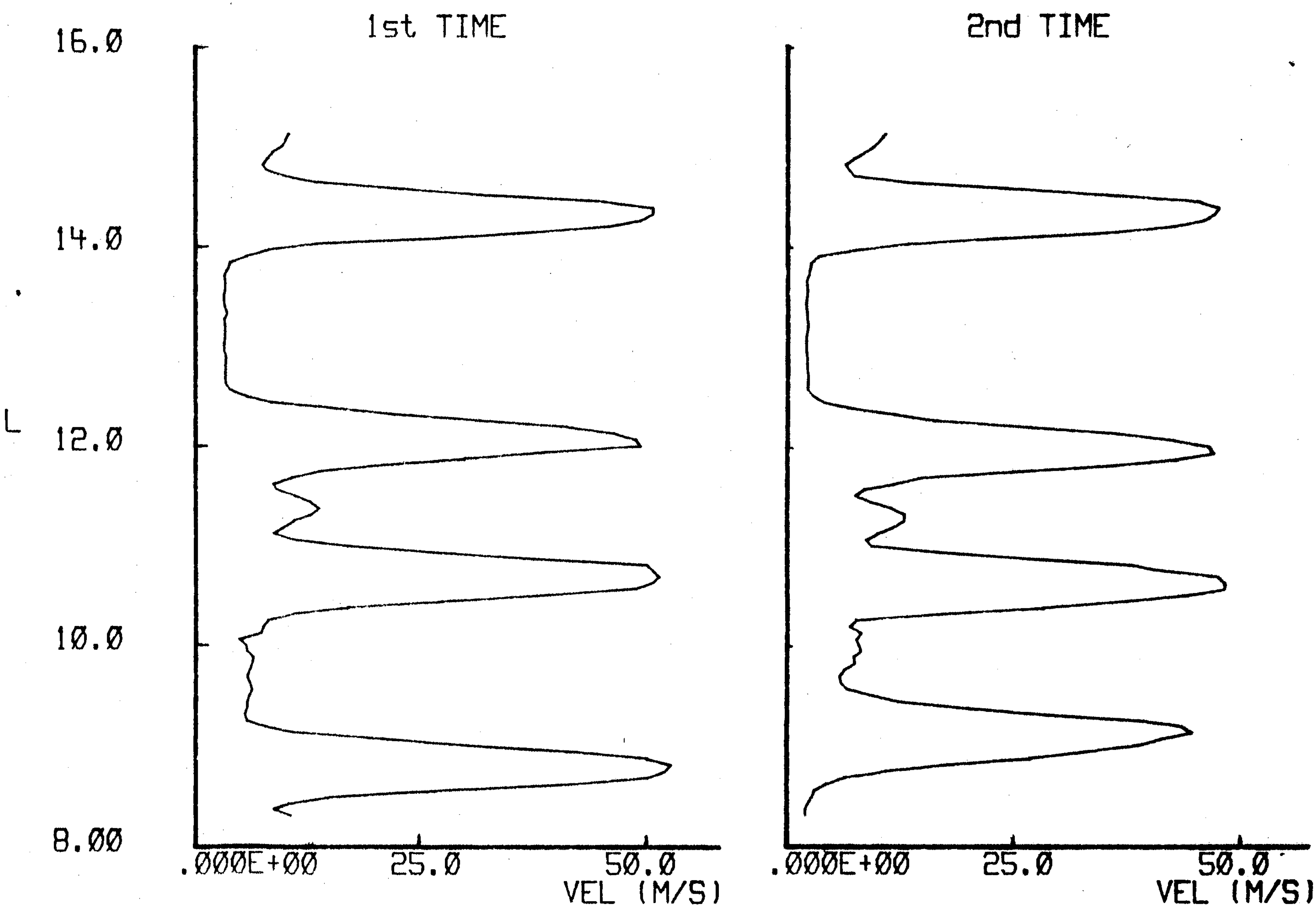


Fig. 17 Comparison of Two Tests of the Same Conditions

