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# Experimental Study of the Stability of Pipe Flow II. Development of Disturbance Generator

A. Kaskel

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JET PROPULSION LABORATORY  
CALIFORNIA INSTITUTE OF TECHNOLOGY  
PASADENA, CALIFORNIA


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**Experimental Study of the Stability of Pipe Flow  
II. Development of Disturbance Generator**

A. Kaskel



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CALIFORNIA INSTITUTE OF TECHNOLOGY  
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## ABSTRACT

The second phase has been completed in an investigation of the stability of pipe flow with respect to disturbances of different frequencies and amplitudes. A disturbance generator capable of producing a symmetrical disturbance has been developed and preliminary measurements, at a nominal  $Re = 7600$  in air, indicate that small-amplitude disturbances do decay as they propagate down the pipe. Wavelength measurements of these disturbances have also been made and show good agreement with theoretically predicted values.

## I. INTRODUCTION

The overall purpose of the present experimental study is to obtain the stability of a fully developed laminar pipe flow with respect to disturbances of different frequencies and amplitudes. The scope of the present investigation includes that of Ref. 1 and, in addition, the effects of large-amplitude disturbances on the pipe flow. In the first phase of this project (Ref. 2), a flow adequate for a stability study of this type has been established.

The second phase of this project will concern itself primarily with the development of a suitable disturbance generator and, secondly, with the development of experimental techniques that can be used to make amplitude and wavelength measurements of the disturbances thus produced.

The first disturbance generator that was developed for this experiment consisted of a circular, metallic ribbon

placed inside a magnetic field. Current was then passed through the ribbon, causing it to vibrate. This type of generator was found to be inadequate because the large amount of current required to obtain a disturbance of reasonable size caused the ribbon to heat up and convect heat into the flow field.

The final configuration uses vibrating reeds as the mechanism for generating the disturbance. It is described fully in Section II, and its method of operation is detailed.

Some preliminary measurements that have been made indicate that the low-frequency, small-amplitude disturbances do decay as they propagate downstream from their source. Wavelength measurements made at frequencies of 10 and 15 cps have also shown good agreement with theoretically predicted values.

## II. EXPERIMENTAL EQUIPMENT AND PROCEDURES

### A. Pipe

The pipe consists of seven sections of 2-in. aluminum pipe, each section being approximately 19 ft long. The internal surface is honed smooth, and the sections are assembled so that mating ends have internal diameters which are equal to within 0.0002 in. (Fig. 1). A measuring station is located one pipe section upstream from the sonic needle valve. Thus there are six sections (totaling approximately 115 ft) provided for the development of the flow.

The sections of pipe are connected by couplings as shown in Fig. 2. The mating portions of a coupling assure a concentric fit; the longitudinal separation of the mating portions assures that the butting surfaces are the ends of the pipe, and the O-rings seal the pipe from the ambient air.

The pipe is supported from the concrete sidewall by channel supports located at about 5-ft intervals. The pipe rests in v-blocks on these channel supports. For alignment purposes, the position of the v-block on the support can be adjusted horizontally and vertically by means of adjusting screws.

For all the measurements made in this phase of the experiment, the velocity  $\bar{U}$  averaged over the cross section was approximately 10 ft/sec, and the nominal Reynolds number based on  $\bar{U}$  and the diameter was 7600.

### B. Disturbance Generator

The disturbance or wave generator used in this experiment is shown in Fig. 3. It consists of an aluminum pipe, 6 in. long, having the same internal and external diameter as the experimental pipe. Mounted circumferentially on this pipe are six equally spaced, cantilevered aluminum reeds, 5 in. long, 0.375 in. wide, and 0.030 in. thick, and twelve coils, which are situated two above each reed. On the upper surface of the free end of each reed, a small permanent magnet is affixed, while on the lower surface of the free end of each reed is mounted a rod that extends, through slots, into the interior of the pipe. Attached to the end of each rod is a 60-deg segment of a ring. Each segment is 0.962 in. long, 0.0625 in. wide, and 0.010 in. thick, and is made of aluminum. The ring segments have an elliptical shaped cross section that was obtained by compressing some thin-walled, small-diameter aluminum tubing. The thickness of each segment as well as the diameter of each rod was chosen such that, under all flow conditions obtainable in the pipe, the Reynolds number based on these dimensions would be low enough so that there would be no vortex shedding from them. Each ring segment is placed 0.020 in. from the wall of the pipe and has 0.010-in. maximum total amplitude when vibrating.

The disturbance in the pipe is generated by having the reeds vibrate, causing the ring segments (referred

