# THE OSCILLATORY FORCES ON A SEMI-SUBMERGED CIRCULAR CYLINDER IN WATER AND IN DILUTE AQUEOUS SOLUTION OF POLY(ETHYLENE OXIDE)

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# THESIS

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ABSTRACT

The oscillatory forces on towed semi-submerged rigid circular cylinders were measured in water and in 100 and 200 ppm aqueous solutions of Polyox WSR301. Cylinders of half-, one-, and two-inch diameters were towed in a small circular towing-tank and the hydrodynamic forces sensed by a strain gauge and analyzed for the time-dependent frequency spectra. The towing speeds ranged from 59 cm/sec to 253 cm/sec corresponding to Reynolds Numbers from $2 \times 10^4$ to $1 \times 10^5$. The Strouhal Numbers based on the dominant frequency of the oscillatory lift were between 0.17 and 0.21 and are in agreement with the existing data for a completely submerged circular cylinder. These frequencies were not influenced by either the air-water interface or the addition of drag reducing polymers. Also independent of the polymer concentration was the amplitude of the life force. Attempts to interpret the oscillatory drag component proved inconclusive.

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ACKNOWLEDGEMENT

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# I. INTRODUCTION

The surprising turbulent-flow friction-reduction effect of dilute solutions of long-chain macromolecules (polymers) in water was discovered in 1948. B. A. Toms [1], using the polymer polymethylmethacrylate in solution with chlorobenzene, observed that with equal pressure gradients applied, the polymer flow rate through a pipe was substantially greater than that of the pure solvent. It has been only during the past few years, however, that there has been significant activity in the fluid-dynamic studies of these solutions. Extensive pipe flow experiments by others [2, 3, 4, 5] verified Toms' conclusion.

Hoyt and Fabula [6] measured the torque reduction on a rotating disk in various polymer solutions and concluded that polymers exhibiting drag reduction are characterized by high molecular weight, solubility, and linear construction. The longer the molecule, the greater was the drag reduction. Polyox WSR301 (manufactured by Union Carbide) proved to be the most effective reducing agent. Friction reduction of as much as 70% was reported for the disk in a dilute solution of Polyox. A concentration of 100 ppm (weight parts per million) resulted in maximum polymer effectiveness.

Merrill [7] observed that no drag reduction occurred in "micro-pipes" until completion of the transition from laminar to turbulent flow.

The turbulent-flow friction-reduction phenomenon was extended to streamlined bodies by Vogel and Patterson [8], while Crawford and Pruitt [9] conducted the earliest known studies of blunt bodies in polymer solution flow.

Lang and Patrick [10], in studying freely falling cones, spheres, disks, and cylinders in dilute polymer solutions, observed that drag reduction was much greater for spheres than for the other body shapes. Dyed-wake photographs of falling spheres showed that the polymer altered the shape of the wake by shifting the point of boundary-layer separation rearward.

Extensive studies of spheres have been conducted at the Naval Postgraduate School. Hayes [11] measured the drag on freely falling spheres and observed: 1) no drag reduction for any concentration of polymer solution for Reynolds number less than $10^4$, 2) an increase of drag reduction with Reynolds number for constant polymer concentration, and 3) maximum drag reduction (54% for a one-inch diameter sphere) for a 100 ppm concentration. Sanders [12] postulated that the long-chain polymer flow stabilizes the laminar boundary layer by delaying separation, thereby reducing wake size, thus reducing drag.

Chenard [13] worked in a higher Reynolds number region and found drag reduction in dilute polymer solutions to increase with velocity up to a Reynolds number of $10^5$. Woolery [14] measured drag reduction past the critical Reynolds number (about $4.5 \times 10^5$), though the drag curve was similar to that of water.

The study of the circular cylinder, another blunt body, in polymer solutions has been of relatively limited extent. James [15] measured the drag of small circular cylinders in various polymer solutions for Reynolds numbers for which separation does not take place (up to $10^2$) and found that the drag coefficient increased with increasing polymer concentration. Mc Clanahan and Ridgely [16] conducted a further series of polymer-solution experiments on the circular cylinder and found that for Reynolds numbers greater than $10^4$ drag reduction occurred and increased with increasing Reynolds number. ($R = 2 \times 10^5$ was the upper limit of the range considered.) The largest reduction measured was in the 100 ppm solutions.

Kowalski [17] conducted experiments which indicate that the drag-reduction phenomenon may be applied to full size ships. Previously, the huge amounts of polymer thought to be required by water-borne craft precluded the possibility of full-scale application. His tests showed that the polymer exhibits a persistence effect; consequently, pulsing of injection (instead of continuous injection) could be used to produce the same effect with a tenfold saving of the additive.

Another hydrodynamic phenomenon of importance is the oscillatory lift and drag forces experienced by a moving body. In the experiment by Mc Clanahan and Ridgely, the maximum speed obtainable was limited by the coupling of the oscillating lift force experienced by the cylinder to the mechanical resonance of the strut assembly. They observed qualitatively that the oscillatory drag and lift forces were altered in the polymer solutions. The behavior of oscillatory drag and lift forces in ordinary fluids was summarized by Lienhard [18].

Study of the polymer effect on the frequencies of the oscillatory drag and lift to provide quantitative information on the alterations taking place could add valuable insight into the polymer influence on hydrodynamic behavior.

Surface-piercing cylinders were chosen to be studied because: 1) the apparatus to make such a study was available, 2) a surface-piercing strut presented less experimental difficulties than one completely submerged, 3) Lienhard's summary could be used for comparison, as no work on the oscillatory forces acting on surface-piercing cylinders could be found, 4) Mc Clanahan and Ridgely showed that Polyox reduces drag on submerged cylinders, and 5) there exists the possible engineering application to the submarine periscope and to the struts of an hydrofoil.

## II. APPARATUS

The lift and drag on circular cylinders were measured in a circular tow tank with the cylinder mounted on a whirling arm in a position perpendicular to both the surface and the direction of motion. The physical layout is shown in Fig. 2.1. One of the most desirable features of this setup is that the model can be propelled by an electric motor rotating the shaft of the whirling arm. Also, the circular tow path reduces the longest dimension to $1/\pi$ times the tow path length. In addition, the model can coast to a stop upon completion of a run, eliminating need for a braking mechanism. Subsequent runs can be started without having to reposition the model. The only disadvantage of a setup of this type comes if (and when) a run need be longer than the one-pass tow length -- when this occurs, the data recorded after the model has made one complete revolution is not taken under the same condition (that of undisturbed water) as the first revolution.

The tow tank for this research was an annular design with an outside diameter of seven feet, an inside diameter of four feet, and a depth of one and one-half feet. The actual water depth used was never greater than thirteen inches. The one pass length along the centerline of the tank was 17.3 feet.

A Craftsman 1 1/2 hp electric motor, rated at 500 to 5000 rpm, drove the arm through a pulley and belt combination. Pulley ratios possible were 1/3.7, 1/1.55, 1.55/1, 3.7/1. An Alliance Master-reducer reduction gear-train made possible model velocities ranging from 15 cm/sec to 6.1 m/sec. Direction of motion was clockwise.

The velocity of each run was determined by measuring the time required to traverse the distance between two microswitches. This time was determined by the Hewlett Packard Model 5233L Electronic Counter. Details are given by Fletcher [19].

Cylinders used were aluminum and had diameters of one-half, one, and two inches. They were held in a device which consisted of two sections connected in a pivotal arrangement. Figure 2.2A shows the moveable piece, which held the cylinder (in the hold marked "A"). Screw "B" secured the cylinder in place. Figure 2.2B shows the stationary section, in which was the load cell-strain gauge attachment. Screw "C" sat in the load cell. Screw "D" was connected flush against "C" (Fig. 2.2C). Screws "E" and "F" (Fig. 2.2A) limited the maximum relative sideways swing of the two sections. (Consistent experimental results depended very strongly on the precise tuning of the instrument, that is, on the proper positioning of screws D, E, and F.) Four bars connected the two sections with two on the top and two on the bottom. The bars made it possible for only side-to-side relative motion between the two pieces, as once they were attached, the forward-backward distance between the two pieces was rigidly fixed. The lift (or drag) forces acted on the cylinder, causing the whole front piece to move from side to side. This moved "D" toward and away from "C," thus transmitting the oscillatory forces through the load cell to the strain gauge. It was necessary that the centripetal force push "D" into "G" so that, with a DC force always applied, the oscillatory forces could be continuously sensed. Consequently, this device worked effectively (for lift) only when the "load cell side" faced the outside of the tank. To measure drag, the holder was rotated $90^0$ such that the "load cell side" was in the direction of motion. Each time a change of load cell was needed, it was necessary to separate the two sections.

The strain gauge used, a Statham Model UC3, had a basic sensitivity of 0-80 grams. Three different load cell adapters (Statham Model UL4) were used to extend the range to one-half, one, and ten pounds. A readout, the battery powered Statham Model UR4 Precision Readout, provided an output for external recording.

The UR4 was attached to the center of the whirling arm and revolved with the strain gauge. This resulted in the output cord to the recorder winding up, making it necessary to disconnect (from the UR4) and unwind the cord after each five or six revolutions.

The output was recorded on a Bolt, Beranek, and Newman 800 AM y,t recorder. Simultaneously, it was recorded on one FM channel of a Precision Instrument Model PI-6200 taperecorder running at 3.75 ips (inches per second) after going through a Hewlett Packard Model 466A AC Amplifier. The low frequency response of the amplifier was measured and the results are shown in Fig. 2.3. This analog recording could be analyzed by two different methods. One was to digitize the data by combination of an analog/hybrid (Comcor 5000) - digital (Scientific Data System 9300 SDS) computer system, and then analyze the digitized data on the IBM 360 Computer. The second method, the one primarily used in this research, consisted in analyzing the data on the Missilyzer Model 675B (Missile Data Reduction Spectrograph) built by Kay Electric Company.

## III. EXPERIMENTAL PROCEDURE

The first step was to fill the tank to the appropriate depth with water or the specified Polyox solution. The cylinder-holder was attached to the whirling arm and the strain gauge connected to the readout. The readout was then connected simultaneously to the amplifier (its output went to the taperecorder) and to the "y" side of the y,t plotter. The amplifier was turned to 40 dB gain. The taperecorder was set to speed 3.75 ips and to the FM mode of operation. On the y,t plotter, the "Sweep Control" was set at LOCAL, "Rate" at .5 cm/sec, and, on the "y" side, "Multiplier" at 1 or 2 and "Scale" at 10 mv/cm.

To quickly see if the counter, strain gauge, and readout were operational the switch (Switch "S"), which simultaneously started the whirling arm and the y,t recorder, was thrown (after turning the readout and counter on).

The taperecorder was then checked for calibration using as input the General Radio Type 1309-A Oscillator set at 500 mv. The output of the taperecorder was observed on an oscilloscope. If the signal was distorted, the input gain of the module was adjusted.

The Oscillator was then connected through a box to Channel 1 of the taperecorder and the readout to Channel 2. Switch "S" also closed the circuit in this box so that the signal from the oscillator was recorded only during the time that the cylinder was being towed. This signal was used as a reference signal for the computer.

The system was then ready to take data. A typical run may be described as follows: The taperecorder was started. Switch "S" was thrown and held for somewhat more than five seconds, timed on a wristwatch. The counter was also observed and its results mentally noted. Switch "S" was then rethrown; next, the "Reset" on the y,t recorder was pressed, meanwhile letting the taperecorder go for approximately five seconds more (to have a blank piece of tape between runs). The Stop button on the taperecorder was then pressed, the time interval from the counter recorded on the y,t plot, the starting position of the y,t recorder changed to a new position, the speed of the whirling arm changed, and the cord disconnected, unwound, and reconnected. When the water had calmed, the next run was ready.

Recorded on the y,t plot before each set of runs were the tape position, concentration of solution, cylinder size, and load cell used.

After a complete set of runs was taken, the data was analyzed. In the cases of varying the depth at constant velocity and varying the velocity at constant depth, this was immediately accomplished by observing the y,t plots. In all other cases, where frequency components were desired, the taperecording had to be analyzed, which meant using the computer or the Missilyzer.

The computer method of analyzation consisted of three programs. The first converted the data from its analog form to digital form. The circuit wired on the Comcor 5000 sampled data at a rate of 100 times per second (since all frequencies of interest were below 25 Hz, this gave ample resolution). It also filtered out frequencies above 25 Hz, so that a frequency of 30 Hz was down 3 dB and one of 60 Hz was down 14 dB. The program digitized 512 samples per record. (This was the reason for making each run longer than five seconds.) After getting the 512 data points, the computer went into "Hold." (While digitizing data, Channel 1 was observed on an oscilloscope.) When the next reference signal was seen, the computer was immediately put manually into "Compute," and the next run was digitized. During this time the tape-recorder was played at 3.75 ips.

This digitized data (on magnetic tape) was in octal form. The IBM 360 works in hexidecimal form. The second program, GEN20839, converted the contents of the octal tape to hexidecimal form. (GEN20839 did not always convert the first record, but sometimes started with the second. This randomness was not explainable and therefore not corrected.) In hexidecimal form, the data was now ready to be analyzed.

The third program, GEN 10839, did this, using the FFT (Fast Fourier Transform) for the power spectrum. The FFT calculates coefficients which are slightly different from the conventional Fourier coefficients. It is an effective method of calculating the coefficients of a set of evenly-spaced, discrete data. Comparison of the two shows the FFT to be sufficiently accurate for this purpose. It is efficient from a computer standpoint because it requires much less space and takes much less time in computation than the conventional Fourier Transform.

The FFT is $F_n = \sum_{k=0}^{n-1} Z(k) \exp(-j2\pi nk/N)$, where $F_n$ is the $n^{th}$ coefficient of the FFT and $Z(k)$ is the $k^{th}$ sample of N equally-spaced samples. The power spectrum of the signal is generated by multiplying each coefficient in the FFT by its complex conjugate. Resolution in the frequency domain is determined by the equation $\Delta F = 1/(N\ DT)$, where $\Delta F$ is the distance between spectral lines in Hertz, N is the total number of samples, and DT is the sampling time (for this research, $\Delta F = 1/(512)(.01) \cong .2$ Hz). If only a real valued signal is observed (as was the case for this thesis), the coefficients will be Hermitian symmetric about the N/2 spectral line. This means that the useful FFT spectrum will cover from DC to a bandwidth of 1/(2DT) at the N/2 (512/2 = 256) line. The Hermitian symmetry property is that the coefficients beyond the N/2 line will have opposite signs in the imaginary part corresponding to their respective line in the 0 to N/2 coefficients [20]. It was for this reason that GEN10839 plotted only 100 points in the power spectrum (this spread out the representation of the frequencies below 20 Hz). The program also computed and plotted the autocorrelation function of the signal. Output of GEN10839 for power versus frequency and signal versus time may be seen in RESULTS.

