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Neil S. Berman

Eugene E. Cooper

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LASER-DOPPLER MEASUREMENTS OF THE DECAY OF VELOCITY FLUCTUATIONS IN DILUTE POLYMER SOLUTIONS*

Neil S. Berman** and Eugene E. Cooper+
Arizona State University, Tempe, Arizona

ABSTRACT

Finite disturbances were generated in a pipe containing water or a 20 ppm solution of Separan AP-30 in water by oscillating a sleeve at the wall. The sleeve amplitude in the axial direction varied from 0.5 to 2.0 inches and the frequency from 0.25 to 1.0 Hz. Downstream of the sleeve oscillations in the fluid velocity were measured with a laser Doppler flowmeter at various axial and radial positions to determine behavior at the lower frequency part of the stability curve for water. The response amplitude, phase angle and the mean velocities were measured for both fluids at Reynolds numbers from 500 to 2100. The water response was frequency dependent in the experimental range. Transitions from well defined velocity fluctuations following the disturbance frequency to random responses were noted as the frequency changed from 0.25 Hz to 1.0 Hz. The dilute polymer solutions showed reduced response amplitudes and always had well defined fluctuations indicating that the stability limit is at a higher frequency than that for water.

INTRODUCTION

Experimental measurements of the behavior of disturbances in pipe flows of liquids are rare although there have been many theoretical studies. The history of the problem for Newtonian fluids has been outlined recently by Dixon and Hellums.[1] Other recent works by Davey and Drazen[2] and Fox, Lessen and Bhat[3] have contributed to the present understanding of the stability of disturbances in Poiseuille flow. In brief, "small axisymmetric" disturbances in Poiseuille flow are apparently always stable both experimentally and analytically. Decay rates and wave speeds are functions of Reynolds number and frequency. Other disturbances which give rise to non-linear oscillations are stable for all amplitudes and frequencies below a Reynolds number near 2000. The onset of instability is frequency and amplitude dependent at higher Reynolds numbers.

The statements above for non-"small axisymmetric" disturbances can be inferred from the solution to the non-linear problem by Dixon and Hellums and by the experiments of Fox, Lessen and Bhat on an aximuthally periodic disturbance. The finite difference technique of Dixon was used to study the amplitude dependence of the instability at a fixed frequency, while Fox, et al., varied the frequency experimentally and observed the growth or decay of disturbances. Measurements in air by Leite[4] showed some of the same effects but few quantitative results were given for large disturbances. The theoretical problem for non-Newtonian fluids has not been solved and no experimental data are available. Dilute polymer solutions are of interest because they have unusual flow properties when the polymer concentrations are low.

The work to be presented here was undertaken to determine experimentally the effect of varying the frequency and amplitude of a disturbance on Poiseuille flow of water and solutions of polymers in water. To accomplish this objective a method of measurement which does not disturb the flow and can follow fluctuations at a point is required. The laser Doppler flowmeter meets these qualifications. Also a disturbance generator was needed which would actuate the slowest decaying modes of oscillation at the center of the pipe. The work of Fox, Lessen and Bhat showed the low end of frequency dependence of the neutral stability curve to be between 0.2 and 1 Hz. This work is confined to these low frequencies.

EXPERIMENTAL APPARATUS

Laser Doppler Instrument

The laser Doppler instrument used in this work was constructed by Berman and Santos.[5] Recent reviews by Davis[6] and Pike, et al.,[7] discuss the theory and application of the instrument. Figure 1 shows the optical arrangement of the laser Doppler flowmeter used in this study. Only the velocity of particles in the axial direction in the plane formed by the intersection of the scattered and unscattered beams is measured. Optical heterodyning of these beams at the phototube produces a frequency shift proportional to the velocity. The laser was a Perkin Elmer Model 5220 and the detector a RCA 7265 photomultiplier tube.

In order to allow tape recording of laminar flow frequency shifts and to obtain the maximum signal to noise ratio for the measurements, the angle θ was kept between 8° and 10° as measured in air and the two lenses shown in Fig. 1 had focal lengths on the order of 12 cm. The scattering volume then represented approximately the intersection of two cylinders 20 microns in diameter meeting at an angle of six degrees. Under these conditions the frequency spectra at the tube center in steady laminar flow was broadened less than 4%, but the broadening increased to 30% at a radial distance from the center of 75% of the tube radius. At distances closer to the wall the broad signal is difficult to interpret and becomes obscured by low frequency noise.

Frequency measurements in laminar flow to determine steady velocities or spectra bandwidths were obtained with a Singer Metrics Panoramic Model SB 15a Spectrum Analyzer. To measure unsteady flows a continuous measurement of frequency is necessary but a frequency meter requires a signal much larger than the one to ten millivolts output of the photomultiplier. A system consisting of a Hewlett Packard Model 3410A microvoltmeter coupled to a frequency meter was found to be adequate to follow the unsteady flows. The microvoltmeter was used as a tracking amplifier which would produce a four volt square wave output sig-nal at the same frequency as the input. Pegging the meter at the high end was necessary to insure tracking of the heterodyne signal from the laser when the

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*This work has been partially supported by the University Grants Committee of Arizona State University.
**Associate Professor, School of Engineering
+Faculty Associate, School of Engineering