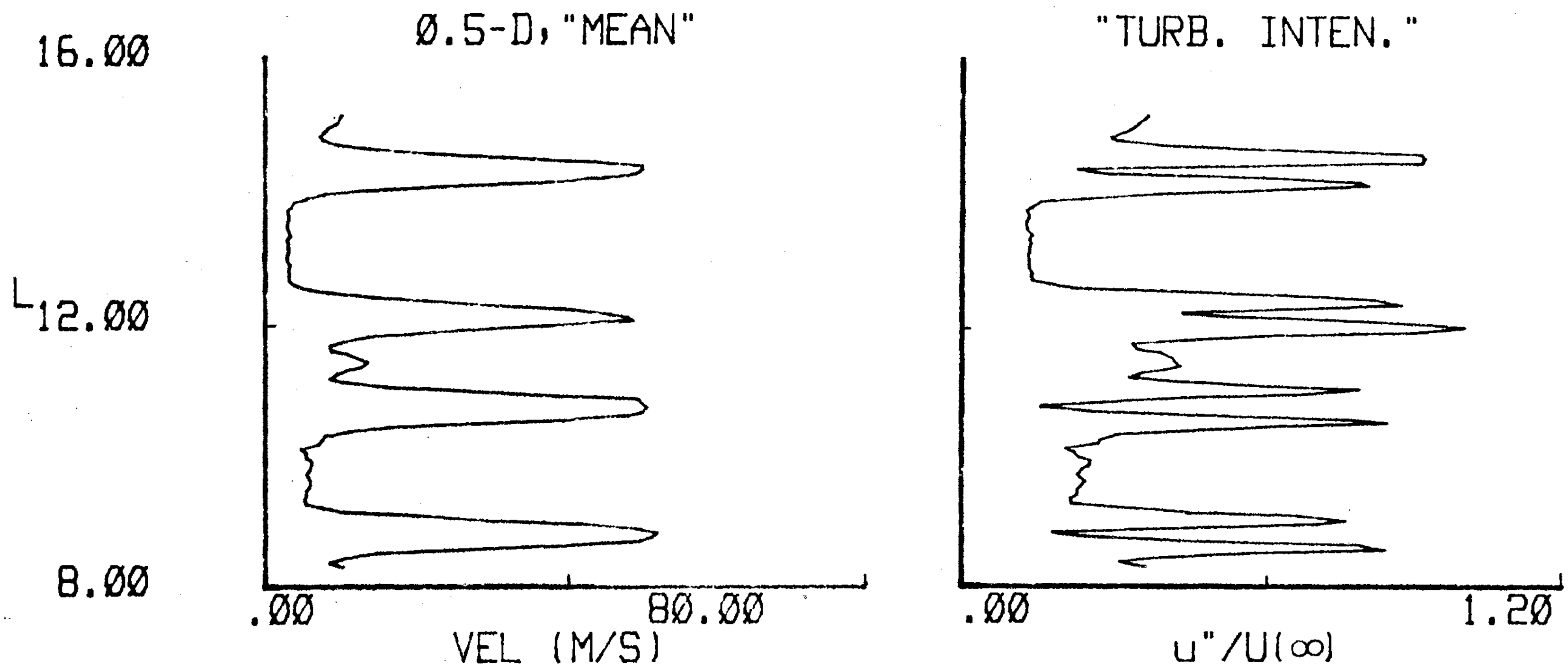


Fig. 18 Comparison of the Mean Velocity And the Turbulence Intensity