Using the Missilyzer, the procedure was as follows: "Marker Level" was set to 7 1/4, "Bandwidth" to NARROW (2 Hz), "Record Gain" to 30, "Shape" to FLAT, "Sectioner" to OFF and "Speed" to LOW-LOW. This speed allowed a frequency range of 5-500 Hz to be recorded, and it permitted 24 seconds of recording time.

Since there were no significant frequencies above 25 Hz, the data was played back into the Missilyzer at a taperecorder speed of 37.5 ips in order to get a better representation of the low frequencies. This permitted 240 seconds of real-time data recording, and it changed the frequency range analyzed to 0.5-50 Hz.

After the data was played into the Missilyzer, the paper was put on the cylinder. By manually spinning the cylinder and observing the "View Meter," it was determined where there was a data-free space -- here, calibration marks were set to mark at every 30 Hz (actually, 3 Hz because of the factor of 10 in playback). Next, the "Speed" was changed to HIGH-HIGH (to quicken the process of putting the data on paper) and, with the "Pattern" set to NORMAL, the machine was made to put the data on paper. The "Pattern" was then changed to EXPANDED and the same data put on (new) paper. The Expanded Pattern presented 0.5-25 Hz in the same space as 0.5-50 Hz was presented in the Normal Pattern, thus spreading out the important part of the presentation. After this the "Sectioner" was switched to LINEAR and the places where amplitude was desired marked by the pins in the top of the cylinder. This data was then put on (new) paper. Examples of these different presentations may be seen in RESULTS.

## IV. RESULTS

Typical y,t plots of the oscillatory lift force on a circular cylinder are shown in Fig. 4.1. These particular results show that the one-inch cylinder (hollow) had to be greater than six inches deep in order for the oscillatory lift force to be significant. The same minimum depth was observed for the half-inch cylinder. The two-inch cylinder (not hollow) oscillated at as little as two inches deep. (It is assumed that this was due to its greater weight.) All runs were made with each cylinder eight inches deep.

Also concluded from y,t plots was that runs made at speeds greater than 200 cm/sec possibly yield unreliable results. At these high speeds the cylinder-holder itself (without a cylinder in it) began to oscillate. The half- and one-inch cylinders in air began to oscillate at about 200 cm/sec. The two-inch cylinder (again, probably because of its heaviness) did not oscillate in air at speeds as great as 340 cm/sec.

The data analyzed on the computer were taken with the one-inch cylinder in water and with the half-pound load cell. Figure 4.2 is a typical signal output. Superimposed on it is the inverse of the Fast Fourier Transform of the signal. (These two waveforms are indistinguishable.) Figures 4.3-4.6 show the power spectra for the same cylinder at different speeds. The variations of the frequencies and the amplitudes of the dominant components are noticeable. Comparison of these curves with the same runs analyzed on the Missilyzer showed that all important aspects of the power spectra were faithfully reproduced on the time-spectra. Because of the relative ease of obtaining results with the Missilyzer this method was used for all further analyses.

The results of lift measurements are shown in Figs. 4.7-4.18, while Figs. 4.19 and 4.20 show results for the oscillating components of the drag.

Figure 4.7 shows the time-spectra for the one-inch cylinder (half-pound load cell) for nine different runs at eight different speeds. The darkness of each area is proportional to the magnitude of that particular frequency at that particular time. Each time-spectrum corresponds to approximately five seconds of run. Since the one-pass tow length is 17.3 feet, any five-second run at a speed greater than 106 cm/sec results in greater than one complete revolution. It appears that when the cylinder began a second revolution the disturbed water did not affect the spectrum, except possibly on the 231 cm/sec run. (At such high speed problems of vibration are possibly serious.)

Figure 4.8 presents the same runs as Fig. 4.7, but in the "Expanded" form (note the expanded frequency scale).

Figure 4.9 shows the time-spectra for the one-inch cylinder, but with the ten-pound load cell in place of the half-pound load cell. The runs were made in water at seven different speeds. Comparison with Fig. 4.8 shows that changing load cells did not change the characteristics of the time-spectra.

Figure 4.10 shows the time-spectra for the two-inch cylinder (ten-pound load cell) in water at six different speeds. The strong upper frequencies appear to be harmonics of the lower.

Figure 4.11 shows time-spectra for the half-inch cylinder (half-pound load cell) in water at seven different speeds.

Figure 4.12 presents a qualitative look at the effect of Polyox on the frequency and amplitude components of the oscillatory lift force on a one-inch circular cylinder at continuously increasing speeds. (The instantaneous velocities are, therefore, unknown.) There appears to be no major effect by the Polyox.

Figures 4.13 - 4.15 present a quantitative look at the effect of Polyox on the frequency of the oscillatory lift force on a one-inch circular cylinder. Polyox is seen to exert no major effect.

Figure 4.16 shows examples of "instantaneous sections" taken from the time-spectra shown in Fig. 4.15. (There are 60 evenly-spaced places at which a Section may be made, corresponding to a time-spacing in this case of four seconds. Therefore, with five-second runs it is possible to get one section for each run.) The relative magnitude (linear scale) is shown as a function of the frequencies of oscillation. In addition, Sections were taken for all the time-spectra shown in Figs. 4.13 - 4.15 to see if the magnitude of the dominant frequency was affected by polymer addition. Figure 4.17 shows the relative magnitudes (measured in cm) of dominant frequencies in water and in Polyox. There is no apparent relationship between the magnitudes and either the Polyox concentration or the speed.

All lift data are summarized in the Strouhal versus Reynolds Number plot of Fig. 4.18. The Strouhal Number (S) is equal to the dominant frequency of oscillation times the diameter of the cylinder divided by its speed. The Reynolds Number (R) is equal to the speed of the cylinder times its diameter divided by the kinematic viscosity of water. (For the dilute polymer solutions used, the kinematic viscosity of the solution is indistinguishable from that of water [6].) The horizontal lines at S = .17 and .21 are the limits as given in Lienhard's summary for this Reynolds region for submerged cylinders.

The results of the drag measurements on the one-inch cylinder in water are shown in Figs. 4.19 and 4.20. The conditions are the same in each case except that the one-pound and ten-pound load cells were used to obtain the data of Figs. 4.19 and 4.20, respectively. Similar frequency structure is visible for those speeds common to both figures. Conspicuous on the time-spectra are two dominant frequencies which are numerically equal to the second and third harmonics of a very weak or absent fundamental at about five or six Hertz. There is only a small increase of those frequencies with velocity and there seems to be no relation between these frequencies and those observed in the lift measurements. Since no work on the frequency of oscillation for drag in this Reynolds range was indicated by Lienhard, there is nothing with which to compare these drag results.

## V. CONCLUSIONS

### A. LIFT

This apparatus can be used to measure the dominant frequencies of the oscillatory lift force on a towed circular cylinder. This conclusion is supported by the agreement of the Strouhal Numbers in water with Lienhard's summary. In addition, the fact that the dominant frequency is not affected by change of load cell indicated that the apparatus does not introduce frequencies of its own.

The short length of travel in undisturbed water with this setup proved to be no problem. Since in the second revolution of a run nearly all outputs from the Missilyzer showed structure similar to the first, it was concluded that disturbed water does not influence the frequency of the oscillatory lift force.

This setup did present one problem in measuring frequencies of oscillation. The weight of the cylinder appeared to be important when deciding upon the depth at which the cylinder is to be submerged. For a relatively light cylinder, the minimum depth for the oscillatory lift forces to be significant was about seven inches. For a heavy two-inch cylinder, a depth of two inches was sufficient to allow significant oscillations.

The procedure used is probably not a very reliable one for measuring amplitudes.

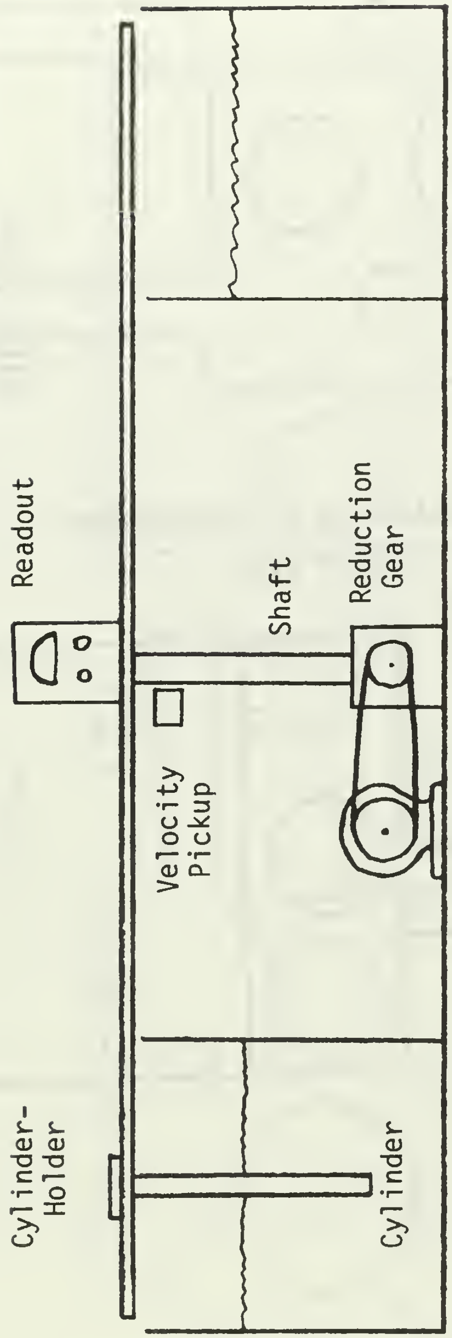
The oscillatory lift force on a cylinder is not influenced by the air-water interface. This conclusion is based on the agreement of the data taken in this research with Lienhard's summary for fully submerged cylinders.

Polyox WSR301 does not exert a significant effect on the amplitude or frequency of the oscillatory lift force on a semi-submerged circular cylinder for concentrations of 100 and 200 ppm.

B. DRAG

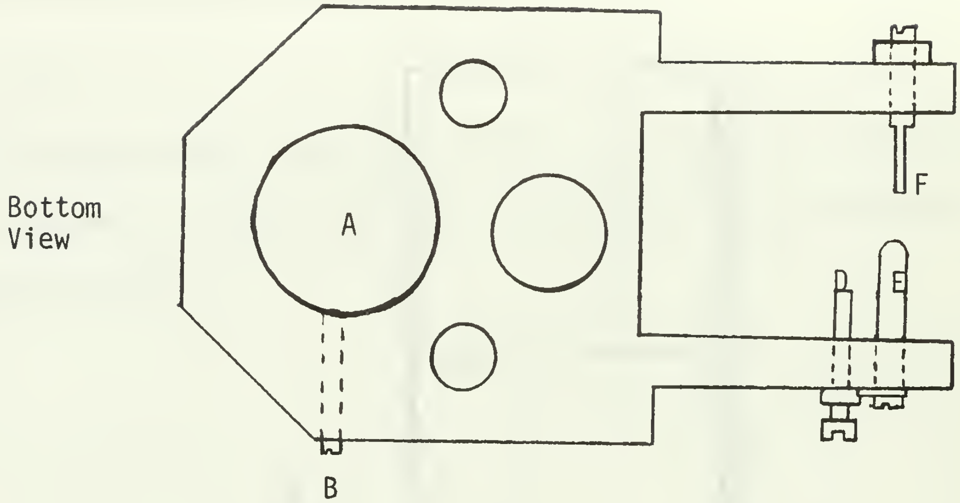
This apparatus did not prove to be a reliable method of measuring the frequencies of the oscillatory drag force on a semi-submerged circular cylinder.