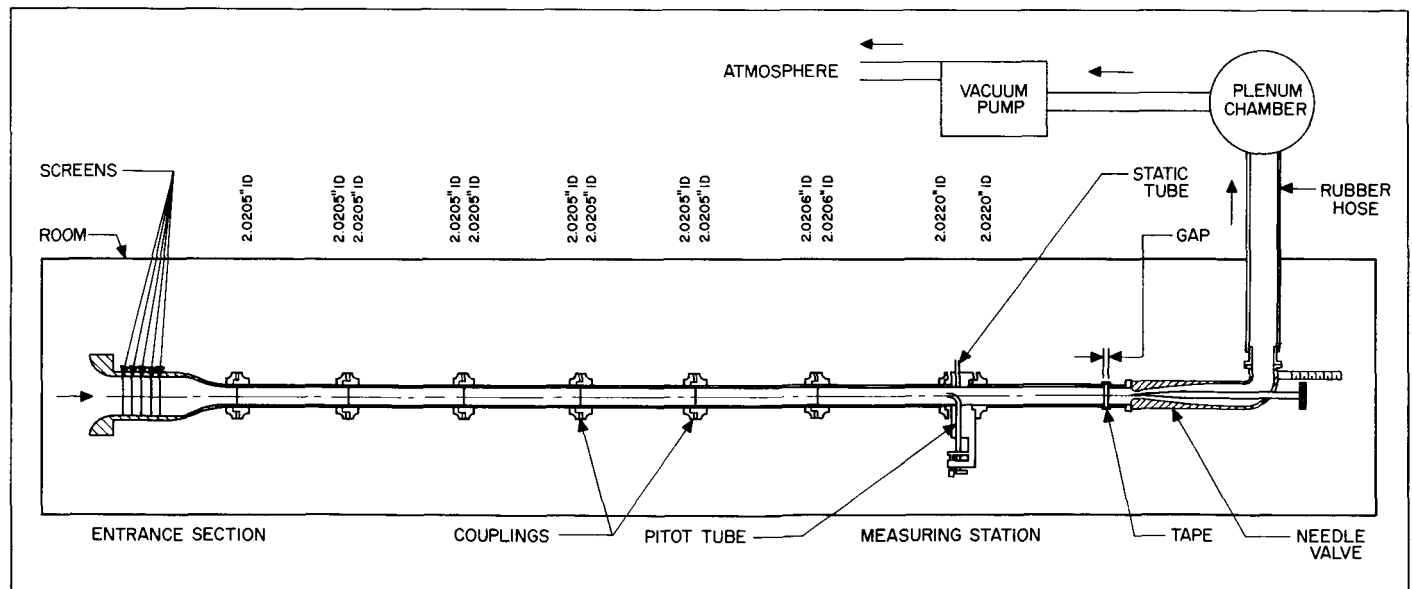


Fig. 1. Schematic layout of pipe flow system

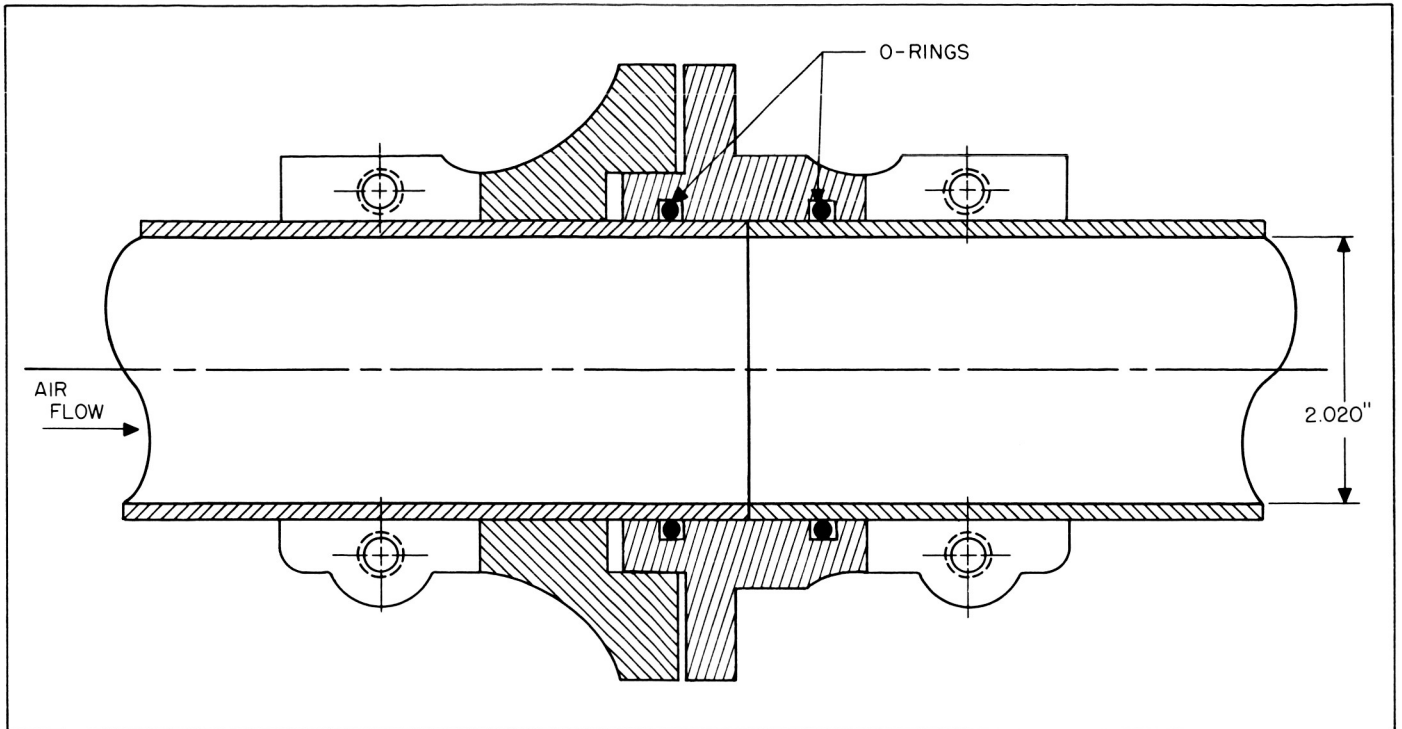


Fig. 2. Pipe coupling assembly

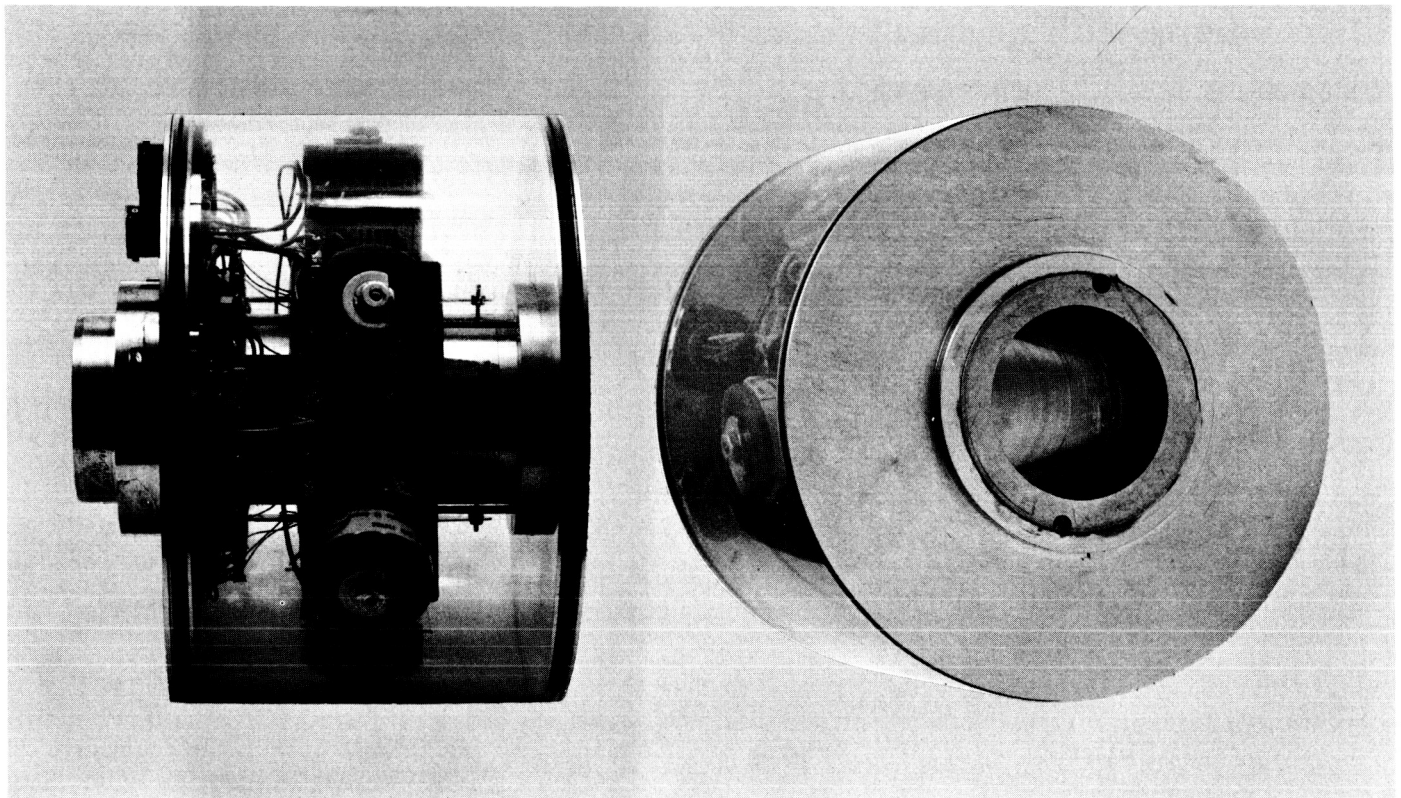


Fig. 3. Disturbance generator

to hereafter as blades) to move in a radial direction inside the pipe. The electronic setup which causes the reeds to vibrate is shown schematically in Fig. 4. The power supply is an audio oscillator which generates a sinusoidal signal of known amplitude and frequency, both of which are adjustable. This signal is then fed into a two-stage transistorized amplifier. There is one amplifier for each reed; each amplifier has its own amplitude control adjustment. The amplified signal is then sent to the coils, converting them into electromagnets. Because the signal sent to the coils is ac, the flux density of the electromagnets constantly changes from positive to negative. The action of this changing flux density on the permanent magnets affixed to the reeds causes the reeds to vibrate. Because the frequency at which the flux density changes is the same as the frequency of the audio oscillator signal, it is assumed that the frequency of vibration of the reeds is also the frequency of the audio oscillator signal. This assumption is based on the fact that the separation distance between the permanent magnets on the reed and the electromagnets is so small that all things behave linearly.

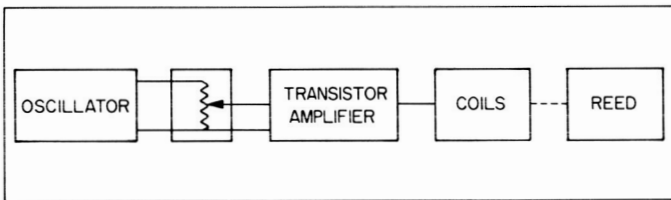