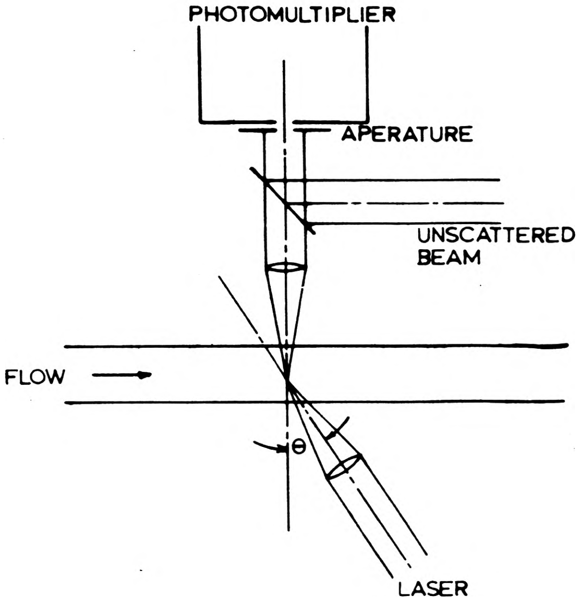


Fig. 1. Laser Doppler flowmeter schematic.

signal strength was varying. Although the tracking system would work when the signal directly from the photomultiplier was used, it was usually desirable to amplify this signal first. The tape recorder amplifier was used as a low noise amplifier in the frequency range of interest.

In summary the heterodyne signal was amplified (or recorded and then amplified) to 0.1 volt or more and processed through the tracking microvoltmeter. The 4 volt square wave signal at the same frequency as the mean of the heterodyne signal was sent to a Hewlett Packard 5210A frequency meter and the amplitude vs. time output was recorded. All measurements were taken in the same manner. At the center of the tube the fluctuations recorded were less than 1% for laminar flow and approximately 4% for fully developed turbulence. As the tube wall was approached the fluctuations increased and the tracking recording system gave measurements higher than the mean of the spectrum when displayed on the spectrum analyzer.

Flow System

The flow was controlled by short lengths of capillary tube at the entrance to a lower constant head tank of a constant head system. An upper constant head tank was 8 feet above the lower one. The fluids were pumped from a lower reservoir up to the upper tank by a centrifugal pump in the case of pure water and by a roller pump at 100-200 rpm for the dilute polymer solutions. Plastic tubing 3/8 inch inside diameter was used in the roller pump.

Two different test sections were used in the study. The first was a 1-inch inside diameter glass pipe ten feet long and the second was made from three sections of glass tube 1.38 cm inside diameter four feet long. The sections were joined together with 5/8 inch Swagelok fittings machined to fit the inside and outside diameters of the tubes. The tubes were selected from standard pyrex tubes so that the ends differed by less than .002 inches in inside diameter. The tube which was being used was mounted on an aluminum channel which was secured to a milling table. The table could be moved so that the scattering volume for the laser Doppler instrument was located at different radial positions across the tube. Under the conditions of the tests the Reynolds number could be changed from zero to 4000. Laminar flow could be sustained up to the highest Reynolds number under proper conditions. Some tests were conducted when intermittent turbulence or permanent turbulent flow was present. In both the pure water and the dilute polymer solution polystyrene spheres 0.500 microns in diameter were added in a concentration of 1:50,000 to increase the intensity of scattered light. The only polymer solution reported here was a 20 ppm solution of Separan AP-30 in water. Separan AP-30 is a partially hydrolyzed polyacrylamide of molecular weight 1 - 3 x 10^6 made by Dow Chemical Company. Both water and the polymer solutions gave the same flow rates when used with the same capillaries in the flow system. The flow rates were measured by collecting and weighing the fluid over a measured period of time. Variations of less than 1% were found over several days of testing.

Disturbance Generation

The disturbance was created by oscillating a sleeve inside the pipe. For the one-inch pipe the sleeve was a two-inch long brass cylinder, 0.020 inches thick and 0.985 inches outside diameter with a 0.25 inch steel section running its length. For the small tube a similar sleeve was made one inch in length and 0.040 inches thick. Figure 2 shows the sleeve and magnetic coupling to supply the motion. Smooth motion could be achieved only if strips of teflon tape, .002 inches thick, were glued on either side of the steel section. The periodic motion was supplied by a Scotch yoke driven by a constant speed motor.

At speeds of 0.25, 0.5 and 1.0 Hz the disturbance frequency variation was less than ± 5% over the time of the measurements. Above 1.0 Hz the sleeve movement was erratic. As a reference the maximum point in the cycle was recorded along with the velocity measurements. The phase angle and wave speed could then be determined. At these low frequencies the reference was called out vocally and recorded on tape or by a second operator.

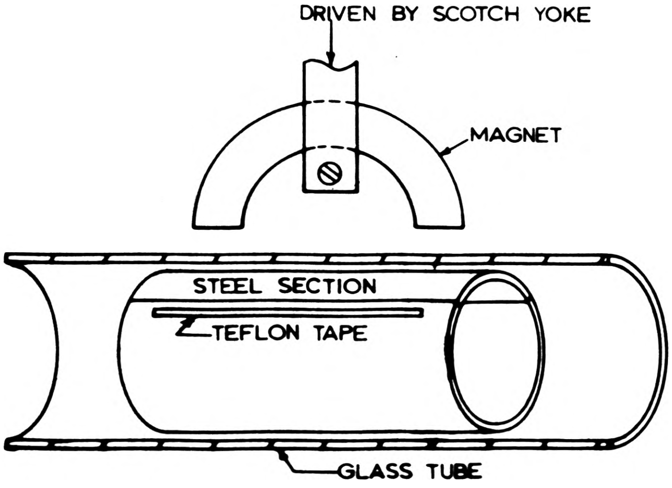


Fig. 2. Disturbance generator.