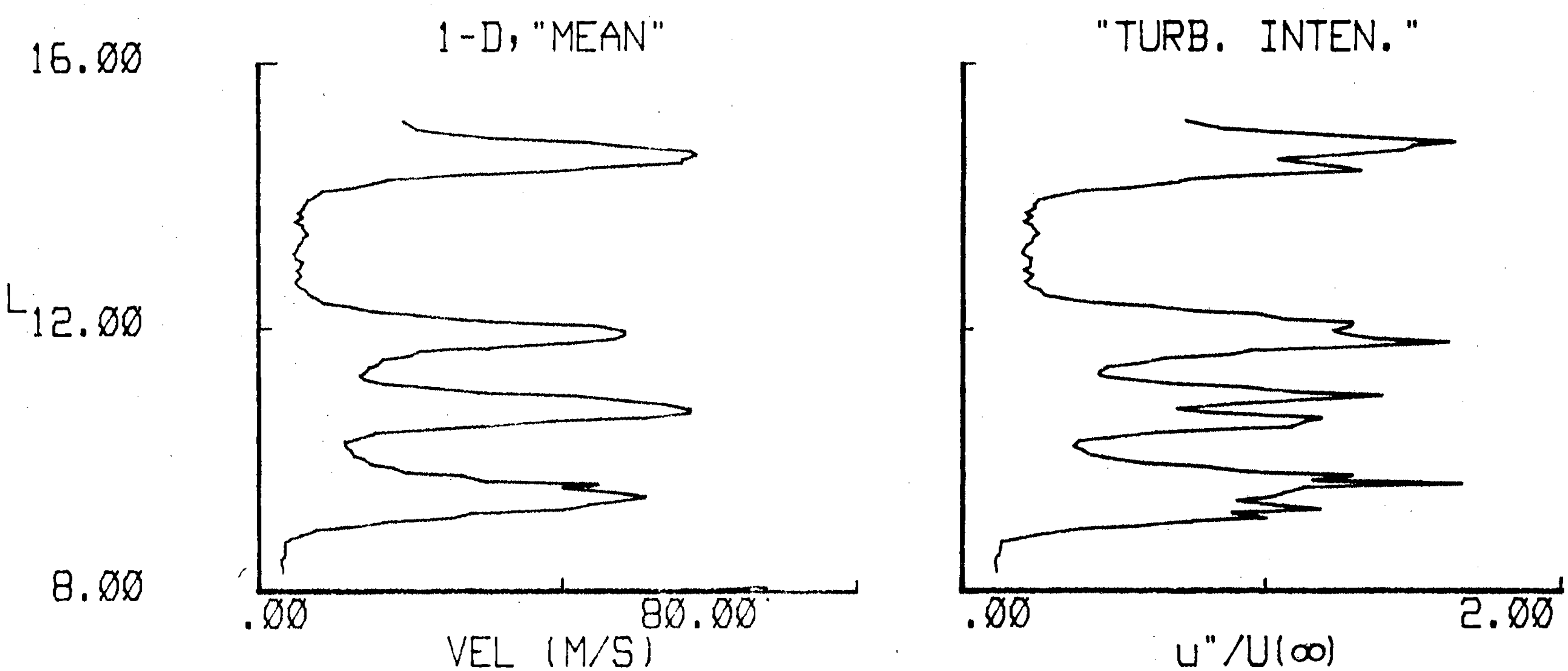
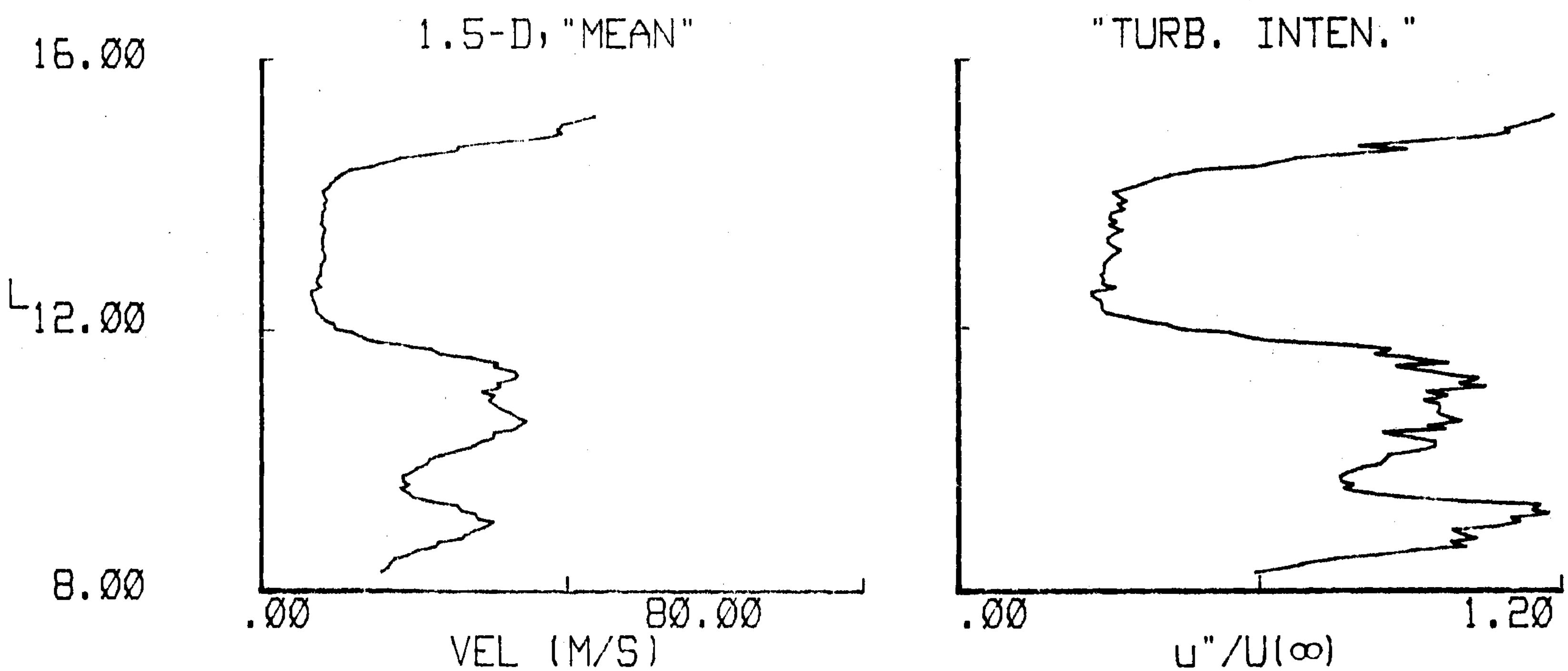


Fig. 18 (continued)