Fig. 4. Electronic setup for the disturbance generator

To measure the amplitude of the vibration, strain gages are placed near the fixed end of each reed. The amplitude of vibration can be computed from the strain gage reading and the frequency and physical and mechanical properties of the reed.

In order to prevent air from entering the pipe through the slots made for the rods, the entire 6-in. pipe section is enclosed in a lucite tube which fits over two flanges fixed at the ends of the pipe. O-rings are provided in these flanges, and the lucite tube can be easily removed by sliding it over the flanges.

### C. Traversing Mechanism

The traversing mechanism used in this experiment is shown in Fig. 5 and 6. It is mounted inside the pipe and was designed so as to be rigid and yet take up only a minimum of cross-sectional area of the pipe. It is capable of 20 in. of axial travel and can traverse radially from the centerline of the pipe to the lower wall only. A circumferential traverse is obtained by fixing the axial and radial position of the probe and rotating the disturbance generator.

Axial movement of the probe is obtained by means of a fixed gear riding on a hollow screw. The screw is supported at the front end by a three-legged spider fixed to the screw; in the rear it is supported by a similar spider fixed to the pipe through which the screw is free to move. The fixed gear can be operated manually by

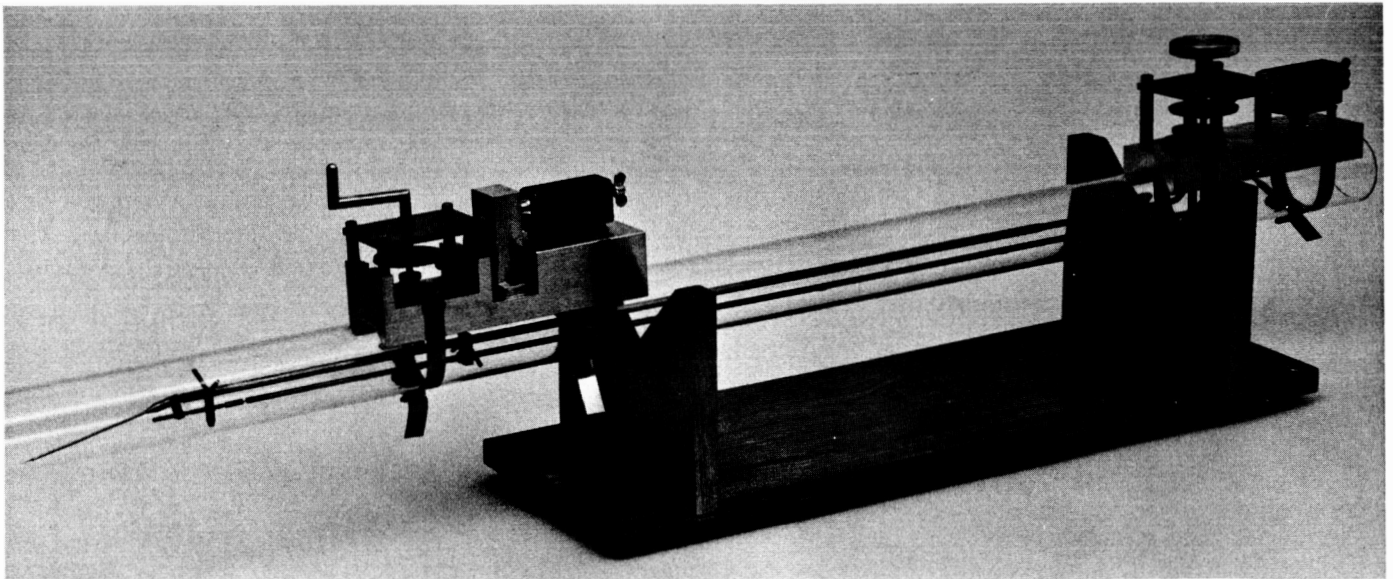
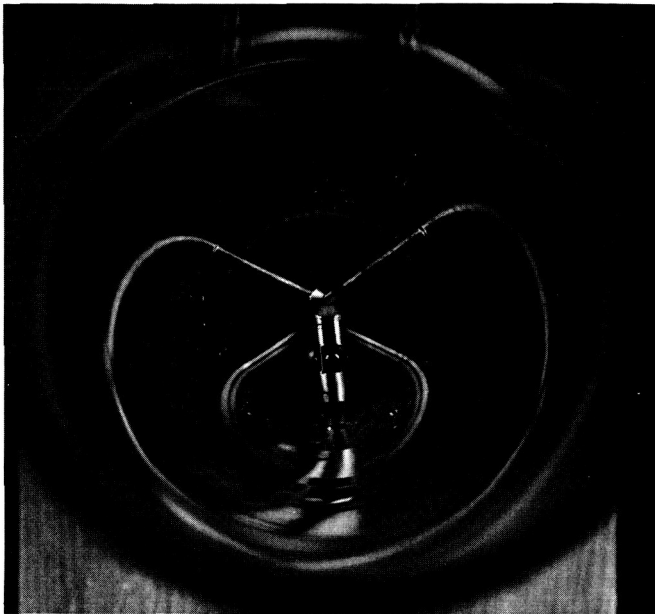