EXPERIMENTAL RESULTS

Extensive measurements have been made using pure water and 20 ppm Separan in water at Reynolds numbers for water of 570, 1060, 2100, and 4000. The first two will be referred to as 500 and 1000 in the text for convenience. Disturbance amplitudes of 1.0 inch and 1.5 inches were used at frequencies of 0.25, 0.5 and 1.0 Hz for most tests. Some data were also obtained with 0.5 and 2 inch amplitudes. It would be impossible to present all the data in a meaningful form, so only selected results are given here. Except for miscellaneous tests the frequency and amplitude were fixed and measurements were made at various radial positions at a fixed distance downstream of the disturbance. These measurements were repeated at distances further downstream. A typical data point is shown in Fig. 3. The amplitude, u', mean velocity, u_m, and phase angle were scaled from the trace as shown on the figure.

Amplitudes, mean velocities and phase angles varied radially and axially. Typical results for the disturbance amplitude comparing pure water and a fresh 20 ppm Separan AP-30 solution are shown in Fig. 4. In all the illustrations the fluctuation amplitudes and mean velocities are divided by the average velocity. At a Reynolds number of 1000 in the one-inch pipe, 0.5 Hz, 1.5 inch amplitude, the polymer solution is considerably damped. Although there is structure to the curves, the behavior at the centerline is representative of the behavior across the pipe.

The situation is the same for the mean velocities. The presence of the the sleeve leads to a mean velocity profile after the sleeve more pointed than for fully developed flow. A "small" disturbance would leave the velocity profile undisturbed, while a large disturbance would change the profile. Fig. 5 shows the mean profile for the same conditions as Fig. 4. The effect on the velocity profile is much greater for pure water than for the polymer solution. The polymer solution has a blunt profile in undisturbed flow compared to the water as reported by Berman[8] previously. Again the centerline behavior can be used to describe the downstream decay of the disturbance.

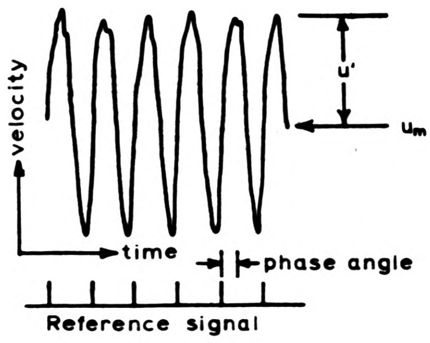


Fig. 3. Typical response signal.

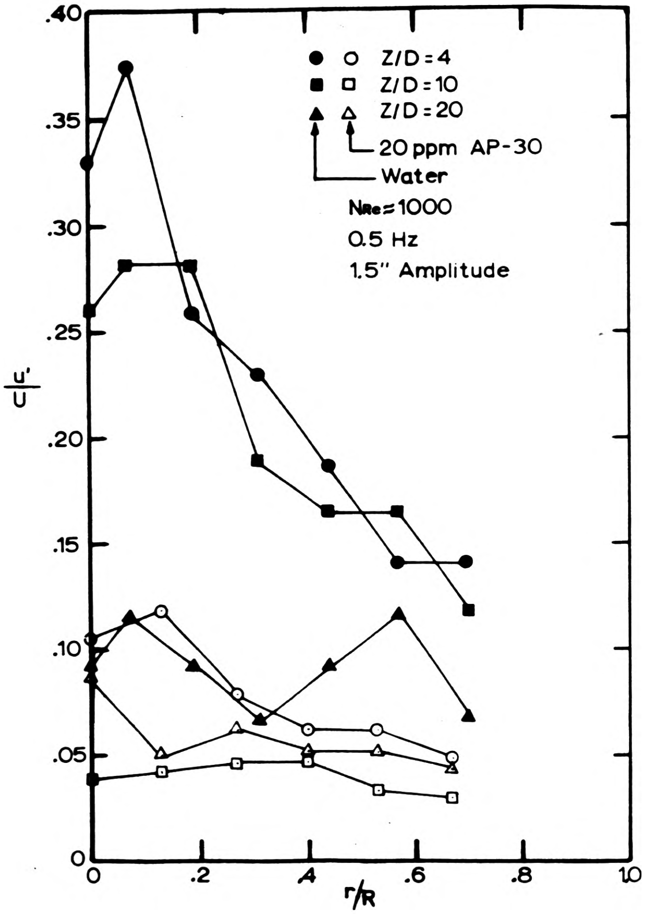


Fig. 4. Radial distribution of response amplitudes, 1.0-inch diameter pipe.