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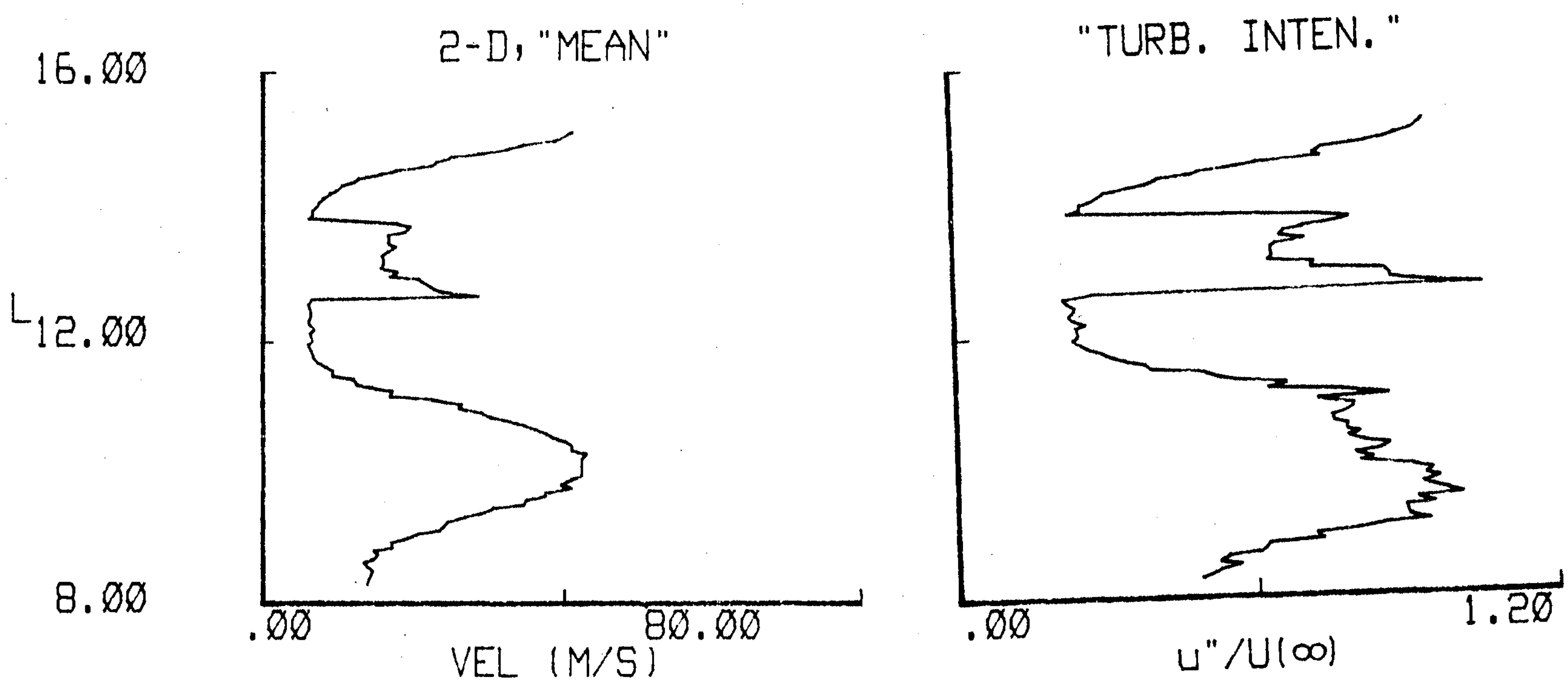