APPENDIX A  FIGURES



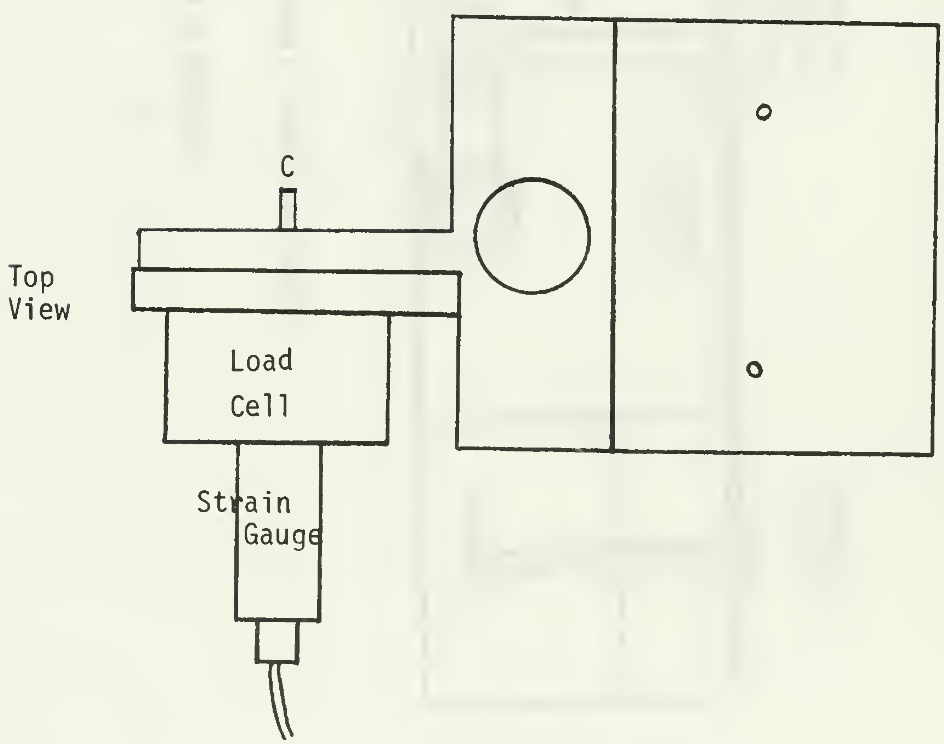

Cross-Sectional View of the Tank

Figure 2.1




Moveable Section of Cylinder-Holder

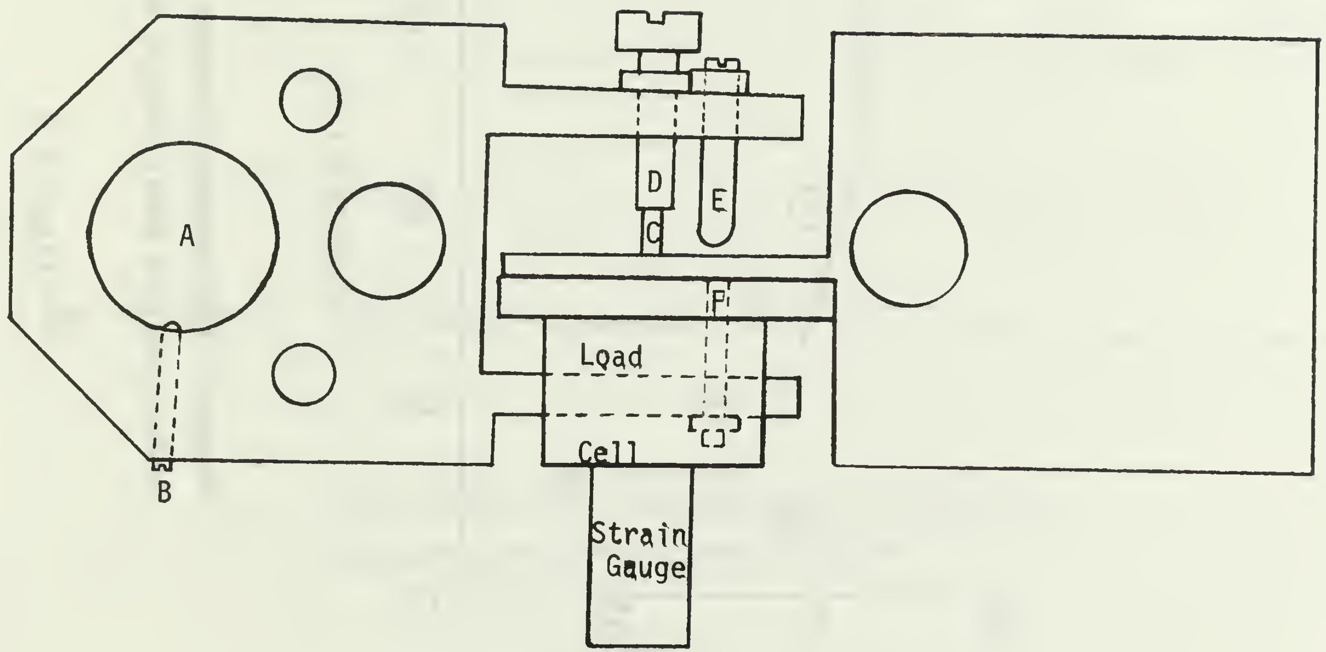
Figure 2.2A




Stationery Section of Cylinder-Holder

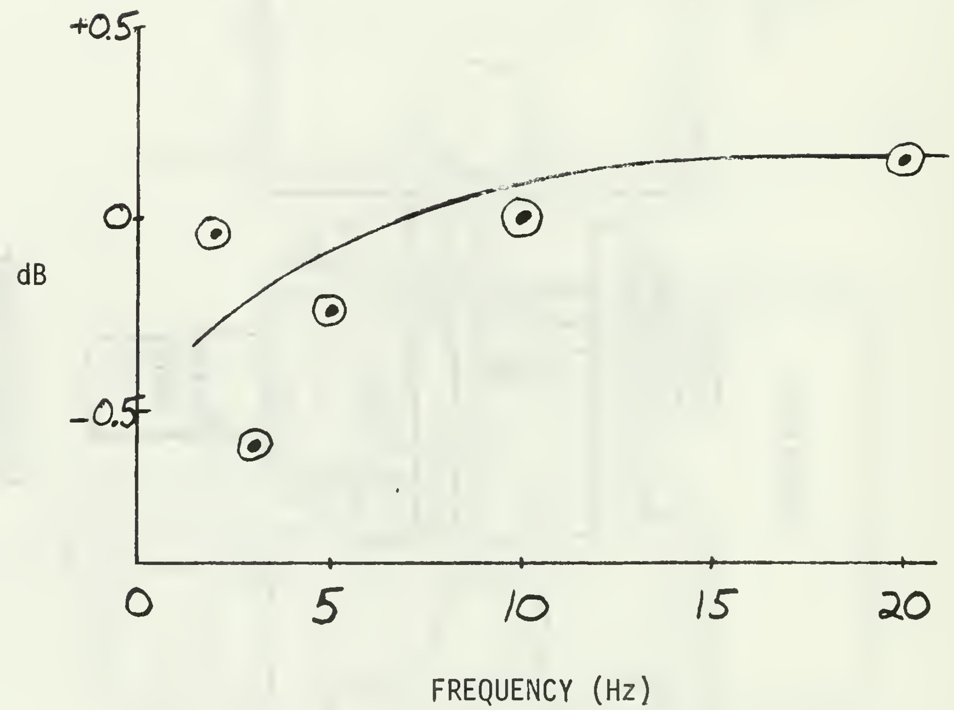
Figure 2.2B

Top View



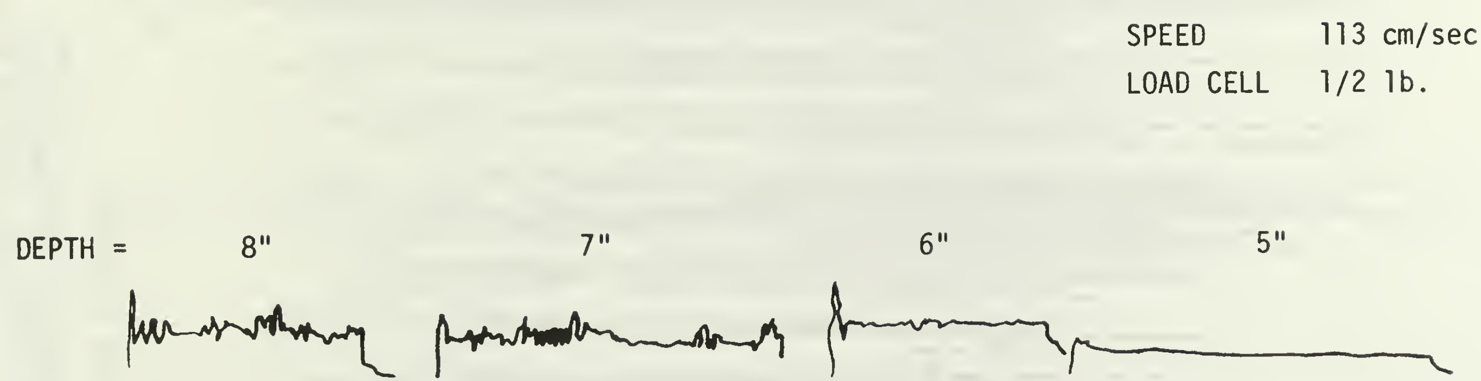

Cylinder-Holder

Figure 2.2C



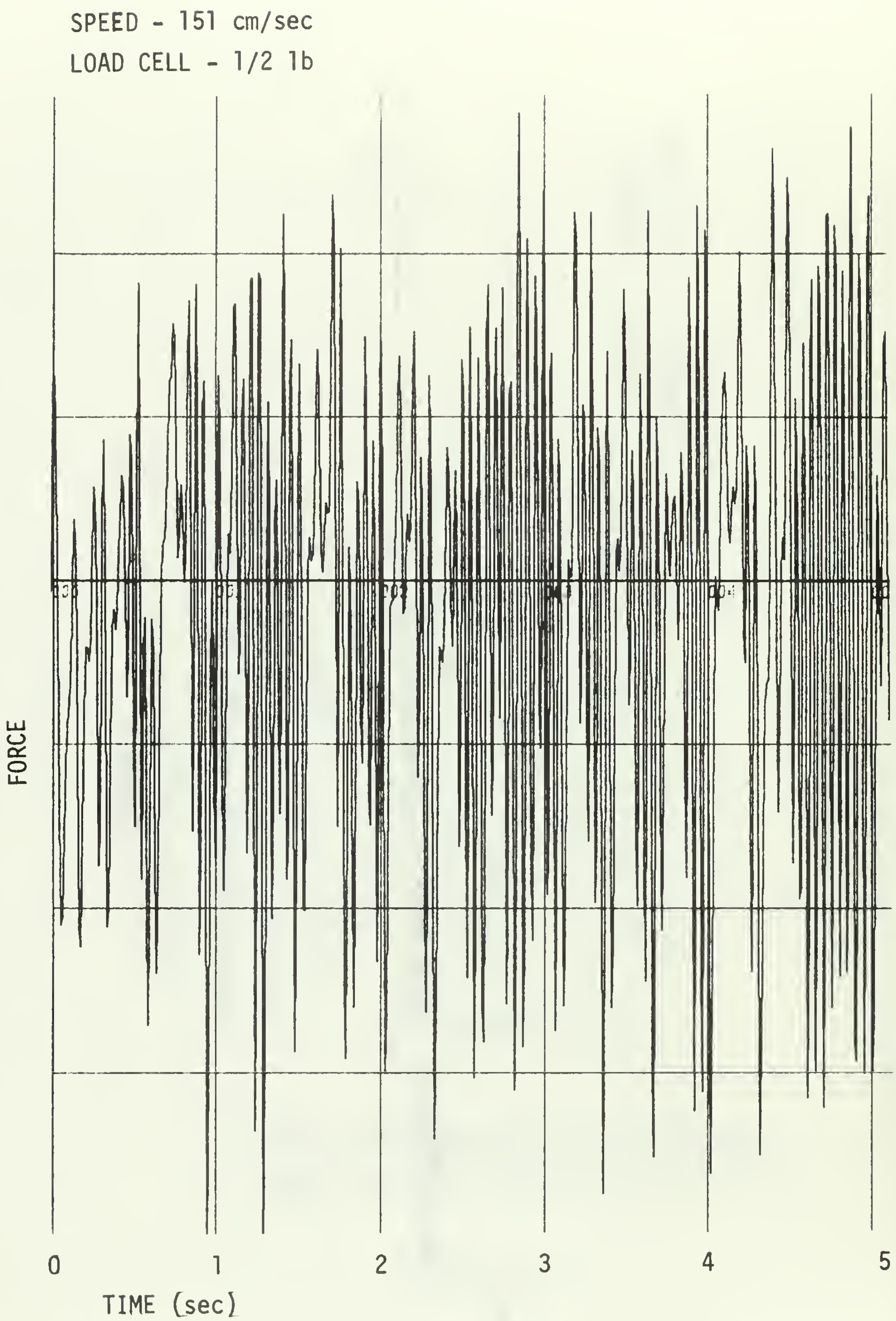

Measured Low-Frequency Response of the
Hewlett Packard Model 466A AC Amplifier

Figure 2.3




Y;T Plots of the Oscillatory Lift Force on a One-Inch Circular Cylinder in Water

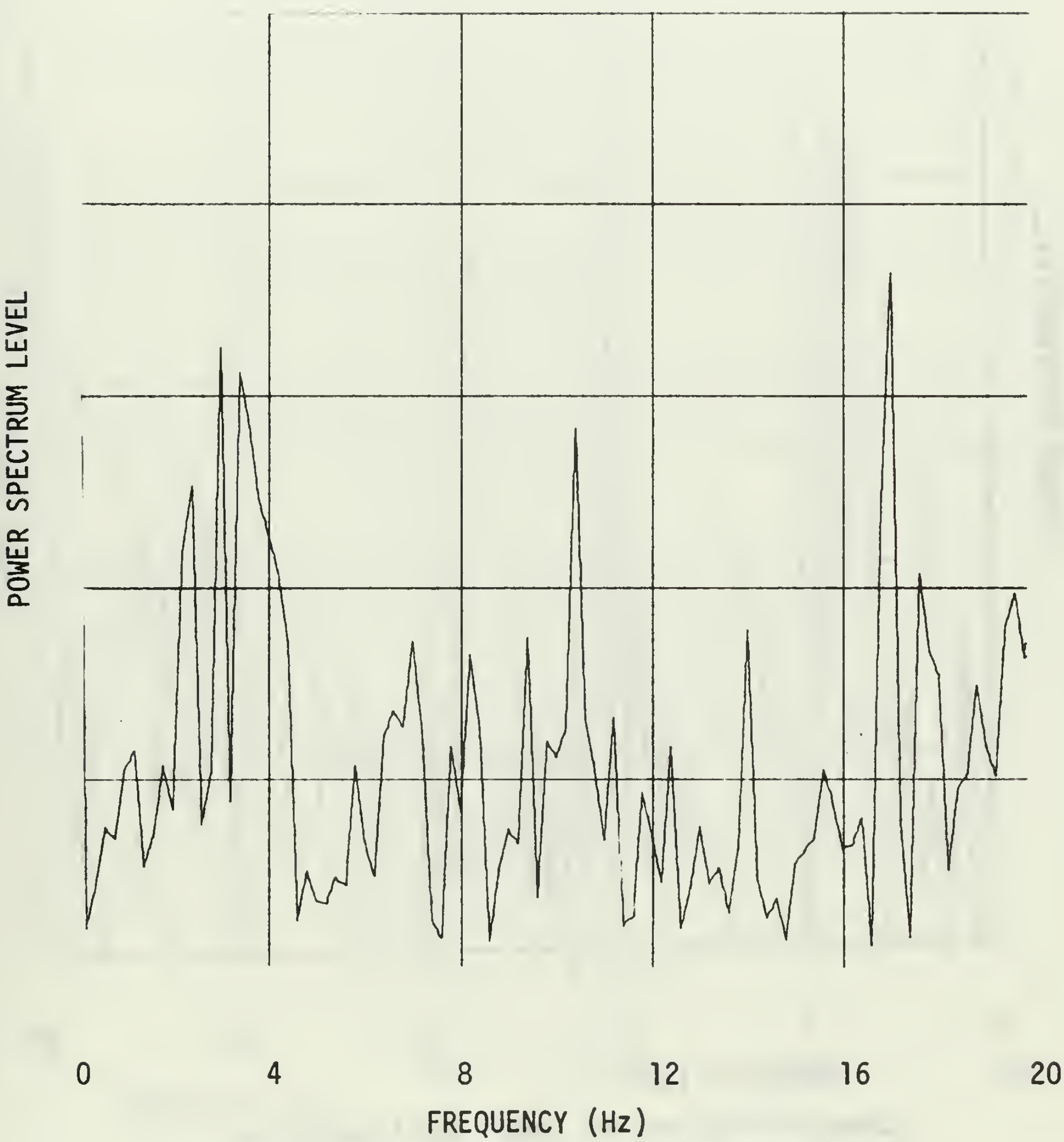
Figure 4.1