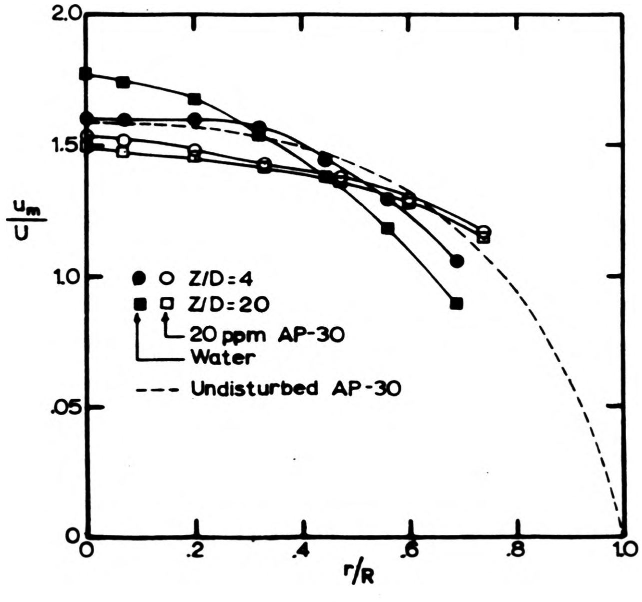


Fig. 5. Velocity profiles of water and 20 ppm Separan, N_{Re} = 1000, 1.0-inch diameter pipe.

Figures 6 and 7 show detailed measurements at the centerline from 4 to 20 diameters downstream of the disturbance. The downstream distance is measured from the mean position of the most forward part of the disturbance generator. Both sets of curves show downstream oscillations with a wave length approximately the same as the wave length measured by determining the downstream distance for a phase shift of 360°. A plot of phase angle vs. downstream distance is a straight line for the center line with wave lengths of 6.0 diameters for the 0.25 Hz and 2.7 diameters for the 0.5 Hz disturbances shown in Figs. 6 and 7. Phase angle measurements at different radial positions show a constant phase angle from the centerline to r/R of 0.4. Then the phase angle increases for the dilute polymer solution. Pure water shows variations in phase angle across the tube along with changes in the structure of the waves. These will be discussed later.

In the smaller tube of diameter 1.38 cm compared to 2.54 cm of the larger, the 0.5 Hz disturbance again had a much higher amplitude in water than the dilute polymer solution as shown on Fig. 8. The disturbance amplitude was 1 inch for this case. Here the wave length was approximately 15 diameters for both water and the dilute polymer. Since the average velocity was much greater than that for the larger pipe, the wave length would be longer. The structure does not show up since only a little more than one cycle is shown but the relative positions of the maxima do appear on this graph. Note that the dilute polymer maximum occurs <u>before</u> that of pure water. Measurements further downstream indicate rapid decay and no further evidence of the waves which were found when the 15 diameter downstream distance represented 5 cycles and not one. When 0.25 and 1.0 Hz disturbances were used, the dilute polymer curves showed smaller amplitudes than the water curves; but the differences were on the order of only 20%.

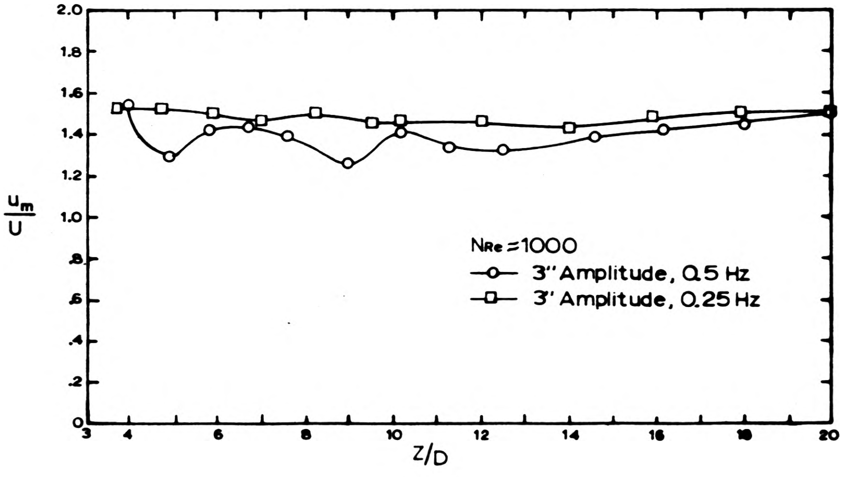


Fig. 6. Centerline mean velocity development for 20 ppm Separan at N_{Re} = 1000, 1.0-inch diameter pipe.

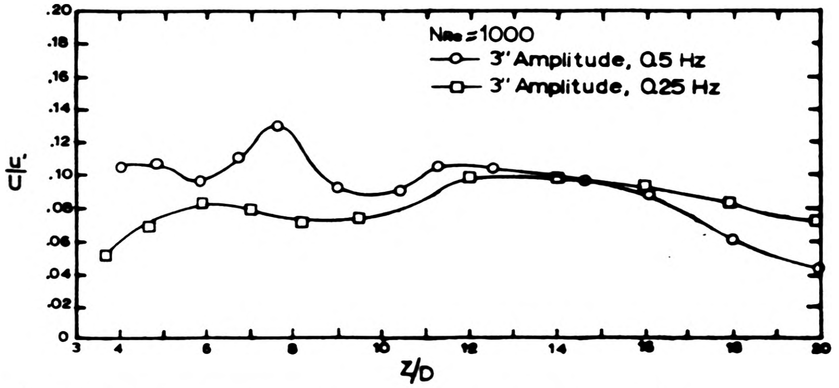


Fig. 7. Centerline response amplitude for 20 ppm Separan at N_{Re} = 1000, 1.0-inch diameter pipe.