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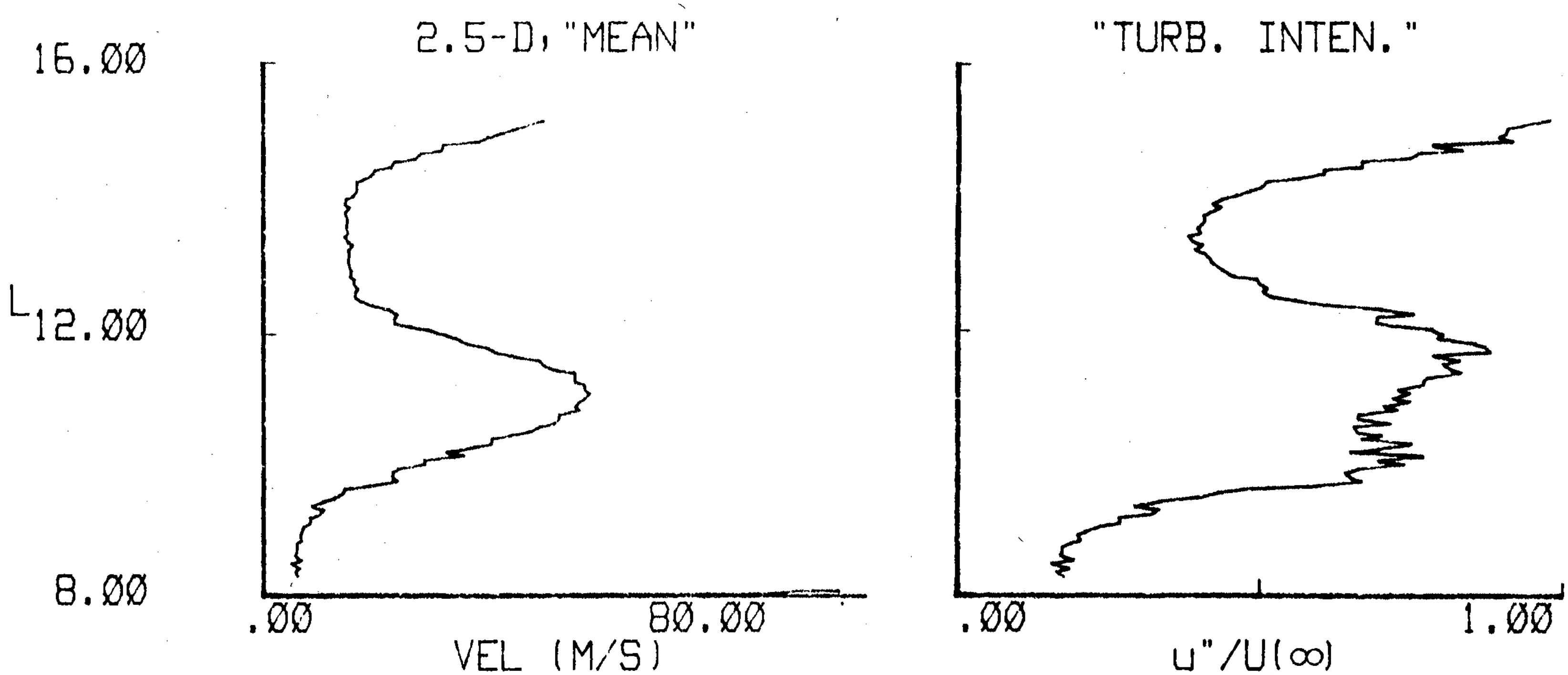