Fig. 5. Traversing mechanism



means of a hand knob, or remotely through a system of gears and a 1 rpm motor. When the gear is operated by the motor, the speed of the traverse is 0.8 in./min.

To obtain radial motion, the connection for holding the probe is attached to the forward end of the screw by means of a hinge and is supported by a small flexure. A mechanical linkage is used to connect the flexure to a manual knob. Turning the knob causes the flexure to twist, which in turn causes the hinged probe connection to move in a radial direction. The use of the flexure and the hinged probe connector enables an axial traverse to be made with the probe fixed in a desired radial position.



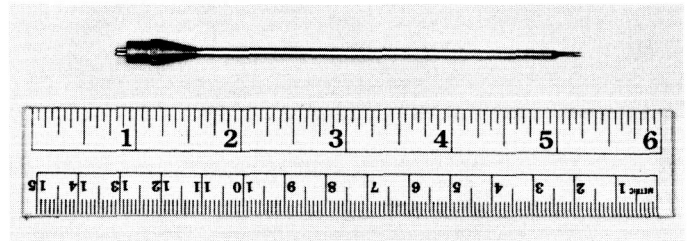
**Fig. 6. End view of the traversing mechanism**

The movement in both the axial and radial directions is measured by means of counters capable of reading to 0.001 in. Circumferential orientation is obtained by a circular scale inscribed into one face of the disturbance generator and a reference line inscribed on the pipe. The circular scale is divided into 5-deg increments and also shows the position of the blades inside the disturbance generator. When the axial traverse is operated remotely, the distance traveled by the probe is measured by both a counter and a potentiometer operated by the motor.

In all cases where holes were cut in the pipe to allow mechanical equipment to be inserted, these holes were made airtight, and the inside surface of the pipe was maintained smooth by using O-rings which were attached to plugs that were inserted in these holes.

#### **D. Hot-Wire Set and Auxiliary Electronic Equipment**

The hot-wire probe used for making measurements in the pipe is shown in Fig. 7. It is 6 in. long and uses a 0.0001-in. platinum-rhodium wire that is 0.030-in. long. The heating circuit for the wire as well as a Wheatstone bridge for measuring the resistance of the wire and a potentiometer for measuring the current supplied to the wire are all contained in a standard Shapiro and Edwards hot-wire set. This set also contains an amplifier and the necessary meters for reading the hot-wire output.



**Fig. 7. Hot-wire probe**

In addition to the hot-wire set, several pieces of auxiliary electronic equipment are used in order to obtain more accurate results: (1) a frequency band-pass filter whose primary purpose is to eliminate all extraneous frequencies from the hot-wire signal, (2) a phase meter for measuring the phase shift of the disturbance in the circumferential direction and the wavelength of the disturbance, (3) an rms voltmeter with a large amount of damping for measuring the hot-wire output as well as acting as an amplifier for the phase meter, (4) a Moseley plotting board for automatic plotting of the hot-wire signal, and (5) a differential amplifier used for measuring the wavelength of the disturbance when the axial traverse is operated automatically.

#### **E. Disturbance Symmetry Measurements**

The circumferential symmetry of the disturbance is measured by using the following experimental procedure:

The hot-wire probe is placed 6 in. downstream of the blades and is traversed radially until the maximum hot-wire output signal is obtained. The probe then remains fixed in this position. The disturbance generator is rotated so that the center of each blade, in turn, is directly opposite the hot wire. The center of each blade is adjusted so as to give the same hot-wire output. The disturbance generator is placed in some initial position and the circumferential traverse is made by rotating the generator.

In order to show that there is no swirl induced into the flow by the blades, the probe is traversed 10 in. downstream of the blades without changing its radial position. The probe is again fixed in this position, and the disturbance generator is rotated to make the circumferential traverse. A comparison of the two traverses will then show whether there is any induced swirl in the flow.

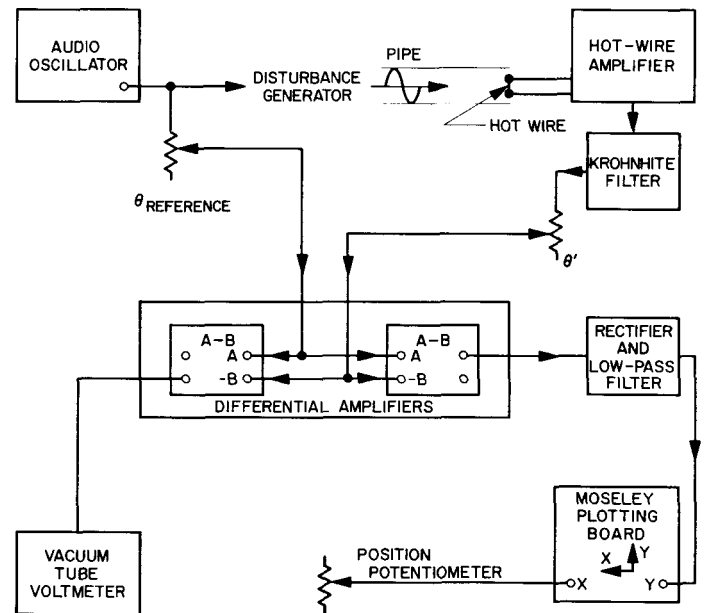
It should be pointed out that this procedure was developed after several disturbance decay measurements were made. At this time, it was ascertained that the eigen oscillations of the pipe flow were not fully developed across the section until they had propagated about a wavelength downstream from their source. Prior to this discovery, all symmetry measurements were made at positions 0.5 in. and 4 in. downstream of the source of the disturbance in a region where the disturbance was just beginning to develop. At the present time, no symmetry data have been collected at positions 6 and 10 in. downstream of the blades, so that all symmetry data presented here are for stations 0.5 and 4 in. downstream of the disturbance source.