The Oscillatory Lift Force on a
One-Inch Circular Cylinder in Water

Figure 4.2

SPEED - 151 cm/sec
LOAD CELL - 1/2 lb

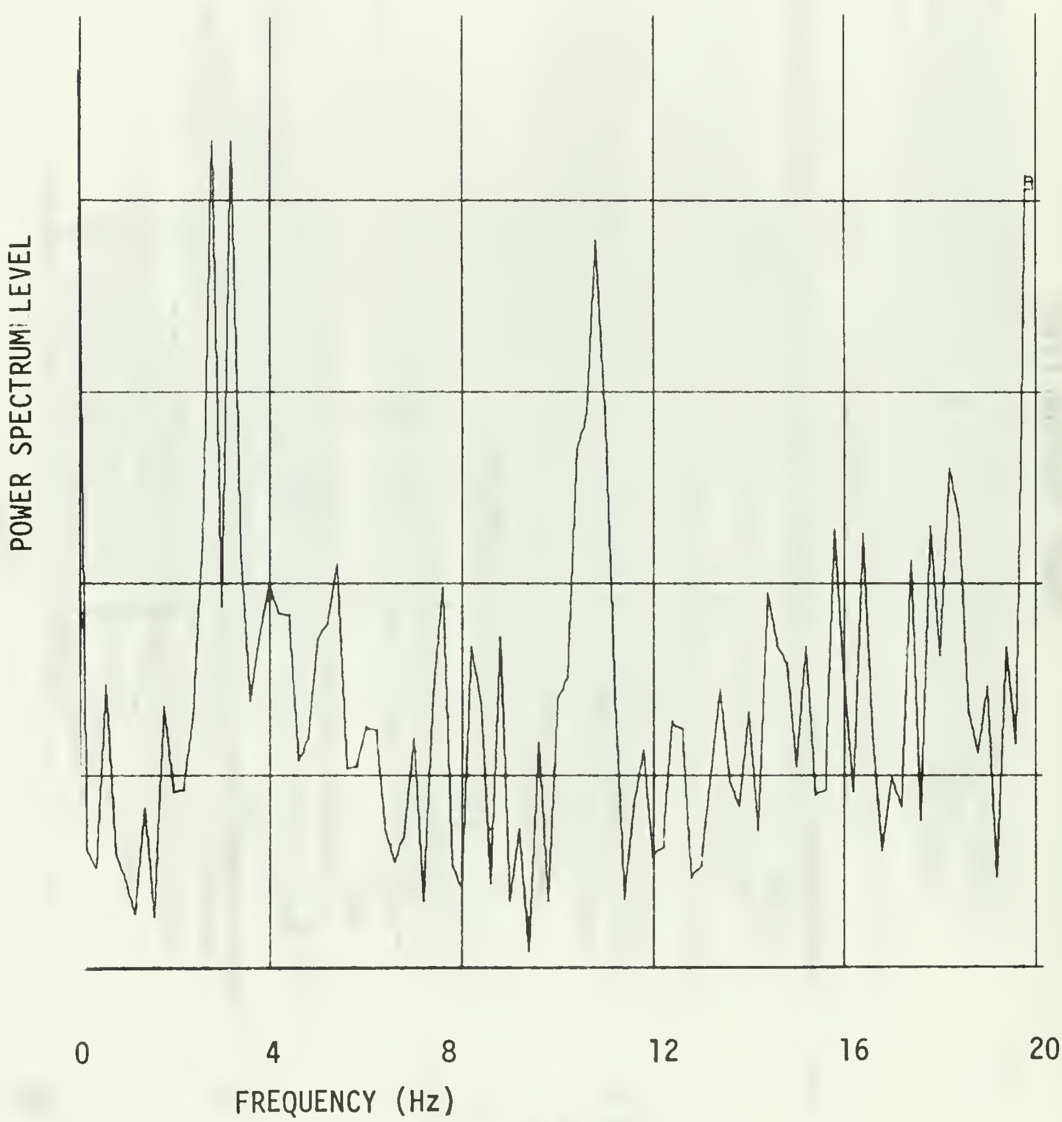



Computer Plot of the Power Spectrum of the Oscillatory Lift Force on a One-Inch Circular Cylinder in Water

Figure 4.3

SPEED - 151 cm/sec

LOAD CELL - 1/2 lb

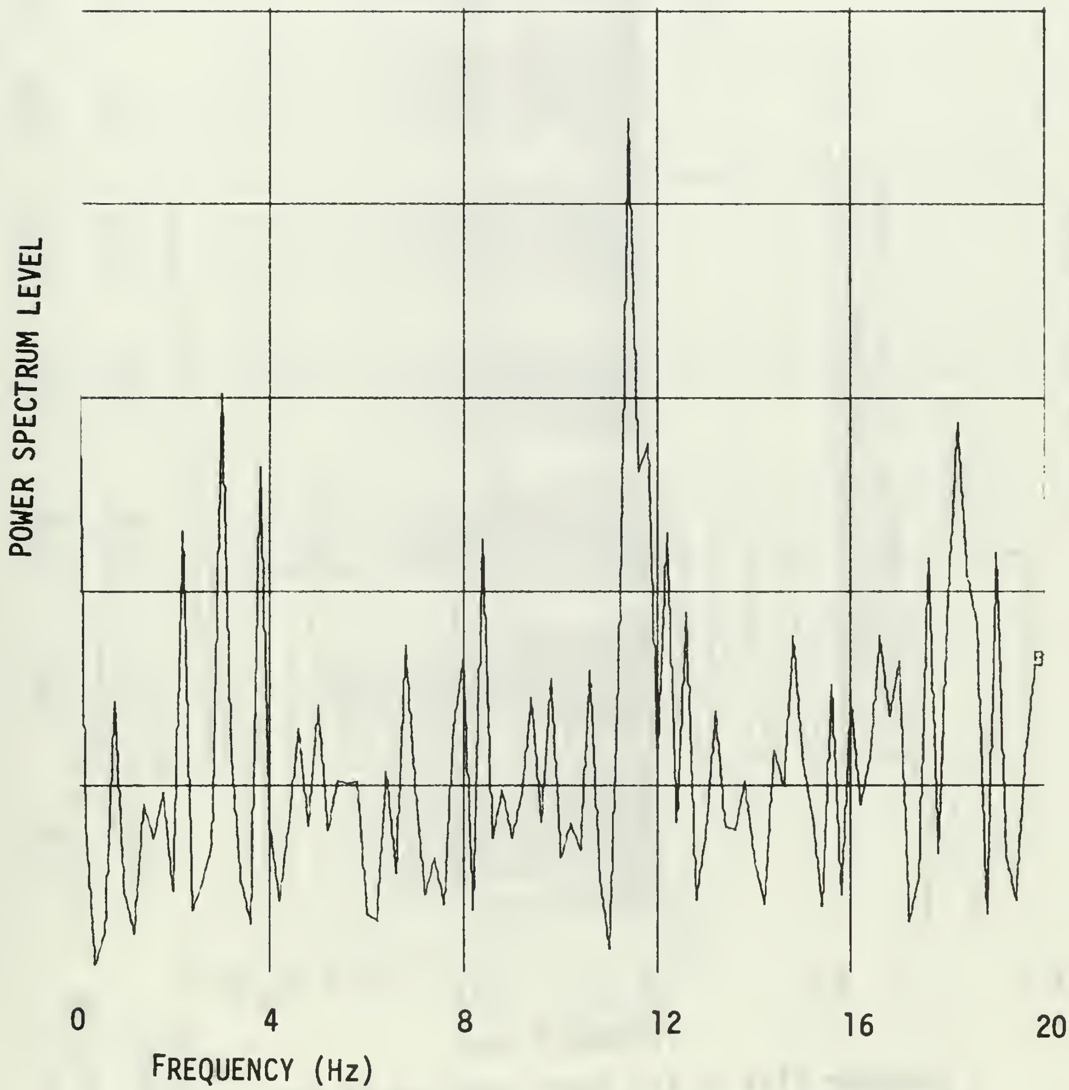



Computer Plot of the Power Spectrum of the Oscillatory Lift Force on a One-Inch Circular Cylinder in Water

Figure 4.4

SPEED - 151 cm/sec

LOAD CELL - 1/2 lb

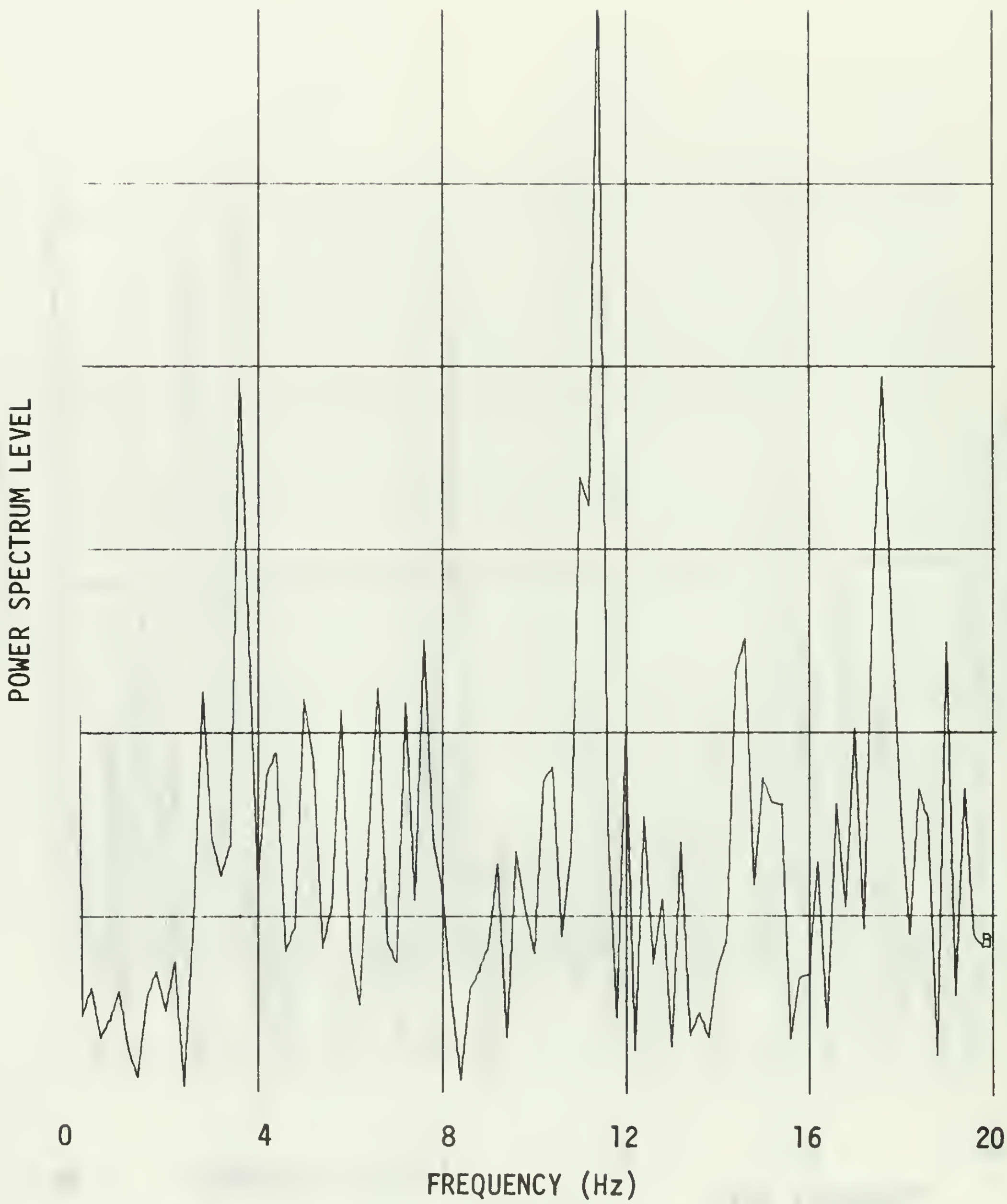



Computer Plot of the Power Spectrum of the Oscillatory Lift Force on a One-Inch Circular Cylinder in Water