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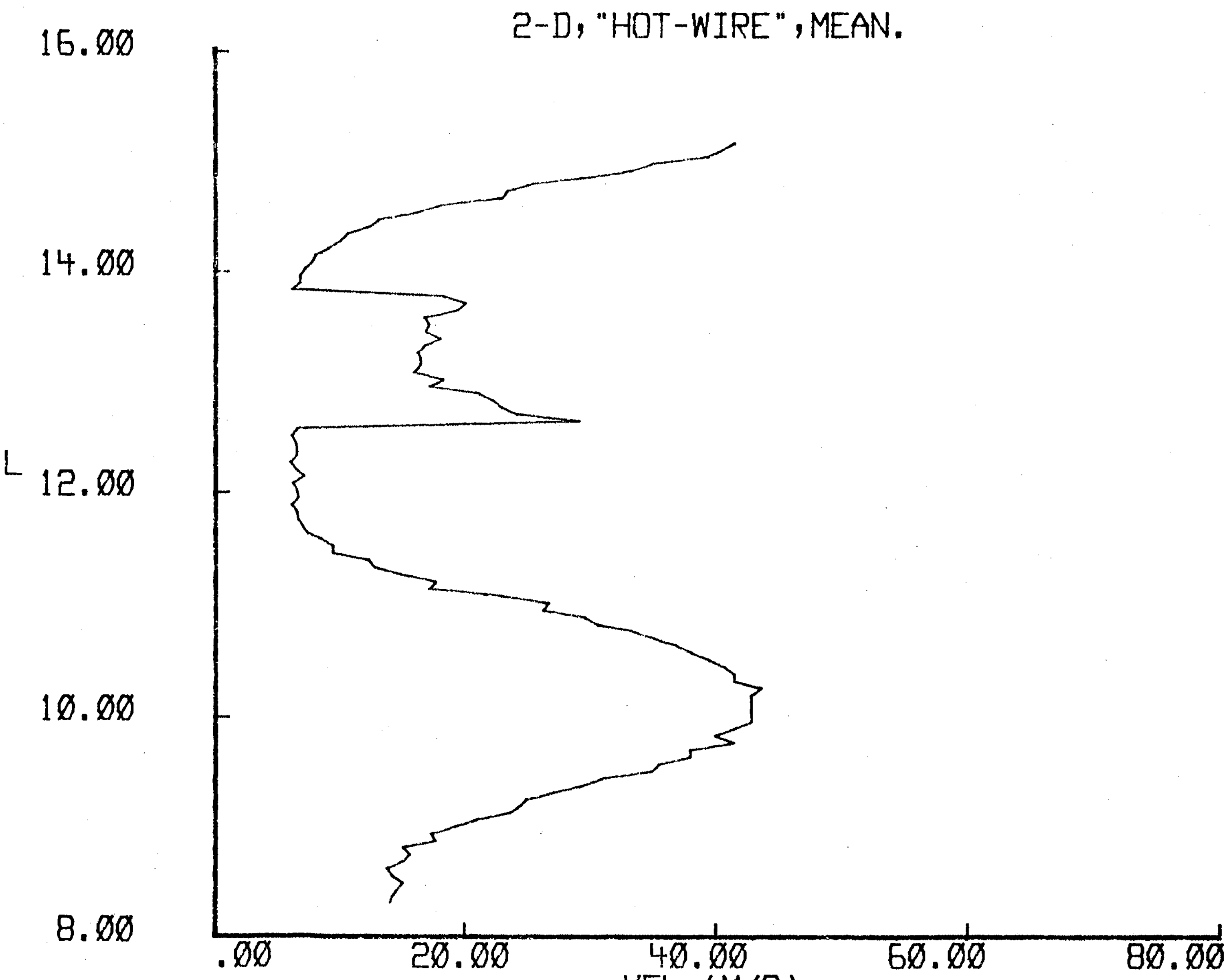

Fig. 19 Mean Velocity