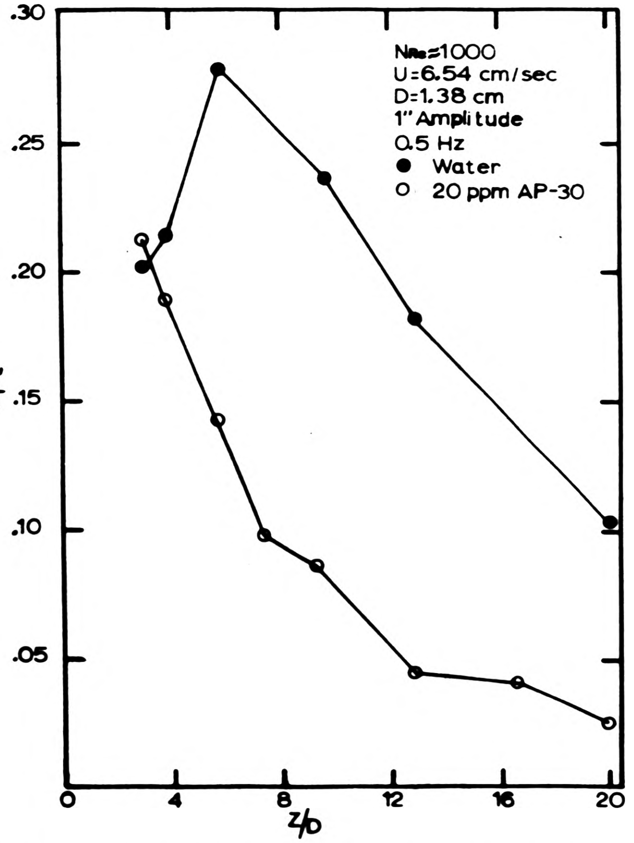


Fig. 8. Centerline response amplitude for 20 ppm Separan at N_{Re} = 1000 1.38-cm diameter tube.

The data at Reynolds numbers for water of 500 and 1000 with the dilute polymer solution at the same flow rate show the same trends for both substances. Only the magnitude is reduced in the dilute polymer case. There is little effect of disturbance amplitude in the range 1.0 inch to 2 inches for the 0.25 and 1 Hz frequencies. The 0.25 Hz disturbance does not affect the mean velocity profile appreciably and the amplitude of the response is low. At 0.5 inch disturbance amplitude the response amplitude is lower than that for the other disturbance amplitudes for this 0.25 Hz frequency. The 0.5 Hz frequency has the most noticeable effect of the three tested. Disturbance amplitudes are of importance. From 0.5 to 1.5 inches increasing the amplitude increases the response amplitude, but the 2.0 inch disturbance amplitude leads to a reduction in the response. The mean profiles are changed significantly in all cases of the 0.5 Hz frequency; increasing the disturbance amplitude lowers the mean velocity at the centerline.

For the 1.0 Hz frequency the response amplitude is large close to the disturbance, but it falls off rapidly to the level of the 0.25 Hz frequency within 5 pipe diameters. The mean velocity profile, however, changes much more than the change from 0.25 to 0.5 Hz. At the Reynolds number of 1000 the minimum mean velocities at the center line within the first 10 diameters downstream of the disturbance are 2, 1.7, and 1.3 for the 0.25, 0.5 and 1.0 Hz frequencies respectively for a disturbance amplitude of 1.0 inch.

The laminar flow results are of interest to compare with results at a Reynolds number of 2100. Figures 9, 10 and 11 show differences from the

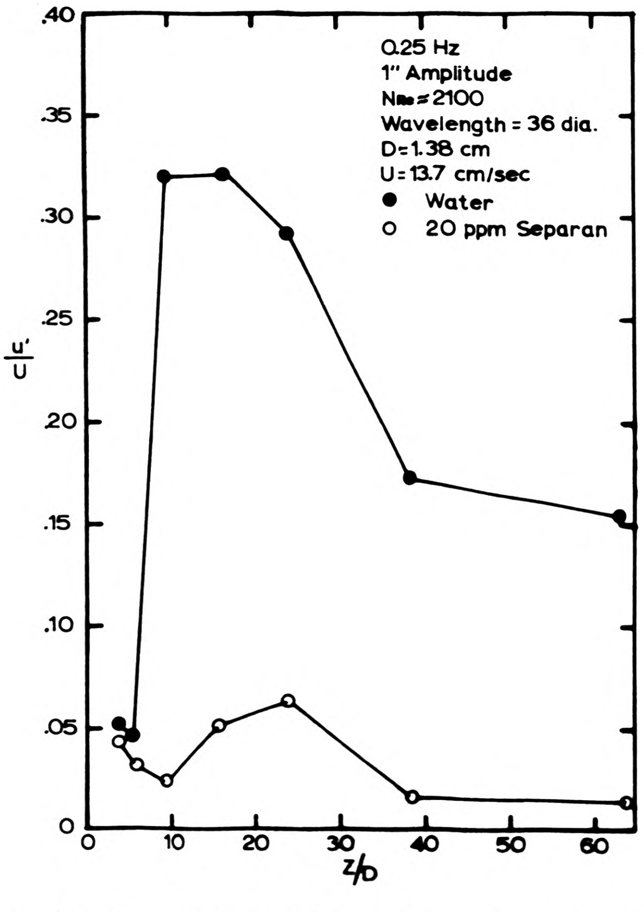


Fig. 9. Centerline response amplitude 1.38-cm diameter tube, N_{Re} = 2100, 0.25 Hz frequency.