Figure 4.5

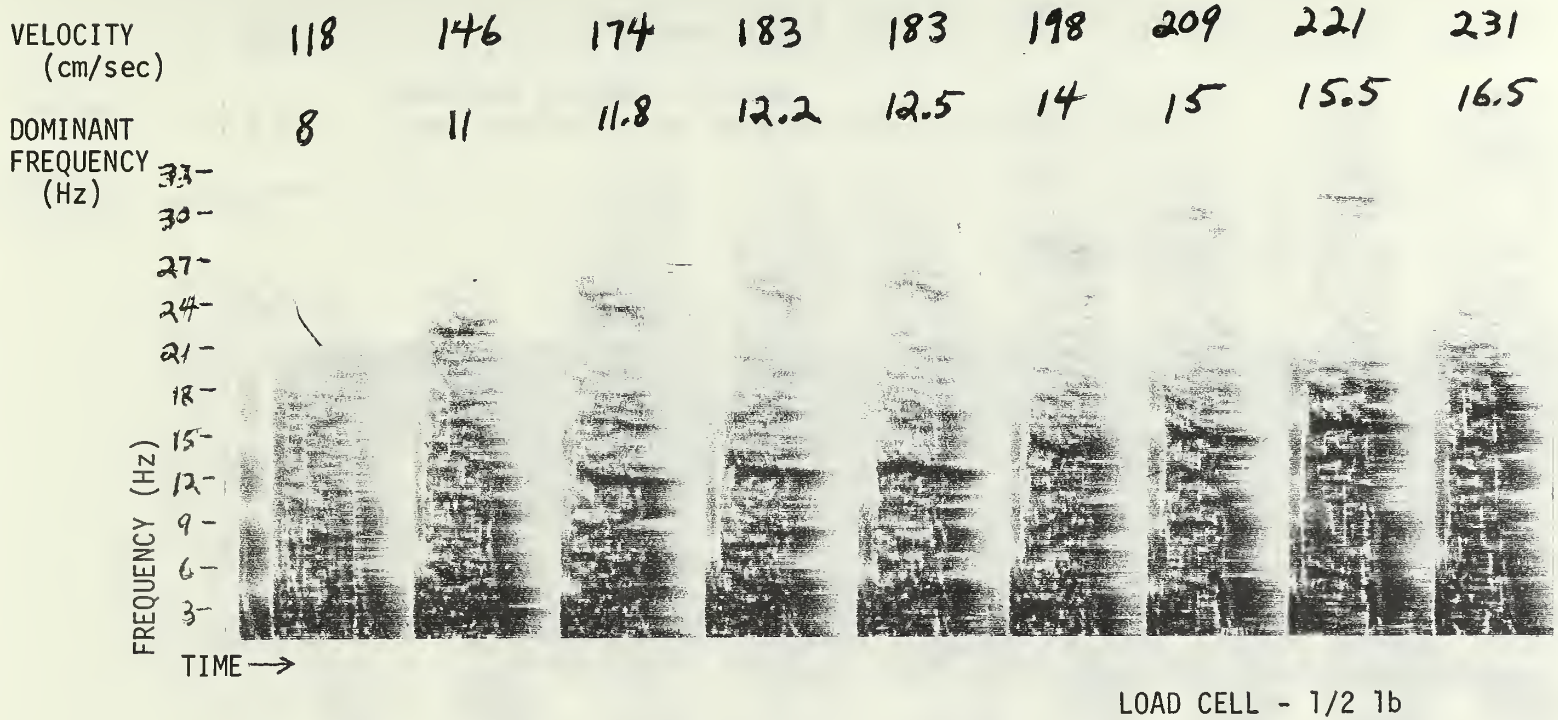
SPEED - 151 cm/sec

LOAD CELL - 1/2 lb



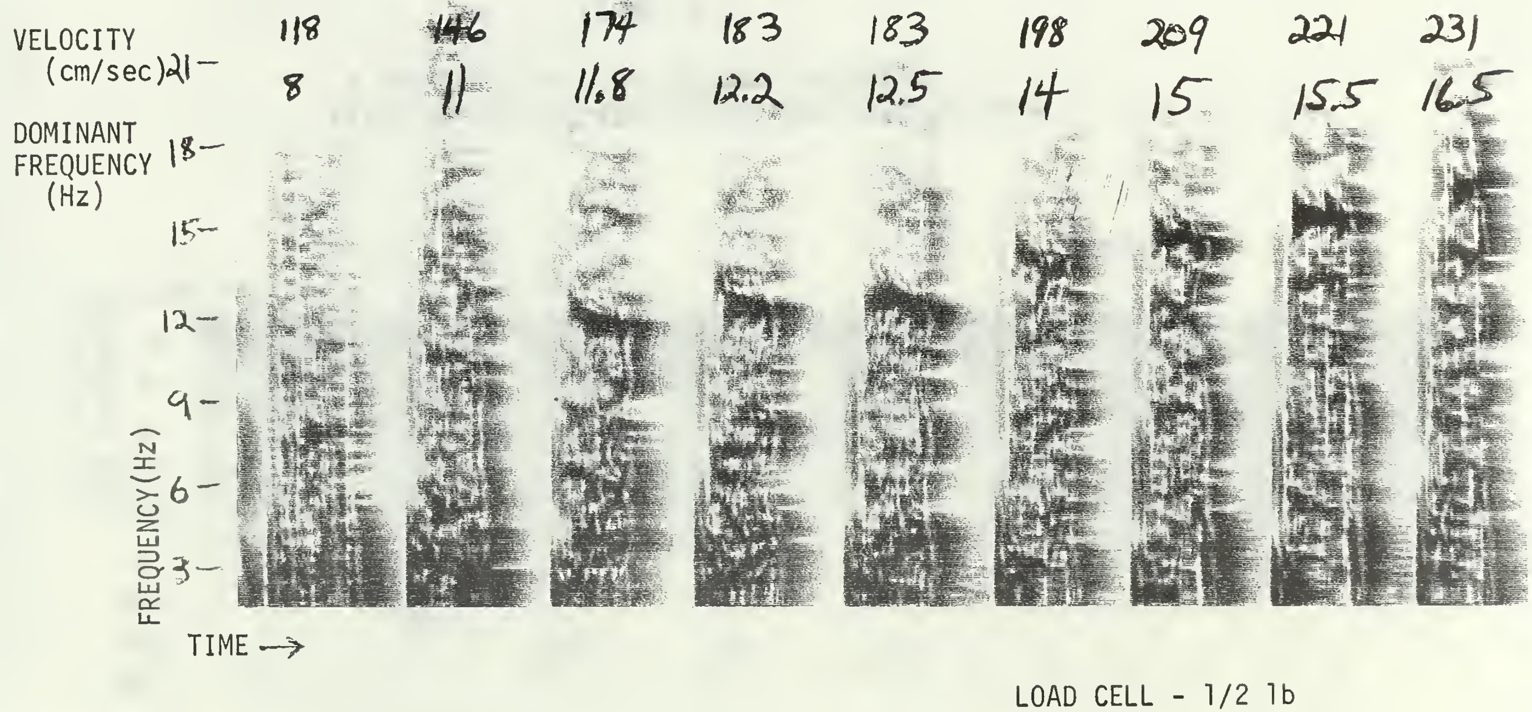

Computer Plot of the Power Spectrum of the Oscillatory Lift Force on a One-Inch Circular Cylinder in Water

Figure 4.6



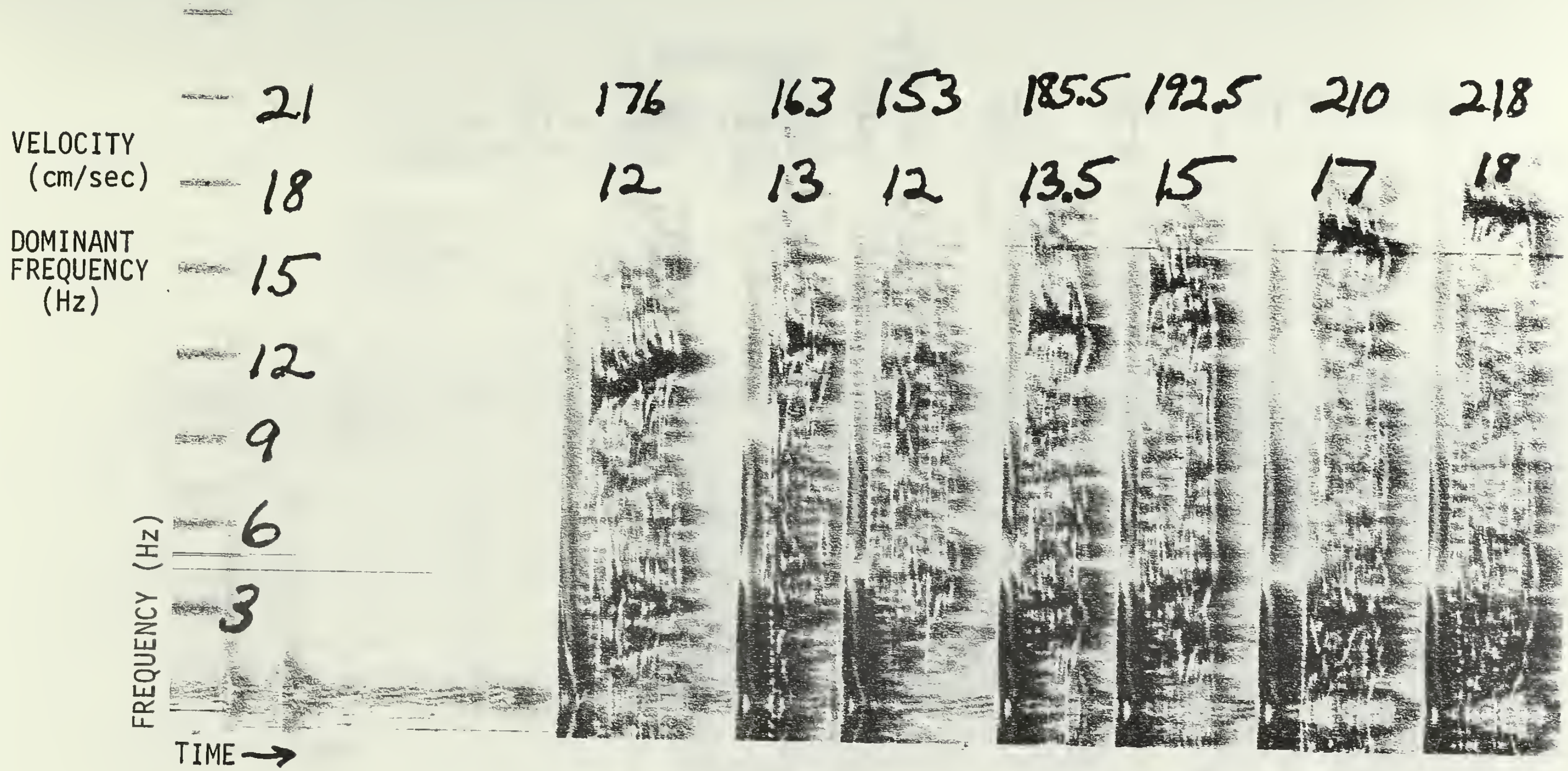

Time-Spectra of the Oscillatory Lift Fo ce on
a One-Inch Circular Cylinder in Water

Figure 4.7




Time-Spectra of the Oscillatory Lift Force on a
One-Inch Cylinder in Water

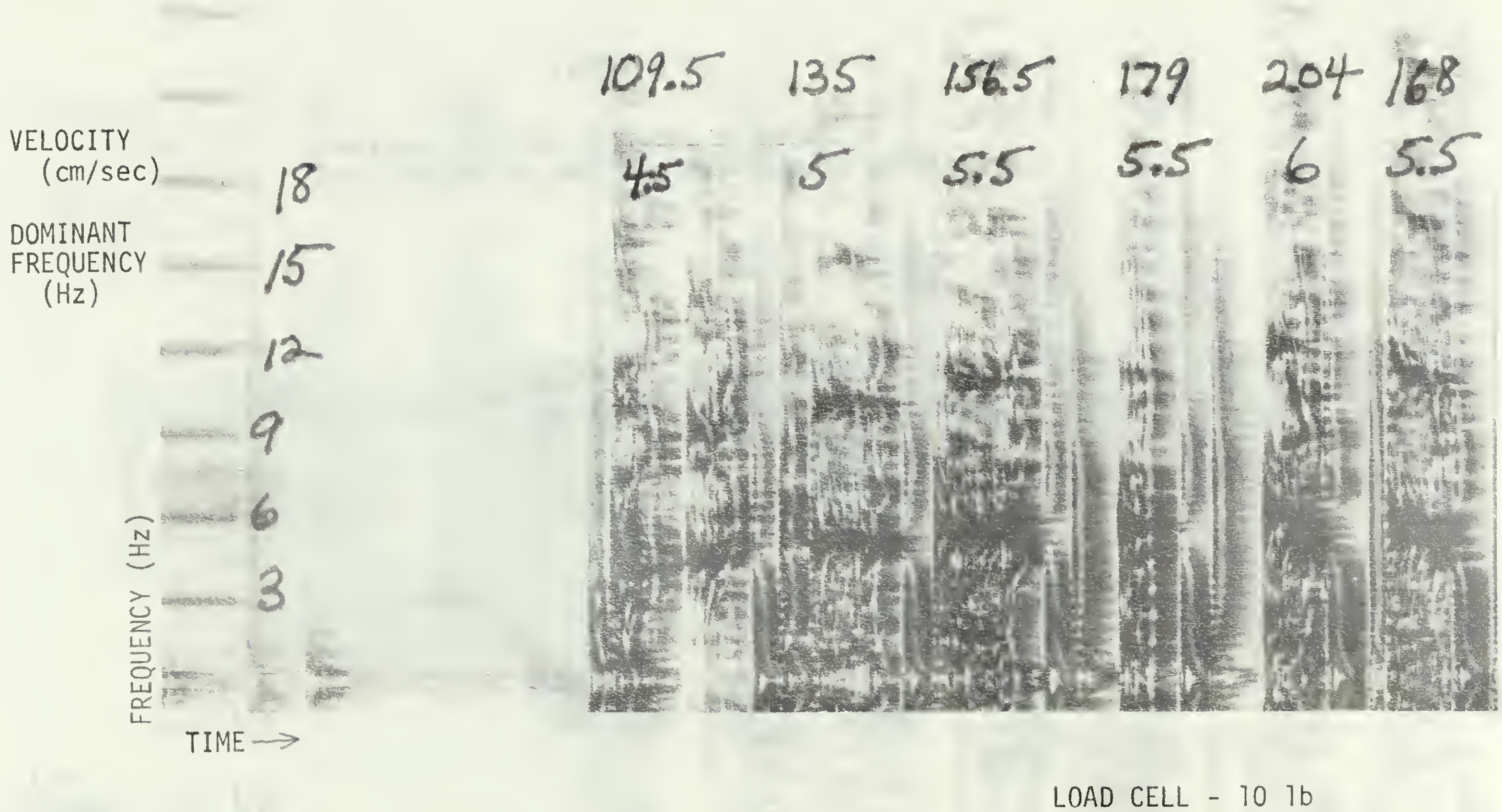
Figure 4.8




LOAD CELL - 10 lb

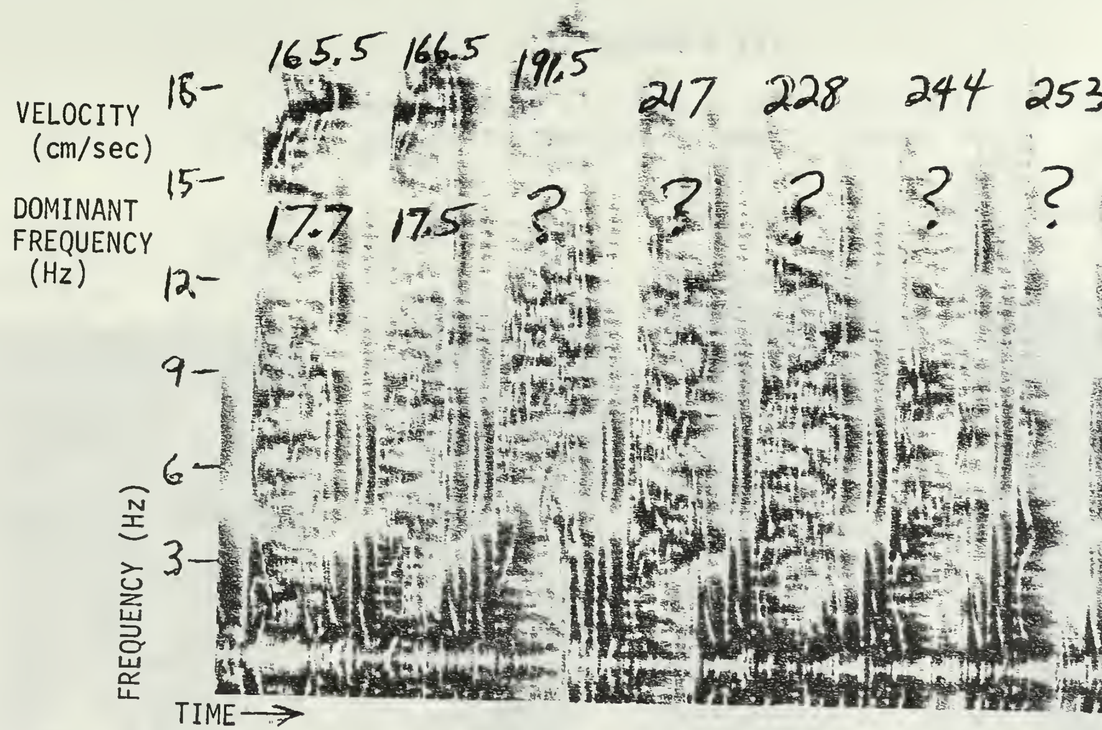
Time-Spectra of the Oscillatory Lift Force on a One-Inch Circular Cylinder in Water