**F. Disturbance Decay Measurements**

The procedure that has been developed for making axial decay measurements is as follows. After the symmetry of the disturbance has been checked and it has been ascertained that there is no induced swirl in the flow, the disturbance generator is placed in some reference position. The probe is then placed anywhere from 6 to 10 in. downstream of the blades. The probe is then traversed radially within the critical layer near the wall of the pipe until the maximum hot-wire output signal is obtained, at which radial position the probe is fixed. The probe is then traversed axially—either manually, at which time readings are taken at specified axial stations, or remotely, at which time a continuous profile is obtained on a Moseley plotting board. Because of friction and drag in the traversing mechanism, the probe is always traversed in the downstream direction when data are being collected.

**G. Disturbance Wavelength Measurements**

Determination of the wavelength of the disturbance is made in two ways. In the first case a phase meter is used and the measurements are made in conjunction with the axial decay measurements. At every 60-deg change of phase between the hot-wire signal and a reference signal, the distance that the probe has traveled is noted. At the end of each experimental run, these distances are averaged and multiplied by 6 to give the wavelength of the disturbance. In the second method, which is used only when the traverse is operated automatically, the mean square of the difference between the instantaneous hot wire and reference signals is recorded. A schematic diagram of this electronic setup is shown in Fig. 8. The resulting signal is then fed to a Moseley plotting board, where it is plotted automatically against the axial distance traveled by the probe. The resultant plot is a sine wave whose wavelength is the same as the wavelength of the disturbance.



**Fig. 8. Electronic setup for wavelength measurements**

### III. RESULTS AND DISCUSSION

#### A. Disturbance Symmetry

The circumferential symmetry of the disturbance, for various frequencies ranging from 1 to 50 cps, was measured at positions 0.5 and 4 in. downstream of the blades. A typical set of measurements for a frequency of 2 cps is shown in Fig. 9 and 10. The profiles are symmetric, within the limits of our measurements, but are not circular because of the method in which the disturbance is generated. Since only the center of each blade is attached to a rod, only the center of each blade moves

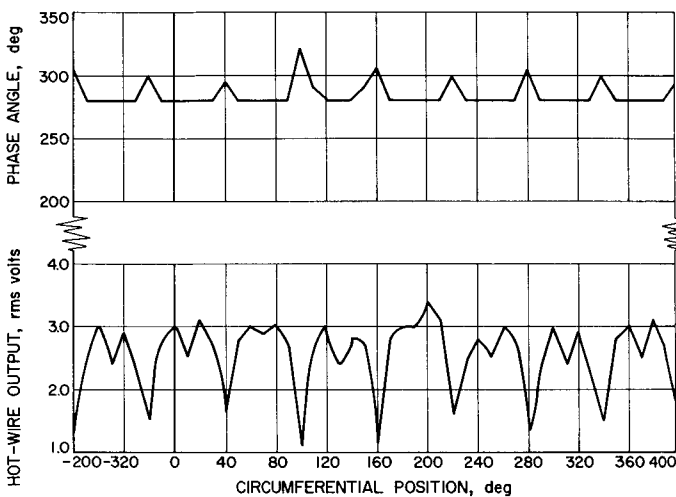


Fig. 9. Circumferential symmetry measurements at  $\frac{1}{2}$ -in. station, frequency = 2 cps

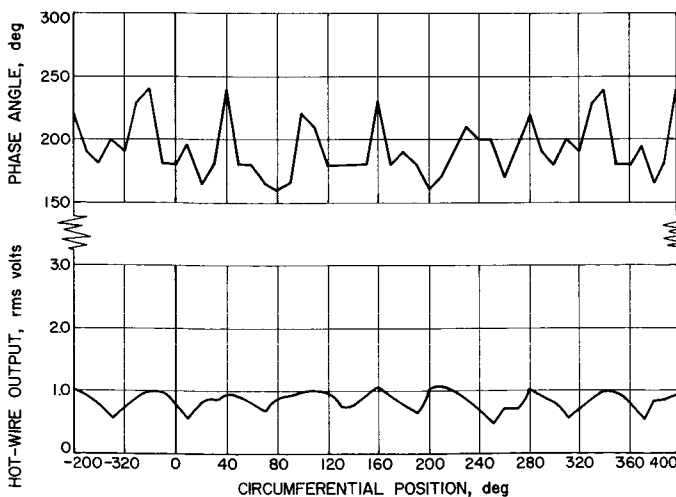


Fig. 10. Circumferential symmetry measurements at 4-in. station, frequency = 2 cps

in a radial direction. All other points on the blade translate relative to the center. Thus the center of each blade moves the greatest radial distance, while the ends of each blade move the smallest distance. The result of this is that each blade contributes a disturbance that has a "sinusoidal" shape. The differences in the shape of the disturbance from each blade are primarily due to the fact that there are slight differences in the curvature of each blade which occur during its manufacture and assembly. The dips that occur at each maximum point in the profiles taken at the 0.5-in. station can be attributed to some disturbance generated from the rods that hold the blades. However, within 2 diameters farther downstream, such as in Fig. 10, it can be seen that the sinusoidal character of the disturbance has been considerably damped.

#### B. Disturbance Decay Profile

The decay profiles for frequencies of 3, 5, 10, and 15 cps are shown in Fig. 11–14, respectively. The "hash" that occurs over the mean profile is a result of a slight vibration of the hot wire that is caused by the fixed gear driving the screw in the axial traversing mechanism. The very sharp peaks are the result of the fixed gear moving over a defective thread on the screw and/or a very sharp noise—such as the slamming of a door—which the sensitive hot wire picks up.

The profiles clearly show that for all frequencies tested, the disturbance begins its development some 1 to 2 in. downstream of the blades as evidenced by the extreme minimum in the profile at that area. Because of this fact, prior to each decay profile measurement, the circumferential symmetry of the disturbance is checked at a position 6 in. downstream of the blades, as explained in Section II-E. The profiles also clearly show, as expected, that the higher-frequency disturbances develop and decay rapidly, while the lower frequencies take a much longer distance to develop and decay. In fact, for frequencies below about 10 cps, modification of the pipe will be necessary in order to allow a longer length to be traversed so that the decay characteristics of these frequencies can be observed.