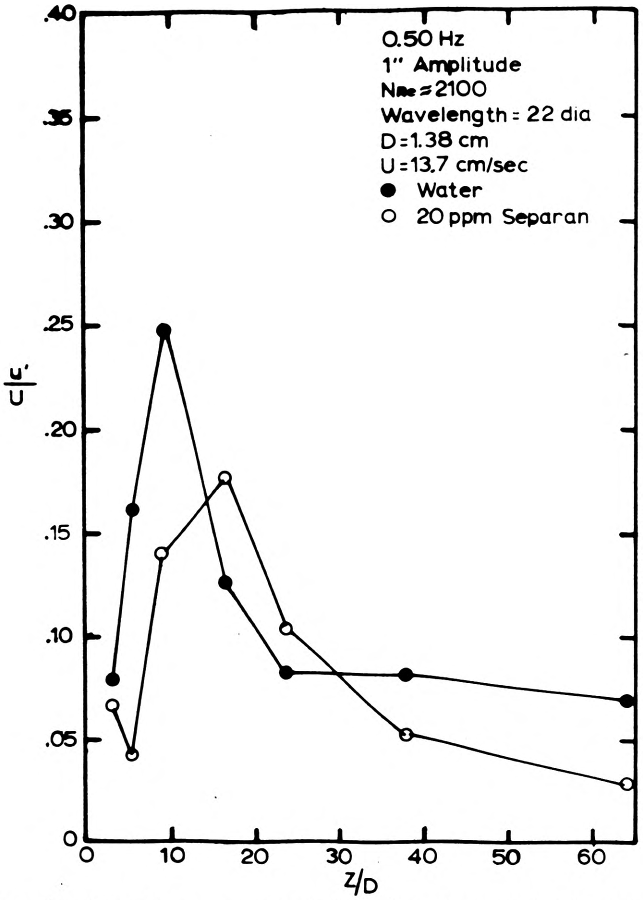


Fig. 10. Centerline response amplitude, 1.38-cm diameter tube, N_{Re} = 2100, 0.5 Hz frequency.

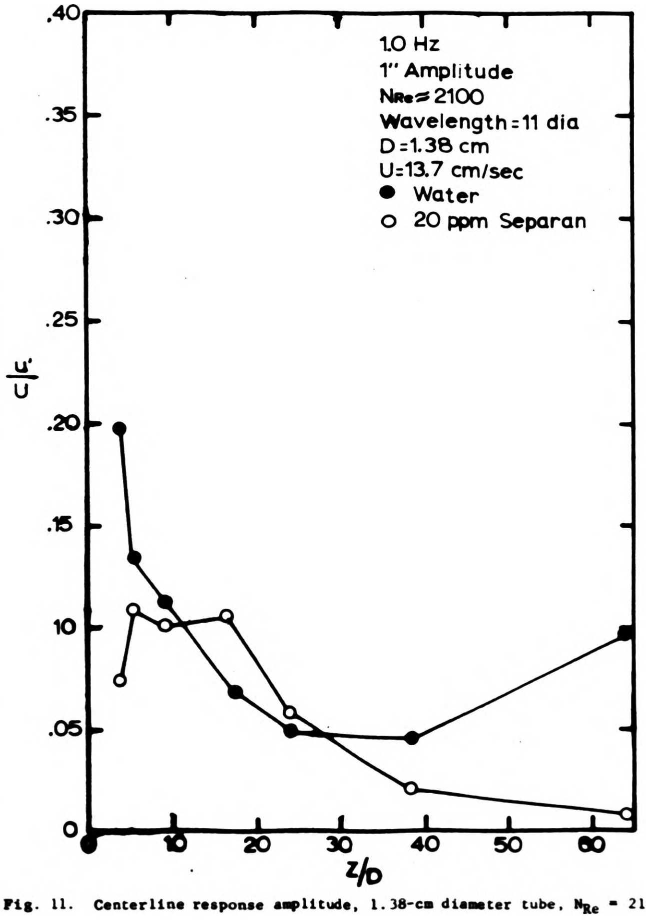


Fig. 11. Centerline response amplitude, 1.38-cm diameter tube, N_{Re} = 2100, 1.0 Hz frequency.

previous results. The 0.25 Hz disturbance has the maximum response amplitudes, and the dilute polymer curve peaks after the water curve. Also the larger differences between water and the dilute polymer are at 0.25 Hz rather than 0.5 Hz. At this Reynolds number the character of the response changed, however. There appeared to be two flow levels which could be stabilized when water was the fluid, possibly representing laminar and turbulent flow. This was not noted with a freshly prepared Separan solution. An old Separan solution which had been used intermittently for six months displayed different properties. Laminar velocity profiles were essentially the same as for the freshly prepared solution. The mildest disturbances at low Reynolds numbers also gave the same results. The more severe disturbances in laminar flow and all cases at the Reynolds number of 2100 showed only a slight reduction in response amplitude compared to water and the two levels were present. The freshly prepared solution was mixed in concentrated form one day, then mixed up to the required concentration on a second day and used after standing 24 hours. Before any measurements were made the solution was circulated through the flow system for one hour or approximately three turnover times of the storage tank. This fresh solution did not show the two-flow levels until the flow rate was doubled to a Reynolds number of 4000.