Profile 2-D After the Tube Row

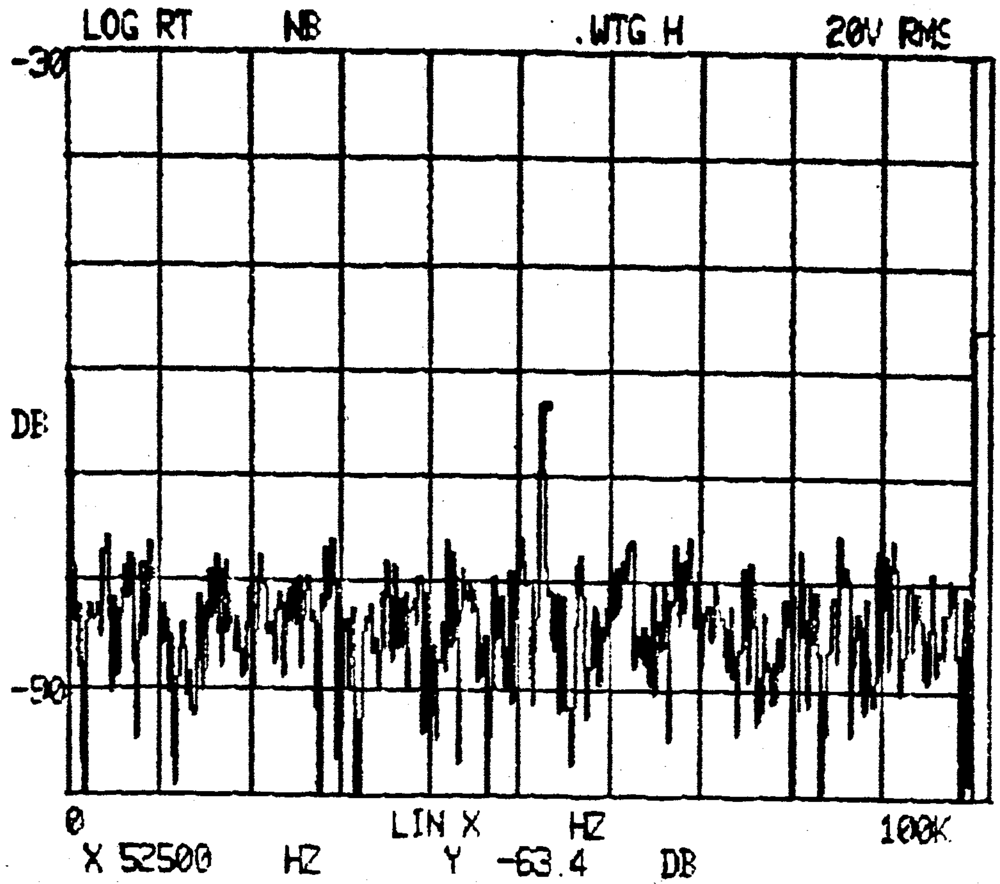

Fig. 20 Frequency Spectrum (noise