Figure 4.9




Time-Spectra of the Oscillatory Lift Force on a Two-Inch Circular Cylinder in Water

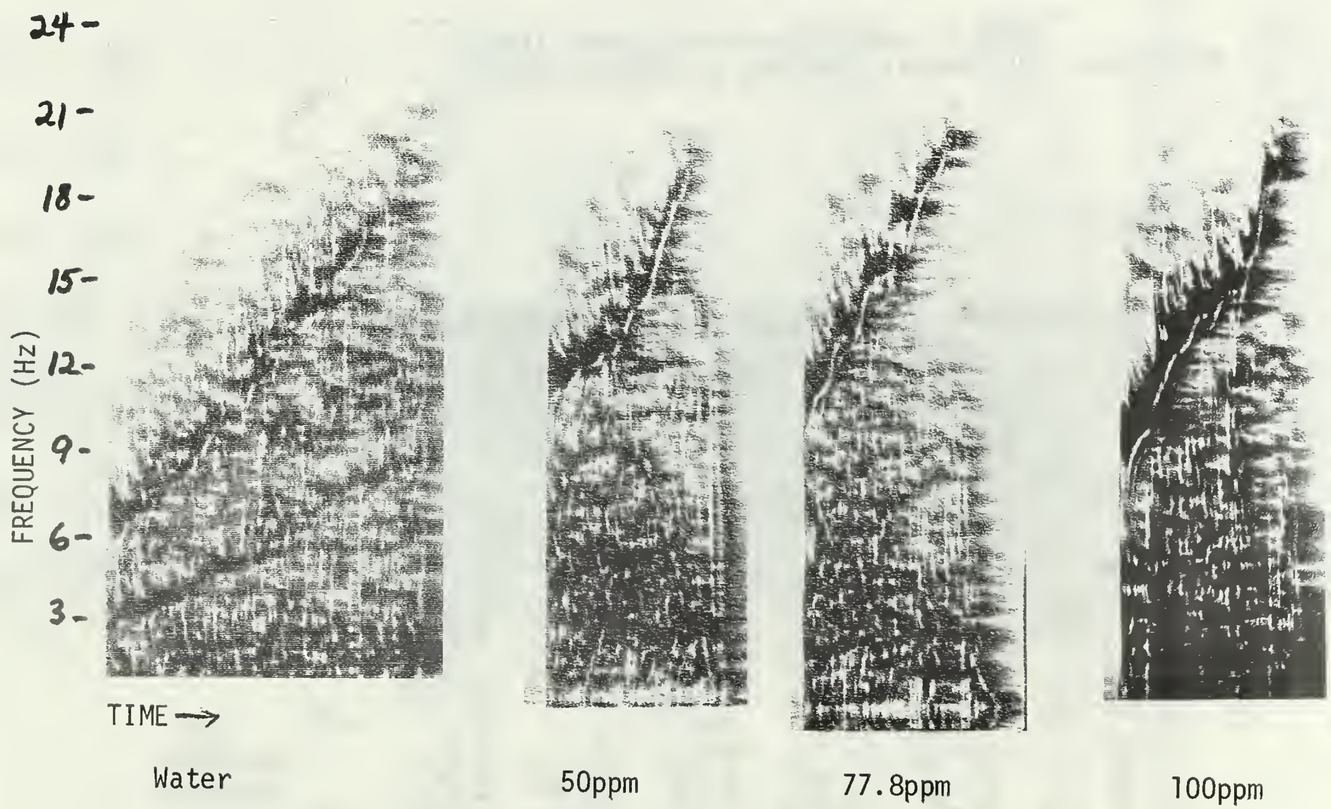
Figure 4.10




LOAD CELL - 1/2 lb

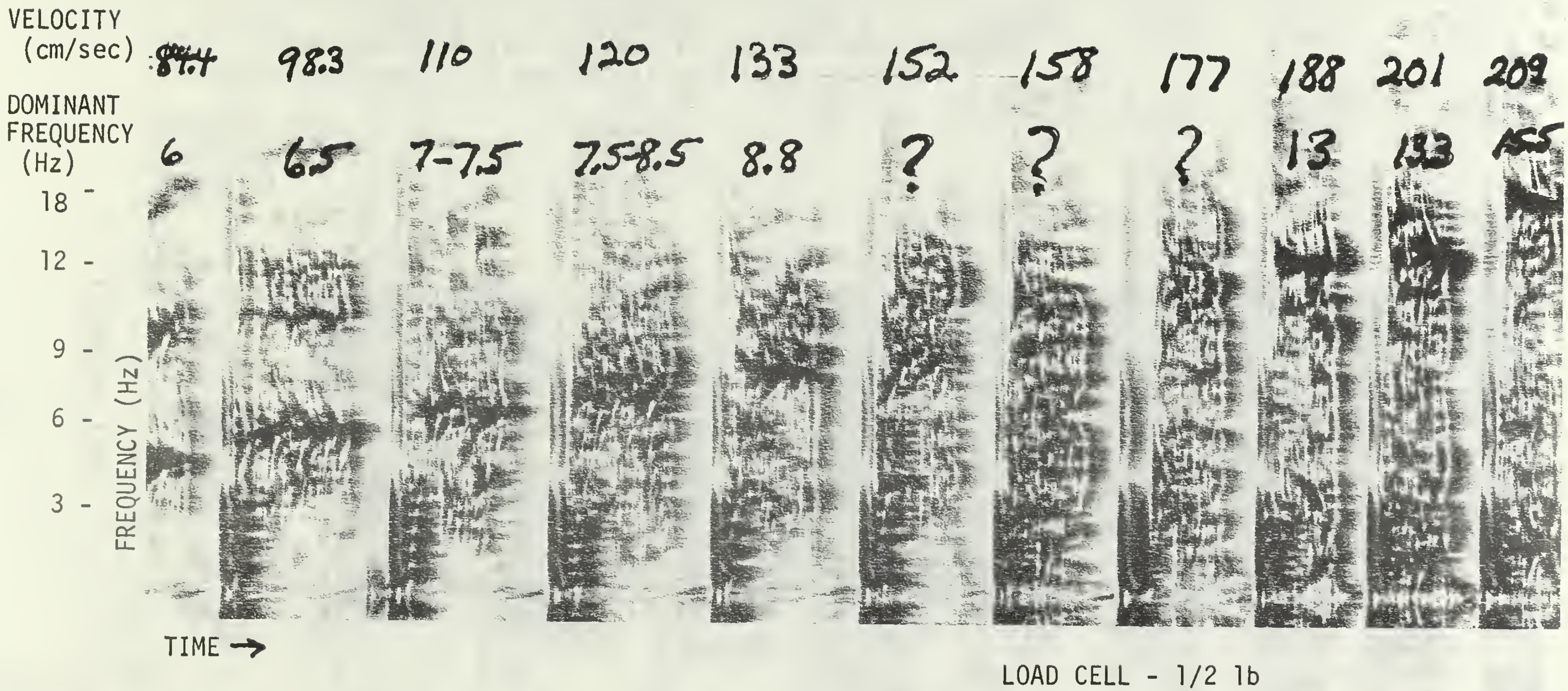
Time-Spectra of the Oscillatory Lift Force on a Half-Inch Circular Cylinder in Water

Figure 4.11



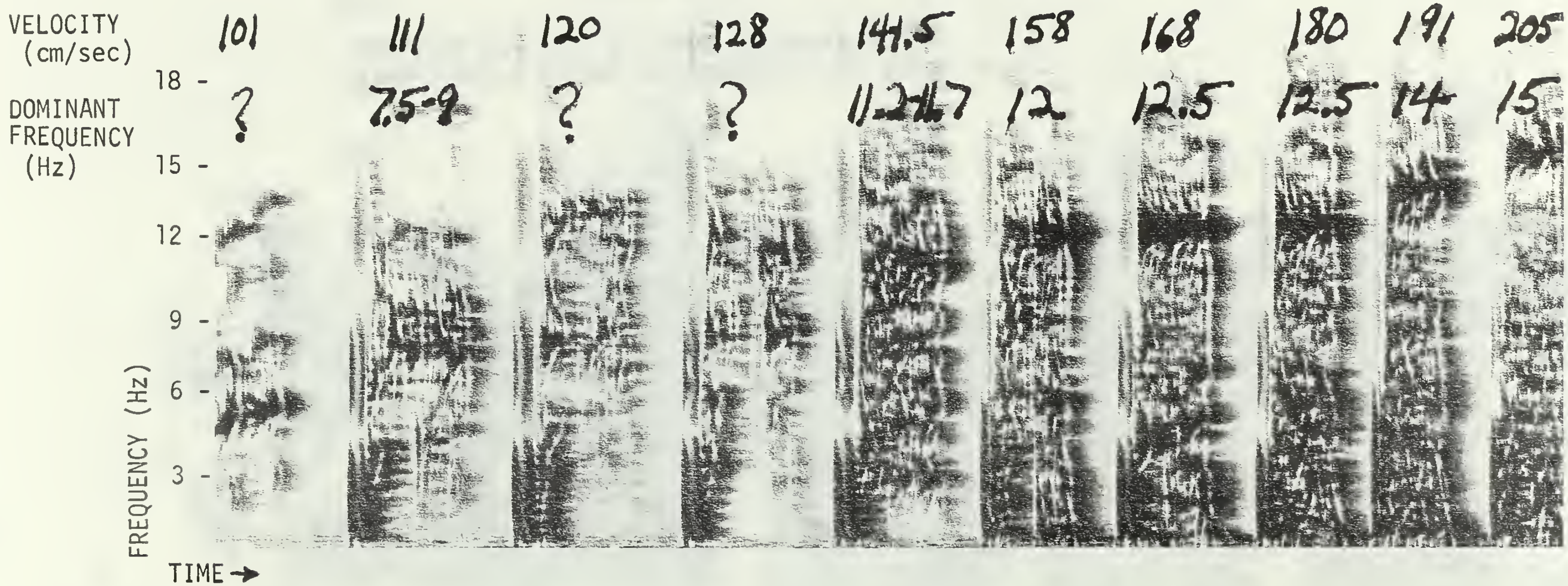

Time-Spectra of the Oscillatory Lift Force on a One-Inch Circular Cylinder in Water and in Polyox WSR301

Figure 4.12




Time-Spectra of the Oscillatory Lift Force on a One-Inch Circular Cylinder in Water