At the Reynolds number of 2100 Fig. 12 shows the mean velocity at the centerline in all cases is returning to the laminar flow level at 60 diameters. Other data for water at a Reynolds number of 2250 show a similar trend. It was not possible in the flow system to measure further downstream without placing the disturbance in the entry region of the pipe. The effect of changing the frequency is shown clearly on Fig. 12. The disturbance produced by this generator leads to a dimensionless wave speed, $\lambda f/U$, between 1.0 and 1.2 at this Reynolds number for all the frequencies. Therefore the 0.25 Hz disturbance has gone through less than two cycles, the 0.5 Hz disturbance, three cycles and the 1.0 Hz disturbance, six cycles on Fig. 12. The minimum in the mean velocity at the center and the maximum response amplitude vary with the downstream distance accordingly. At 60 diameters the 20 ppm Separan solution has returned to the undisturbed mean velocity and the fluctuations are at the noise level of the undisturbed system.

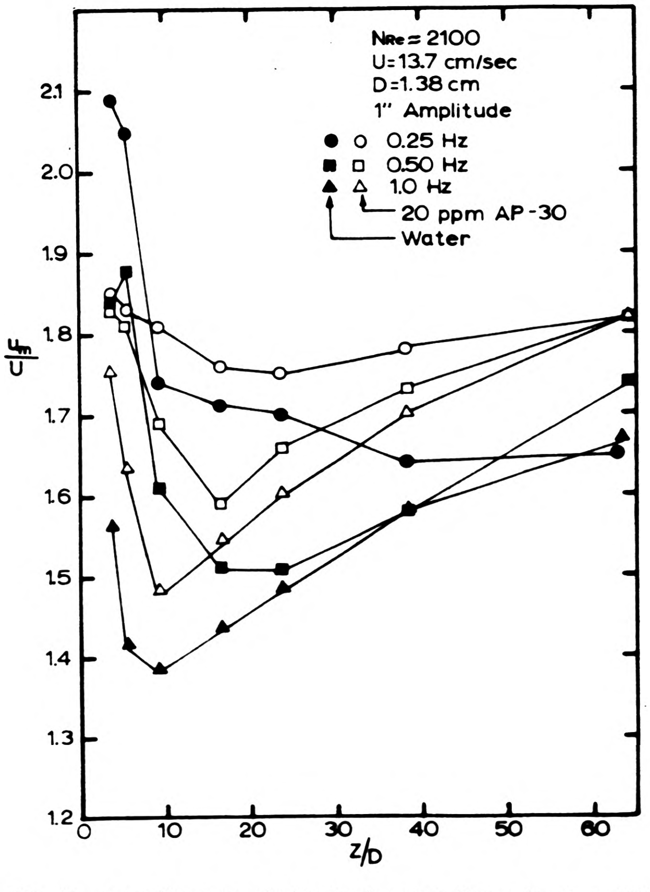


Fig. 12. Centerline mean velocity development 1.38-cm tube, N_{Re} = 2100 for water and Separan.

Another change in the behavior of water but not the dilute polymer solution is shown by the effect of changes in amplitude and frequency at a point. Figure 13 shows the response amplitude vs. disturbance amplitude with disturbance frequency as a parameter for both water and the polymer solution. The polymer solution has the same behavior at lower Reynolds numbers, and water behaves similarly to the dilute polymer except for a higher response amplitude. For water in the transition range either greater disturbance amplitude or greater frequency lowers the response amplitude.

Although the centerline behavior shows representative trends, these curves do not show the form of the response. Typically the response curves for all conditions using a fresh 20 ppm Separan solution are sine-like waves at the same frequency as the disturbance. Rare combinations of disturbance modes could be detected as shown in Fig. 14a. In water the responses vary from sine waves to random fluctuations as the frequency is increased at all Reynolds numbers studied. A disturbance frequency of 0.25 Hz was always

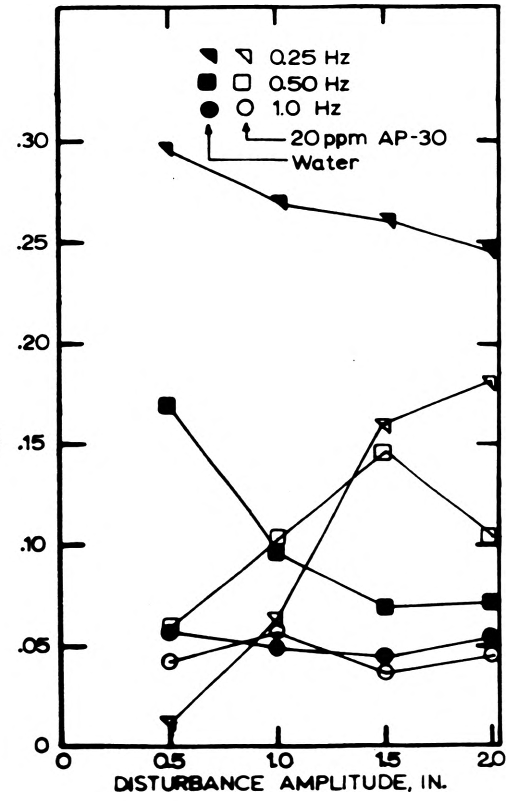
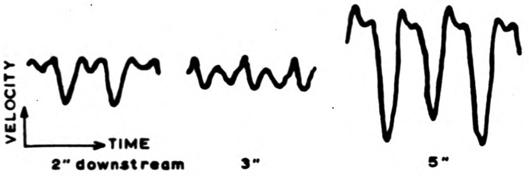
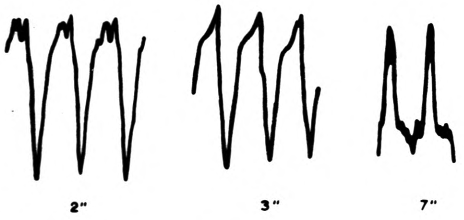