#### C. Disturbance Wavelengths

Wavelength measurements were made in conjunction with the decay profiles. The dashed appearance of the

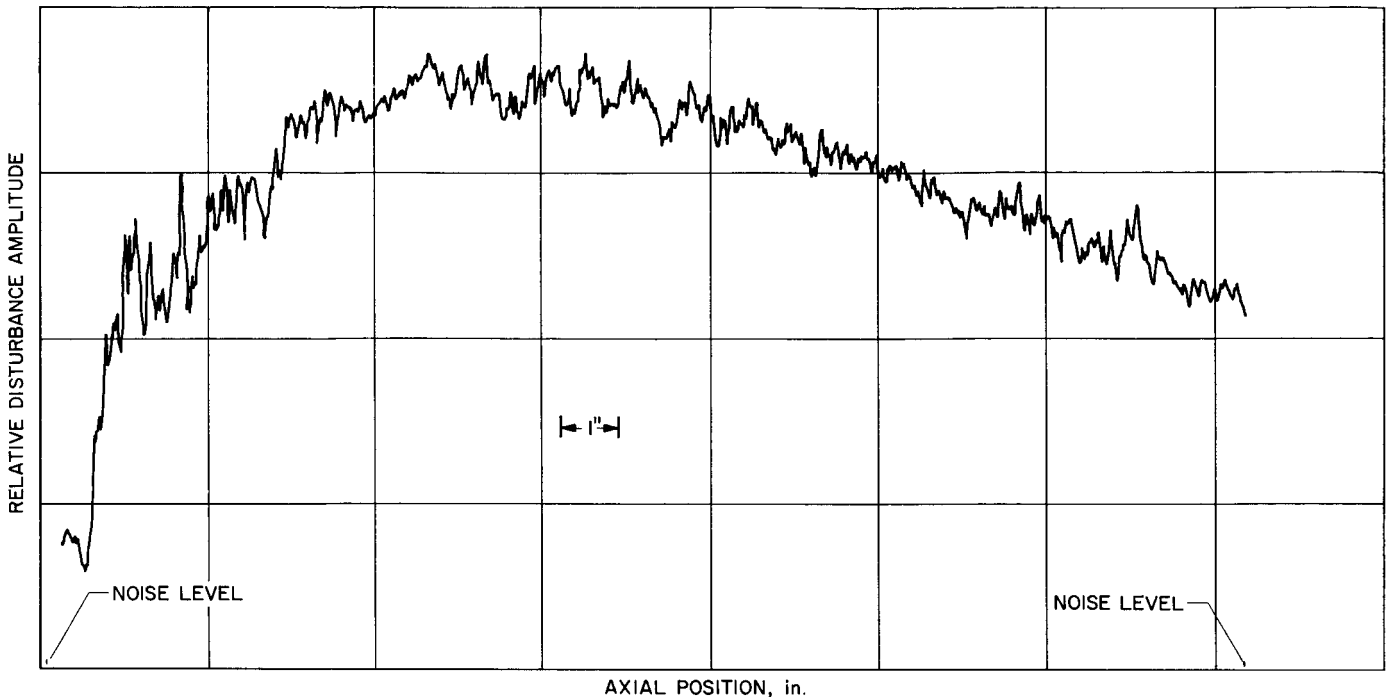


Fig. 11. Decay profiles, frequency = 3 cps

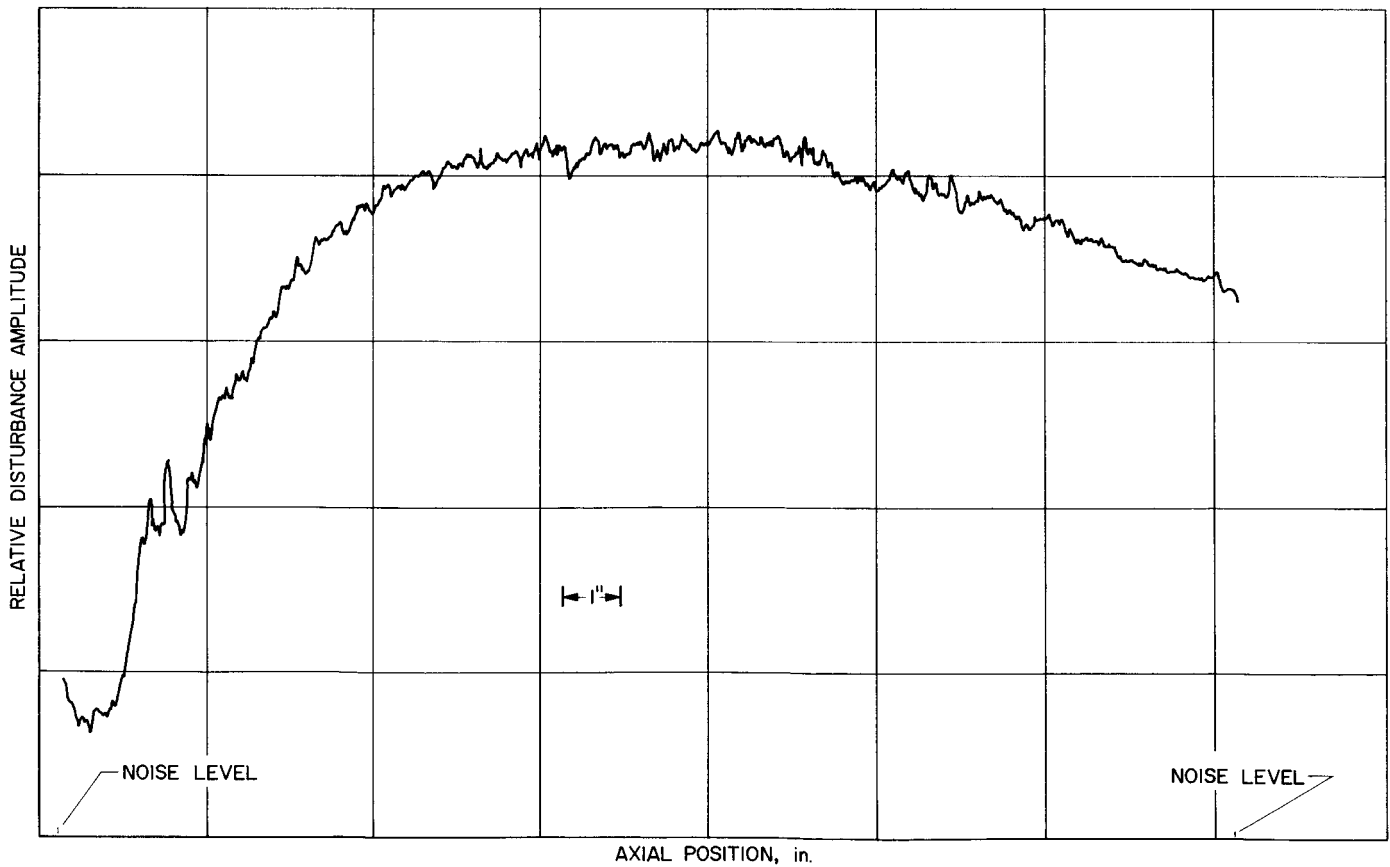


Fig. 12. Decay profiles, frequency = 5 cps

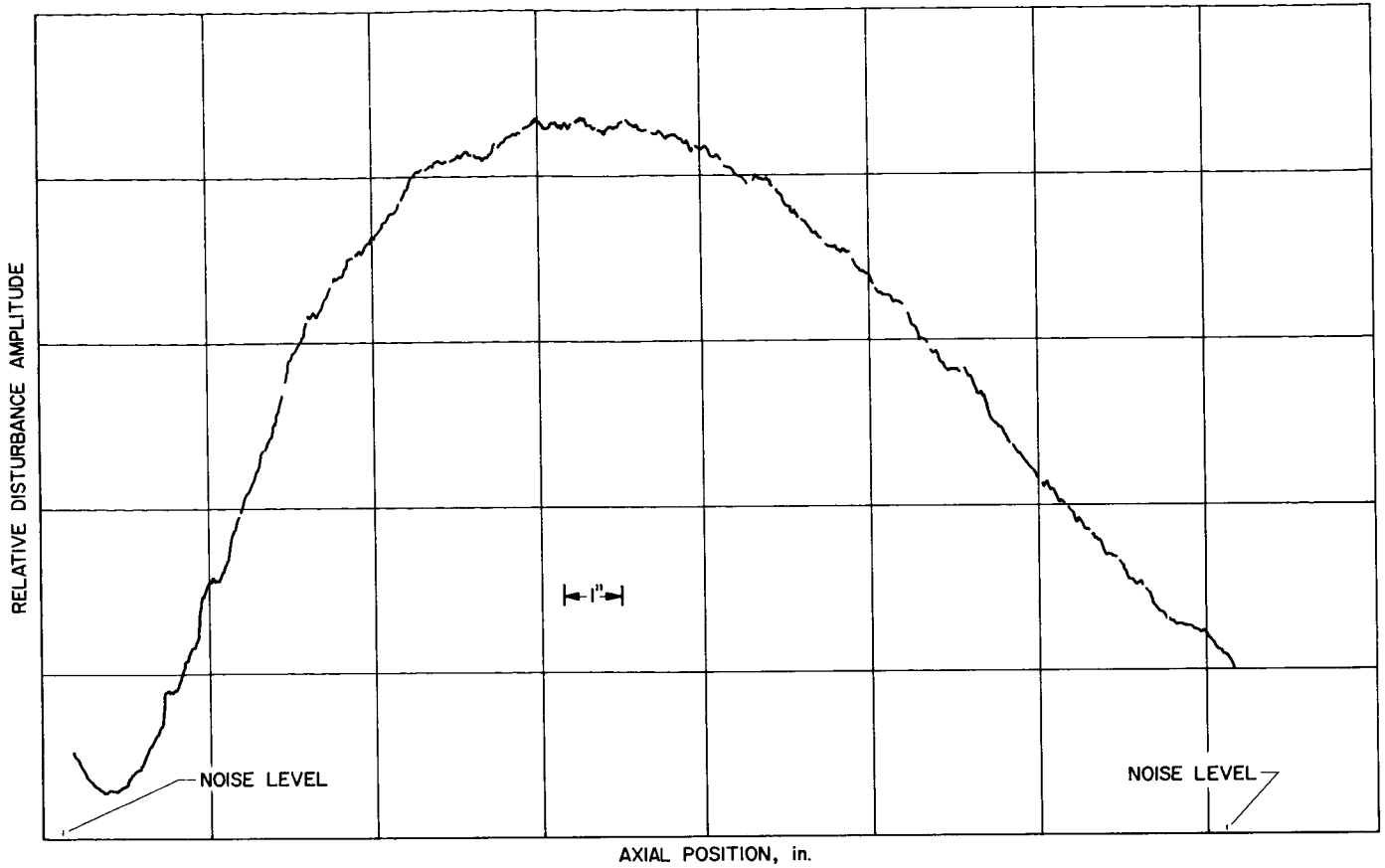


Fig. 13. Decay profiles, frequency = 10 cps

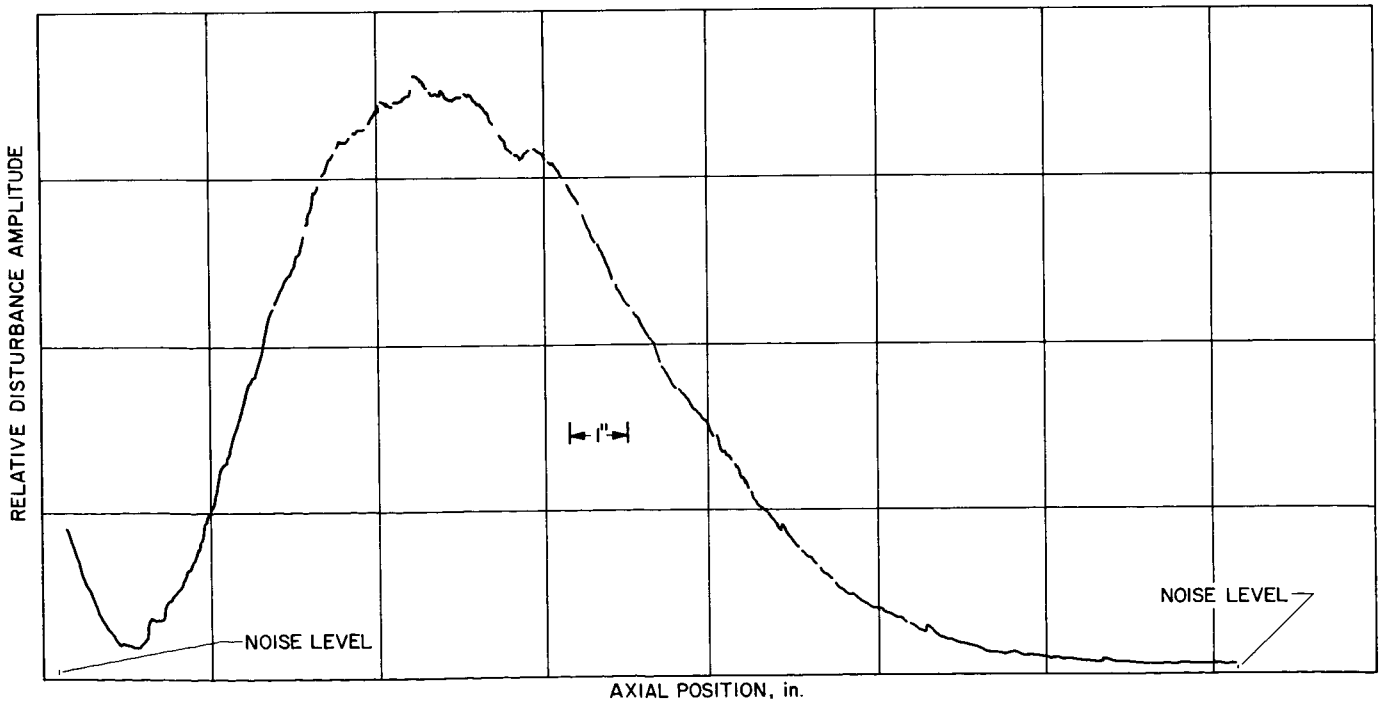


Fig. 14. Decay profiles, frequency = 15 cps

profiles shown in Fig. 11-14 indicate the points at which the pen on the Moseley plotting board was lifted. These spaces correspond to 60-deg changes in the phase of the hot-wire signal. The distance between these separations was measured and averaged, then multiplied by 6 to give the wavelength of the disturbance. Only those distances that occur in the region where the disturbance is fully developed were used in the averaging process. The wavelength as determined by this method for frequencies of