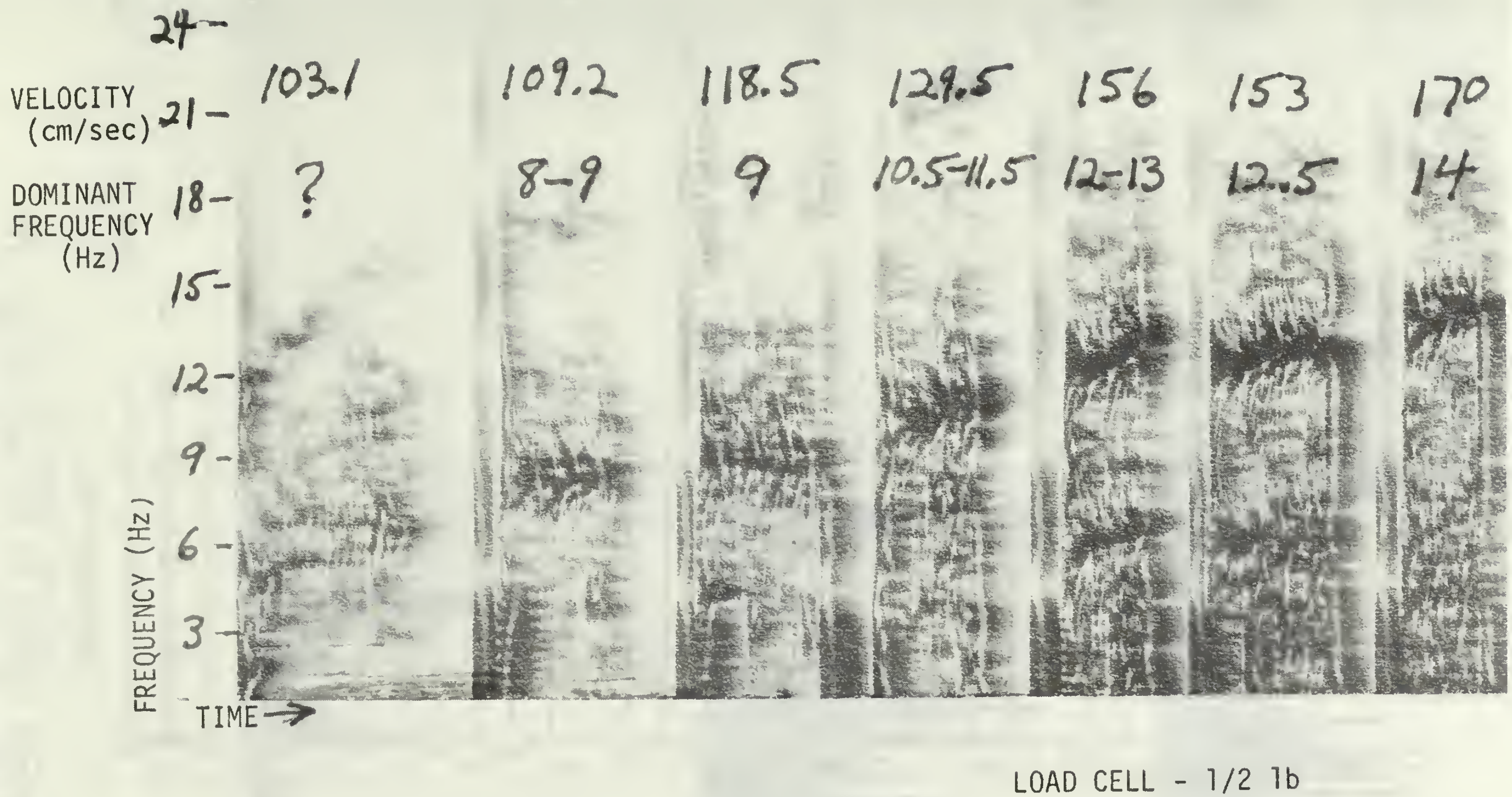
Figure 4.13




LOAD CELL - 1/2 lb

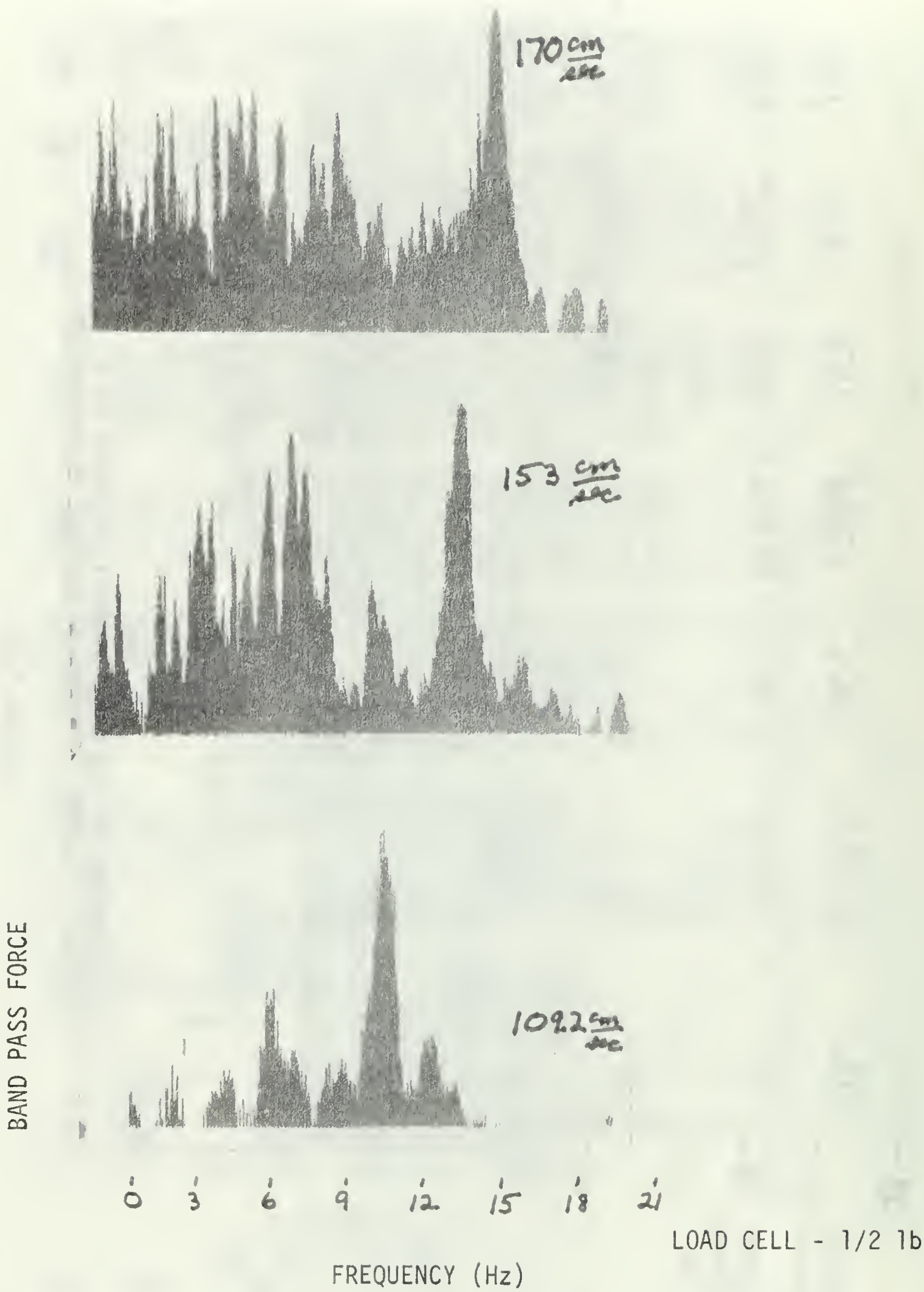
Time-Spectra of the Oscillatory Lift Force on a One-Inch Circular Cylinder in 100 ppm Polyox WSR301

Figure 4.14



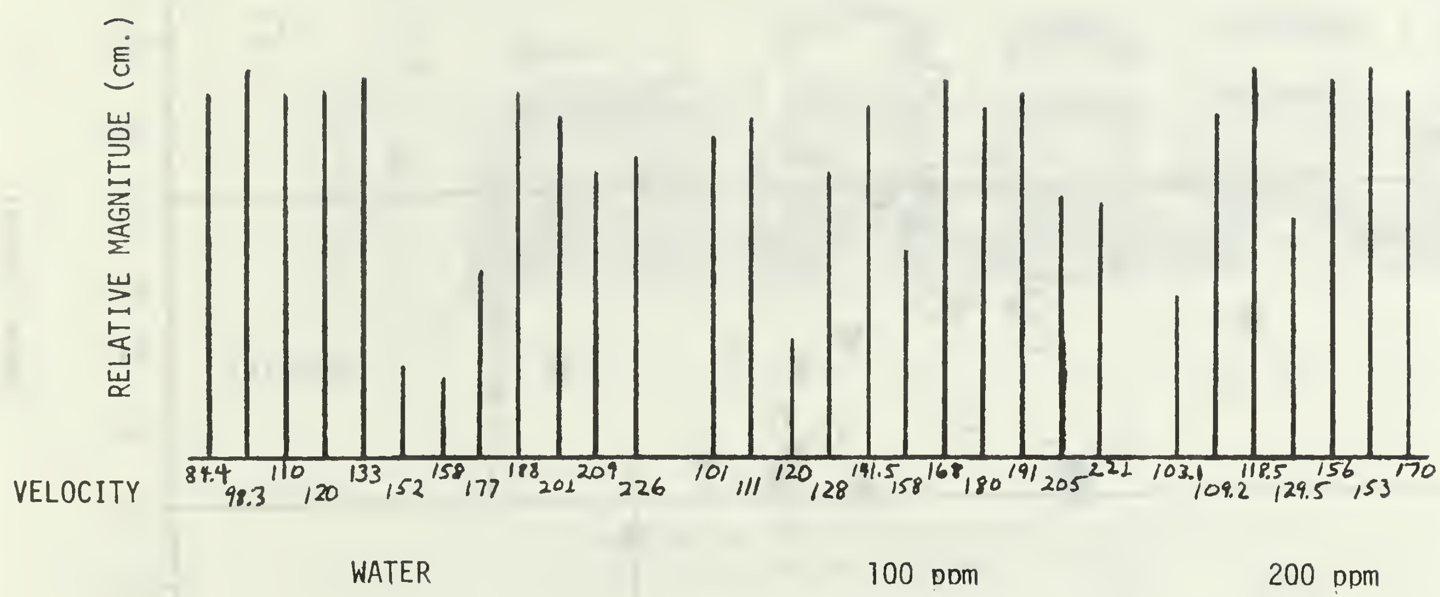

Time-Spectra of the Oscillatory Lift Force on a One-Inch Circular Cylinder in 200 ppm Polyox WSR301

Figure 4.15



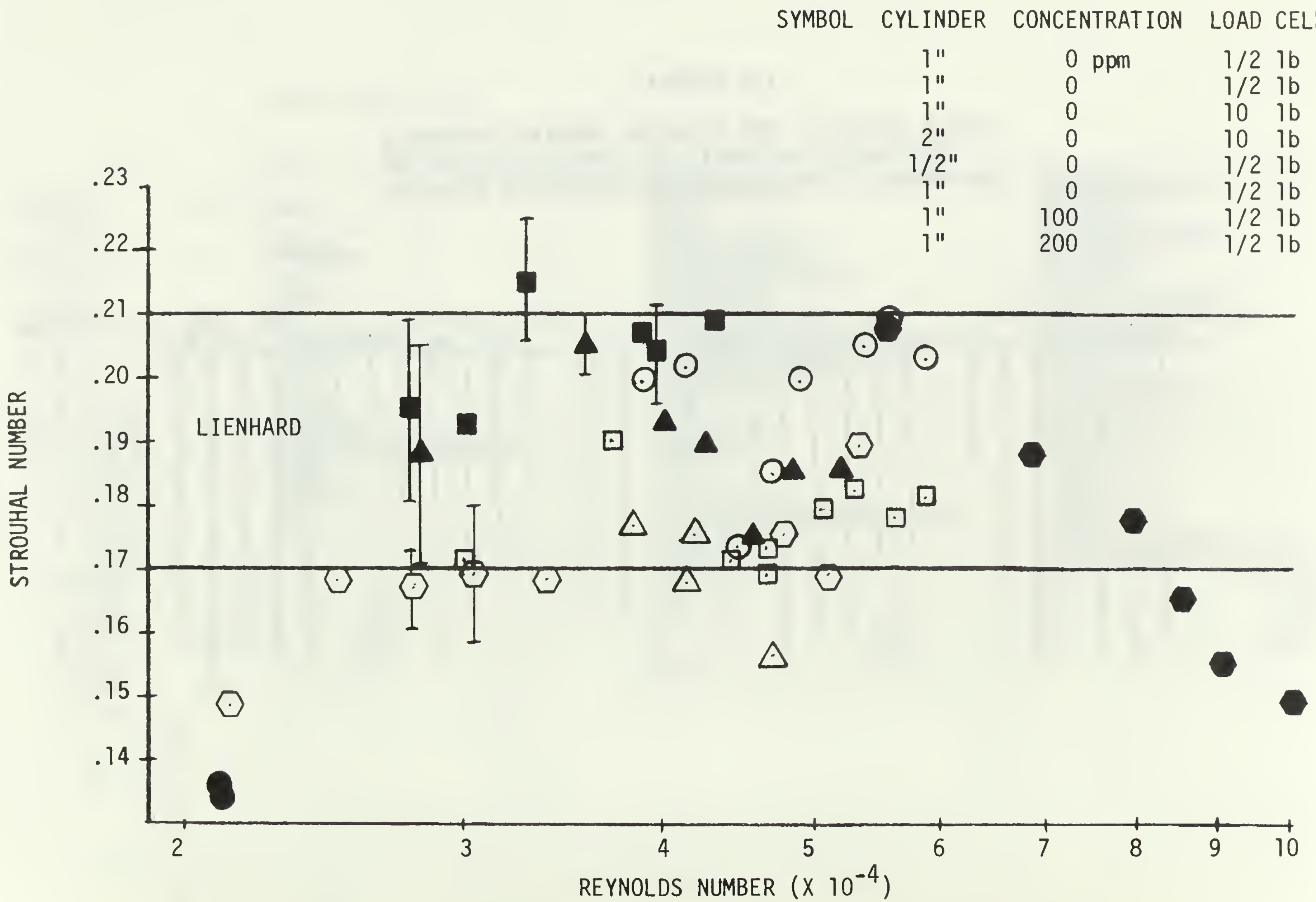

Instantaneous Spectra of the Oscillatory Lift Force on a One-Inch Circular Cylinder in 200 ppm Polyox WSR301