of the background)

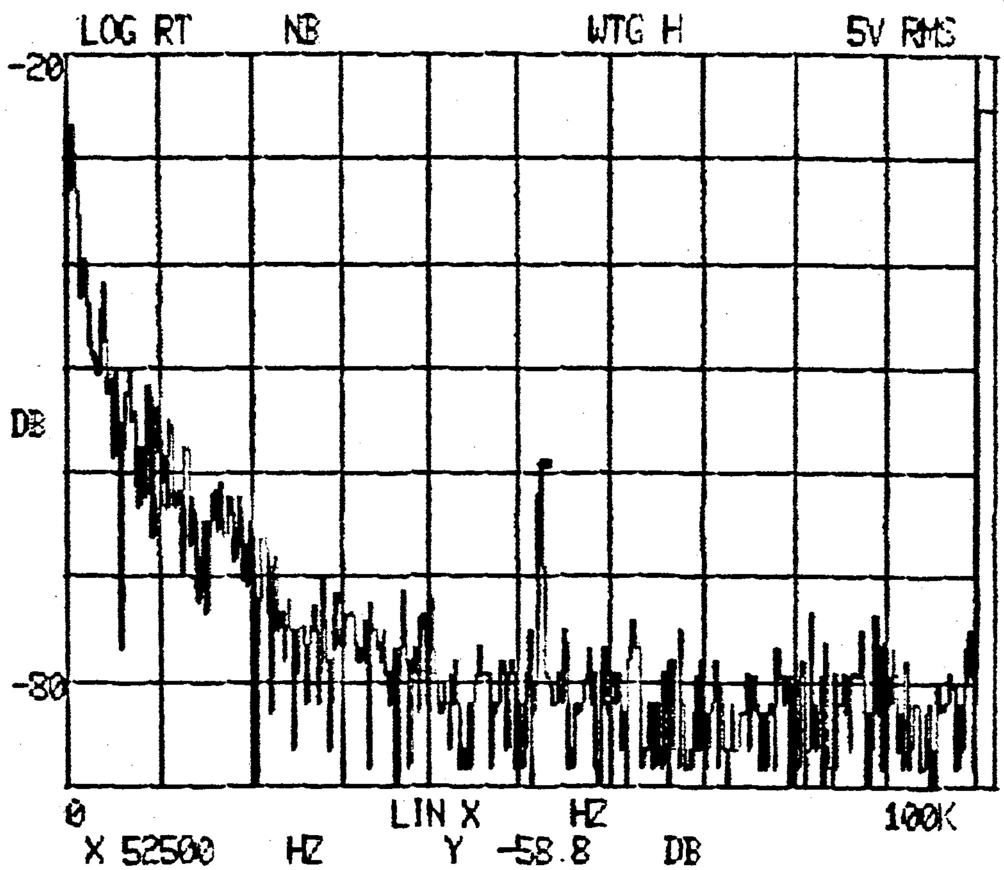

Fig. 21 Frequency Spectrum (in the wake)