10 cps (5.59 in.) and 15 cps (3.60 in.) compare very well with the theoretical data presented in Ref. 1. In order to obtain data at lower frequencies, the second method of obtaining wavelengths as described in Section II-G was used. A trace made at 5 cps is shown in Fig. 15 and clearly shows that in the distance traveled by the probe the disturbance has not yet become fully developed, so that it is not possible to obtain wavelengths at this and lower frequencies.

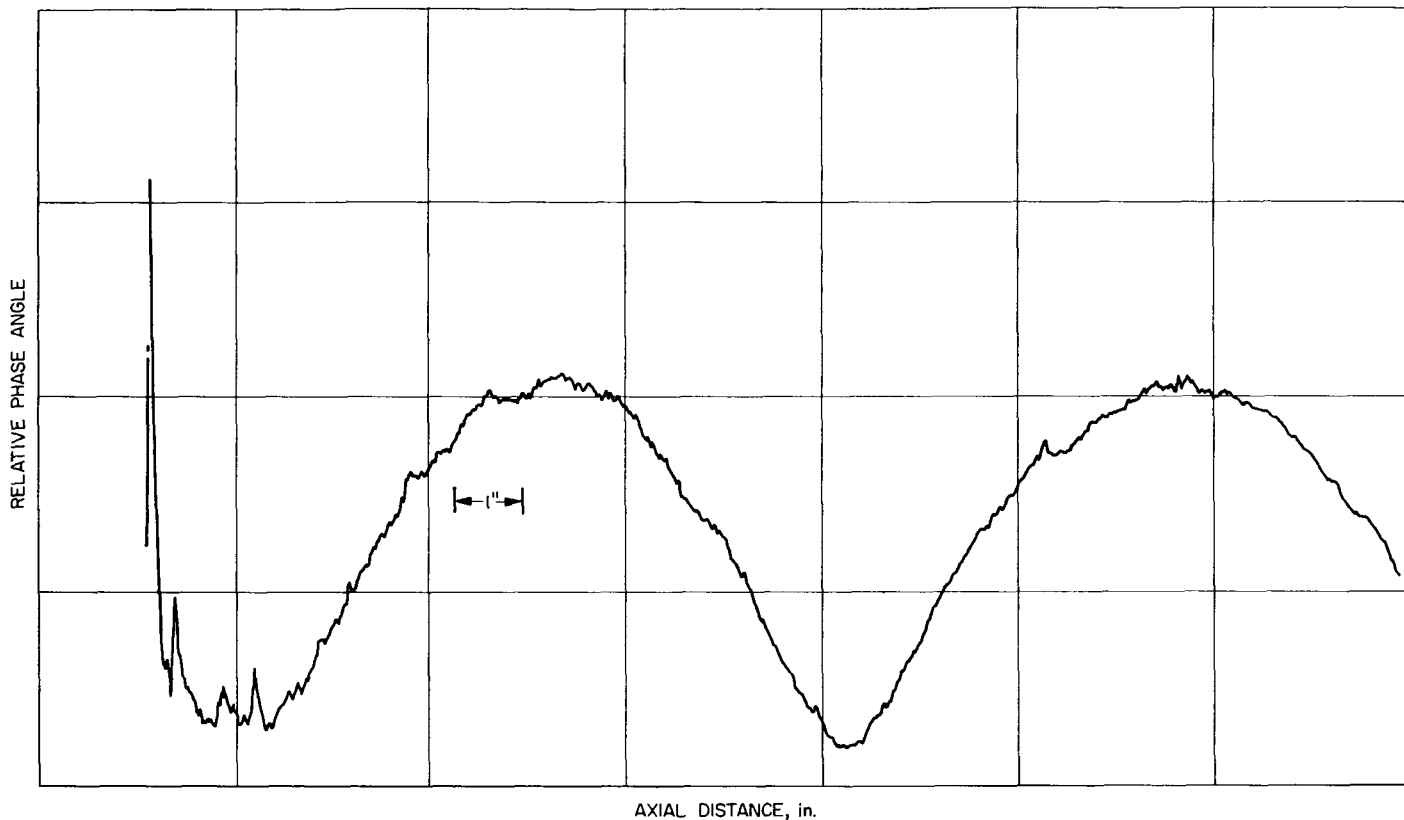


Fig. 15. Wavelength measurement, frequency = 5 cps

## IV. CONCLUSIONS

From the data gathered in this phase of the experiment, several conclusions can be made regarding the techniques and equipment used in performing this experiment. These conclusions can be enumerated as follows:

1. For all practical purposes, the disturbance generator used in this experiment has been shown to be successful in that it can produce symmetrical disturbances.
2. The disturbance becomes fully developed within about a wavelength downstream from the generator.

3. Finally, it is evident that the present length traversed by the hot wire is not sufficient to make measurements of the wavelength and decay of disturbances with frequencies below 10 cps.

As a result of the latter conclusion, work has been started on a modification to the pipe that will allow approximately 11 ft of axial travel of the hot wire. At the same time the disturbance generator is being modified so that both large- and small-amplitude disturbances can be generated. It is hoped that with these additions some definite data regarding large-amplitude disturbances can be obtained.

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2. Reshotko, E., *Experimental Study of the Stability of Pipe Flow I. Establishment of an Axially Symmetric Poiseuille Flow*, Progress Report No. 20-364. Jet Propulsion Laboratory, California Institute of Technology, October 24, 1958.