Figure 4.16



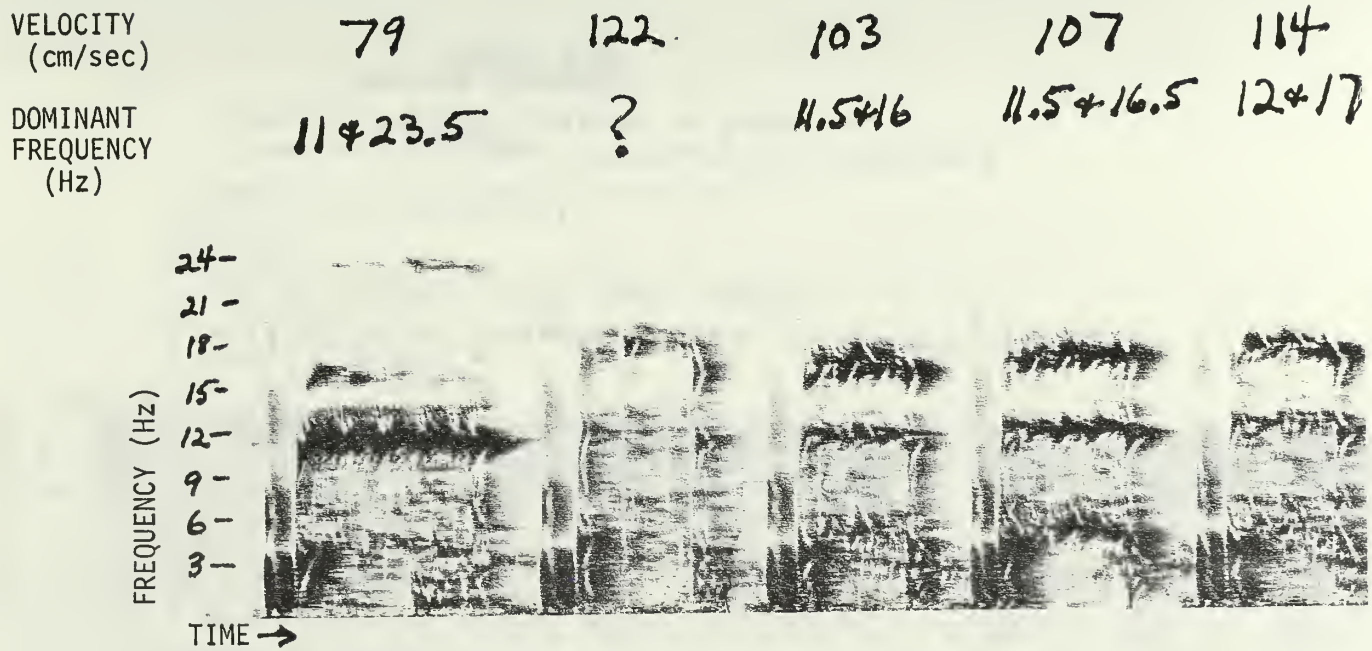

Relative Amplitudes of the Dominant Frequencies of the Oscillatory Lift Force on a One-Inch Circular Cylinder in Water and in Polyox WSR301

Figure 4.17




Dominant Frequency Components of the Oscillatory Lift Force on Circular Cylinders in Water and in Polyox WSR301

Figure 4.18




LOAD CELL - 1 lb

Time-Spectra of the Oscillatory Drag Force on
a One-Inch Circular Cylinder in Water

Figure 4.19

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| VELOCITY (cm/sec) | 109 | 109 | 140 | 125.5 | 163.5 | 151 | 172 | 186 |
| DOMINANT FREQUENCY (Hz) | 18.5 | 18.5 | 19.7 | 19.5 | 19.5 | 19.7 | 20.5 | ? |


LOAD CELL - 10 lb

Time-Spectra of the Oscillatory Drag Force on a
One-Inch Circular Cylinder in Water

Figure 4.20

GEN20839

```
      DIMENSICN INCATA(512),DATA(512)
      FACTOR=100.0/(2**31-1)
      REWIND 2
      REWIND 4
C     J IS THE NUMBER OF RECORDS (RUNS)
      DO 31 J=1,20
      READ(2,3,END=40,ERR=50) INDATA
    3 FORMAT(8(64A4))
      CALL FORM(INDATA)
      WRITE(6,70) J
   70 FORMAT ('1',10X,'RECORD NO.=',I4)
      DO 1 I=1,512
    1 DATA(I)=INDATA(I)*FACTOR
      WRITE (6,66) (DATA(I),I=1,512)
   66 FORMAT (1X,8E16.8)
      WRITE (4,3) DATA
      GO TO 31
   50 WRITE (6,51) J
   51 FORMAT ('0',5X,'READ ERROR, RECCRD NC.=',I3)
   31 CONTINUE
      STOP
   40 WRITE (6,41) J
   41 FORMAT ('0',5X,'END OF TAPE, RECORD NO.=',I3)
      STOP
      END
//ASM.SYSIN  DD  *
FORM     START 0
*        SUBROUTINE FORM(INDATA)
* THIS SUBRCUTINE WILL CCNVERT 24 BIT BINARY WORDS STORED IN INDATA OF
* AN ARRAY LENGTH SPECIFIED BY THE INDEX VALUE TO 32 BIT BINARY WORDS
* AND PLACE THESE SAME WORDS BACK INTO INDATA
*
         STM   14,12,12(13)       THIS SUBROUTINE CONVERTS
         BALR  6,0                24 BIT BINARY WORDS TO
         USING *,6                32 BIT WCRDS
         USING DATA,7
         SR    7,7
         L     11,=F'512'       THIS IS THE INDEX VALUE
         L     12,0(1)
LOOP     L     2,NUM(12)
         LR    3,7
         SRDL  2,6
         SRL   2,2
```

```
         SRDL  2,6
         SRL   2,2
         SRDL  2,6
         SRL   2,2
         SRDL  2,6
         ST    3,NUM(12)
         LA    12,4(12)
         BCT   11,LOOP
         LM    2,12,28(13)
         MVI   12(13),X'FF'
         BCR   15,14
DATA     DSECT
NUM      DS    1F
         END
//GO.FT02F001 DD UNIT=OCO,VOL=SER=GENSTIL,LABEL=(,NL),                 *
//             DISP=(OLD,KEEP),DCB=(DEN=0,RECFM=F,BLKSIZE=2048)
//GO.FT04F001 DD UNIT=2400,VOL=SER=NPS228,LABEL=(,SL),DISP=(NEW,KEEP), *
//             DCB=(DEN=2,RECFM=F,BLKSIZE=2048),DSNAME=GEN0839
```

GEN10839

```
C       RED DECK
      REAL*4LABEL(5)/20HB     AG    A      ADOT                          /
      REAL*8JTITLE(12)/96HCORR VS TAU        S. M. GENSTIL
     1   RED DECK                                                        /
      REAL*8KTITLE(12)/96HSQRTPOW VS FREQ  S. M. GENSTIL
     1   RED DECK                                                        /
      REAL*8ITITLE(12)/96HSIGNAL VS TIME   S. M. GENSTIL
     1   RED DECK                                                        /
      DIMENSION XG(900),YG(900),YC(900)
      DIMENSION X(5500),TAU(500),COR(500),Y(5500)
      DIMENSIONB(900),AG(900)
      DIMENSION S(1012),INV(1012),M(3)
      COMPLEX*8 C(1024,1,1)
      COMPLEX*8 A(1024,1,1)
      COMPLEX*8 D
      COMPLEX*8 Q
      COMPLEX*8R
      COMPLEX*8 SS
      REAL*4 DATA(512)
      PI=3.1415927
      ITYPE=2
      KK=9
      TIME =ITIME(0)*0.01
      N1=2**KK
      NPT=N1
      NST=NPT/10
      XN=N1
      T=0.0
      DT=0.01
      DD=1.0/DT
      D=DD
      F=1.0
      N2=1
      N3=1
      M(1)=KK
      M(2)=0
      M(3)=0
C     J IS THE NUMBER OF RECORDS (RUNS)
      DO 4 J=1,10
      READ (4,50) (DATA(I),I=1,512)
   50 FORMAT(8(64A4))
      DO 2 I1=1,N1
      DO 2 I2=1,N2
```

```
      DO 2 I3=1,N3
    2 A(I1,I2,I3)=DATA(I1)
      DO 3 I1=1,N1
      XG(I1)=I1
      DO 3 I2=1,N2
      DO 3 I3=1,N3
      Y(I1)=REAL(A(I1,1,1))
      X(I1)=Y(I1)
    3 T=T+DT
      CALL CORREL(X,Y,TAU,NPT,NST,COP,XM,YM,VARXY,SIGXYM,SIGXY)
      WRITE(6,44) (COR(I),I=1,102 )
      WRITE (6,45)XM,YM,VARXY,SIGXYM,SIGXY
   44 FORMAT(//' COR(I)'/((10E10.2)))
   45 FORMAT(/' XM= ',F10.6,5X,'YM= ',F10.6,5X,'VARXY=',F10.6,5X,
     & 'SIGXYM= ',F10.6,5X,'SIGXY= ',F10.6)
      CALL DRAW(NST,TAU,COR,0,0,LABEL(1),JTITLE,0.,0.,0,0,0,0,8,8, 1,LAS
     & T)
      WRITE(6,40)DT,T,F,N1
   40 FORMAT(////3X,'SAMPLING INTERVAL=',F10.6,10X,'TOTAL TIME=',F10.6,
     &10X,'FREQ=',F10.6,10X,'NO.OF DATA POINTS=',I5/)
      WRITE(6,10)(((I1,       A(I1,I2,I3),I3=1,N3),I2=1,N2),I1=1,N1)
   10 FORMAT(//' AMPLITUDE OF FOURIER FUNCTION TO BE TRANSFORMED'/(4(1X,
     &'A(',I4,      ')=',1X,   2F7.3,4X)))
      CLOCK=ITIME(0)*0.01
      CALL HARM(A,M,INV,S,-1,IFERR)
      CLOCK=ITIME(0)*0.01-CLOCK
      DO 33I1=1,N1
      XG(I1)=I1-1
   33 B(I1)=CABS(A(I1,1,1))
      CALL DRAW(100,XG,B ,0,0,LABEL(1),KTITLE,0.,0.,0,0,0,0,8, 8,1,LAST)
      WRITE(6,9999)CLOCK
      WRITE(6,20)(((I1,       A(I1,I2,I3),I3=1,N3),I2=1,N2),I1=1,N1)
   20 FORMAT(//' FOURIER TRANSFORM A(I1,I2,I3)'/(4(1X,'A('I4,       ')=',
     &1X,   2F7.3,4X)))
 9999 FORMAT( ' ELAPSED COMPUTING TIME=',1F6.2/)
      CALL HARM(A,M,INV,S,1,IFERR)
      WRITE(6,10)(((I1,       A(I1,I2,I3),I3=1,N3),I2=1,N2),I1=1,N1)
      DO 41 I=1,N1
      YC(I)=REAL(C(I,1,1))
      B(I )=CABS(A(I ,1,1))
      AR=REAL(A(I ,1,1))
      IF(AR.LE.1.E-05)AR=1.0E-05
      AI=AIMAG(A(I ,1,1))
      AG (I )=57.29578*ATAN2(AI,AR)
   41 YG(I)=REAL(A(I ,1,1))
      CALL DRAW(NPT,XG,YG,1,0,LABEL(4),ITITLE,0.,0.,0,0,0,0,8,8, 1,LAST)
      CALL DRAW(NPT,XG,Y ,3,0,LABEL(3),ITITLE,0.,0.,0,0,0,0,8, 8,1,LAST)
      TIME =ITIME(0)*0.01-TIME
```

```
      WRITE(6,9999)TIME
      ITYPE=2
   35 CONTINUE
    4 CONTINUE
      END


      SUBROUTINE POINTS(POX,POY,JB,ITYPE,IN,MULCV)
      DIMENSION POX(900),POY(900),PX(30),PY(30)
      REAL*8ITITLE(12)/96HSIGNAL VS TIME    S. M. GENSTIL
     1                                                                  /
      REAL*8LABEL(5)/40H                                                /
C     IN IS A VARIABLE FOR INITIALIZING A POINT PLOT.
C  ALSO IN INDICATES WHETHER OR NOT THIS IS A SINGLE (0),INITIAL (1),
C     INTERMEDIATE (2), OR TERMINAL (3) PLOT.
C   MULCV  SETS INTERMEDIATE (2), AND TERMINAL PLOTS(3).  SET TO 3 UNLESS
C    ADDITIONAL PLOTS ARE TO BE CALLED ON THIS GRAPH.
      NPP=0
      JF=1
      JL=JB
      MC=IN
      IREP=JB/30
      IF(IREP-1)43,41,41
   43 MC=MULCV
      GO TO 13
   41 IF(JB-IREP*30)30,12,11
   11 IREP=IREP+1
   12 DO 30 I=1,IREP
      IF(I-IREP)2,3,3
    3 MC=MULCV
      JL=JB
      GO TO 13
    2 IF(I-1)4,4,5
    5 MC=2
      JF=(I-1)*30+1
    4 CONTINUE
      JL=I*30
   13 DO 21 J=JF,JL
      NPP=NPP+1
      PX(NPP)=POX(J)
   21 PY(NPP)=POY(J)
      CALL DRAW(NPP,PX,PY,MC,ITYPE,LABEL,ITITLE,0.,0.,0,0,0,0,8,8,1
     1,LAST)
      NPP=0
      JF=JL+1
   30 CONTINUE
```

```
      RETURN
      END


      SUBROUTINE  CORREL(X,Y,TAU,NPT,NST,COR,XM,YM,VARXY,SIGXYM,SIGXY)
      DIMENSION X(5500),TAU(500),COR(500)
      DIMENSION Y(5500)
      DO 1J=1,NST
      TAU(J)=J-1
      P=0.0
      K=J-1
      NM=NPT-K
      DO 2 I=1,NM
    2 P = P + X(I)*Y(I+K)
      XN=NM
      COR(J)=P/XN
    1 CONTINUE
      XM=0
      YM=0
      DO 3 J=1,NPT
      XM=XM+X(J)
    3 YM=YM+Y(J)
      XPT=NPT
      XM=XM/XPT
      YM=YM/XPT
      VARXY=COR(1)
      SIGXY =SQRT( COR(1)-XM*YM)
      SIGXYM=SIGXY/SQRT(XPT)
      END
//GO.FT06F001 DD SPACE=(CYL,(20,2))
//GO.FT04F001 DD UNIT=2400,VOL=SER=NPS229,LABEL=(,SL),DISP=(OLD,KEEP), *
//             DCB=(DEN=2,RECFM=F,BLKSIZE=2048),DSNAME=GEN0839
```

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13. ABSTRACT

The oscillatory forces on towed semi-submerged rigid circular cylinders were measured in water and in 100 and 200 ppm aqueous solutions of Polyox WSR301. Cylinders of half-, one-, and two-inch diameters were towed in a small circular towing-tank and the hydrodynamic forces sensed by a strain gauge and analyzed for the time-dependent frequency spectra. The towing speeds ranged from 59 cm/sec to 253 cm/sec corresponding to Reynolds Numbers from $2 \times 10^4$ to $1 \times 10^5$. The Strouhal Numbers based on the dominant frequency of the oscillatory lift were between 0.17 and 0.21 and are in agreement with the existing data for a completely submerged circular cylinder. These frequencies were not influenced by either the air-water interface or the addition of drag reducing polymers. Also independent of the polymer concentration was the amplitude of the life force. Attempts to interpret the oscillatory drag component proved inconclusive.

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| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Circular Cylinder | | | | | | |
| Strouhal Number | | | | | | |
| Polyox | | | | | | |
| Surface-Piercing Struts | | | | | | |
| Drag Reduction | | | | | | |