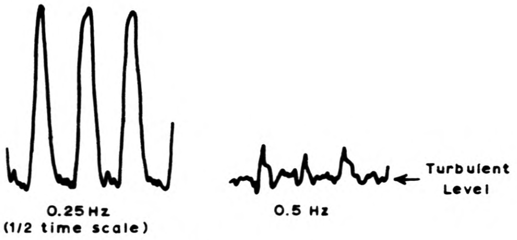
Fig. 13. Centerline response amplitude vs. disturbance amplitude at 23.8 cm from the disturbance.



a) Separan, 0.5Hz



b) Water, 0.5 Hz



c) Water, N_{Re} = 2100

Fig. 14. Response signals illustrating unusual behavior.

well reproduced in the fluid while the 1.0 Hz frequency rarely showed up after one wave length downstream. Either random fluctuations were noted or one-half the frequency appeared in most cases. The 0.5 Hz frequency showed the most variations. Particularly interesting was the growth and decay of an intermediate peak. Figure 14b shows the change downstream as one part of a peak decays and another apparently remains stable. In Fig. 14c the stabilizing effect of the 0.25 Hz disturbance is shown. The bottom of the wave represents a turbulent level in the pipe. A 0.5 Hz disturbance can barely be distinguished over the turbulence.

DISCUSSION

The response of pure water to disturbances of 0.25 to 1.0 Hz frequency in laminar and transition flow shows that the lower frequency disturbance excites a few modes in the pipe which decay downstream and are readily observable. The higher frequency disturbance results in the excitation of a large number of modes, pronounced flattening of the velocity profile, and apparent decay downstream of random fluctuations of less amplitude than the lower frequency responses at least up to Reynolds numbers of 2250. In transition flow the downstream distance at which the response amplitude reaches a peak is moved closer to the disturbance than in laminar flow. This occurs possibly because turbulence is developed and the response amplitude drops in the turbulent flow if it is maintained superimposed on the flow at all. The results tend to confirm those of Fox, et al., who show the lower limit of the stability curve in the same frequency range. The behavior for laminar flow, however, is also interesting and not completely explained.

The possibility that the tracking system could not follow the changes has been considered. Tape recordings run at one quarter or twice the speed failed to give any different results. The data were repeated several times with no differences at 0.25 or 1.0 Hz and only slight changes in velocity profile at 0.5 Hz. The 0.5 Hz was probably near the limit of forming stable modes in the flow as noted in the experimental results. The long wave lengths observed for these low frequency disturbances indicate that long lengths of pipe are necessary to make meaningful measurements on fluid responses to fluctuations.

The dilute polymer solution studied in this work behaved like a fluid with a higher viscosity than water at the center of the pipe. In laminar flows, the condition present up to a flow rate for which water has a Reynolds number of 2100, the response of the polymer solution was more rapid than water and the fluctuations in general were reduced in amplitude. The rapid response can be attributed to the ability of large volumes of the fluid to act together as observed by Shaver and Merrill.[9] Then the frequency range 0.25 to 1.0 Hz does not have the same significance in the dilute polymer case as it does for water. Frequencies which generate interacting modes or lead to turbulence must be higher than the 1.0 Hz used here. It is also possible that secondary flows are generated, but this was not investigated.

Linear plots of phase angle vs. downstream distance indicate that the modes at the centerline have the same wave velocity or that a single mode is excited. More detailed analysis of the data is necessary to consider these oscillation modes. Only small differences in wave length were noted between water and the dilute polymer at the center of the pipe. Major differences between the two fluids may be in the mechanism of propagation of the disturbance from the generator to the fluid and the mechanism of excitation of the interacting modes.

This study has shown that the laser Doppler velocimeter with suitable electronic tracking can be used in stability studies of pipe flow. Studies are continuing on the response of other polymer solutions and at higher frequencies.

ACKNOWLEDGMENTS

The authors are indebted to Dr. Daniel F. Jankowski for many discussions of the problem and to Wayne A. Hanson and John Bacs for taking some of the experimental data.

SYMBOLS

D = pipe diameter
f = frequency, Hz
N_{Re} = Reynolds number
r = pipe radial distance
R = pipe radius
U = average velocity
u_m = mean velocity of fluctuating flow
u' = amplitude of velocity fluctuation

z = axial distance

θ = scattering angle

λ = wave length

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